

F I B R E G R A T I N G R E F L E C T O R S
A N D
B A C K W A R D - W A V E - C O U P L E R S

by

Christos Elia Vassilopoulos

A Thesis Submitted for the Degree of
Doctor of Philosophy
in the
University of London .

Department of Electrical Engineering,
Imperial College of Science and Technology,
London SW7 2BT .

July 1987

To Joanna
and to my parents
Elias and Stella

A B S T R A C T

Fibre grating reflectors and backward-wave-couplers have found applications mainly as narrow-band optical filters for Wavelength-Division-Multiplexing, as spectrally selective mirrors for fibre laser cavities and as external feedback elements for linewidth narrowing of conventional semiconductor lasers.

A complete theoretical analysis has been conducted on both devices, and structures with typical coupled bandwidths of 0.01 nm, for interaction lengths of 1 cm, have been designed. In the case of the backward-wave-coupler, the effects of direct reflection and forward coupling on the coupling process, for a nearly symmetrical configuration, have also been examined. Special cases involving combinations of forward and backward coupling between two and three waveguides have been considered, in the design of a four-port device.

An extensive fabrication program has been devised to produce holographic gratings, initially on flat plates, and later on the flat side of D-shaped optical fibres, kindly made available to us by Andrew Corporation (A.C) and British Telecom. (B.T.). After suitable etching to gain access to the evanescent field of the core, the fibres were conveniently potted in epoxy, floating with their flat side in

the surface. The gratings were holographically produced on photoresist with periodicities $0.279\text{ }\mu\text{m}$ for operation at 800 nm with the A.C fibre, and $0.358\text{ }\mu\text{m}$ at 1000 nm for the B.T. fibre. Some reactive ion etching experiments were also undertaken, showing that it is possible to transfer the grating from the photoresist mask into the fibre.

The grating reflectors have been tested, using both an experimental, tunable Styrl 9 Dye laser and a standard monochromator, demonstrating coupled bandwidths of a few Å and reflectivities around 70 % , for grating lengths of a few mms. Consideration is also given to further developments, required to narrow the bandwidth and increase the reflectivity.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr J.R. Cozens for his encouragement, support and advice throughout this work.

Additional thanks,

to Prof. M. Green , Dr K. Leaver and all the members of the group of Optical and Semiconductor Devices for their moral support,

to Dr R. Taylor of the Physics Department, for allowing me to use their laser facilities, and for his help with the Dye laser experiments,

to the Andrew Foundation for financial support,

to the Andrew Corporation and to the British Telecom for providing the special D-shaped fibre, and the Monochromator testing equipment.

Finally, I would like to thank Ian Healey for his help in the fabrication work, in the latter stages of this project.

CONTENTS

Abstract

Aknowledgements

CHAPTER 1 : INTRODUCTION pp. 8 - 44

1.1	Narrow band filtering requirements for optical communications	8
1.2	Filtering devices for wavelength division multiplexing	14
1.3	Devices based on grating couplers and reflectors	36
1.4	Summary	43

CHAPTER 2 : THEORY pp. 45 - 121

2.1	Coupling theory	48
2.2	Directional coupling	53
2.3	Grating assisted directional couplers	57
2.3.1	Contradirectional Coupling	57
2.3.2	Bragg reflection in a periodic waveguide	66
2.3.3	Codirectional coupling	70
2.4	Composite coupling processes	72
2.4.1	Synchronous operation	75
2.4.2	Near-synchronous operation	85
2.5	Three-waveguide structures	91
2.5.1	Directional versus contradirectional coupling in a three-waveguide structure	92
2.5.2	Three-waveguide grating coupler	103
2.6	Evaluation of the coupling coefficients for different waveguide models	106

2.6.1	The slab waveguide reflector	106
2.6.2	The slab waveguide coupler	110
2.6.3	The rectangular waveguide grating coupler	115

CHAPTER 3 : DESIGN pp. 122 - 148

3.1	Design parameters: bandwidth, beatlength, reflectivity and sensitivity	122
3.2	Design procedure	129
3.3	Numerical design based on asymmetric slab waveguides	131
3.4	Numerical design for fibre couplers based on the rectangular waveguide model	145

CHAPTER 4 : FABRICATION pp. 149 - 224

4.1	Techniques for grating fabrication	149
4.2	Grating fabrication on photoresist films	152
4.3	Fabrication of holographic gratings on plane glass substrates	159
4.3.1	Sample preparation	159
4.3.2	Exposure and development	165
4.3.3	Evaluation of the grating masks	169
4.3.4	Reactive ion etching	178
4.4	Fabrication of holographic gratings on optical fibres	186
4.4.1	Fibre availability	186
4.4.2	Fabrication of grating masks on "free" fibre lengths	193

4.4.3	Fibre potting techniques	197
4.4.4	Grating fabrication on potted fibre lengths	200
4.5	The grating coupler configuration	207
4.5.1	Available coupler configurations	207
4.5.2	Grating coupler fabrication	212
4.6	Embossing technique for grating fabrication on polymer films	220
4.7	Grating fabrication by duplication	223
CHAPTER 5 : EXPERIMENTAL WORK		pp. 225 - 252
5.1	Diffraction experiments	225
5.2	Grating reflector experiments	229
5.2.1	Dye laser experiments	229
5.2.2	Monochromator Experiments	240
5.2.3	Theoretical verification	249
CHAPTER 6 : DISCUSSION AND CONCLUDING COMMENTS		
		pp. 253 - 261
6.1	Discussion	253
6.2	Tuning	258
6.3	Concluding comments	260
REFERENCES		pp. 262 - 290

CHAPTER 1

INTRODUCTION

1.1 Narrow Band Filtering Requirements for Optical Communications

Despite recent developments in the area of optical communications, anticipated future needs for analogue or digital transmission of video, audio and data signals through optical fibres will soon demand a significantly greater bandwidth availability.

Single mode fibres characterised by low attenuation and large bandwidth allow the encoded information to be transmitted at increasingly high bit rates. The signal can either be modulated at the source, using directly modulated semiconductor lasers and pulsed lasers, or externally, using high speed electro-optic modulators and switches, thus avoiding spectral width broadening and instability problems associated with high-frequency modulated lasers. Their design is usually based on directional couplers surrounded by or fabricated in electro-optic material with switching voltages of 5 V capable of 2 Gbit/sec rates in the 1300-1500 nm

wavelength region (1.1).

Although the highest reported bit rate is 6 Gbit/sec (1.2) an "electronic barrier" at around 8 Gbit/s is generally acceptable (1.3). It must be clear, however, that optical components have the capability to operate at far higher bit rates.

In data encoding and time-division-multiplexing the transmission and detection performances are based on optical power rather than optical electromagnetic field. To exploit the true potential of the optical spectrum, light must be treated as a carrier medium which can be amplitude, frequency and phase modulated, in a manner similar to microwave radio systems. This implies that operation at 1500 nm will correspond to an optical frequency of 200,000 GHz.

Optical frequency-division multiplexing (Fig.1.1), primarily used with coherent systems, is based on a single optical-frequency master oscillator. Its signal is divided between frequency converters generating a number of different subcarriers which are individually modulated and then combined to be transmitted through an optical fibre (1.4). At the receiver a heterodyne process is used, with local oscillator lasers locked into the incoming signal, to separate the different subcarriers and recover the original data.

A basic precondition for a coherent system, using optical frequency-division multiplexing, is the development of very stable laser oscillators with extremely narrow linewidths. At the moment, distributed feedback lasers (DFB) are becoming commercially available (1.5). These use a grating

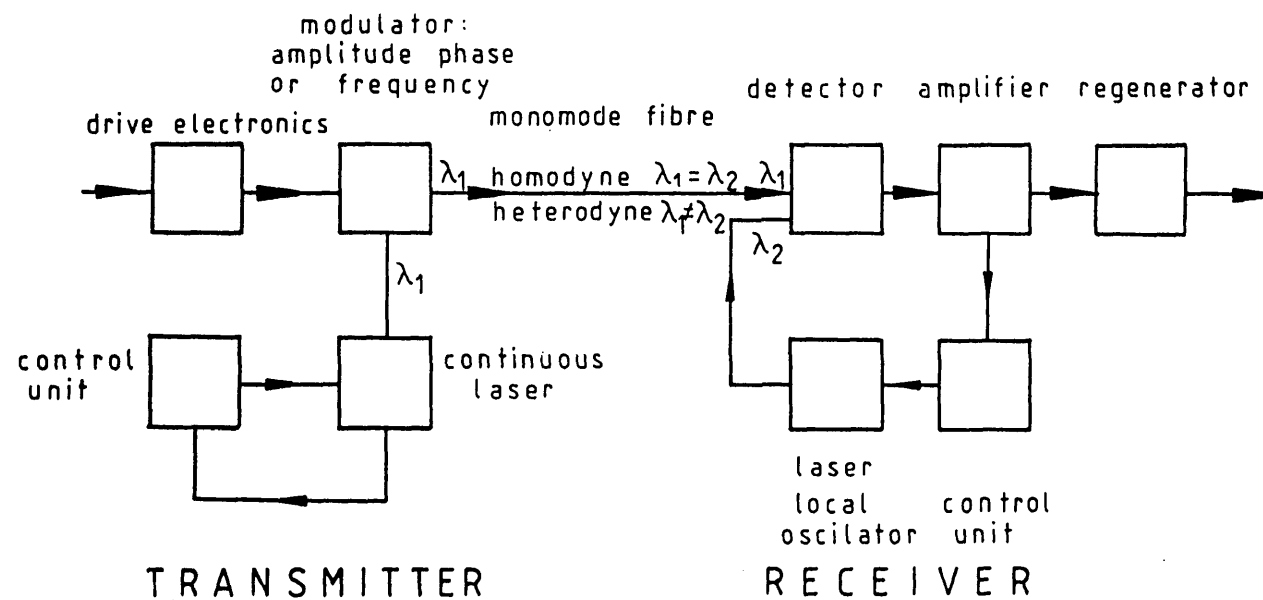


Fig. 1.1

Schematic configuration of a coherent communications system as presented in (1.4).

structure, close to the active region, to provide distributed optical feedback, preferentially selecting wavelengths related to the grating period, of spectral linewidths less than 20 MHz .

Wavelength Division Multiplexing (W.D.M.) combines some of the merits of data encoding and frequency division multiplexing, without the necessary precondition of coherence, by allowing a number of modulated signals from sources at distinctly different wavelengths to be simultaneously transmitted through a single fibre (1.6). The received signal is then separated into its individual components and the information is finally recovered.

Although W.D.M. technology has not yet matured, it has already been introduced into some practical, mainly experimental systems (1.7, 1.8, 1.9) , and is expected to play a major role in future optical communications.

W.D.M. makes full use of the low loss characteristics of single-mode optical fibres over a wide wavelength range. Consequently, the transmission capacity per fibre can be tremendously increased, resulting in significant cost reduction. Other advantages include simultaneous transmission of different modulation schemes and potential flexibility in system upgrading, including easy expansion after fibre installation to accomodate future additional services.

Fig. 1.2 shows a schematic representation of a hypothetical four-wavelength transmission link using a single fibre. Such a system can either be unidirectional, with all the information travelling one way from a transmitting to a

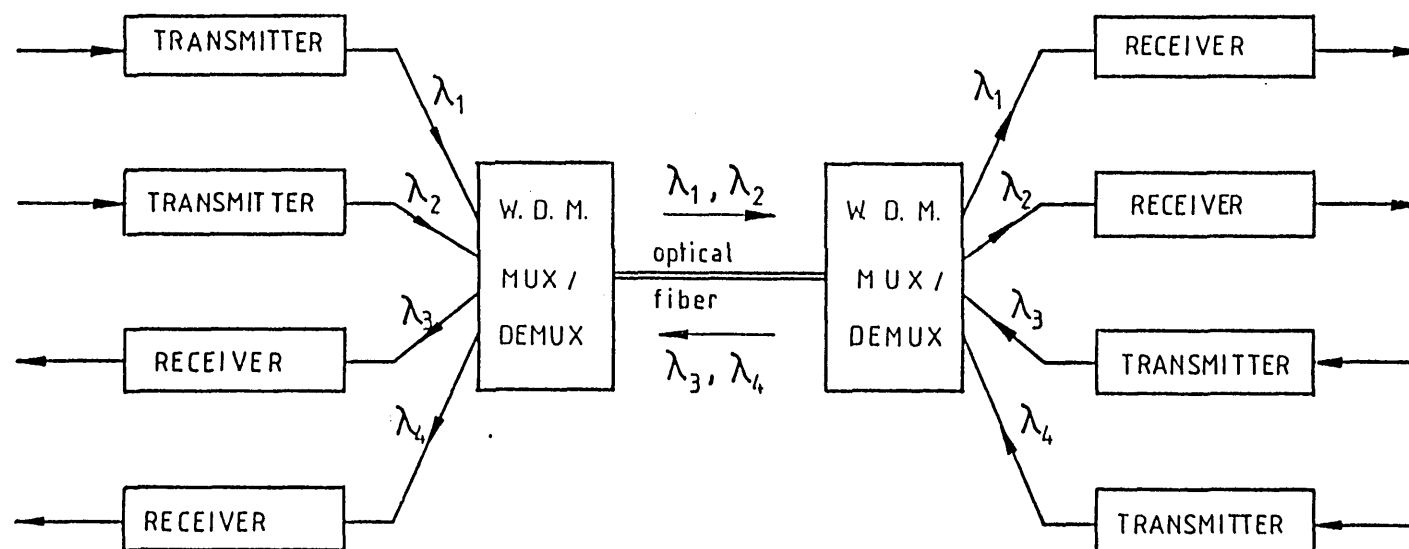


Fig. 1.2

Wavelength division multiplexing in a hypothetical four-wavelength channel optical-fibre transmission link using a single fibre (1.9).

receiving station, or bi-directional with data flowing in both directions simultaneously.

The carrier wavelengths are optically mixed and separated using spectrally selective devices at both ends, called multiplexers (MUX) and demultiplexers (DEMUX) respectively. MUX/DEMUX must be characterised by low insertion loss and high spectral selectivity. Their half intensity emission bandwidth must lie below, say 1 nm to allow light from a number of modulated laser diodes to be inserted into a single fibre and separated at the other end with low loss, thus minimising the undesirable effects of chromic dispersion and crosstalk. They must be designed to operate at the 1.3-1.5 μm region, corresponding to the minimum loss range for single mode silica fibres.

For effective W.D.M. it is important to develop laser diodes which avoid spectral broadening during high frequency modulation, by maintaining a single longitudinal mode emission. Some encouraging results have been obtained with dynamic single-mode (DSM)-DBR laser diodes, which retain linewidths of 0.2-0.4 nm at modulation frequencies of 1.5-2 GHz (1.10). This is also an area where fibre lasers of narrower bandwidths are expected to find application.

1.2 Filtering Devices for Wavelength Division Multiplexing

A number of different devices have been proposed and implemented as MUX/DEMUX for WDM. They are broadly based on diffraction gratings and thin film interference filters, on optical directional couplers and on axial grating reflectors and couplers. They vary in terms of sophistication, spectral narrowness and selectivity, tunability, loss, cross-talk isolation, and complexity of fabrication. A brief examination of some of these devices would, therefore, be useful, in order to point out the potential advantages of grating reflectors and couplers over the other devices.

- i) Devices using dispersive elements and dielectric thin film interference filters.

Angularly dispersive devices have the advantage of being capable of multiplexing and demultiplexing a large number of channels, using a single element such as a prism or a grating. Earlier devices employed prisms (1.11), but were found to be impractical due to their low angular dispersion. At present, diffraction gratings and blazed gratings are being used as the main angularly dispersive element.

A most popular and widely studied design is the Littrow-type DEMUX (1.12), Fig.1.3a . The composite optical signal

from the input fibre is collimated by a lens arrangement and reaches the diffraction grating, where it is angularly dispersed, the different reflected wavelength components being directed back and focused by the lens on their corresponding receiving fibres. Both the input and output fibre must be arranged to lie on the focal plane of the lens. A superior design (1.13), Fig.1.3.b, includes a GRIN-rod lens, achieving greater compactness and ease of alignment. A rare variation uses different lenses for the input and output fibres (1.14).

The particular device shown in Fig.1.3.b, proposed as a MUX/DEMUX (1.15) uses four different channels, from 812 nm to 885 nm with losses between 4 - 7 dB. An interchannel separation of 18 nm is required for a crosstalk isolation of 40 dB; these are typical figures for the performance achieved by grating DEMUX. Although up to 20-channel grating demultiplexers for operation between 1.2 - 1.7 μm have been proposed (1.16), no substantial improvement in the passband width has been reported.

For efficient operation, grating MUX/DEMUX require multi-mode fibres with large cores to collect the dispersed signals. The use of single-mode fibre significantly degrades the coupling efficiency into the receiving fibres, increasing the loss; such degradation is more severe in MUX. Hence, even though a grating may be applicable to demultiplexing, it is not very suitable for MUX or MUX/DEMUX units.

On the other hand, multiplexers can be realised by making use of the wavelength selectivity of dielectric thin film filters; their filtering characteristics designed independ-

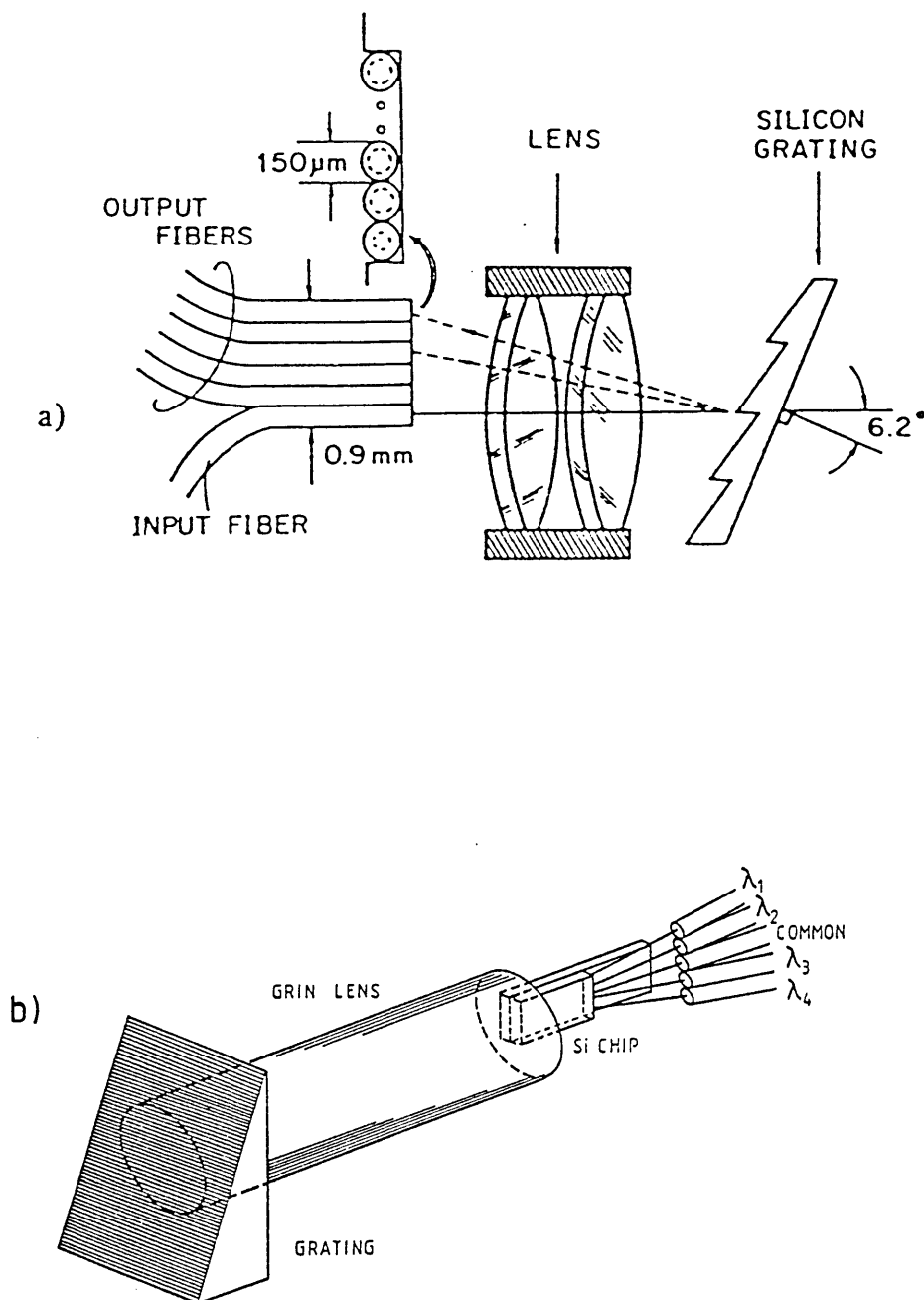


Fig. 1.3

Littrow-type grating demultiplexer:

a) Original design (1.12) ,

b) Improved design with Grin-rod lens (1.13) .

ently of the fibre parameters.

A dielectric thin film filter consists of a large number of alternate high and low refractive index dielectric films (1.18). It is possible to design and fabricate different types of filters, both bandpass and edge-filters (i.e. long-wavelength-pass and short-wavelength-pass filters), to suit WDM requirements. A wide range of devices using thin-film filters have been designed, including the GRIN-rod lens type (1.18), Fig.1.4.a, the multi-reflection type (1.19), Fig.1.4.b, and the fibre-end type (1.20), Fig.1.4.c. A more interesting variation uses the beam-splitter principle with interference filters and three-butt coupled fibres (1.21), which has been realised using both multimode and single-mode fibres, the latter requiring a more precise alignment. For single mode devices, typical performance includes losses of 0.5 - 1 dB/device and interchannel separation of 30 - 100 nm (determined from the interference filter) with a crosstalk attenuation of 20 - 50 dB for operation in the 0.8 - 1.3 μm range. Since it is basically a two-channel device, a number of these, each one with different characteristics, will have to be cascaded for multi-channel operation, increasing the total loss.

It is possible to use fibre end-type devices for both MUX and DEMUX, although grating DEMUX appear to be superior. Hybrid-type devices (1.22), incorporate gratings for DEMUX and dielectric thin film filters for MUX (Fig.1.5), as MUX/DEMUX units for bidirectional WDM systems.

Devices using dispersive elements and/or thin-film

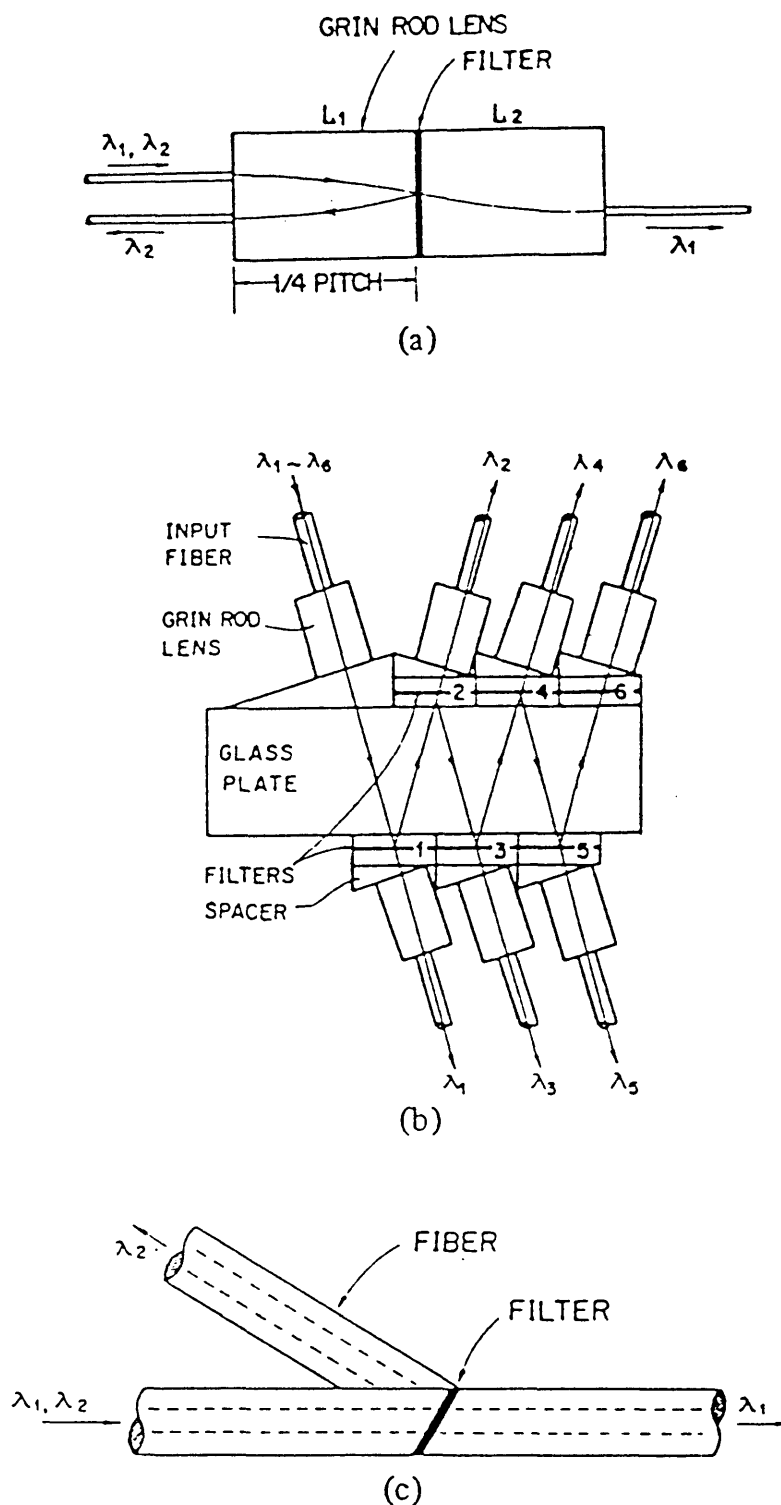


Fig. 1.4

Demultiplexer designs based on thin film dielectric filters:

- a) GRIN-rod lens type (1.18) ,
- b) Multi-reflection type (1.19) ,
- c) Fibre-end type (1.20) .

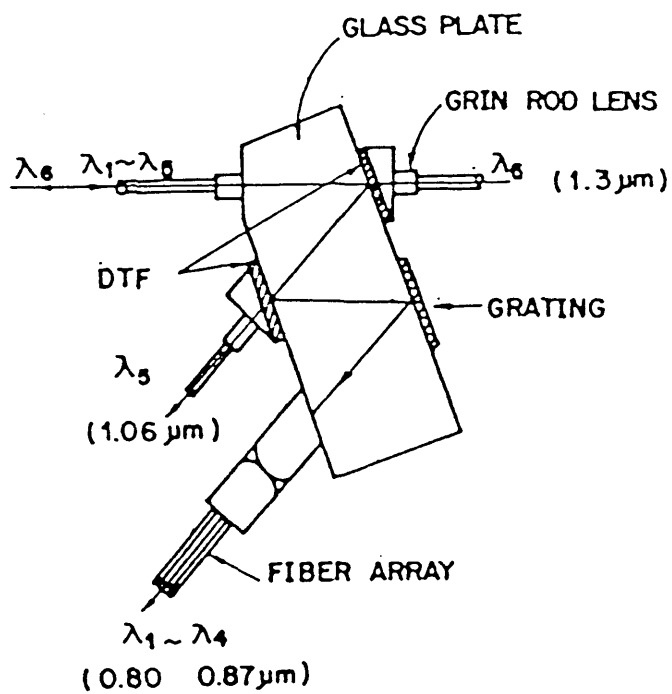


Fig. 1.5

MUX / DEMUX unit incorporating gratings and dielectric thin film filters (1.22) .

dielectric filters are usually bulky, mainly designed for multimode fibres. Gratings have the advantage of separating a number of channels simultaneously, though this is counteracted by fabrication complexity, losses, and poor coupling efficiencies resulting from severe alignment problems, in particular with single-mode fibres. On the other hand, the smallest inter-channel separation recorded is no better than 20 nm for a 30 dB crosstalk isolation with 7 dB losses, limiting the number of the possible available channels in the useful wavelength region.

ii) Devices using directional couplers.

In comparison to gratings and thin film interference filters, directional couplers offer simpler designs, fewer losses, and architectural compactness. Although they are basically two channel devices, a number of them can be cascaded for multi-channel operation.

Evanescent couplers rely on the near equality of the phase velocities of two adjacent, parallel waveguides to effect significant power exchange. The coupling process is periodic and the minimum length over which the light is completely transferred from one core into the adjacent core, known as the beatlength, is given by

$$L = \pi / (2 * c) ,$$

where c is the coupling coefficient for the two interacting waveguide modes.

Directional couplers have been implemented both in integrated-optic and fibre-optic forms and have found applications as switches and modulators for data encoding, beam splitters for interferometric applications, sensors etc.

Coupling between identical waveguides appears to be rather insensitive to the wavelength of operation, the coupling process only influenced by the wavelength dependance of the coupling coefficient, and hence of the beatlength. The filtering characteristics of couplers using identical waveguides over a single beatlength, appear to be of little practical interest.

For couplers with dissimilar waveguides, the phase matching condition becomes wavelength dependant and there will be a wavelength range for which significant power transfer will occur. All the different coupler designs proposed for MUX/DEMUX applications employ dissimilar waveguides, in an attempt to maximise the angle between the two dispersion characteristics, thus enhancing the wavelength selectivity. The coupled bandwidth can be further reduced by extending the distance between the two guides, thus weakening the coupling strength, but this has the undesirable effect of increasing the beatlength, resulting in longer devices. Although the wavelength selectivity can be, in general, improved by the combined efforts of guide dissimilarity and weak coupling, directional couplers suffer from fabrication tolerances. Some form of tuning is, therefore, necessary in order to "hit" the phase matching condition at a specified wavelength.

Wavelength filters with dissimilar waveguides have been

fabricated as Ti-diffused strip waveguides in LiNbO_3 (1.23), demonstrating nearly 100 % transfer, with a 3 dB bandwidth of 20 nm for a beatlength of 1.5 cm and for crosstalk levels above 17 dB. Typical tuning rates of 11 nm/V over 60 nm have been reported.

Fabrication in materials compatible with optoelectronic integrated circuits offers the advantage of monolithic integration with sources, detectors, and electronic circuitry to form wavelength multiplexing and demultiplexing units. An integrated optics filter (Fig. 1.6.a) fabricated in InGaAsP-InP (1.25) has demonstrated a 3 dB bandwidth of 22 nm for a surprisingly short beatlength of 1.9 mm, by using two very dissimilar waveguides, both in indices and dimensions, to enhance the wavelength selectivity of the coupler. No information is provided about the crosstalk isolation, though it is expected to be of the same order as for the LiNbO_3 device. No particular reference is made to the loss factor, but for an InGaAsP-InP waveguide produced by liquid phase epitaxy, the absorption loss for single mode guiding is at least 4 dB/cm (1.25). By comparison the loss of a directional coupler fabricated in LiNbO_3 is 1 dB/cm (1.26).

Integrated optic filters offer potential monolithic integration in optoelectronic integrated circuits. The availability of a wide range of materials with different indices and large electro-optic effects, combined with the development of sophisticated masking techniques for precise fabrication, make the implementation of integrated optical filters rather attractive. Their usefulness is, however, limited by loss

and incompatibility with existing communication fibres. Despite a lot of research in this area (1.27), efficient power coupling from a planar waveguide to an optical fibre still remains an unsolved problem, posing a serious challenge to the implementation of integrated optics systems.

On the other hand, losses of 1 - 4 dB/cm, though not severe by integrated optics standards, appear huge by comparison to the 0.16 dB/km obtained with single-mode laboratory fibres at 1.55 μm .

Single-mode optical fibre couplers look promising for wavelength-multiplexing applications, because of their inherently low transmission losses. Different variations of fibre couplers have been reported, the most popular being the polished coupler, the coaxial-directional-coupler, and the fused biconical taper coupler.

Polished couplers (1.28, 1.29), Fig. 1.6.b, rely on dissimilar fibres to improve the wavelength selectivity. Typical coupled bandwidths of 90 nm have been reported for interaction lengths of 3 mm in the 1 - 1.5 μm range. Although there is a small loss of 0.5 dB from scattering, due to imperfect polishing, very high coupling efficiencies can be obtained. Tunability is available either by means of lateral displacement (1.30) or in terms of variations in the refractive index of the intermediate layer. A shift in the crossover wavelength of about 15 nm has been demonstrated by using an intermediate layer of 1.3 % lower index (1.29).

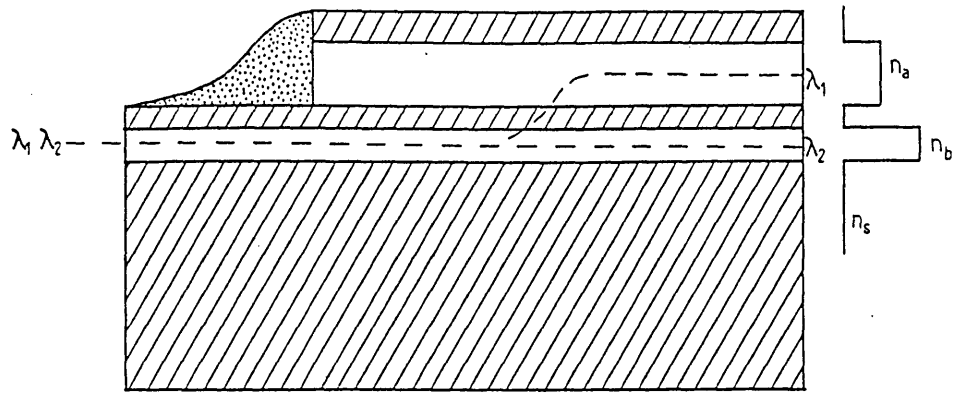
Due to the poor crosstalk isolation of the coupler (10 to 25 dB), when used for demultiplexing channels of narrow spac-

ings, an additional narrow-band filter must be inserted to improve crosstalk suppression.

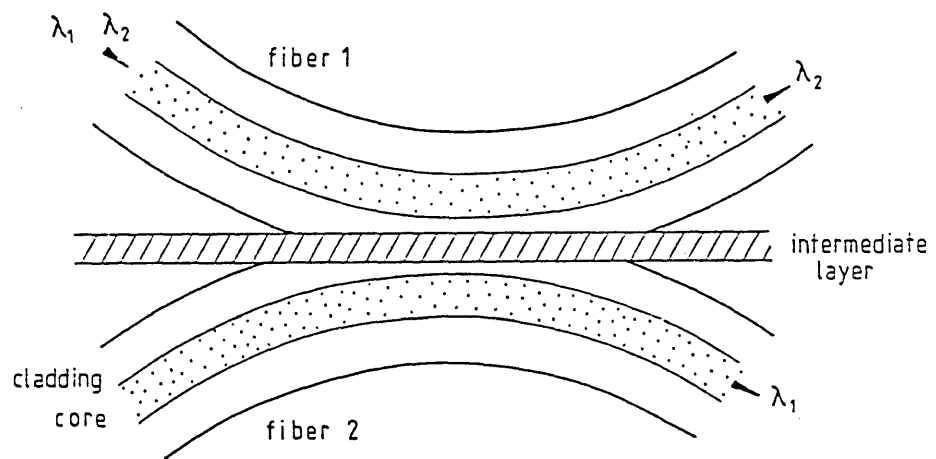
The dissimilarity argument can be fully exploited by using fibres, different, not only in dimensions and indices, but also in type; for example one may be a step-index type, while the other may have a triangular or parabolic profile (1.31). On the other hand, directional coupling can be considered between a rod and a tube waveguide. The coaxial-directional-coupler, was originally realised using Chance-Pilking-ton BSC glasses and has been extensively studied (1.32, 1.33), with applications both as an electro-optic modulator and a sensor element. It has being recently fabricated in silica, and its potential as a filter for W.D.M. is currently under investigation.

The coaxial coupler has a stop-band filtering response, although, when used in a more elaborated manner similar to that in (1.34), a bandpass response can be obtained (Fig. 1.6.c). Its filtering characteristic has not yet been satisfactorily demonstrated, though a bandwidth of 10 nm is anticipated for an interaction length of 10 cm. The light ending in the tube is not easily recoverable, so the coaxial coupler, in its present form, cannot find application as a multiplexer/demultiplexer. It can be, however, effectively employed as an in-line pre- or post-filter for suppressing unwanted wavelengths, improving crosstalk isolation.

Fused biconical-taper couplers (1.35) rely on the dependence of the coupling process on the interaction length. For couplers with identical fibres, the wavelength response is



a)



b)

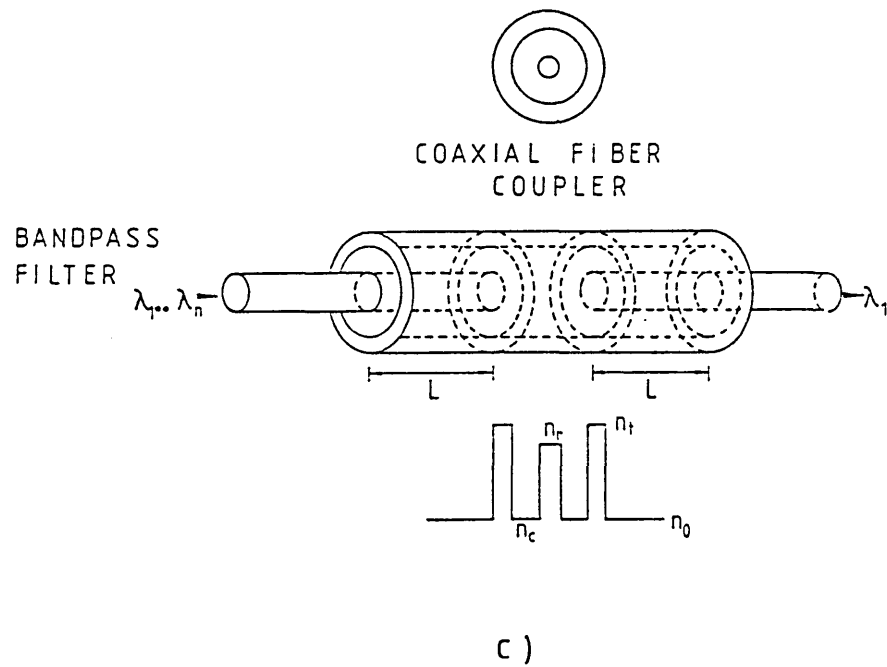


Fig. 1.6

MUX / DEMUX filtering devices based on directional couplers:

a) Integrated Optics Coupler ,

Fibre Optics Filters based:

b) Polished Coupler ,

c) Coaxial Directional Coupler .

Elaborate configuration for bandpass response.

rather slow over a single beatlength, but becomes more interesting for multi-beatlength operation. If the light is allowed to oscillate for a number of times between the two cores, an approximately sinusoidal response can be obtained, its frequency dependent on the ratio of the beatlength to the interaction length (1.36). Concatenated filters have been successfully realised by cascading a number of fused tapered couplers (1.37). Typical figures, for a device using two such couplers with 20 mm and 200 mm interaction lengths, include a 3 dB bandwidth of 20 nm, 1 dB loss and 20 dB cross-talk isolation (1.38).

In general, single-mode fibre coupler multiplexers/demultiplexers, though suffering from poor crosstalk isolation, are clearly superior to gratings and interference filters in terms of fibre compatibility, loss, and potential spectral selectivity.

iii) Devices based on grating reflectors and couplers

Since the wavelength selectivity of a conventional coupler depends on the size of the angle, between the intersecting dispersion characteristics of the two guided modes, larger angles can be expected for coupling by means of a periodic perturbation in the form of a grating. Even for co-directional coupling, modest filter bandwidths in the order of 4.5 to

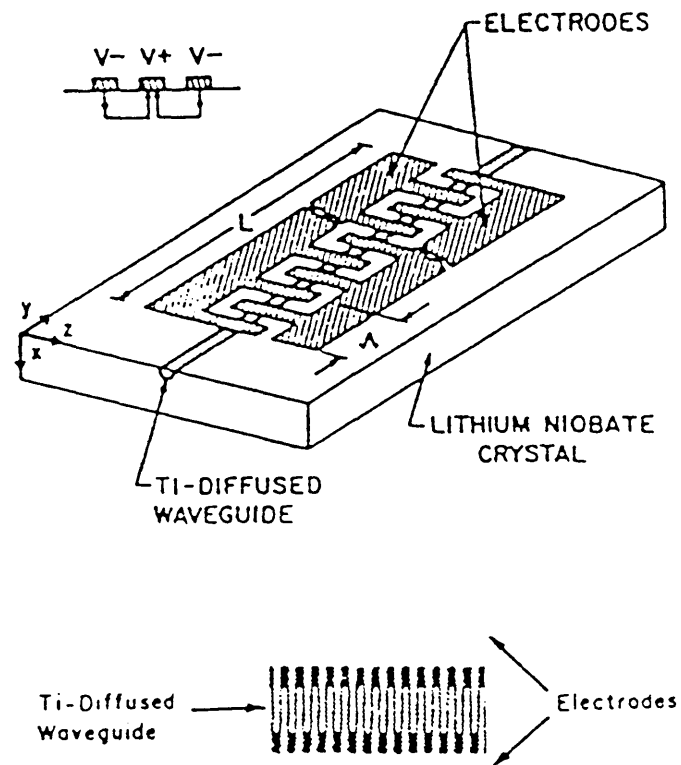
15 Å have been reported (1.39, 1.40) for single-mode electro-optic TE - TM mode converters, Fig.1.7.a, based on a Ti-diffused lithium niobate waveguide, with an electrode periodicity of $\sim 7 \mu\text{m}$.

Cascaded Bragg gratings of different periodicities, fabricated by means of direct electron-beam writing on a charco-genide waveguide film (1.41), have also been proposed for separating different wavelengths, focusing them onto photodiodes integrated in the Si substrate, Fig.1.7.b, with selectivity of a few nm.

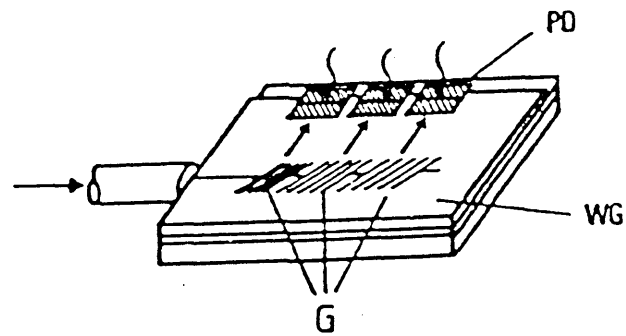
The full potential of grating-assisted coupling in narrow-band filtering can be explored by considering contradirectional coupling. A periodic perturbation with pitch equal to half the guide wavelength, results in coupling between a forward and a backward travelling mode, giving rise to reflection or backward wave coupling. The simplest structure, that can be considered, is the Bragg-type waveguide reflector, realised by fabricating a grating on a waveguide surface.

Bragg reflectors, based on thin film optical waveguides, have been reported as early as 1974, with bandwidths of 2 Å (1.42) and even as narrow as 0.1 Å (1.43) for operation at $0.633 \mu\text{m}$, with reflectivities around 70 %. An integrated optics version of the Bragg reflector has been also realised in GaAs/GaAlAs rib waveguides (1.44) with centre wavelengths at $1.5 \mu\text{m}$, demonstrating coupled bandwidths of 5 Å and reflectivities of 80 %.

More recent devices tend to utilise grating structures



a)



b)

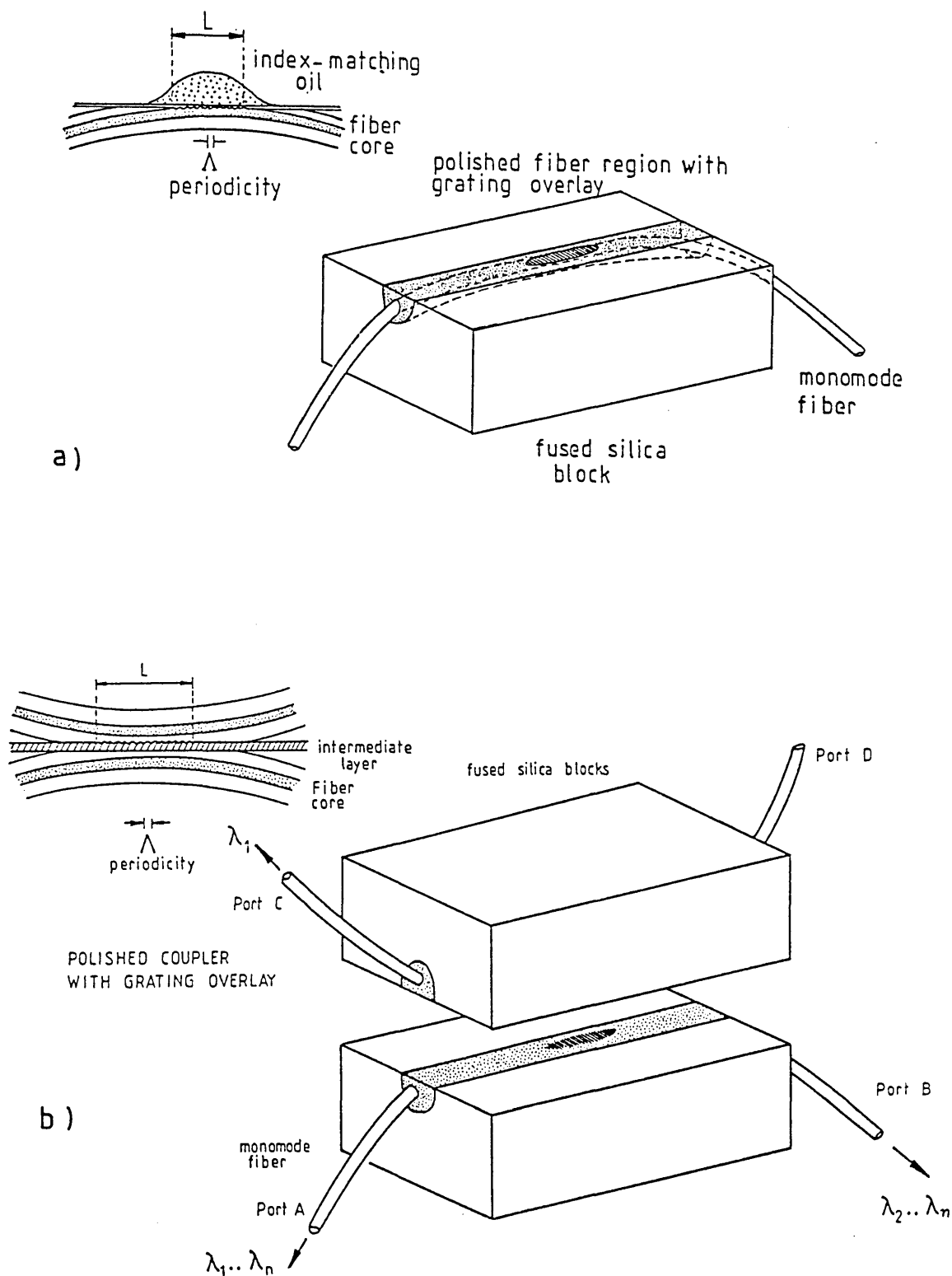
Fig. 1.7

- a) $TE \rightleftharpoons TM$ mode convertor based on a Ti-diffused LiNbO_3 waveguide, with an electrode periodicity of $\sim 7 \mu\text{m}$.
- b) Cascaded Bragg gratings G of different periodicities on a thin film waveguide WG, for directing the guided light onto the integrated photodetectors PD (1.41).

with monomode optical fibres. A single-mode fibre evanescent grating reflector was originally demonstrated, by placing a commercially available holographic reflection grating in contact with the surface of a fibre, suitably potted and polished to reveal the core (1.45). An index oil was applied between the fibre and grating surfaces to ensure good contact. In this way, a reflection bandwidth of $2.8 \text{ \AA}$ was obtained, at around $0.808 \text{ }\mu\text{m}$, for a grating periodicity of $0.278 \text{ }\mu\text{m}$. The reflectivity was relatively poor, 38 %, mainly due to an excessive 3 dB loss from the metallised grating surface.

In a similar design (1.46), the grating was fabricated directly on a polished-fibre surface, Fig.1.8.a. A thin (80 nm), high index ($n=1.68$) aluminium oxide layer was deposited over the grating, in order to distort the fibre field profile in the grating region, increasing its overlap for higher coupling efficiency. A bandwidth of $18 \text{ \AA}$ with reflectivities of 92 % were demonstrated around $1.3 \text{ }\mu\text{m}$, for a grating periodicity of $0.449 \text{ }\mu\text{m}$ and length 1 mm. Recent results by the same authors (1.47), show bandwidths of $8 \text{ \AA}$ and reflectivities around 90 %.

For grating reflectors to be employed as MUX/DEMUX for WDM fibre communication systems, it is necessary to place a conventional directional coupler before the grating in order to sample part of the reflected signal. A weakness of this, otherwise, simple configuration, at least for WDM of several communication channels, results from the excessive loss associated with the coupler. Even for a nominal 3 dB coupl-



- a) Grating reflector configuration, with a surface relief grating fabricated on a polished fibre block.
- b) Grating coupler using polished blocks with dissimilar fibres, with a grating fabricated into the cladding region of one of the waveguides.

er and for a 100 % reflectivity grating, there is an additional 3 dB loss on all the passing radiation and a 6 dB loss on the filtered signal.

This serious disadvantage can be overcome by a more elaborate configuration, using backward wave coupling between two waveguides. The phenomenon of contra-directional coupling has been fully analyzed since as early as 1980. Although the coupling mechanism is very similar to that of the grating reflector, the situation becomes more complicated if forward coupling and straight reflection are also included in the analysis. For two fairly similar waveguides, the three coupling processes occur at nearly the same frequency, competing for a share of the optical power. By designing the two guides to be dissimilar, however, it is possible to isolate the grating coupling from the influence of the two other processes.

Even though the precise configuration of the guides and the periodic perturbation does not need to be accurately specified for the development of the theory, a number of different configurations have been proposed for implementation in both integrated optics and fibre optics form.

The grating coupler has only very recently been experimentally demonstrated (1.48), using a polished coupler of slightly dissimilar fibres, with a diffraction grating etched directly into the cladding region of one of the waveguides (Fig.1.8.b). The grating periodicity was $0.53 \mu\text{m}$, for operation at $1.55 \mu\text{m}$, holographically produced over a length of 2 mm. The device was examined using an F-centre

laser with tunability range between 1.49-1.53 μm in 1 $\text{\AA}$ steps. A coupled bandwidth of 6 $\text{\AA}$ was measured, with a coupling efficiency of 25 %. The reflection bandwidth in the input fibre was 4.5 $\text{\AA}$, spectrally shifted from the coupled band by 12 $\text{\AA}$. This seems rather surprising, since the coupling process appears to be stronger than the reflection, even though the grating is fabricated closer to the core of the input fibre. The device was also found to suffer losses of 0.8 dB from scattering in the polished fibre, a further 0.6 dB were contributed to forward coupling.

Grating reflectors and couplers are in general very sensitive to variations in the fabrication parameters, especially when associated with the grating periodicity. Even though, there is always likely to be a wavelength reflected for a given grating periodicity, in order to "hit" the matching condition at a predetermined wavelength, an extremely high precision in the grating fabrication is required. Some form of tuning is therefore always necessary, to compensate for fabrication tolerances.

When an external grating is being used with the grating reflector, or in the polished grating coupler situation, some limited tuning is available by slightly rotating the grating block with respect to the fibre surface.

A continuous variation in the grating periodicity has been recently reported (1.49), allowing a wide range of wavelength tuning for the reflected signal. This has been accomplished using a novel, "fan" type, first-order diffract-ion grating placed in contact with a polished fibre. The fan

grating was written by electron beam lithography over an area of $2\text{ mm} \times 6\text{ mm}$, its periodicity varying from $0.497\text{ }\mu\text{m}$ at one end to $0.537\text{ }\mu\text{m}$ at the other, providing a nominal tuning range of $835\text{ }\text{\AA}$, an improvement by a factor of 100 over previously reported results. Although a reflection bandwidth of $8\text{ }\text{\AA}$ was obtained, coupling efficiencies of only 11 % were possible, mainly due to loss from the metallised grating surface.

A similar "fan" grating type was fabricated holographically, and has been used with a polished fibre, with linewidths of approximately $10\text{ }\text{\AA}$, over tuning ranges in excess of $650\text{ }\text{\AA}$, with 88 % reflectivities (1.50).

Grating reflectors and backward-wave couplers are characterised by a massive wavelength selectivity, with potential narrow-band filtering capability of $0.1\text{ }\text{\AA}$ or less. This, combined with the development of "coherent" laser sources of comparable linewidths, will make it possible to combine and separate hundreds of closely spaced channels covering a nominally narrow wavelength range. The application of the grating reflector in wavelength division multiplexing is somewhat limited by the significant loss introduced by the 3 dB coupler (beam-splitter), used to isolate part of the reflected signal. The backward-wave coupler on the other hand, with the light reflected into a different fibre by the grating, allows the whole of the filtered signal to be recovered, without any additional loss on the passing radiation. Future bidirectional multiplexers / demultiplexers are, therefore, expected to rely on these devices for narrow-

band filtering.

Present day WDM systems are mainly unidirectional, employing grating demultiplexers and thin-film interference filter multiplexers. Such devices have been already implemented (1.7, 1.8, 1.9) in practical systems and were found to operate satisfactorily at relatively slow rates, usually with multimode fibres and always for large channel spacings. Only few bidirectional systems are currently in operation (1.8), using a different set of wavelength-carriers for each direction.

Future systems are expected to be mainly bidirectional, with greater emphasis on compactness, low loss, and narrow-channel-spacing in order to accomodate more channels. Near future designs of multiplexers / demultiplexers will be based on low-loss fibre devices, either directional couplers or even grating couplers; the former appear more favourable, because of their simpler fabrication. Eventually ,however, with the subsequent evolution of "coherent" laser sources, the appetite for a further increase in the number of available channels could only be satisfied by more sophisticated fibre devices based on grating couplers and reflectors with massive spectral selectivity, low loss and greater architectural compactness.

1.3 D e v i c e s B a s e d o n G r a t i n g C o u p l e r s a n d R e f l e c t o r s

So far, grating couplers and reflectors have been considered only in terms of their potential application in wavelength division multiplexing. Even so, the effect of gratings on guided waves has been utilised in a variety of devices, with potential applications ranging from optical communication and processing to sensing.

Coupling light into a thin film by means of a dielectric grating has been reported as early as 1970 (1.51), with reported efficiencies of around 40 %. The main disadvantage of the grating coupler, as compared with the prism coupler, is that a substantial amount of the incident energy is transmitted through the film and is eventually lost into the substrate, accounting for the low coupling efficiencies.

Alternatively, a grating fabricated on an optical waveguide can couple light into a radiation mode at the Bragg angle, used as a beam expander or a high resolution spectrometer. A constant-period grating on a planar waveguide may act as a beam expander, by diffracting the guided light into a wider beam. Expanded beam diameters of 5 to 10 mm have been reported (1.52), with a more uniform intensity profile obtained by introducing a depth taper along the grating.

A similar design has been proposed as a high-resolution single-mode fibre-optic spectrometer (1.53), exploiting the wavelength dependence of the diffraction angle. A spectral

resolution of $1.3 \text{ \AA}$ has been reported for this device, with potential improvement to $0.003 \text{ \AA}$. The latter is possible by imposing the grating onto different parts of the same fibre, coiled into a number of turns. This configuration may act as an array of parallel, "coherent" line sources; the large optical path difference resulting in a pronounced intensity modulation of the main intensity envelope and breaking the far-field pattern into an array of fine peaks, each as narrow as $0.003 \text{ \AA}$ or 250 MHz .

A fibre grating reflector may also be viewed as an in-line wavelength selective mirror for "coherent" fibre lasers and other Fabry-Perot type devices, with applications both in optical frequency-division and wavelength-division multiplexing.

The advantages of single-mode fibre lasers are profound: compatibility with single-mode transmission fibres and other fibre devices such as couplers, polarizers, filters and modulators, low-loss for large dopant concentration, very low thresholds for high gains, good power handling characteristics, with minimum thermal effects, greater economy, and compact packaging. Two rare earth dopands (Nd^{3+} and Er^{3+}) incorporated into silica fibres (1.54) have been used for fibre lasers operating at 1.08 and $1.535 \text{ }\mu\text{m}$ respectively. Originally, butted mirrors were used in conjunction with a circulating fibre coupler, or an external diffraction grating, to provide wavelength selective feedback. A significant improvement towards an all-fibre device has been achieved, by replacing one of the mirrors with a high-reflectivity fibre-

grating reflector to provide feedback. A Nd^{3+} doped fibre was butted to the input mirror at one end and at the other to a grating reflector of 70 % reflectivity at 1092 nm, with a nominal bandwidth of 1.9 nm. The system was pumped by a single-mode GaAlAs semiconductor laser. Lasing action was demonstrated at 1084 nm, with a threshold less than 2 mW, a slope efficiency of 19 % and a linewidth of 0.6 Å (1.55). Due to modal gain competition, the latter is significantly narrower than the bandwidth of the grating reflector, and several orders of magnitude narrower than the linewidth corresponding to the conventional fibre laser cavity design. Further improvements may include the fabrication of grating reflectors of higher reflectivities and narrower bandwidths directly on the doped fibre, avoiding the butting losses and obtaining higher slope efficiencies and finer linewidths.

Comparable results have also been reported for Er^{3+} doped fibre lasers (1.56), with fibre grating reflectors operating around 1.540 μm , which makes them particularly attractive to optical communications. Er^{3+} , however, being a three level system, requires tighter fabrication tolerances for the grating reflector, since the doped fibre is very absorbing at its ground state, requiring half of the Er^{3+} ions to be pumped into the excited state before lasing can occur.

The idea of the wavelength selective mirror can be further exploited by employing a fibre Bragg-reflector as an external feedback element for spectral narrowing of conventional multi-mode or single-mode semiconductor lasers. The arrange-

ment consists of two coupled cavities, the actual laser cavity and the one formed between the laser facet and the fibre reflector. Provided that a line of the free running laser falls within the bandwidth of the fibre Bragg-reflector, a constructive interference between the reflections from the two cavities forces single mode operation. This technique has been demonstrated with commercial multimode laser diodes operating at $1.3\text{ }\mu\text{m}$, by using a 2 m long fibre length supporting a low reflectivity photoresist grating reflector (1.57), and at $1.55\text{ }\mu\text{m}$, with a shorter fibre cavity of 11 cm and a higher reflectivity grating, etched into the fibre (1.58). Mode hopping between the neighbouring semiconductor laser modes has also been reported, by employing a tunable grating reflector with an external fan-shaped grating (1.50).

A grating reflector can be also utilised with conventional semiconductor injection lasers in a monolithic configuration, to form an electro-optic modulator. Two variations have been proposed (1.59): the distributed-feedback (DFB) modulator, based on a single grating, and the distributed-Bragg-reflector (DBR) modulator, employing two gratings in a Fabry-Perot formation. For the DFB, modulation is achieved by means of electro-optically changing the effective guide index, thus affecting the wavelength of the guided mode. A voltage of 46 V is calculated to be sufficient for a 100 % optical switching. For the Fabry-Perot type DBR, modulation is effected by electro-optically varying the effective cavity length, and a voltage of 17 V is

required for optical switching. Comparative calculations show the DBR modulator design to be more effective than the DFB modulator.

The narrow-band filtering capability of grating reflectors and couplers can also find application in the emerging field of microwave optics. It would be useful, for example, to separate the side-bands of an optical carrier modulated at microwave frequency, introduce a phase shift onto one of them and then recombine them. In this way, the phase of the microwave signal generated from the recombined side-bands could be controlled; this form of processing could be applied to phased antenna arrays.

As mentioned earlier, it is possible to modulate a Bragg reflector by changing the effective guide index, thus altering the wavelength of the guided mode. For broadband operation, a shift in the nominal value of the reflected wavelength will be an indirect measure of the change in the effective waveguide index and the parameter that has caused it. In this sense, the grating reflector can be viewed as a sensor element (3.1). Even though, there is hardly any improvement in sensitivity over directional couplers, for broadband operation, the considerable reduction in the coupled bandwidth of the grating reflector would provide more resolvable points.

Apart from being itself considered as a sensing element, a narrow-band grating fibre filter could be a vital component in a distributed fibre sensor based on Brillouin scattering, where a weak scattered signal has to be separat-

ed from the unshifted, stronger Rayleigh scattering. The selectivity required, less than about $0.3 \text{ \AA}$, is within the realistic capabilities of the grating coupler.

Even though the main application of grating couplers is in narrow-band filtering, they can also be used as components in a number of different devices, utilising their ability to reflect an optical signal into a different waveguide with very low loss.

Given that it is difficult to fabricate tight bends in integrated optics without incurring significant radiation losses, a grating coupler could be effectively used to allow more optical devices to be packed into the available chip length. Although an edge reflector based on a directional coupler has already been proposed (1.60), grating couplers appear to offer greater flexibility and lower losses. A similar application is in fibre-optic signal processing as a replacement for the recirculating fibre coupler.

The recirculating (feed-backward) coupler, Fig. 1.9, (1.61) is being extensively used in fibre optic signal processors performing various high-speed time-domain and frequency-domain operations, from matrix operations (1.62) to frequency filtering (1.63). More specifically, a basic recirculating loop can be used as a transient buffer memory and data rate transformer, a notch filter, a systolic processor, and a building block for single mode fibre lattice filters (1.64). By implementing the rather simple but bulky recirculating coupler, in terms of the more sophisticated cascaded grating couplers in an integrated

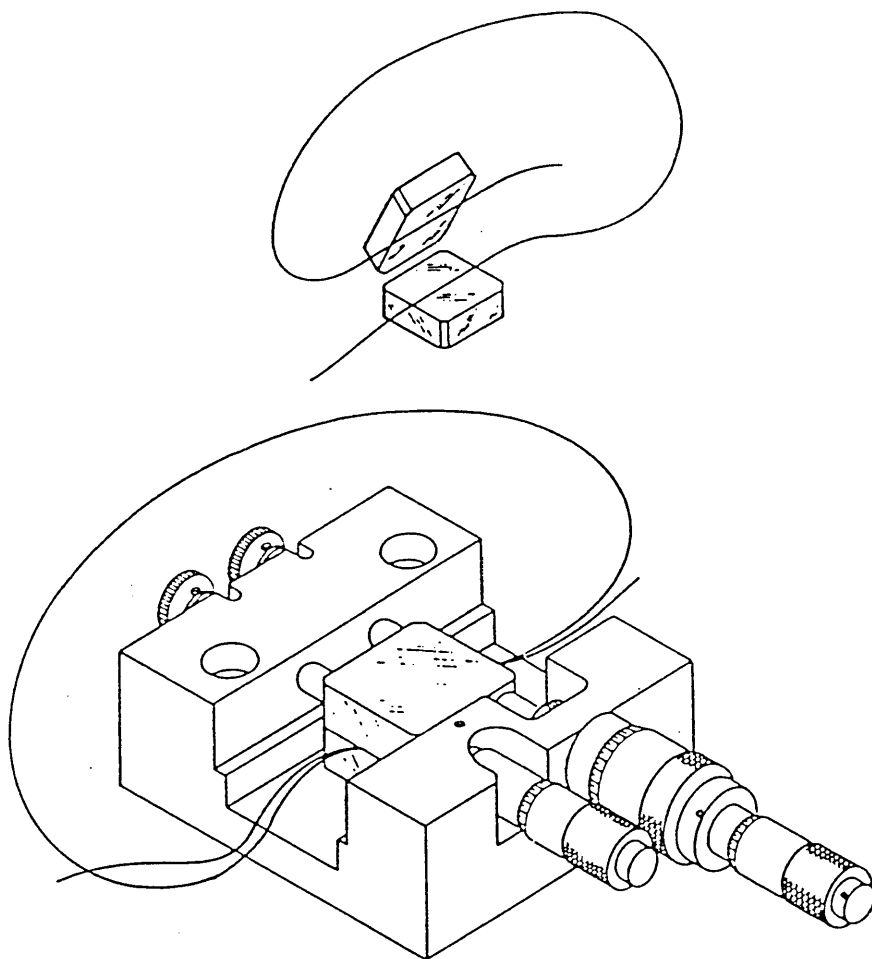


Fig. 1.9

The recirculating fibre coupler .

fibre form, one trades system complexity for greater architectural compactness.

1.4 Summary

From the previous sections, it is apparent that narrow-band filtering devices based on grating couplers and reflectors are expected to play a major part in the development of future Optical Communications. Fibre device implementations, in particular, with low loss and fibre compatibility, appear more promising for WDM, filtering, and fibre laser applications.

We have fabricated surface relief gratings of different periodicities on the surface, close to the core, of special D-shaped fibres, using a simple and inexpensive holographic process, for the realisation of grating reflectors. Coupled bandwidths of $7 \text{ \AA}$ and reflectivities of approximately 70 % have been demonstrated (1.65), with potential improvement to sub- $\text{\AA}$ bandwidths and reflectivities of 95 % for grating-on-fibre lengths as long as 2 cm.

Even though the grating coupler was not realised, a special fibre has been designed for this purpose, based on the twin-waveguide integrated fibre coupler. Different possible implementations of the grating coupler have also been considered, the simpler consisting of two D-shaped dissimilar fibres, with a grating overlay fabricated on

one of them, while a more interesting design consists of an untwisted fused coupler in a polished fibre block, with a fan-shaped external grating for continuous wavelength tuning.

CHAPTER 2

THEORY

Significant power exchange between two adjacent waveguides can take place whenever they are in near synchronism, that is, when the phase velocities of the guided modes in either guide are approximately equal in the absence of coupling. Identical waveguides are always in synchronism, and provided they lie in close proximity to one another, are strongly coupled.

Asynchronous waveguides are not generally coupled, since guided modes of different phase velocities cannot interact effectively. It is, however, possible to couple asynchronous waveguides by means of a periodic perturbation, such as a diffraction grating, whose periodicity matches the beat wavelength of the nonsynchronous waveguides for codirectional or contradirectional coupling.

Both synchronous and asynchronous - grating assisted - couplers can be analysed by normal mode analysis, involving the computation of the compound supermodes of the coupler, treated as a single guiding structure. In the synchronous symmetrical case (i.e. identical individual waveguides) the two compound supermode solutions appear to have even and odd symmetry. However, even for an asymmetrical synchronous coupler, the two supermodes can be usually superimposed to

reconstruct the initial launching condition, with the mode fields cancelling in one guide and adding in the other, to allow all the power in the input waveguide. After some particular length, the phase relationship between the supermodes has been reversed, and superposition results in field cancelation in the input waveguide and effective transfer of all the optical energy in the other waveguide (2.1) .

For the asymmetric asynchronous grating coupler (2.2) the analysis can again proceed in terms of the compound supermodes of the combined structure. This time, however, their role is different, since in the absence of the grating all the power is predominantly carried by one waveguide, and superposition of the two supermodes cannot lead to power exchange. Power coupling between these modes is only effected by the diffraction grating.

The use of normal mode analysis for synchronous and grating couplers provides an exact but complicated mathematical description of the coupling process. Alternatively, one could use the simpler, approximate coupled mode analysis, with the supermodes replaced by a linear combination of the individual waveguide modes, linked by first order differential equations, known as the coupling equations. The coupling coefficient appearing in these equations, is a measure of the coupling strength, and can be approximately expressed as an overlap integral.

Coupled mode analysis (2.3 , 2.4 , 2.5) provides simple, closed form analytical expressions for the coupling process, in close agreement with the results obtained by the exact

normal mode analysis for "weak" coupling. Comparisons between normal and coupled mode analyses are presented in (2.6 , 2.7) .

In the following sections, a general form of coupled mode analysis will be presented, with the coupling equations derived and solved for both synchronous and asynchronous grating couplers. The grating reflector will be considered as a special case of a grating coupler, as perceived from normal mode analysis. The analysis will be then extended to treat more complicated coupling combinations between guided modes in two and three waveguide systems, showing how the optical power is distributed between competing coupling processes. This will be followed by the analysis of specific waveguide and grating configurations, with the derivation of approximate expressions for the different coupling parameters. The analysis will cover both slab and rectangular waveguide geometries.

For simplicity, only single mode waveguides will be considered, bearing one forward and one backward-going mode. The terms codirectional and contradirectional coupling will be used to distinguish coupling between modes travelling in the same direction from modes travelling in opposite directions respectively.

2.1 Coupling Theory

Consider the propagation of electromagnetic modes in two adjacent, arbitrary dielectric waveguides along the z -direction. The transverse electric and magnetic fields associated with the mode of each individual waveguide can be written as:

$$\begin{aligned}\underline{E}_a &= \hat{E}_a \cdot \exp\{j(\omega t \pm \beta_a z)\} \\ \underline{H}_a &= \hat{H}_a \cdot \exp\{j(\omega t \pm \beta_a z)\}\end{aligned}\quad , \quad (2.1.1)$$

for guide (a) and similarly

$$\begin{aligned}\underline{E}_b &= \hat{E}_b \exp\{j(\omega t \pm \beta_b z)\} \\ \underline{H}_b &= \hat{H}_b \exp\{j(\omega t \pm \beta_b z)\}\end{aligned}\quad , \quad (2.1.2)$$

for guide (b), where $\hat{E}_a$, $\hat{H}_a$, $\hat{E}_b$, $\hat{H}_b$ are the field amplitudes and β_a , β_b are the propagation constants of the two modes. A negative sign in front of a propagation constant indicates a forward-going wave, while a positive sign denotes a backward-going wave.

The electromagnetic fields of each guide satisfy Maxwell's equations:

$$\begin{aligned}\nabla_t \times \underline{H}_a \pm j\beta_a (\underline{z} \times \underline{H}_a) - j\omega\epsilon_0 n_a^2 \cdot \underline{E}_a &= 0 \\ \nabla_t \times \underline{E}_a \pm j\beta_a (\underline{z} \times \underline{E}_a) + j\omega\mu_0 \underline{H}_a &= 0\end{aligned}\quad , \quad (2.1.3)$$

and

$$\begin{aligned}\nabla_t \times \underline{H}_b \pm j\beta_b (\underline{z} \times \underline{H}_b) - j\omega\epsilon_0 n_b^2 \cdot \underline{E}_b &= 0 \\ \nabla_t \times \underline{E}_b \pm j\beta_b (\underline{z} \times \underline{E}_b) + j\omega\mu_0 \underline{H}_b &= 0\end{aligned}\quad , \quad (2.1.4)$$

where ∇_t is the transverse part of the ∇ vector operator

and n_a^2, n_b^2 are both $f(x,y)$ describing the index distribution of the unperturbed medium. For contradirectional coupling between modes of the same waveguide, $n_a^2 = n_b^2$. The total field of the combined waveguide structure, can be expressed as a linear combination of the unperturbed fields. For weak perturbation, they can be approximated to the fields of the individual waveguide modes, i.e.

$$\begin{aligned}\underline{E} &= A(z) \underline{E}_a + B(z) \underline{E}_b, \\ \underline{H} &= A(z) \underline{H}_a + B(z) \underline{H}_b,\end{aligned}\quad (2.1.5)$$

where the field amplitudes $A(z)$ and $B(z)$ are slowly varying functions of z . The above expressions are only approximately correct. A more exact analysis should also include the residual fields $E_r(x,y,z)$ and $H_r(x,y,z)$ (2.4). These terms are, however, small in comparison with the transverse fields for weak perturbation, and can thus be neglected.

The total fields must also satisfy Maxwell's equations,

$$\begin{aligned}\nabla \times \underline{H} &= j\omega \epsilon_0 n^2 \underline{E}, \\ \nabla \times \underline{E} &= -j\omega \mu_0 \underline{H},\end{aligned}\quad (2.1.6)$$

where n^2 is the composite refractive index distribution, and may be a function of z .

Substituting equation (2.1.5) into (2.1.6), separating longitudinal and transverse field components and considering that

$$\nabla = \left[\nabla_t + \underline{z} \frac{\partial}{\partial z} \right],$$

results in:

$$A(z) \cdot \left[\nabla_t \times \underline{H}_a \pm j\beta_a (\underline{z} \times \underline{H}_a) \right] + \frac{\partial A(z)}{\partial z} (\underline{z} \times \underline{H}_a) - j\omega \epsilon_0 n^2 \underline{E}_a A(z) +$$

$$+ B(z) \cdot [\nabla_{\perp} \times \underline{H}_b + j \beta_b (\underline{z} \times \underline{H}_b)] + \frac{\partial B(z)}{\partial z} (\underline{z} \times \underline{H}_b) - j\omega \epsilon_0 n^2 \underline{E}_b B(z) = 0, \quad (2.1.7)$$

and similarly

$$\begin{aligned} & A(z) [\nabla_{\perp} \times \underline{E}_a + j \beta_a (\underline{z} \times \underline{E}_a)] + \frac{\partial A(z)}{\partial z} (\underline{z} \times \underline{E}_a) + j\omega \mu_0 A(z) \underline{H}_a + \\ & + B(z) [\nabla_{\perp} \times \underline{E}_b + j \beta_b (\underline{z} \times \underline{E}_b)] + \frac{\partial B(z)}{\partial z} (\underline{z} \times \underline{E}_b) + j\omega \mu_0 B(z) \underline{H}_b = 0. \end{aligned} \quad (2.1.8)$$

By using equations (2.1.3) and (2.1.4), the above expressions can be simplified to give:

$$\begin{aligned} & \frac{\partial A(z)}{\partial z} (\underline{z} \times \underline{H}_a) - j\omega \epsilon_0 \Delta n_2^2 A(z) \underline{E}_a + \frac{\partial B(z)}{\partial z} (\underline{z} \times \underline{H}_b) - \\ & - j\omega \epsilon_0 \Delta n_1^2 B(z) \underline{E}_b = 0, \end{aligned} \quad (2.1.9)$$

and

$$\frac{\partial A(z)}{\partial z} (\underline{z} \times \underline{E}_a) + \frac{\partial B(z)}{\partial z} (\underline{z} \times \underline{E}_b) = 0, \quad (2.1.10)$$

where Δn_1^2 , Δn_2^2 denote the difference in the refractive index profile caused by the perturbation. Note that in the case of mode coupling in a single waveguide $\Delta n_1^2 = \Delta n_2^2$.

For lossless propagation (i.e. real refractive indices), the time dependance of the above equations can be removed by taking the scalar products of equations (2.1.9) and (2.1.10) by $\underline{E}_a^*$ and $\underline{H}_a^*$ respectively, where the subscript * indicates a complex conjugate quantity. Following the scalar products, the equations are integrated over the whole cross-section, leading to:

$$\iint_{-\infty}^{\infty} \left\{ \frac{\partial A(z)}{\partial z} [\underline{E}_a^*(z \times \underline{H}_a) - \underline{H}_a^*(z \times \underline{E}_a)] + \frac{\partial B(z)}{\partial z} [\underline{E}_a^*(z \times \underline{H}_b) - \underline{H}_a^*(z \times \underline{E}_b)] - \right. \\ \left. - j\omega \epsilon_0 \Delta n_2^2 A(z) \underline{E}_a \underline{E}_a^* - j\omega \epsilon_0 \Delta n_1^2 B(z) \underline{E}_b \underline{E}_a^* \right\} dx dy = 0 \quad (2.1.11)$$

Fortunately, this rather complicated expression can be simplified by neglecting small terms. The terms Δn_1^2 , Δn_2^2 are only non vanishing in the region of the perturbation. In the two waveguide case, the term $\Delta n_2^2 \underline{E}_a \underline{E}_a^*$ can be normally neglected since Δn_2^2 is only non-zero inside the second waveguide, where the field contribution of the first waveguide $\underline{E}_a \underline{E}_a^*$ is very small. Since both $A(z)$ and $B(z)$ are slow varying functions of z , weak field overlapping will make the product:

$$\frac{\partial B(z)}{\partial z} [\underline{E}_a^*(z \times \underline{H}_b) - \underline{H}_a^*(z \times \underline{E}_b)]$$

of second order, and can, therefore, be neglected.

With the above simplifications, equation (2.1.11) becomes:

$$\iint_{-\infty}^{\infty} \left\{ \frac{\partial A(z)}{\partial z} [\underline{E}_a^*(z \times \underline{H}_a) - \underline{H}_a^*(z \times \underline{E}_a)] - j\omega \epsilon_0 \Delta n_1^2 B(z) \underline{E}_a \underline{E}_b^* \right\} dx dy = 0,$$

hence

$$\frac{\partial A(z)}{\partial z} = j c_1 B(z) \exp\{j(\beta_a \pm \beta_b)z\}, \quad (2.1.12)$$

where c_1 is the coupling coefficient, providing a direct measure of the coupling strength, and

$$c_1 = -\omega \epsilon_0 \frac{\iint_{-\infty}^{\infty} \Delta n_1^2 \hat{E}_a^* \hat{E}_b dx dy}{\iint_{-\infty}^{\infty} z \{(\hat{E}_a^* \times \hat{H}_a) + (\hat{E}_a \times \hat{H}_a^*)\} dx dy} \quad (2.1.13)$$

In the case of contradirectional coupling in a single

waveguide, $\Delta n_1^2 = \Delta n_2^2$ and $\underline{E}_a = \underline{E}_b$, $\underline{H}_a = \underline{H}_b$. By taking into account the opposite direction of power flow in the two modes, equation (2.1.11) can be written as:

$$\iint_{-\infty}^{\infty} \left\{ \left[\frac{\partial A(z)}{\partial z} - \frac{\partial B(z)}{\partial z} \right] [\underline{E}_a^*(z \times \underline{H}_a) - \underline{H}_a^*(z \times \underline{E}_a)] + \right. \\ \left. + j\omega \epsilon_0 \Delta n_1^2 [A(z) + B(z)] \underline{E}_a \underline{E}_a^* \right\} dx dy = 0 \quad ,$$

which after considering $Q(z) = A(z) - B(z)$ and $R(z) = A(z) + B(z)$ results in the equivalent expression:

$$\frac{\partial Q(z)}{\partial z} = j c_1 R(z) \exp\{j 2 \beta_a z\} \quad ,$$

with c_1 as in (2.1.13), with $a=b$.

Similarly, multiplication of equations (2.1.9) and (2.1.10) with $\underline{E}_b^*$ and $\underline{H}_b^*$ respectively, followed by suitable manipulation leads to equation:

$$\frac{\partial B(z)}{\partial z} = j c_2 A(z) \exp\{-j(\beta_a \pm \beta_b) z\} \quad , \quad (2.1.14)$$

where c_2 is the coupling coefficient, essentially similar to (2.1.13). Also for single waveguides:

$$\frac{\partial R(z)}{\partial z} = j c_2 Q(z) \exp\{-2j \beta_a z\} \quad .$$

Hence, a general form of the coupling equations has been derived, which is valid for both synchronous and grating assisted couplers with single mode waveguides, considered either singly or in combination.

2.2 Directional Coupling

The most commonly examined form of co-directional coupling results from the mutual perturbation of two synchronous parallel waveguides separated by a finite distance, and is better known as directional coupling (2.3 , 2.8).

For directional coupling between modes of two adjacent waveguides, the coupling equations take the form:

$$\begin{aligned}\frac{\partial A(z)}{\partial z} &= j c_1 B(z) \cdot \exp\{ j(\beta_a - \beta_b) \cdot z \} , \\ \frac{\partial B(z)}{\partial z} &= j c_2 A(z) \cdot \exp\{-j(\beta_a - \beta_b) \cdot z\} ,\end{aligned}\tag{2.2.1}$$

with c_1 and c_2 given by (2.1.13) .

The denominators of the expressions for c_1 and c_2 are representations of the Poynting vector

$$P = (1/2) [\underline{\tilde{E}} \times \underline{\tilde{H}}^*]$$

and indicate the power carried by each mode. For real field amplitudes $\hat{E}_a$, $\hat{H}_a$, $\hat{E}_b$, $\hat{H}_b$ the expressions for the coupling coefficients can be simplified to

$$\begin{aligned}c_1 &= \frac{-\omega \epsilon_0}{4P_a} \iint_{-\infty}^{\infty} \Delta n_1^2 |\hat{E}_a \cdot \hat{E}_b| dx \cdot dy \\ \text{and} \\ c_2 &= \frac{-\omega \epsilon_0}{4P_b} \iint_{-\infty}^{\infty} \Delta n_2^2 |\hat{E}_a \cdot \hat{E}_b| dx \cdot dy ,\end{aligned}\tag{2.2.2}$$

where P_a , P_b is the power carried by each mode.

For coupling between identical waveguides the above equations become equal, so

$$c_1 = c_2$$

This can be perceived as a direct consequence of the power conservation argument. If the power carried by each mode is proportional to $|A(z)|^2$ and $|B(z)|^2$ respectively, then the z -derivative of the total power carried in both guides becomes

$$\frac{d}{dz} [|A(z)|^2 + |B(z)|^2] = 2 \operatorname{Re} \{ j(c_2 - c_1) A(z) \cdot B(z) \} . \quad (2.2.3)$$

For power conservation the above expression must be zero, which is clearly satisfied when

$$c_1 = c_2 ,$$

for real values of coupling coefficients.

Although the above argument appears to be generally true, in principle, as following from power conservation considerations, it is not strictly correct, because (2.1.5) used for the derivation of the above analytical expressions for c_1 and c_2 , ignores cross terms resulting from the integrated overlap of the individual waveguide mode fields all over space (2.9). For weak coupling the neglected terms are comparatively small, leading to $c_1 \approx c_2$.

Solving the system in (2.2.1), results in two second order differential equations:

$$\begin{aligned} & \frac{\partial^2 A(z)}{\partial z^2} - j(\beta_a - \beta_b) \frac{\partial A(z)}{\partial z} + c_1 c_2 A(z) = 0 \\ \text{and} \quad & \frac{\partial^2 B(z)}{\partial z^2} + j(\beta_a - \beta_b) \frac{\partial B(z)}{\partial z} + c_1 c_2 B(z) = 0 . \end{aligned}$$

If power is originally fed in mode (a), $A(0)=A_0$ and $B(0)=0$. Subject to these conditions, the solutions of the above

equations are:

$$B(z) = A_0 \cdot c_1 \frac{\sin\{\sqrt{[c_1 \cdot c_2 + (\Delta\beta/2)^2]} \cdot z\}}{\sqrt{[c_1 \cdot c_2 + (\Delta\beta/2)^2]}} \exp\{-j\Delta\beta \cdot z/2\}$$

and (2.2.4)

$$A(z) = A_0 [\cos\{\sqrt{[c_1 \cdot c_2 + (\Delta\beta/2)^2]} \cdot z\} - j\Delta\beta \frac{\sin\{\sqrt{[c_1 \cdot c_2 + (\Delta\beta/2)^2]} \cdot z\}}{\sqrt{[c_1 \cdot c_2 + (\Delta\beta/2)^2]}}] \exp\{j\Delta\beta \cdot z/2\},$$

(2.2.5)

where $\Delta\beta = \beta_a - \beta_b$ is a measure of the mismatch between the two waveguides. In terms of power the solution becomes:

$$P_b(z) = P_0 \frac{c^2}{c^2 + (\Delta\beta/2)^2} \sin^2\{\sqrt{[c^2 + (\Delta\beta/2)^2]} \cdot z\}$$

(2.2.6)

and

$$P_a(z) = P_0 - P_b(z)$$

(2.2.7)

where $P_0 = |A(0)|^2 = A_0^2$, and $c = \sqrt{c_1 c_2}$.

Equation (2.2.6) shows that substantial amounts of power can be transferred to mode (b), only if the waveguides are approximately phase matched (i.e. $\Delta\beta \approx 0$, $\beta_a \approx \beta_b$).

Equations (2.2.4) and (2.2.5) become:

$$B(z) = A_0 \sin(c \cdot z),$$

$$A(z) = A_0 \cos(c \cdot z),$$

(2.2.8)

with complete power transfer over a length:

$$L = \pi/(2 \cdot c).$$

For $\Delta\beta \neq 0$, the maximum fraction of coupled power is proportional to

$$\frac{c^2}{c^2 + (\Delta\beta/2)^2}$$

When $\Delta\beta \gg 2 \cdot c$ the power exchange between the two modes becomes negligible, as shown in Fig.2.1.

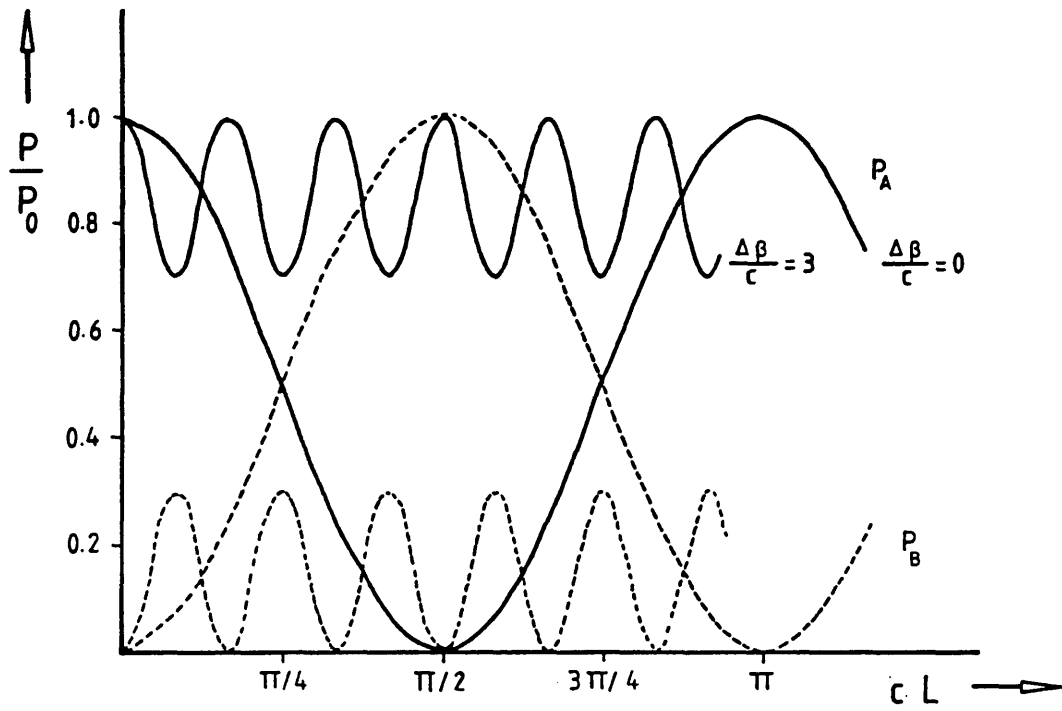


Fig. 2.1

Power distribution in a directional coupler as a function of interaction length, for different amounts of mismatch.

2.3 Grating - Assisted Directional Couplers

Efficient directional coupling between two single-mode waveguides by means of a periodic perturbation is achieved when its periodicity satisfies the phase matching requirement

$$(\beta_a - \beta_b) = 2\pi / \Lambda \quad (2.3.1)$$

Depending on the size of the periodicity, both codirectional (2.10) and contradirectional coupling (2.11, 2.12) may occur, the latter raising greater interest because of its higher wavelength selectivity. For codirectional coupling

$$\Lambda = \lambda_0 / (n_{EF1} - n_{EF2}), \quad (2.3.2)$$

while for contradirectional coupling

$$\Lambda = \lambda_0 / (n_{EF1} + n_{EF2}), \quad (2.3.3)$$

where λ_0 is the wavelength at which the matching condition is satisfied, and n_{EF1} , n_{EF2} are the effective indices of the two waveguides. It is evident from the above equations that contradirectional coupling requires a substantially finer grating periodicity. Even so, the use of the same grating for codirectional and contradirectional coupling at widely different wavelengths has been suggested (2.13).

2.3.1 CONTRADIRECTIONAL COUPLING

Consider the case of contradirectional coupling in two single-mode parallel waveguides phase-matched by a periodic

perturbation of periodicity Λ , such that :

$$\beta_a + \beta_b = 2\pi/\Lambda ,$$

where β_a, β_b are the propagation constants of the waveguides. Generally the two waveguides are asynchronous, and $\beta_a \neq \beta_b$, although for the special case of the single waveguide grating reflector $\beta_a = \beta_b$.

The perturbation usually takes the form of a surface corrugation on a core / cladding interface. It is assumed to be sinusoidal, of depth h and can be described by a refractive index distribution:

$$\Delta n^2(x,y) = \begin{cases} (n_1^2 - n_0^2) & -h \leq x \leq 0 , \\ 0 & \text{elsewhere,} \end{cases} \quad (2.3.4)$$

where n_1, n_0 are the core and cladding indices respectively.

The field amplitudes of the two modes $A(z)$, $B(z)$ are related by the coupled mode equations:

$$\begin{aligned} \frac{\partial A(z)}{\partial z} &= j c_1 B(z) \exp\{ j(\beta_a + \beta_b) z \} , \\ \frac{\partial B(z)}{\partial z} &= j c_2 A(z) \exp\{-j(\beta_a + \beta_b) z \} , \end{aligned} \quad (2.3.5)$$

where c_1, c_2 are the coupling coefficients, approximately expressed as the integral of the product of the mode fields in the perturbed region. Due to the contrary directions of power flow in the two waveguides,

$$c_1 = -c_2 = c ,$$

which comes as a direct consequence of the conservation of power:

$$\frac{d}{dz} [|A(z)|^2 - |B(z)|^2] = 2 \cdot \text{Re} \{ j (|c_1| - |c_2|) \cdot A(z) \cdot B(z) \} = 0 . \quad (2.3.6)$$

The perturbation is assumed to vary periodically in the z -direction (i.e. direction of propagation), so

$$c = 2\delta \cdot \cos(k \cdot z) = \delta \cdot [\exp\{jk \cdot z\} + \exp\{-jk \cdot z\}] , \quad (2.3.7)$$

where k is the perturbation momentum, i.e. $k = 2\pi/\Lambda$.

Substituting 2.3.7 in the coupling equations 2.3.5 gives:

$$\frac{\partial A(z)}{\partial z} = j\delta B(z) [\exp\{-j(k - \beta_a - \beta_b)z\} + \exp\{j(k + \beta_a + \beta_b)z\}] , \quad (2.3.8)$$

$$\frac{\partial B(z)}{\partial z} = -j\delta A(z) [\exp\{j(k - \beta_a - \beta_b)z\} + \exp\{-j(k + \beta_a + \beta_b)z\}] .$$

The rapidly varying factors of 2.3.8 can be made redundant, since significant coupling is expected to occur only when $k \approx \beta_a + \beta_b$. Thus the coupling equations take the form:

$$\begin{aligned} \frac{\partial A(z)}{\partial z} &= j\delta B(z) \exp\{-j[k - (\beta_a + \beta_b)]z\} , \\ \frac{\partial B(z)}{\partial z} &= -j\delta A(z) \exp\{j[k - (\beta_a + \beta_b)]z\} , \end{aligned} \quad (2.3.9)$$

where δ is the magnitude of the coupling coefficient, given by

$$\delta = \frac{-\omega \epsilon_0}{4 P_0} \iint_{-\infty}^{\infty} \Delta n^2(x, y) |\hat{E}_a \cdot \hat{E}_b| dx \cdot dy . \quad (2.3.10)$$

Equations 2.3.9 can be written in a simpler equivalent form by introducing the wave amplitudes:

$$\begin{aligned} a(z) &= A(z) \exp\{-j\beta_a z\} , \\ b(z) &= B(z) \exp\{j\beta_b z\} , \end{aligned}$$

for which the coupling equations become:

$$\begin{aligned}\frac{\partial a(z)}{\partial z} &= -j\beta_a a(z) + j\delta \exp\{-jk \cdot z\} \cdot b(z) , \\ \frac{\partial b(z)}{\partial z} &= j\beta_b b(z) - j\delta \exp\{jk \cdot z\} \cdot a(z) .\end{aligned}\quad (2.3.11)$$

A further simplification results from removing the z -dependance of the coupling coefficient by considering:

$$\begin{aligned}\tilde{a}(z) &= a(z) \exp\{jk \cdot z/2\} , \\ \tilde{b}(z) &= b(z) \exp\{-jk \cdot z/2\} ,\end{aligned}$$

for which the equations of 2.3.11 take the form

$$\begin{aligned}\frac{\partial \tilde{a}(z)}{\partial z} &= -j(\beta_a - k/2) \cdot \tilde{a}(z) + j\delta \cdot \tilde{b}(z) , \\ \frac{\partial \tilde{b}(z)}{\partial z} &= j(\beta_b - k/2) \cdot \tilde{b}(z) - j\delta \cdot \tilde{a}(z) ,\end{aligned}\quad (2.3.12)$$

with all the coefficients being constant.

The above system results in two second order differential equations for $a(z)$ and $b(z)$ respectively:

$$\begin{aligned}\frac{\partial^2 \tilde{a}(z)}{\partial z^2} + j(\beta_a - \beta_b) \frac{\partial \tilde{a}(z)}{\partial z} + [(\beta_a - k/2)(\beta_b - k/2) - \delta^2] \cdot \tilde{a}(z) &= 0 , \\ \frac{\partial^2 \tilde{b}(z)}{\partial z^2} + j(\beta_a - \beta_b) \frac{\partial \tilde{b}(z)}{\partial z} + [(\beta_a - k/2)(\beta_b - k/2) - \delta^2] \cdot \tilde{b}(z) &= 0 ,\end{aligned}\quad (2.3.13)$$

the solution depending on the sign of the determinant of the characteristic equation:

$$s^2 = \left\{ -\left[\frac{\beta_a - \beta_b}{2} \right]^2 - [(\beta_a - k/2)(\beta_b - k/2) - \delta^2] \right\} = \delta^2 - (\Delta\beta/2)^2 ,$$

where $\Delta\beta = k - (\beta_a + \beta_b)$ is the effective phase mismatch. Subject to the boundary conditions $\tilde{a}(0)=a_0$ and $\tilde{b}(L)=0$ for a grating of length L , the coupled field amplitude

$$\tilde{b}(z) = \frac{j\delta a_0 \sinh[s(z-L)]}{s \cosh(sL) - j(\Delta\beta/2) \sinh(sL)} \cdot \exp\{-j(\beta_a - \beta_b)z/2\} \quad (2.3.14)$$

for $s^2 > 0$ i.e. $(\Delta\beta/2)^2 < \delta^2$,

$$\tilde{b}(z) = \frac{j\delta a_0 (z-L)}{1 - j\delta L} \exp\{-j(\beta_a - \beta_b)z/2\} \quad (2.3.15)$$

for $s^2 = 0$ i.e. $(\Delta\beta/2)^2 = \delta^2$, and

$$\tilde{b}(z) = \frac{j\delta a_0 \{\cos(sz) - \cos[s(2L-z)] + j\{\sin(sz) - \sin[s(2L-z)]\}\}}{[(\Delta\beta/2) - s] + [(\Delta\beta/2) + s]\cos(2sL) - j[(\Delta\beta/2) + s]\sin(2sL)} \cdot \exp\{-j(\beta_a - \beta_b)z/2\} \quad (2.3.16)$$

for $(\Delta\beta/2)^2 > \delta^2$, where $s^2 = (\Delta\beta/2)^2 - \delta^2$.

The power distribution in the two modes is given by

$$P_b = \frac{P_0 \delta^2 \sinh^2[s(L-z)]}{[s^2 \cosh^2(sL) + (\Delta\beta/2)^2 \sinh^2(sL)]} \quad (2.3.17)$$

for $|\Delta\beta/2| < \delta$,

$$P_b = \frac{P_0 \delta^2 (L-z)^2}{1 + \delta^2 L^2} \quad (2.3.18)$$

for $|\Delta\beta/2| = \delta$ and

$$P_b = \frac{P_0 \delta^2 \sin^2[s(L-z)]}{[s^2 \cos^2(sL) + (\Delta\beta/2)^2 \sin^2(sL)]} \quad (2.3.19)$$

for $\Delta\beta/2 > \delta$, with $P_a = 1 - P_b$.

The normalised power propagation in the receiving guide P_b as a function of distance along the direction of propagation z is shown in Fig.2.2, for an interaction length L . For $|\Delta\beta/2\delta| < 1$, the reflected power rises monotonically in the negative z -direction. The variation in P_b is also examined as a function of interaction length (i.e. grating length), for different measures of mismatch, as shown in Fig.2.3.

These curves illustrate two significant properties of backward wave devices in general; that precise phase matching is not required for strong reflection, provided that the interaction length is sufficiently long; and that the variation of coupled power with length has an asymptotic character in the near matching region, so that a precise determination of an interaction length is not required, in marked contrast with the periodic power transfer in forward couplers. For values of $|\Delta\beta/2\delta| > 1$, the amount of coupled power reduces and varies periodically with the interaction length.

It is possible to write the near phase-matching requirement in terms of the deviation in angular frequency ω from the frequency at resonance ω_0 , as

$$|\Delta\beta| = |(n_{EF1} + n_{EF2})[\omega - \omega_0]/\check{c}| \leq 2\delta \quad (2.3.20)$$

where n_{EF1} and n_{EF2} are the effective waveguide indices, and $\check{c}$ is the velocity of light.

The width of the frequency gap is given by

$$(\Delta\omega)_{\text{gap}} = 4\delta \check{c} / (n_{EF1} + n_{EF2}) \quad (2.3.21)$$

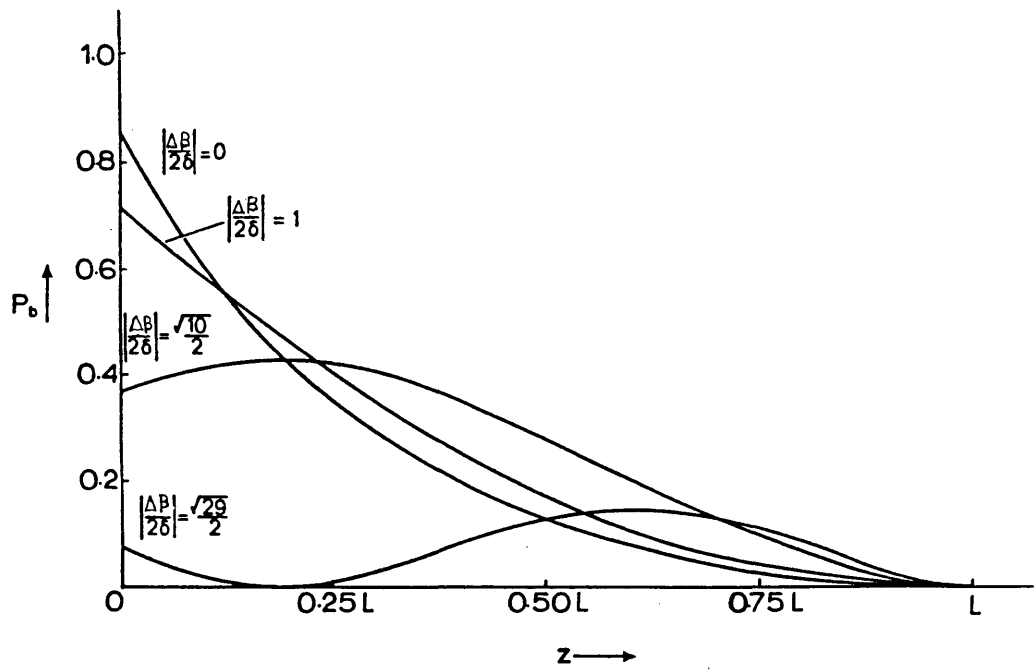


Fig. 2.2

Coupled power variation along the grating length for a contradirectional coupler.

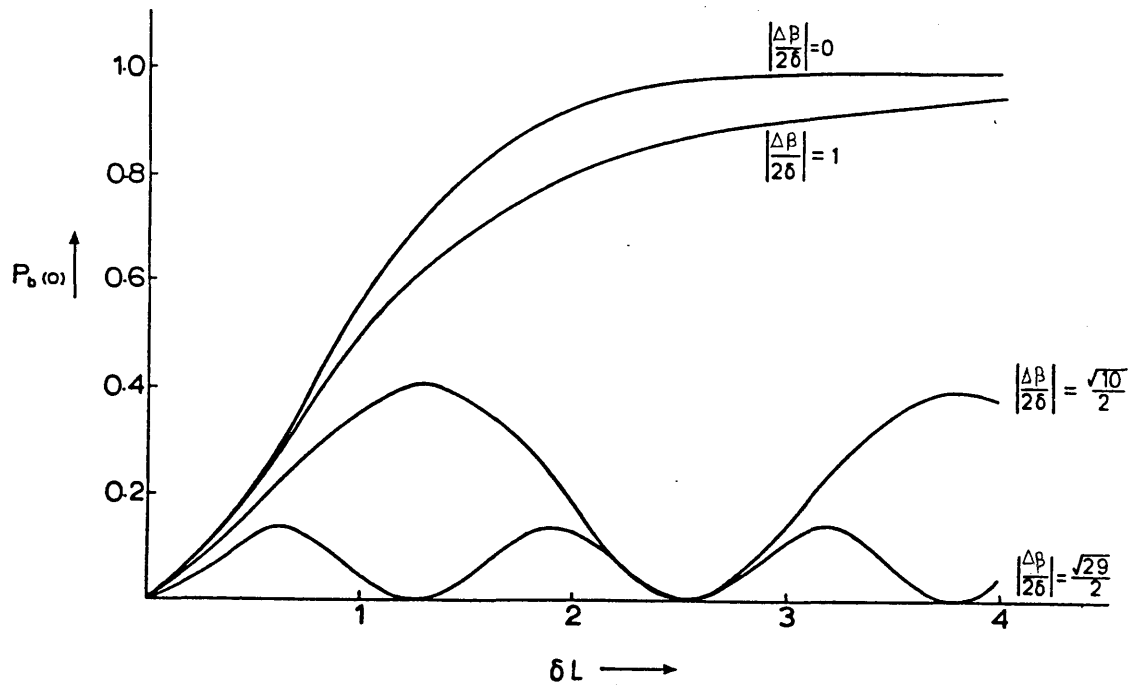


Fig. 2.3

Coupled power as a function of the grating length δL .

and is better known as the "forbidden gap" or coupled bandwidth of the contradirectional coupler.

The mode reflectivity is defined as the fraction of the power coupled

$$R = \frac{|B(0)|^2}{|A(0)|^2} = \frac{P_b(0)}{P_a(0)},$$

and is given by:

$$R = \frac{\delta^2 \sinh^2(sL)}{[s^2 \cosh^2(sL) + (\Delta\beta/2)^2 \sinh^2(sL)]} \quad (2.3.22)$$

Under phase matching, the reflectivity reaches its maximum value

$$R = \tanh^2(\delta \cdot L) \quad (2.3.23)$$

Outside the "forbidden gap", i.e. for $|\Delta\beta/2|^2 > \delta^2$, the reflectivity is given by

$$R = \frac{\delta^2 \sin^2(sL)}{[s^2 \cos^2(sL) + (\Delta\beta/2)^2 \sin^2(sL)]} \quad (2.3.24)$$

and is responsible for the appearance of sidelobes, clearly indicated by the existence of minima and maxima in the above equation; minima for $sL = n\pi$, and maxima for $sL = (2n+1) \cdot \pi / 2$, for $n=0,1,2\dots$

Thus, the level of the n^{th} sidelobe in the reflectivity is given by

$$R_n = \frac{1}{1 + [(2n+1)\pi / (2\delta L)]^2} \quad (2.3.25)$$

The variation in reflectivity as a function of the effective

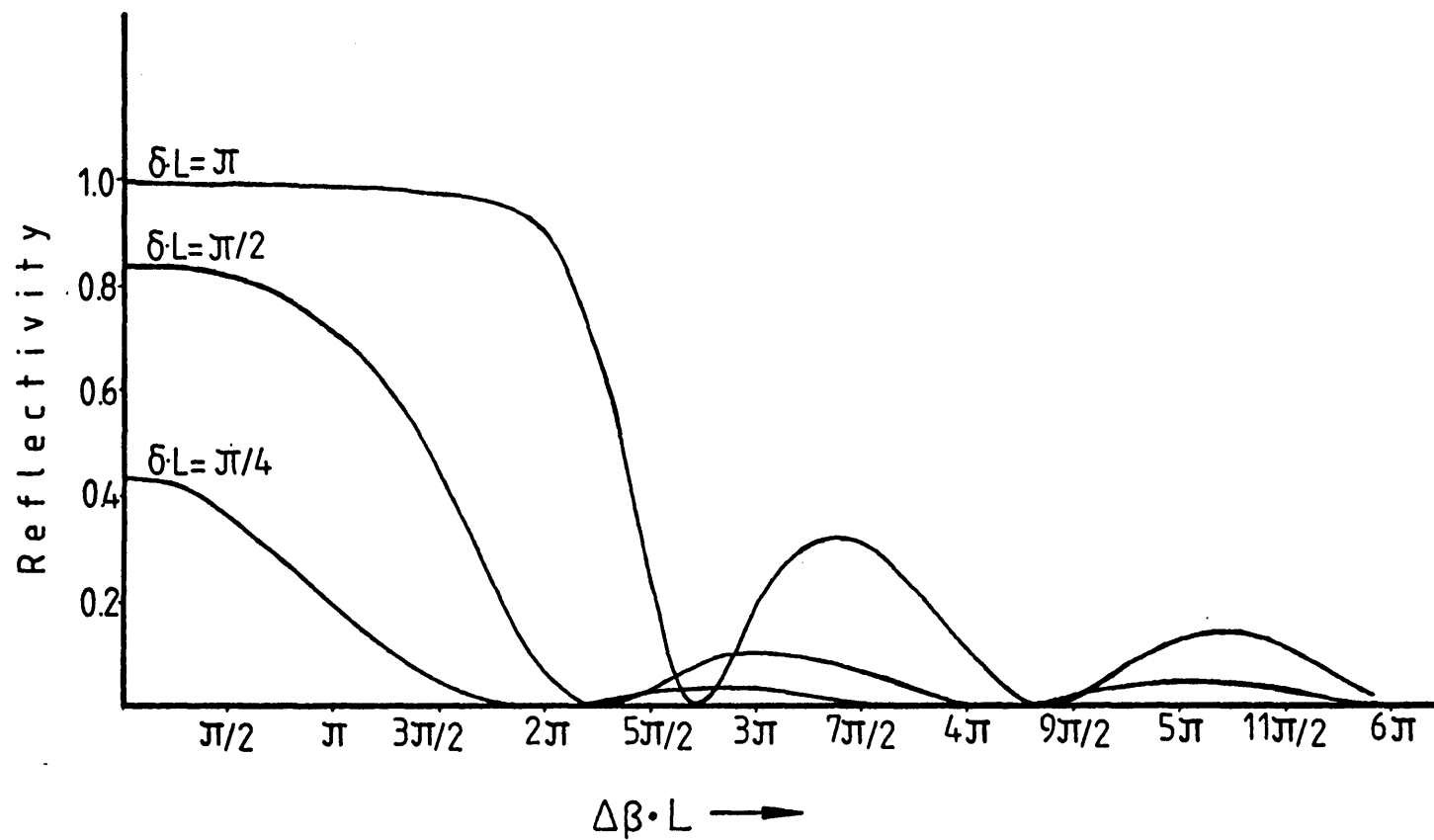


Fig. 2.4

Grating reflectivity as a function of mismatch $\Delta\beta \cdot L$.

mismatch $\Delta\beta \cdot L$ is shown in Fig.2.4. For high reflectivities large δL products, result in severe sidelobe presence.

Note also that for narrow bandwidths (2.3.21) and high reflectivities (2.3.23) long grating lengths are required.

2.3.2 BRAGG REFLECTION IN A PERIODIC WAVEGUIDE

A periodic perturbation on a single mode dielectric waveguide may result in power being reflected from a forward to a backward-going mode, when the periodicity Λ satisfies the momentum conservation requirement:

$$\beta_a = \pi / \Lambda \quad . \quad (2.3.26)$$

The phenomenon is similar to that of Bragg reflection from a periodic layered medium (2.14), and analogous to Bragg scattering of Bloch electron waves in a crystal along the Brillouin zone by the crystal periodicity (2.15).

Bragg reflection can be treated as a special case of contradirectional coupling between modes of the same waveguide, where $\beta_b = \beta_a$ (2.16) .

The coupling equations can be presented as

$$\begin{aligned} \frac{\partial A(z)}{\partial z} &= j c_1 B(z) \cdot \exp\{j2\beta_a \cdot z\} , \\ \frac{\partial B(z)}{\partial z} &= j c_2 A(z) \cdot \exp\{-j2\beta_a \cdot z\} , \end{aligned} \quad (2.3.27)$$

and for a sinusoidal perturbation along the z-direction :

$$\begin{aligned}\frac{\partial A(z)}{\partial z} &= j\delta \cdot B(z) \cdot \exp\{-j(k - 2\beta_a)z\}, \\ \frac{\partial B(z)}{\partial z} &= -j\delta \cdot A(z) \cdot \exp\{j(k - 2\beta_a)z\},\end{aligned}\quad (2.3.28)$$

where $k = 2\pi/\Lambda$ is the Bragg momentum, and δ is the magnitude of the perturbation coupling coefficient given by

$$\delta = \frac{-\omega \cdot \epsilon_0}{4P_0} \iint_{-\infty}^{\infty} \Delta n^2 \cdot |\hat{E}_a|^2 dx \cdot dy. \quad (2.3.29)$$

Solving the system of equations (2.3.28) for $A(z)$ and $B(z)$, results in two second order differential equations:

$$\begin{aligned}\frac{\partial^2 A(z)}{\partial z^2} + j(k - 2\beta_a) \frac{\partial A(z)}{\partial z} - \delta^2 A(z) &= 0 \\ \text{and} \quad \frac{\partial^2 B(z)}{\partial z^2} - j(k - 2\beta_a) \frac{\partial B(z)}{\partial z} - \delta^2 B(z) &= 0.\end{aligned}\quad (2.3.30)$$

For a grating length L , if $A(0)=A_0$, then $B(L)=0$, since $B(z)$ is generated by the perturbation.

Defining $\Delta\beta = |k - 2\beta_a|$ and $S^2 = \delta^2 - (\Delta\beta/2)^2$, the solutions of 2.3.30, subject to the above boundary conditions, will depend on the sign of S^2 . For $S^2 > 0$, the solution for (b) takes the form

$$B(z) = A_0 \frac{j2\delta \sinh[S(z-L)]}{[-\Delta\beta \sinh(SL) + j2S \cosh(SL)]} \cdot \exp[-j\Delta\beta z/2]. \quad (2.3.31)$$

Under phase matching conditions, $\Delta\beta = 0$ and $S = \delta$, the above equation is simplified into

$$B(z) = A_0 \frac{\sinh[\delta \cdot (z-L)]}{\cosh[\delta \cdot L]} \quad (2.3.32)$$

For the special case, where $|\Delta\beta| = 2\delta$, i.e. $S^2 = 0$, the solution becomes:

$$B(z) = A_0 \frac{j \delta \cdot (z-L)}{1 - j \delta \cdot L} \exp\{-j \delta \cdot z\} \quad (2.3.33)$$

Finally, for $\delta^2 < (\Delta\beta/2)^2$ and $S^2 = (\Delta\beta/2)^2 - \delta^2$, the solution takes the form

$$B(z) = A_0 \frac{j 2\delta \{\cos(Sz) - \cos[S(2L-z)] + j [\sin(Sz) - \sin[S(2L-z)]]\}}{[(\Delta\beta - 2S) + (\Delta\beta + 2S) \cdot \cos(2SL) - j (\Delta\beta + 2S) \cdot \sin(2SL)]} \exp[-j \Delta\beta z/2] \quad (2.3.34)$$

In terms of power, the above expressions give:

$$P_b = \frac{P_0 \delta^2 \sinh^2[S(L-z)]}{[S^2 \cosh^2(SL) + (\Delta\beta/2)^2 \sinh^2(SL)]} \quad (2.3.35)$$

for $|\Delta\beta/2| < \delta$,

$$P_b = \frac{P_0 \delta^2 (L-z)^2}{1 + (\delta \cdot L)^2} \quad (2.3.36)$$

for $|\Delta\beta/2| = \delta$, and

$$P_b = \frac{P_0 \delta^2 \sin^2[S(L-z)]}{[S^2 \cos^2(SL) + (\Delta\beta/2)^2 \sin^2(SL)]} \quad (2.3.37)$$

for $|\Delta\beta/2| > \delta$, while for all cases

$$P_a = P_0 - P_b \quad (2.3.38)$$

Under phase matching conditions, i.e. for $\Delta\beta = 0$,

$$P_b = P_0 \frac{\sinh^2 [\delta(L-z)]}{\cosh^2 (\delta L)} \quad (2.3.39)$$

The above equations bear a close resemblance to those derived for contradirectional coupling in a two waveguide structure (2.3.17-19), for $\beta_b = \beta_a$. There is no fundamental distinction between these coupling processes, but purely difference in detail arising from the different magnitudes of the coupling coefficient [(2.3.29) , (2.3.10)] , which for contradirectional coupling is also a function of the waveguide separation.

The variation in coupled power along the interaction length, and as a function of different grating lengths, presented in Figs.2.2 and 2.3 for the contradirectional coupler, also hold for the Bragg reflector, with $\Delta\beta = k - 2\beta_a$ and δ as given by (2.3.29) .

The "forbidden gap" or coupled bandwidth is given by

$$(\Delta\omega)_{\text{gap}} = 2\delta\check{c} / n_{EF} \quad , \quad (2.3.40)$$

and is generally of the same order as the one for the grating coupler (2.3.21), for perturbations of equal strength, i.e. when the coupling coefficients are made equal.

The reflectivity is defined as in (2.3.22-24) and experiences side-lobe presence as shown in Fig.2.4 .

2.3.3 CODIRECTIONAL COUPLING

Consider two single-mode waveguides in the presence of a periodic perturbation, such as a surface corrugation. If the periodicity is large enough to satisfy the momentum equation :

$$\beta_a - \beta_b = 2\pi/\Lambda \quad , \text{ with } \beta_a \neq \beta_b \quad ,$$

where β_a , β_b are the co-propagating modes of the two waveguides, then these modes are strongly coupled and power exchange can occur, similarly to a conventional directional coupler.

The mode amplitudes $A(z)$ and $B(z)$ are interrelated by the coupling equations, which for a sinusoidal longitudinal perturbation take the form:

$$\begin{aligned} \frac{\partial A(z)}{\partial z} &= j \delta \cdot B(z) \cdot \exp\{-j[k - (\beta_a - \beta_b)]z\} \quad , \\ \frac{\partial B(z)}{\partial z} &= j \delta \cdot A(z) \cdot \exp\{ j[k - (\beta_a - \beta_b)]z\} \quad . \end{aligned} \quad (2.3.41)$$

Due to the codirectional power flow in the two modes, both coupling coefficients have the same sign, their amplitude δ given by

$$\delta = \frac{-\omega \epsilon_0}{4P_0} \iint_{-\infty}^{\infty} \Delta n^2 |\hat{E}_a| |\hat{E}_b| dx \cdot dy \quad . \quad (2.3.42)$$

Note also, that the total power carried by the two modes is conserved, since :

$$\frac{d}{dz} \{ |A(z)|^2 + |B(z)|^2 \} = 0 \quad .$$

Separating the individual mode amplitudes from (2.3.41) results in two second order differential equations:

$$\begin{aligned} \frac{\partial^2 A(z)}{\partial z^2} + j[k - (\beta_a - \beta_b)] \frac{\partial A(z)}{\partial z} + \delta^2 A(z) &= 0, \\ \frac{\partial^2 B(z)}{\partial z^2} - j[k - (\beta_a - \beta_b)] \frac{\partial B(z)}{\partial z} + \delta^2 B(z) &= 0, \end{aligned} \quad (2.3.43)$$

the solution of which, subject to the boundary conditions $A(0)=A_0$ and $B(0)=0$, becomes:

$$B(z) = -j A_0 (\delta / S) \cdot \sin(Sz) \cdot \exp\{j \Delta\beta \cdot z / 2\} \quad (2.3.44)$$

and

$$A(z) = A_0 [\cos(Sz) + j(\Delta\beta/2S) \cdot \sin(Sz)] \cdot \exp\{-j \Delta\beta \cdot z / 2\}, \quad (2.3.45)$$

where $\Delta\beta = |k - (\beta_a - \beta_b)|$ and $S^2 = \delta^2 + (\Delta\beta/2)^2$.

In terms of power:

$$P_b = P_0 (\delta / S)^2 \sin^2(Sz), \quad (2.3.46)$$

and $P_a = P_0 - P_b$.

Note that the coupling process is periodic, provided that the grating length is sufficiently long. Complete power transfer may occur only under phase matching (i.e. $\Delta\beta = 0$) and over a grating length $\pi/2\delta$. For $\Delta\beta \neq 0$, the maximum transferable fraction of power is given by

$$\delta^2 / [\delta^2 + (\Delta\beta/2)^2]. \quad (2.3.47)$$

The above equations look similar to those, obtained for directional coupling (2.2.8), where $\Delta\beta = \beta_a - \beta_b$.

In both situations coupling is periodic and of similar nature, a small difference arising in the matching requirement and in the calculation of the coupling coefficient. In

the present case, the latter is usually weaker for the same waveguide separation, requiring longer interaction lengths.

Strong coupling occurs only for $\Delta\beta < 2\delta$ (2.3.47), over a coupled bandwidth

$$(\Delta\omega)_{\text{gap}} = 4\delta\check{c}/(|n_{\text{EF1}} - n_{\text{EF2}}|) \quad (2.3.48)$$

where $\check{c}$ is the velocity of light, and $n_{\text{EF1}} - n_{\text{EF2}}$ is the difference in the effective indices of the two guides.

Note that the coupled bandwidth increases for similar waveguides when $n_{\text{EF1}} \approx n_{\text{EF2}}$, i.e. $n_{\text{EF1}} - n_{\text{EF2}}$ is small.

2.4 Composite Coupling Processes

Even though the three main coupling processes i.e. directional coupling, Bragg reflection and contradirectional coupling have been considered individually, it is clear that for a two waveguide system perturbed by a surface corrugation, all three may act simultaneously. The range of coupling possibilities can be visualised most readily by reference to the dispersion diagram shown in Fig.2.5 for two dissimilar guides (a) and (b), and a single periodic perturbation of pitch Λ and momentum $k = 2\pi/\Lambda$. Forward directional coupling occurs at frequencies around ω_1 , where $\beta_a(\omega_1) \approx \beta_b(\omega_1)$. Power launched in guide (a) will be reflected back at frequencies around ω_2 , where $\beta_a(\omega_2) \approx \pi/\Lambda$, and similarly power launched in guide (b) will be reflected in (b) around ω_3 , where $\beta_b(\omega_3) \approx \pi/\Lambda$. Finally, contradirectional

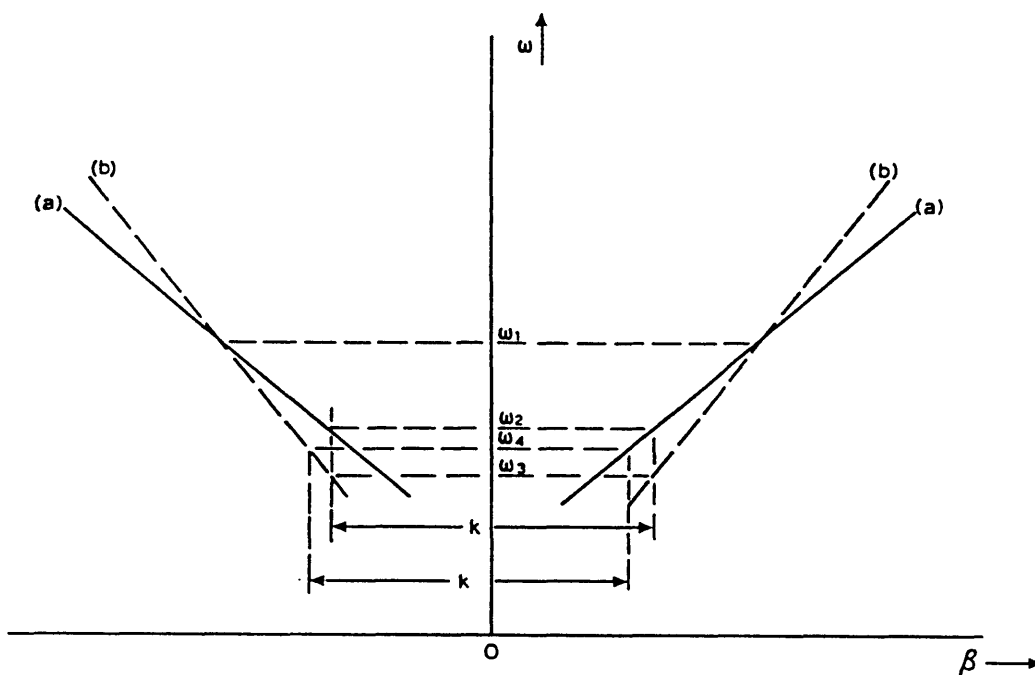


Fig. 2.5

Dispersion diagram showing the coupling possibilities between two dissimilar guides (a) and (b) in the presence of a periodic perturbation.

coupling between the guides will occur at frequencies around ω_4 , where $\beta_a(\omega_4) + \beta_b(\omega_4) \approx 2\pi/\Lambda$. By appropriate choice of the dispersion characteristic of the individual guides and the periodicity Λ , the various frequencies of strong coupling can be adequately isolated and a simple two-mode analysis can be carried out for each process separately.

If, however, all the different coupling processes are allowed to overlap, a more interesting situation arises with all four modes (one forward and one backward for each guide) competing for a share of the power, finally distributed among all four ports of the device.

Considering the different coupling processes interacting with the same central frequency, i.e. $\omega_1 = \omega_2 = \omega_3 = \omega_4$, two modes of operation will be examined, the synchronous; at the central frequency, and the nearly-synchronous; at neighbouring frequencies.

A device operating in full synchronism is only influenced by the comparative strengths of the different coupling coefficients, while for near-synchronous operation coupling is also affected by the wavelength selectivity of the individual coupling processes.

The analysis of composite coupling processes will be based on coupled mode theory, generally treated as a four wave problem. A simple analytical solution does not always exist, in which case numerical solutions will be offered. Although a similar type of analysis was carried out in (2.17), some new results are presented, and also some consideration is given to possible implementation restrictions in the relative magnitudes of the various coupling coefficients.

2.4.1 SYNCHRONOUS OPERATION

Consider two single-mode dielectric waveguides and a periodic perturbation of Bragg momentum k (see Fig.2.6), with both the phase matching and the momentum conservation requirements satisfied at the same central frequency ω_0 .

For operation at ω_0 , the individual field amplitudes A , B , C , D are related by the coupling equations:

$$\begin{aligned}
 \frac{dA(z)}{dz} &= j c_{ab} B(z) + j c_{ac} C(z) + j c_{ad} D(z) , \\
 \frac{dB(z)}{dz} &= j c_{ba} A(z) + j c_{bc} C(z) + j c_{bd} D(z) , \\
 \frac{dC(z)}{dz} &= j c_{ca} A(z) + j c_{cb} B(z) + j c_{cd} D(z) , \\
 \frac{dD(z)}{dz} &= j c_{da} A(z) + j c_{db} B(z) + j c_{dc} C(z) ,
 \end{aligned}
 \tag{2.4.1}$$

where c_{ij} are the different coupling coefficients; (i) denoting the source and (l) the destination of the energy. The above equations have originated from a four-wave coupled mode analysis, similar to the one presented in section 2.1 for the two-wave case.

The coupling coefficients can be regrouped into those of the four coupling processes;

$c_{ab} = -c_{ba} = \kappa_1$ and $c_{cd} = -c_{dc} = \kappa_2$ for Bragg reflection in the individual waveguides,

$c_{ac} = c_{ca} = -c_{bd} = -c_{db} = c_0$ forward directional coupling, and

$c_{ad} = c_{cb} = -c_{da} = -c_{bc} = \delta$ contradirectional coupling in

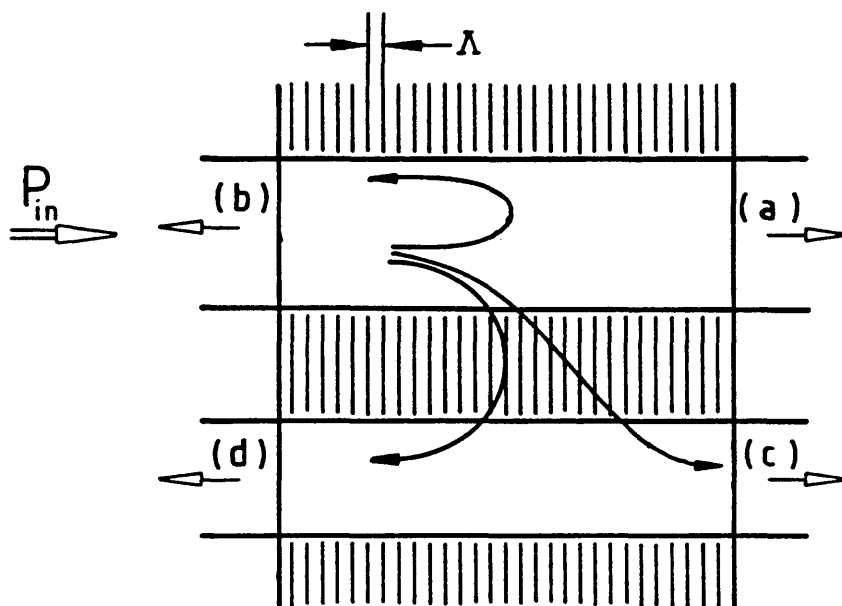


Fig. 2.6

Schematic diagram of a grating coupler operated as a four port device.

the two waveguides. For simplicity consider a symmetrical structure, where the reflection coefficients in both waveguides are approximately equal i.e. $\kappa_1 = \kappa_2 = \kappa$. This can be achieved, either by fabricating a grating on each waveguide, or a single grating equidistant from the two guides.

The coupling equations:

$$\begin{aligned}
 \frac{dA(z)}{dz} &= j\kappa B(z) + jc_0 C(z) + j\delta D(z), \\
 \frac{dB(z)}{dz} &= -j\kappa A(z) - j\delta C(z) - jc_0 D(z), \\
 \frac{dC(z)}{dz} &= jc_0 A(z) + j\delta B(z) + j\kappa D(z), \\
 \frac{dD(z)}{dz} &= -j\delta A(z) - jc_0 B(z) - j\kappa C(z),
 \end{aligned}
 \tag{2.4.2}$$

result in four fourth order differential equations of the form:

$$\frac{d^4 \psi}{dz^4} - 2(\kappa^2 + \delta^2 - c_0^2) \frac{d^2 \psi}{dz^2} + \{(\kappa^2 + \delta^2 - c_0^2)^2 - (2\delta\kappa)^2\} \psi = 0.
 \tag{2.4.3}$$

The roots of the characteristic equation are given by

$$\rho_{1,2,3,4} = \pm \sqrt{(\kappa \pm \delta)^2 - c_0^2},
 \tag{2.4.4}$$

the form of solution depending on the comparative strengths of the different coupling processes, as influenced by the coupler design.

For a grating fabricated close to the core of a guide, the reflection coefficient κ , as given by the integral of (2.3.29), depends on the dimensional parameters of the

grating, i.e. its depth and its proximity to the core, and is not influenced by the presence of other waveguides. The directional coupling coefficient c_0 , as given by (2.2.2), depends on the evanescent field penetration of both guides and their separation, and is not affected by the presence of the grating. The contradirectional coupling coefficient δ , as given by (2.3.10), results from the field of the two guides overlapping over the perturbation region and thus depends on the grating characteristics, field penetration and waveguide separation.

For a grating imposed on the core / cladding interface of one of the waveguides, the contradirectional coefficient is usually smaller than the reflection coefficient in the waveguide on which the grating has been imposed, due to "weaker" field overlap, and is bigger than the reflection coefficient in the neighbouring guide.

If the grating is fabricated on both guides, or in the cladding half-way between the two cores, the contradirectional coefficient δ and the reflection coefficients in both guides κ_1 and κ_2 are approximately equal, although usually smaller than the forward coupling coefficient c_0 . It is, therefore, reasonable to assume that $c_0 \gg \kappa \approx \delta$.

In this case all four roots of the characteristic equation are imaginary:

$$\begin{aligned} \rho_{1,2} &= \pm j\sqrt{c_0^2 - (\kappa + \delta)^2} = \pm j\gamma_1, \\ \rho_{3,4} &= \pm j\sqrt{c_0^2 - (\kappa - \delta)^2} = \pm j\gamma_2. \end{aligned} \quad (2.4.5)$$

Subject to the boundary conditions $A(0)=A_0$, $C(0)=0$, $B(L)=0$ and $D(L)=0$, for a grating length L (interaction length), the

field solutions at the four output ports are:

$$\begin{aligned}
 A(L) &= \frac{A_0}{2} \left[\frac{\gamma_1}{\gamma_1 \cos(\gamma_1 L) - j c_0 \sin(\gamma_1 L)} + \frac{\gamma_2}{\gamma_2 \cos(\gamma_2 L) + j c_0 \sin(\gamma_2 L)} \right], \\
 B(0) &= \frac{A_0}{2} \left[\frac{j(\kappa + \delta) \sin(\gamma_1 L)}{\gamma_1 \cos(\gamma_1 L) - j c_0 \sin(\gamma_1 L)} + \frac{j(\kappa - \delta) \sin(\gamma_2 L)}{\gamma_2 \cos(\gamma_2 L) + j c_0 \sin(\gamma_2 L)} \right], \\
 C(L) &= \frac{A_0}{2} \left[\frac{\gamma_1}{\gamma_1 \cos(\gamma_1 L) - j c_0 \sin(\gamma_1 L)} - \frac{\gamma_2}{\gamma_2 \cos(\gamma_2 L) + j c_0 \sin(\gamma_2 L)} \right], \\
 D(0) &= \frac{A_0}{2} \left[\frac{j(\kappa + \delta) \sin(\gamma_1 L)}{\gamma_1 \cos(\gamma_1 L) - j c_0 \sin(\gamma_1 L)} - \frac{j(\kappa - \delta) \sin(\gamma_2 L)}{\gamma_2 \cos(\gamma_2 L) + j c_0 \sin(\gamma_2 L)} \right],
 \end{aligned}
 \tag{2.4.6}$$

and expressions in terms of power can be obtained by considering:

$$P_a = |A(L)|^2, \quad P_b = |B(0)|^2, \quad P_c = |C(L)|^2, \quad P_d = |D(0)|^2,$$

satisfying the conservation of power requirement:

$$P_a + P_b + P_c + P_d = |A_0|^2. \tag{2.4.7}$$

Fig.2.7 shows the power distribution in the four ports of the device as a function of interaction length L . For values of $c_0 \gg \kappa \approx \delta$ (Fig.2.7.i), there is hardly any power in (b) and (d), and the device behaves generally as a forward directional coupler with periodic power exchange between modes (a) and (c). For smaller differences between the directional and contradirectional coupling strengths (see Fig.2.7.ii), power is distributed in all four ports, though most of it is still being handled by the two forward-going modes and the process remains basically periodic.

A more interesting situation arises when the coupling coefficients of the three different processes are of

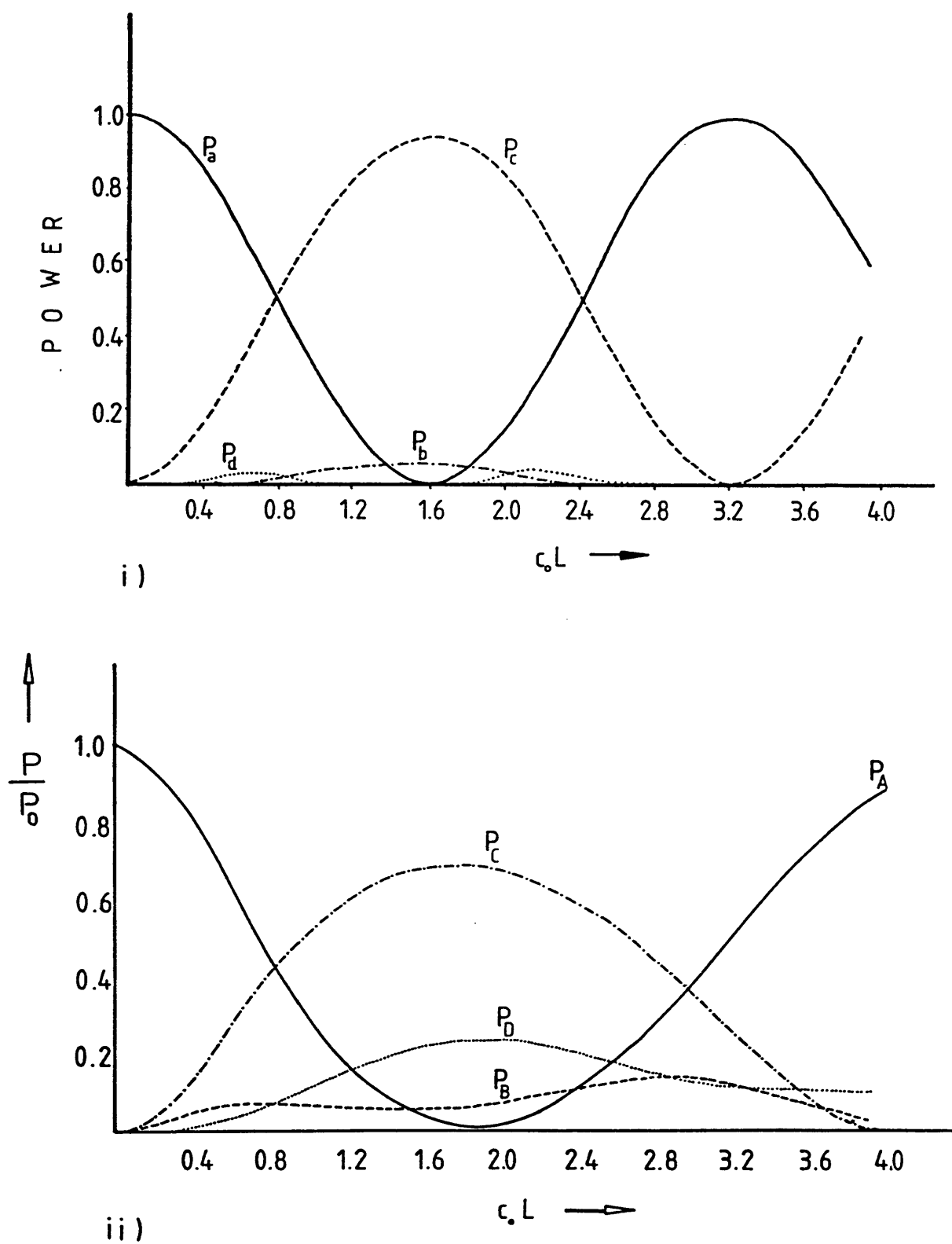


Fig. 2.7

Power distribution in the four output ports as a function of interaction length for i) $c_0 \gg \kappa + \delta$,

ii) $c_0 > \kappa + \delta$.

comparable strength,

$$\text{i.e. } (\delta - \kappa)^2 < c_o^2 < (\delta + \kappa)^2$$

and the roots of the characteristic equation become:

$$\begin{aligned} \rho_{1,2} &= \pm \sqrt{(\kappa + \delta)^2 - c_o^2} = \pm \Delta \quad \text{real ,} \\ \rho_{3,4} &= \pm j \sqrt{(c_o^2 - (\kappa - \delta)^2)} = \pm j \gamma \quad \text{imaginary . (2.4.8)} \end{aligned}$$

In this case the field expressions of the output ports are:

$$\begin{aligned} A(L) &= \frac{A_o}{2} \left[\frac{\Delta}{\Delta \cosh(\Delta \cdot L) - j c_o \sinh(\Delta \cdot L)} + \frac{\gamma}{\gamma \cos(\gamma \cdot L) + j c_o \sin(\gamma \cdot L)} \right] , \\ B(0) &= \frac{A_o}{2} \left[\frac{j(\kappa + \delta) \sinh(\Delta \cdot L)}{\Delta \cosh(\Delta \cdot L) - j c_o \sinh(\Delta \cdot L)} + \frac{j(\kappa - \delta) \sin(\gamma \cdot L)}{\gamma \cos(\gamma \cdot L) + j c_o \sin(\gamma \cdot L)} \right] , \\ C(L) &= \frac{A_o}{2} \left[\frac{\Delta}{\cosh(\Delta \cdot L) - j c_o \sinh(\Delta \cdot L)} - \frac{\gamma}{\gamma \cos(\gamma \cdot L) + j c_o \sin(\gamma \cdot L)} \right] , \\ D(0) &= \frac{A_o}{2} \left[\frac{j(\kappa + \delta) \sinh(\Delta \cdot L)}{\Delta \cosh(\Delta \cdot L) - j c_o \sinh(\Delta \cdot L)} - \frac{j(\kappa - \delta) \sin(\gamma \cdot L)}{\gamma \cos(\gamma \cdot L) + j c_o \sin(\gamma \cdot L)} \right] , \end{aligned} \quad (2.4.9)$$

and again expressions for the power distribution can be obtained from eq.2.4.7 .

In this case power is more evenly distributed among the four ports (see Fig.2.8.i) and the process appears to have lost its periodic profile. The power variation with grating length is rather slow, and a length exists, for which the two forward and the two backward modes carry equal amounts of power. A most interesting development occurs when

$$\delta = \kappa > c_o , \quad (\text{Fig.2.8.ii})$$

and the outputs from all four ports tend to the same value, acting as a four way power divider. Note, that a further increase in the interaction length does not produce any

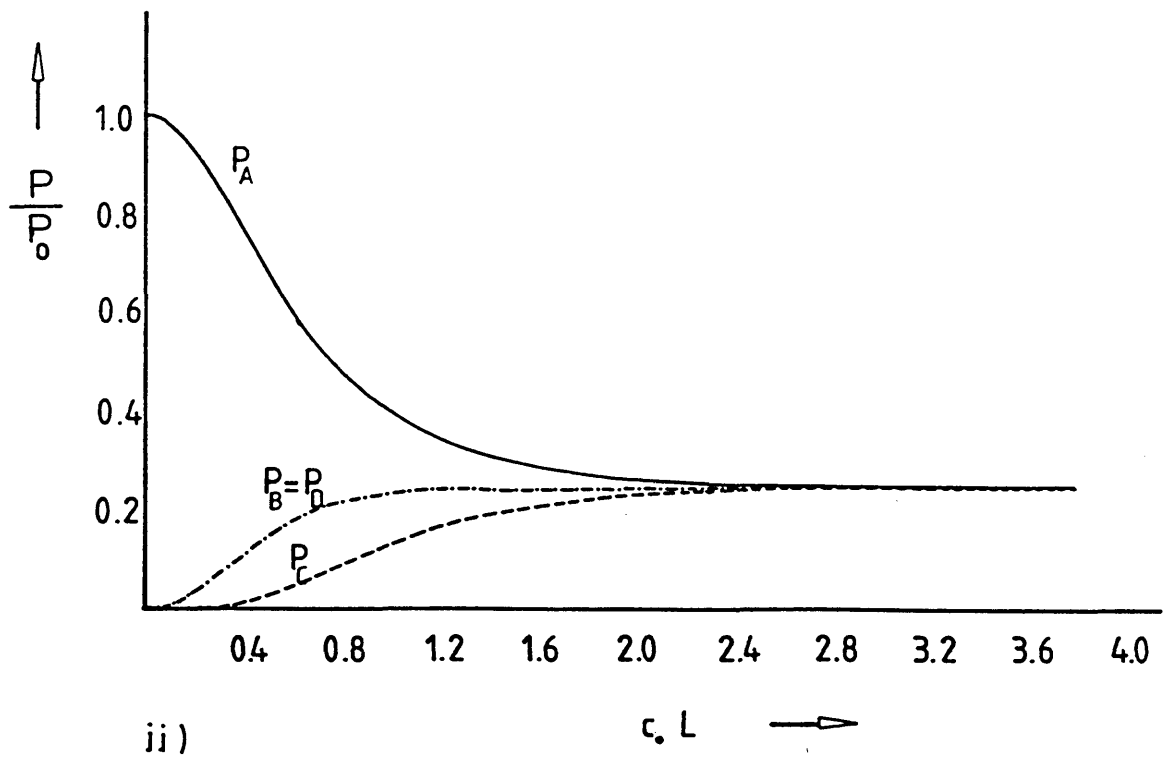
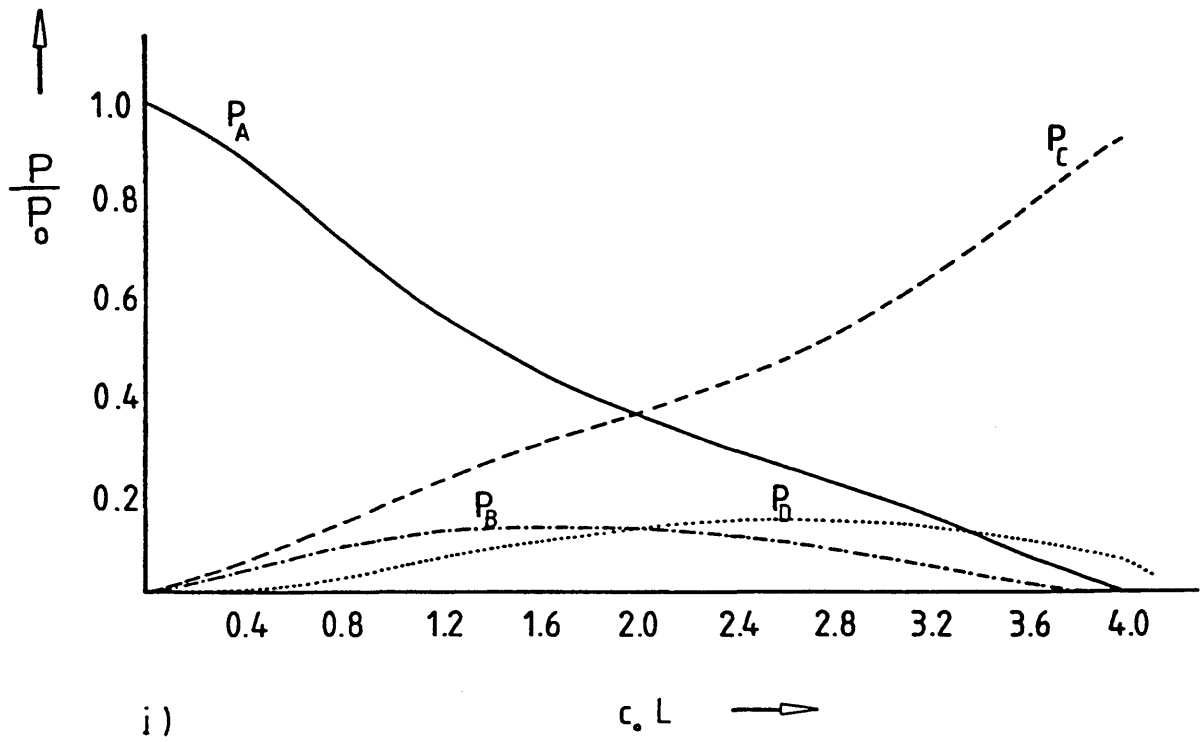


Fig. 2.8

Power distribution in the four output ports as a function of interaction length for i) $\chi + \delta > c_0 > |\chi - \delta|$,
 ii) $\chi + \delta > c_0$ and $\chi = \delta$.

change in the distribution of power.

Finally, if c_o is considered to be much smaller than either κ or δ i.e. $(\kappa+\delta)^2 > (\kappa-\delta)^2 > c_o^2$,

all the roots of the characteristic equation become real:

$$\begin{aligned} \rho_{1,2} &= \pm \sqrt{(\kappa+\delta)^2 - c_o^2} = \pm \Delta_1, \\ \rho_{3,4} &= \pm \sqrt{(\kappa-\delta)^2 - c_o^2} = \pm \Delta_2, \end{aligned} \quad (2.4.10)$$

the field solutions in the four output ports are given by:

$$\begin{aligned} A(L) &= \frac{A_o}{2} \left[\frac{\Delta_1}{\Delta_1 \cosh(\Delta_1 L) - j c_o \sinh(\Delta_1 L)} + \frac{\Delta_2}{\Delta_2 \cosh(\Delta_2 L) + j c_o \sinh(\Delta_2 L)} \right], \\ B(0) &= \frac{A_o}{2} \left[\frac{j(\kappa+\delta) \sinh(\Delta_1 L)}{\Delta_1 \cosh(\Delta_1 L) - j c_o \sinh(\Delta_1 L)} + \frac{j(\kappa-\delta) \sinh(\Delta_2 L)}{\Delta_2 \cosh(\Delta_2 L) + j c_o \sinh(\Delta_2 L)} \right], \\ C(L) &= \frac{A_o}{2} \left[\frac{\Delta_1}{\Delta_1 \cosh(\Delta_1 L) - j c_o \sinh(\Delta_1 L)} - \frac{\Delta_2}{\Delta_2 \cosh(\Delta_2 L) + j c_o \sinh(\Delta_2 L)} \right], \\ D(0) &= \frac{A_o}{2} \left[\frac{j(\kappa+\delta) \sinh(\Delta_1 L)}{\Delta_1 \cosh(\Delta_1 L) - j c_o \sinh(\Delta_1 L)} - \frac{j(\kappa-\delta) \sinh(\Delta_2 L)}{\Delta_2 \cosh(\Delta_2 L) + j c_o \sinh(\Delta_2 L)} \right], \end{aligned} \quad (2.4.11)$$

which can again be expressed in terms of power.

Since forward coupling is rather weak, we expect reflection and contradirectional coupling to dominate, with most of the power being shared between the backward modes (b) and (d), and only for short grating lengths some of it remains in (a) or finds its way into (c), as shown in Fig.2.9. Note also that the power distribution for different interaction lengths, has lost its periodic nature and has assumed the well known exponential Bragg-type response.

The above treatment clearly indicates, that for a combination of directional and contradirectional coupling

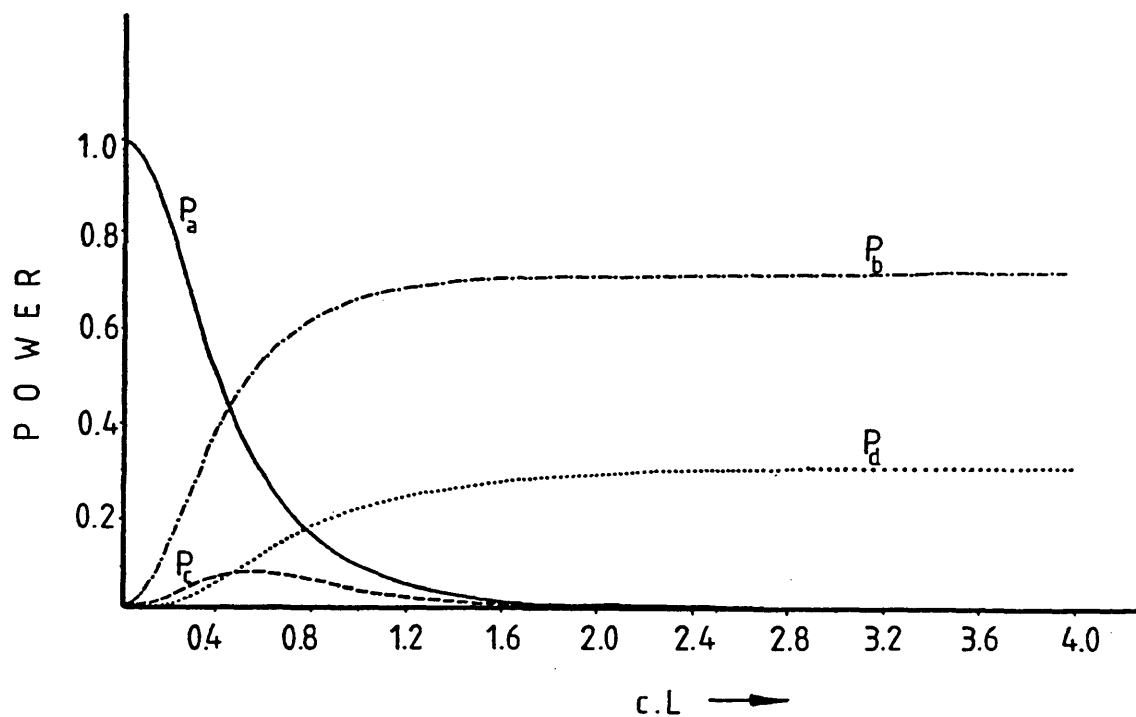


Fig. 2.9

Power distribution in the four output ports as a function of interaction length for $\kappa + \delta > |\kappa - \delta| > c_0$.

in synchronism, with the directional coupling stronger for a realistic waveguide separation and a perturbation magnitude, the device behaves mainly as a forward coupler, with only a minute amount of power handled by the grating coupling processes.

2.4.2 NEAR-SYNCHRONOUS OPERATION

For near-synchronous operation, the phase-matched modes of the previous section are driven at a frequency ω , other than their matching frequency ω_0 , thus being pulled slightly off matching. The change in frequency or rather in wavelength, introduces the effective mismatches $\Delta\beta_{\lambda 1}$ and $\Delta\beta_{\lambda 2}$ on the propagation constants of the two guides where,

$$\begin{aligned}\beta_a(\omega) &= \beta_a(\omega_0) + \Delta\beta_{\lambda 1}, \\ \beta_b(\omega) &= \beta_b(\omega_0) + \Delta\beta_{\lambda 2}.\end{aligned}\quad (2.4.12)$$

Note that for dissimilar waveguides $\Delta\beta_{\lambda 1} \neq \Delta\beta_{\lambda 2}$.

The field amplitudes A, B, C, D are related via the coupling equations :

$$\begin{aligned}\frac{dA}{dz} &= j\Delta\beta_{\lambda 1}A + j\kappa_1B + jc_0C + j\delta D, \\ \frac{dB}{dz} &= -j\kappa_1A - j\Delta\beta_{\lambda 1}B - j\delta C - jc_0D, \\ \frac{dC}{dz} &= jc_0A + j\delta B + j\Delta\beta_{\lambda 2}C + j\kappa_2D, \\ \frac{dD}{dz} &= -j\delta A - jc_0B - j\kappa_2C - j\Delta\beta_{\lambda 2}D,\end{aligned}\quad (2.4.13)$$

for mismatches $\Delta\beta_{\lambda 1}$, $\Delta\beta_{\lambda 2}$ and where κ_1 , κ_2 are the reflection, c_o the directional, and δ the contradirectional coupling coefficients.

A simple analytical solution does not always exist for the above system of equations. Only when $\kappa_1 = \kappa_2 = \kappa$ and for $\Delta\beta_{\lambda 1} = \Delta\beta_{\lambda 2}$ it is possible to resolve (2.4.13) into a fourth order differential equation of a form similar to (2.4.3). The roots of the characteristic equation are given by

$$\rho_{1,2,3,4} = \pm \sqrt{(\kappa \pm \delta)^2 - (c_o \pm \Delta\beta_{\lambda})^2} \quad (2.4.14)$$

Two identical waveguides, as is the case for $\Delta\beta_{\lambda 1} = \Delta\beta_{\lambda 2}$, remain phase-matched at all frequencies, while Bragg-reflection and contradirectional coupling are pulled off matching. The significantly broader bandwidth of the forward coupling process, combined with the generally stronger coupling coefficient c_o , make the device behave as a directional coupler, with most of the power shared between modes (a) and (c).

The field solutions for different combinations of c_o , κ and δ can be obtained from (2.4.14), and are of similar form to those presented in section 2.4.1 for the synchronous case where

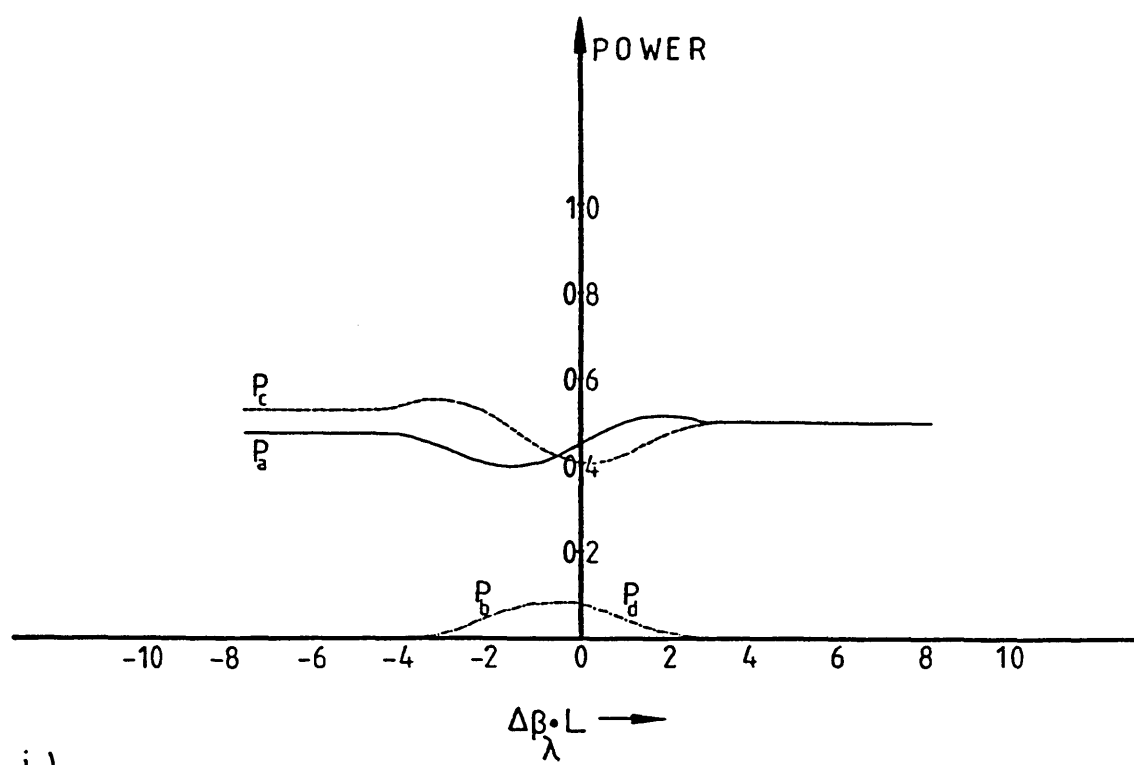
$$|\gamma_1| = |\Delta_1| = |\sqrt{(\kappa + \delta)^2 - (c_o + \Delta\beta_{\lambda})^2}| \quad (2.4.15)$$

and

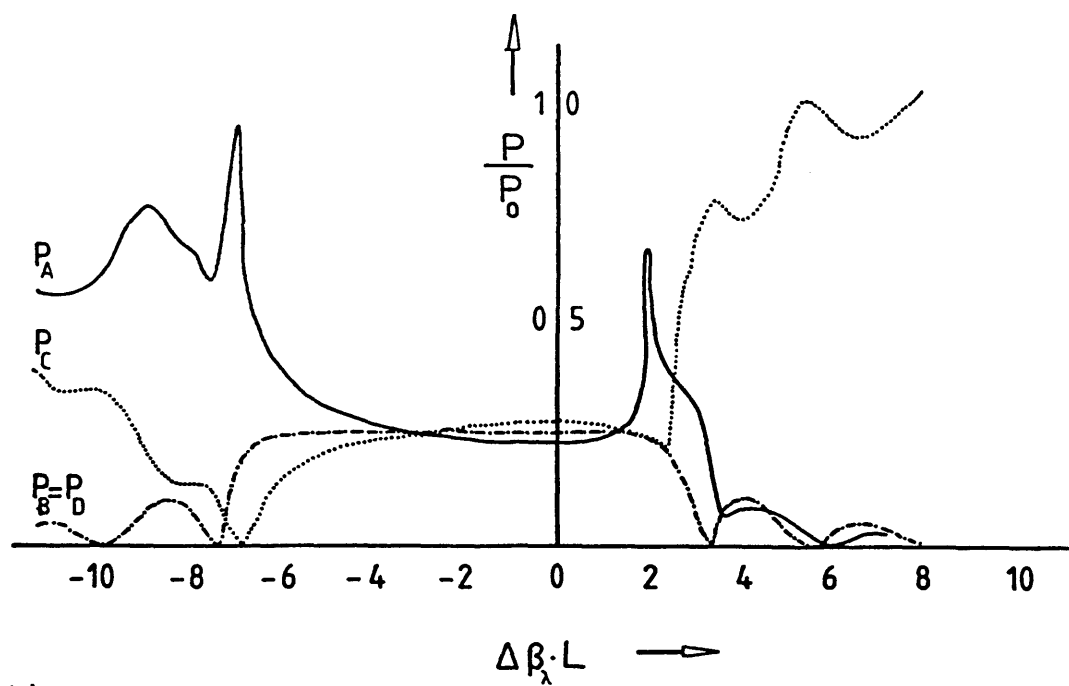
$$|\gamma_2| = |\Delta_2| = |\sqrt{(\kappa - \delta)^2 - (c_o - \Delta\beta_{\lambda})^2}|$$

The power distribution among the four output ports, as a function of mismatch $\Delta\beta_{\lambda}$, is shown in Fig. 2.10.i,ii,iii for $c_o^2 > (\kappa + \delta)^2$, $c_o = \kappa = \delta$ and $c_o^2 \ll (\kappa - \delta)^2$ respectively, for an interaction length L .

In Fig. 2.10.i, for large $\Delta\beta_{\lambda}$, all the power is contained



i)



ii)

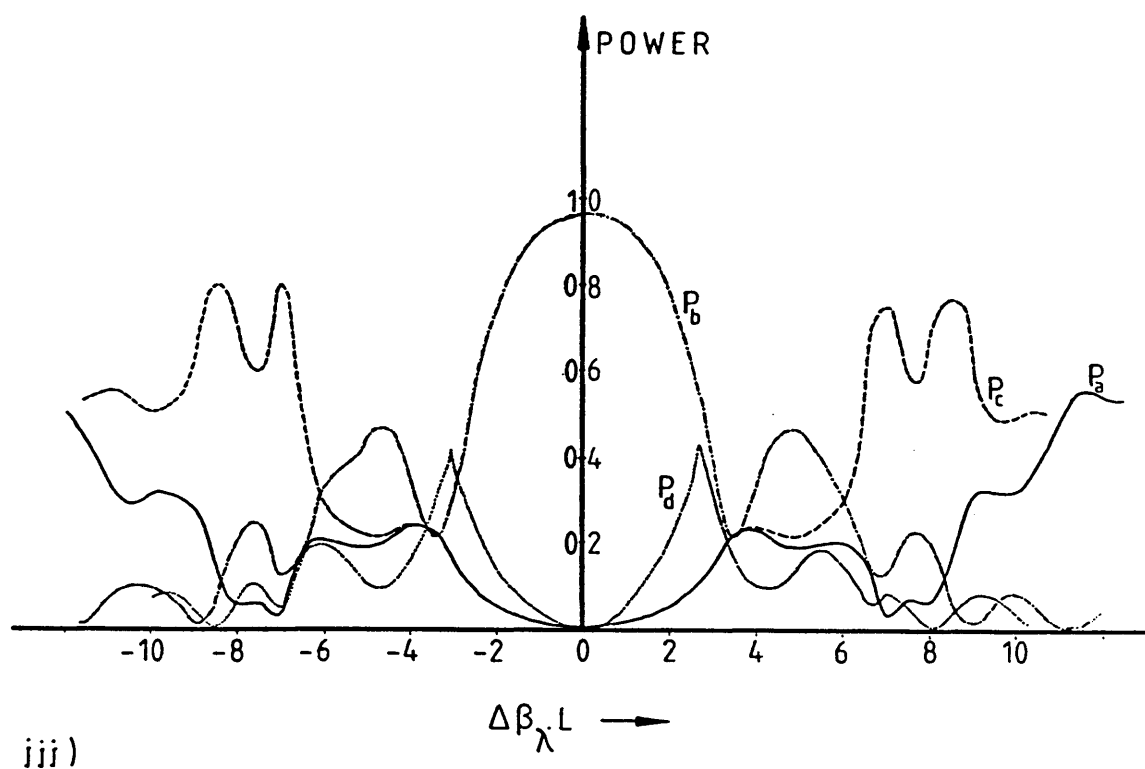


Fig. 2.10

Power distribution in the four output ports as a function of mismatch $\Delta\beta_\lambda L$ for

- i) $c_o^2 > (\kappa + \delta)^2$,
- ii) $c_o = \kappa = \delta$,
- iii) $c_o^2 < (\kappa - \delta)^2$.

within modes (a) and (c), and even for $\Delta\beta_\lambda=0$, where the grating coupling processes are mostly effective, only 16 % of the total power finds its way into (b) and (d).

An interesting development appears in Fig.2.10.ii, when $c_0 = \kappa = \delta$. Although for large values of $\Delta\beta_\lambda$ the power is being shared by (a) and (c), for small $\Delta\beta_\lambda$ a "flat" wavelength range exists, where the power is being equally split among all four ports the device acting as a four way power divider, insensitive to small variations in λ .

Finally, when $c_0^2 \ll (\kappa - \delta)^2$ (Fig.2.10.iii) for small $\Delta\beta_\lambda$ all the power is being handled by (b) and (d), but for larger $\Delta\beta_\lambda$, and as the Bragg-type processes are being pulled off matching, power ends into (a) and (c), which remain phase-matched.

A more general numerical solution of (2.4.15) has also been obtained for the case of two dissimilar waveguides and a grating fabricated on one of the cores in between the two guides, i.e. $\Delta\beta_{\lambda 1} \neq \Delta\beta_{\lambda 2}$ and $\kappa_1 \neq \kappa_2$. The power distribution in the four ports as a function of wavelength is shown in Fig.2.11, for a design defined in the above Fig.

Note that these results were obtained for large perturbation values; grating depth 28 % of the actual waveguide width, which gave $c_0 = 0.001111 / \mu\text{m}$, $\kappa_1 = 0.001506 / \mu\text{m}$, $\kappa_2 = 0.000073 / \mu\text{m}$ and $\delta = 0.000254 / \mu\text{m}$, and seem to be in general agreement with the results presented in Figs.2.10.i,ii,iii, although for such large perturbations the accuracy of coupled mode analysis becomes questionable.

Concluding, although the different coupling processes

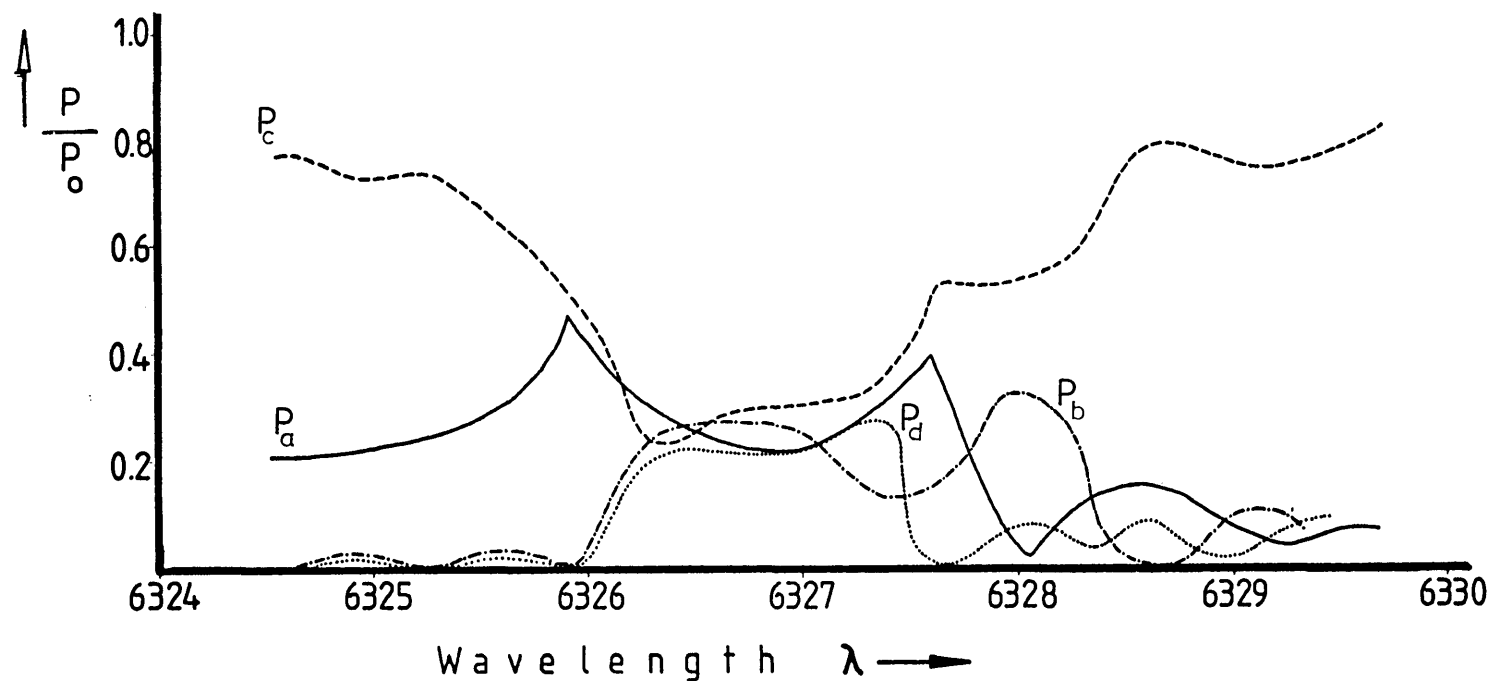


Fig. 2.11

Power distribution in the four output ports as a function of wavelength. Results obtained numerically for a grating coupler operated at 632.8 nm. Slab waveguides of thicknesses 1.5 μm and 1.02 μm separated by 1 μm . Core indices 1.512 and 1.516 respectively, with cladding indices 1.508, 1.506 and 1.500. Grating of periodicity 0.209 μm and depth 0.28 μm . Interaction length 1.5 mm.

compete vigorously for a share of the available power, it is forward coupling that generally dominates, because of its stronger coupling coefficient and the significantly broader bandwidth (wavelength insensitivity) for a realistic coupler design.

2.5 Three Waveguide Structures

Although three-waveguide directional couplers have been fully analysed (2.18 , 2.19), combinations of codirectional and contradirectional coupling in three waveguide structures are presented here for the first time. An advantage of this scheme is the relative insensitivity of the power distribution to small variations in the interaction length, provided that contradirectional coupling is stronger and that the grating length is sufficiently long.

The feasibility of a realistic three-port switch in integrated optics form is examined, where nearly all of the input power can come out from any of the three output ports, with detuning voltages not larger than those for a conventional directional coupler. Another application may involve power division into the three guides at prescribed ratios.

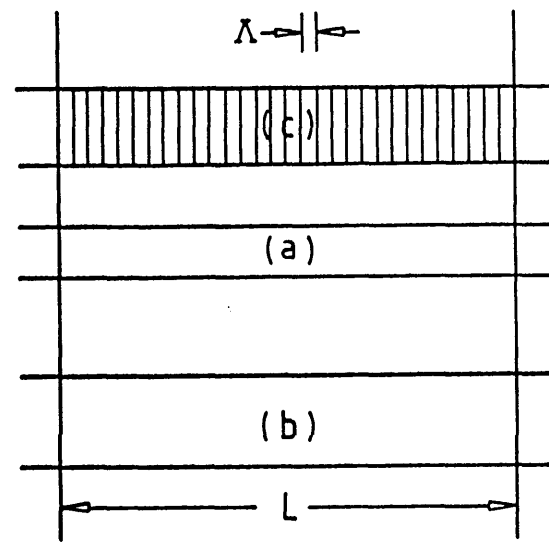
2.5.1 DIRECTIONAL VERSUS CONTRADIRECTIONAL COUPLING IN A THREE WAVEGUIDE STRUCTURE.

The dependence of the contradirectional coupling strength on the directional coupling strength c_0 for a two waveguide coupler, can be removed, by separating the two coupling processes into different waveguides, in a three-guide coupler. In this way, any desirable δ/c_0 ratio could be achieved by suitable scaling of the waveguide separations.

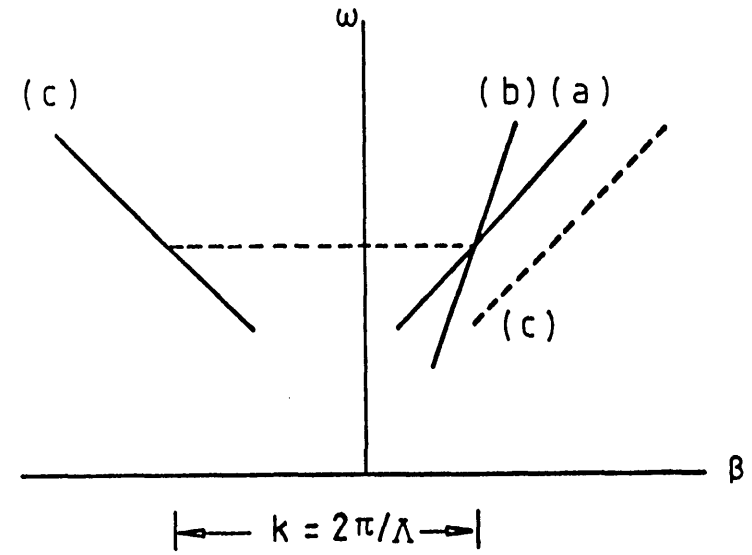
Consider three adjacent single mode waveguides (a), (b) and (c) as shown in Fig.2.12.i, where the modes (a) and (b) are phase matched through equality of their phase velocities, i.e. $\beta_a = \beta_b$, and modes (a) and (c) are phase matched via a grating of momentum k , i.e. $\beta_a + \beta_c = k$, where (c) is a backward-going mode. For synchronous operation both coupling processes occur at the same central frequency ω_0 , where generally the three waveguides are dissimilar as shown in Fig.2.12.ii, with $\beta_a(\omega_0) = \beta_b(\omega_0) \neq \beta_c(\omega_0)$. The field amplitudes A, B and C of the three modes satisfy the coupling equations:

$$\begin{aligned} \frac{d\hat{A}}{dz} &= j(k/2 - \beta_a) \cdot \hat{A} + jc_0 \cdot \hat{B} + j\delta \cdot \hat{C}, \\ \frac{d\hat{B}}{dz} &= j(k/2 - \beta_b) \cdot \hat{B} + jc_0 \cdot \hat{A}, \\ \frac{d\hat{C}}{dz} &= -j(k/2 - \beta_c) \cdot \hat{C} - j\delta \cdot \hat{A}, \end{aligned} \quad (2.5.1)$$

where $A = \hat{A} \exp\{-jk \cdot z/2\}$, $B = \hat{B} \exp\{-jk \cdot z/2\}$, $C = \hat{C} \exp\{jk \cdot z/2\}$



i)



ii)

Fig. 2.12

- i) Schematic diagram of a three waveguide coupler combining directional and contradirectional coupling ,
- ii) $\omega - \beta$ diagram of the three waveguide coupler .

and assuming negligible coupling between modes (b) and (c). The propagation constant β , under an assumed $\exp\{-j\beta \cdot z\}$ dependence, is the root of the determinantal equation:

$$\beta^3 + \beta^2[k/2 - \beta_a - \beta_b + \beta_c] + \beta[(k/2 - \beta_a)(k/2 - \beta_b) - (k/2 - \beta_c)(k - \beta_a - \beta_b) - (c_o^2 - \delta^2)] - [(k/2 - \beta_a)(k/2 - \beta_b)(k/2 - \beta_c) + c_o^2(\beta_c - k/2) + \delta^2(\beta_b - k/2)] = 0, \quad (2.5.2)$$

which does not appear to have a simple analytical solution. Considerable simplification is achieved for synchronous operation, where $\beta_a = \beta_b$ and $\beta_a + \beta_c = k$ and (2.5.2) becomes:

$$\beta^3 + (3\beta/2)\beta^2 + [3\beta^2/4 - (c_o^2 - \delta^2)]\beta + [\beta^3/8 - (c_o^2 - \delta^2)\beta/2] = 0, \quad (2.5.3)$$

where $\beta = \beta_c - \beta_a$, with roots:

$$\beta_1 = -\beta/2 \quad \text{and} \quad \beta_{2,3} = -(\beta/2) \pm \sqrt{(c_o^2 - \delta^2)}. \quad (2.5.4)$$

The nature of the solution will depend on the comparative strength of the two coupling processes. For $c_o > \delta$ a periodic response is expected, while for $\delta > c_o$ the system should assume an exponential Bragg type response.

Subject to the boundary conditions $A(0)=A_o$, $B(0)=0$ and $C(L)=0$ for a grating length L , the power distribution in the three output ports for $\delta > c_o$ is given by:

$$\begin{aligned} P_a &= \frac{|A_o|^2 [(\delta/c_o)^2 - \cosh(\Delta \cdot L)]^2}{[(\delta/c_o)^2 \cosh(\Delta \cdot L) - 1]^2}, \\ P_b &= \frac{|A_o|^2 [(\delta/c_o)^2 - 1] \sinh^2(\Delta \cdot L)}{[(\delta/c_o)^2 \cosh(\Delta \cdot L) - 1]^2}, \\ P_c &= \frac{|A_o|^2 (\delta^2/c_o^2) [(\delta/c_o)^2 - 1] \sinh^2(\Delta \cdot L)}{[(\delta/c_o)^2 \cosh(\Delta \cdot L) - 1]^2}, \end{aligned} \quad (2.5.5)$$

where $\Delta = \sqrt{\delta^2 - c_0^2}$.

Note, that for long grating lengths, i.e. $\Delta \cdot L \gg 0$, the power in the three ports P_a , P_b , P_c tends to $(c_0/\delta)^4 \cdot |A_0|^2$, $(c_0/\delta)^2 \cdot [1 - (c_0/\delta)^2] \cdot |A_0|^2$ and $[1 - (c_0/\delta)^2] \cdot |A_0|^2$ respectively, and further increase in the grating length has no effect on the power distribution.

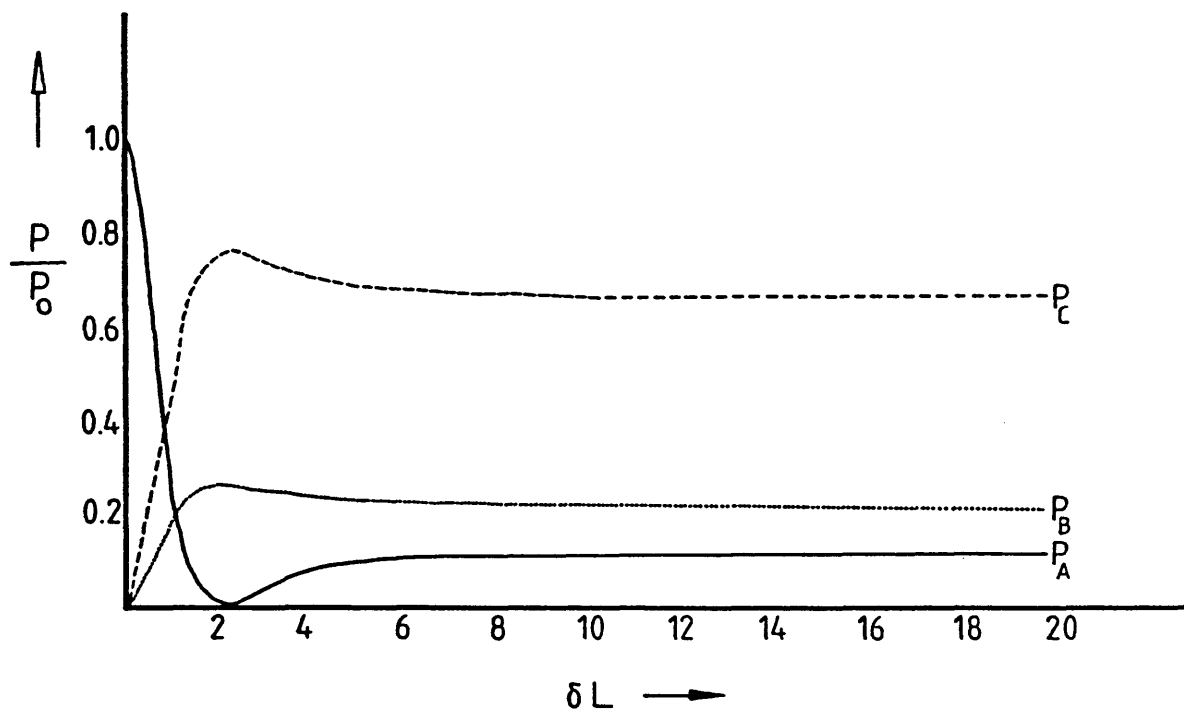
For $c_0 > \delta$, the solution takes the form:

$$\begin{aligned} P_a &= \frac{|A_0|^2 \cdot [1 - (c_0/\delta)^2 \cdot \cos(\Delta \cdot L)]^2}{[\cos(\Delta \cdot L) - (c_0/\delta)^2]^2}, \\ P_b &= \frac{|A_0|^2 \cdot (c_0/\delta)^2 \cdot [(c_0/\delta)^2 - 1] \cdot \sin^2(\Delta \cdot L)}{[\cos(\Delta \cdot L) - (c_0/\delta)^2]^2}, \\ P_c &= \frac{|A_0|^2 \cdot [(c_0/\delta)^2 - 1] \cdot \sin^2(\Delta \cdot L)}{[\cos(\Delta \cdot L) - (c_0/\delta)^2]^2}, \end{aligned} \quad (2.5.6)$$

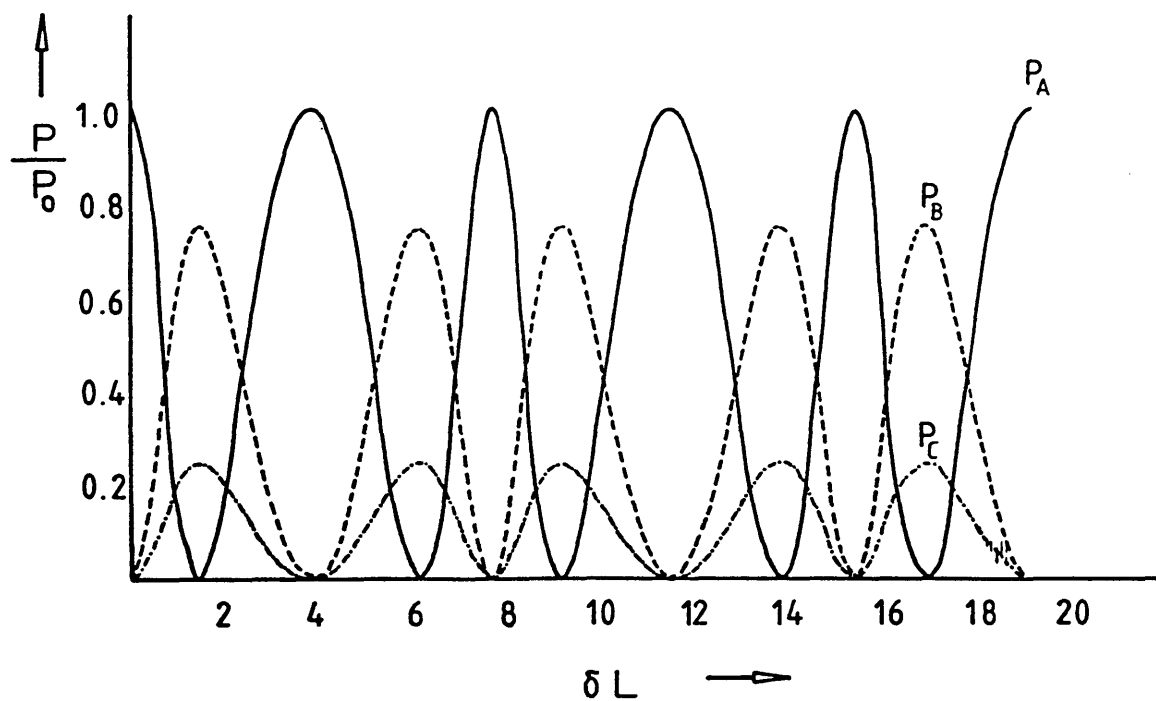
where $\Delta = \sqrt{c_0^2 - \delta^2}$.

Note, that the power variation is of periodic form, with all the power returning to the input mode (a) for interaction lengths $L = 2n\pi/\Delta$, where n is an integer. The maximum power transfer to (b) and (c) occurs every $L = (2n+1)\pi/\Delta$ and is proportional to $[1 - (\delta^2/c_0^2)]$ and $(\delta^2/c_0^2) \cdot [1 - (\delta^2/c_0^2)]$ respectively.

Expressions similar to (2.5.5) and (2.5.6) can be derived for different input conditions. Figs. 2.13.i, ii-15.i, ii show the power distribution in the output ports as a function of interaction length, for different input conditions, when $(\delta/c_0) = \sqrt{3}$ and $(c_0/\delta) = \sqrt{3}$ respectively. For $c_0 > \delta$ the power distribution assumes a periodic profile, though complete power transfer to any other mode is not possible.



i)



ii)

Fig. 2.13

Power distribution in the output ports as a function of interaction length δL . Input port (a) with

i) $(\delta / c_0) = \sqrt{3}$, ii) $(c_0 / \delta) = \sqrt{3}$.

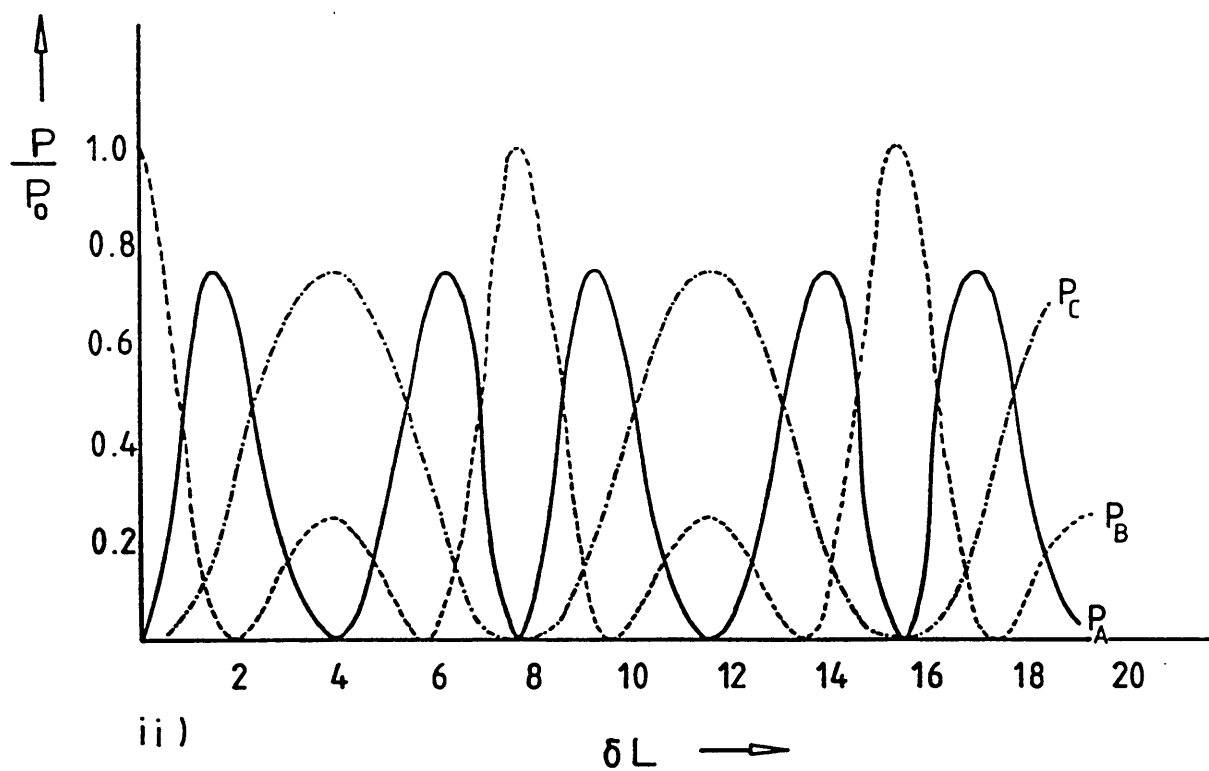
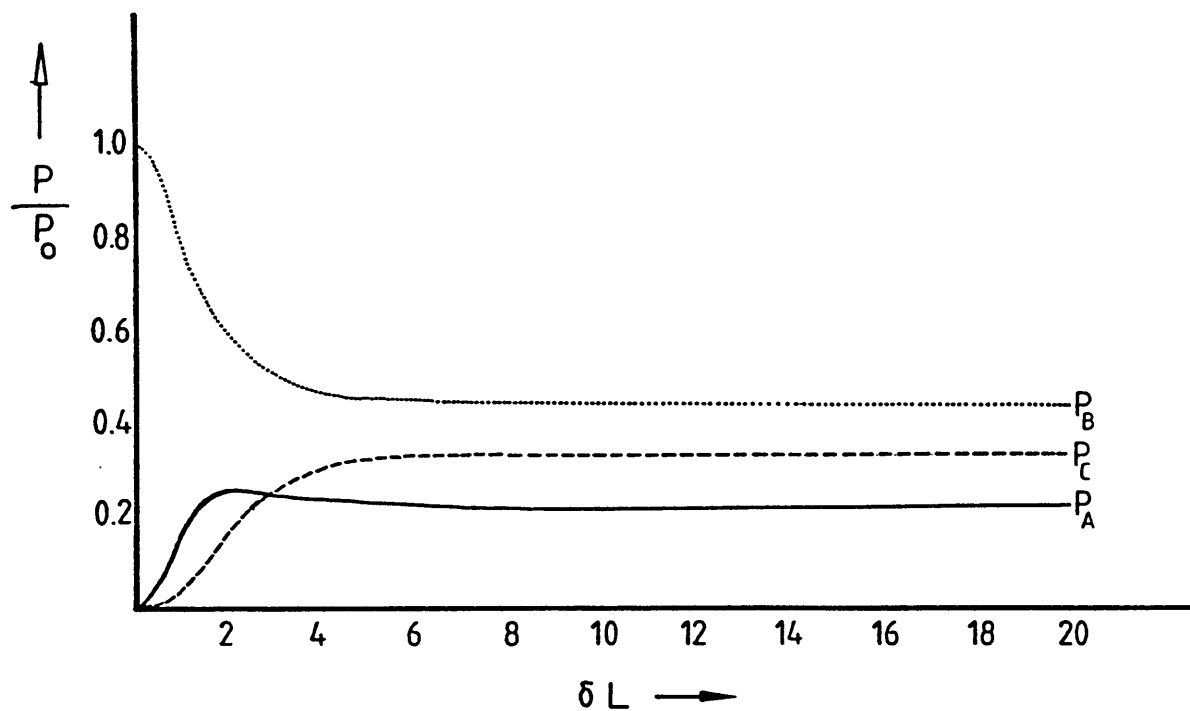


Fig. 2.14

Power distribution in the output ports as a function of interaction length $\delta \cdot L$. Input port (b) with

$$\text{i) } (\delta / c_s) = \sqrt{3} \quad , \quad \text{ii) } (c_s / \delta) = \sqrt{3} \quad .$$

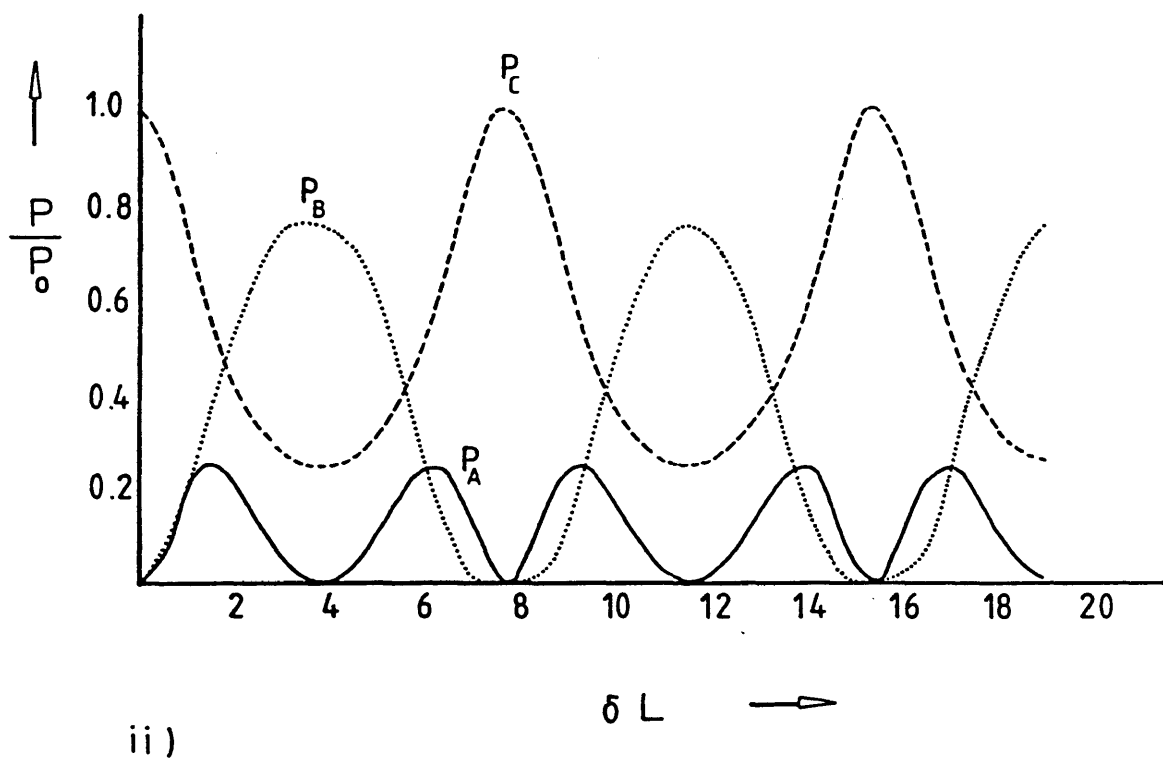
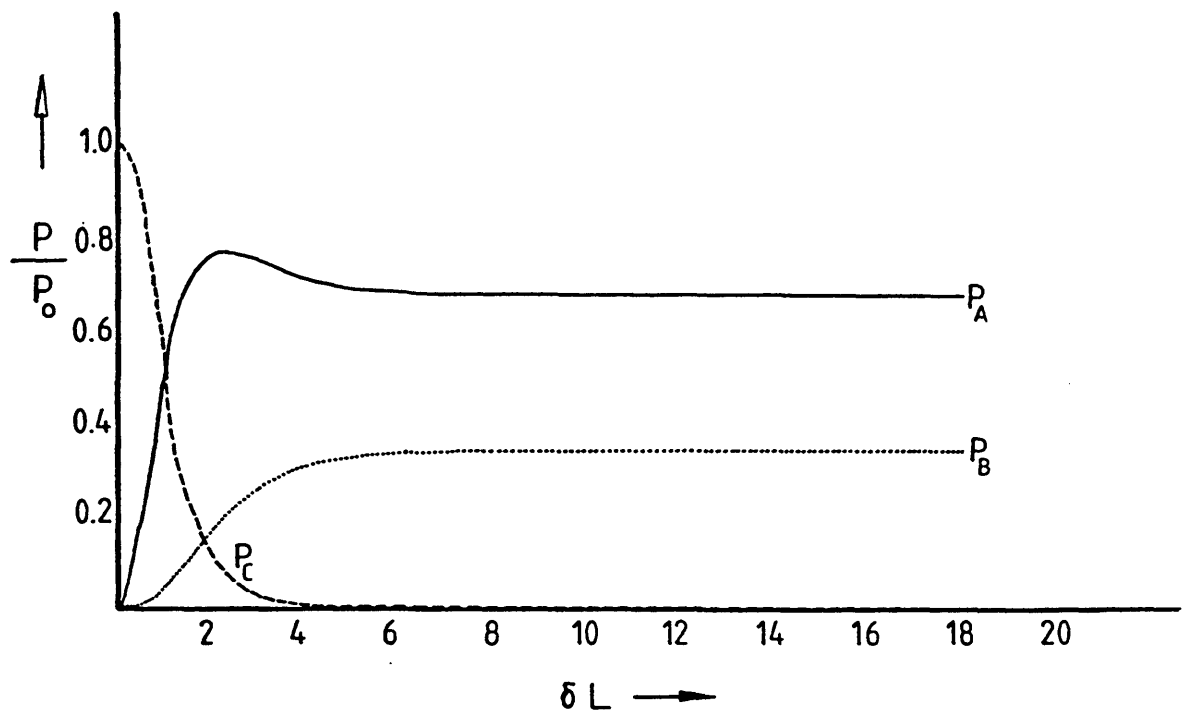


Fig. 2.15

Power distribution in the output ports as a function of interaction length $\delta \cdot L$. Input port (c) with

$$\text{i) } (\delta / c_0) = \sqrt{3} \quad , \quad \text{ii) } (c_0 / \delta) = \sqrt{3} \quad .$$

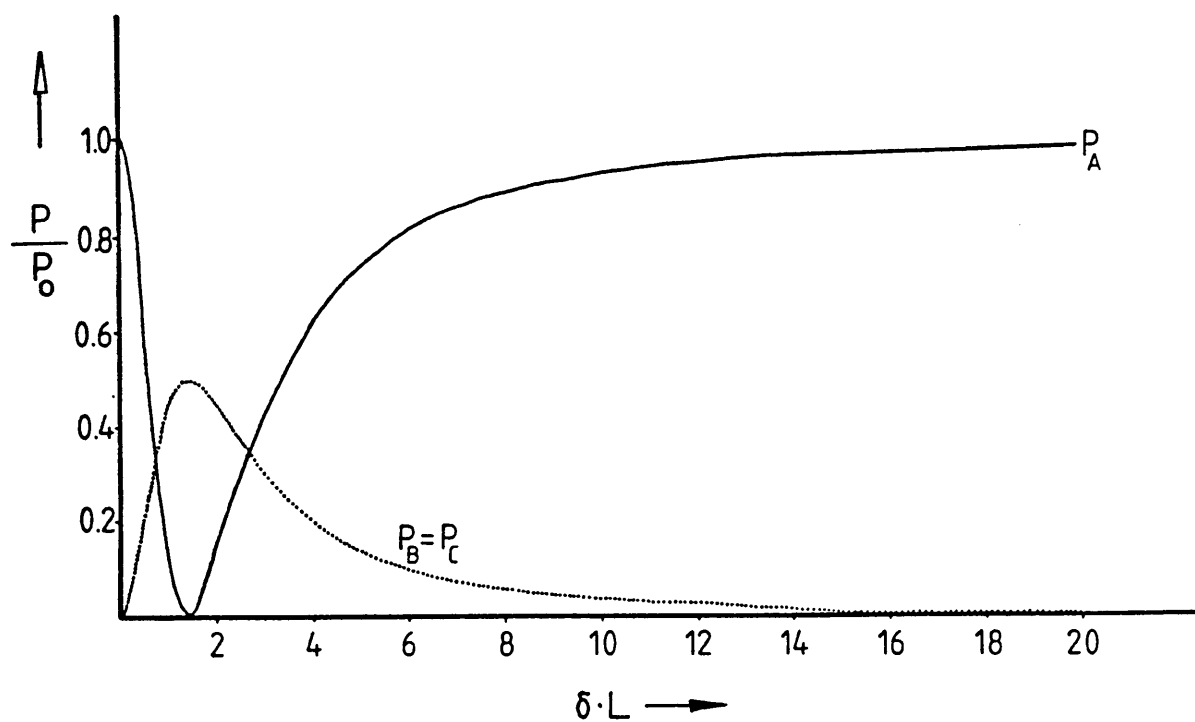
For $\delta > c_0$, and provided that the interaction (grating) length is sufficiently long, the power in the three output ports tend to the limits defined by the δ/c_0 ratio.

It is, therefore, possible to influence the power division in the three output ports by appropriate choice of δ/c_0 , without the need for a precise interaction length, provided the grating is sufficiently long.

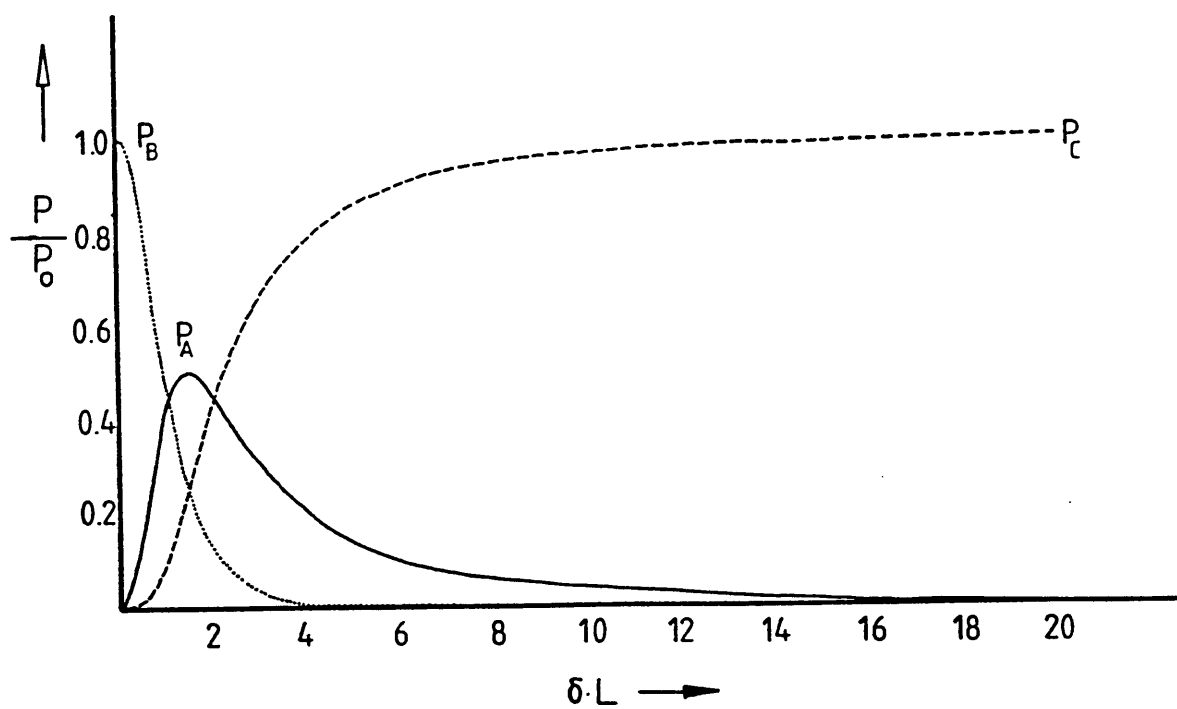
A most interesting situation arises when $\delta = c_0$. The output power distribution for different input conditions is shown in Fig.2.16.i,ii,iii. If power is launched into the central waveguide mode (a), although some coupling into (b) and (c) occurs for short lengths, all the power eventually returns into (a). For short interaction lengths the process starts as periodic, but finally becomes exponentially asymptotic for longer grating lengths.

If power is launched into modes (b) or (c) (Fig.2.16ii,iii) for long interaction lengths, the power comes out from (c) or (b) respectively. This may be compared with the periodic power exchange between the side waveguides in the case of a three waveguide directional coupler operating in synchronism (2.19). By employing a combination of directional and contradirectional coupling, a similar result can be achieved independent of a precise definition of interaction length.

Such a device could be realised in an integrated optics form, with suitable electrodes deposited over guides (a) and (b) and the grating fabricated only on guide (c), as shown in Fig.2.17. The waveguide separations have been designed to allow $\delta = c_0$ and the grating is sufficiently long. If



i)



ii)

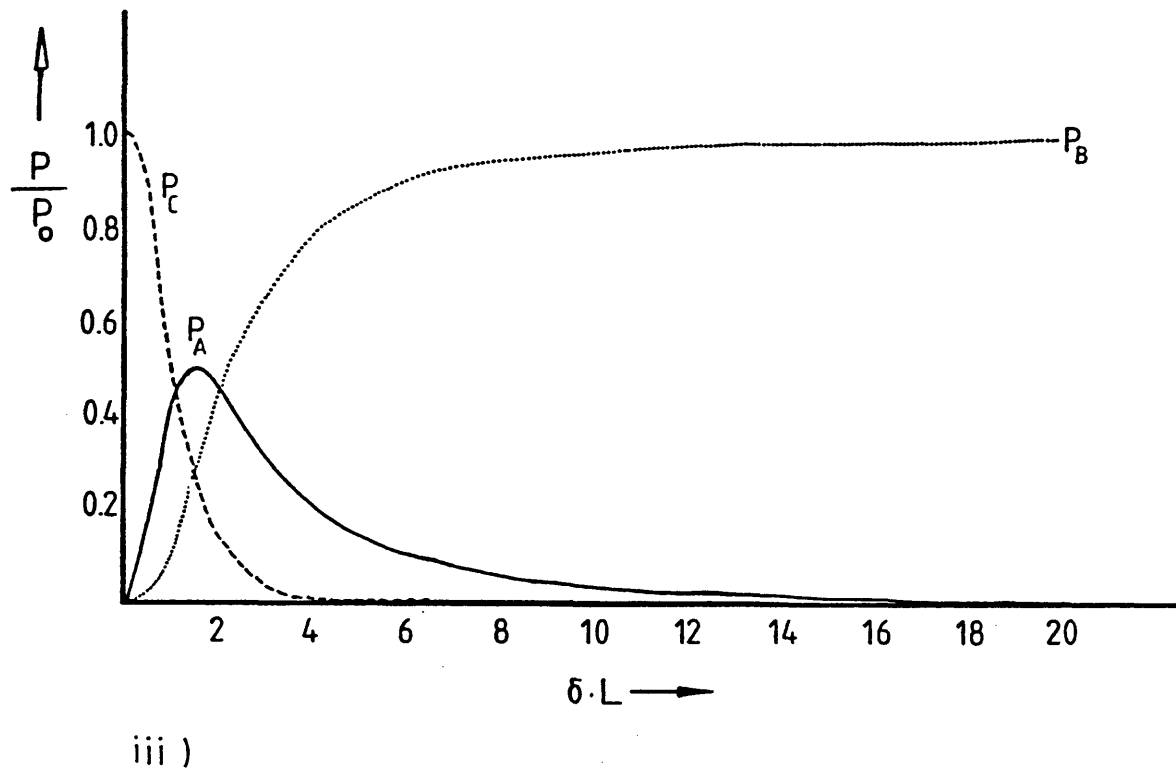
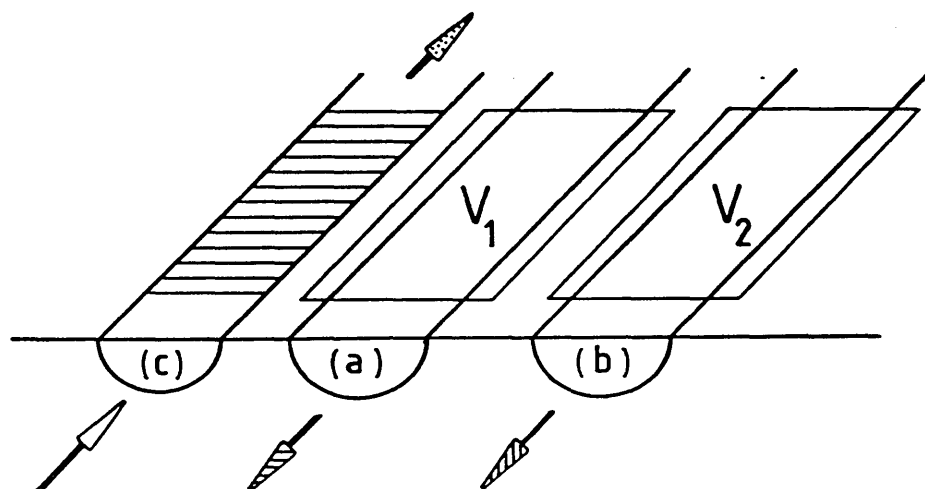


Fig. 2.16

Power distribution in the three output ports as a function of $\delta \cdot L$ with $\delta = c_0$ for

- i) input port (a)
- ii) input port (b)
- iii) input port (c)



	$V_1 = V_2 = 0$
	$V_1 = 0 \quad V_2 = V_0$
	$V_1 = V_0 \quad V_2 = 0$

Fig. 2.17

Schematic representation of a three port switch based on the three waveguide directional versus contradirectional coupler design, for realisation in integrated optics form with electrodes deposited over (a) and (b).

power is originally launched into guide (c), and there is no voltage applied on the electrodes, the three-waveguide coupler operates in synchronism and all the power comes out of (b). By applying a detuning voltage on (b), the waveguide can be pulled off synchronism, and since guides (a) and (c) remain phase-matched by the grating, all the power will come out of (a); the device operates as a two-wave contra-directional coupler. Finally by pulling (a) off tuning, both coupling processes are affected and the optical power remains on (c). Thus, by applying suitable detuning voltages on the electrodes (a) and (b), the three waveguide coupler can be operated as a three-port switch for time division multiplexing, or even as an electro-optic decoder for optical processing applications. The level of detuning voltages are expected to be comparable to the ones used in a conventional directional coupler.

2.5.2 THREE - WAVEGUIDE GRATING COUPLER

The special case of a three-waveguide system, phase matched by a grating of momentum k , has also been considered. A combination of codirectional and contradirectional coupling, possibly by two gratings of different periodicities, results in a behaviour very similar to the one presented for directional versus contradirectional coupling in the previous section.

For a three waveguide contradirectional coupler, the coupling equations take the form:

$$\begin{aligned}\frac{dA}{dz} &= j(k/2 - \beta_a) A + j\delta_1 B, \\ \frac{dB}{dz} &= -j(k/2 - \beta_b) B - j\delta_1 A - j\delta_2 C, \\ \frac{dC}{dz} &= j(k/2 - \beta_c) C + j\delta_2 B,\end{aligned}\tag{2.5.7}$$

where A , B and C are the field amplitudes of the three modes, β_a , β_b and β_c are their propagation constants and δ_1 , δ_2 the coupling coefficients between the central waveguide (b) and the side ones (a) and (c). Note that coupling between (a) and (c) is assumed to be negligible.

For the three modes to be phase matched at a single frequency ω_0 ,

$$\beta_a(\omega_0) + \beta_b(\omega_0) = k \quad \text{and} \quad \beta_a(\omega_0) = \beta_c(\omega_0).$$

For identical (a) and (c), an analytical solution to (2.5.7) exists, with the roots of the determinantal equation given by

$$\beta = \beta_b - k/2, \quad \beta = (\beta_a - \beta_b)/2 \pm j\sqrt{\delta_1^2 + \delta_2^2 - [k - (\beta_a + \beta_b)]^2/4},$$

for an assumed solution of the type $\exp\{j\beta z\}$.

Even though expressions for the power distribution at the three ports have been obtained for different input conditions, they appear to be of little interest.

If power is launched into the central waveguide (b), for a sufficiently long grating length, it is divided between (a) and (c), with splitting ratio $\delta_1^2/(\delta_1^2 + \delta_2^2)$ and $\delta_2^2/(\delta_1^2 + \delta_2^2)$

respectively.

If power is launched into any of the side waveguides (a) and (c), it is distributed among all output ports, the splitting ratio related to the ratio of the coupling coefficients, without being in general possible to get all the power out of a single port at will.

2.6 Evaluation of the Coupling Coefficients for different Waveguide Models.

The coupled mode theory as presented in section 2.1 is independent of waveguide geometry. The evaluation of the coupling coefficients as given from (2.2.2) , (2.3.10) and (2.3.29) requires the analysis of specific coupler geometries.

The slab waveguide model is the simplest structure used to analyse mode conversion properties of dielectric waveguides (2.20). Although not a realistic model, its results are usually somewhat applicable to optical waveguides of different geometries.

In the analysis presented in this section, both symmetric and asymmetric waveguides are considered and expressions for the directional and contradirectional coupling coefficients are obtained. Finally, a rectangular waveguide model is examined, as more accurate, for the description of a grating coupler configuration based on the integrated fibre.

2.6.1 THE SLAB - WAVEGUIDE REFLECTOR

A grating reflector is more easily visualised as an asymmetric slab waveguide, consisting of a thin film of thickness d and refractive index n_0 , sandwiched between

media of indices n_1 and n_2 respectively. A grating of periodicity Λ and amplitude h is imposed on one of the interfaces as shown in Fig.2.18.

In general, a slab waveguide can support a finite number of guided T.E and T.M modes. By limiting the analysis to T.E modes only, and assuming $\frac{\partial}{\partial y} = 0$ (since the guide extends infinitely in the y direction), the only non-zero field components H_x , H_z and E_y are related by Maxwell's equations:

$$\begin{aligned} H_x &= -\frac{j}{\omega\mu_0} \frac{\partial E_y}{\partial z}, \\ H_z &= \frac{j}{\omega\mu_0} \frac{\partial E_y}{\partial x}. \end{aligned} \quad (2.6.1)$$

The transverse field component E_y obeys the wave equation

$$\frac{\partial^2 E_y}{\partial x^2} + (n^2 k_0^2 - \beta^2) E_y = 0, \quad (2.6.2)$$

where β is the propagation constant of the guided modes, n^2 is the index distribution of the structure, and $k_0 = 2\pi/\lambda$. Solving eq.2.6.2 results in:

$$E_y = \begin{cases} A \cdot \exp\{-\gamma_1 x\} & 0 \leq x < +\infty, \\ A \cdot [\cos(\kappa x) - (\gamma_1/\kappa) \sin(\kappa x)] & -d \leq x \leq 0, \\ A \cdot [\cos(\kappa d) + (\gamma_1/\kappa) \sin(\kappa d)] \exp\{\gamma_2(x+d)\} & -\infty < x \leq -d, \end{cases} \quad (2.6.3)$$

$$\begin{aligned} \text{where } \gamma_1^2 &= \beta^2 - n_1^2 k_0^2, \\ \kappa^2 &= n_0^2 k_0^2 - \beta^2, \\ \gamma_2^2 &= \beta^2 - n_2^2 k_0^2, \end{aligned} \quad (2.6.4)$$

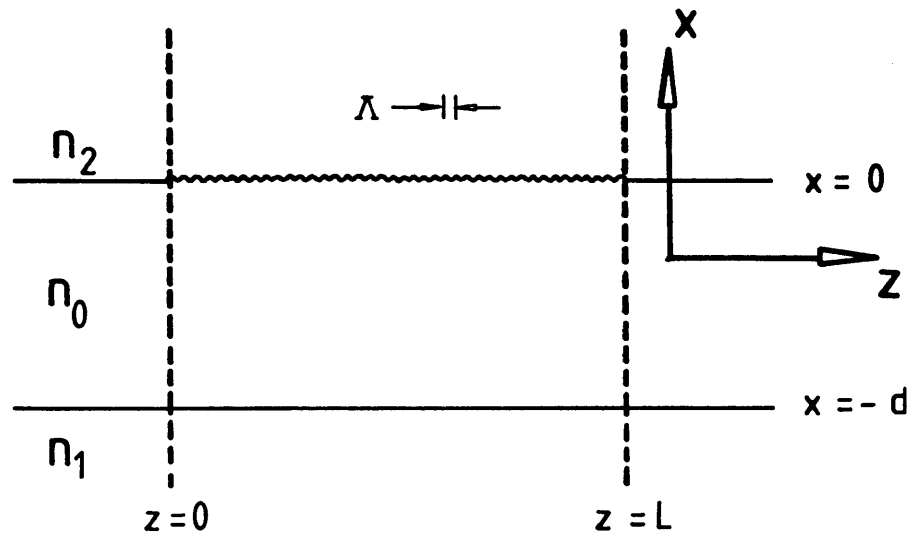


Fig. 2.18

Slab waveguide grating reflector configuration.

and A is the field amplitude constant.

For E_y and H_z to be continuous at the two interfaces, i.e. for $x=0$ and $x=-d$, the eigenvalue equation:

$$\tan(\kappa \cdot d) = \frac{\kappa(\gamma_1 + \gamma_2)}{(\kappa^2 - \gamma_1 \gamma_2)} \quad (2.6.5)$$

must be obeyed, from which the propagation constant β of the different confined T.E modes can be obtained. For single mode operation, the waveguide thickness d and index difference Δn^2 can be designed to allow only one eigen-solution in (2.6.5), that of the lowest order even T.E mode. The constant A can be obtained by normalising the power flow in the waveguide. The normalisation condition:

$$-\frac{1}{2} \int_{-\infty}^{+\infty} E_y H_x^* dx = \frac{\beta}{2\omega\mu_0} \int_{-\infty}^{+\infty} [E_y(x)]^2 dx = 1, \quad (2.6.6)$$

results in:

$$A = 2\kappa \sqrt{\left[\frac{\omega \cdot \mu_0}{|\beta|(d + 1/\gamma_1 + 1/\gamma_2) \cdot (\kappa^2 + \gamma_1^2)} \right]} \quad (2.6.7)$$

As discussed in section 2.3, when the Bragg condition:

$$\beta \approx \pi/\Lambda$$

is approximately satisfied, strong reflection will occur into the same mode, travelling in the opposite direction. The reflection coefficient for normalised power flow can be written as:

$$\delta = \frac{\omega \cdot \epsilon_0}{\pi} \int_{-h}^0 (n_0^2 - n_1^2) [E_y(x)]^2 dx$$

and evaluated as

$$\delta = \frac{4\pi\kappa^2(n_0^2 - n_1^2)}{\lambda^2|\beta|(d + 1/\gamma_1 + 1/\gamma_2)(\kappa^2 + \gamma_1^2)} \cdot \left\{ \frac{\gamma_1}{\kappa^2} \sin^2(\kappa h) + \frac{h}{2} \left[1 + \frac{\gamma_1^2}{\kappa^2} \right] + \frac{1}{4\kappa} \left[1 - \frac{\gamma_1^4}{\kappa^4} \right] \sin(2\kappa h) \right\} \cdot \quad (2.6.8)$$

2.6.2 THE SLAB - WAVEGUIDE COUPLER

The slab waveguide grating coupler can be analysed as a multilayered structure, consisting of two adjacent slab waveguides, with a grating of periodicity Λ imposed on one of the interfaces, as shown in Fig.2.19. The exact location of the grating will depend on the different implementations of this simple model. If, for example, the device is to be implemented by means of two D-shaped fibres, it will be reasonable to place the grating in between the two guides (Fig.2.19.i). On the otherhand, if an integrated fibre is used, the grating will be placed on the top waveguide interface (Fig.2.19.ii).

Consider two adjacent asymmetric slab waveguides. In the absence of any perturbation, and limiting the analysis to T.E modes only, the two waveguides can be analysed independently (as in section 2.6.1), and their transversal field components E_{y_1} , E_{y_2} can be obtained.

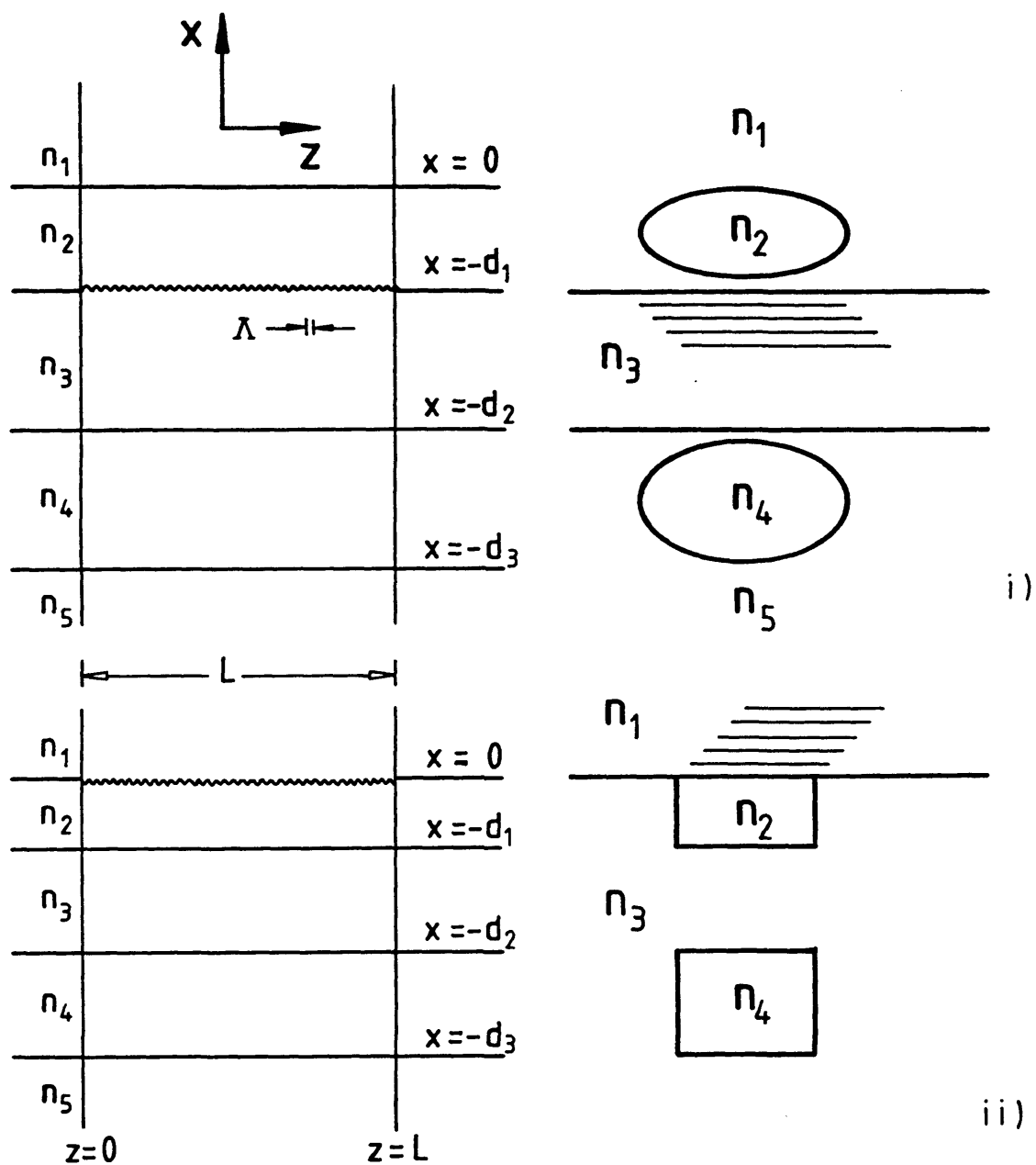


Fig. 2.19

Slab waveguide grating coupler configuration for
 different implementations: i) polished coupler ,
 ii) integrated fibre coupler.

$$E_{y_1} = \begin{cases} L \cdot [\cos(\kappa_1 d_1) + \frac{\gamma_1}{\kappa_1} \sin(\kappa_1 d_1)] \exp\{\gamma_2(x+d_1)\} & -\infty < x \leq -d_1, \\ L \cdot [\cos(\kappa_1 x) - \frac{\gamma_1}{\kappa_1} \sin(\kappa_1 x)] & -d_1 \leq x \leq 0, \\ L \cdot \exp\{-\gamma_1 x\} & 0 \leq x < +\infty, \end{cases} \quad (2.6.9)$$

and

$$E_{y_2} = \begin{cases} R \cdot [\cos\{\kappa_2(d_3-d_2)\} + \frac{\gamma_3}{\kappa_2} \sin\{\kappa_2(d_3-d_2)\}] \exp\{\gamma_4(x+d_3)\} & -\infty < x \leq -d_3, \\ R \cdot [\cos\{\kappa_2(x+d_2)\} - \frac{\gamma_3}{\kappa_2} \sin\{\kappa_2(x+d_2)\}] & -d_3 \leq x \leq -d_2, \\ R \cdot \exp\{-\gamma_3(x+d_2)\} & -d_2 \leq x < +\infty, \end{cases} \quad (2.6.10)$$

$$\begin{aligned} \text{where } \gamma_1^2 &= \beta_1^2 - n_1^2 k_0^2, & \gamma_3^2 &= \beta_2^2 - n_3^2 k_0^2, \\ \kappa_1^2 &= n_2^2 k_0^2 - \beta_1^2, & \text{and } \kappa_2^2 &= n_4^2 k_0^2 - \beta_2^2, \\ \gamma_2^2 &= \beta_1^2 - n_3^2 k_0^2, & \gamma_4^2 &= \beta_2^2 - n_5^2 k_0^2, \end{aligned} \quad (2.6.11)$$

with β_1, β_2 being the propagation constants of the two waveguides, and R, L the field amplitudes.

Considering normalised power flow in the two waveguides, R and L can be evaluated as in section 2.6.1 :

$$L = 2 \kappa_1 \sqrt{\left[\frac{\omega \cdot \mu_0}{|\beta_1| \cdot (d_1 + 1/\gamma_1 + 1/\gamma_2) \cdot (\kappa_1^2 + \gamma_1^2)} \right]} \quad (2.6.12)$$

and

$$R = 2 \kappa_2 \sqrt{\left[\frac{\omega \cdot \mu_0}{|\beta_2| \cdot (d_3 - d_2 + 1/\gamma_3 + 1/\gamma_4) \cdot (\kappa_2^2 + \gamma_3^2)} \right]} \quad (2.6.13)$$

Continuity of the E_y and H_z fields at the interfaces results in the two eigenvalue equations:

$$\tan(\kappa_1 d_1) = \frac{\kappa_1 (\gamma_1 + \gamma_2)}{\kappa_1^2 - \gamma_1 \gamma_2}, \quad (2.6.14)$$

and

$$\tan[\kappa_2(d_3 - d_2)] = \frac{\kappa_2 (\gamma_3 + \gamma_4)}{\kappa_2^2 - \gamma_3 \gamma_4}, \quad (2.6.15)$$

providing the eigensolutions β_1 , β_2 for the confined T.E modes of the two guides. By proper design of the guide parameters, propagation can be limited to the lowest order even T.E mode in each guide, thus ensuring single mode operation.

If the waveguides are identical, or a frequency ω_1 exists, for which $\beta_1(\omega_1) = \beta_2(\omega_1)$ then the two modes are phase-matched at this frequency, and directional coupling takes place between the guides. For normalised power flow, the directional coupling coefficient c has been evaluated from (2.2.2) as:

$$c = \frac{4 \cdot \pi \cdot (n_2^2 - n_3^2) \kappa_1 \kappa_2}{\lambda^2 (\gamma_3^2 + \kappa_1^2) \sqrt{\beta_1 \beta_2 (d_1 + 1/\gamma_1 + 1/\gamma_2) (\kappa_1^2 + \gamma_1^2) (d_3 - d_2 + 1/\gamma_3 + 1/\gamma_4) (\kappa_2^2 + \gamma_3^2)}} \cdot$$

$$[\exp[\gamma_3(d_1 - d_2)] \{ (\gamma_1 - \gamma_3) \cos(\kappa_1 d_1) + (\kappa_1 + \gamma_1 \gamma_3 / \kappa_1) \sin(\kappa_1 d_1) +$$

$$+ (\gamma_1 - \gamma_3) \exp[-\gamma_3 d_2] \}] \quad (2.6.16)$$

If a grating of periodicity Λ is situated in the interface between the two waveguides (Fig.2.19.i), and at a frequency ω_2 , for which the Bragg momentum conservation requirement

$$\beta_1(\omega_2) + \beta_2(\omega_2) = 2\pi/\Lambda, \quad \text{with} \quad \beta_1(\omega_2) \neq \beta_2(\omega_2)$$

is satisfied, contradirectional coupling will occur between the two modes. For normalised power flow, the coupling coefficient δ , defined by (2.3.10), can be expressed as:

$$\delta = \frac{\omega \cdot \epsilon_0}{4\pi} \int_{-d_1}^{-d_1+h} (n_2^2 - n_3^2) \cdot |E_{\gamma_1}(x) \cdot E_{\gamma_2}(x)| dx$$

and evaluated as :

$$\delta = \frac{4 \cdot \pi \cdot (n_2^2 - n_3^2) \kappa_1 \cdot \kappa_2}{\lambda^2 \cdot (\gamma_3^2 + \kappa_1^2) \cdot \sqrt{(\beta_1 \cdot \beta_2) \cdot (d_3 - d_2 + 1/\gamma_3 + 1/\gamma_4) \cdot (d_1 + 1/\gamma_1 + 1/\gamma_2) \cdot (\kappa_1^2 + \gamma_1^2) \cdot (\kappa_2^2 + \gamma_3^2)}} \cdot \{ (\kappa_1 + \gamma_1 \gamma_3 / \kappa_1) [\sin(\kappa_1 d_1) \exp[-\gamma_3(d_2 - d_1)] - \sin[\kappa_1(d_1 - h)] \exp[-\gamma_3(d_2 - d_1 + h)]] + (\gamma_1 - \gamma_3) [\cos[\kappa_1(d_1 - h)] \exp[-\gamma_3(d_2 - d_1 + h)] - \cos(\kappa_1 d_1) \exp[-\gamma_3(d_2 - d_1)]] \}$$

(2.6.17)

Modelling the integrated fibre as a combination of a symmetric and an asymmetric waveguide, the grating has to be situated on the top of the asymmetric waveguide (Fig.2.19.ii).

The eigenvalue equation of the symmetric guide is

$$\tan[\kappa_2(d_3 - d_2)/2] = \kappa / \gamma, \quad (2.6.18)$$

while (2.6.15) remains unchanged. The coupling coefficient can be expressed as

$$\delta = \frac{\omega \cdot \epsilon_0}{4 \cdot \pi} \int_{-h}^0 (n_2^2 - n_1^2) \cdot |E_{y_1}(x) \cdot E_{y_2}(x)| dx$$

and can be evaluated in a form similar to (2.6.17). It is expected, however, to be weaker since the field interaction in the perturbation region is smaller.

2.6.3 RECTANGULAR WAVEGUIDE GRATING COUPLER

The integrated fibre coupler can be more accurately modelled by rectangular waveguides, using Marcitili's approximate analytical solution (2.21) to obtain expressions for the different coupling coefficients.

The structure under consideration is shown in Fig.2.20. Although the guides may in general have different widths, this causes inconsistency in the field evaluation of the coupling coefficients, since according to the model used the field in the shaded areas is completely ignored. An approximate solution to this problem results from considering a mean guide width, $\bar{b} = (b_1 + b_2) / 2$, for the calculation of the coupling coefficients (2.22). To avoid this, however, both guides are designed to have the same width b .

Each rectangular waveguide can support two types of modes, E_{pq}^x , predominantly polarised in the x-direction, and E_{pq}^y , polarised in the y-direction. By suitable choice of indices and dimensions, the modes can be limited to one from each type, i.e. E_{11}^x and E_{11}^y .

For the E_{11}^x , the transverse field component E_x is dominant in both waveguides, E_y and H_x are nearly zero, and E_x can be expressed in terms of the longitudinal components E_z, H_z as

$$E_x = - \frac{j}{n^2 k_0^2 - \beta^2} \left[\beta \frac{\partial E_z}{\partial x} + \omega \mu_0 \frac{\partial H_z}{\partial y} \right], \quad (2.6.19)$$

where n^2 is the index distribution of the two guides and β is the propagation constant of the guided modes.

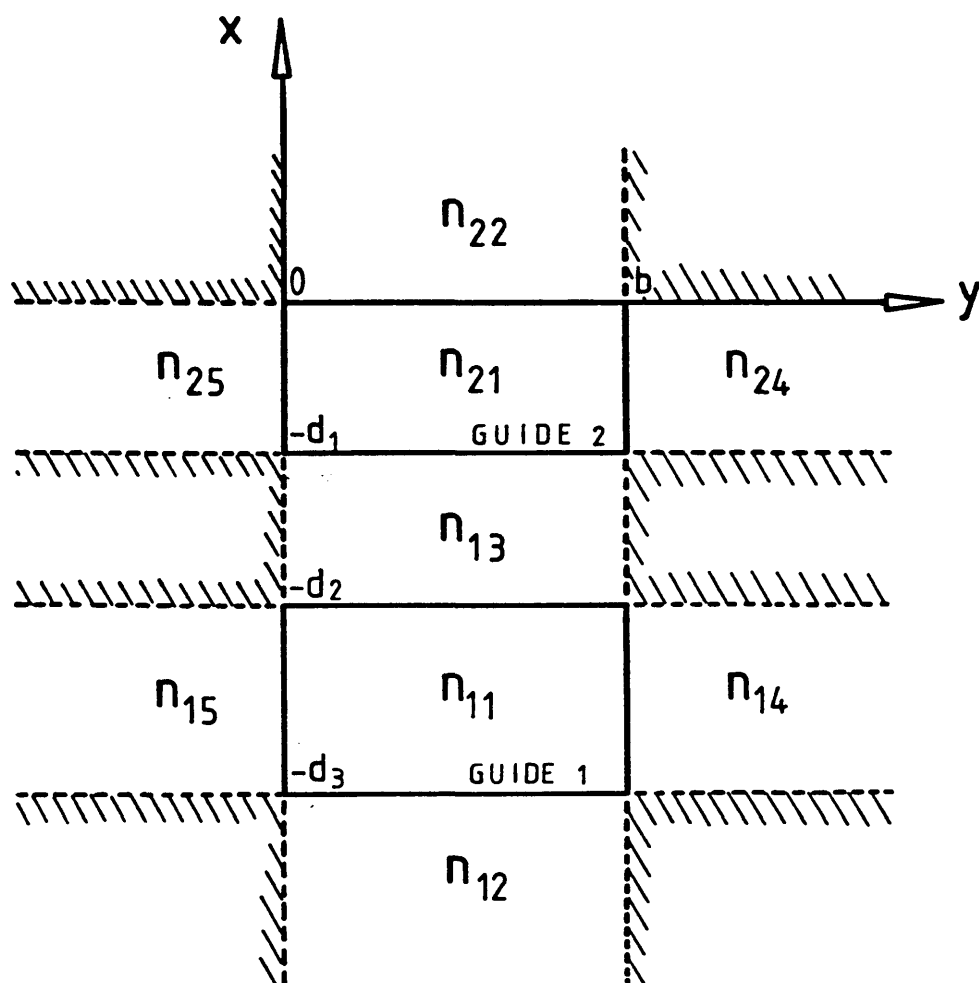


Fig. 2.20

Rectangular waveguide coupler configuration

For waveguide 1, the transverse field component E_{x_1} is given by

$$\begin{aligned}
 E_{x_1} &= \frac{jA}{\kappa_1 \beta_1} \cdot (n_{11}^2 k_o^2 - \kappa_1^2) \sin[\kappa_1(x+d_2+\xi)] \cos[\bar{\kappa}_1(y+\eta)] \\
 &\quad \text{for } -d_3 \leq x \leq -d_2 \text{ and } 0 \leq y \leq b, \\
 E_{x_1} &= \frac{jA}{\gamma_{12} \beta_1} \cdot (\gamma_{12}^2 + n_{12}^2 k_o^2) \cos[\kappa_1(\xi+d_2-d_3)] \exp\{\gamma_{12}(x+d_3)\} \cos[\bar{\kappa}_1(y+\eta)] \\
 &\quad \text{for } -\infty < x \leq -d_3 \text{ and } 0 \leq y \leq b, \\
 E_{x_1} &= \frac{-jA}{\gamma_{13} \beta_1} \cdot (\gamma_{13}^2 + n_{13}^2 k_o^2) \cos(\kappa_1 \xi) \exp\{-\gamma_{13}(x+d_2)\} \cos[\bar{\kappa}_1(y+\eta)] \\
 &\quad \text{for } -d_2 \leq x < +\infty \text{ and } 0 \leq y \leq b, \\
 E_{x_1} &= \frac{jA}{\kappa_1 \beta_1} \cdot (n_{14}^2 k_o^2 - \kappa_1^2) \cdot (n_{11}^2/n_{14}^2) \cdot \cos[\bar{\kappa}_1(b+\eta)] \sin[\kappa_1(x+d_2+\xi)] \exp\{-\gamma_{14}(y-b)\} \\
 &\quad \text{for } -d_3 \leq x \leq -d_2 \text{ and } b \leq y < +\infty, \\
 E_{x_1} &= \frac{jA}{\kappa_1 \beta_1} \cdot (n_{15}^2 k_o^2 - \kappa_1^2) \cdot (n_{11}^2/n_{15}^2) \cdot \cos[\bar{\kappa}_1 \eta] \sin[\kappa_1(x+d_2+\xi)] \exp\{\gamma_{15} y\} \\
 &\quad \text{for } -d_3 \leq x \leq -d_2 \text{ and } -\infty < y \leq 0,
 \end{aligned}
 \tag{2.6.20}$$

$$\begin{aligned}
 \text{where } \gamma_{12}^2 &= \bar{\kappa}_1^2 - (n_{12}^2 k_o^2 - \beta_1^2), \\
 \gamma_{13}^2 &= \bar{\kappa}_1^2 - (n_{13}^2 k_o^2 - \beta_1^2), \\
 \gamma_{14}^2 &= \kappa_1^2 - (n_{14}^2 k_o^2 - \beta_1^2), \\
 \gamma_{15}^2 &= \kappa_1^2 - (n_{15}^2 k_o^2 - \beta_1^2), \\
 \kappa_1^2 + \bar{\kappa}_1^2 &= n_{11}^2 k_o^2 - \beta_1^2
 \end{aligned}
 \tag{2.6.21}$$

and A is the field amplitude of the guide.

For waveguide 2 the transverse field component E_{x_2} can be written as:

$$\begin{aligned}
 E_{x_2} &= \frac{jB}{\kappa_2 \beta_2} (n_{21}^2 k_o^2 - \kappa_2^2) \sin[\kappa_2(x+\bar{\xi})] \cos[\bar{\kappa}_2(y+\bar{\eta})] \\
 &\quad \text{for } -d_1 \leq x \leq 0 \text{ and } 0 \leq y \leq b, \\
 E_{x_2} &= \frac{jB}{\gamma_{23} \beta_2} (\gamma_{23}^2 + n_{23}^2 k_o^2) \cos[\kappa_2(\bar{\xi}-d_1)] \exp\{\gamma_{23}(x+d_1)\} \cos[\bar{\kappa}_2(y+\bar{\eta})] \\
 &\quad \text{for } -\infty < x \leq -d_1 \text{ and } 0 \leq y \leq b,
 \end{aligned}$$

$$\begin{aligned}
E_{x_2} &= \frac{-jB}{\gamma_{22}\beta_2} \cdot (\gamma_{22}^2 + n_{22}^2 k_o^2) \cos(\kappa_2 \bar{\xi}) \exp\{-\gamma_{22}x\} \cos[\bar{\kappa}_2(y+\bar{\eta})] \\
&\quad \text{for } 0 \leq x < +\infty \text{ and } 0 \leq y \leq b, \\
E_{x_2} &= \frac{jB}{\kappa_2\beta_2} (n_{24}^2 k_o^2 - \kappa_2^2) \cdot (n_{21}^2/n_{24}^2) \cdot \cos[\bar{\kappa}_2(b+\bar{\eta})] \sin[\kappa_2(x+\bar{\xi})] \exp\{-\gamma_{24}(y-b)\} \\
&\quad \text{for } -d_1 \leq x \leq 0 \text{ and } b \leq y < +\infty, \\
E_{x_2} &= \frac{jB}{\kappa_2\beta_2} (n_{25}^2 k_o^2 - \kappa_2^2) \cdot (n_{21}^2/n_{25}^2) \cdot \cos(\bar{\kappa}_2\bar{\eta}) \sin[\kappa_2(x+\bar{\xi})] \exp\{\gamma_{25}y\} \\
&\quad \text{for } -d_1 \leq x \leq 0 \text{ and } -\infty < y \leq 0,
\end{aligned}
\tag{2.6.22}$$

$$\begin{aligned}
\text{where } \gamma_{23}^2 &= \bar{\kappa}_2^2 - (n_{23}^2 k_o^2 - \beta_2^2), \\
\gamma_{22}^2 &= \bar{\kappa}_2^2 - (n_{22}^2 k_o^2 - \beta_2^2), \\
\gamma_{24}^2 &= \kappa_2^2 - (n_{24}^2 k_o^2 - \beta_2^2), \\
\gamma_{25}^2 &= \kappa_2^2 - (n_{25}^2 k_o^2 - \beta_2^2), \\
\kappa_2^2 + \bar{\kappa}_2^2 &= n_{21}^2 k_o^2 - \beta_2^2,
\end{aligned}$$

and B is the field amplitude of the guide.

The field constants A and B can be evaluated by considering normalised power flow in the two guides, giving:

$$\begin{aligned}
A &= \sqrt{\left\{ \left(\frac{2\beta_1}{\omega\epsilon_o} \right) \right\} \left[\frac{n_{11}^2}{\kappa_1^2} \cdot \left[\frac{d_3 - d_2}{2} + \frac{1}{4\kappa_1} \cdot \{\sin[2\kappa_1(d_2 - d_3 + \xi)] - \sin(2\kappa_1\xi)\} \cdot (n_{11}^2 k_o^2 - \kappa_1^2) \cdot [b/2 + \frac{1}{4\bar{\kappa}_1} \cdot \{\sin[2\bar{\kappa}_1(b+\eta)] - \sin(2\bar{\kappa}_1\eta)\}] + \right. \right. \\
&\quad + (n_{11}^2/n_{14}^2) \cdot (n_{14}^2 k_o^2 - \kappa_1^2) \cdot \frac{1}{2\gamma_{14}} \cdot \cos^2[\bar{\kappa}_1(b+\eta)] + (n_{11}^2/n_{15}^2) \cdot (n_{15}^2 k_o^2 - \kappa_1^2) \cdot \frac{1}{2\gamma_{15}} \cdot \cos^2(\bar{\kappa}_1\eta) + \\
&\quad + [b/2 + \frac{1}{4\bar{\kappa}_1} \cdot \{\sin[2\bar{\kappa}_1(b+\eta)] - \sin[2\bar{\kappa}_1\eta]\}] \left[\frac{n_{12}^2}{\gamma_{12}^2} (\gamma_{12}^2 + n_{12}^2 k_o^2) \cdot \frac{1}{2\gamma_{12}} \cdot \right. \\
&\quad \left. \left. \cos^2[\kappa_1(\xi + d_2 - d_3)] + \frac{n_{13}^2}{\gamma_{13}^2} \cdot (\gamma_{13}^2 + n_{13}^2 k_o^2) \cdot \cos^2(\kappa_1\xi) \cdot \frac{1}{2\gamma_{13}} \right] \right\}}
\end{aligned}
\tag{2.6.23}$$

and

$$\begin{aligned}
B = & \sqrt{\left\{ \left(\frac{2\beta_2}{\omega\epsilon_0} \right) \right\} / \left[\frac{n_{21}^2}{\kappa_2^2} \cdot [d_1/2 + \frac{1}{4\kappa_2} \{ \sin[2\kappa_2(-d_1 + \bar{\xi})] - \sin(2\kappa_2\bar{\xi}) \}] \cdot \right. \\
& \cdot [(n_{21}^2 k_0^2 - \kappa_2^2) \cdot (b/2 + \frac{1}{4\bar{\kappa}_2} \cdot \{ \sin[2\bar{\kappa}_2(b + \bar{\eta})] - \sin(2\bar{\kappa}_2\bar{\eta}) \})] + \\
& + \frac{n_{21}^2}{n_{24}^2} \cdot (n_{24}^2 k_0^2 - \kappa_2^2) \cdot \frac{1}{2\gamma_{24}} \cdot \cos^2[\bar{\kappa}_2(b + \bar{\eta})] + \frac{n_{21}^2}{n_{25}^2} \cdot (n_{25}^2 k_0^2 - \kappa_2^2) \cdot \\
& \cdot \frac{1}{2\gamma_{25}} \cos^2(\bar{\kappa}_2\bar{\eta}) + [b/2 + \frac{1}{4\bar{\kappa}_2} \{ \sin[2\bar{\kappa}_2(b + \bar{\eta})] - \sin[2\bar{\kappa}_2\bar{\eta}] \}] \cdot \\
& \left. [\frac{n_{13}^2}{2\gamma_{23}^3} \cdot (\gamma_{23}^2 + n_{13}^2 k_0^2) \cdot \cos^2[\kappa_2(\bar{\xi} - d_1)] + \frac{n_{22}^2}{2\gamma_{22}^3} \cdot (\gamma_{22}^2 + n_{22}^2 k_0^2) \cdot \cos^2(\kappa_2\bar{\xi})] \right\} .
\end{aligned}
\tag{2.6.24}$$

Continuity of the tangential fields E_x and H_z at the four interfaces for each waveguide, results in the following set of eigenvalue equations:

$$\tan[\kappa_1(d_3 - d_2)] = \frac{n_{11}^2 \kappa_1 \cdot (n_{13}^2 \gamma_{12} + n_{12}^2 \gamma_{13})}{(n_{13}^2 \cdot n_{12}^2 \kappa_1^2 - n_{11}^4 \gamma_{12} \gamma_{13})} ,
\tag{2.6.25}$$

$$\tan[\bar{\kappa}_1 b] = \frac{\bar{\kappa}_1 (\gamma_{14} + \gamma_{15})}{(\bar{\kappa}_1^2 - \gamma_{14} \gamma_{15})} ,$$

$$\tan[\kappa_2 d_1] = \frac{n_{21}^2 \kappa_2 \cdot (n_{22}^2 \gamma_{23} + n_{13}^2 \gamma_{22})}{(n_{22}^2 n_{13}^2 \kappa_2^2 - n_{21}^4 \gamma_{22} \gamma_{23})} ,
\tag{2.7.26}$$

$$\tan[\bar{\kappa}_2 b] = \frac{\bar{\kappa}_2 (\gamma_{24} + \gamma_{25})}{(\bar{\kappa}_2^2 - \gamma_{24} \gamma_{25})} ,$$

leading to the eigensolutions β_1 and β_2 for the two guides respectively, with the phase parameters ξ , $\bar{\xi}$, η , $\bar{\eta}$ given by:

$$\tan(\kappa_1 \xi) = - \frac{n_{13}^2}{n_{11}^2} \cdot (\kappa_1 / \gamma_{13}) , \quad \tan(\bar{\kappa}_1 \eta) = - \gamma_{15} / \bar{\kappa}_1 ,
\tag{2.7.27}$$

$$\tan(\kappa_2 \bar{\xi}) = - \frac{n_{22}^2}{n_{21}^2} \cdot (\kappa_2 / \gamma_{22}) \quad , \quad \tan(\bar{\kappa}_2 \bar{\eta}) = - \gamma_{25} / \bar{\kappa}_2 \quad . \quad (2.7.28)$$

For $\beta_1(\omega_1) = \beta_2(\omega_1)$ forward coupling occurs, the coupling coefficients c_1, c_2 evaluated from eqs.2.2.2 as:

$$c_1 = \omega \epsilon_0 \frac{AB \cdot (n_{11}^2 - n_{13}^2) \cdot (n_{11}^2 k_o^2 - \kappa_1^2) \cdot (\gamma_{23}^2 + n_{13}^2 k_o^2)}{\beta_1 \cdot \beta_2 \cdot \kappa_1 \cdot \gamma_{23} \cdot (\gamma_{23}^2 + \kappa_1^2) \cdot (\bar{\kappa}_1^2 - \bar{\kappa}_2^2)} \cdot \cos[\kappa_2(\bar{\xi} - d_1)] \cdot$$

$$\cdot \{ \exp[-\gamma_{23}(d_2 - d_1)] \cdot \{ \gamma_{23} \sin(\kappa_1 \bar{\xi}) - \kappa_1 \cos(\kappa_1 \bar{\xi}) \} - \\ - \exp[-\gamma_{23}(d_3 - d_1)] \cdot \{ \gamma_{23} \sin[\kappa_1(d_2 - d_3 + \bar{\xi})] - \kappa_1 \cos[\kappa_1(d_2 - d_3 + \bar{\xi})] \} \} \\ \{ \bar{\kappa}_1 [\sin[\bar{\kappa}_1(b + \eta)] \cos[\bar{\kappa}_2(b + \bar{\eta})] - \sin[\bar{\kappa}_1 \eta] \cos[\bar{\kappa}_2 \bar{\eta}]] - \\ - \bar{\kappa}_2 [\cos[\bar{\kappa}_1(b + \eta)] \sin[\bar{\kappa}_2(b + \bar{\eta})] - \cos[\bar{\kappa}_1 \eta] \sin[\bar{\kappa}_2 \bar{\eta}]] \} ,$$

and (2.7.29)

$$c_2 = \omega \epsilon_0 \frac{AB \cdot (\gamma_{13}^2 + n_{13}^2 k_o^2) \cdot \cos(\kappa_1 \bar{\xi})}{\beta_1 \cdot \beta_2 \cdot \gamma_{13} \cdot (\bar{\kappa}_1^2 - \bar{\kappa}_2^2)} [\bar{\kappa}_1 \{ \sin[\bar{\kappa}_1(b + \eta)] \cos[\bar{\kappa}_2(b + \bar{\eta})] -$$

$$- \sin[\bar{\kappa}_1 \eta] \cos[\bar{\kappa}_2 \bar{\eta}] \} - \bar{\kappa}_2 \{ \cos[\bar{\kappa}_1(b + \eta)] \sin[\bar{\kappa}_2(b + \bar{\eta})] -$$

$$- \cos[\bar{\kappa}_1 \eta] \sin[\bar{\kappa}_2 \bar{\eta}] \}] \cdot \{ (n_{21}^2 - n_{13}^2) \cdot (n_{21}^2 k_o^2 - \kappa_2^2) \cdot \frac{1}{\kappa_2(\kappa_2^2 + \gamma_{13}^2)} \cdot$$

$$[\exp\{-\gamma_{13} d_2\} \cdot \{ -\gamma_{13} \sin[\kappa_2 \bar{\xi}] - \kappa_2 \cos[\kappa_2 \bar{\xi}] \} - \exp\{-\gamma_{13}(d_2 - d_1)\} \cdot$$

$$\{ -\gamma_{13} \sin[\kappa_2(\bar{\xi} - d_1)] - \kappa_2 \cos[\kappa_2(\bar{\xi} - d_1)] \}] + (n_{22}^2 - n_{13}^2) \cdot (\gamma_{22}^2 + n_{22}^2 k_o^2) \cdot$$

$$\cdot \cos(\kappa_2 \bar{\xi}) \cdot \frac{1}{\gamma_{22}(\gamma_{13} + \gamma_{22})} \cdot \exp[-\gamma_{13} d_2] \}$$

(2.7.30)

For a grating of periodicity Λ and amplitude h imposed on the top waveguide, such that

$$\beta_1(\omega_0) + \beta_2(\omega_0) = 2\pi / \Lambda ,$$

contadirectional coupling takes place between the two modes,

the coupling coefficient δ evaluated from eq.2.3.10 as:

$$\delta = \omega \epsilon_0 \frac{(n_{21}^2 - n_{22}^2) \cdot AB \cdot (n_{21}^2 k_0^2 - \kappa_2^2) \cdot (\gamma_{13}^2 + n_{13}^2 k_0^2) \cos(\kappa_1 \xi)}{\beta_1 \beta_2 \cdot \kappa_2 \cdot \gamma_{13} \cdot (\bar{\kappa}_1^2 - \bar{\kappa}_2^2) \cdot (\kappa_2^2 + \gamma_{13}^2)} \cdot$$

$$\cdot [\exp\{-\gamma_{13} d_2\} \{-\gamma_{13} \sin[\kappa_2 \bar{\xi}] - \kappa_2 \cos[\kappa_2 \bar{\xi}]\} - \exp\{-\gamma_{13}(d_2 - h)\} \{-\gamma_{13} \sin[\kappa_2(\bar{\xi} - h)] - \kappa_2 \cos[\kappa_2(\bar{\xi} - h)]\}] \cdot [\bar{\kappa}_1 \{\sin[\bar{\kappa}_1(b + \eta)] \cdot \cos[\bar{\kappa}_2(b + \bar{\eta})] - \sin(\bar{\kappa}_1 \eta) \cos[\bar{\kappa}_2 \bar{\eta}]\} - \bar{\kappa}_2 \{\cos[\bar{\kappa}_1(b + \eta)] \cdot \sin[\bar{\kappa}_2(b + \bar{\eta})] - \cos(\bar{\kappa}_1 \eta) \sin(\bar{\kappa}_2 \bar{\eta})\}] .$$

(2.7.31)

In the case of the integrated fibre coupler,

$n_{11} = n_{21} = n_0$ is the core index in both guides,

$n_{24} = n_{25} = n_{12} = n_{13} = n_{14} = n_{15} = n_s$ is the substrate index,

and $n_{22} = n_c$ is the external cladding index,

a lot of simplification for the above general expressions can be achieved.

A similar analysis can be followed for the E_{11}^y polarisation resulting in expressions for c_1 , c_2 and δ .

CHAPTER 3

DESIGN

3.1 Design Parameters: Bandwidth Beatlength, Reflectivity and Sensitivity.

The performance of grating couplers and reflectors can be most readily evaluated in terms of parameters such as the coupled bandwidth, the reflectivity, the beatlength and the sensitivity.

The coupled bandwidth has been previously defined (eqs. 2.3.21, 2.3.40), as the frequency range for which the matching condition $|\Delta\beta| \leq 2\delta$ is satisfied. In terms of wavelength, the coupled bandwidth is approximately given by

$$\Delta\lambda_R \approx \delta \cdot \lambda_0^2 / (\pi \cdot n_{EF}) \quad (3.1.1)$$

for the grating reflector and

$$\Delta\lambda_C \approx 2\delta \cdot \lambda_0^2 / [\pi (n_{EF_1} + n_{EF_2})] \quad (3.1.2)$$

for the grating coupler, where δ is the contradirectional coupling coefficient, n_{EF} the effective waveguide index and λ_0 the wavelength of operation. Since $n_{EF} \approx (n_{EF_1} + n_{EF_2})/2$, for equal coupling strengths, the bandwidths $\Delta\lambda_R$ and $\Delta\lambda_C$ are approximately equal.

In close analogy, the bandwidth of a directional coupler

is defined as the wavelength range for which the mismatch $|\Delta\beta| < 2 c_0$, approximately given by :

$$\Delta\lambda = 2 \cdot c_0 \lambda_0^2 / [\pi (n_{EF_1} - n_{EF_2})] \quad (3.1.3)$$

where c_0 is the directional coupling coefficient. Note that for identical waveguides, i.e. $n_{EF_1} = n_{EF_2}$, $\Delta\lambda \rightarrow \infty$ and the waveguides remain phase matched at all wavelengths.

By comparing eqs 3.1.2 and 3.1.3, the coupled bandwidth of the contradirectional coupler appears to be

$$(n_{EF_1} + n_{EF_2}) / |n_{EF_1} - n_{EF_2}|$$

times smaller than that of the directional coupler. A difference of 0.1 % in effective indices, corresponds to a bandwidth ratio of 2000. Thus, the wavelength selectivity of grating couplers and reflectors is by far superior to that of conventional directional couplers.

The periodic power exchange in directional couplers allows complete power transfer, when $\Delta\beta = 0$ (see Fig.2.1) and over an interaction length

$$L_B = \pi / (2 \cdot c_0), \quad (3.1.4)$$

known as the beatlength.

In the case of contradirectional coupling, the variation of coupled power with length has an asymptotic character in the near matching region (see Fig.2.3), and 100 % power transfer is only approached as $L \rightarrow \infty$, even at the precise resonant condition. For a specific grating length L , the reflectivity of the device R , defined as the fraction of the reflected power, takes its maximum value under phase matching conditions, where

$$R = \tanh^2(\delta \cdot L) \quad (3.1.5)$$

It is, therefore, convenient to define an equivalent "beatlength" in terms of a prescribed reflectivity value. Even so, a precise determination of the interaction length is not essential, in marked contrast to conventional directional couplers.

The sensitivity, often being referred to as tunability, is defined as the change in the cladding index Δn_c required to shift the central wavelength of the coupled band by one bandwidth. Although smaller changes in index may well be detectable, dependent, for example, on the detection scheme, the above definition provides a useful basis for comparison (3.1) .

The dependance of coupled bandwidth and sensitivity on the beatlength, and thus on the coupling strength, is shown in Fig.3.1 simultaneously for directional and contradirectional couplers. In both cases, narrower bandwidths and finer sensitivities (i.e. larger $1/\Delta n_c$ values) can be obtained for longer beatlengths. Note, however, that although the corresponding bandwidths may differ by some 4 orders of magnitude, the sensitivities appear to be of the same order. The reason for this can be better understood, by referring to the dispersion characteristics of the two waveguides, schematically presented in Fig.3.2 . It can be seen that the significantly wider intersection angle of the contradirectional coupler required for narrower bandwidth, inevitably makes the shift $\Delta\omega$ of the crossing point less sensitive to changes in the cladding index n_c (3.2). Hence, the shift in the phase matching frequency with index decreases for

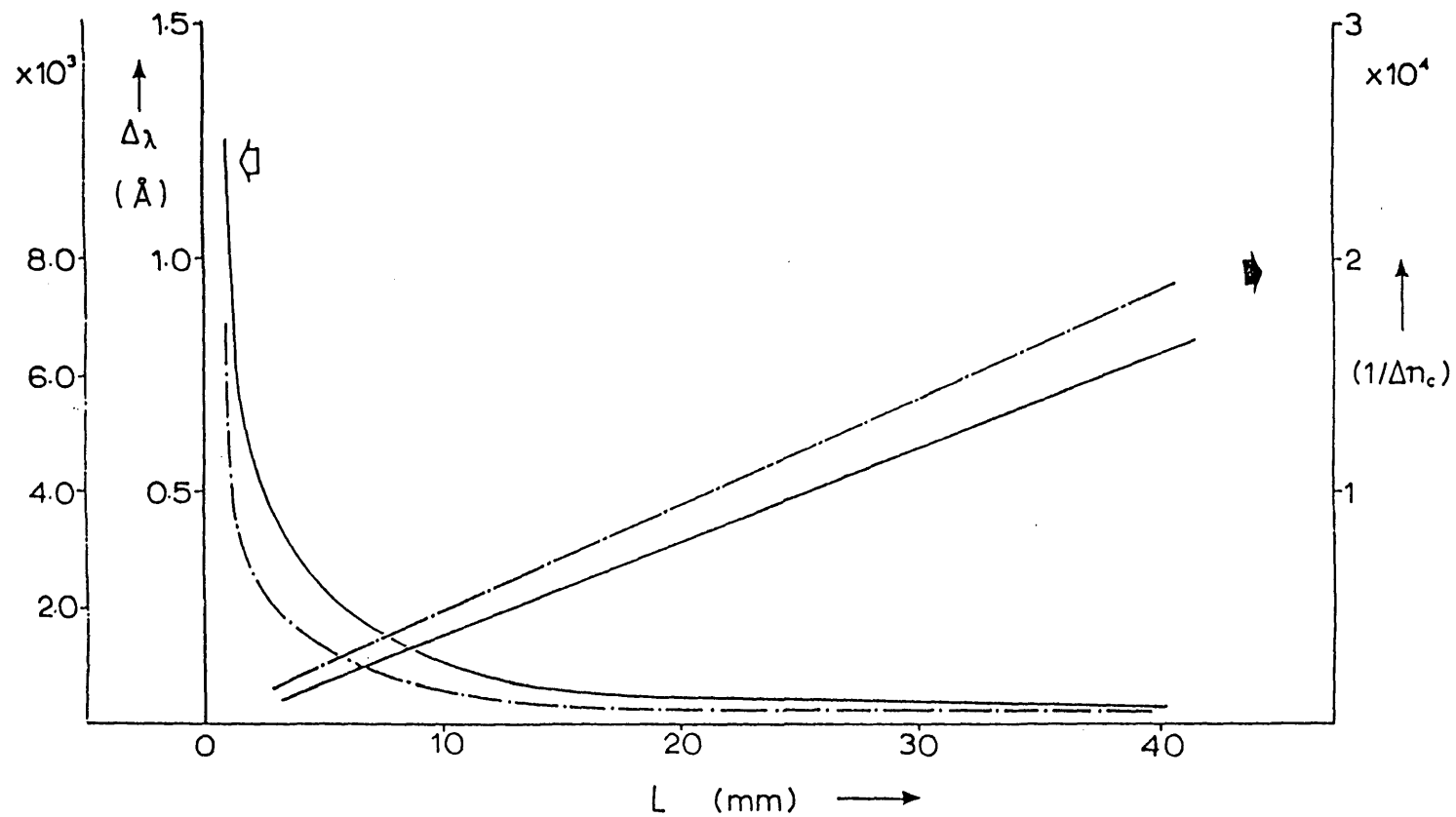


Fig. 3.1

Bandwidth and Sensitivity as function of beatlength for "Equivalent" designs of Directional (---) and Contradirectional (—) Couplers.

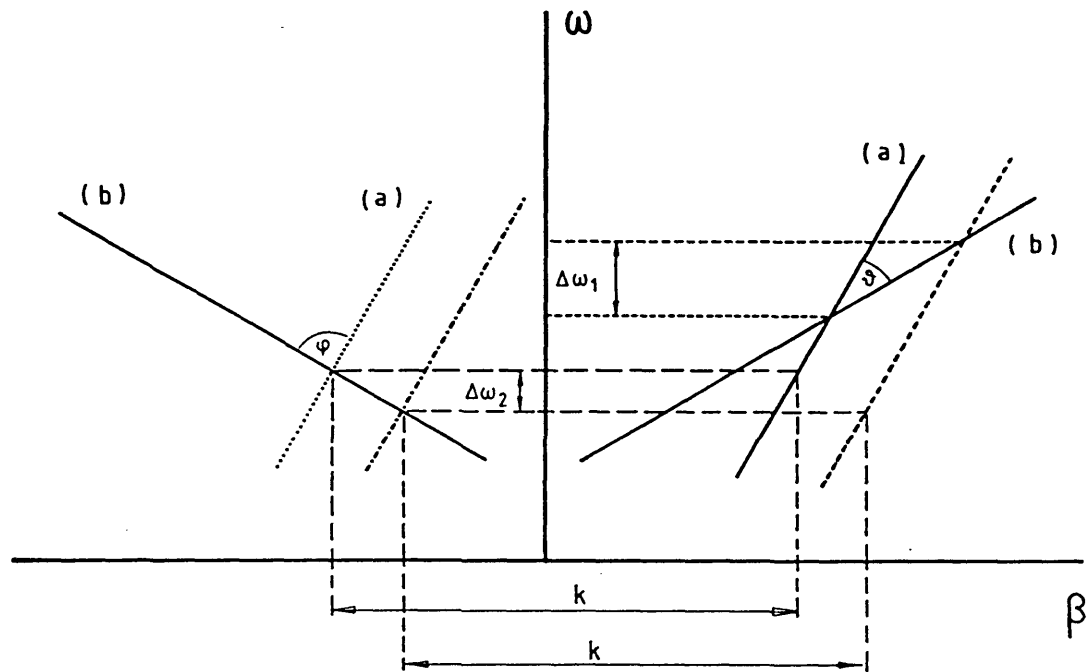


Fig. 3.2

Schematic $\omega - \beta$ diagram for directional and contradiirectional coupling between guides (a) and (b) with variations in the outer cladding n_c of (a).

larger angles, i.e. narrower bandwidths, the two effects essentially cancel.

The limits to the achievable sensitivity for a given interaction length, while not significantly affected by the coupling process, can be influenced by a common feature of the waveguide design. The important factor is the fraction of the propagating power, $\Delta P/P_0$, which experiences the changes in the cladding index being sensed. For a slab waveguide model, similar to that of Fig.2.18, the power fraction in the cladding index n_3 is given by:

$$\frac{\Delta P}{P_0} = \frac{\int_0^\infty E_y \cdot H_x^* dx}{\int_{-\infty}^\infty E_y \cdot H_x^* dx} = \frac{\kappa_1^2}{\gamma_1(d + 1/\gamma_1 + 1/\gamma_2)(\kappa_1^2 + \gamma_1^2)} \quad (3.1.6)$$

The ratio $\Delta P/P_0$ depends on the structural waveguide parameters, such as the index distribution and guide thickness (V value), while the coupling strength and hence the beatlength can be maintained by adjusting the waveguide separation. The variation in sensitivity, $\Delta n_c \times L_B$, with the fractional power in the cladding for constant beatlength, is shown in Fig.3.3 for directional and contradirectional couplers. Although small differences exist, the sensitivity in both cases increases for larger $\Delta P/P_0$ values, the two characteristics becoming essentially indistinguishable.

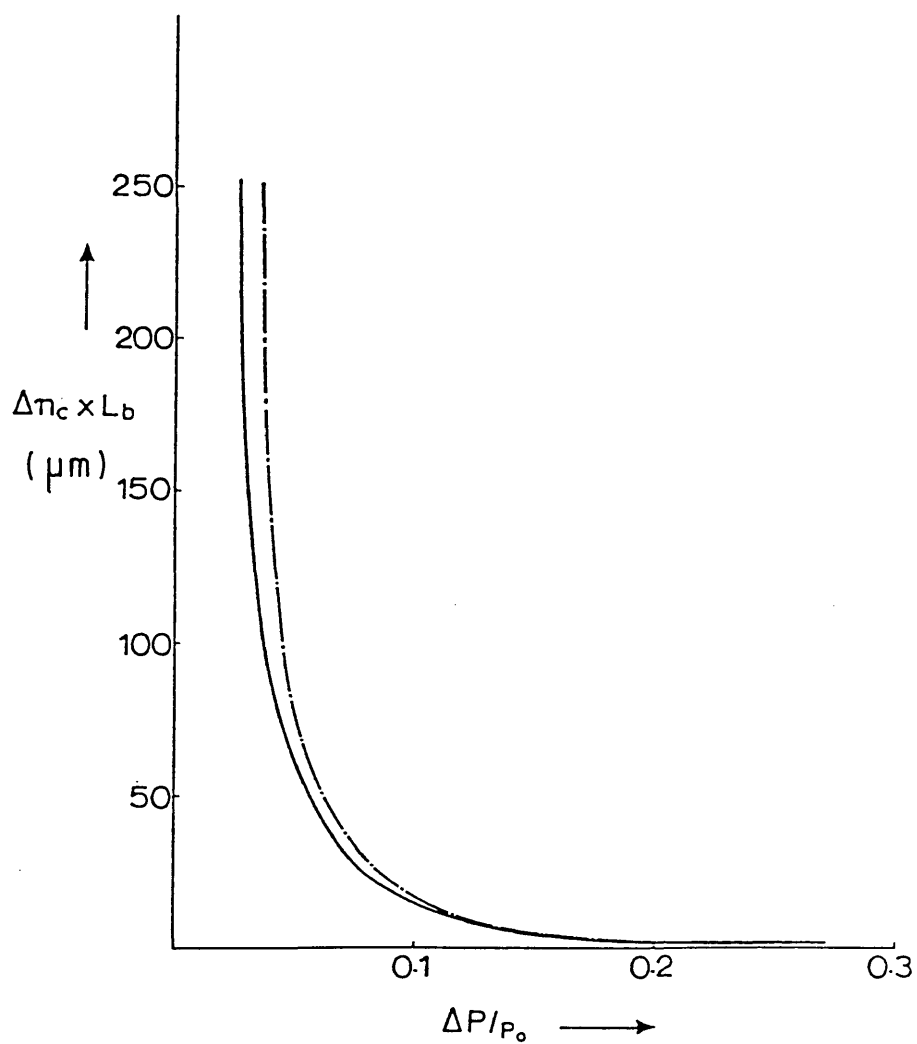


Fig. 3.3

The variation of the product of the minimum detectable change in cladding index, n_c , and the beatlength, L_b , with the fractional power in the cladding, $\Delta P/P_0$, for both directional (- · - · - · -) and contradirectional (—) couplers.

3.2 Design Procedure

If the coupler is to be implemented by standard communication fibre, the structural waveguide parameters (i.e. indices and core diameter) are fixed, and the design is limited to the periodicity and strength of the perturbation, both subject to grating fabrication constraints.

It is, however, possible to design a coupler configuration (see Fig.2.19 or 2.20) based on the planar geometry of an integrated fibre, fabricated by pulling a fused borosilicate composite preform down to the required dimensions. For a design based on the asymmetric slab waveguide model, single-mode operation (i.e. lowest order T.E. mode) requires the waveguide thickness d to be bounded by:

$$\frac{\tan^{-1}(\Delta n_{3,2} / \Delta n_{1,3})}{2 \cdot \pi \cdot \Delta n_{1,3}} < \left[\frac{d}{\lambda_0} \right]_{\text{T.E.}} < \frac{[\pi + \tan^{-1}(\Delta n_{3,2} / \Delta n_{1,3})]}{2 \cdot \pi \cdot \Delta n_{1,3}}, \quad (3.1.7)$$

with $\Delta n_{3,2}^2 = n_3^2 - n_2^2$, $\Delta n_{1,3}^2 = n_1^2 - n_3^2$, where n_1 is the core and n_2, n_3 the cladding indices and λ_0 the wavelength of operation.

Note, that for the symmetric case (i.e. $n_2 = n_3$) eq.3.1.7 becomes:

$$(d / \lambda_0)_{\text{T.E.}} < 1 / (2 \Delta n_{1,3}), \quad (3.1.8)$$

with no lower cut-off.

For improved sensitivity weak guiding with low V value (i.e. $V = 2\pi \Delta n_{1,3} \cdot d / \lambda_0$) is desirable, with $n_3 > n_2$ to allow a greater fraction of the propagating power into the external cladding medium 3.

The choice of wavelength, subject to the filtering requirements, will define the waveguide thickness and set the nominal index values from the dispersion characteristic of the glasses, although the effect on the index differences Δn_{13} , Δn_{32} is expected to be minimal.

Once the structural waveguide parameters have been defined, the eigenvalue equation (eq. 2.6.5) can be solved for the propagation constant β .

In the case of the grating coupler, contradirectional coupling must be isolated from directional coupling and reflection in the individual waveguides, by designing the two guides to be profoundly dissimilar, i.e. $|\beta_1 - \beta_2| \gg 0$, at the wavelength of operation. Although the exact placing of the grating depends on the implementation, it can be shown (2.12), that a better crosstalk isolation is achieved when the grating is imposed on the interface of the receiving waveguide, thus making reflection in the input waveguide significantly weaker than contradirectional coupling.

From the knowledge of the propagation constants at the wavelength of operation, the grating periodicity Λ can be accurately defined; eq. 2.3.3 for the grating coupler, or eq. 2.3.26 for the reflector. The grating length, L , is limited by fabrication constraints to no more than a few cms, which for a prescribed reflectivity, provides a direct measure of the required coupling coefficient (eq. 3.1.5), giving an estimate of the coupled bandwidth (eq. 3.1.1 or 3.1.2). For example, for a grating length of 2 cm and 95 % reflectivity, the required coupling coefficient is 108.91 /m,

with a coupled bandwidth of $0.1 \text{ \AA}$, for an effective index of 1.55 .

The required coupling strength of a reflector, with the grating imposed on the core/cladding interface, can be obtained, by appropriate choice of the corrugation depth h , from eq. 2.6.8. If $\delta = 108.91 \text{ /m}$, a corrugation depth into the core of $h = 520 \text{ \AA}$ is required.

In the case of a grating coupler, the desired coupling strength can be obtained by the combined action of the perturbation depth and the waveguide separation, as given from eq. 2.6.17. For $\delta = 108.91 \text{ /m}$, a corrugation depth $h = 1250 \text{ \AA}$ and a waveguide separation $t = 2.5 \text{ }\mu\text{m}$ are required. The corrugation depth is usually limited by fabrication to less than the grating periodicity, so, for a specific grating depth h , a waveguide separation can be set for the required coupling coefficient.

3.3 Numerical Design Based On Asymmetric Slab Waveguides

Wavelength selective devices based on grating reflectors and couplers can be designed in accordance with the guidelines set in the previous section. Some numerical examples will be presented, in order to give a clearer insight of the practical aspects of contradirectional coupler design.

Four different wavelengths of operation are considered,

i.e. $0.633\text{ }\mu\text{m}$, $0.8\text{ }\mu\text{m}$, $1.0\text{ }\mu\text{m}$ and $1.5\text{ }\mu\text{m}$, covering a wide range of possible applications, from spectrally selective mirrors to multiplexers. In each case, the design was optimised by preserving the V-value and retaining the reflectivity for the same grating length, with both the waveguide thickness and the grating characteristics (i.e. periodicity and modulation depth) properly adjusted to compensate for the change in wavelength.

"Equivalent" designs for grating couplers and reflectors at four different wavelengths are presented in Tables 3.1 and 3.2 respectively. In both cases, for a beatlength of 2 cm and a reflectivity of 98 %, a coupling strength of 138.8 /m is required, which can be obtained and retained by suitable choice of the grating depth.

Comparison between the characteristics of the grating coupler with those of the reflector, show no difference in terms of coupled bandwidth, and only a small improvement in sensitivity, influenced by the presence of the second waveguide. The bandwidth appears to broaden for longer wavelengths from $0.114\text{ }\text{\AA}$ at $0.633\text{ }\mu\text{m}$ to $0.646\text{ }\text{\AA}$ at $1.5\text{ }\mu\text{m}$, approximately proportional to the square of the wavelength of operation i.e. $\Delta\lambda \propto \lambda_0^2$ (eqs. 3.1.1 and 3.1.2) .

Fig. 3.4 shows the filtering characteristics of a contra-directional coupler for different grating lengths. Designs based on long interaction lengths for high reflectivity values, are characterised by a flat passband response followed by sharp cut-off with considerable sidelobe presence in the stopband. For a given coupling strength, both the

TABLE 3.1
GRATING COUPLER

Indices of the glasses used in the design (at 633 nm):

substrate : 1.5560 , core : 1.5620 , cladding : 1.55 .

Dispersion associated with glasses:

0.02223 / μm for substrate and core , 0.0223 for cladding.

Wavelength (μm) :	0.633	0.8	1.0	1.5
Thickness 1 (μm) :	2.0	2.53	3.16	4.77
Thickness 2 (μm) :	1.5	1.89	2.37	3.01
Separation (μm) :	1.2	1.2	1.2	1.2
β_1 / m :	15,476215	12,216489	9,744872	6,448559
β_2 / m :	15,466741	12,208971	9,737100	6,442221
Grat. period (μm):	0.203	0.257	0.322	0.487
Grat. depth ($\text{\AA}$) :	1564	1 670	2012	2695
Grat. length (cm):	2	2	2	2
Coupl. coef. :	138.8	138.8	138.8	138.8
/ m				
Reflectivity :	0.984	0.984	0.984	0.984
Bandwidth ($\text{\AA}$) :	0.113	0.182	0.285	0.647
Sensitivity :	0.576	0.724	0.932	1.216
($\times 10^3$)				
Isolation from directional coupling and reflection:				
$(\Delta\beta/2 \cdot c_0)^2$:	48.5	21.4	18.3	12.2
$(\Delta\beta/2 \cdot \kappa)^2$:	48,408	7,387	2,330	364.2

TABLE 3.2
GRATING REFLECTOR

Indices of the glasses used in the design (at 633 nm):

substrate : 1.5560 , core : 1.5620 , cladding : 1.55 .

Dispersion associated with glasses:

0.02223 / μm for substrate and core , 0.0223 for cladding.

Wavelength (μm)	: 0.633	0.8	1.0	1.5
Thickness (μm)	: 2.0	2.53	3.16	4.77
β / m	: 15,476215	12,216489	9,744872	6,448559
Grat. period (μm):	0.203	0.257	0.322	0.487
Grat. depth ($\text{\AA}$)	: 266	422	649	1450
Grat. length (cm):	2	2	2	2
Coupl. coef.	: 138.8	138.8	138.8	138.8
/ m				
Reflectivity	: 0.984	0.984	0.984	0.984
Bandwidth ($\text{\AA}$)	: 0.114	0.181	0.284	0.646
Sensitivity	: 0.693	0.893	1.071	1.600
($\times 10^3$)				

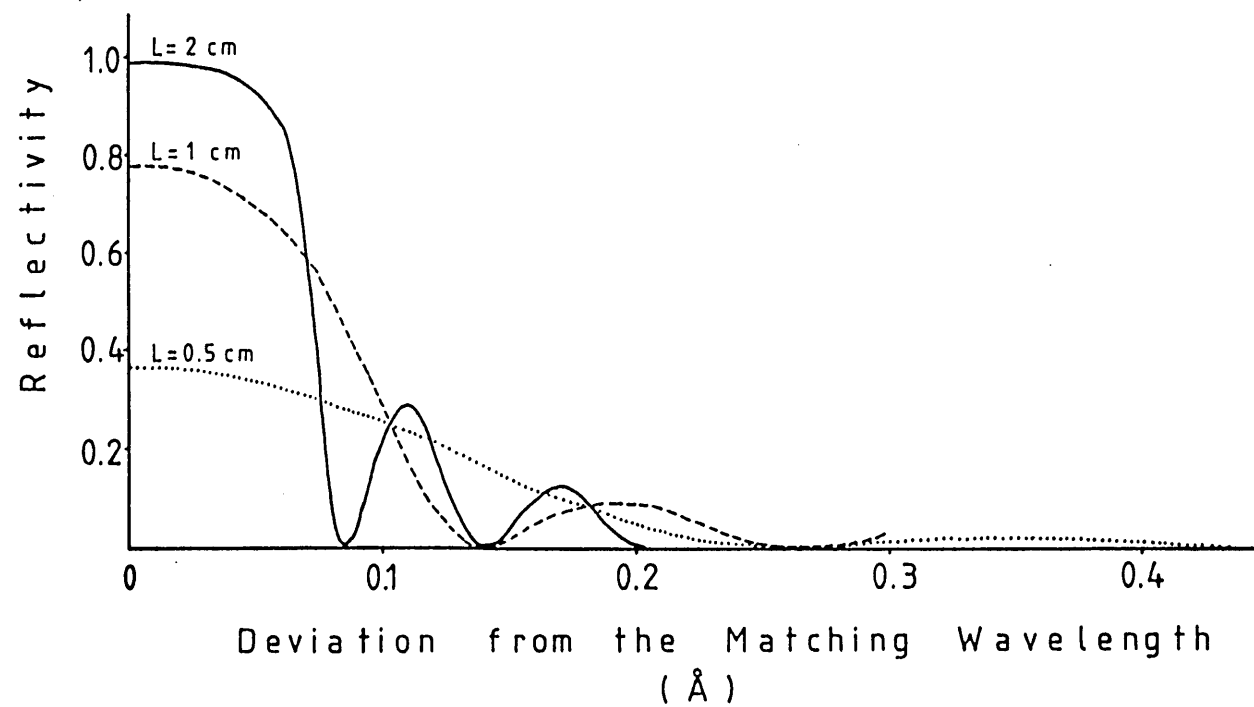


Fig. 3.4

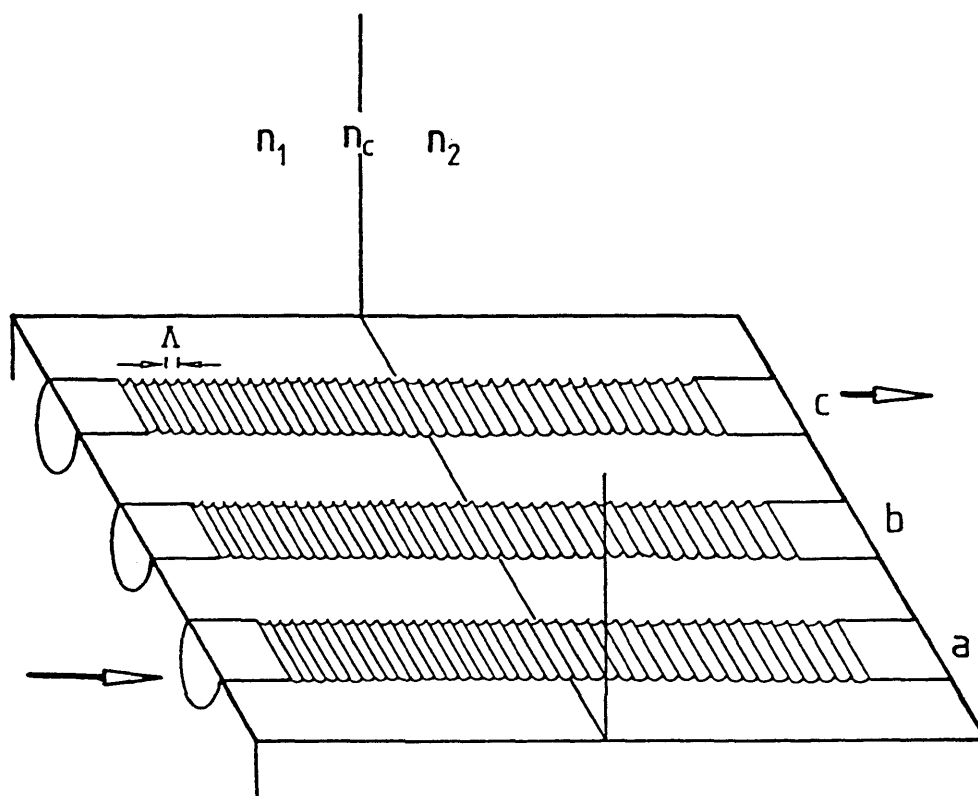
Variation in Reflectivity with deviation from the matching wavelength for different grating lengths.

reflectivity and the sidelobe level increase with longer grating lengths according to eqs. 2.3.24 and 2.3.25. There is usually a trade off between the maximum reflectivity or peak filter efficiency and the permitted ripple level. When high reflectivities with flat passband response and sharp cut-off are required, high ripple levels must be tolerated.

Severe sidelobe presence may cause problems for multiplexing applications, resulting in crosstalk between adjacent data channels. The unwanted sidelobe level can be reduced by varying the coupling strength gradually along the grating length, either by means of tapering the grating depth (3.3) or by changing the width of the grating between the two waveguides (2.11). Alternatively, the sidelobe level can be suppressed by cascading two grating couplers in a three waveguide formation, schematically shown in Fig. 3.5.

The grating length is divided between two cladding media, each one permitting coupling between the centre and one of the side waveguides at the same wavelength, effectively squaring the filter response. The effect is shown in Fig. 3.6 for a high reflectivity grating coupler (0.999). With a small additional loss in the passband response, the sidelobe levels are significantly reduced.

The sensitivity of both grating reflectors and couplers appears to reduce for longer wavelengths (Tables 3.1 & 3.2) from 0.693×10^{-3} at $0.633 \mu\text{m}$ to 1.60×10^{-3} at $1.5 \mu\text{m}$; this is mainly due to broadening of the coupled bandwidth, varying approximately as $\Delta n_c \propto \lambda_0$, with the overall sensitivity reduced linearly with wavelength.



$$\begin{aligned}
 n_c &= n_2 & \beta_a(\omega_0) + \beta_b(\omega_0) &= \frac{2\pi}{\Lambda} \\
 n_c &= n_1 & \beta'_b(\omega_0) + \beta'_c(\omega_0) &= \frac{2\pi}{\Lambda}
 \end{aligned}$$

Fig. 3.5

Schematic configuration of two cascaded grating couplers in a three waveguide formation for sidelobe level suppression.

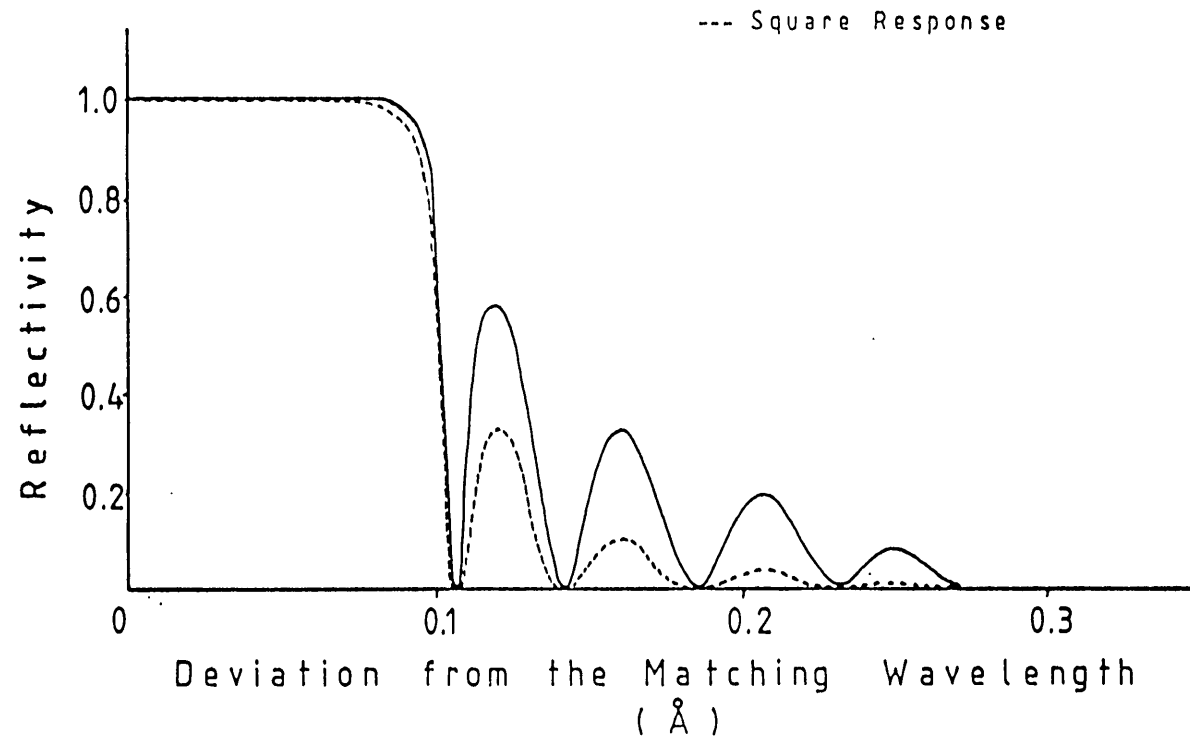


Fig. 3.6
Filtering characteristic of two cascaded grating couplers
compared to that of a single grating coupler.

The dependence of the coupling efficiency on variations in the outer cladding index n_c is shown in Fig. 3.7, for two devices phase-matched at different cladding indices. The sensitivity, defined as the width of the coupled band, is significantly broader for the lower cladding index, even though the wavelength selectivity (i.e. coupled bandwidth) remains unchanged. Phase-matching at a higher outer cladding index results in weaker guiding, stimulating a larger portion of the total field in the sensed cladding, improving the sensitivity of the device. The variation in sensitivity for core-cladding index differences is shown in Fig. 3.8. Notice, that even though the sensitivity may improve by one order of magnitude (from 6.928×10^{-4} at $n = 1.55$ to 0.618×10^{-4} at $n = 1.56$), the effect on the coupled bandwidth is minimal.

The coupled bandwidth, defined by eqs. 3.1.1 and 3.1.2, depends on the choice of wavelength, the magnitude of the coupling strength and the effective indices of the guides. For a given wavelength, both the coupling coefficient and the effective index may be influenced by variations in the structural waveguide parameters, such as the waveguide thickness. The dependence of the coupled bandwidth and reflectivity on the thickness of the receiving waveguide is shown in Figs. 3.9 and 3.10 respectively, for the same grating depth, in an attempt to define a nominal waveguide thickness. For grating length of 2 cm, the reflectivity remains above 90 % over an optimum thickness range $(d/\lambda_0): (1/0.633) - (2.5/0.633)$, above which the reflectivity drops sharply, the

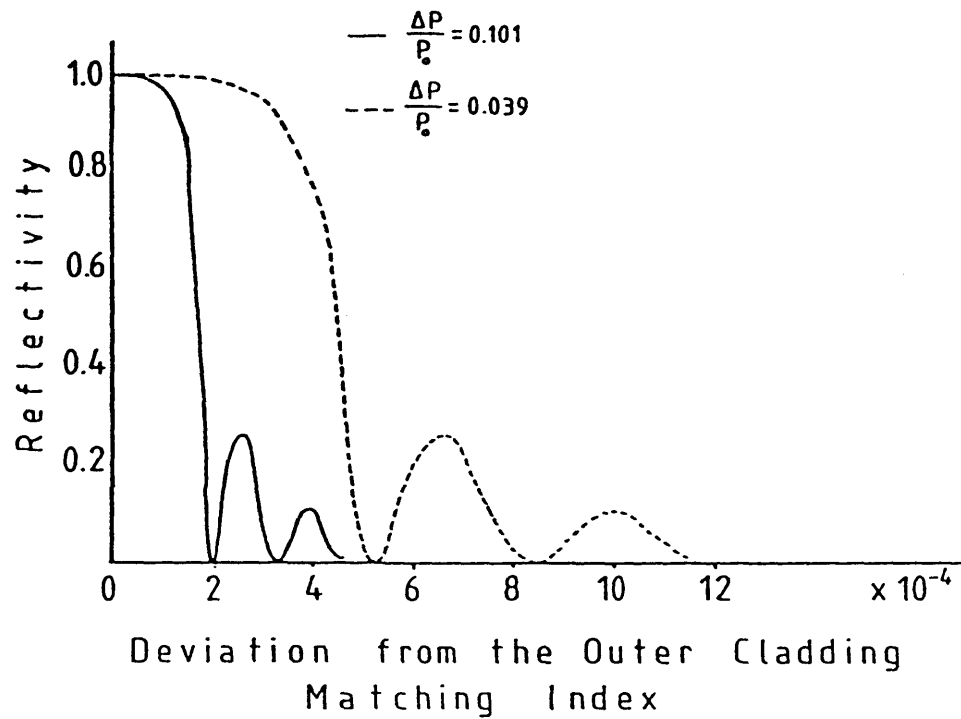


Fig. 3.7

Coupling Efficiency with variations in the outer cladding index for grating coupler designs of different sensitivities.

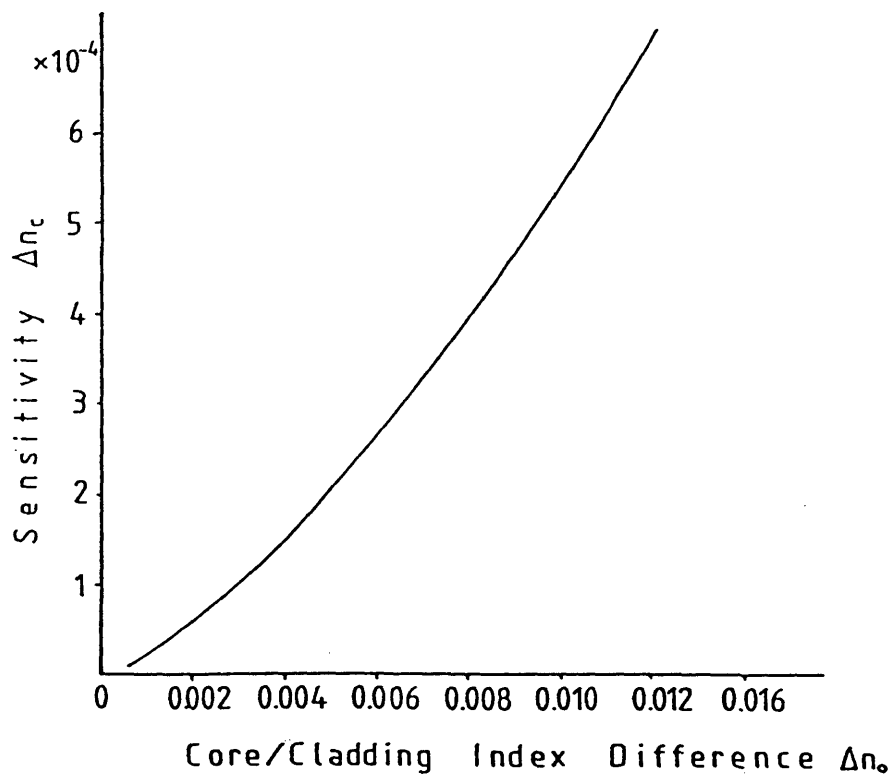


Fig. 3.8

Sensitivity as a function of core/cladding index difference of the sensing guide. The waveguide thickness remains fixed.

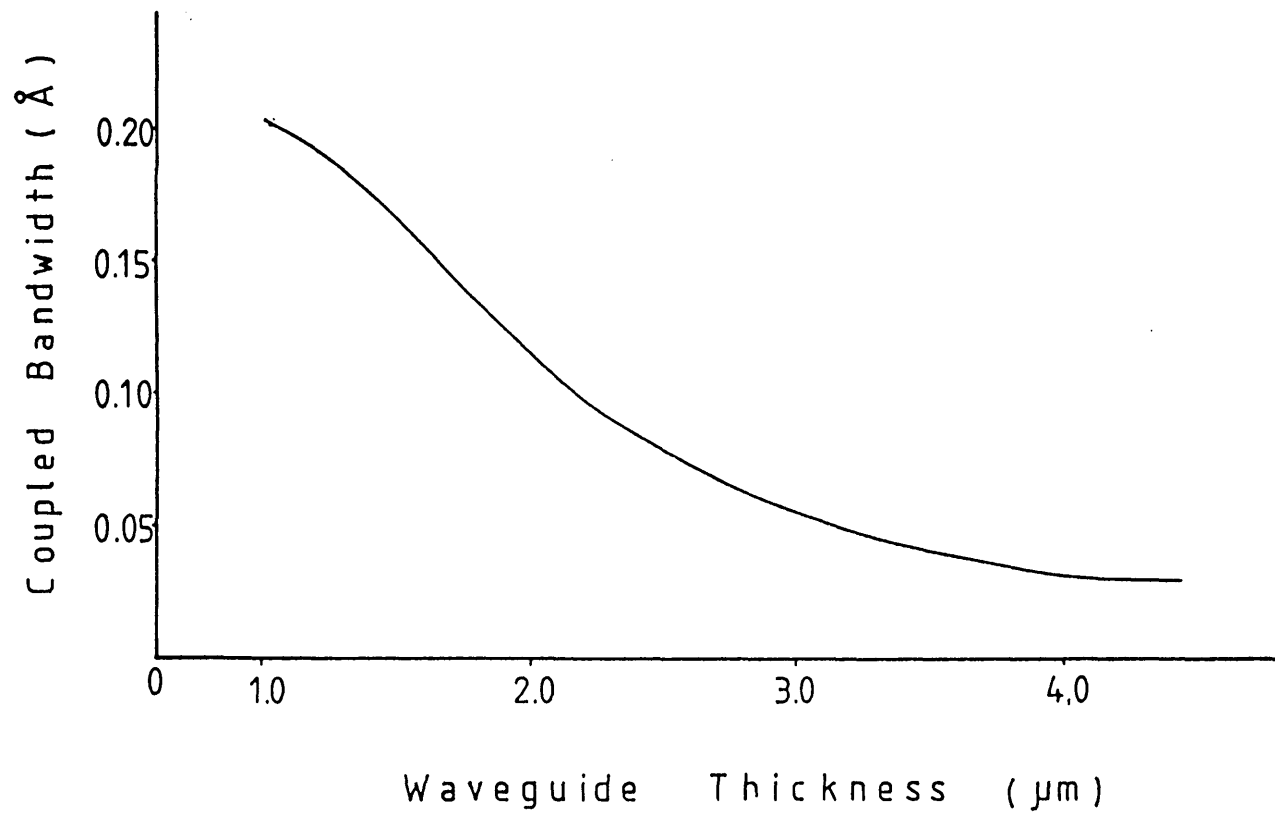


Fig. 3.9

Coupled bandwidth as a function of thickness variation in the receiving guide. The index distribution remains unchanged.

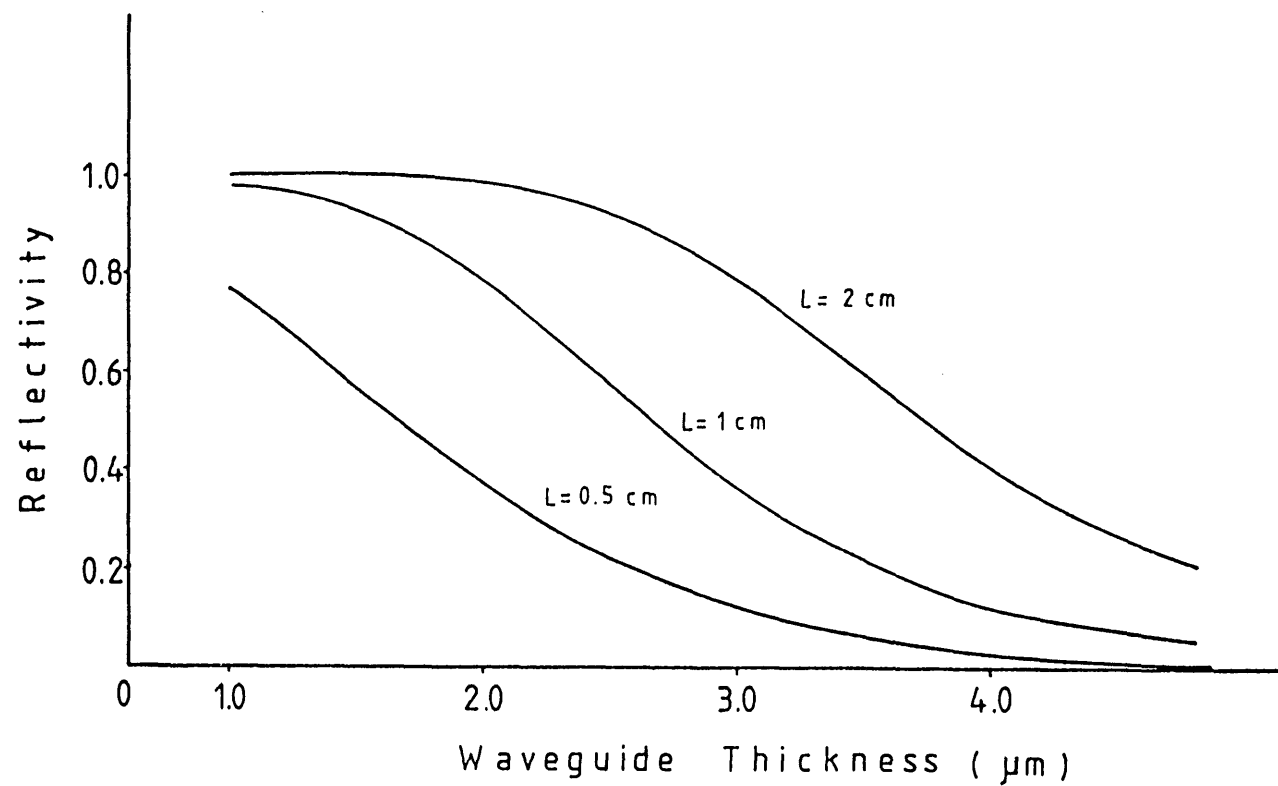


Fig. 3.10

Reflectivity as a function of thickness variation in the receiving guide for different grating lengths.

waveguide becoming eventually multimode. For shorter grating lengths the optimum thickness range becomes narrower, $(1/0.633) - (1.6/0.633)$ for a grating length of 1 cm, while for a 5 mm grating length the reflectivity drops rapidly for values above $(1/0.633)$. Notice, that the lower thickness limit has been arbitrarily chosen.

A smaller waveguide thickness results in weaker guiding, simultaneously reducing the effective guide index and increasing the coupling strength, due to a larger field presence over the perturbation region. The coupled bandwidth is, therefore, expected to become narrower for larger waveguide thickness, as shown in Fig. 3.9.

For direct comparison between contradirectional and directional couplers, the filtering characteristics of "equivalent" forward coupler designs at the four wavelengths of operation are presented in Table 3.3. In all cases the thickness of the second waveguide has been chosen to phase match the first guide at the wavelength of operation, with the separation scaled to provide a beatlength of 2 cm, compensating for the change in wavelength.

The dependance of the coupled bandwidth and sensitivity on the wavelength of operation, is similar to that for contradirectional couplers, approximately described by

$$\Delta\lambda \propto \lambda_0^2 \quad \text{and} \quad \Delta\eta_c \propto \lambda_0.$$

As expected, for the same interaction length, the bandwidths of the directional couplers are significantly broader (three orders of magnitude) than those of contradirectional couplers, even though the sensitivity of both processes is of the same order.

TABLE 3.3
DIRECTIONAL COUPLER

Indices of the glasses used in the design (at 633 nm):

substrate : 1.5560 , core : 1.5620 , cladding : 1.55 .

Dispersion associated with glasses:

0.02223 / μm for substrate and core , 0.0223 for cladding.

Wavelength (μm)	: 0.633	0.8	1.0	1.5
Thickness 1 (μm)	: 2.0	2.53	3.16	4.77
Thickness 2 (μm)	: 1.732	2.190	2.735	4.05
Separation (μm)	: 4.280	5.117	6.075	7.32
β_1 / m	: 15,476215	12,216489	9,744872	6,448559
β_2 / m	: 15,476215	12,216489	9,744872	6,448559
Coupl. coef.	: 78.5398	78.5398	78.5398	78.5398
/ m				
Beatlength (cm)	: 2	2	2	2
Bandwidth ($\text{\AA}$)	: 372	596	914	2070
Sensitivity	: 0.792	0.998	1.240	1.851
($\times 10^3$)				

3.4 Numerical Design For Integrated Fibre Couplers Based On The Rectangular Waveguide Model.

The results presented in the previous section were all based on the slab waveguide model. An integrated fibre coupler, however, can be more accurately described using the rectangular waveguide model presented in section 2.6.3 .

The basic design procedure is repeated, with the propagation constants of the individual waveguides obtained by solving the eigenvalue eqs. 2.6.25 & 2.6.26 , and the coupling coefficients calculated from eqs. 2.6.29 & 2.6.30 for directional coupling, and eq. 2.6.31 for contradirectional coupling. The characteristics of "equivalent" coupler designs for operation at the four wavelengths of interest are presented in Tables 3.4.1 & 3.4.2, respectively for contradirectional and directional couplers of 2 cm beat-lengths.

Comparison, between designs based on rectangular and slab waveguide models, shows that, although some small differences may arise from the smaller propagation constants of rectangular guides, the bandwidth and sensitivity remain unchanged for equal coupling strengths, and the relative design considerations discussed for slab waveguides in the previous section also hold for rectangular guides.

A marked difference results from the positioning of the

TABLE 4.1

GRATING COUPLER

Indices of the glasses used in the coupler design (at 633 nm):

substrate : 1.5560 , core : 1.5620 , cladding : 1.55 .

Design based on Fig.2.20 .

Wavelength (μm) :	0.633	0.8	1.0	1.5
Thickness 1 (μm) :	2.0	2.53	3.16	4.77
Width 1 (μm) :	2.0	2.53	3.16	4.77
β_1 /m :	15,455173	12,199835	9,731523	6.439911
Thickness 2 (μm) :	2.0	2.53	3.16	4.77
Width 2 (μm) :	2.0	2.53	3.16	4.77
β_2 /m :	15,451416	12,196861	9,729134	6.438268
Separation (μm) :	0.4	0.4	0.4	0.4
Grat. period (μm):	0.203	0.257	0.323	0.488
Grat. depth ($\text{\AA}$) :	2860	3621	4362	5843
Grat. length (cm):	2	2	2	2
Coupl. coef. :	138.5	138.5	138.5	138.5
/m				
Reflectivity :	0.984	0.984	0.984	0.984
Bandwidth ($\text{\AA}$) :	0.113	0.181	0.284	0.646
Sensitivity :	0.578	0.725	0.933	1.218
$\times 10^3$				

TABLE 4.2

DIRECTIONAL COUPLER

Indices of the glasses used in the coupler design (at 633 nm):

substrate : 1.5560 , core : 1.5620 , cladding : 1.55 .

Design based on Fig.2.20 .

Wavelength (μm) :	0.633	0.8	1.0	1.5
Thickness 1 (μm) :	2.0	2.53	3.16	4.77
Width 1 (μm) :	2.0	2.53	3.16	4.77
β_1 /m :	15,455173	12,199835	9,731523	6.439911
Thickness 2 (μm) :	2.262	3.99	3.575	4.863
Width 2 (μm) :	2.0	2.53	3.16	4.77
β_2 /m :	15,455176	12,199838	9,731523	6.439912
Separation (μm) :	3.145	4.035	5.124	7.102
Coupl. coef.	78.54	78.5395	78.5398	78.541
/m				
Beatlength (mm) :	2	2	2	2
Bandwidth ($\text{\AA}$) :	378	601	915	2083
Sensitivity	0.796	1.002	1.247	1.863
$\times 10^3$				

grating on the exposed interface of the top waveguide, effectively reducing the perturbation strength. The coupling strength can be restored by increasing the grating depth and reducing the waveguide separation. The latter, however, has the undesirable effect of increasing the strength of the forward coupling process, resulting in crosstalk, while the former is limited by the grating fabrication constraints.

CHAPTER 4

FABRICATION

4.1 Techniques For Grating Fabrication.

Corrugated surfaces of sub-micron periods are extensively being used in distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers, couplers, beam expanders, narrow-band filters, light deflectors, and phase-matching elements for integrated and fibre optic applications. A large number of different procedures have, therefore, been developed for grating fabrication on crystalline GaAs, InP and silica substrates.

The most commonly used techniques are based on optical interference methods, with two coherent laser beams creating an interference pattern on a substrate. For III-V semiconductor substrates, the increased electrochemical activity of the exposed area will result in selective etching (4.1, 4.2), when immersed in etchant during exposure, yielding a series of parallel grooves (4.3, 4.4). Alternatively, a thin layer of photoresist may be used, with subsequent development to produce a grating relief pattern, which can then be

transferred into the substrate by chemical etching (4.5), plasma etching (4.6) or reactive ion milling (4.7).

Holographic techniques have been used to fabricate large, commercially available grating areas (4.8), with the periodicity controlled by the choice of wavelength and angle between the interfering beams. The smallest attainable periodicity is limited by the laser wavelength rather than the photoresist resolution, and can be reduced to less than $0.1\text{ }\mu\text{m}$ with the use of shorter wavelengths.

Grating fabrication by electron beam lithography (4.9) employs the high resolution and dimensional precision of computer programmed scanning electron microscopes (SEM), developed for the production of integrated circuit masks, to write grating patterns on PMMA or other suitable masking resists, as part of an integrated optic circuitry. After various processing stages, the resist is finally used as a mask for etching the pattern into the substrate. The minimum periodicity is limited by the size of the writing beam and the resist resolution, while the maximum grating length is, at best, a few mms (4.10), limited by the effect of lens aberration on the scanned beam. Grating fabrication by electron beam writing requires sophisticated, state of the art equipment, with a large number of complex masking stages, including additional Al and NiCr masks for silica substrates, that make this technique more expensive and time consuming than conventional holographic processes.

In comparison to holographic and electron beam writing techniques, embossing (4.11) provides a cheap, simple and

fast alternative for grating fabrication into thin films. Embossed gratings are formed on a soft semi-dried dip coated film, deformable while still in the gel state, by pressing it against a hard commercially available master grating. The embossed film is subsequently hardened by drying and baking. Large grating areas have been successfully fabricated on $\text{SiO}_2/\text{TiO}_2$ films (4.12), with the grating periodicity limited by the availability of master gratings, while the corrugation depth decreases from the centre to the sides. The embossing apparatus consists of a number of master gratings with different periodicities and a facility for producing dip coated films. Thus, a large number of devices can be produced in a relatively short time, without the need for sophisticated equipment and masking techniques. It is, however, limited mainly to thin films, even though some work has also been carried out in embossing channel waveguides and other integrated optical components.

An alternative approach is based on the "spontaneous generation" of periodic surface structures, or ripples resulting during illumination of moderately transparent substrates by intense laser pulses (4.13), with the spatial periods closely related to the laser wavelength and the incident angle.

A similar technique makes use of the photosensitivity in the core region of Ge-doped silica fibres to induce a periodic index variation in the core / cladding interface (4.14). The deformation is produced by using an Argon ion beam to set up a standing wave pattern inside a fibre, with

interference between the propagating and the Fresnel-reflected beam. The periodicity of the effective grating, permanently induced into the fibre, can be tailored by the choice of wavelength, with the possibility of superimposing different periodicities into the same fibre. This rather simple technique is, however, limited by the reduction in photon energy at higher wavelengths.

Such "spontaneous generation" techniques may provide a useful one-step process for producing periodic index variations, albeit with a limited range of periodicities.

We have decided to use interference methods for grating fabrication, first on plates and subsequently on the flat face of D-shaped optical fibres.

4.2 Grating Fabrication on Photorealist Films

Two coherent beams intersecting at an angle 2θ form an interference pattern with fringe spacing:

$$\Lambda = \lambda_0 / (2 \cdot n_c \sin \theta) \quad (4.2.1)$$

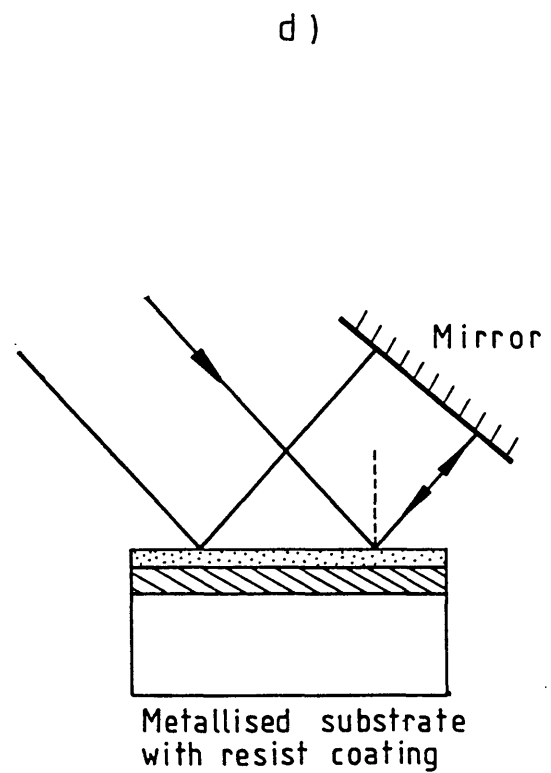
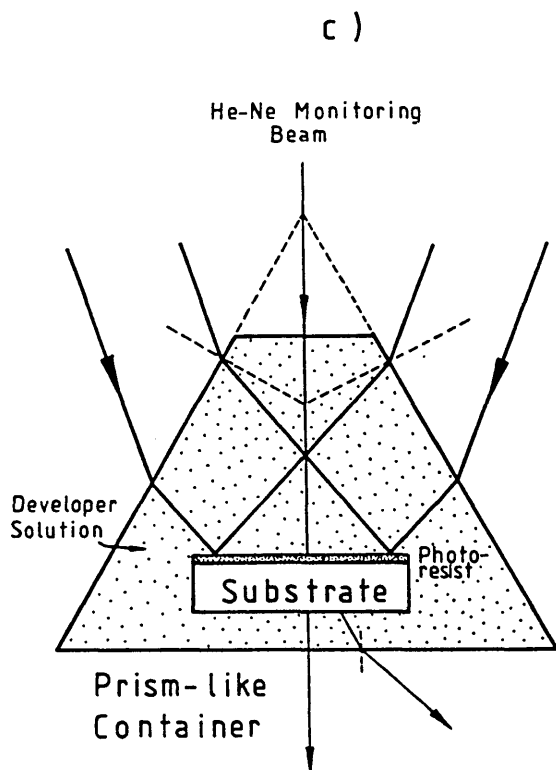
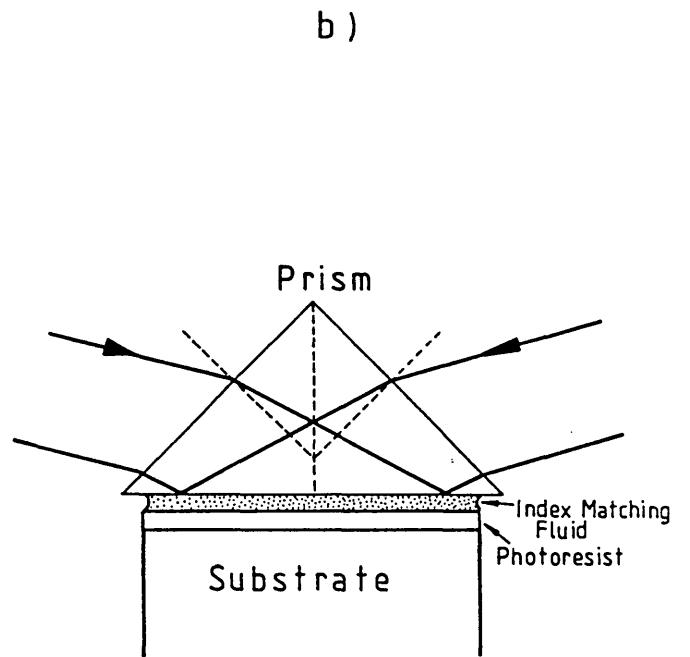
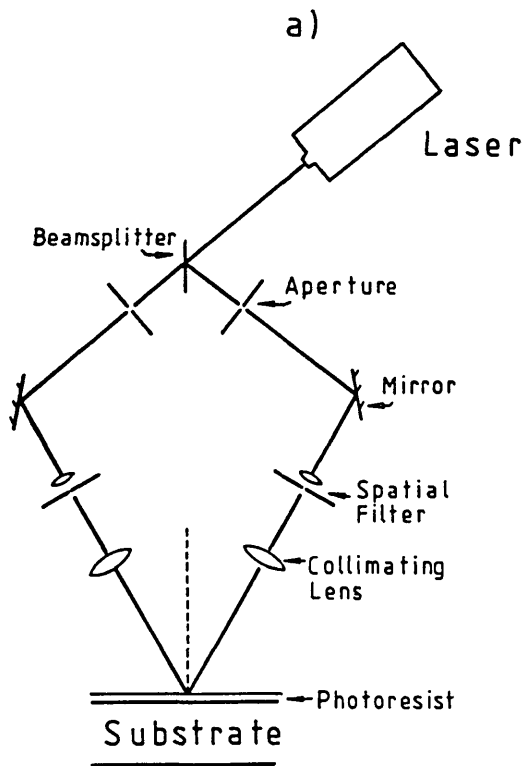
where λ_0 is the wavelength in vacuum, and n_c is the refractive index of the surrounding medium. Notice, that the minimum attainable periodicity $\lambda_0 / (2 \cdot n_c)$ is half the effective wavelength.

The intensity distribution across the interference plane

can be directly recorded on a thin photoresist film. The photoresist most commonly used for grating fabrication is Shipley 1350 positive (4.15, 4.16). It consists of three basic components: a photoactive compound, a base resin and a suitable organic solvent system. Without the photoactive compound, the base resin becomes soluble to an aqueous alkaline developer solution at a rate of approximately 15 nm/s, as compared to 0.1-0.2 nm/sec in the presence of this compound. Radiation in the wavelength range 300-450 nm destroys the local photoactive compound, resulting in an increased film dissolution of the exposed areas in developer, creating a modulated surface relief pattern.

A large variety of interferometer designs have been proposed for the fabrication of diffraction gratings on positive photoresist, and are presented in Fig. 4.1. To avoid the catastrophic effects of external vibrations short exposure times are desirable. Even though the 325 nm He-Cd laser line appears to be more effective on photoresist, requiring shorter exposure times, most of the work has been concentrated on the visible 457.9 nm line of the Argon laser, avoiding special U.V optics. Fig.4.1.a shows the conventional experimental set up used for making diffraction gratings. Laser radiation is divided into two beams by a beam splitter, which are then filtered, collimated and superimposed to form an interference pattern on a substrate coated in photoresist.

To reduce the long exposure times required by the comparatively low sensitivity of the photoresist to the 457.9 nm



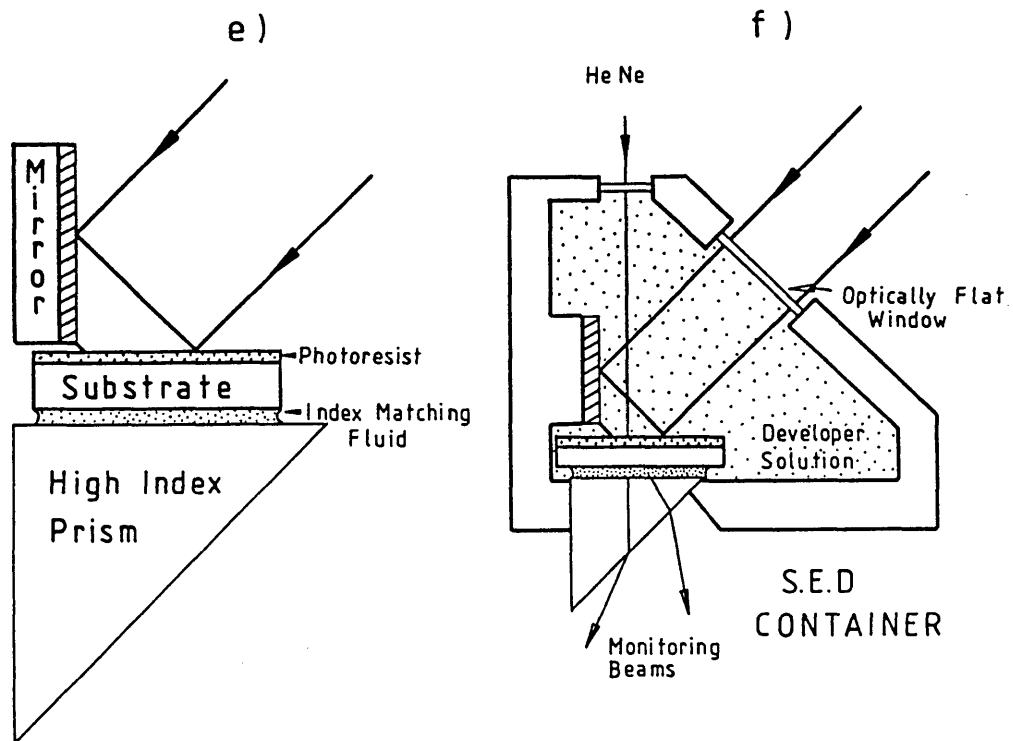


Fig. 4.1

Interferometer designs proposed for grating fabrication:

- a) Conventional Interferometer ,
- b) Shank's Prism ,
- c) Simultaneous Exposure and Development ,
- d) Reflective Substrate ,
- e) Lloyd's Mirror ,
- f) Lloyd's Mirror with S.E.D. incorporated.

laser line, a pre-exposure stage has been suggested (4.17). The photoresist film is exposed to a uniform illumination, prior to its exposure to the interference pattern, with reduction in the typical exposure times by 25 % from those necessary without pre-exposure.

The use of the 457.9 nm line limits the minimum grating periodicity to 0.229 μm for exposure in air. The ultimate limit of grating period can be improved by exposure through a prism, as shown in Fig. 4.1.b, with the effective wavelength reduced by the refractive index of the prism. This technique has been used with a He-Cd laser to fabricate gratings of periodicities around 0.1 μm (4.18).

Simultaneous exposure and development (SED) accomplishes both shorter exposure times and finer grating periodicities. It employs a prislake container with walls made of optically flat glass filled with developer, as shown in Fig. 4.1.c. Exposure takes place inside the container, with the newly exposed surface constantly being developed, as the photoactive compound in the photoresist breaks down, the removal rate progressively increasing with increasing depth. Notice, that this is contrary to the conventional method, where during development the removal rate slows down with increasing depth. In this way, SED offers significant improvement in the required exposure time, with sharp edges and deep profiles. Additionally, the effective wavelength is reduced by the refractive index of the developer solution, resulting in finer periodicities. Gratings of periodicity down to 0.2 μm and groove depth up to 0.8 μm have been

fabricated on $1.3\text{ }\mu\text{m}$ thick photoresist films by SED using a weak 488.8 nm Argon laser line, with optimum exposure times of 10 min (4.19). Even though conventional methods require five times as long, the long exposure can be significantly reduced by using a more powerful laser beam at shorter wavelengths, reducing the photoresist thickness or by increasing the developer concentration.

A comparatively simpler design, shown in Fig. 4.1.d, uses the substrate itself as one of the interferometer mirrors (4.20) and needs, therefore, to be metallised before being coated in photoresist. A major advantage of this scheme is that the pattern is independent of the substrate refractive index. Due, however, to the large asymmetry between the interferometer arms, the laser source must have a sufficiently long coherence length, requiring the use of a Fabry Perot etalon in the laser cavity. Additionally, the relative simplicity of the interferometer design is counteracted by the complexity of having to etch twice, once into the metallised surface and then through the metallised mask into the substrate.

We have designed an interferometer based on Lloyd's mirror, with a single mirror creating an interference pattern between the spatial halves of an expanded and collimated laser beam, as shown in Fig. 4.1.e. To avoid reflections from the back of the glass substrate, a high index prism was placed in good contact with the substrate using index fluid.

The interferometer design is simple, versatile, stable

(relatively insensitive to vibrations), and economic (using the minimum possible number of optical components). Both chirped and curved grating profiles could be simply implemented, by adding cylindrical or spherical lenses to the interferometer. Simultaneous exposure and development is easily incorporated into the design, by placing the interferometer in a water tight container with optically flat windows, filled with a developer solution, as shown in Fig. 4.1.f . The grating periodicity can be fine tuned, not only through small variations in the angle of interference, but also by changing the refractive index of the surrounding medium, when mixing the developer with distilled water. Finally, the diffraction efficiency of the grating can be monitored in situ throughout fabrication, by comparing the intensity of the zero order of a He-Ne laser beam incident on the grating, with that of the first order beam as development proceeds. Development can be conveniently stopped at the appropriate moment, by diluting the developer with excessive distilled water.

Lloyd's mirror interferometers for grating fabrication have also been proposed by other authors (4.4, 4.21).

4.3 F a b r i c a t i o n o f H o l o g r a p h i c G r a t i n g s o n p l a n e g l a s s s u b s t r a t e s

The different stages involved in the fabrication of holographic gratings on both soda lime glass and silica substrates are presented in the following sections.

4.3.1 S A M P L E P R E P A R A T I O N

Prior to coating, the substrates have to be thoroughly cleaned, avoiding damage of the surface quality. For this purpose, they are left soaking in a mildly abrasive detergent (DECON) solution for about ten minutes, scrubbed with a cotton swab, rinsed, first in running hot water and then in deionized water, and dried in a clean environment. The final cleaning stage involves wiping the substrates with a lens tissue lightly wetted by a few drops of pure alcohol, in the fashion used for cleaning laser mirrors and windows (4.22). The clean slides are inspected by examining the surface scattering when illuminated by a collimated light source, with the small specks of dirt, surface imperfections and organic residue, showing clearly as they scatter light.

This simple, but effective cleaning procedure was found to give results as good as other more elaborate standard techniques (4.23,4.24).

The clean substrates are then coated by Shipley 1350 positive photoresist, the properties of which are given in (4.15). Two different techniques have been investigated dip coating (4.25) and spinning (4.15), both widely used for the formation of films from liquid solutions.

a) Dip coating

Dip coating results from drawing a sample out of a photoresist solution, simultaneously covering it in a liquid film. The apparatus used, is schematically shown in Fig. 4.2.a, with the substrate mounted by waxing on a glass carrier and then lifted out of the solution, sliding onto a vertical glass cover slide, held by the surface tension of the liquid. The lifting movement has to be completely smooth and shockless, avoiding vibrations from the driving motor or by uncontrolled air currents. Starting the motion creates an initial disturbance, causing a variation in thickness over the first few mms. Once the lifting speed has been stabilised, the film formation on the substrate develops uniformly over the central region, with narrow 3 mm zones of increased thickness along the edges. The dependance of the film thickness on the lifting speed, the angle of inclination ϕ of the coated surface in respect to the liquid level, and the concentration of the solution are presented in Fig. 4.2.b,c,d as given by (4.26). Other parameters that may affect the film thickness are: temperature, viscosity, surface tension and vapour pressure of the solution.

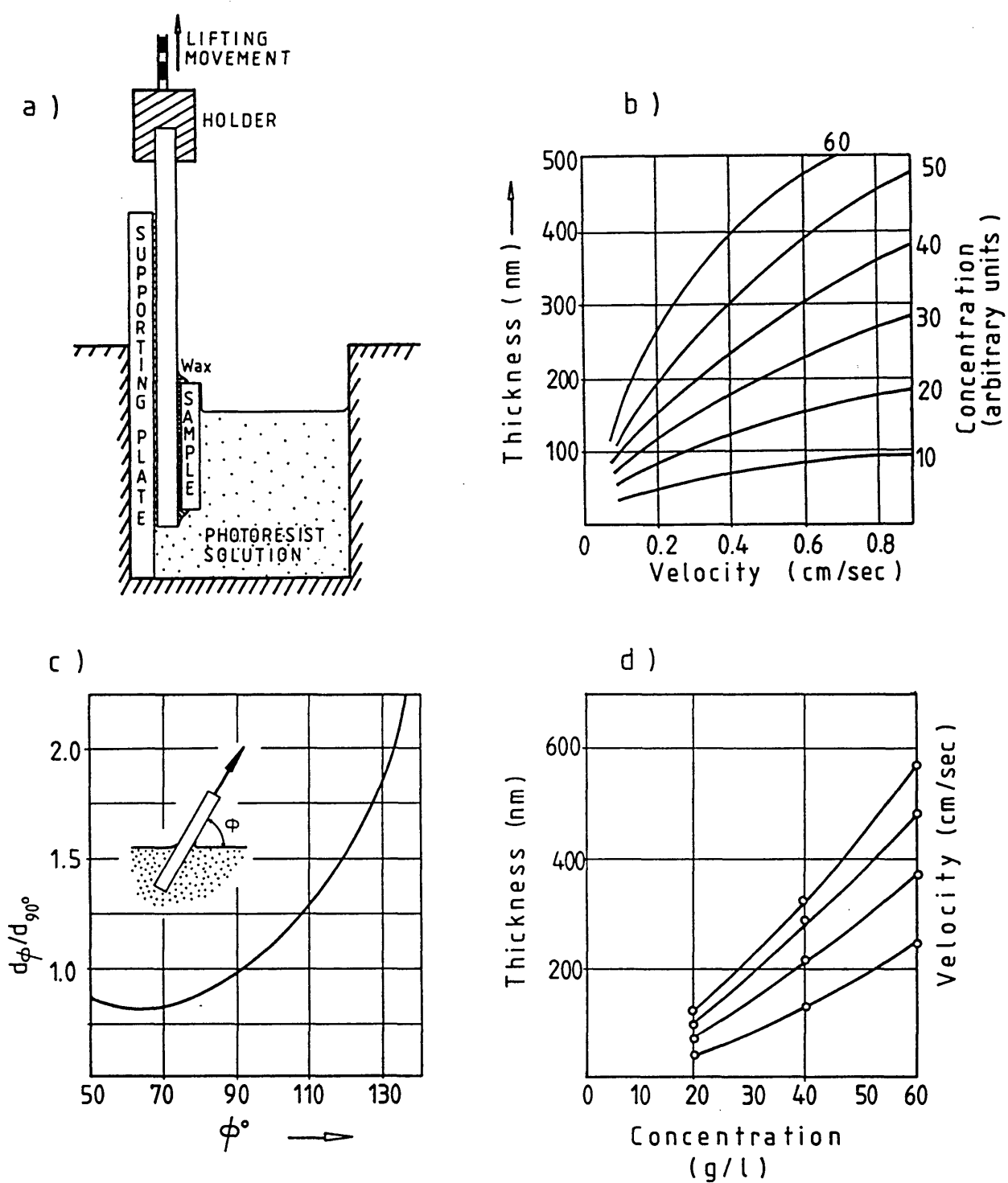


Fig. 4.2

Dip coating by lifting from a liquid solution.

a) Coating apparatus .

Film thickness as a function of:

b) Lifting Speed ,

c) Angle of Inclination ,

d) Concentration of the Solution .

We have used a lifting speed of 0.21 mm/s , which for an undiluted photoresist solution gives a nominal film thickness of 0.6 μm . In the central region, a typical 5 % variation in film thickness was measured over a distance of 1cm . Thinner photoresist films can be obtained by diluting the photoresist in an organic solvent. For example, a solution of 1 part thinner in 1 part photoresist gives a film thickness of 0.28 μm .

b) Spin coating

Spin coating is universally being used in the deposition of photoresist films on plane surfaces for lithographic or holographic processes. The substrate is first flooded by photoresist solution, and then spun around an axis normal to the surface to remove the excess (Fig. 4.3.a). The resulting film appears to be completely even, over a large central diameter, with an increased thickness along the four edges. Specks of dust, originally left on the substrate, surface irregularities and solid residue from unfiltered photoresist show as spirals on the clear glossy surface, damaging the thickness uniformity. Samples failing this simple test are cleaned and coated again.

The thickness of the spin coated film depends mainly on the rotation speed and the concentration of the photoresist solution. The variation in film thickness with rotation speed for undiluted photoresist is shown in Fig. 4.3.b . For maximum coating uniformity, speeds between 3000 and 5000 rpm are recommended by the manufactures, giving film thickness

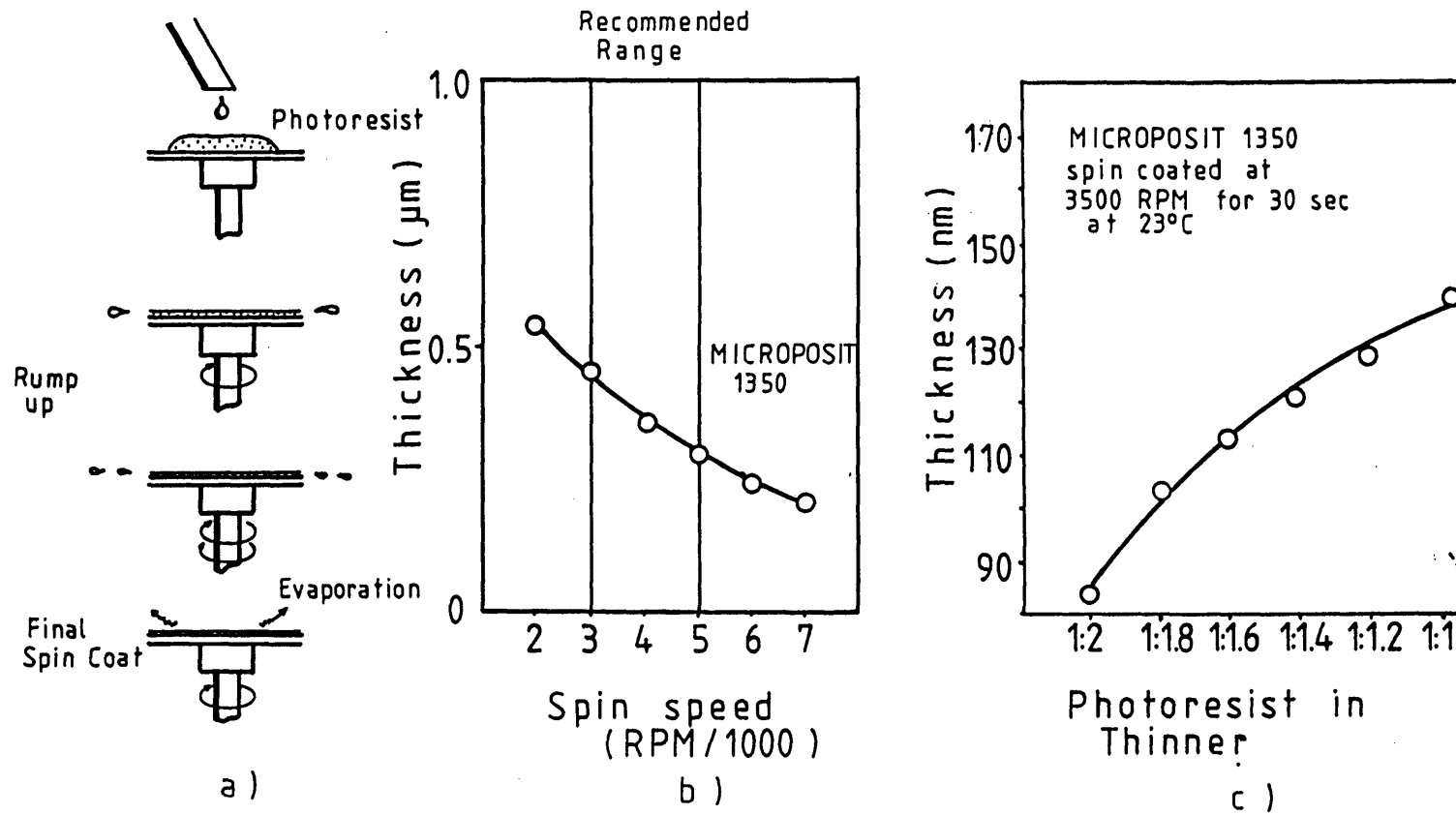


Fig. 4.3

Spin coating. a) Schematic Configuration

Film Thickness as a function of: b) Speed , c) Dilution in Thinner

of 0.43 to 0.29 μm . For thinner masks, the photoresist must be diluted in thinner. Fig. 4.3.c shows the variation in the resulting film thickness with the percentage concentration of photoresist in thinner, for a film spin coated at 3500 rpm for 30 sec at 23°C. For a 50 % dilution, i.e 1 part thinner in 1 part photoresist, a thickness of 0.14 μm can be obtained.

We have coated rectangular substrates with both thinned and unthinned photoresist. A rotating speed of 3500 rpm was used, with typical spinning times between 30 and 45 sec. Smooth glossy films of very good uniformity over a 2 cm diameter were obtained, with a nominal thickness of 0.4 μm for unthinned photoresist.

In general, spin coating was found to be more stable and better controlled than dip coating, producing films of higher uniformity and quality.

The coated substrates are soft baked for 25 min in a forced air convection oven, maintaining an optimum temperature of 90°C . Soft baking reduces the film thickness due to reduction in solvent content by evaporation. The choice of temperature has a direct effect on the exposure requirements. For higher softbake temperatures, a longer exposure is needed, while lower temperatures may result in shorter times, but increase the solubility of the unexposed photoresist, thus reducing the processing latitude. The baked substrates are then allowed to cool down to room temperature in a clean environment, prior to further processing.

4.3.2 EXPOSURE AND DEVELOPMENT

The samples are exposed by the 457.9 nm line of an Argon ion laser operating in the TEM_{00} mode and delivering a nominal power of 500 mW. The laser beam was expanded by a x10 microscope objective, filtered through a 10 μ m diameter pinhole, and collimated into a uniform Gaussian beam of 3 cm diameter.

Two versions of a Lloyd's mirror interferometer were used for exposing the photoresist coated substrates. The initial design, of Fig. 4.1.f, was constructed in a liquid tight perspex container, with optically flat windows to avoid profile deterioration of the incoming beam. It was intended for the fabrication of grating periodicities around 0.2 μ m, incorporating the simultaneous exposure and development (SED) technique for short exposures and deep profiles. A revised design, shown in Fig. 4.4, was used for larger grating periodicities.

For uniform exposure, great emphasis was placed on the quality of the expanded beam, since the interfering halves belong to different parts of the beam.

Fig. 4.5 shows the reduction in film thickness as a function of exposure level, followed by a 30 sec development in a solution of 1 part distilled water in 3 parts developer maintained at 25°C. The experimental curve was obtained by exposing the substrate, partially covered by an opaque screen, to a number of 5 sec radiation doses from a collimated laser beam. In the interval between successive

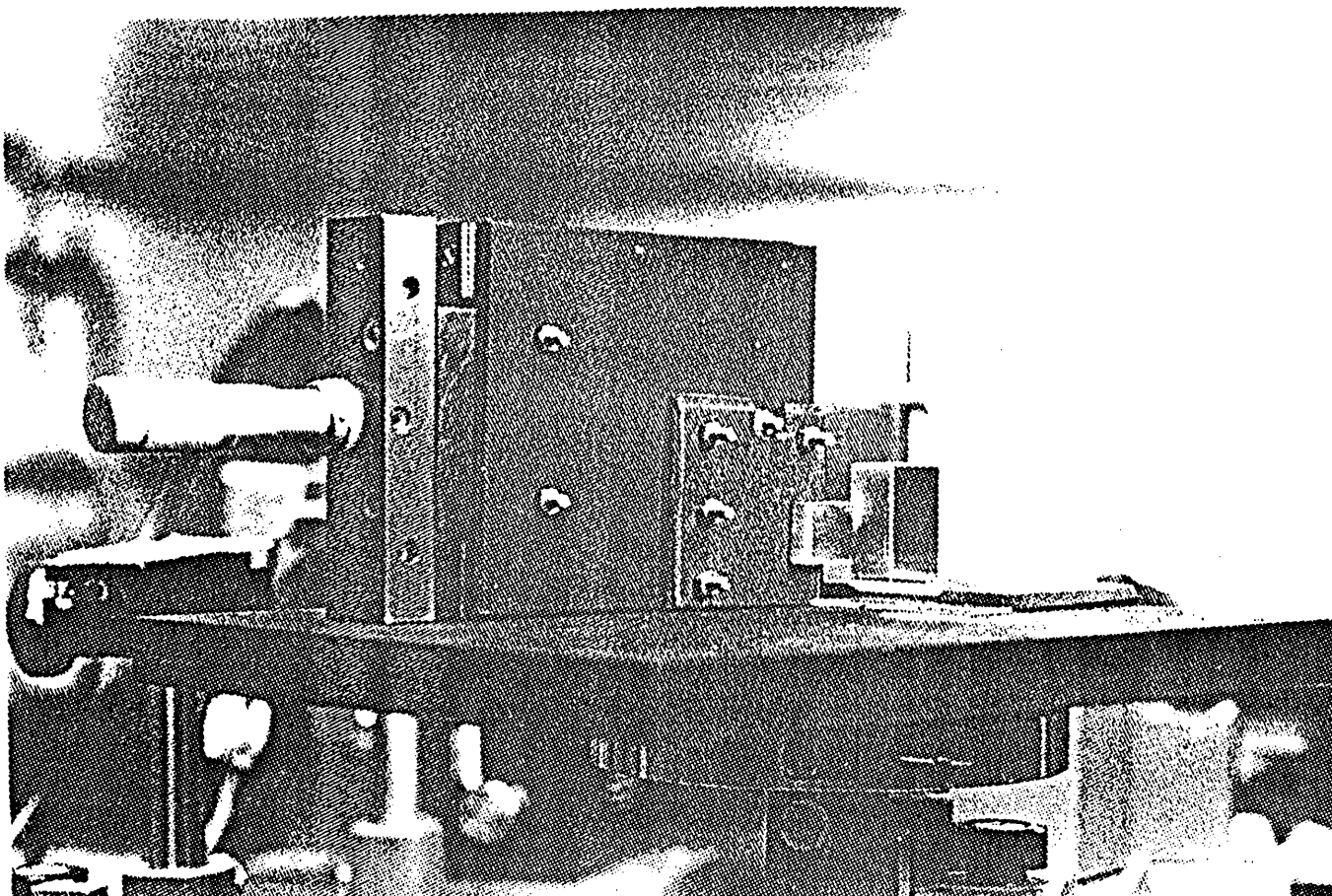


Fig.4.4

Lloyd's Mirror Interferometer used for Grating Fabrication.

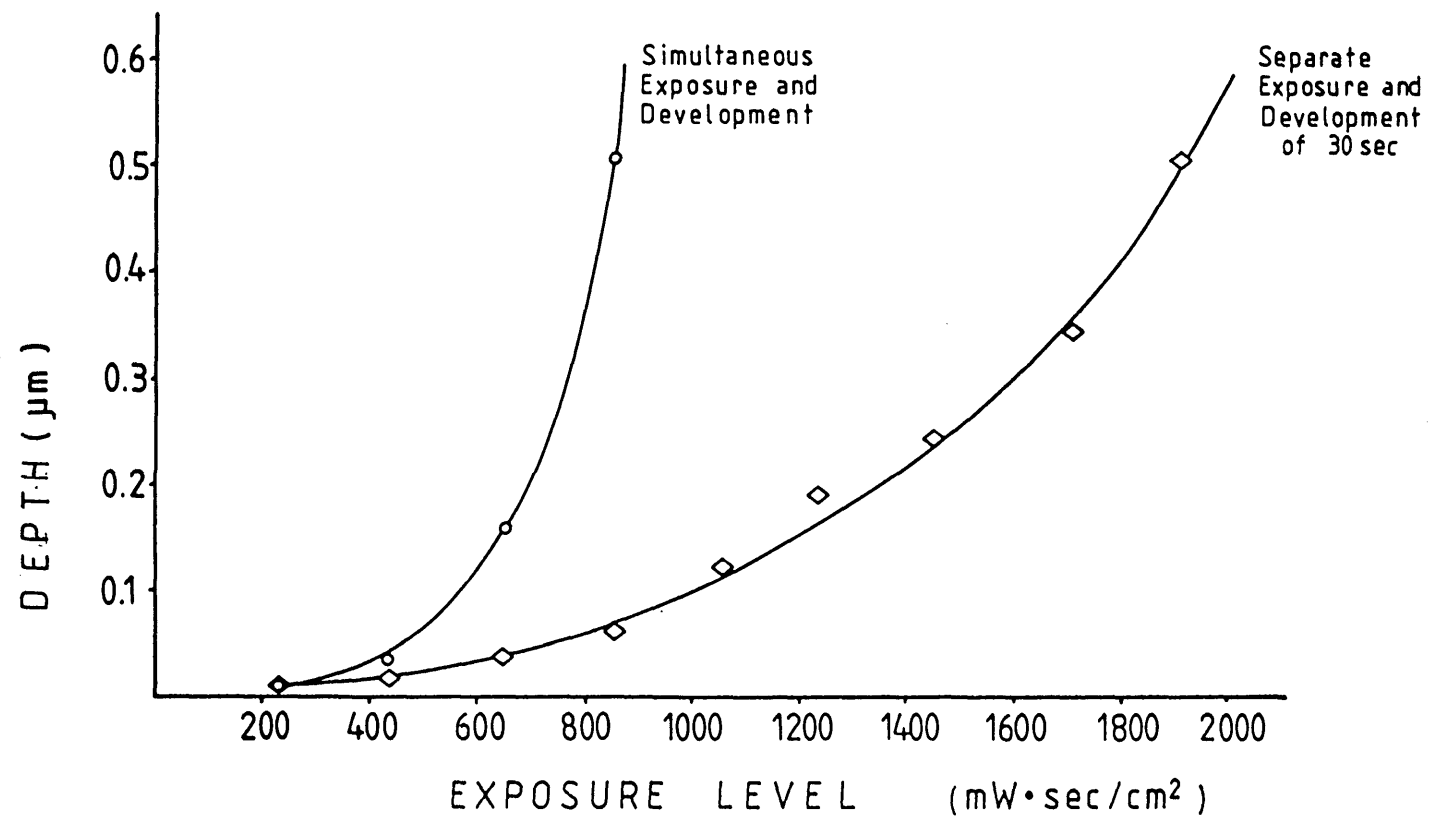


Fig.4.5

Reduction in Photoresist Thickness as a function of the Exposure Level for a 30 sec development.

exposures, the sample was shifted by 2 mm revealing a further part of the unexposed area. After development, the step size and the film thickness corresponding to each exposure level were measured and recorded. Thus, for a power density of 42.5 mW/cm the exposure time necessary for removing 0.5 μ m of photoresist thickness is approximately 45 sec. In a similar experiment using SED, the required time was reduced to 20 sec, offering an improvement by a factor of two. In Lloyd's mirror interferometers the exposed areas receive a maximum dose of twice the normal power density of the laser beam, and are, therefore, expected to require half the normal exposure time, i.e. 25 sec for a dry exposure and 10 sec for SED.

After a dry exposure, the samples are developed in a bath of 3 parts developer and 1 part distilled water, at 25°C. Higher developer concentration may give faster development, but increases the dissolution rate of the unexposed photoresist. Immersion times between 20 and 60 sec are recommended. Shorter development times minimise the attack on the unexposed resist. Notice also, that a higher developer temperature results in faster development.

In general, there is a trade off between exposure and development times. It is possible to adjust the latter to compensate for possible variations in exposure level.

The developed samples are washed thoroughly in clean distilled water for about 1 min and are then baked for 25 min in a forced air convection oven at 120°C. Higher temperatures increase the resistance to subsequent process-

ing stages, but may result in thermal distortion of the photoresist mask.

We have fabricated gratings of three different periodicities, around $0.21\text{ }\mu\text{m}$, $0.28\text{ }\mu\text{m}$ and $0.34\text{ }\mu\text{m}$. The first two were fabricated using the interferometer of Fig.4.1.f . The interfering angle was set at $55^\circ \pm 5^\circ$, limited by the relative dimensions and position of the optically flat window, producing grating periodicities in the range 0.264 to $0.298\text{ }\mu\text{m}$ for a dry exposure, and 0.198 to $0.224\text{ }\mu\text{m}$ for simultaneous exposure and development in a solution of index 1.33 . The gratings of periodicity $0.34\text{ }\mu\text{m}$ were fabricated using the interferometer of Fig.4.4 in air, with an angle of 42° between the interfering beams.

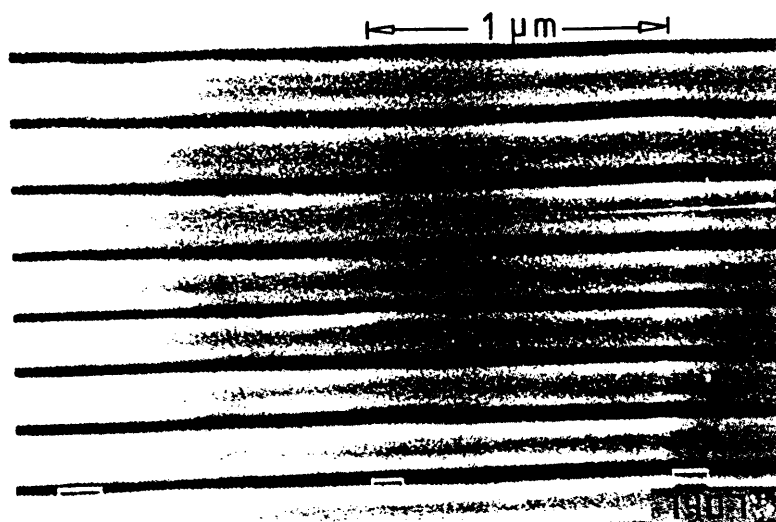
4.3.3 EVALUATION OF THE GRATING MASKS

Once the grating masks have been fabricated on the substrates, they need to be examined in order to evaluate their quality, prior to any further processing. A simple test that establishes the presence of a grating, relies on its dispersive power, when illuminated by a white light source. Additionally, a He-Ne laser beam can be used to determine the diffraction efficiency of the grating, by comparing the zero and first order beam intensities. These rather simple techniques, however, are not applicable to gratings of periodicities around $0.2\text{ }\mu\text{m}$, in which case the use of a

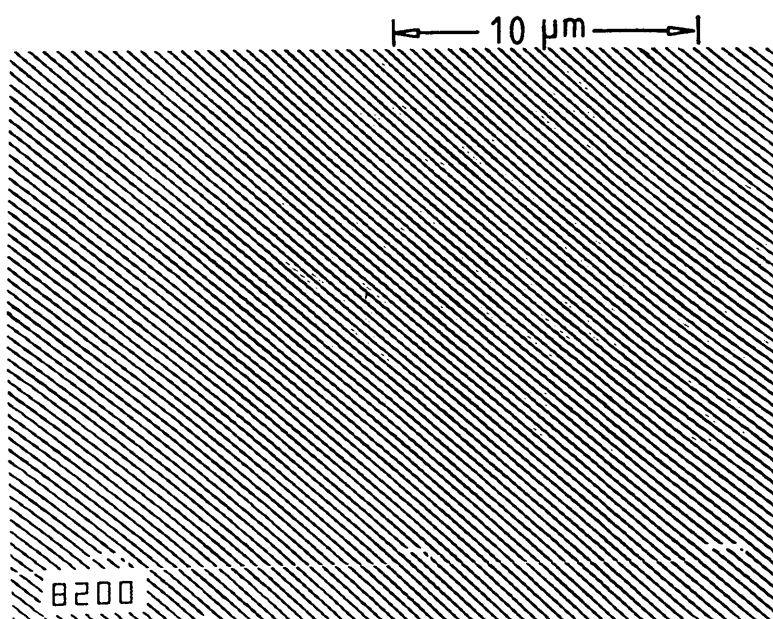
scanning electron microscope (SEM) becomes necessary. The substrate containing the grating mask is broken to a number of smaller pieces, of size suitable for mounting onto microscope stubs, which are coated in a 200 Å gold film by sputtering, thus becoming useless for further processing.

The grating patterns shown in Fig.4.6, have periodicities around $0.206\text{ }\mu\text{m}$, and were produced by exposure in a liquid surrounding medium of index around 1.33. One of them (Fig.4.6.a,b), was produced by a SED of 15 sec on a $0.6\text{ }\mu\text{m}$ dip coated photoresist film, while the other (Fig.4.6.c) was fabricated by exposing in distilled water for 30 sec, followed by a 15 sec development. On the whole, for the same development time, SED gives deeper profiles with shorter exposure times. Even though some isolated, very high quality grating patterns were fabricated by exposing in a liquid environment, over the whole area, the mask appears patchy (see Fig.4.7.a,b,c) swelling from water absorption, with islands of proper exposure surrounded by areas that are either overexposed and washed out or underexposed and blank. The effect becomes more profound in the presence of dirt or other impurities from contaminated photoresist, allowing the water to tunnel under the film, causing photoresist delamination, lifting and "popping". Soft baking at the higher temperature of 100°C reduces the patchiness, although longer exposure times are required. Some improvement can also be achieved by using thinner and cleaner spin coated films.

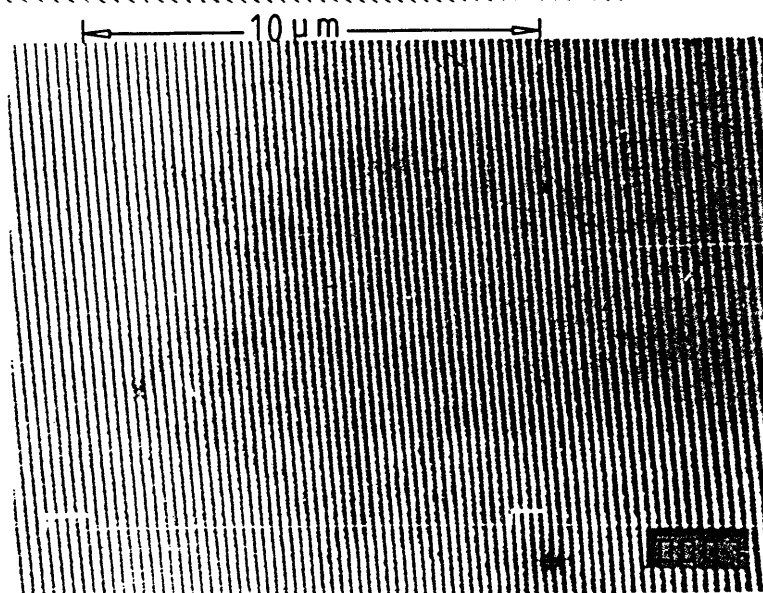
The grating masks shown in Figs.4.8.a,b & 4.8.c,d with periodicities 0.28 and $0.34\text{ }\mu\text{m}$ respectively, were produced



a)



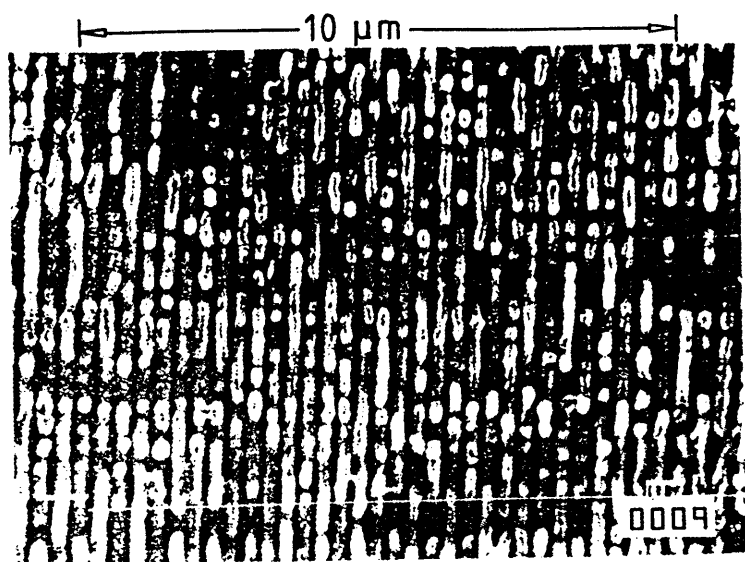
b)



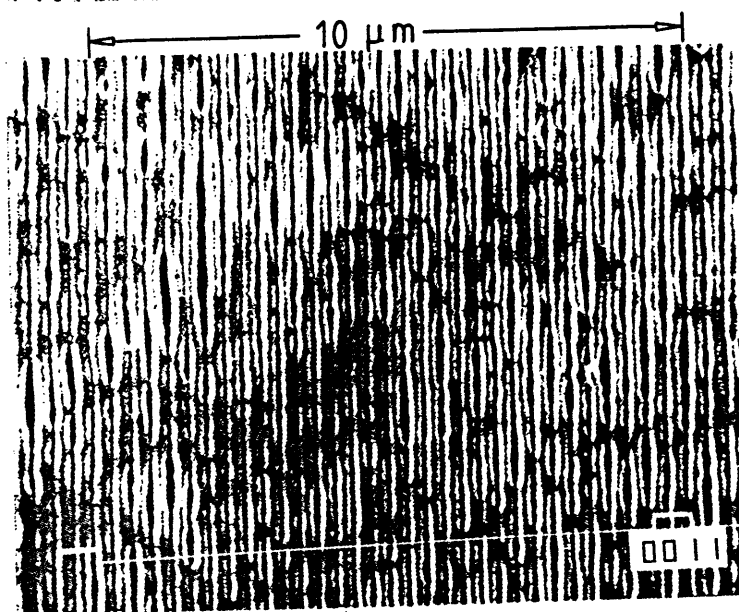
c)

Fig.4.6

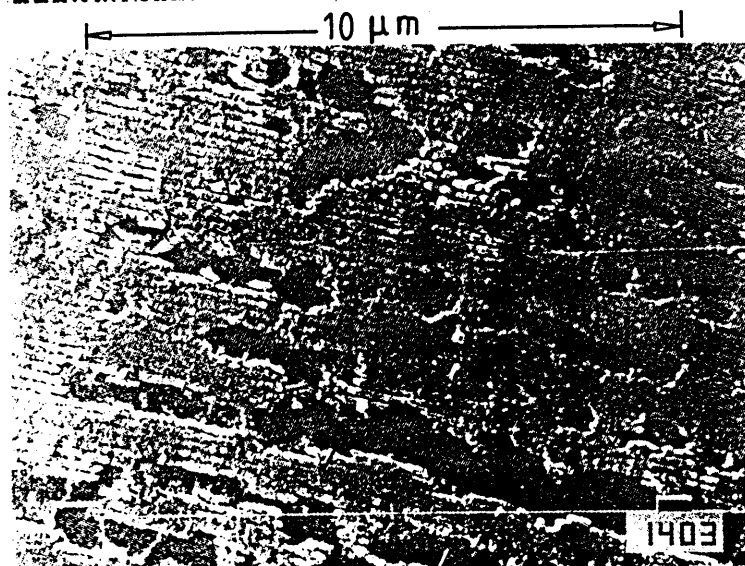
Grating patterns produced by exposure in a liquid medium:
 a), b) by S.E.D. and c) by separate exposure and development.



a)



b)



c)

Fig.4.7

Typical defects of grating patterns exposed in a liquid environment.

by dry exposures of 10 to 45 sec , depending on the laser power output and on the photoresist thickness. The small difference in exposure requirements between soda glass and silica substrates, may be accounted for by the difference in refractive indices (1.50 for soda glass and 1.46 for silica), resulting in different amounts of reflection from the photoresist (index: 1.65) /substrate interface. In fact, the lower index silica substrate reflects more light from the interface, resulting in faster exposure. Generally, variations in exposure level can be compensated by adjusting the development time. Although some good quality grating masks were fabricated on dip coated films, mostly thinner spin coated substrates were used, because of their superiority in thickness uniformity and cleanliness necessary for reproducibility. Fig.4.9.a,b shows a cross-section of a $0.28\text{ }\mu\text{m}$ periodicity grating with a modulation depth of $0.13\text{ }\mu\text{m}$, fabricated on a $0.3\text{ }\mu\text{m}$ thick photoresist film. Since the substrate surface is not exposed, the grating pattern cannot be used as a mask for direct etching, without removing the remaining $0.15\text{ }\mu\text{m}$ of photoresist thickness by "ashing" in an oxygen plasma. Alternatively, a thinned photoresist film of $0.14\text{ }\mu\text{m}$ (1 part thinner in 1 part photoresist) gives a "complete" grating mask with an $800\text{ }\text{\AA}$ processing latitude, as shown in Fig.4.9.c,d . The exposed substrate areas can be directly processed by chemical or reactive ion etching.

A very important factor necessary for the fabrication of high quality grating masks is the cleanliness, not only of

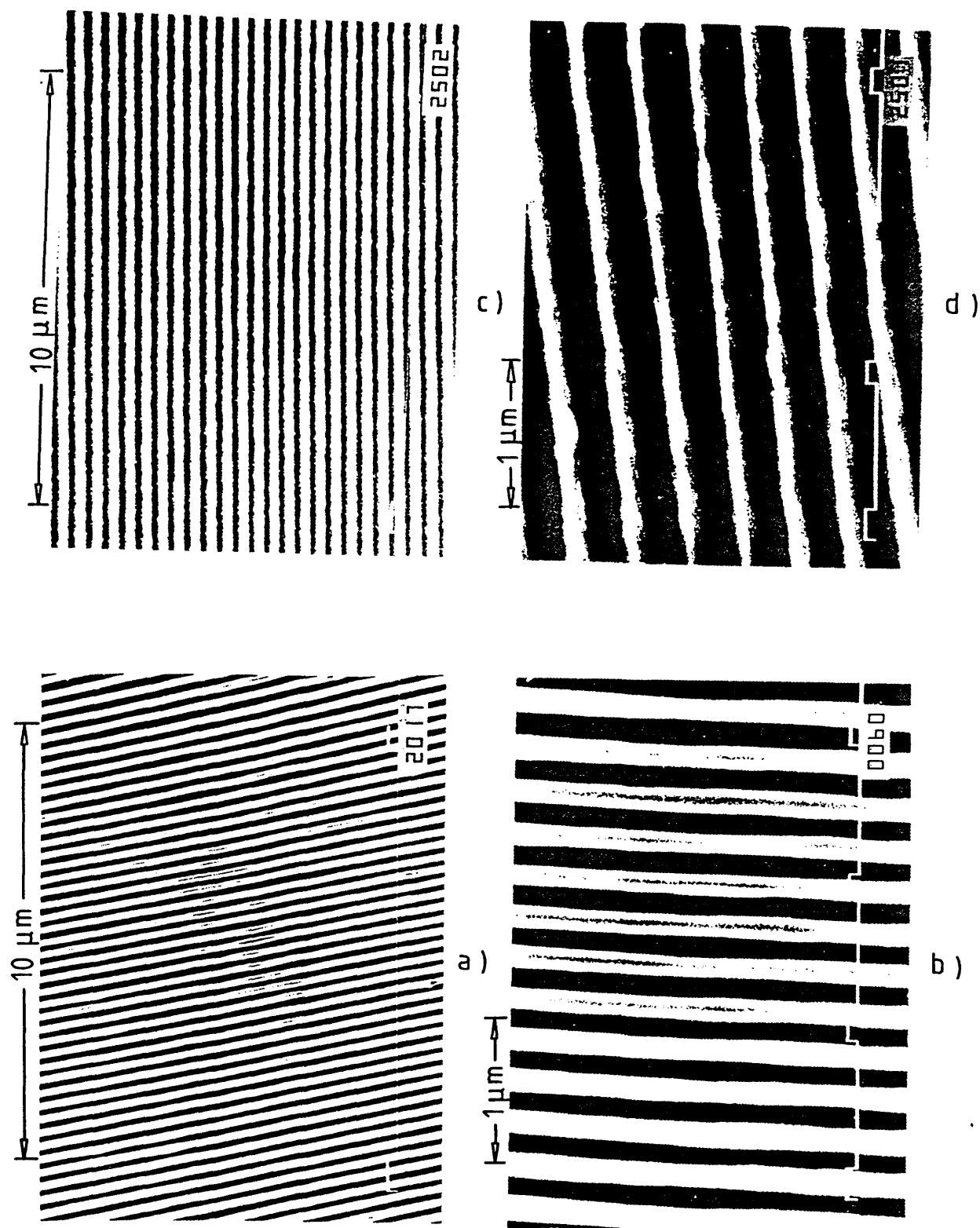


Fig.4.8

High quality grating patterns on photoresist by dry exposure
 with periodicities: a), b) 0.28 μm ,
 c), d) 0.34 μm .

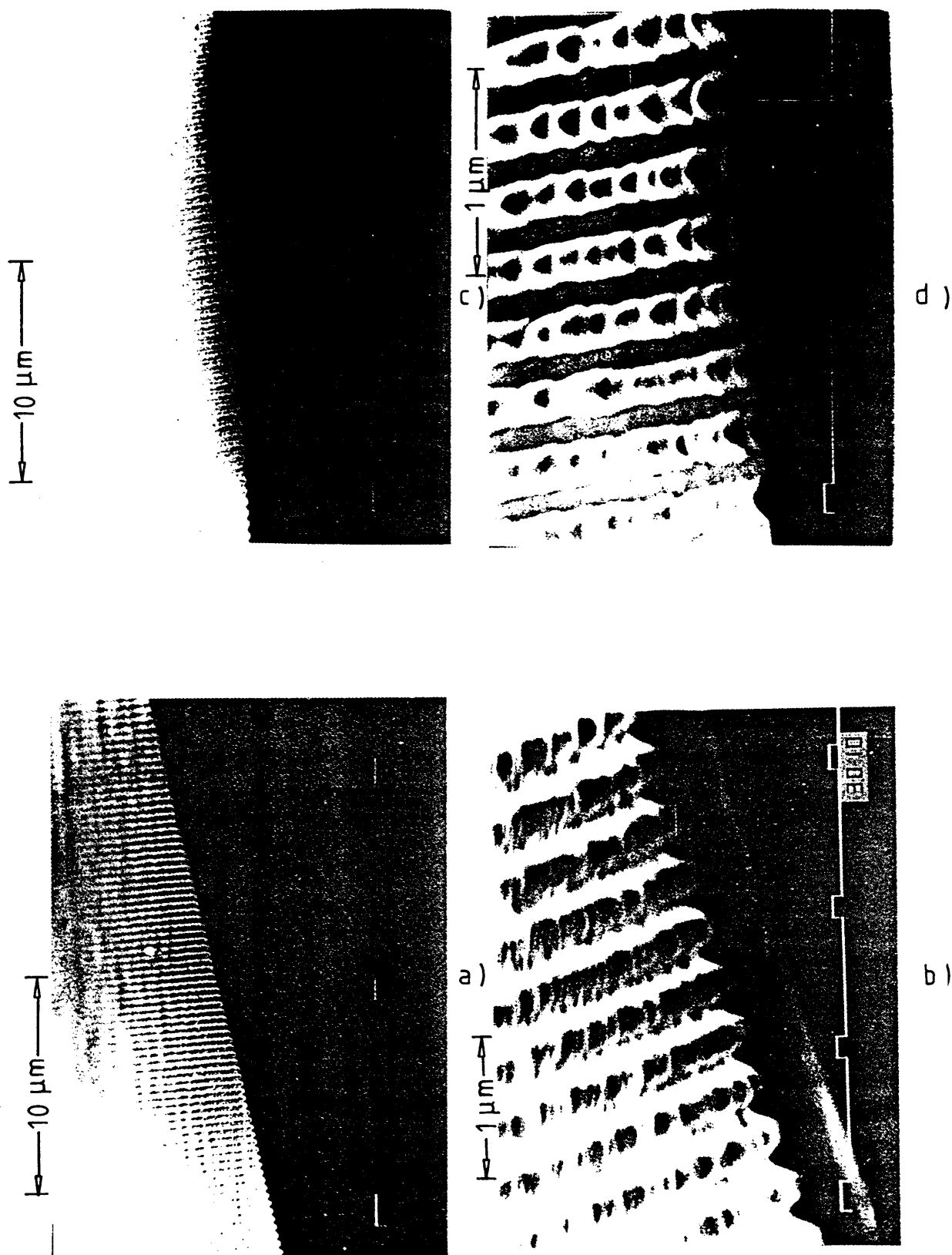
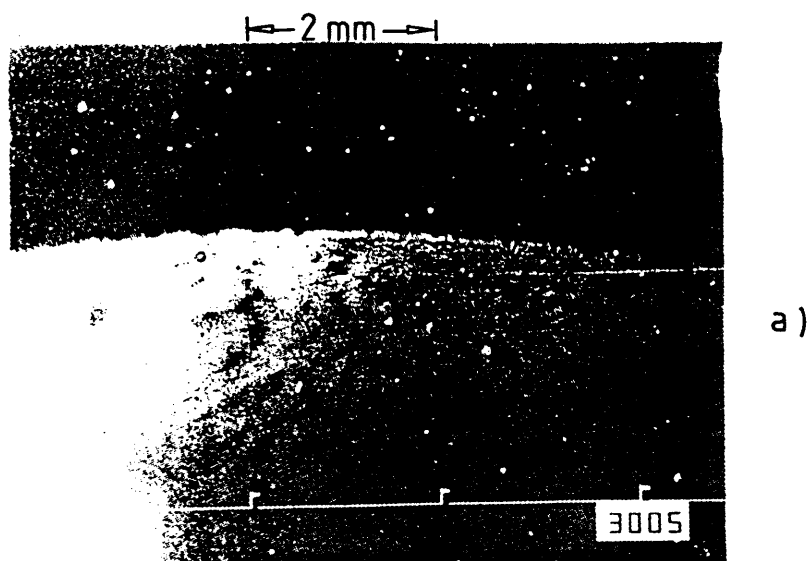


Fig.4.9

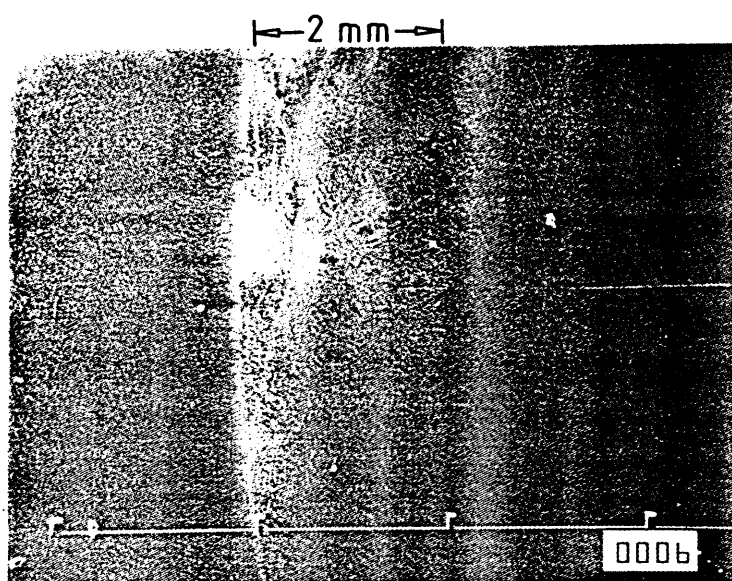
Cross-sectional view of photoresist grating masks:

- a), b) incomplete mask ,
 c), d) complete mask .

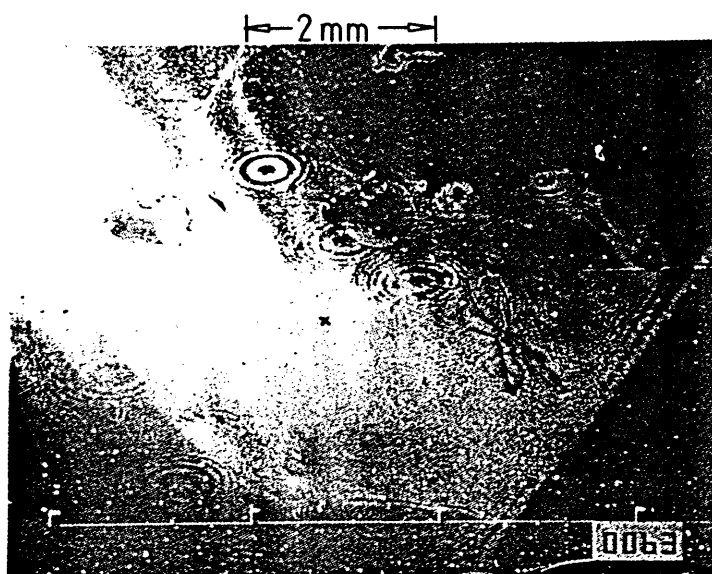
the photoresist films, but also of all the optical components of the interferometer. Uniformity of the intensity profile of the laser beam, operating in the lowest order TEM_{00} mode, is another precondition for balancing the interfering parts with uniform exposure. Under misalignment, the laser may shift to the TEM_{01} mode with disastrous effects on the exposed area. Typical defects of the photoresist mask may be observed, by viewing the exposed area at low magnification, as shown in Fig.4.10.a,b, for dry and wet exposures respectively. The difference in exposure level is due to reduction in the laser beam power, reflected on the window and absorbed by the liquid solution. There are three main sources capable of effecting significant spatial variations in the intensity of the incident beams, both on a microscopic or macroscopic level: (i) diffraction from scratches and dust particles on the optical surfaces; (ii) reflections from air bubbles inside the liquid container, or in the matching liquid; (iii) spurious reflections from the optical components. Additionally, dust and dirt particles on the photoresist surface subsequent to coating, may result in small areas of over or under exposure either by scattering the incident radiation, or by "casting a shadow" of under-exposure. The presence of dust particles on either the beam dividing mirror or the collimating lens is illustrated in Fig.10.c, with a number of isolated diffraction rings superimposed on the original fringe pattern. A small scratch on the collimating lens is responsible for a series of such rings (see Fig.4.10), aligned along the exposed area. Fresnel



a)



b)



c)

Fig. 4.10

Exposed area at low magnification for (a) dry and (b) wet exposures. Typical defects (c).

diffraction fringes are also recorded at the beginning of the exposed area, caused by the "half screen" effect of the mirror edge. Aperturing the laser beam, results in an additional set of Fresnel rings.

All the defects described above are superimposed on the original grating pattern, producing areas of over and under exposure on the grating mask. In order to avoid them, special care must be taken, with thorough cleaning of all optical components used in the interferometer, and in particular the beam dividing mirror and the collimating lens. Some improvement may also be achieved by pre-exposing the entire film to a level, below that needed for complete exposure, increasing the gamma of the photo-resist film, thus suppressing the lower contrast stray patterns (4.17).

4.3.4 REACTIVE ION ETCHING

The grating pattern can be transferred into the glass substrate by reactive ion etching (4.6, 4.20), using the system schematically shown in Fig.4.11 (4.27) . In order to expose the substrate directly to the ion attack, the residual photoresist must be completely removed from the lower part of the grooves. This can be accomplished by exposing the pattern to $1\frac{1}{2}$ min of oxygen plasma prior to ion etching, uniformly thinning the mask, until eventually all the

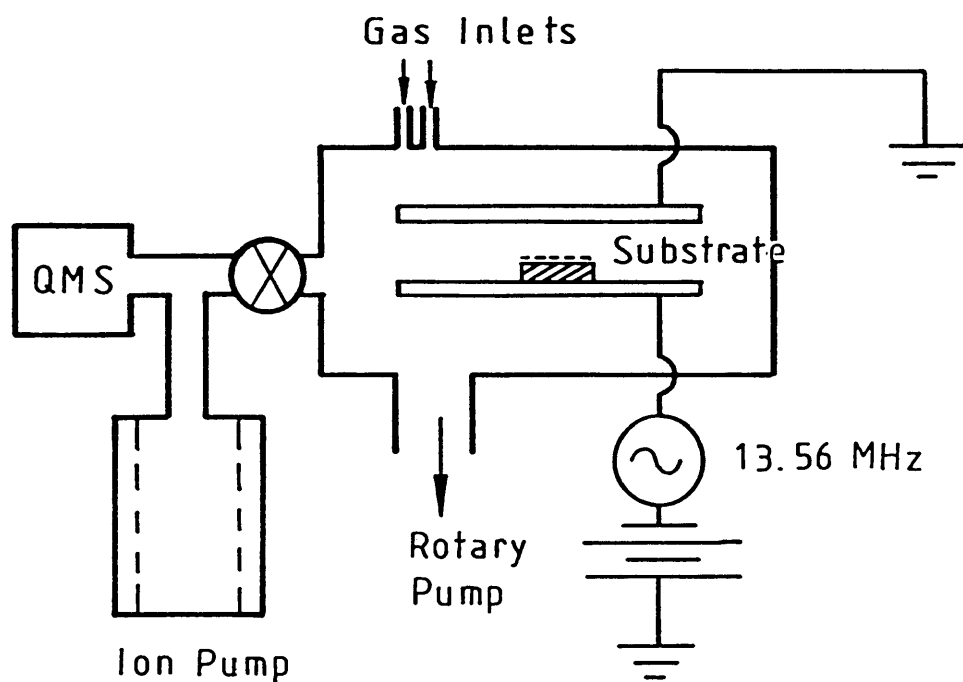


Fig.4.11

Schematic diagram of the etching system.

residual photoresist has been eliminated from the grooves. The only disadvantage of the oxygen plasma treatment is that it reduces the overall photoresist film thickness, and thus the potential depth of etch.

The processed samples were etched for 10 to 20 min using a gas flow rate of 10 cc/min with rf powers of 50 to 80 W and the temperature maintained at ambient levels. Two different etching gases were investigated, CF_4 and CHF_3 , the latter providing some improvement in selectivity. When CF_4 gas was used, the pressure in the chamber throughout etching was kept at 70 $\mu\text{m Hg}$, and for CHF_3 around 40 $\mu\text{m Hg}$, with an estimated etching rate of approximately 100 $\text{\AA}/\text{min}$. It was found that operation at lower power and lower pressure levels, over longer times reduces the effective roughness of the etched surface, resulting in a smoother finish. After etching, the remaining photoresist was removed in acetone and the specimens were thoroughly cleaned.

The etched surface was examined by SEM. Fig.4.12.a,b,c,d shows high quality etched grating patterns transferred into silica substrates, with periodicities around 0.21, 0.28 and 0.34 μm respectively. Gratings have also been fabricated into soda glass substrates, as shown in Fig.4.13.a,b, with the etching rate found to be substantially slower than for silica, under the same etching conditions, possibly due to the presence of heavier impurity molecules delaying the destruction of SiO_2 in the substrate.

The quality of the fabricated grating is at best limited by the quality of the photoresist mask. Examination of the

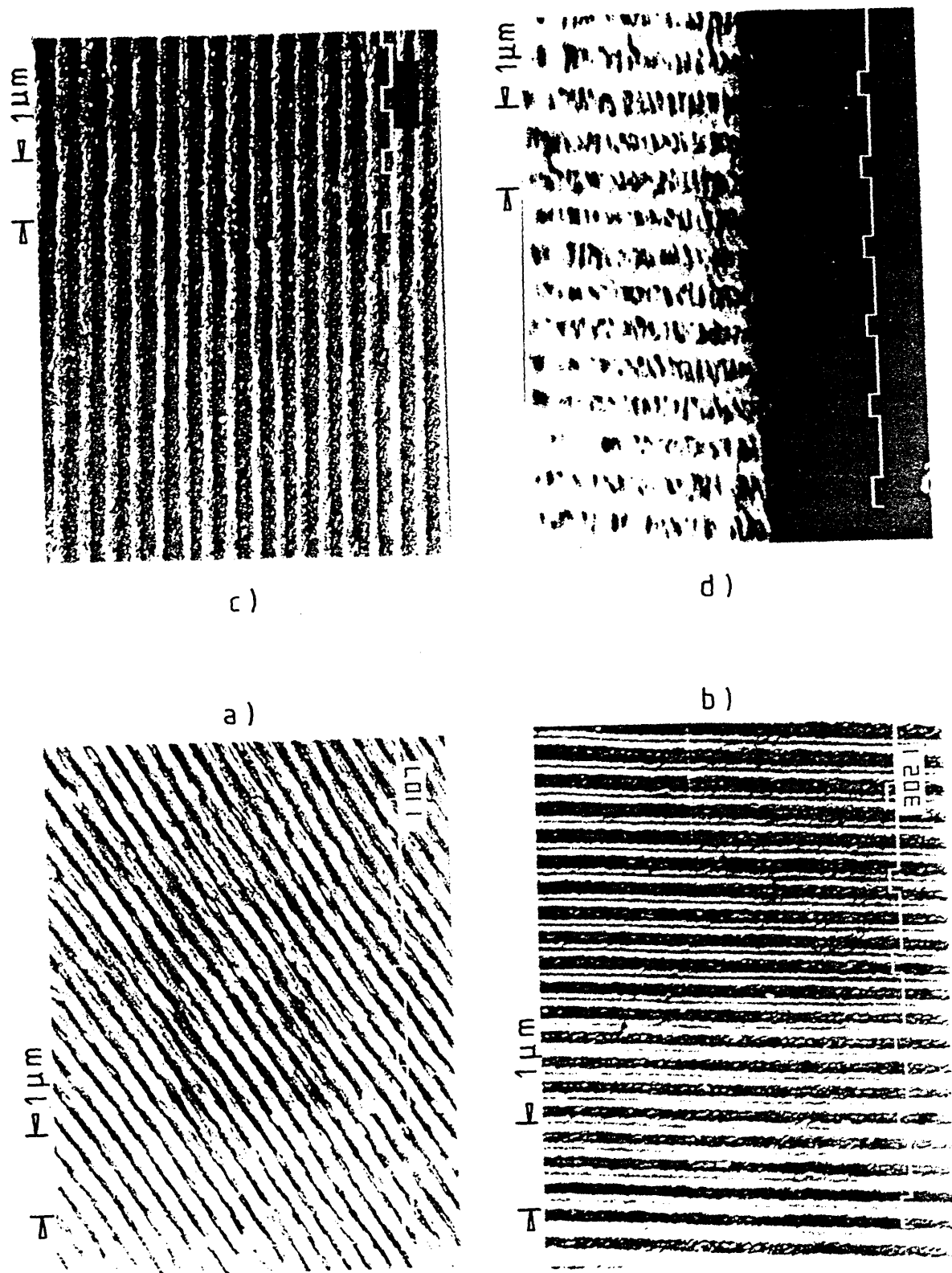


Fig.4.12

Grating patterns etched into silica substrates, with periodicities: a) $0.21 \mu\text{m}$, b) $0.28 \mu\text{m}$, and c), d) $0.34 \mu\text{m}$.

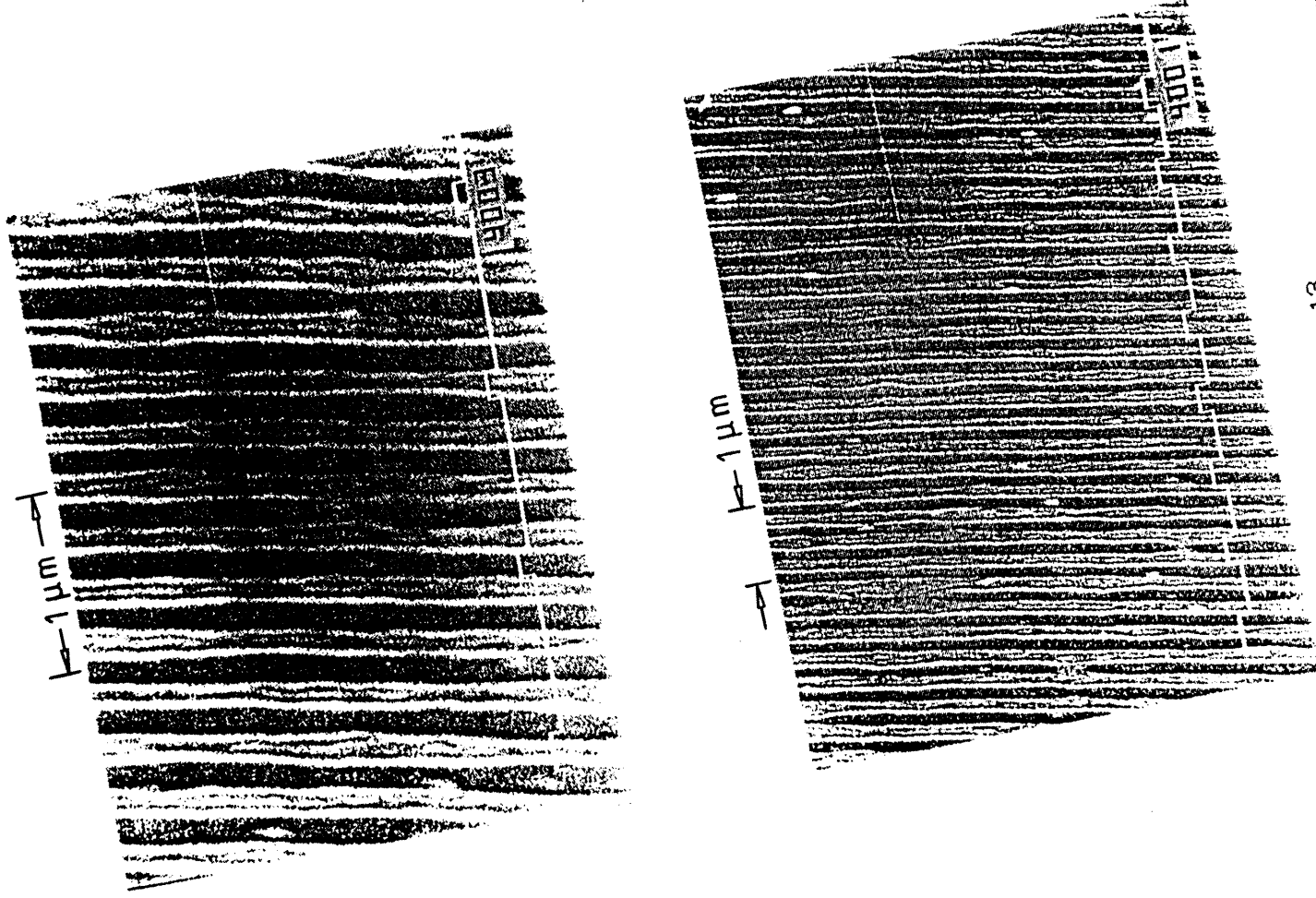
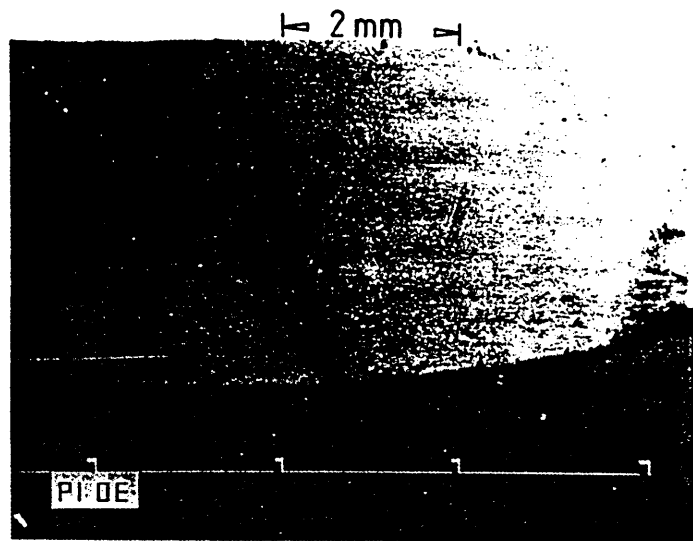


Fig. 4.13
Grating patterns etched into soda glass substrates.

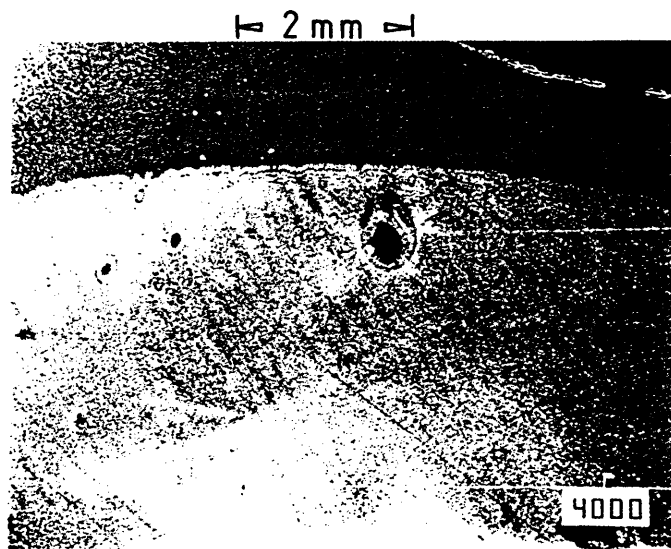
etched surface at low magnification (see Fig. 4.14.a,b,c), reveals the defects inherited from the photoresist mask (as compared with Fig.4.10), superimposed on the corrugated surface. Additionally, for substrates etched in CF_4 some stray, scratch like lines (see Fig.4.14.b) appear to have been etched into the surface, without being present in the original photoresist mask. No such lines were detected in patterns etched by CHF_3 .

By examining the etched grating pattern at high magnification, it is possible to study the surface roughness for different etching parameters. Fig.4.15.a,b,c shows the quality of the etched surface, for substrates subjected to different power/pressure combinations. The surface damage originally effected by etching in CF_4 at 80 W for 10 min and at 90 $\mu\text{m Hg}$ (Fig.4.15.a), has been minimised by etching at 50 W for 20 min, at a pressure of 60 $\mu\text{m Hg}$ (Fig.4.15.b). Gratings of comparable quality have been also obtained for samples etched in CHF_3 at 60 W for 15 min and at 40 $\mu\text{m Hg}$ (see Fig.4.15.c).

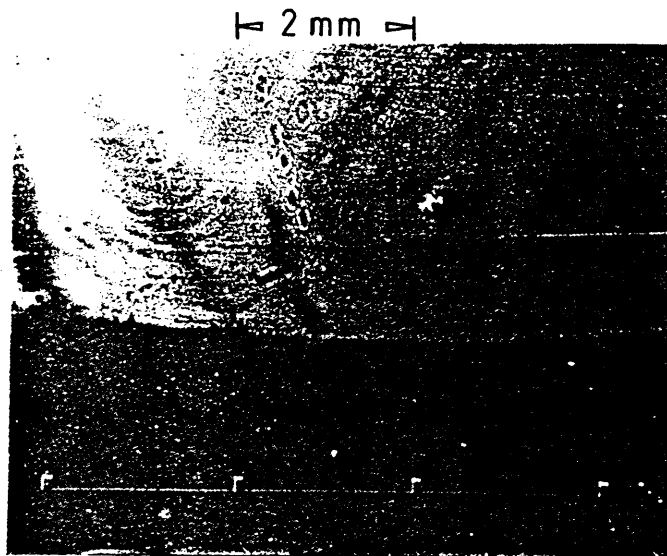
Thus, by carefully controlling the etching parameters, it is possible to minimise the roughness of the etched surface and fabricate high quality smooth grating patterns from high quality photoresist masks.



a)



b)



c)

Fig.4.14

Etched pattern at low magnification. Typical defects visible.

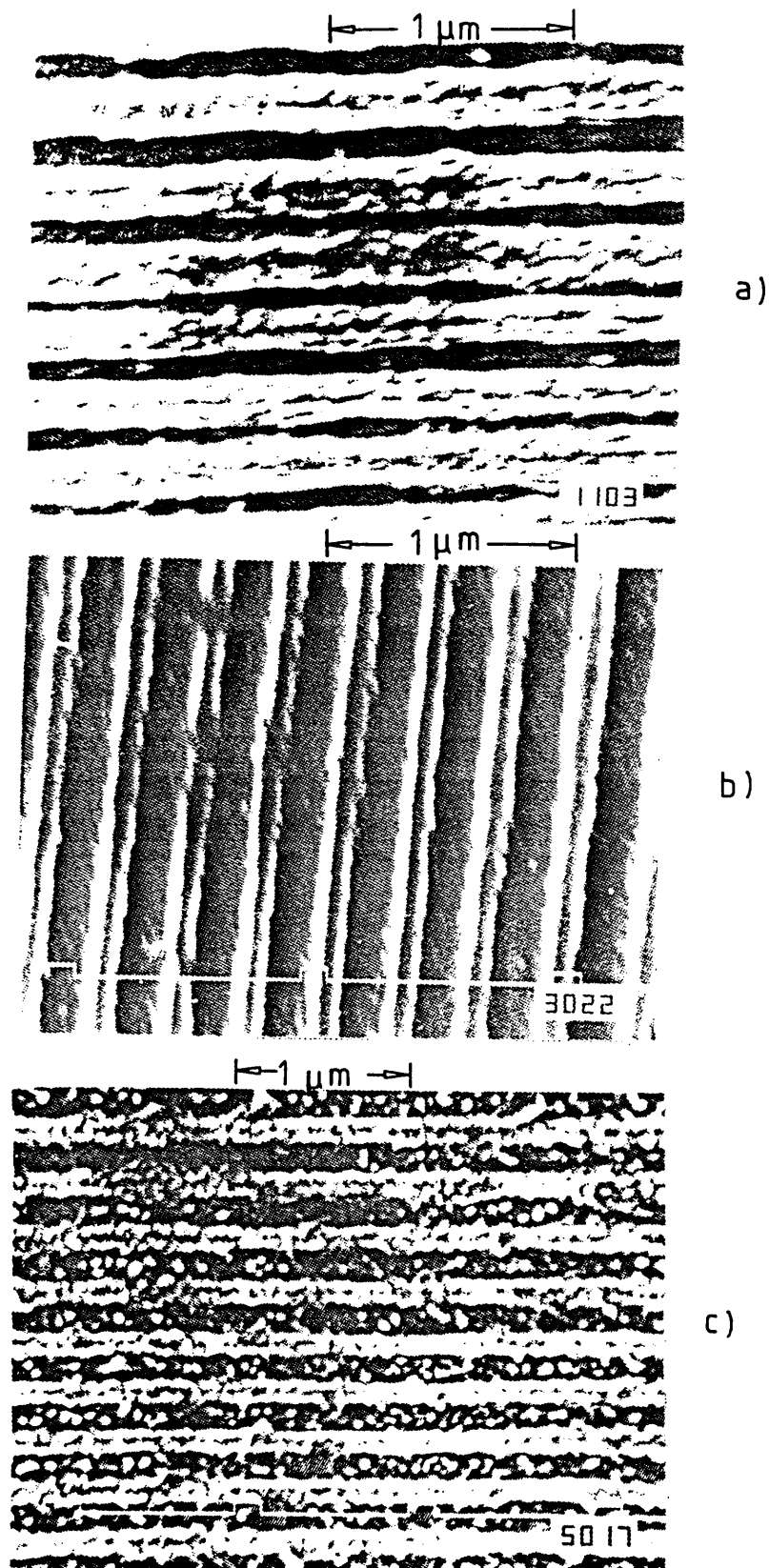


Fig.4.15

Quality of the etched surface for different etching parameters.

4.4 F a b r i c a t i o n o f H o l o g r a p h i c G r a t i n g s o n O p t i c a l F i b r e s

4.4.1 FIBRE AVAILABILITY

Fabricating holographic gratings on optical fibres requires a plane fibre surface, in close proximity to the guiding medium. This can be obtained, either by grinding and polishing the surface of a conventional communication fibre, in a manner similar to the one used for the preparation of polished couplers, or by using special fibers with plane surfaces, like the D-shaped fibre and the integrated fibre coupler (see Fig.4.19).

i) Polished Fibre Blocks

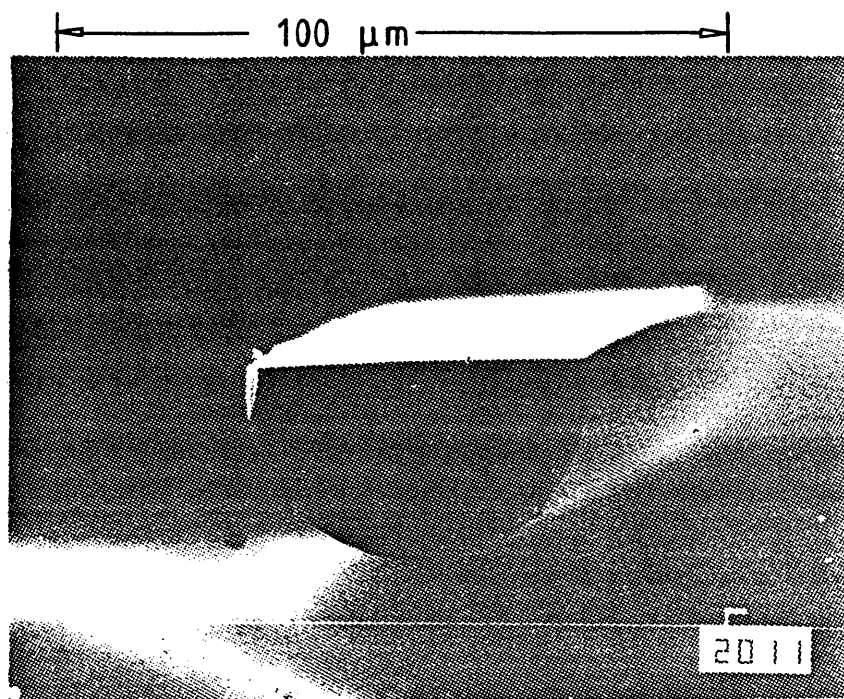
Over the last few years, a large number of techniques has been developed for the fabrication of polished fibre blocks. Even though the basic idea is simple and straight forward in principle, it requires a lot of care and practice. The fibre is first cemented into a curved slot of the correct depth machined onto a silica substrate, with a suitable potting compound. The surface is then ground and polished, until the required distance from the core is reached. The process can be monitored either by frequent microscopic examination of the polished surface (4.28), or by means of the variation in the transmission characteristic of the fibre throughout the lapping and polishing process (4.29). Usually, an additional "fine tune" polishing (4.30) with a finer slurry is necessary, to reach the required standards. The effective

interaction length of a polished fibre block is limited by the curvature of the potted fibre. For a 20 cm radius of curvature, the interaction length, within 1 μm from the fibre core, is 0.9 mm, while a radius of 1 m increases the interaction length to 2.8 mm. The restriction in the available interaction length, limiting the effective fibre-grating length, is a serious drawback for the use of polished fibre blocks.

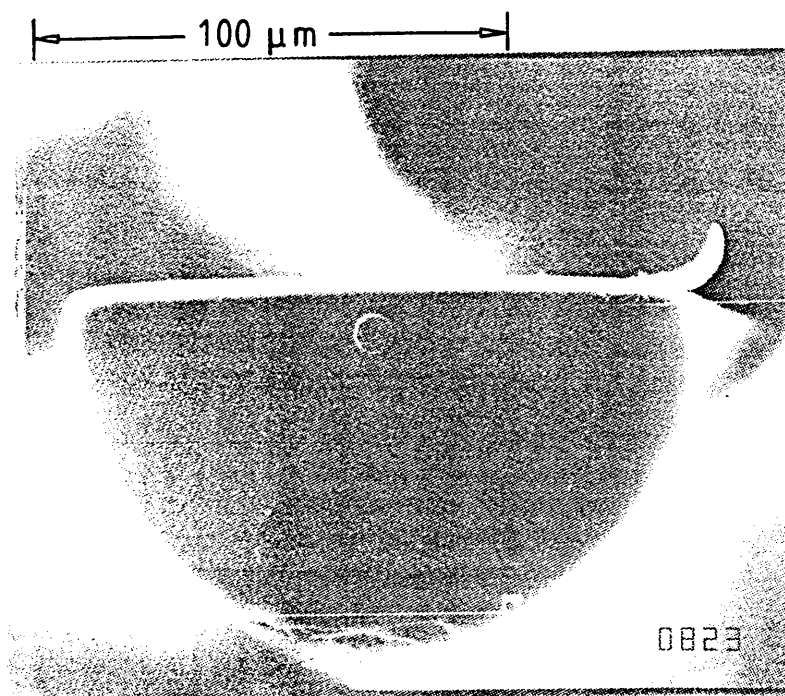
ii) D-shaped Fibres

D-shaped fibres can be fabricated by grinding and polishing a flat face on a standard fibre preform, prior to pulling. When the preform is then drawn into a fibre, the D shape is maintained. The guiding region of a D-shaped fibre is close to the flat surface, so, even though the fields are normally contained within the fibre, the removal of a small amount of cladding from the flat side will bring the fields to the surface. The accessibility of the guiding region, makes such fibres valuable basic components for fibre device applications.

Two different fibres have been made available to us; an Andrew Corporation polarisation holding fibre with an elliptical core (4.31, 4.32) (Fig.4.16.a), and a British Telecom. fibre with a circular core (see Fig.4.16.b). The D-shaped fibres have the same transmission characteristics as standard elliptically cored (4.33) and circularly cored (4.34) communication fibres. For the A.C fibre, the flat face is parallel to the major axis of the elliptical core, with a large index difference ($\Delta n=0.035$) between the



a)



b)

Fig.4.16

Cross-sections of D-shaped fibres: a) Andrew Corporation Fibre,
b) British Telecom. Fibre .

germanium doped core and the fluorine doped depressed silica cladding, of index below that of the outer support tube, necessary for maintaining the polarisation. The B.T. fibre has a smaller index difference ($\Delta n=0.0063$) and no depressed cladding. The fibres were found to have a preferred curvature, with the flat face on the outside of the curve for the A.C. fibre and on the inside of the curve for the B.T. fibre. In fact, the curvature could be justified in terms of two opposing orientations, one induced by the fibre shape and the other by the core composition. In the case of the A.C. fibre, the large index difference sets a dominating orientation, through the difference in expansion coefficients between core and cladding. For the B.T. fibre, the effect of the smaller index difference is overpowered by the orientation induced by the shape of the fibre. This self-orientating property is an advantage for easy fibre handling.

In order to gain access to the guiding region, the D-shaped fibers must be lightly etched in a buffer HF solution, calibrated originally for etching at 30°C in a constant temperature bath (Fig.4.17), and later for etching at 20°C in a clean room environment. Both hand made* and the industrial "silicon dioxide etch" (4.35) solutions have been tried. Etching A.C. fibres very close to the core, distorts the flat face of the fibre immediately above the core (see Fig.4.18), due to faster etching of the fluorine doped depressed cladding. This rather undesirable effect is avoided when using B.T. fibres.

* $6[2(\text{NH}_4\text{F}) : 3(\text{H}_2\text{O})] : [\text{HF}]$

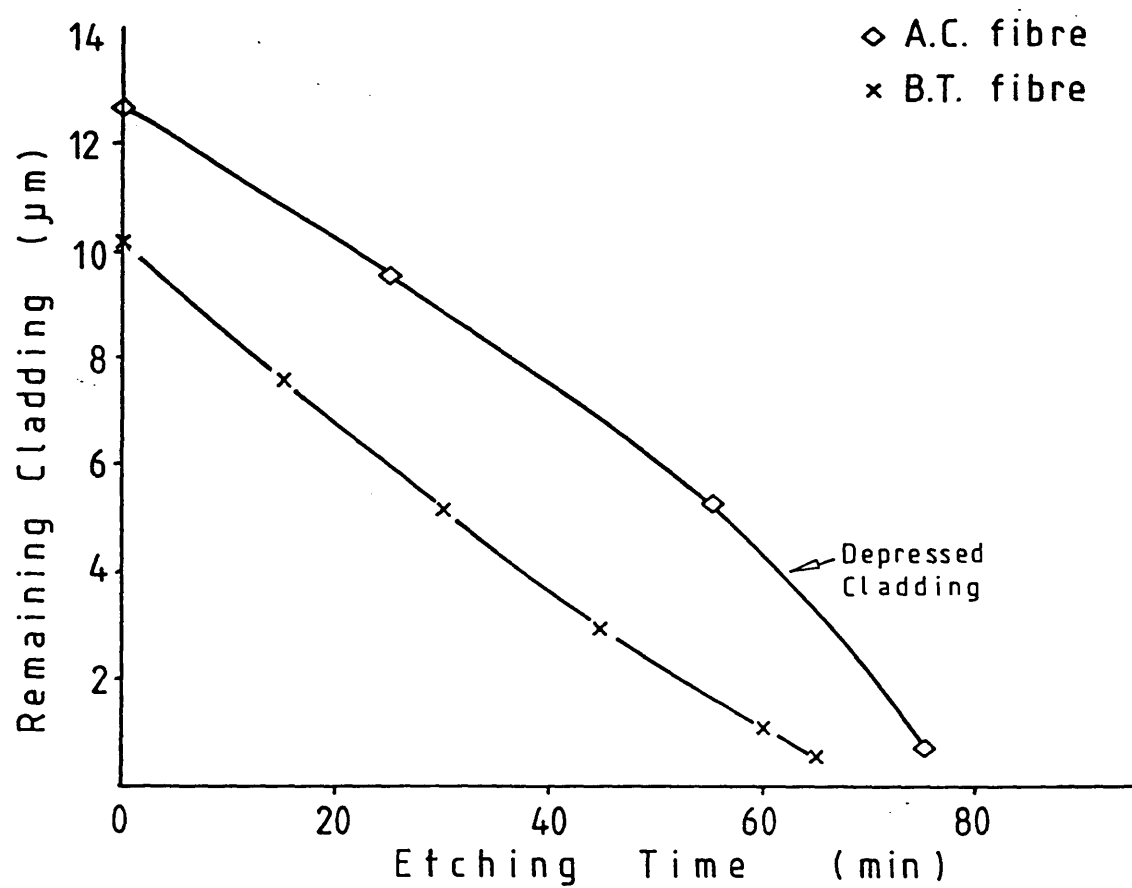


Fig.4.17

Calibration curve of D-shaped fibres etched in a buffer HF solution.

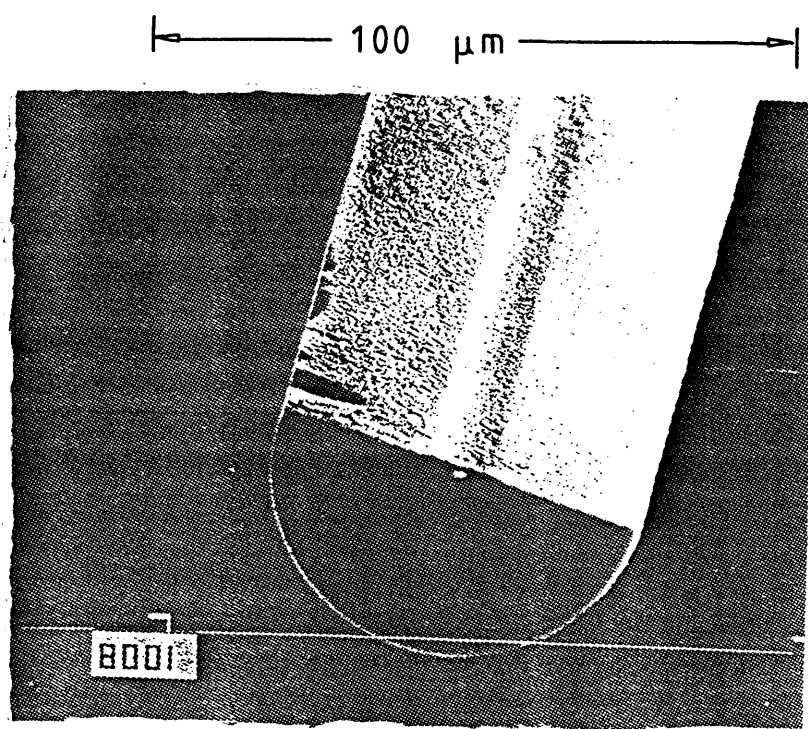


Fig.4.18

Heavily etched A.C. D-shaped fibre. The faster etching rate of the depressed cladding distorts the surface flatness above the core.

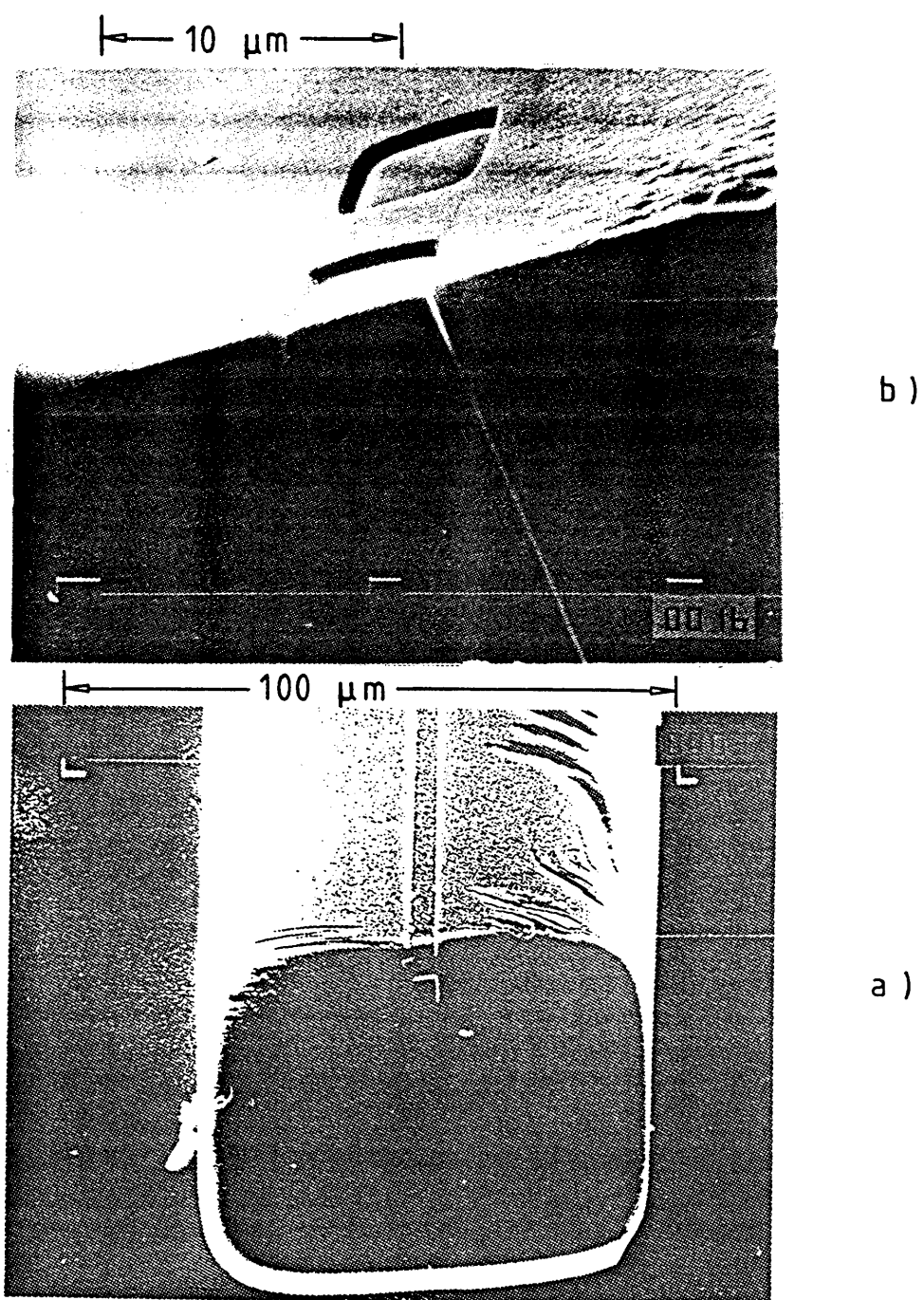


Fig.4.19

Integrated Fibre coupler. Cross-sectional view of the
a) fibre , b) twin core .

iii) Integrated Fiber Coupler

The integrated fibre coupler, shown in Fig.4.19 was conceived, designed and fabricated (4.36) at Imperial College. It is a fibre device based on the plane rectangular geometry, compatible with integrated optics, having the top face of a rectangular guide exposed to refractive index variations in the external cladding. The fibre was fabricated by pulling a fused borosilicate preform, assembled from numerous optically polished pieces, of the chosen refractive indices and dimensions. At the "correct" pulling temperature the fibre retains the original preform shape and dimensional ratio. To obtain the large fibre size, useful for easy handling, the device was fabricated by a double pull, first of the guiding region, which after incorporation into a bigger supporting cladding was pulled once more, to produce the final fibre.

4.4.2 FABRICATION OF GRATING MASKS ON "FREE" FIBRE LENGTHS

The rectangular $200 \times 100 \mu\text{m}$ ribbon fibre with a $5 \mu\text{m}$ guiding layer, shown in Fig.4.20.a,b, was used to examine the possibility of fabricating grating patterns on "free", i.e. unsupported, fibre substrates. The ribbon fibre was cleaned and dip coated in a $0.6 \mu\text{m}$ photoresist film, as described in section 4.3. After soft baking, the fibre was

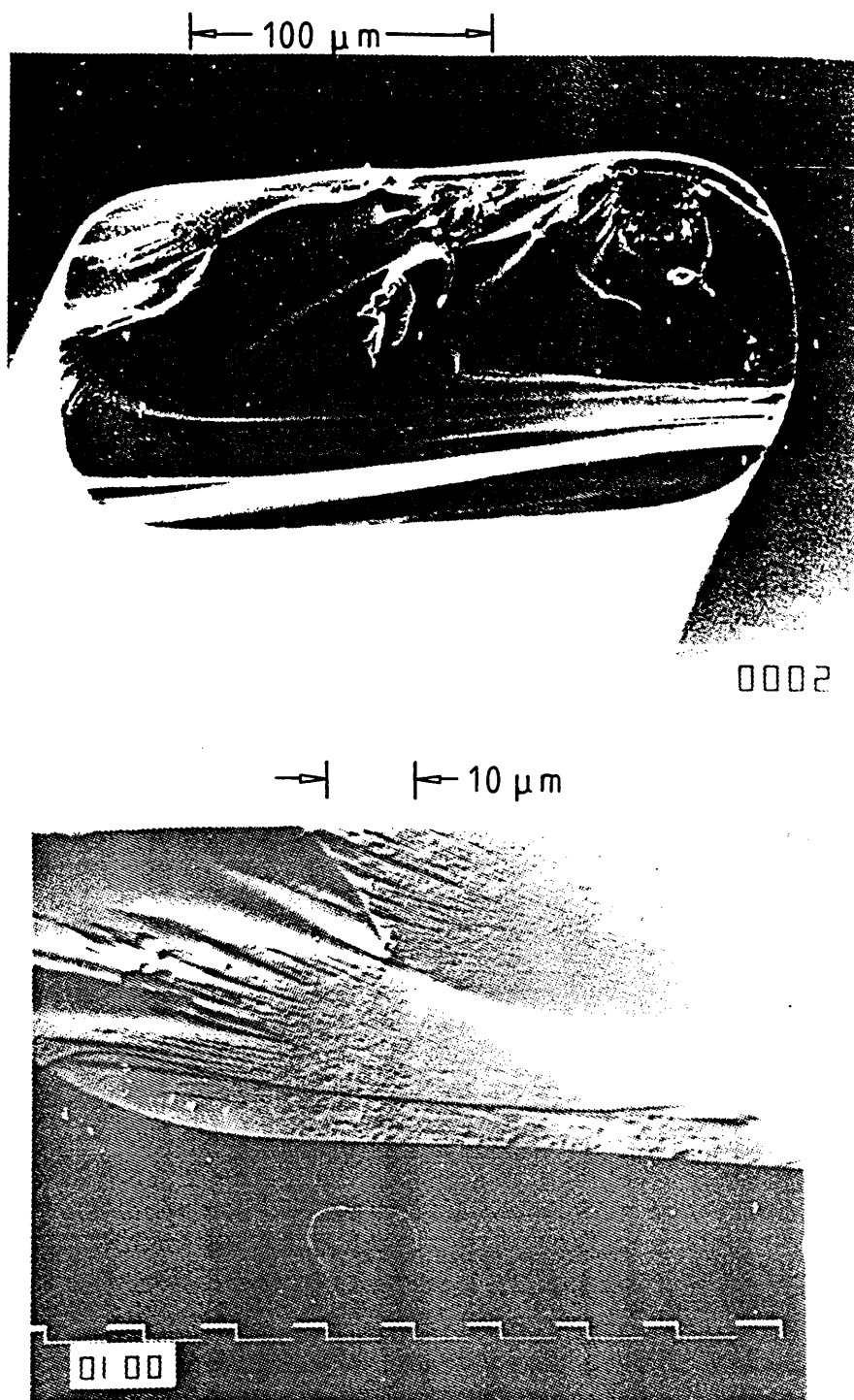
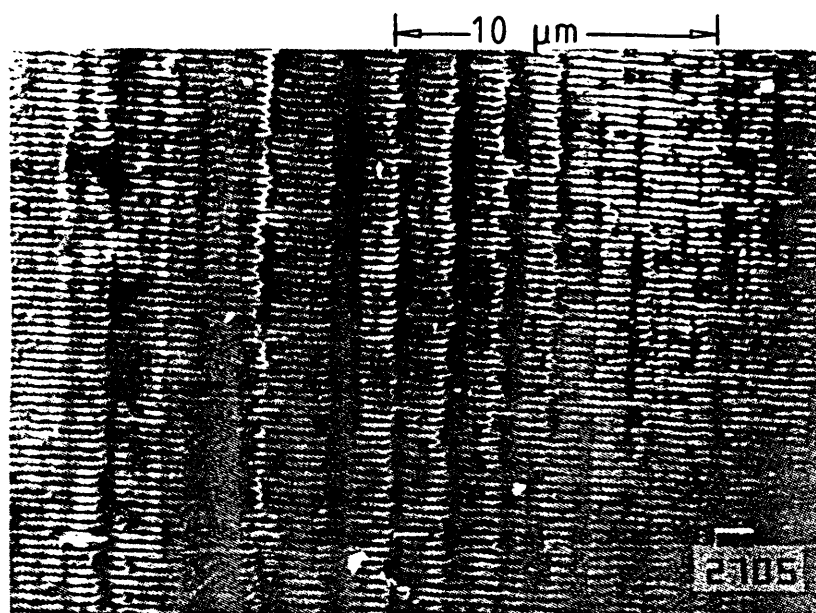


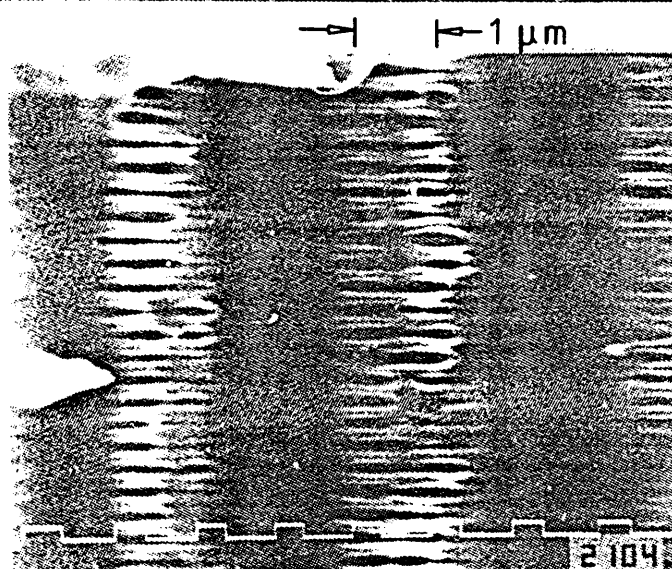
Fig. 4.20
Rectangular ribbon fibre.

exposed in air for 45 sec and developed for 30 sec. Examination by SEM revealed a series of stray longitudinal fringes superimposed on the original grating pattern, spaced along the fibre length, as shown in Fig.4.21.a . The catastrophic effects of the longitudinal fringes on the uniformity of the photoresist mask can be clearly seen in Fig.4.21.b, with stripes of overexposed grating patterns separated by areas of underexposure, with no visible fringes. The unwanted pattern appears to have a variable pitch and results from stray reflections of the interfering beams at the three "free" fibre / air boundaries and rounded edges. The situation can be slightly improved by laying the ribbon fiber on a flat plate throughout exposure, being held by the surface tension of an index matching fluid, thus eliminating reflection from its back surface. Under the same exposure and development treatment a better overall result was obtained (see Fig.4.21.c), even though the longitudinal fringe pattern is clearly visible, with areas of over and under exposure damaging the uniformity of the grating mask.

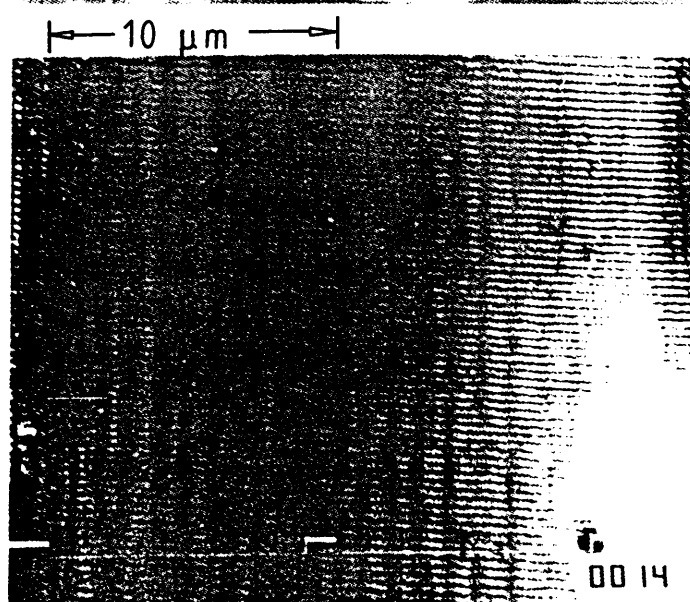
In view of these observations, it would seem reasonable to expect, that spurious fringes might be completely eliminated by surrounding the fibre with a material of higher index.



a)



b)



c)

Fig.4.21

Longitudinal spurious fringes on "free" ribbon fibre superimposed on the grating pattern.

4.4.3 FIBRE POTTING TECHNIQUES

A fibre potted in a suitable compound with its flat side exposed, provides a permanently orientated plane surface for the holographic fabrication of grating patterns. Polished fibre blocks offer such an arrangement, with the flat (polished) fibre surface integrated into a larger supporting plane. All attempts, however, to fabricate polished fibre blocks with long interaction lengths using D-shaped fibres failed to give satisfactory results and proved both expensive and time consuming. A number of alternative potting techniques were also investigated with varying degrees of success.

A very simple, fast and inexpensive scheme for potting D-shaped fibres, with their flat side floating naturally at the surface of a thick epoxy film is outlined in Fig.4.22 . The fibre is first orientated on a curved metal frame with its flat side facing upwards, the correct orientation preserved, by fixing sections of the fibre on two supporting plates. A two component epoxy (EPOTEC 301) is then thoroughly mixed and spread over a clean coverslide, giving a thick film. The curing time of the epoxy is very temperature dependant, and after heating for 20 min at 70°C on a hot plate, the epoxy surface becomes more viscous, but easily deformable. At this point, the coverslide is placed horizontally on the curved metal frame underneath the fibre, which is slowly lowered over the semicured epoxy and is pressed lightly onto it. The rounded surface of the fibre

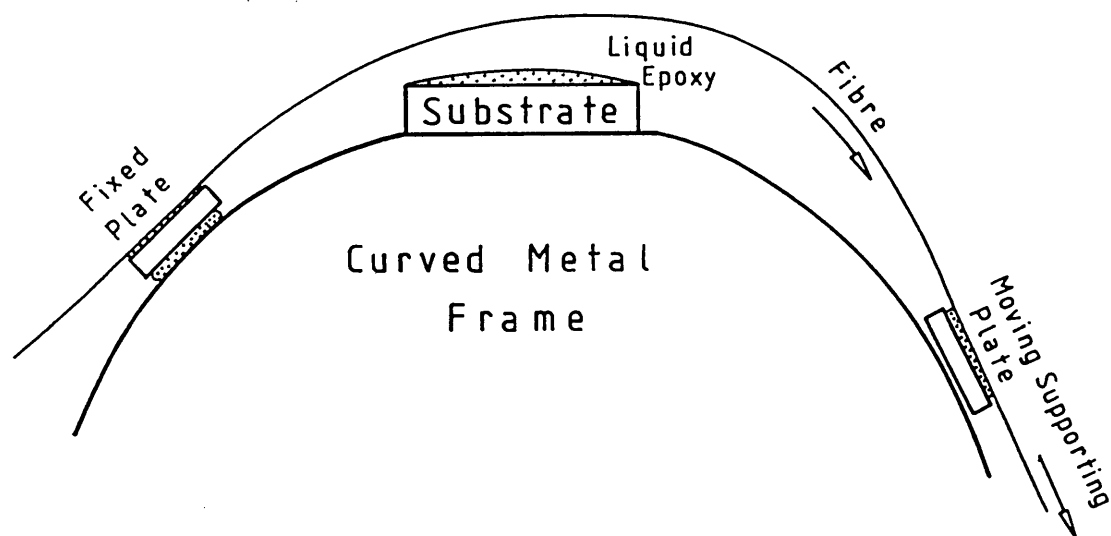


Fig.4.22

Schematic configuration outlining the potting technique.

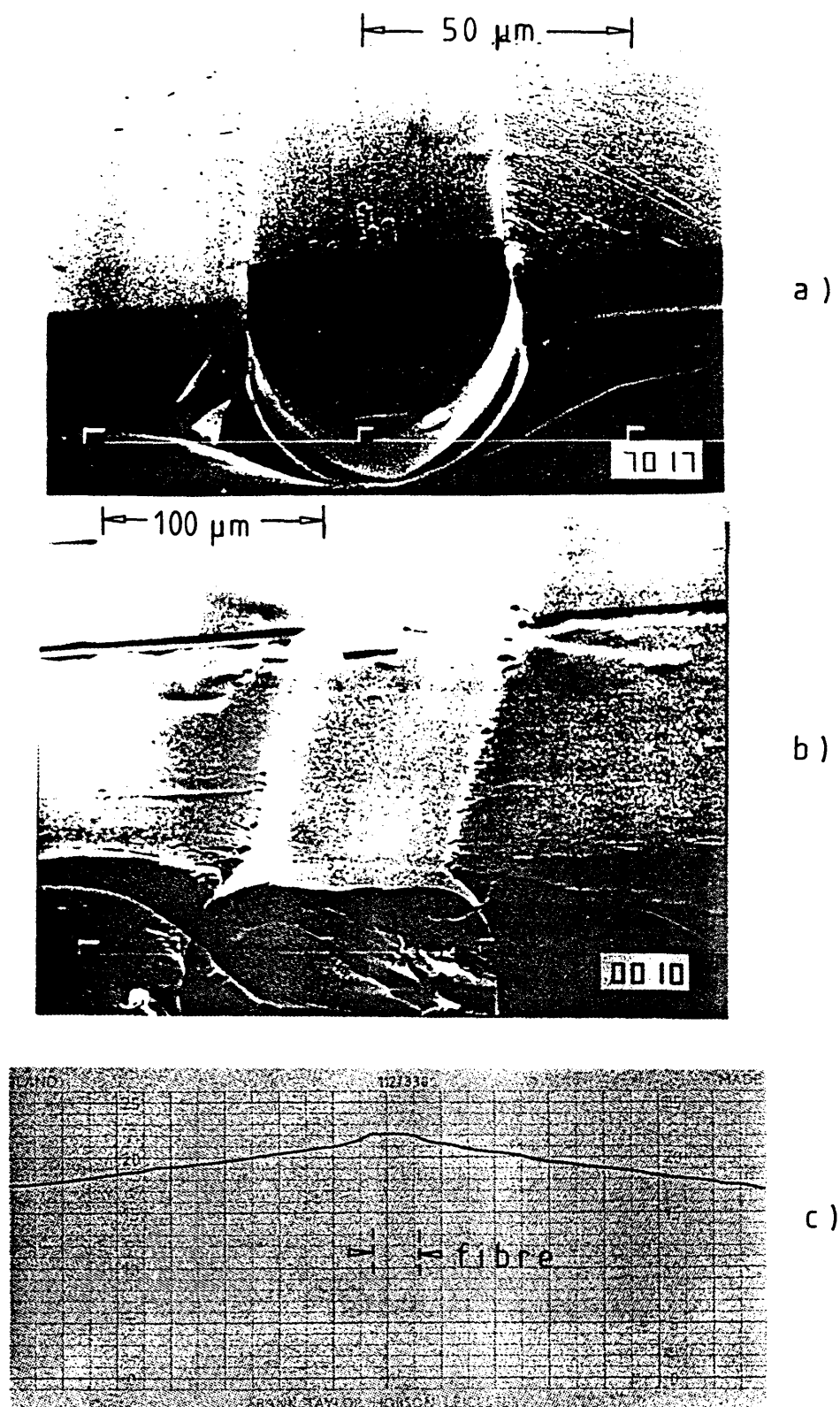


Fig.4.23

Cross-sections of potted fibres: a) D-shaped Fibre ,
 b) Ribbon Fibre .
 c) Thickness Variation across the potted fibre section.

sinks, but surface tension keeps the flat side afloat, approximately at the same level as the epoxy. The film is then left to dry properly overnight, until completely cured. Very satisfactory, repeatable results have been obtained with both D-shaped and rectangular fibres, as shown in Fig.4.23.a,b . The epoxy film is clear and hard with good optical and physical properties (see APPENDIX), and has been found to be immune to photoresist and to the cleaning solvents at room temperature. The composite fibre / epoxy surface is smooth, but not flat. In fact, the fibre surface is positioned slightly higher than the rest, though surface tension ensures that the epoxy is in good contact with the fibre sides, resulting in a gradual decrease in film thickness away from the fibre (Fig.4.23.c). The change in epoxy thickness is not expected to have any effect on the uniformity of the grating on the flat fiber surface, as long as the higher epoxy index strips all the light from the fibre body eliminating stray reflections. For this purpose the epoxy must be allowed to dry slowly, avoiding the formation of air bubbles at the fibre / epoxy interface.

4.4.4 GRATING FABRICATION ON POTTED FIBRE LENGTHS

A D-shaped fibre length, lightly etched, to bring the core closer to the surface, was embedded in epoxy using the simple potting technique described previously, thoroughly

cleaned and spin-coated in a "thinned" $0.15\text{ }\mu\text{m}$ photoresist film. It was then soft baked at 80°C for 25 min, exposed in air for 30 sec, and developed for 20 sec in a fresh developer solution.

Examination by SEM discloses a continuous grating pattern of excellent quality, shown in Fig.4.24.a,b,c,d, extending over 2 mm of fibre length. The grating mask is highly uniform (Fig.4.24.b,c,d), with deep fringes and only very few defects, probably from dust or dirt on the fibre surface. The unwanted longitudinal fringes have almost disappeared, and only a ghost image remains, with minimal effects on the film uniformity, demonstrating the effectiveness of the potting technique. Over the fiber edges, the epoxy appears to override the fibre, bringing the fringe pattern to an abrupt end (see Fig.4.25.a). A light polish will in general remove the epoxy completely from the flat fibre surface. The grating pattern is not limited to the fibre, but appears to extend over the epoxy, with fringes of similar quality. An interesting observation reveals, that the photoresist covering the epoxy appears to receive a lower exposure level from that over the fibre, possibly due to their difference in refractive index. This can be clearly seen by examining a fibre / epoxy interface in Fig.4.25.b, with the significantly deeper grating fringes on the fibre surface indicating a difference in exposure level.

As mentioned earlier, etching a D-shaped fibre through the depressed cladding close to the core, distorts the flatness of the fibre surface with the appearance of a

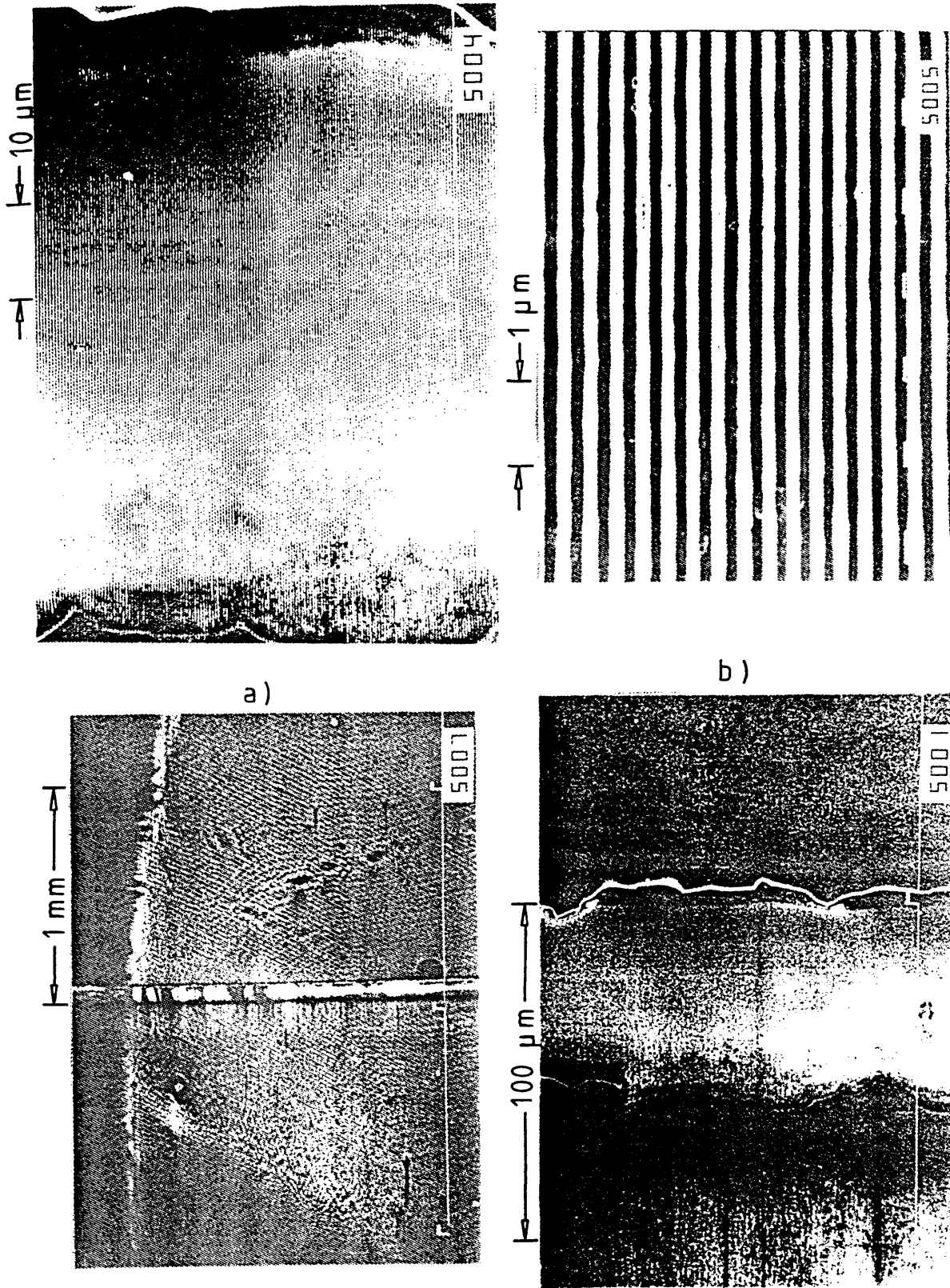


Fig.4.24

High quality photoresist grating patterns on potted D-shaped fibre lengths; a), b) fibre view , c), d) grating pattern on the fibre at low and high magnification.

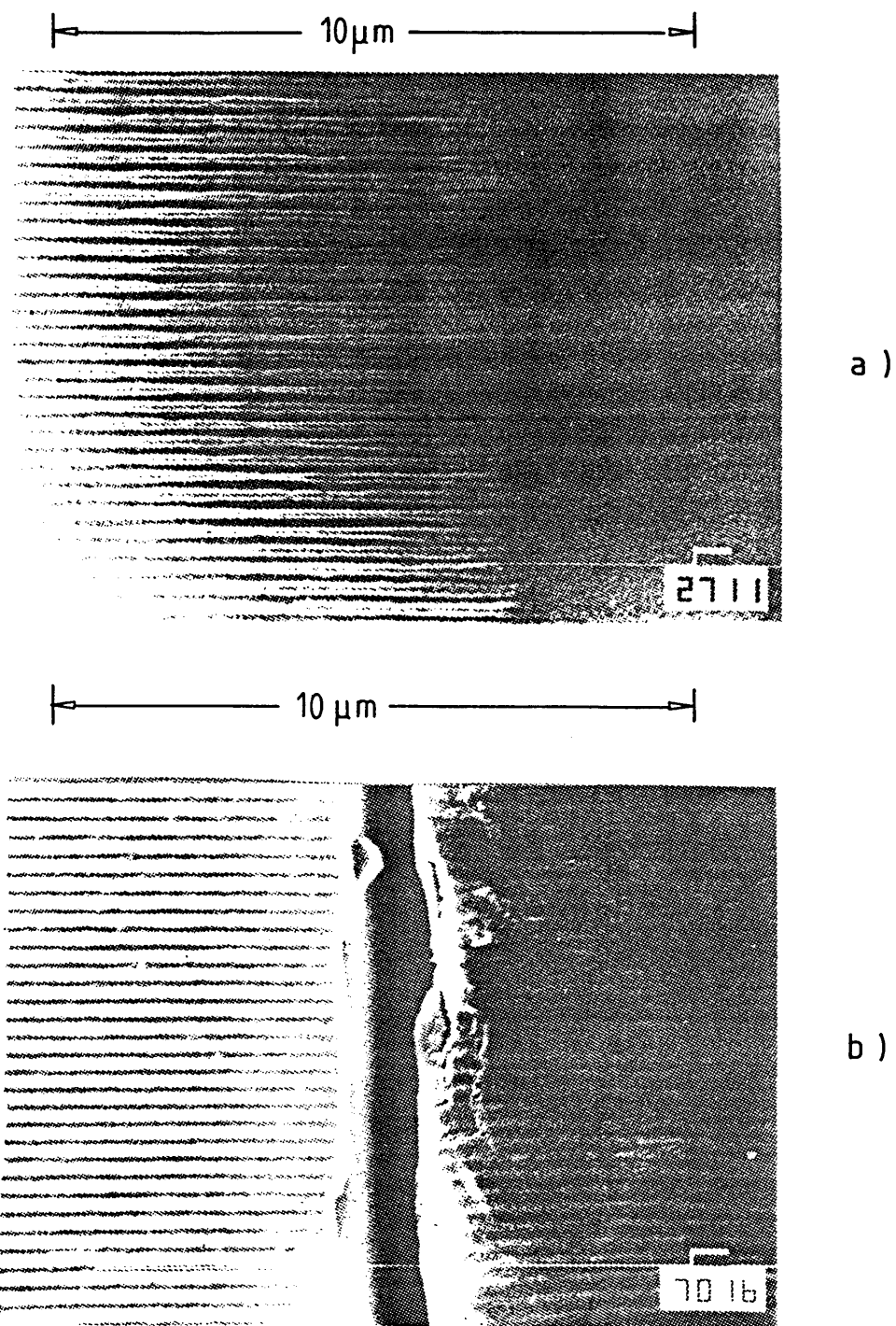
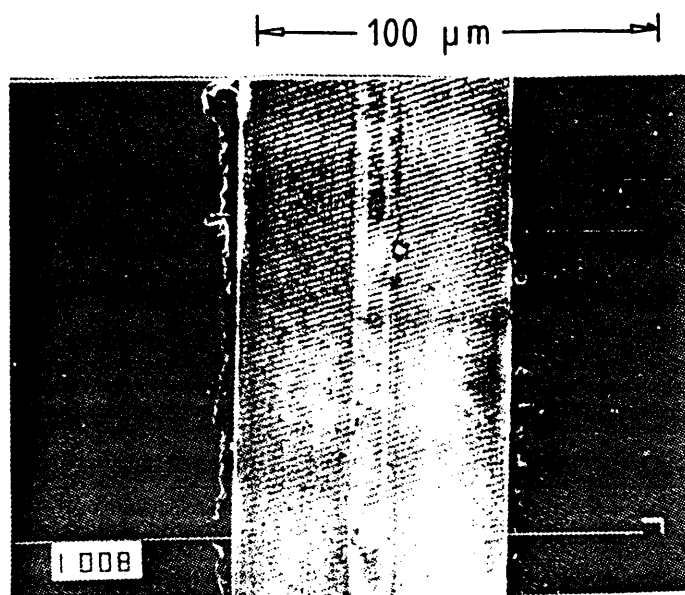


Fig.4.25

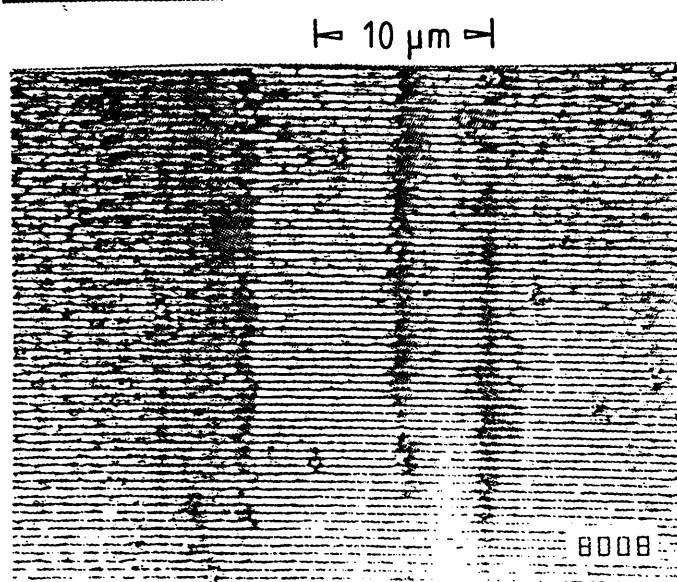
- a) Grating pattern ends abruptly near the interface .
- b) Grating pattern extending over a fibre / epoxy interface;
Note difference in modulation depth .

curved section immediately above the core. Such a fibre, heavily etched to within $0.5\text{ }\mu\text{m}$ of the core, was potted in epoxy, coated in photoresist, exposed and developed under exactly the same conditions as above, in order to examine the effect of the curvature on the grating uniformity. The results are presented in Fig.4.26.a,b,c, showing a continuous grating pattern of good quality fringes, with the central overetched region easily distinguishable. There are defects, some caused by dirt and others by a stray weaker fringe pattern resulting from double reflection at the collimating lens, with areas of different exposure levels. Over the central curved region, the grating pattern appears to extend more or less uniformly, with some variation in modulation depth. Hence, in general, the presence of the curved overetched section degrades the overall quality of the grating mask. This situation must be tolerated, when using depressed cladding fibres, with the grating close to the core. Even so, over the very narrow effective corewidth ($\sim 1\text{ }\mu\text{m}$), the variation in the grating profile is not expected to be significant.

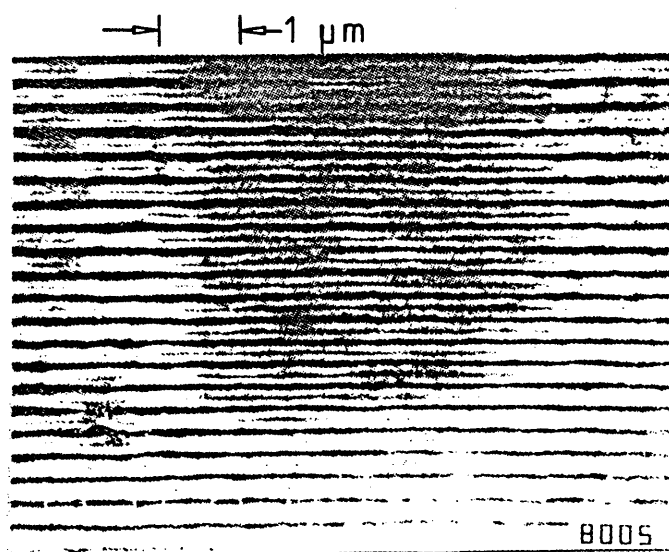
Once a photoresist mask of the appropriate quality has been fabricated, the grating can be directly transferred into the fibre body by reactive ion etching, as described in section 4.3.4. The typical etched pattern shown in Fig.4.27.a,b,c,d appears to extend uniformly along the fibre length, with some additional defects resulting from the etching process, including stray "scratch" like lines and surface roughening. These defects are identical to those



a)



b)



c)

Fig.4.26

Photoresist grating pattern on heavily etched A.C. fibre:

a) potted fibre overview ,

b), c) grating patterns over the central overetched region .

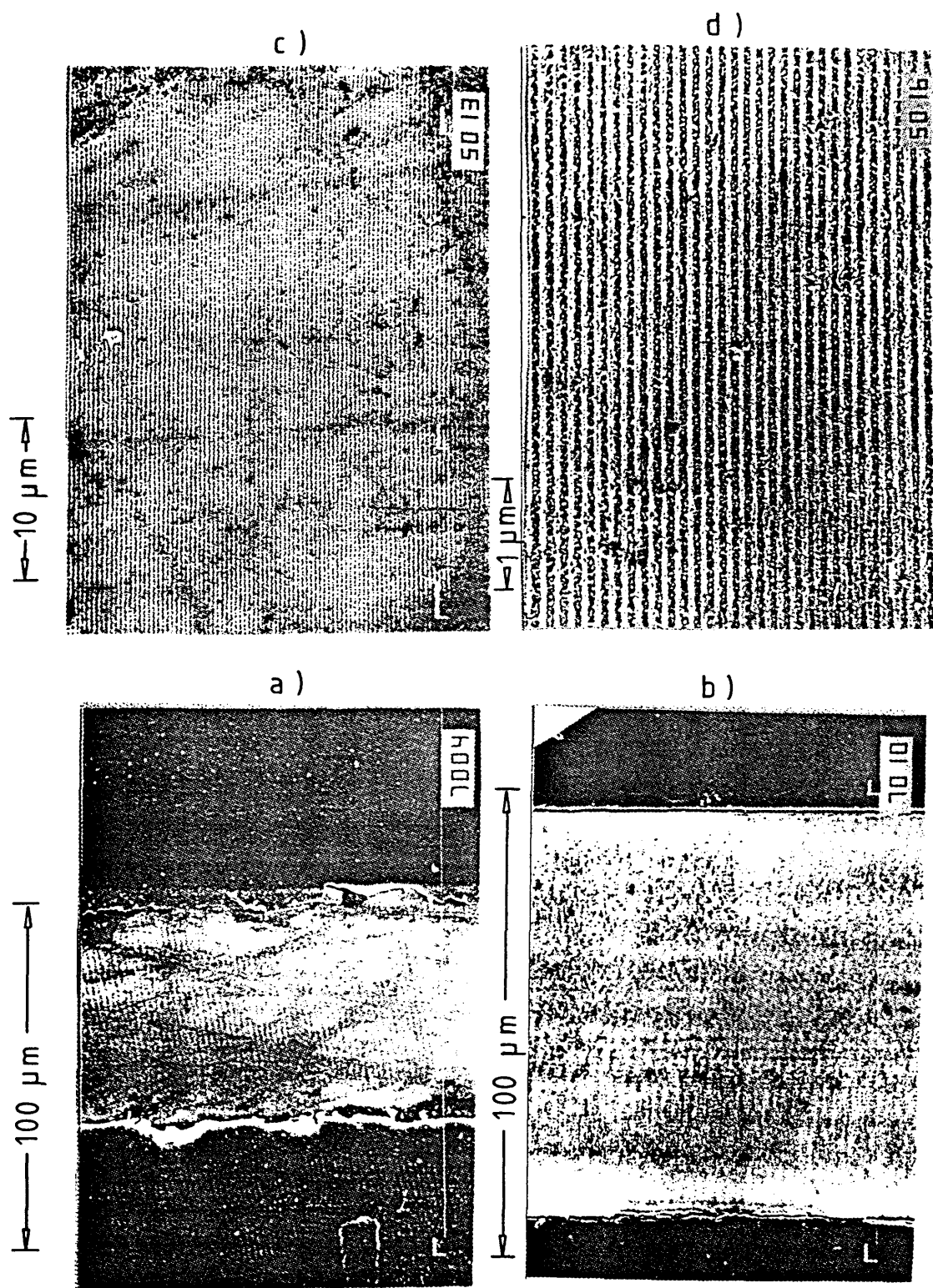


Fig.4.27

Grating pattern etched into the fibre surface:

a), b) overview of the etched fibre ,

c), d) etched grating patterns on the fibre .

confronted with etched silica substrates, and can be usually minimised by etching at lower power and pressure combinations, over longer times. Better results were obtained by etching using CHF_3 instead of CF_4 .

4.5 T h e G r a t i n g C o u p l e r C o n f i g u r a t i o n

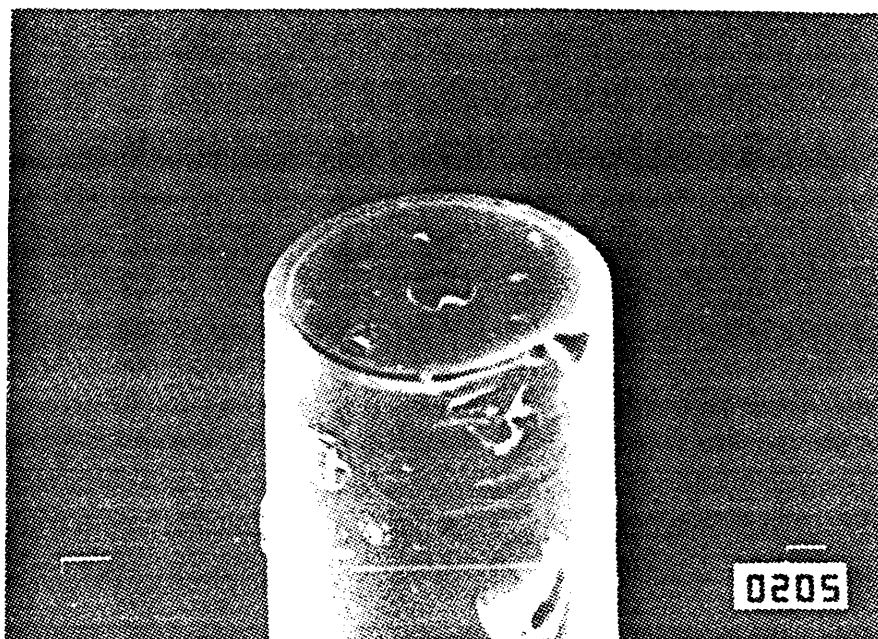
In the previous section, a technique was developed for implementing a grating fibre reflector, by means of fabricating a holographic grating on a potted D-shaped fibre length. The more sophisticated grating coupler, however, requires the grating to be imposed on a two waveguide coupler configuration.

4.5.1 A V A I L A B L E C O U P L E R C O N F I G U R A T I O N S

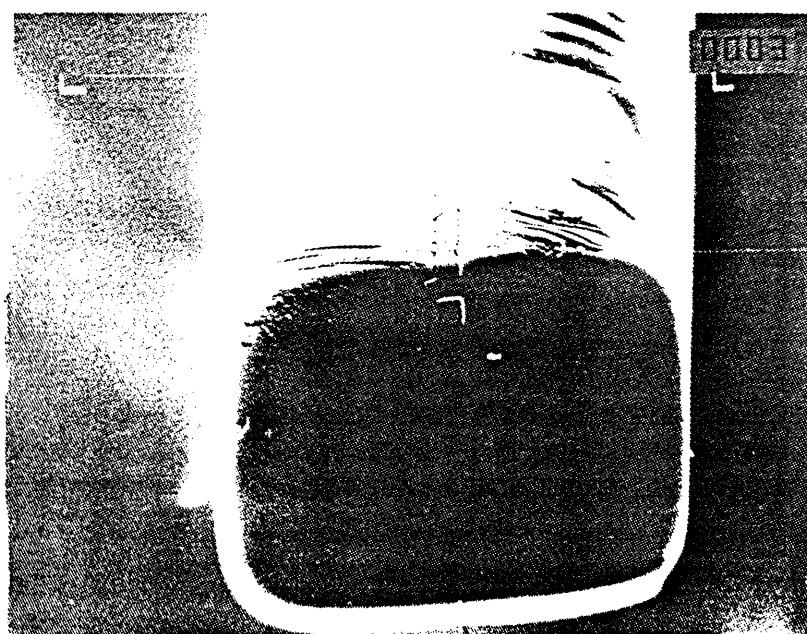
There are two basic groups of conventional directional couplers; one based on special fibre types like the coaxial coupler (4.37) and the integrated fibre coupler (4.36), while the other includes couplers fabricated from standard communication fibres, like polished (4.28) and fused (4.38) couplers. Even though coaxial and integrated fibre couplers offer a very well defined coupler configuration, the presence of both waveguides in the same fibre body complicates the process of recovering both the coupled and

the uncoupled signal. On the other hand, more conventional fibre couplers balance the advantage of isolating the coupled signal into a different fibre with a somewhat empirical description of the coupling process.

Coaxial directional couplers are combinations of dielectric rod and tube waveguides (Fig.4.28.a), efficiently coupled under phase matching conditions. The integrated fibre coupler (Fig.4.28.b) is a plane version of the coaxial coupler, operating under the same principle. A grating coupler based on the coaxial fibre can be realised, by polishing part of the external cladding of the tube, and fabricating a grating on the flat face, as shown in Fig.4.29.a. The integrated fibre coupler (Fig.4.29.b) is probably the better candidate, since the grating can be fabricated directly on the exposed top waveguide, over long fibre lengths potted in epoxy, as described in section 4.4. In both cases, a special fibre design is necessary in order to avoid co-directional coupling, with the two waveguides close enough to allow efficient contradirectional coupling for reasonable grating lengths. The polished fibre coupler consists of two polished fibre blocks properly aligned by a micromanipulator arrangement, until the two cores are strongly coupled. By fabricating a grating on one of these blocks, and making sure that the two waveguides have different characteristics, thus avoiding competition from directional coupling, a grating coupler can be most readily realised (see Fig.4.29.c). Even though the interpretation of the grating coupler by polished fibre blocks is by far the



a)



b)

Fig.4.28

- a) Coaxial directional fibre coupler ,
b) Twin cored integrated fibre coupler .

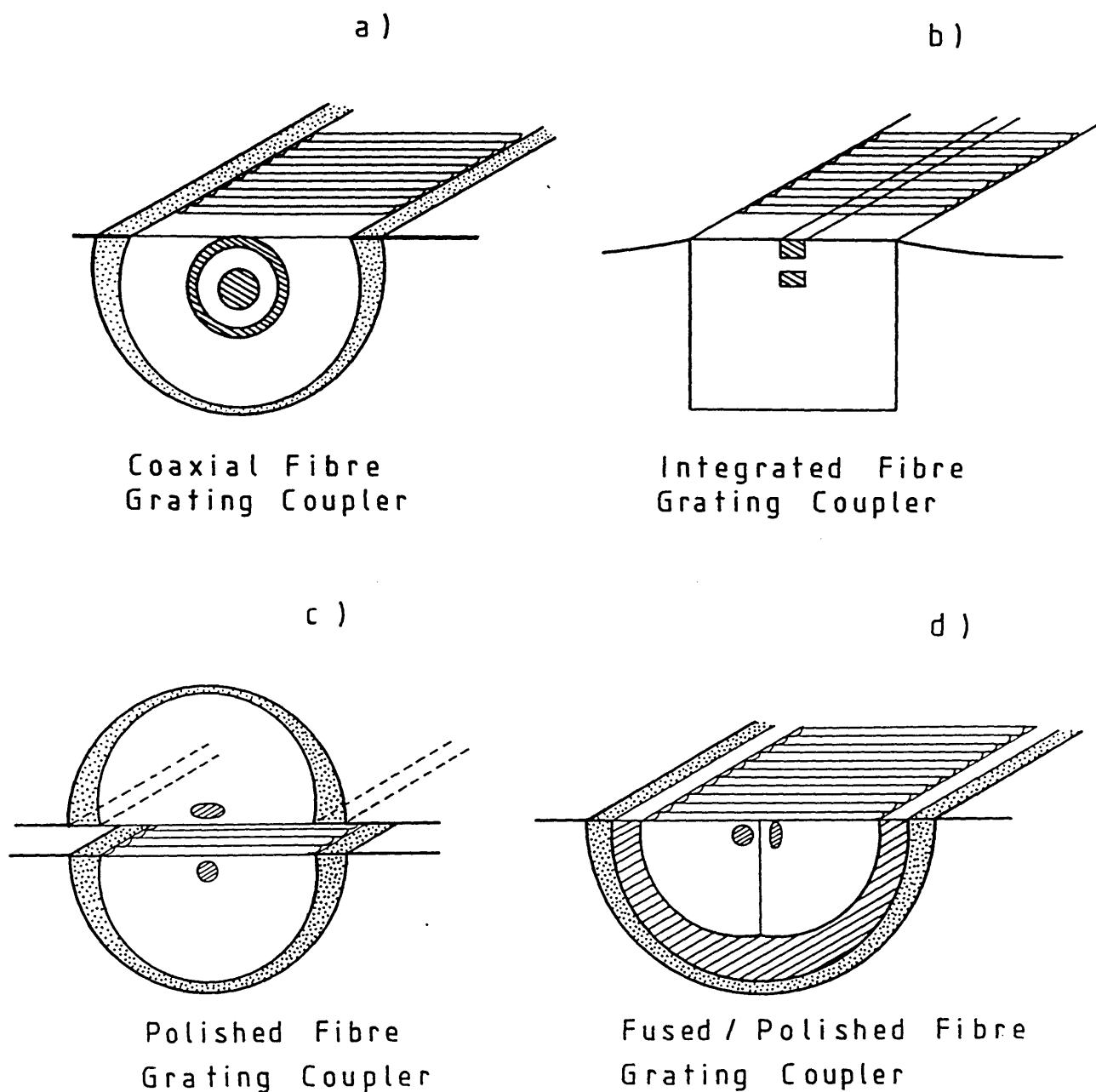


Fig.4.29

Grating coupler implementation using:

- a) Coaxial fibre coupler , b) Integrated fibre coupler ,
c) Polished fibre coupler , d) Polished fused fibre coupler .

easiest and simplest approach (1.48), it imposes restrictions on the effective grating length, thus limiting the coupling efficiency for narrow coupled bandwidths.

Fused biconical couplers can be made, by pulling two fibres under a hot flame, with a slight twist to ensure that the fibres remain in good contact, while they are being fused together. To avoid twisting the fibres, chemical vapour deposition treatment can be used, to bind the two aligned fibre sectors prior to fusion (4.39). For the directional coupler configuration, coupling can be monitored throughout fabrication, with the tapering stopped when the desired splitting ratio has been reached. A similar type of fused coupler configuration is based on two D-shaped fibres (4.40), which are lightly etched to expose the guiding region, and aligned inside a thick vycor tube, with their flat sides facing each other over the etched region. The tube is then heated and pulled to shrink, holding the fibres in position. Vycor is a material high in silica, so at the collapsing temperature, the fibres are heated only enough to fuse together along their flat surfaces, without any deterioration in cross-sectional geometry. The coupling process can be tuned, either by slightly tapering the fused section (4.41), or by means of a controlled diffusion of the Ge-doped core into the F-doped depressed cladding, effectively changing the field overlap and the coupling strength (4.42). A grating coupler configuration based on fused, untwisted fibres can be realised by potting and polishing the fused section in a fiber block configuration, with the

grating imposed on the fused polished face over the two cores, as shown in Fig.4.29.d .

Instead of fusing the two D-shaped fibres, a coupler can be realised by joining them with a suitable intermediate material like polysiloxane, whose refractive index is just below that of silica. The two fibres are coated in polysiloxane and aligned inside a thin capillary tube, with the core spacing minimised by the surface tension of the liquid coating. After the coating has dried the capillary is removed, and the joint can be stabilised by embedding in hard plastic (4.43).

4.5.2 GRATING COUPLER FABRICATION

It was originally intended to realise the contadirectional coupler by growing a second guiding layer over the grating pattern, on the flat side of the D-shaped fibre. For this purpose, thin film deposition by plasma polymerization of organosilicones in microwave discharges was investigated. Relevant published work (4.44, 4.45) describes the fabrication of high quality optical films, with well controlled thickness and refractive index profiles in the range 1.45 - 1.75 , tuning either by varying the substrate temperature during deposition (4.46), or by extra treatment in oxygen, nitrogen, or chlorine atmospheres (4.47) . A microwave discharge apparatus was constructed for the deposition of

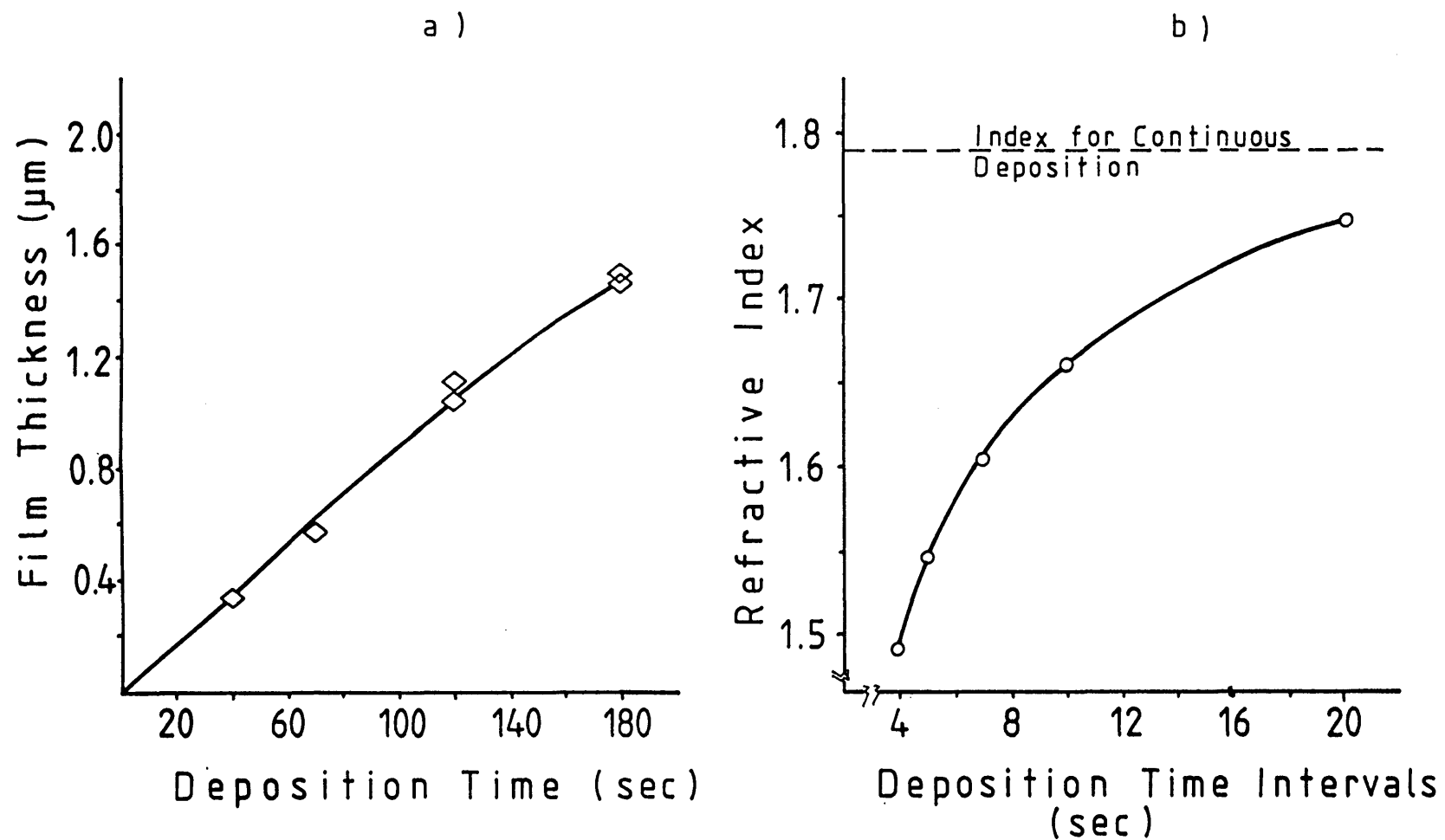


Fig.4.30

Film deposition by plasma polymerization of organosilicones
in microwave discharges:

- a) Film thickness as a function of deposition time ,
b) Refractive index for different deposition time intervals.

plasma polymerised hexamethyldisilazane films on soda glass substrates. A deposition rate of approximately $0.51 \mu\text{m}/\text{min}$ was estimated for a power level below 50 W and a pressure of 0.2 Tor , at a microwave frequency of 2.45 GHz (Fig.4.30.a). Although the film thickness uniformity appears to be satisfactory over a radius of 1 cm, the localised non-uniformity in refractive index was due to variation in substrate temperature during deposition. As the discharge power is absorbed by the cavity, the substrate temperature increases throughout deposition. A better index control may be achieved by dividing the deposition time into a large number of shorter intervals, and allowing sufficient time in between for the substrate to cool. The variation in refractive index as a function of deposition time intervals is shown in Fig.4.30.b . Even though some encouraging preliminary results were obtained, the work was finally abandoned, with more emphasis placed on fibre devices.

A fibre coupler can be fabricated from two D-shaped fibres, using techniques similar to those described in section 4.5.1 . Once the grating has been fabricated on a single fibre, it is convenient to combine it with an extra fibre and form a contradirectional coupler.

We have developed a simple and flexible technique for aligning and joining D-shaped fibres in directional coupler formations. Each fibre is forced into alignment in-between two supporting plates, as shown in Fig.4.31 , with the flat, lightly etched sections facing each other. The curvature can be altered by changing the distance between the two plates.

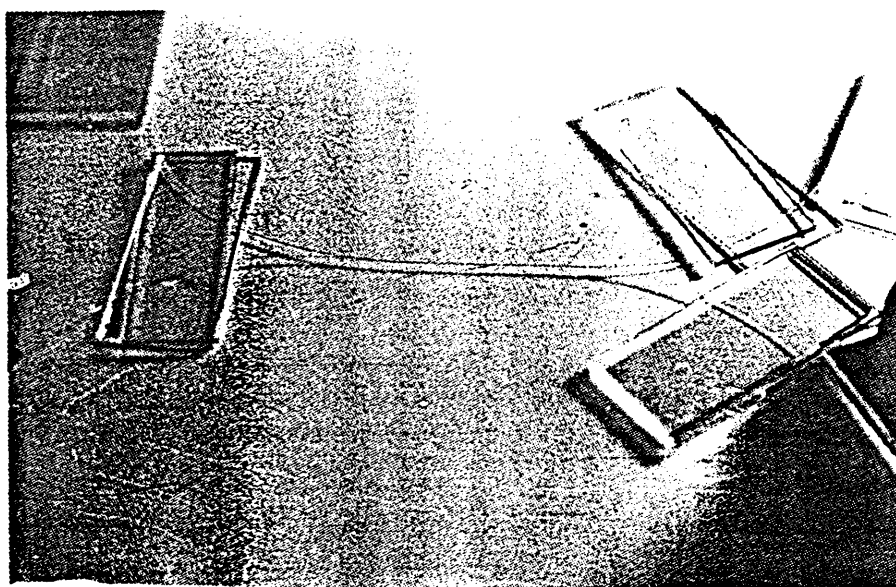
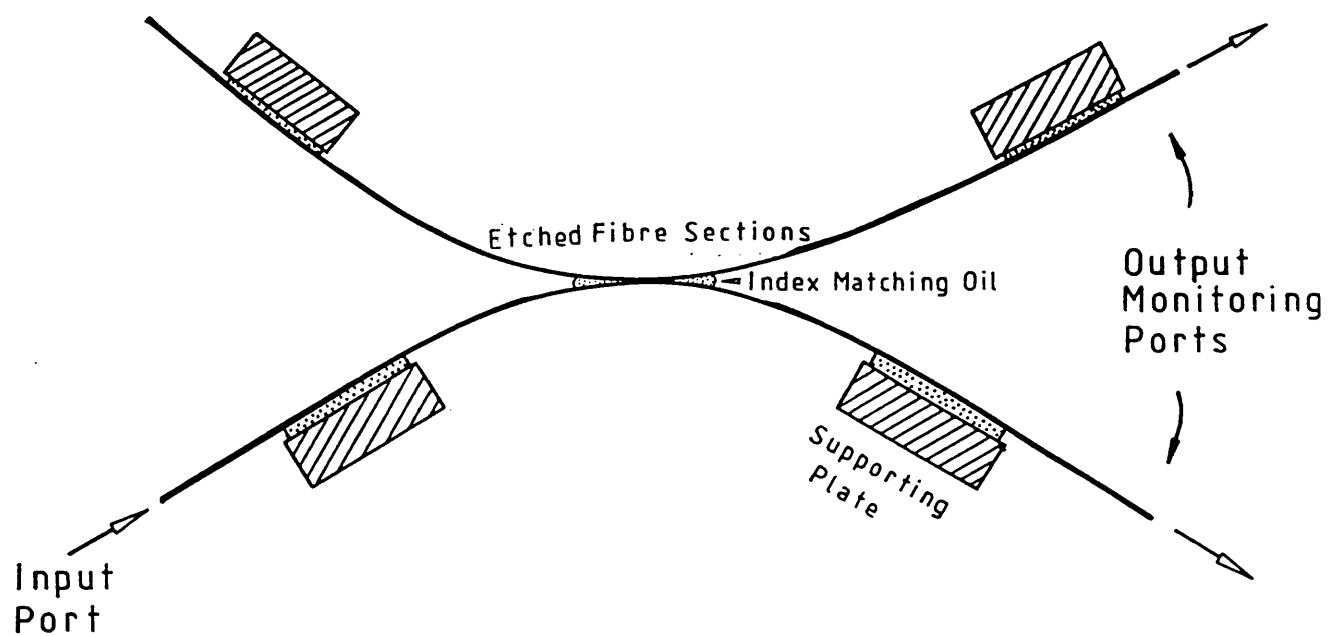
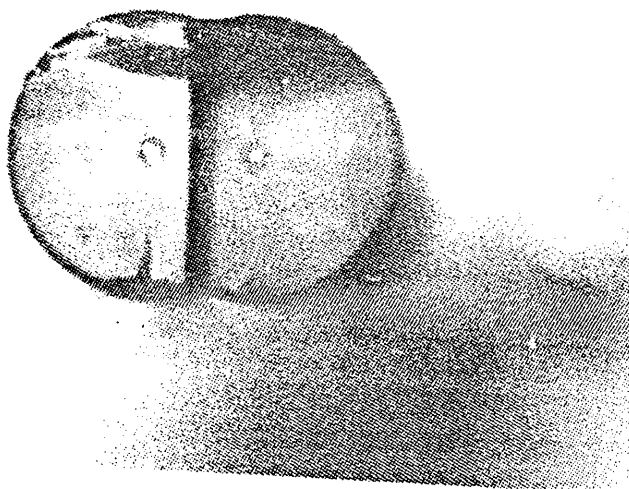


Fig.4.31

D-shaped fibres aligned in a directional coupler formation.

A large curvature is initially selected, and the two fibres are brought closer, until some contact is established. The joint is then given a rich coat by a suitable liquid agent. The curvature is then carefully relaxed, and the liquid spreads over a longer fibre length, its surface tension aligning the two fibres with a thin intermediate layer. Originally, a solution of "nail enamel" in acetone was used, having a refractive index (1.454) close to that of silica. Once the acetone has evaporated, the adhesive power of the enamel keeps the fibres joined in a coupler formation. The joint was found to be clean and strong, and its strength can be further increased by a thicker external coating. A cross-section of the coupler is shown in Fig.4.32.a, with a lengthwise view of the section in Fig.4.32.b. A fused coupler can also be fabricated by collapsing a pyrex tube around two properly aligned D-shaped fibres. Even though the temperature is not hot enough to fuse the flat sides of the fibres, the external pyrex jacket forces them in good contact. Fig.4.33.a,b shows unetched and etched sections of a fused-like coupler. Note, that the difference in thermal expansion coefficients between pyrex and silica, causes thermal stress to build up in the "fused" section.

At higher wavelengths, the rich in aromatics enamel becomes increasingly lossy, and silicone oil of index 1.45 can be used instead. The surface tension of the oil aligns the fibres properly, and allows the possibility of tuning the coupling process, by adjusting the interaction length in relation to the beatlength. The measured wavelength response



a)

b)

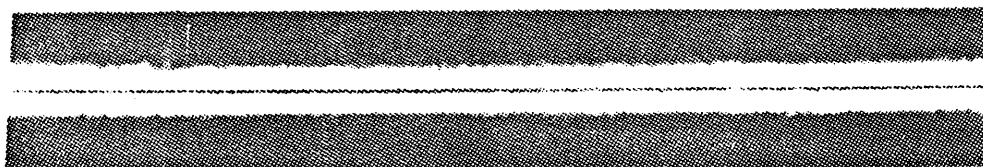
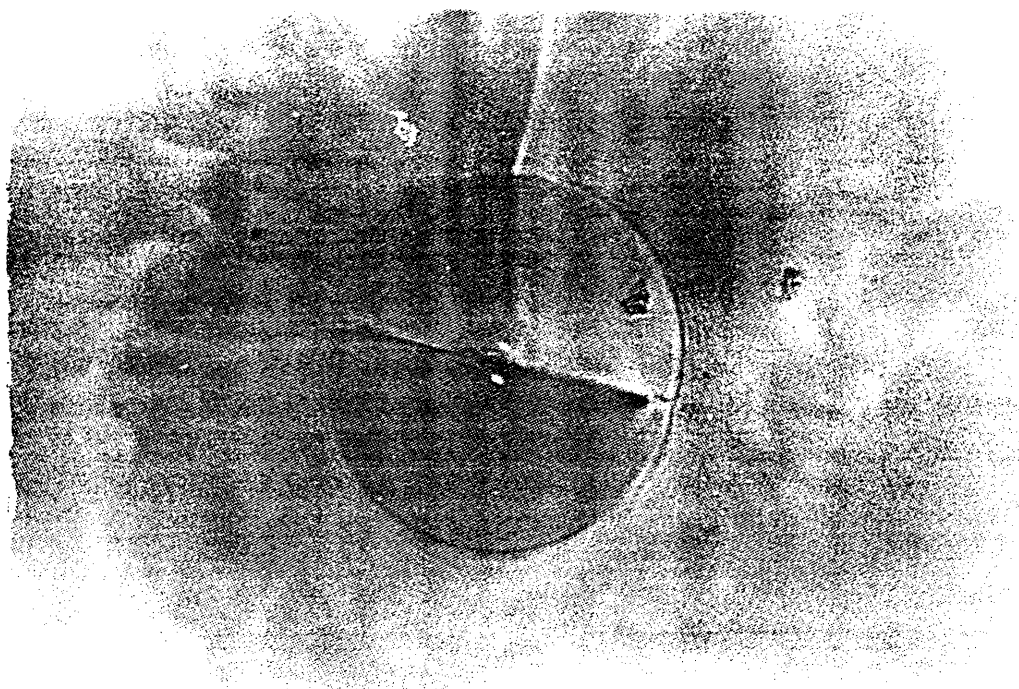
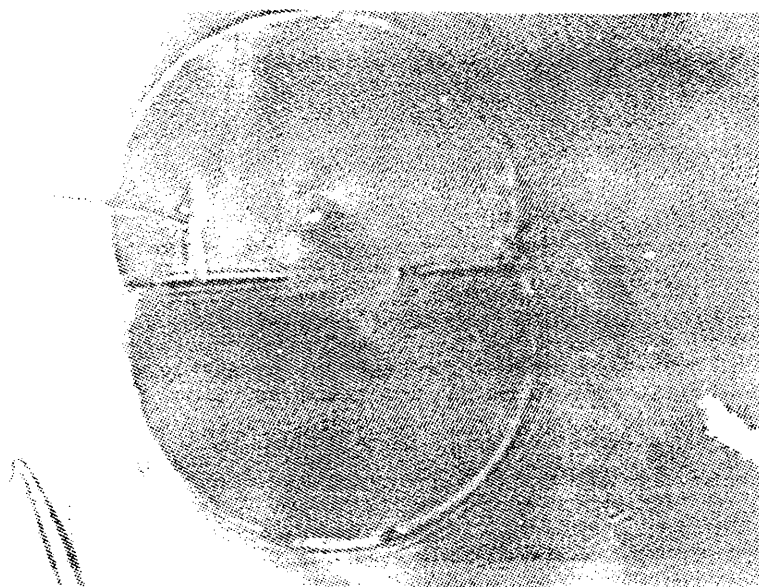


Fig.4.32
D-shaped fibre coupler: a) cross-sectional view,
b) lengthwise view .



a)



b)

Fig.4.33

"Fused" D-shaped fibre coupler fabricated by collapsing a pyrex tube around two properly aligned fibres:

a) etched fibre section , b) unetched fibre section .

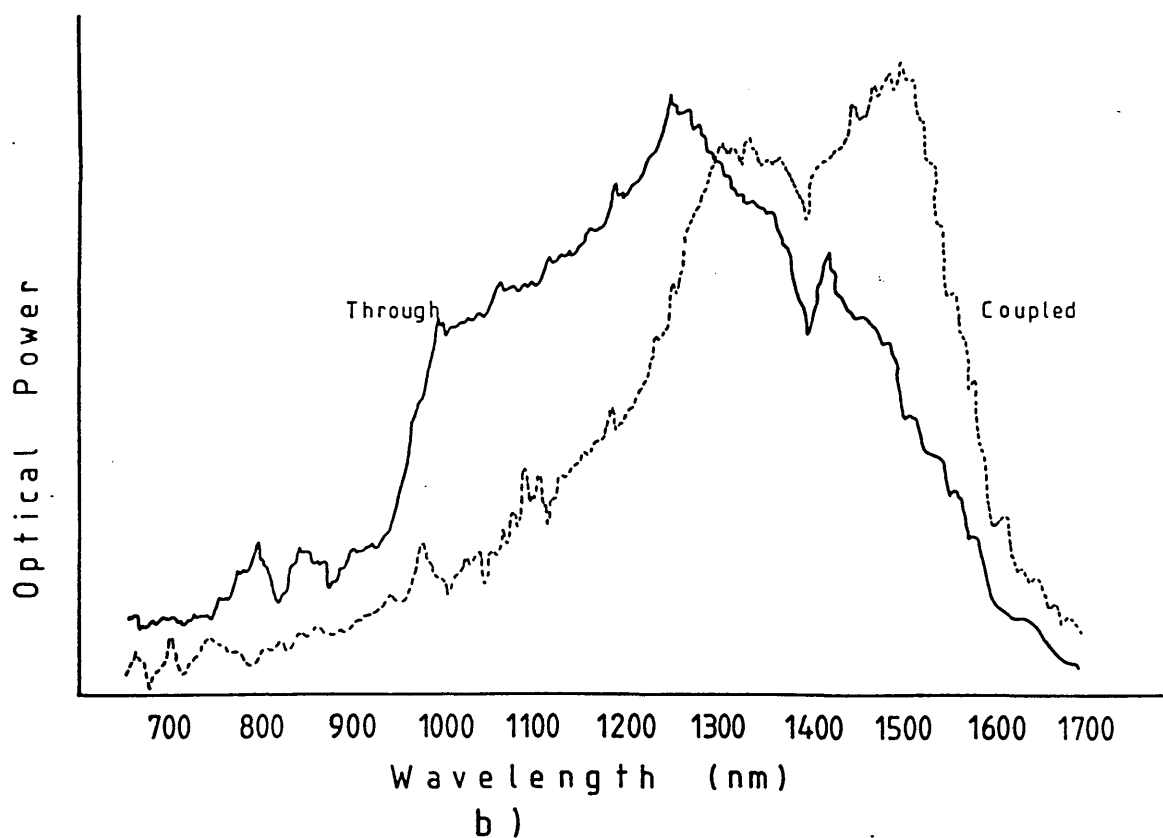
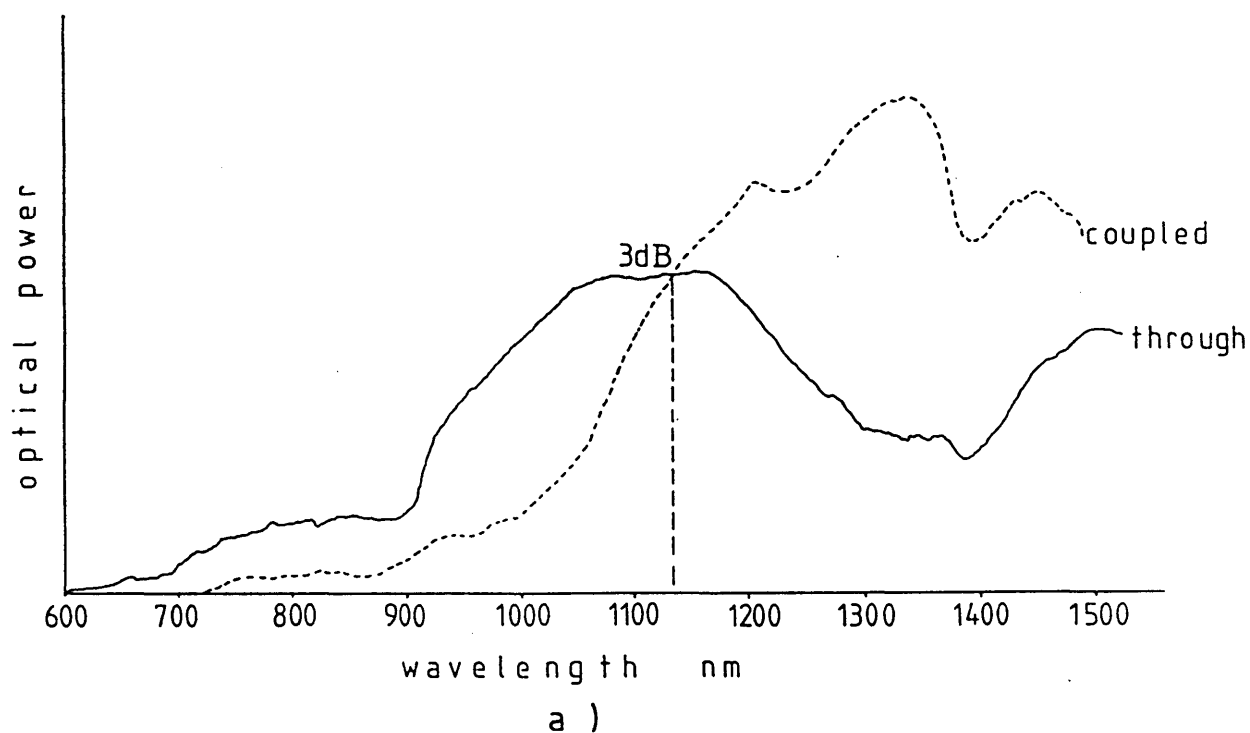


Fig.4.34

Measured wavelength response of a directional coupler

- a) fabricated from two etched D-shaped fibres aligned by an intermediate oily layer, as compared with that of
- b) a commercially available polished coupler .

of the coupler is presented in Fig.4.34, in comparison with that of a commercial polished coupler. Even though the coupler configuration of Fig.4.31 was expected to be unstable, no apparent deterioration in the coupling strength was observed over a period of two weeks.

This rather simple and tunable coupler implementation can be used to realize both the grating coupler and the 3 dB coupler, used for sampling the reflected signal in a grating reflector. The latter is straightforward, with the coupler being assembled in the fibre length prior to the grating, from identical fibres. For the contradirectional coupler the two fibres must be dissimilar. It is possible to alter the propagation characteristics of one of the fibres by inter-diffusion of the core and cladding materials after sufficient heat treatment, effectively changing the refractive index profile and field distribution over the etched region, prior to the coupler formation.

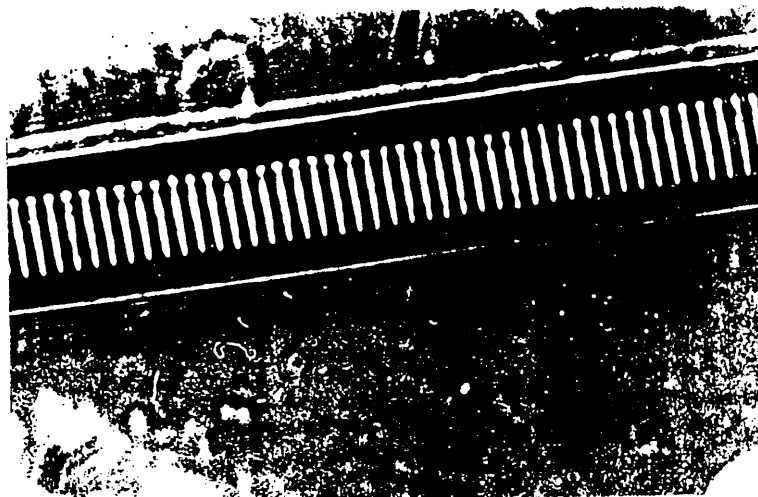
4.6 E m b o s s i n g T e c h n i q u e f o r G r a t i n g F a b r i c a t i o n o n P o l y m e r F i l m s

Embossing gratings onto semi-dried films, provides a simple and inexpensive alternative to holographic techniques. We have embossed gratings on polymer films, using two commercially available master gratings of 160 lines/mm and

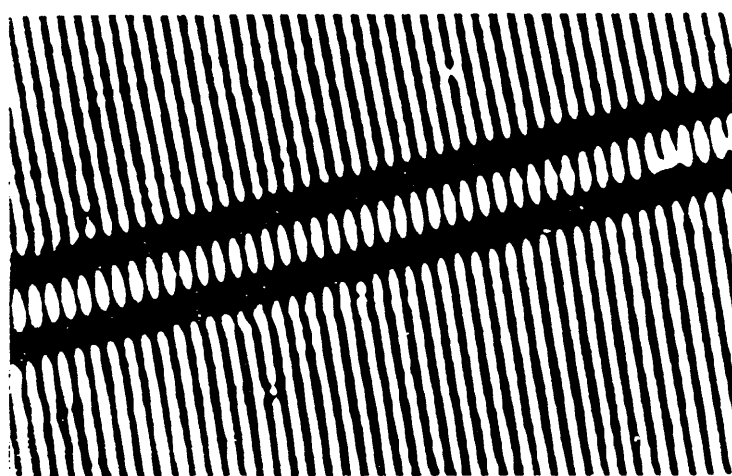
600 lines/mm. The same technique should be applicable for gratings of finer periodicities.

A polymer mixture was prepared by dissolving amorphous Polymethyl-Methacrylate in butanone. The refractive index of the solution can be varied from 1.48 to 1.525 by adding a suitable amount of Polyvinyl-Chloride. The solution was poured onto a horizontal slide, which was then brought to a vertical position for approximately 30 sec, allowing the excess solution to drip off. After the polymer film had partially dried for 2 min, it was pressed against the master grating, applying moderate force. The embossed grating pattern was hardened by baking for 1 hour at 120°C.

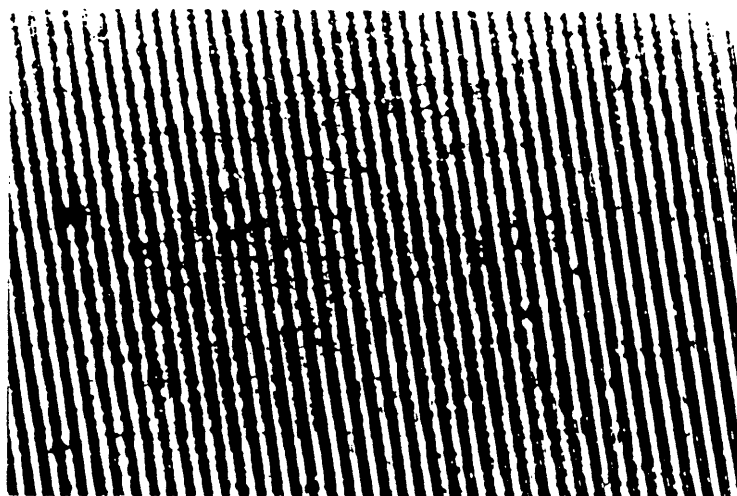
Fig.4.35.a shows a high quality embossed surface relief grating on a soft PMMA film. Embossed gratings were also successfully fabricated on optical fibers, coated either fixed on a plane substrate, (see Fig.4.35.b) or dip coated separately (see Fig.4.35.c). Although high quality, long grating-on-fibre lengths were fabricated, the moderate polymer film thickness prevented the grating presence from influencing the guiding properties of the fibre. It might be possible to emboss gratings of finer periodicities (0.4 μm) on thinner polymer films (0.2 μm). In that case, embossing would provide a simpler, faster and inexpensive alternative to conventional elaborate holographic methods for grating fabrication on optical fibre devices.



c)



b)



a)

Fig.4.35

Embossed grating patterns on PMMA films :

a) over plane surfaces ,

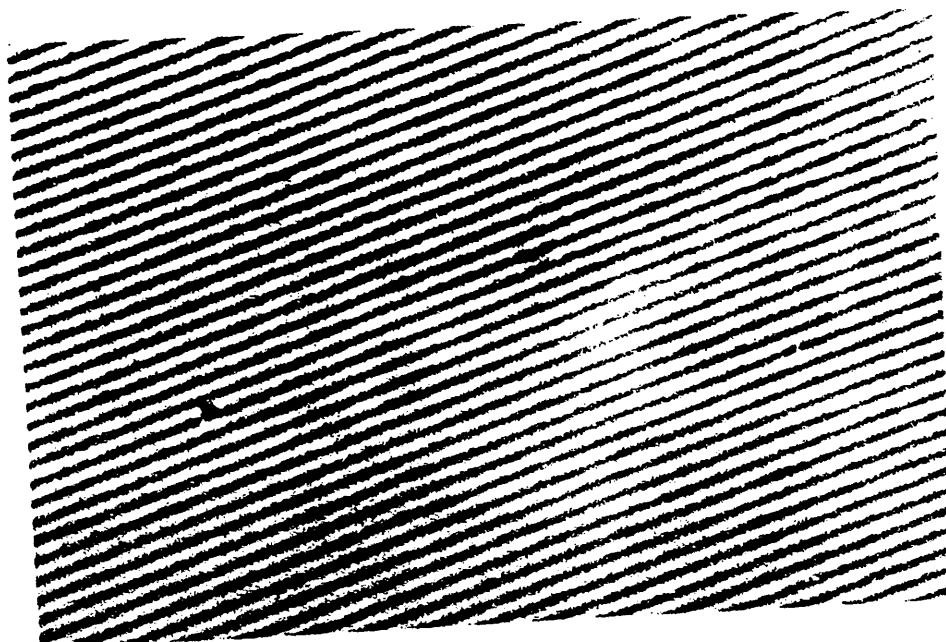
b),c) on dip coated optical fibres .

4.7 Grating Fabrication by Duplication

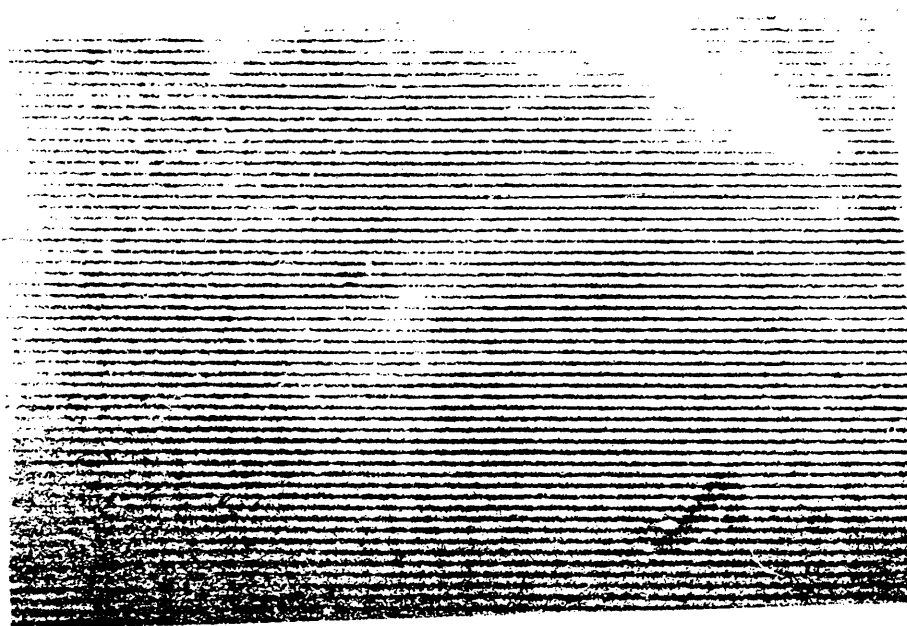
We have developed a technique similar to embossing, for fabricating large grating areas on flexible silicon rubber films. It requires a master grating of the appropriate periodicity, which is thoroughly cleaned, heated at 80°C for 20 min, and then covered by the silicon rubber solution. The solution solidifies after 10 min of subsequent baking, forming a clear optically transparent film, which can be easily peeled off giving a high quality grating replica.

We have used this simple duplication technique to fabricate high quality grating replicas of 600 lines/mm (Fig.4.36.a) and 1200 lines/mm (Fig.4.36.b) on silicon rubber, with the possibility of extending it to finer periodicities and to polymer films.

The periodicity of a silicon rubber grating can be easily tuned by stretching or compressing the rubber. Preliminary experiments, showed the reflection orders of a rubber grating illuminated by a HeNe beam, to move considerably when stretching the rubber film, denoting a change in periodicity. Such a tunable device may find application as an external tuning element for grating reflectors or couplers.



a)



b)

Fig.4.36

Duplicated grating pattern on a silicon rubber film.

a) 600 lines/mm , b) 1200 lines/mm

CHAPTER 5

EXPERIMENTAL WORK

5.1 Diffraction Experiments

Once grating-on-fibre lengths of the appropriate periodicity have been fabricated, the effectiveness of the grating can be qualitatively examined, by conducting simple diffraction experiments using a HeNe laser source. Since the source wavelength is shorter than that required for Bragg reflection, as defined by the grating periodicity, the guided optical power is gradually diffracted out of the fibre along the grating length (5.1 , 5.2) , with the output radiation emerging as one or more discrete collimated beams, propagating in free space at well defined angles φ_q , given by

$$\cos \varphi_q = N_{EF} + q \cdot \lambda_o / \Lambda \quad , \quad (5.1.1)$$

where N_{EF} is the effective index of the guiding medium, λ_o the wavelength of operation, i.e 633 nm for HeNe, Λ the grating periodicity, and q an integer denoting the diffraction order.

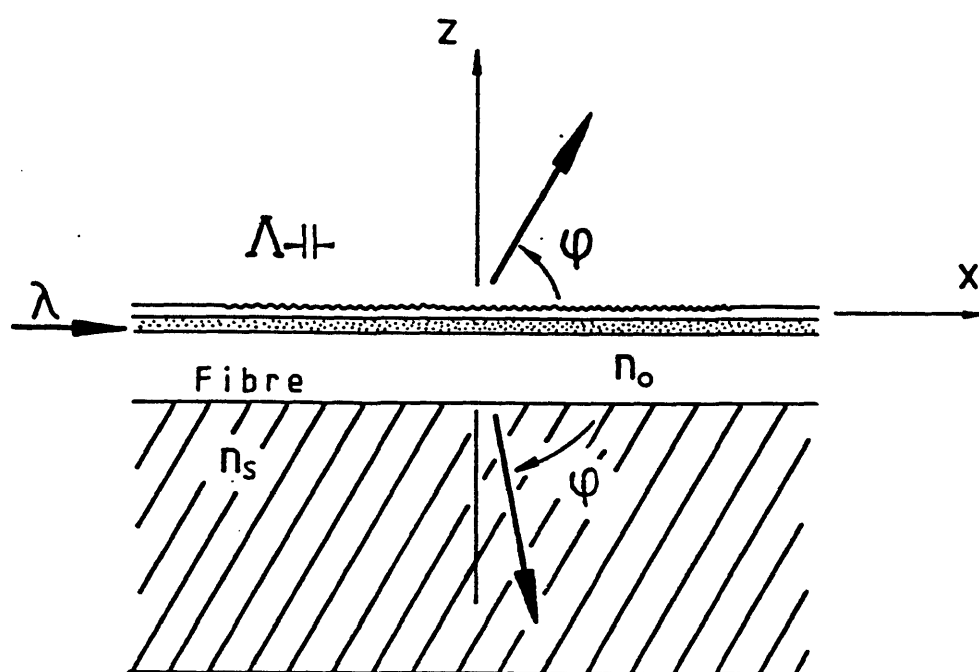
Light is also diffracted into the substrate, with the various diffraction orders appearing at angles φ'_q , given by:

$$\cos \varphi'_q = N_{EF} / n_o + q \cdot \lambda_o / (\Lambda \cdot n_o) \quad , \quad (5.1.2)$$

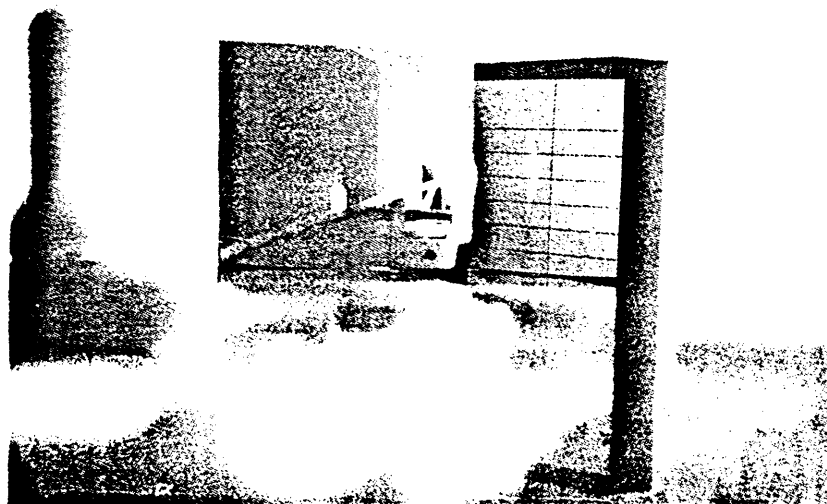
where n_0 is the substrate index. If N_{EF} is of the same order as λ_0/Λ , then φ_q is real for only one value of q , i.e. $q=-1$, and one diffraction order appears in each medium (see Fig. 5.1.a) .

We have used diffraction experiments to test gratings of periodicity $0.279 \mu\text{m}$ and $0.358 \mu\text{m}$, fabricated on two different types of D-shaped fibres, as described in chapter 4. The angle of the diffracted beam was accurately measured using a travelling screen attached to a micrometer arrangement, from which the diffraction angles were calculated to be 145° and 105° respectively. The A.C fibre used was single mode at 633 nm , with an effective index of 1.473 . The grating presence and the partial removal of the cladding alter the propagation characteristic of the fibre, changing its effective index. Assuming small variations in the effective index, the diffraction angle can be estimated directly from eq.5.1.1, to be 143° , for a grating of periodicity $0.279 \mu\text{m}$. In the same way, for a B.T. fibre with an effective index of 1.465 , the diffraction angle was estimated to be 108° , for a grating periodicity of $0.358 \mu\text{m}$. Note, that the B.T. fibre used was multimode at the wavelength of operation, although the diffraction spots corresponding to the different modes cannot be angularly resolved.

The above results appear to be in good agreement with the measured angles, given the uncertainty in both the effective index and grating periodicity values. Although measurements were only made for the beam diffracted into free space,



a)



b)

Fig. 5.1

Grating coupling into radiation.

- a) Schematic configuration of the grating coupler.
- b) Photograph of the coupler with the two diffraction spots clearly distinguishable.

similar calculations apply to the beam directed into the substrate, taking into account the refractive indices and thickness of the epoxy and the supporting coverslide, underneath the fibre body. A photograph showing the two diffracted beams emerging from both sides of the fibre is presented in Fig.5.1.b .

5.2 Grating Reflector Experiments

A fibre grating reflector can be evaluated using a tunable radiation source. For operation in the visible and near infra-red, tunable dye lasers appear to be the best candidates, delivering high power levels over narrow linewidths. At longer wavelengths, tunable F-centre lasers may be used to the same effect.

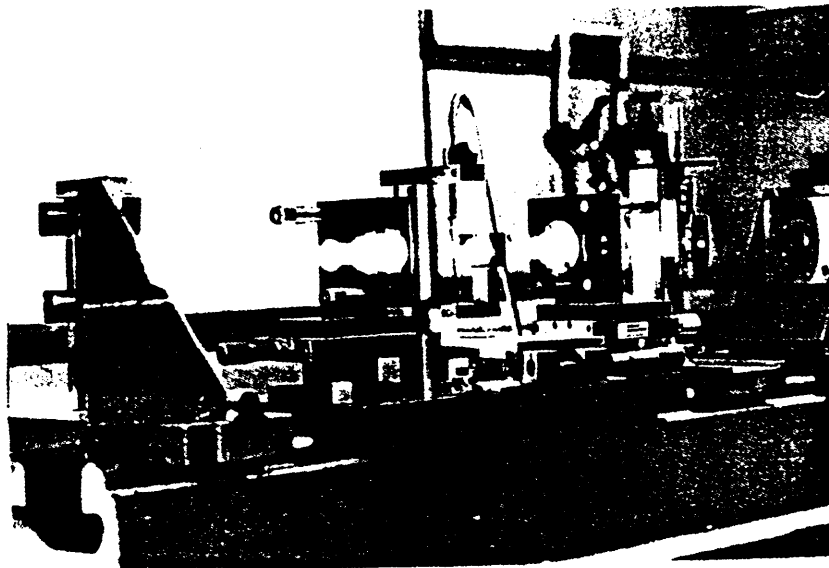
Alternatively, a white light source and a high resolution monochromator, with a stepping motor control and a low noise detection scheme, allow operation at low power levels. In both cases, for effective detection the linewidth of the grating reflector should not exceed the resolution of the monochromator.

5.2.1 DYE LASER EXPERIMENTS

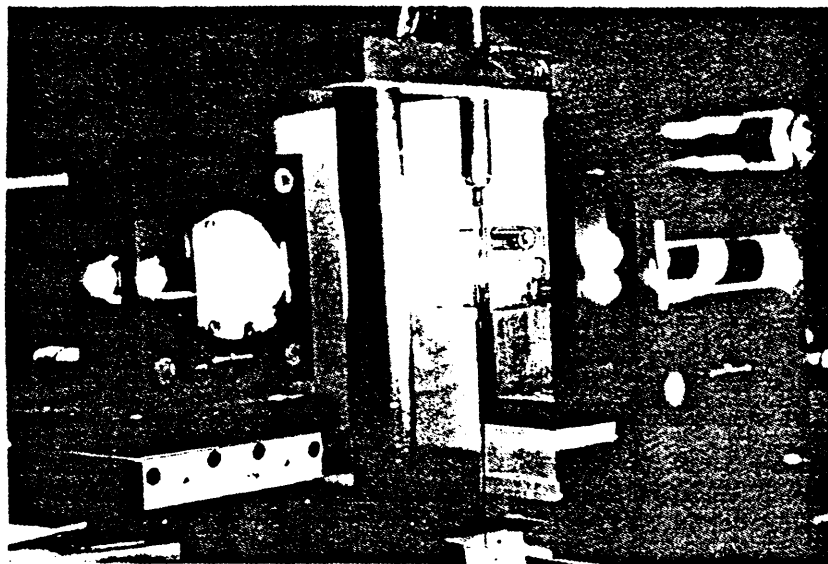
A fibre grating reflector, with a photoresist grating of periodicity $0.279\ \mu\text{m}$ fabricated on an A.C D-shaped fibre, for operation around $800\ \text{nm}$, was tested using a tunable Styryl 9 Dye Laser.

i) The Dye Laser: Construction and Calibration

The experimental Dye Laser configuration is shown in Fig.5.2.a. It operates on a three mirror cavity (5.3), pumped by a 6 W Argon laser at full power. The pumping beam is directed by the input (pumping) mirror, towards a vertical jet of a Styryl 9 Dye solution in Ethylene Glycol and Propylene Carbonate (see Fig.5.2.b) . The radiation is absorbed by the dye, exciting its molecules into a higher energy state. Most of the excited molecules then decay to the ground state, resulting in the spontaneous emission of photons (5.4). Lasing action occurs only when the mirror cavity is properly aligned. The spherical mirrors must be accurately positioned to focus and overlap their fluorescence spots on the flat output mirror, which is then adjusted to retrace their path back to the central cavity. For a near alignment position, the laser goes into operation. At this point, the pumping power is reduced, and the cavity components are re-adjusted. The process is repeated, until the laser threshold, i.e. the minimum pumping power required for lasing action, is reached for an optimum mirror alignment. For a fresh dye solution, a threshold power of



a)



b)

Fig. 5.2

Photographs of the experimental Styryl 9 Dye Laser.

a) Overall view.

b) Dye jet, pumping mirror and spherical mirror cavity.

500 mW was originally measured, which after two weeks increased to 3 W . No further deterioration was observed over a period of five weeks. The lifetime of the laser was increased, by cooling the dye solution throughout operation.

The laser emission spectrum shown in Fig.5.3 , is centred at 813 nm , with a spectral width of 3 nm . The nominal wavelength and bandwidth of the emission spectrum can be considerably shifted, by changing the concentration of the dye solution (5.5, 5.6). For an output mirror of 95 % reflectivity, a moderate power output of 15 mW was obtained. The full available bandwidth can be only accessed, by introducing a tuning element in the laser cavity (5.7), as shown in Fig.5.4.a . A high selectivity double birefringence filter was used, driven manually by a micrometer, placed in agreement with the polarization of the dye laser, and at Brewster's angle to minimise reflection loss. The output power can be sampled, either from the cavity mirror or from the birefringence filter, with different lines selected by rotating the micrometer of the filter. The emission spectrum of the mode locked continuous dye laser is presented in Fig.5.4.b , with a spectral width of 0.17 nm . By analysing the laser output for different micrometer settings the micrometer was calibrated over the available wavelength spectrum, with the calibration curve given in Fig.5.5.a . The micrometer scale did not vary linearly with wavelength, its step size increasing for shorter wavelengths, i.e larger micrometer readings. The useful spectrum extended from 841 nm (micr. setting -20) to below 821 nm (120),

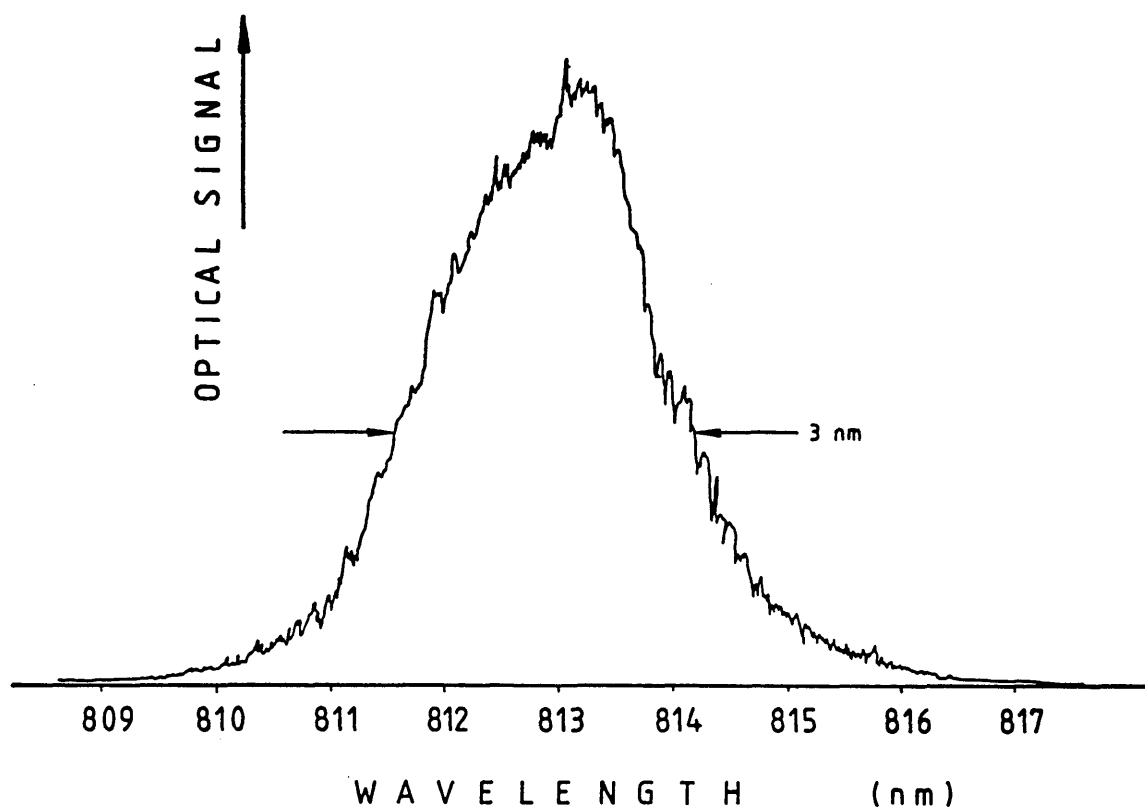


Fig. 5.3

Emission spectrum of the Dye Laser without a wavelength selective element in the laser cavity.

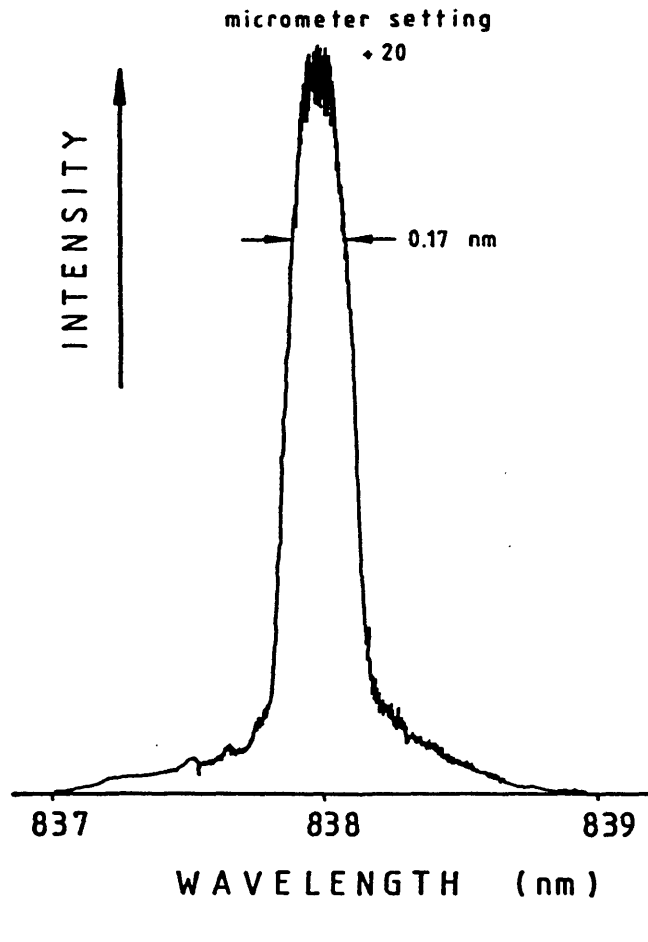
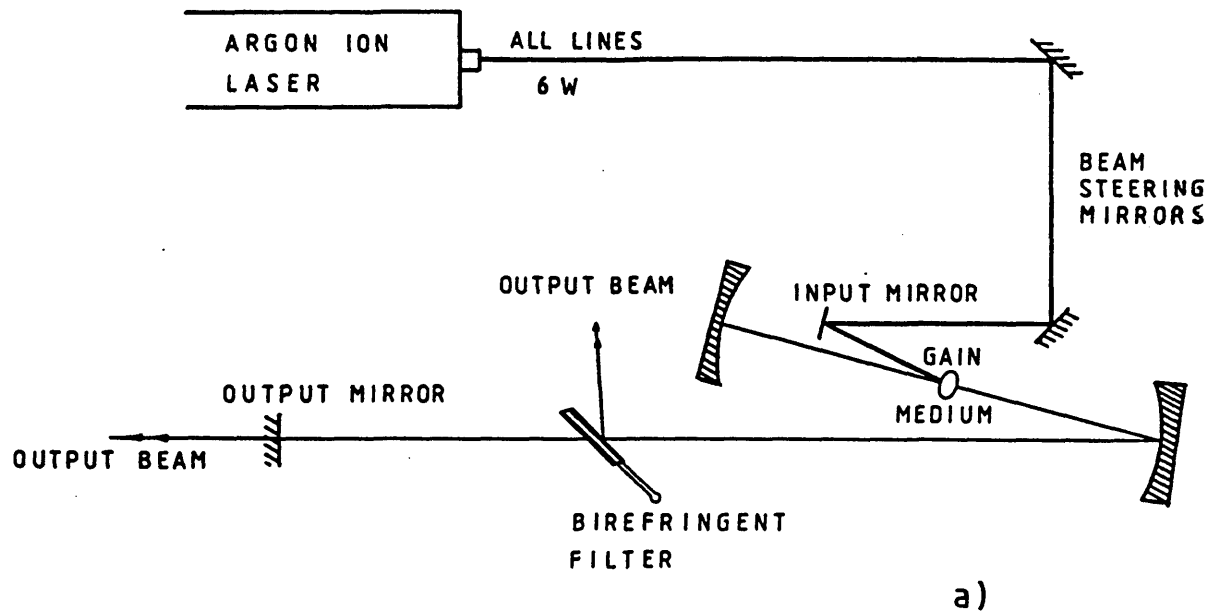


Fig. 5.4

Mode locked Dye Laser with birefringence filter for wavelength tuning. a) Schematic configuration of the Dye Laser. b) Emission Spectrum.

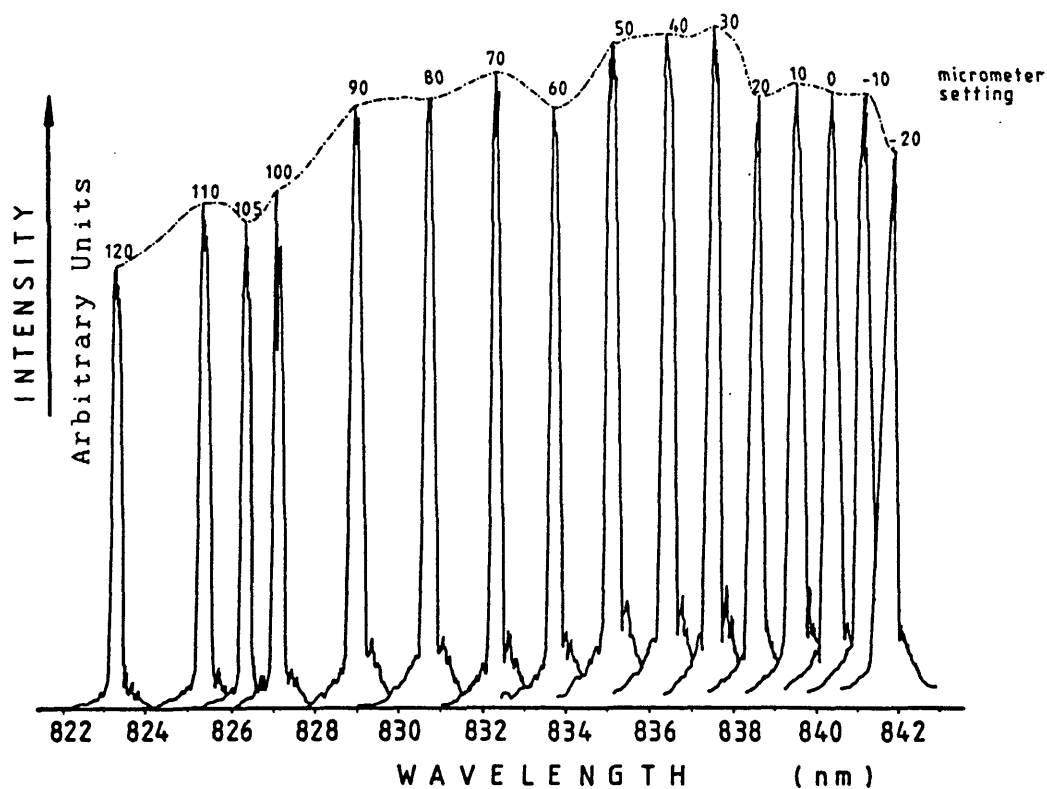
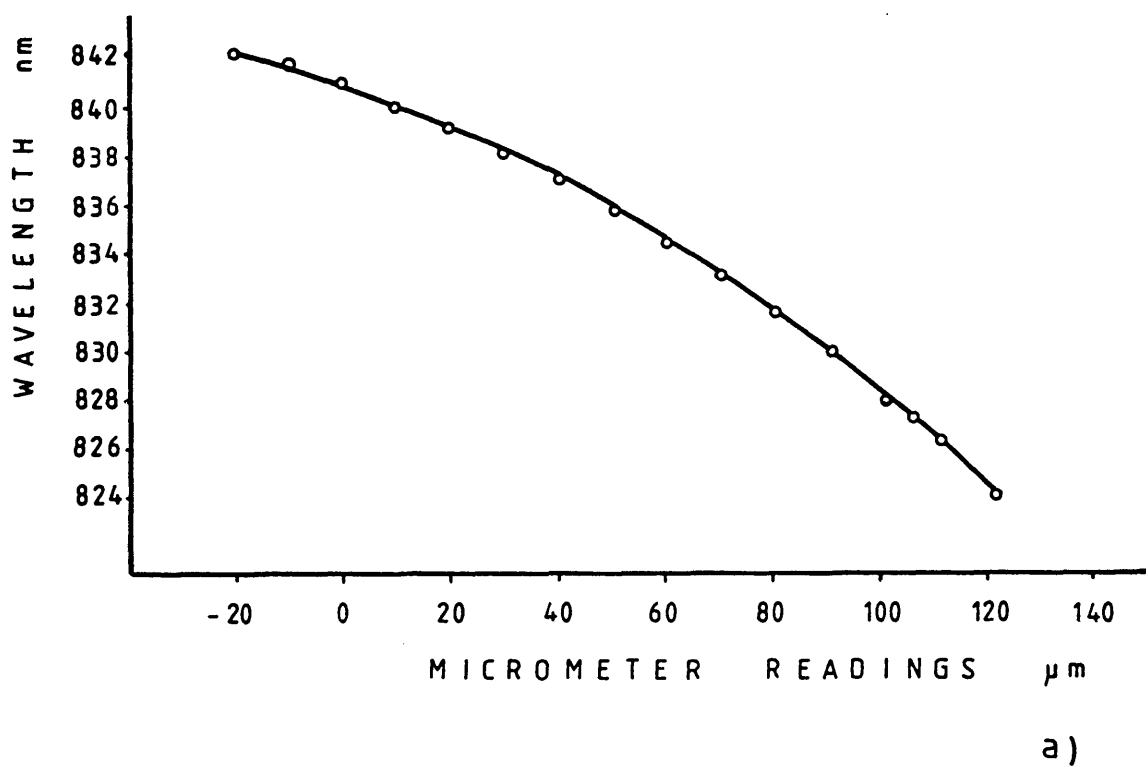


Fig. 5.5

- a) Calibration curve of the tuning element.
- b) Available tuning range for different settings of the birefringence filter.

as shown in Fig.5.5.b . Even though lasing continues above 841 nm , these wavelengths were beyond the tuning range of the filter and could not be sampled. Fluctuations in the output power level were mainly due to vibration pick up of the discrete cavity components, from the near-by motor, driving the dye jet.

ii) Experimental Procedure and Results

The experimental arrangement is shown in Fig.5.6 . The Dye laser output beam was divided by a beam splitter, prior to launching into a cleaved D-shaped fibre grating reflector, via a x40 microscope objective. The beam splitter serves a double purpose; it divides the input beam for in situ monitoring of the wavelength of operation, and at the same time provides an output path for the reflected signal. For monitoring purposes, the reflection from the birefringence filter could also be used. Both the "through", i.e. the direct fibre output, and reflected signals were detected by silicon photodiode circuitry, with an additional low pass filter for reducing fluctuations, caused by vibration of the optical components in the laser cavity. The reflected signal includes reflections, not only from the fibre-grating, but also from the lens and fibre end, though the latter are not expected to be very wavelength dependant. The intensity variation of the "through" and reflected signals were recorded at different wavelengths, and their characteristics are presented in Figs.5.7.a,b . The transmission characteristic shows an absorption band centred at 837.7 nm, with a

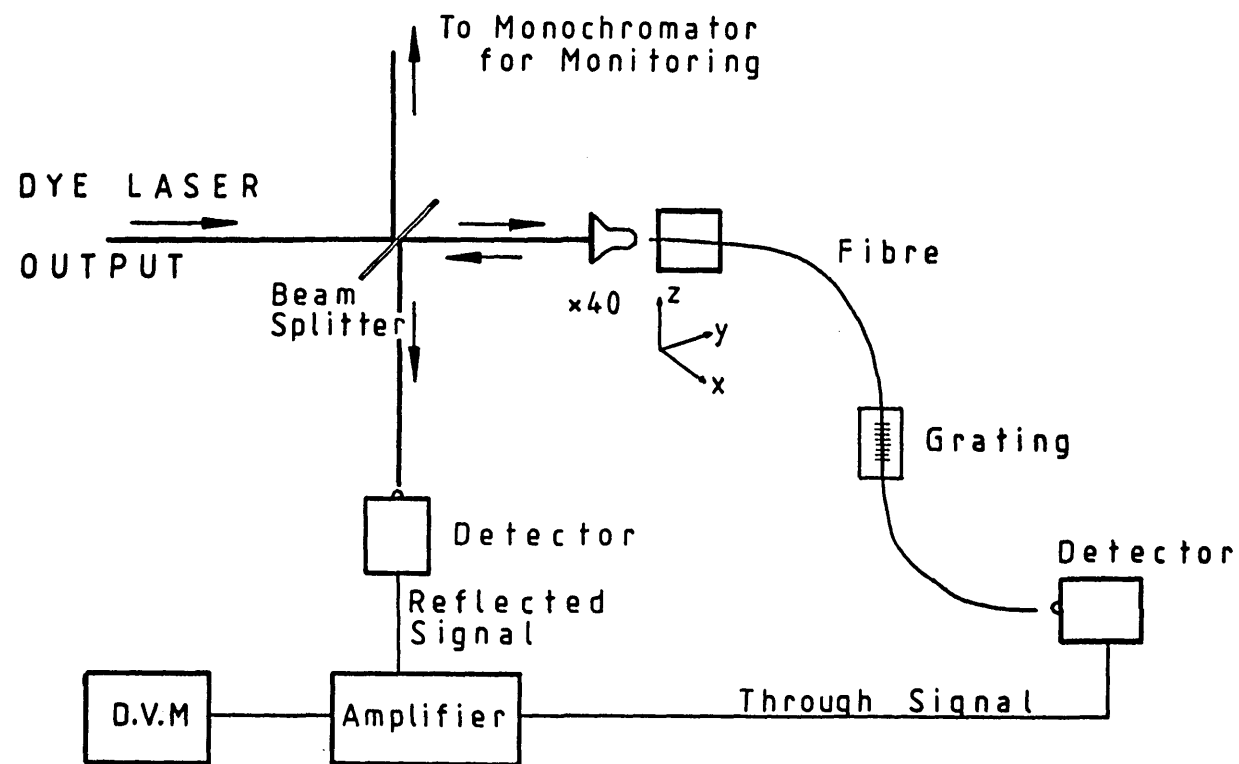


Fig. 5.6

Experimental setup for testing grating reflectors with a tunable Dye Laser.

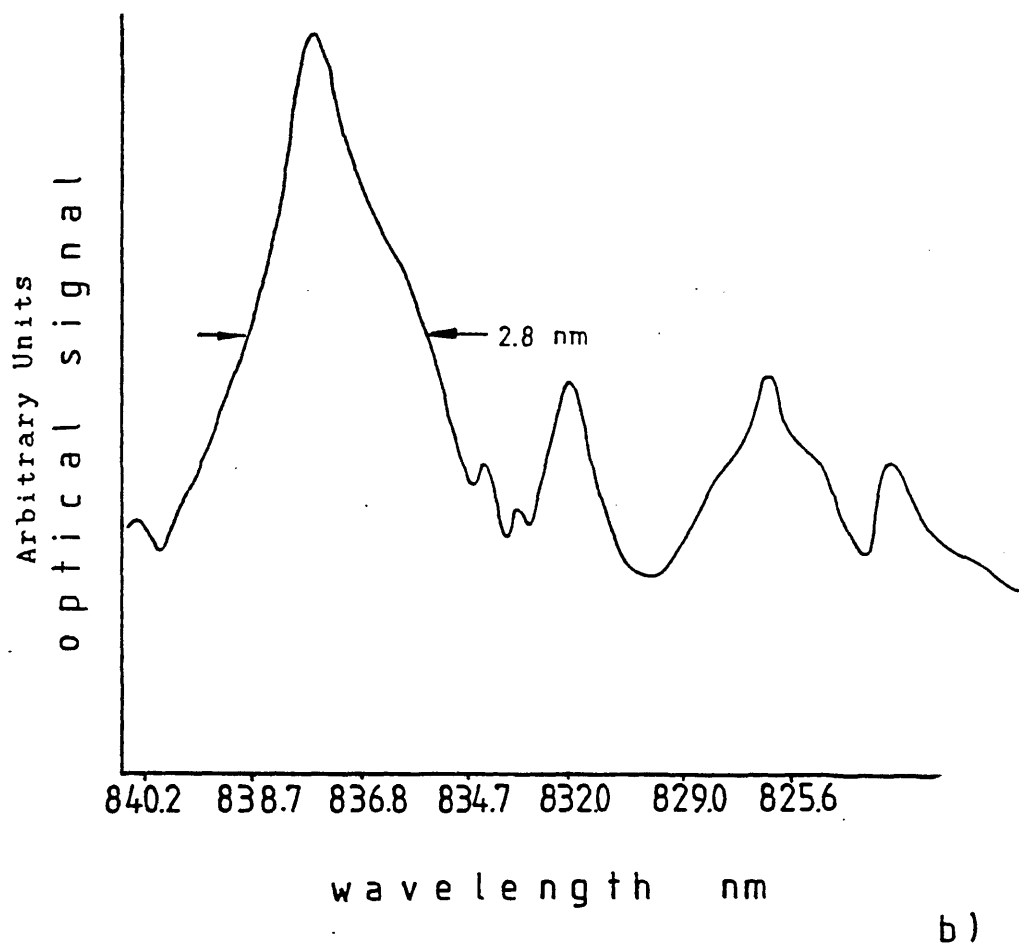
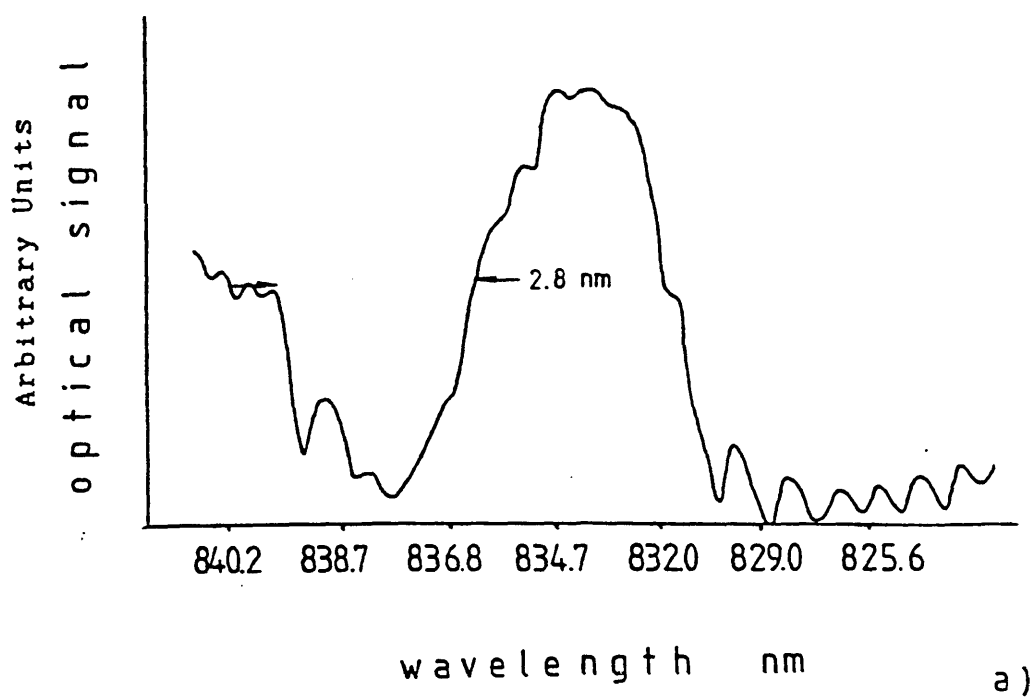
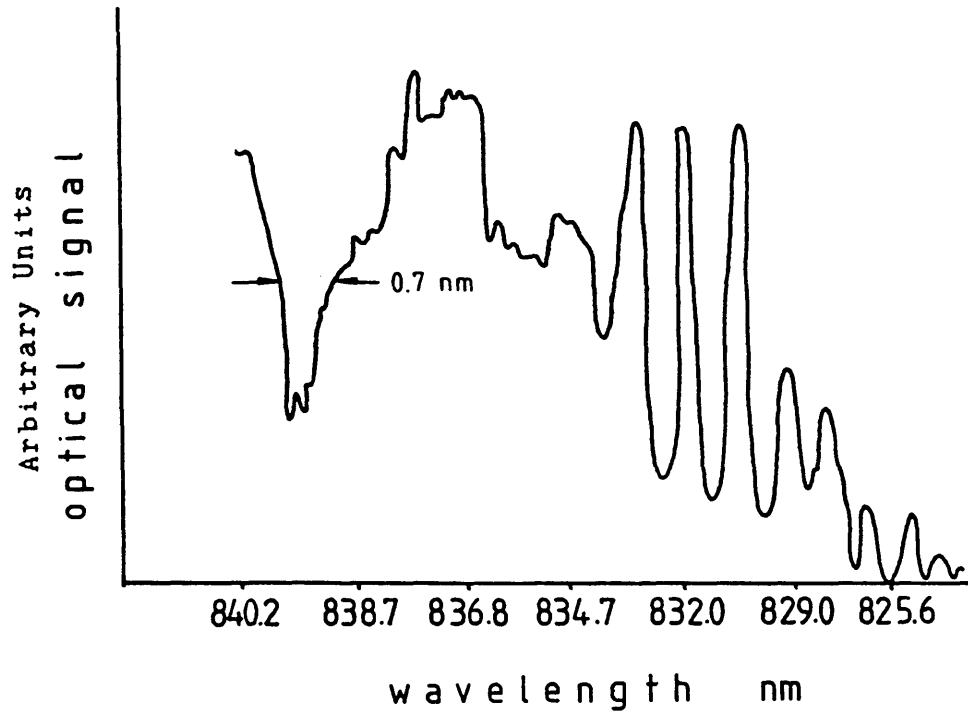


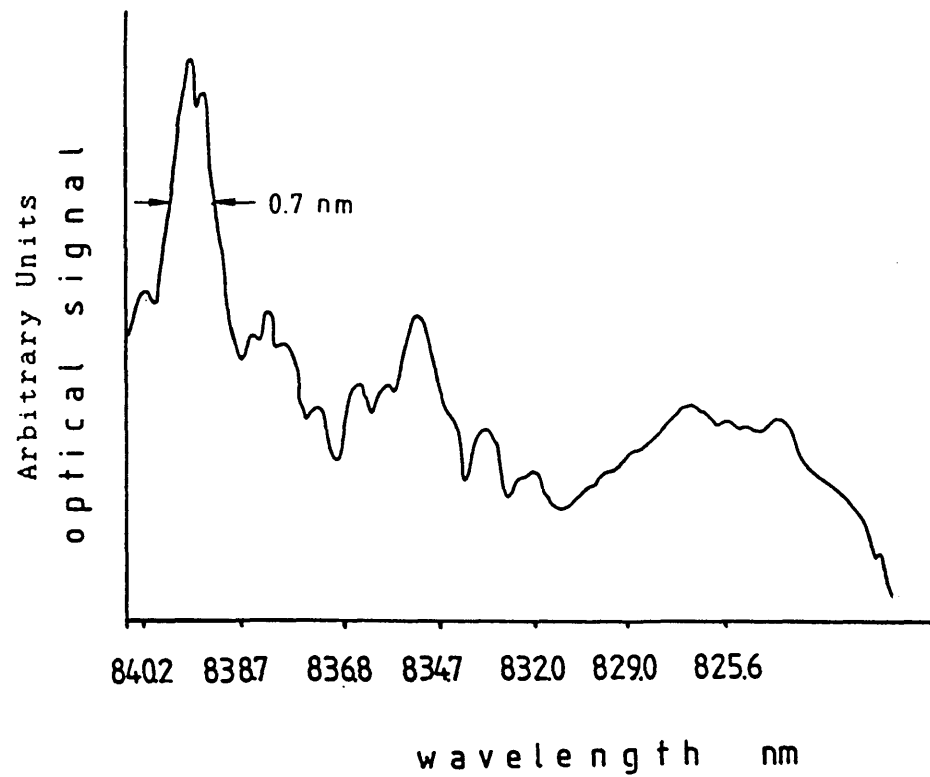
Fig. 5.7

Transmission (a) and Reflection (b) characteristics of a fibre grating reflector with air as the outer cladding.

bandwidth of 2.8 nm , corresponding to a reflection peak of similar dimensions in the reflected signal. For wavelengths below 832 nm, the transmitted signal level drops considerably, due to coupling into radiation modes, effected by the grating periodicity. The reflectivity was estimated from the transmission characteristic to be 90 % . Variations in the refractive index of the outer material affect both the field distribution and coupling strength of the grating reflector. The previous results were obtained for a grating surface exposed to air, and thus for a very large index perturbation. By using a distilled water cladding instead, i.e. $n = 1.33$, the coupling strength was reduced, resulting in a narrower bandwidth for the same grating length and, therefore, in lower reflectivity. Additionally, changes in the outer cladding index influence the propagation characteristic of the fibre, shifting the matching wavelength of the grating reflector. The transmission and reflection characteristics of the grating reflector for a distilled water outer cladding, are presented in Figs.5.8.a,b . The central wavelength has shifted to 839.15 nm, with the bandwidth reduced to 0.7 nm and the reflectivity estimated at 70 % . Small shifts in wavelength can be justified in terms of drift and misalignment in the laser cavity. Even narrower bandwidths at lower reflectivities can be achieved by using higher index oil claddings, thus weakening even further the effect of the perturbation.



a)



b)

Fig. 5.8

Transmission (a) and Reflection (b) characteristics of a fibre grating reflector with distilled water outer cladding.

5.2.2 MONOCHROMATOR EXPERIMENTS

A standard Bentham M300 monochromator with stepping motor control was used to investigate grating reflectors on both A.C. and B.T. D-shaped fibres. The experimental set up is schematically outlined in Fig.5.9. Light from a general purpose halogen lamp, controlled by a current stabilised power supply, was focused on the monochromator input slit using a suitable condenser lens. The output radiation was collected by a lens arrangement and launched into the fibre, with a low noise photodiode circuitry detecting the optical signal at the other end. The detection sensitivity was enhanced by modulating the source light with a chopper and separating the signal with a lock-in amplifier. The monochromator selectivity is directly related to the slit size, but even though a resolution of less than 0.6 nm can be obtained, for the appropriate slit size, i.e less than 50 μm , the optical signal is considerably reduced in intensity. The available resolution is, therefore, limited by the noise level of the detector circuitry, and is of the order of 0.6 nm, for a silicon photodiode operating around 800 nm. For operation above 900 nm, the significantly higher noise level of germanium detectors lowers the monochromator resolution to 1 nm at best.

i) Operation at 800 nm

The operation of the A.C. grating reflector, previously tested with the dye laser, was also verified with a mono-

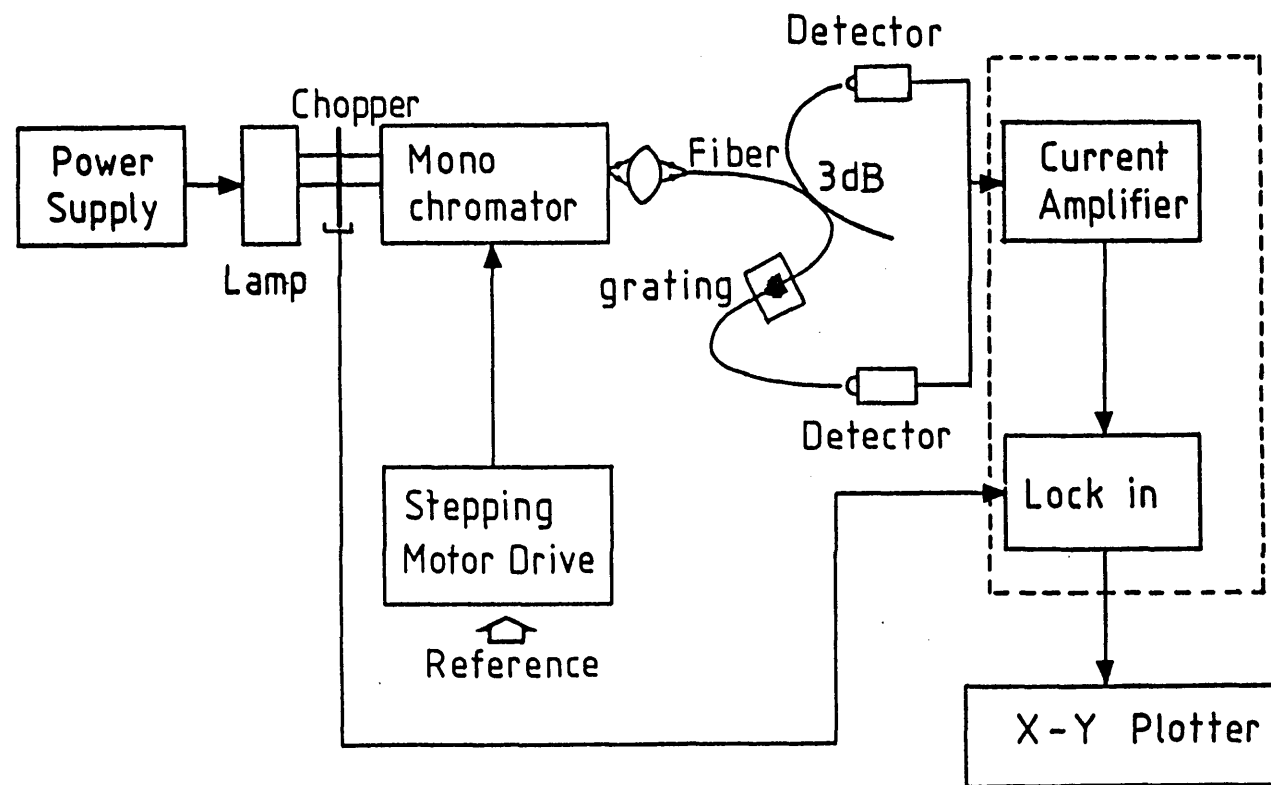
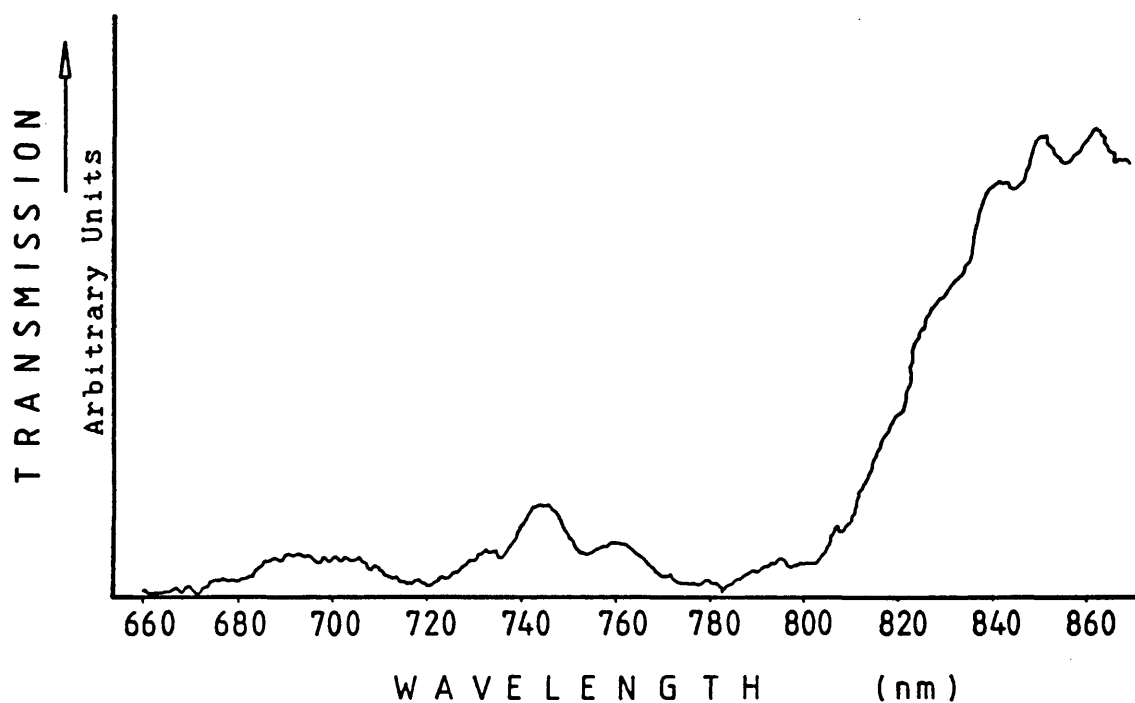


Fig. 5.9

Experimental configuration for testing fibre grating reflectors with a broad band source and a high resolution monochromator.

chromator experiment. The fibre was set up, as described earlier in the section, with the output detected by a silicon photodiode connected through a lock-in amplifier to an X-Y plotter. For a 1 mm slit size (i.e. resolution 10 nm), the monochromator output was scanned from 600 nm to 860 nm at a constant speed, and at the same time the variation in the output light intensity was recorded, presented in Fig.5.10.a. Even though, due to the poor monochromator resolution, an absorption band is not clearly distinguishable in the transmission characteristic of the fibre reflector, there exists a transition band around 830 nm, below which the output level drops sharply by grating coupling into radiation, while for higher wavelengths, the output remains unaffected by the grating presence. The monochromator selectivity was enhanced by reducing the slit size to 50 μm , with the output variation recorded for a slow scan over the transition band, as presented in Fig.5.10.b. An absorption band is clearly centred around 838 nm, with a bandwidth of 2.4 nm, and appears to be in very good agreement with the results obtained in the dye laser experiments. A neighbouring absorption band is probably caused by reflection of the vertical polarization of the elliptical, polarization preserving fibre. The monochromator light is unpolarized and, therefore, both polarizations are excited. Theoretical calculations show the reflection bands corresponding to the two polarizations of the elliptical waveguide for the same grating periodicity to be 2 nm apart, which is in close



a)

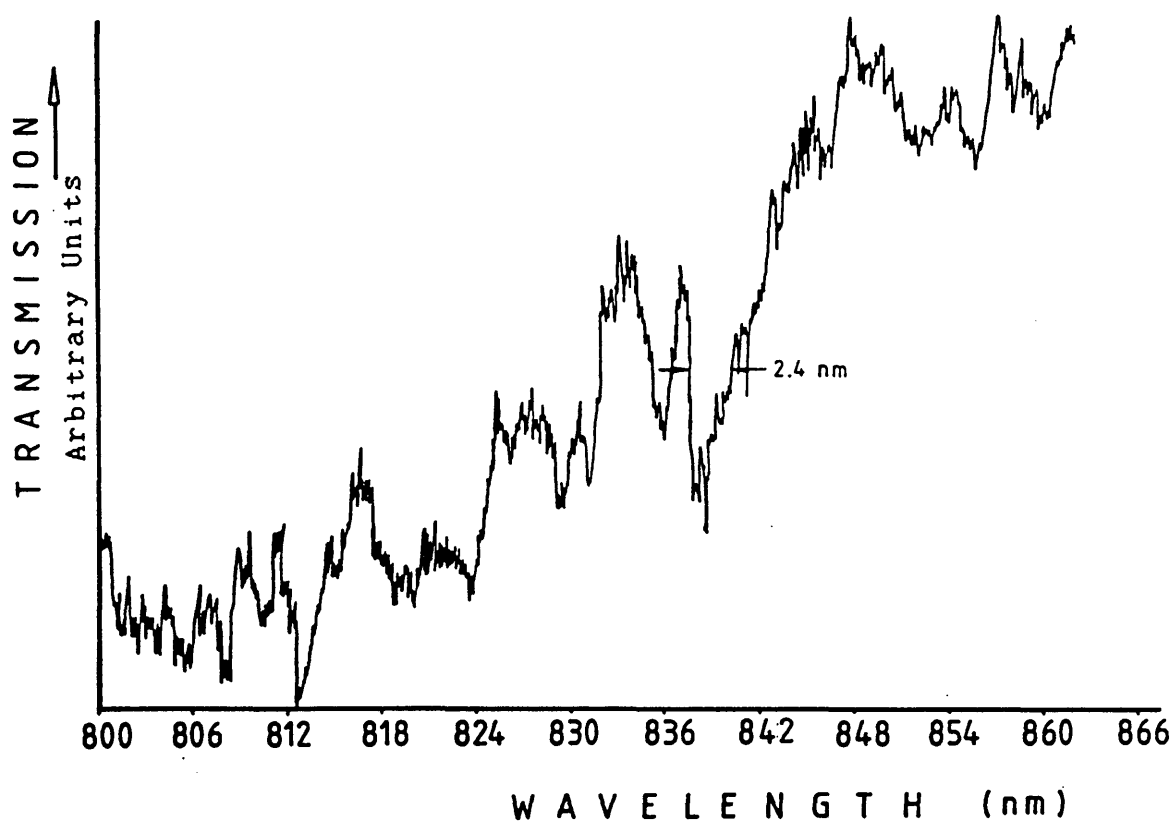


Fig. 5.10

b)

Transmission characteristics of a grating reflector for operation around 800 nm . a) Low resolution .

b) High resolution .

agreement to the picture of Fig.5.10.b . The dye laser light was horizontally polarized, so there was no reflection associated with the vertical polarization state of the fibre.

Due to the low power level, a beam splitter cannot be effectively used to sample the reflected signal. This is possible by means of a forward coupler, fabricated in the fibre length prior to the grating. An optimum splitting ratio of 3 dB is required for a maximum recovery of 25 % of the reflected signal. A suitable coupler for this purpose was only developed using B.T. fibre, for operation around $1\text{ }\mu\text{m}$.

ii) Operation around $1\text{ }\mu\text{m}$

A fibre grating reflector, realised by fabricating a photoresist grating of periodicity $0.338\text{ }\mu\text{m}$ on a B.T. fibre for operation around $1\text{ }\mu\text{m}$, was investigated using the monochromator arrangement of Fig.5.9 , with a germanium photodiode. Its transmission characteristic is presented in Fig.5.11 , for different external cladding media; air (i) and distilled water (ii), compared to the photodiode characteristic (iii). Even though it was not possible to distinguish a clear absorption band corresponding to the reflected signal, a sharp transition from radiation into guiding around $1\text{ }\mu\text{m}$ denotes the grating presence. The transition band shifts for variations in the outer cladding index, that alter the propagation constant of the fibre.

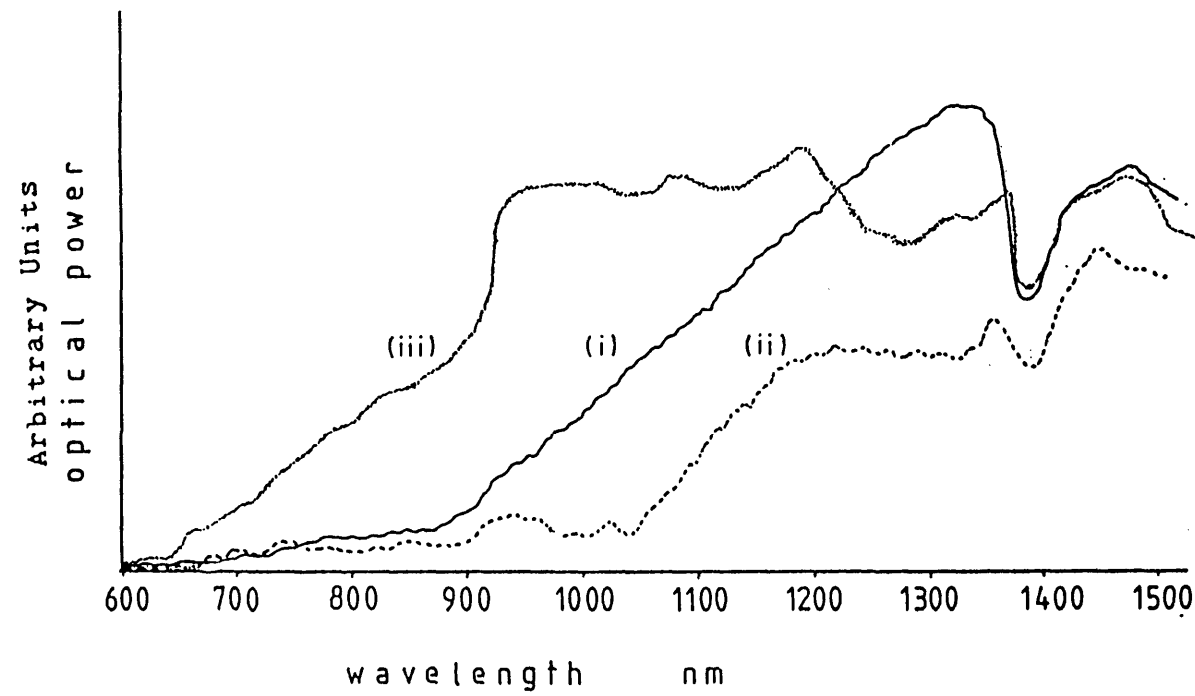


Fig. 5.11

Transmission characteristics of a grating reflector for operation around $1\text{ }\mu\text{m}$ for air (i) and water (ii) outer claddings.

The reflected signal was partly recovered by employing a directional coupler, effectively acting as a beam splitter, in the fibre length prior to the grating. The coupler was fabricated, initially by etching the fibre sections down to within $1\text{ }\mu\text{m}$ of their core, and then aligning them suitably, with their flat sides facing each other along the etched region. A small drop of index matching oil ensured good contact, by means of surface tension. The process was monitored by recording the transmitted and coupled intensities throughout alignment, and by controlling the interaction length for an optimum splitting ratio, as shown in Fig.5.12. In order to improve the coupling ratio at the appropriate wavelength range, and select the required detector sensitivity, the output fibre end of the grating reflector was temporarily butted with matching oil against a mirrored surface, and the reflected signal, passing twice through the coupler, was detected from the back end of the separate fibre, where the grating reflection was also expected. By varying the interaction length of the directional coupler, the overall reflected signal was increased over the wavelength region 900 to 1100 nm, as shown in Fig.5.13.a. Even though it was not possible to achieve the favourable 3 dB splitting ratio over the wavelength range of interest, when the mirror was removed from the fibre end, a feeble, but clear reflection band was observed (see Fig.5.13.b) at 901 nm, with a coupled bandwidth of less than $12\text{ }\text{\AA}$, and a reflectivity around 50 %, for an oily cladding of 1.45. The signal level can be improved by

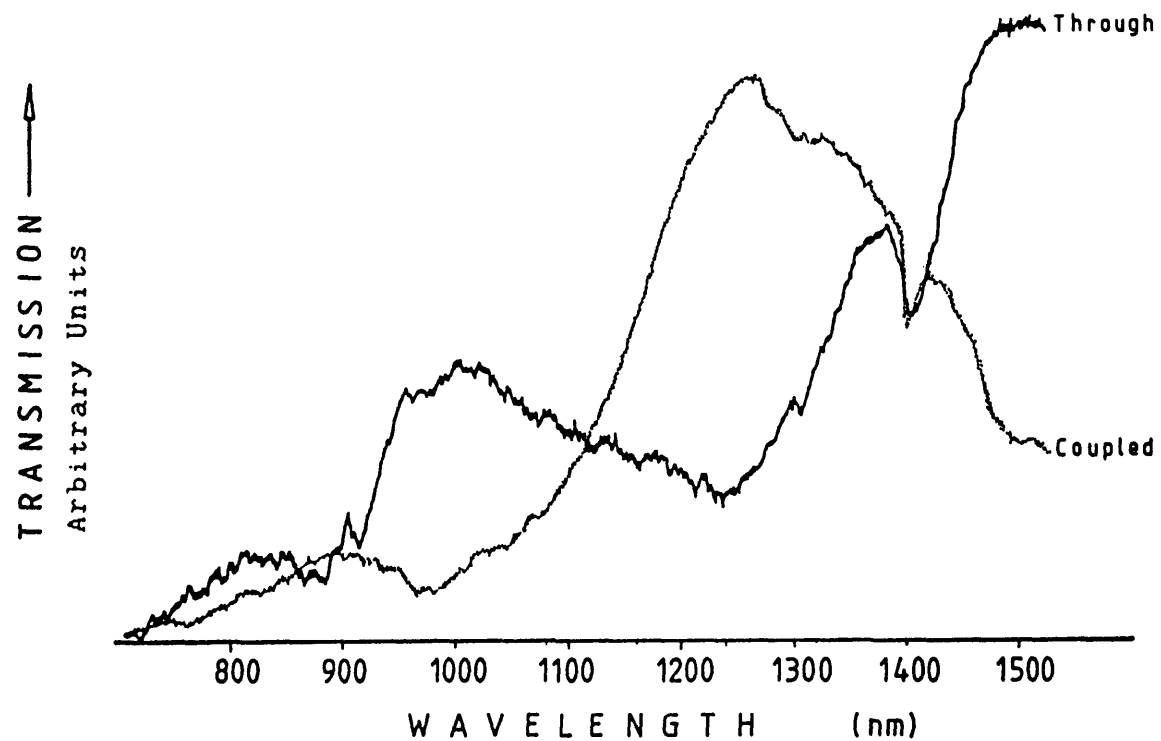


Fig. 5.12

Transmission characteristics of a grating reflector for operation around 1 μm with a forward coupler in the fibre length prior to the grating.

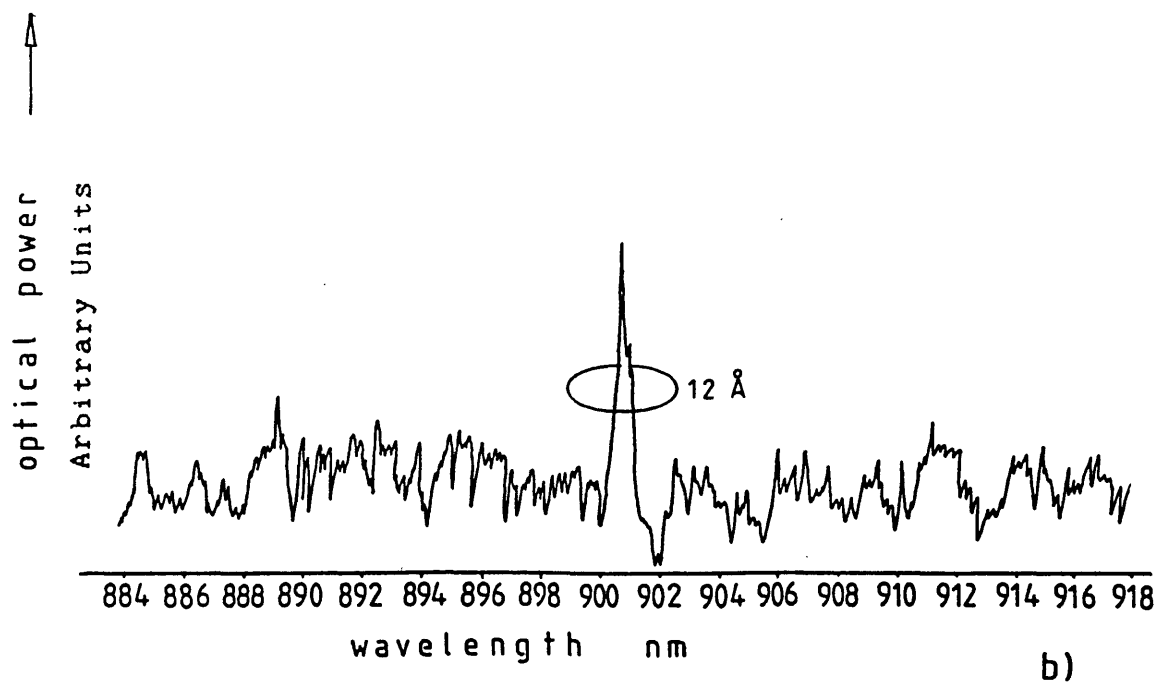
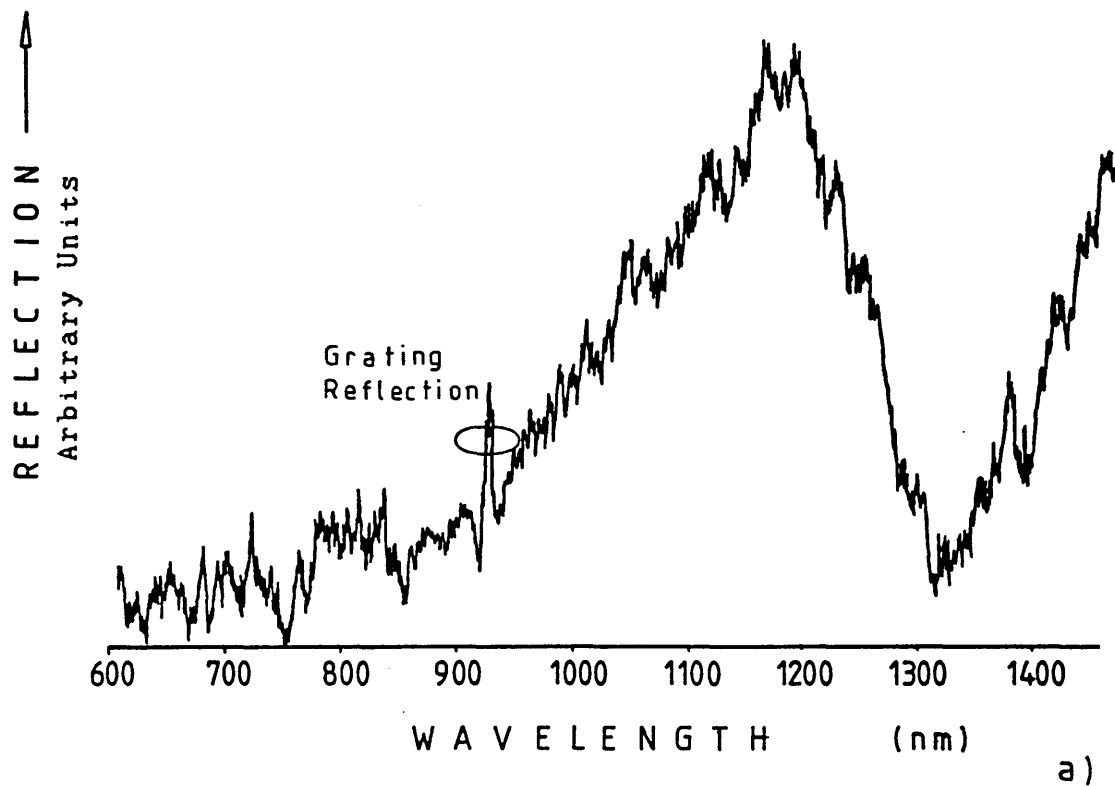


Fig. 5.13

Reflection characteristic of the fibre grating reflector as sampled by the directional coupler.

a) For a fibre end butted against a mirrored surface.

b) For a fibre end in index matching oil to avoid reflection.

increasing the forward coupling strength, either by etching the fibres closer to the core, or by using an intermediate oil of higher index.

5.2.3 THEORETICAL VERIFICATION

The operation of a grating reflector has been demonstrated in the previous section for two different types of D-shaped fibres. An attempt will be now made to fit the experimental results in a theoretical model.

Fig.5.14.a,b shows schematically, cross-sections of the two different waveguides in the corrugated region.

The A.C fibre (Fig.5.14.a) is an elliptically cored, polarization maintaining fibre (major/minor axis=2.17), with a large core/cladding index difference ($\Delta n=0.035$). It is nonomode above 633 nm, so at the wavelength of operation (840 nm) it is expected to be guiding weakly, with a large portion of the total field in the outer cladding, making the presence of the perturbation more effective. The curved profile, caused by the faster etching rate of the depressed cladding, gives a peculiar shape to the field pattern, which is difficult to formulate.

The B.T fibre (Fig.5.14.b) on the otherhand is a standard communication fibre, with a relatively small index difference ($\Delta n=0.0063$) and a large diameter (8.1 μm). At the wavelength of operation (1 μm) it is expected to be slightly

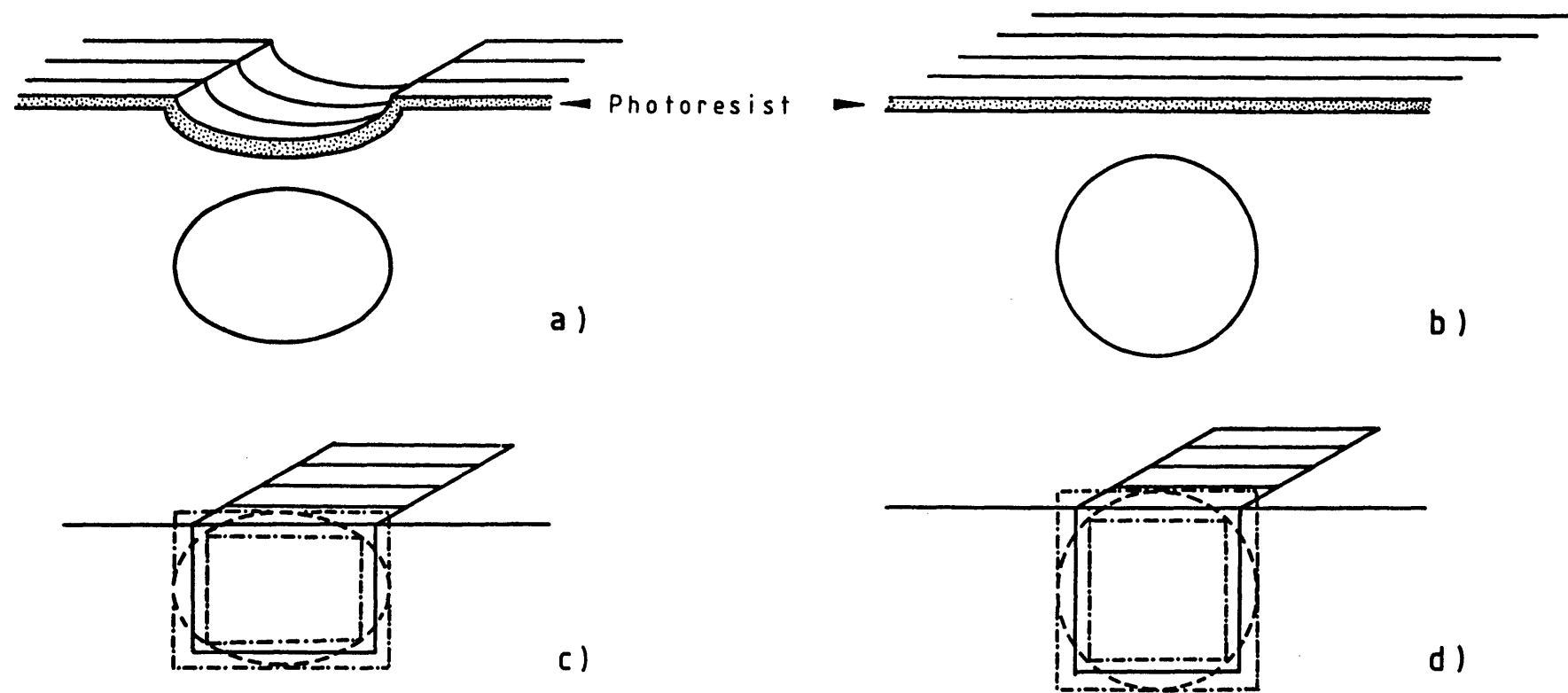


Fig. 5.14

Schematic configuration of cross-sections of the different D-shaped fibres in the corrugated region.

a) A.C. fibre , b) B.T. fibre .

c,d) Equivalent structures for theoretical verification.

multimode and guiding strongly, with less field in the cladding, which reduces the effect of the perturbation. In both cases the photoresist grating, fabricated on a thin lossy film of index 1.65 and thickness $0.15\text{ }\mu\text{m}$, may increase the effect of the perturbation by stimulating more field into the cladding, but complicates the exact analysis even further, by introducing an extra lossy layer in the index distribution of the guiding structure.

Instead of analysing the exact complex configuration, it is more convenient to assume an "equivalent" rectangular waveguide model, with the same propagation characteristics at the wavelength of operation. "Equivalent" structures of the two waveguides are presented in Fig.5.14.c,d respectively. The A.C. elliptical waveguide has been replaced by a rectangular waveguide of the same index distribution and dimensional ratio, with the propagation constants at both polarizations, approximately matched for a uniform cladding at the wavelength of operation. The matching dimensions fit between those of the rectangles, inscribed and circumscribed by the elliptical core. The model can be then analysed with its perturbed top face exposed to an external cladding medium. For a realistic perturbation amplitude of $0.09\text{ }\mu\text{m}$, the coupled bandwidth was calculated to be approximately 2 nm with an air cladding and 0.9 nm with a distilled water cladding, which is not far from the experimental values (2.4 and 0.7 nm respectively). The shift in the central wavelength of reflection, from air to water claddings was estimated to be 1.36 nm, in close agreement to the measured

value of 1.45 nm . An accurate estimate of the reflectivity, would require knowledge of the grating length. Even though high quality grating lengths of up to 2 mm (as measured by SEM) have been fabricated on fibres, the exact length of the grating in the fibre under investigation was not known. If a 2 mm grating length is assumed in the rectangular waveguide model, the estimated reflectivity of 99.99 % for both claddings is very different from the measured 90 % and 70 % values. The discrepancy is probably due the effect of the photoresist film thickness on the coupling efficiency (5.8), which has been completely neglected in the analysis. For an "effective" grating length of 180 μm , however, the rectangular waveguide model gives reflectivities of 94 % and 68 % for air and water claddings respectively, close to the measured values.

The circular core of the B.T. fibre was approximated to a square waveguide with the same propagation constant at the wavelength of operation. As expected, the "equivalent" waveguide dimensions (7.37 μm x 7.37 μm) lay between those of the squares inscribed and circumscribed by the circular core. For a perturbation depth of 0.4 μm and an "effective" grating length of 180 μm , the coupled bandwidth and reflectivity were calculated to be 1.01 nm and 46.7 %, which is in good agreement with the measured response.

The simple "equivalent" rectangular model, designed to preserve the propagation constant of the elliptical and circular waveguides at the wavelength of operation, appears to predict accurately the experimentally measured parameters for the grating reflector.

CHAPTER 6

DISCUSSION AND CONCLUDING COMMENTS

6.1 Discussion

Grating couplers and reflectors are characterised by very high wavelength selectivity, due to the wider intersection angle of their dispersion characteristics, and are expected to find extensive application in narrow-band filtering. Even so, a lot of improvement is still required both in design and fabrication in order to realize the potential sub-Å bandwidths, and overcome more conventional devices based on directional couplers, thin film filters and dispersive elements.

As a sensor for detecting changes in the outer cladding index, the contradirectional coupler is not more sensitive than directional couplers, even though the significant reduction in coupled bandwidth would provide more resolvable points for broad band operation, and allow the use of an L.E.D. or even a laser diode as a source.

Additionally, compared to periodic directional coupling, the exponentially decaying nature of the contradirectional

process does not require a "unique" accurate definition of the "beatlength", provided that the grating is long enough to reflect significant amounts of power.

Designs of grating couplers and reflectors, based on both slab and rectangular waveguide models, show potential coupled bandwidths of $0.1 \text{ \AA}$ and reflectivities of 95 %, for grating lengths of 2 cm.

In principle, there is no difference in the theoretical treatment of grating couplers and reflectors, although in the design of grating couplers dissimilar waveguides must be used, in order to isolate contradirectional from directional coupling and reflection in the individual waveguides.

By allowing, on the other hand, the different coupling processes to interact, the power is generally distributed between the four different ports of the device. The analysis of composite coupling processes, in both two and three waveguides, reveals some interesting filtering and switching characteristics. As a switch, the three waveguide coupler may prove more promising, with the interacting coupling processes in different waveguides, their strength independently adjusted, by controlling the separation between the central and side waveguides. For equal strengths the device behaves as a three port switch, with the input signal coming out from any of the three output ports. The switching action may be effected by suitably placed electrodes for an integrated optics implementation, with controlling voltage levels similar to those of directional coupler switches. The advantage of this device in comparison to the one based on

directional coupling between three waveguides is its relative insensitivity to variations in interaction length, for a sufficiently long grating. For stronger grating coupling the overall process assumes an exponentially decaying nature, with the optical power distributed among the output ports, the splitting ratio closely related to the coupling coefficients. In this respect, the three waveguide configuration may be used as a three port power divider.

The realisation of narrow bandwidth-high reflectivity grating reflectors and couplers is critically dependant on the successful fabrication of long grating-on-fibre lengths.

Nearly all the relevant work published by other researchers has been based on holographic grating fabrication on polished fibre blocks. Although this offers a rather simple fabrication procedure, using the well established techniques developed for the preparation of polished couplers, it imposes restrictions on the effective grating length, limiting the potential wavelength selectivity, for a given reflectivity. Typical published results refer to bandwidths of 10 Å and 85 % reflectivities, for a grating length of 2 mm. Even though narrower bandwidths have been reported for weaker coupling, the reflectivity appears to suffer from the limitation in grating length.

We strongly believe that this restriction can be removed by using special D-shaped fibres. Polished fibre blocks can be avoided by potting lightly etched sections of D-shaped fibres in a higher index epoxy, floating naturally, with their flat face on the surface, and fabricating the grating

using a standard holographic process. Provided that the fibre surface is flat, the surrounding medium acts only in removing the laser light of the interfering beams from the fibre body, eliminating reflections at the fibre/epoxy interface, during the exposure stage.

Earlier results showed grating lengths of only 2 mm, restricted by limitations imposed by the optical component sizes in the interferometer. More recently, grating lengths of up to 7 mm have been fabricated, with potential extension to 2 cm. Even though the grating profile could have been transferred directly into the fibre body, by reactive ion etching through the photoresist mask, most of the initial testing experiments were conducted with photoresist gratings, the higher refractive index of the thin photoresist film stimulating a higher portion of the guided field into the cladding, thus increasing the perturbation strength. In this sense, it acts in the same way as the additional thin Al_2O_3 layer, deposited over the etched grating surface by other researchers.

We have successfully fabricated and tested grating reflectors of different periodicities, for operation around 0.8 and 1 μm , using a Styryl 9 dye laser and a monochromator arrangement, demonstrating coupled bandwidths of 7 $\text{\AA}$ and reflectivities of approximately 70 %. These initial results are comparable to the best reported for polished fibre grating reflectors, and could be further improved by fabricating "weaker"-longer grating lengths, further away from the core. In order to make the gratings more durable and avoid loss

from the photoresist film, the grating pattern will have to be etched into the fibre surface. Grating lengths of 7 mm have only recently been successfully etched on D-shaped fibres.

By etching the grating into the fibre, thus eliminating the high index photoresist film, will weaken the perturbation strength, increasing the wavelength selectivities. For sub-Å bandwidths, the monochromator selectivity will not be sufficient, in which case, a spectrum analyser Fabry-Perot device will have to be used.

In respect of the grating fabrication, the realisation of the grating coupler is not different from that of the grating reflector.

We have again avoided polished couplers and designed a twin-waveguide integrated fibre, with the grating to be fabricated on its top flat face, in the same way as for the grating reflector. The fibre was only recently fabricated, so we did not have time to test such a device. It is anticipated, however, that the relative fabrication simplicity will be balanced by the complexity, in separating the optical signals from the two waveguides in the same fibre.

On the other hand, devices realised from discrete fibres offer four different detection ports. In this respect, a grating coupler could be realised using etched sections of D-shaped fibres with a grating fabricated on one of them, properly aligned by the capillary action of a thin intermediate matching oil layer. A directional coupler based on this principle has been realised with identical fibres

and tested, in sampling part of the reflected signal in a grating reflector configuration. It proved to be simple but effective, flexible and tunable, by varying the coupling length. For a grating coupler realisation, dissimilar fibres will have to be used (i.e. possibly one elliptically, the other circularly cored), to isolate contradirectional coupling from the other coupling processes.

Another interesting scheme, involves the use of a fused untwisted fibre coupler, properly integrated into a polished block configuration, with the grating fabricated on the polished interface, perturbing both waveguides. Such a design can easily incorporate some of the tuning techniques that are to be examined in the following section, to realise a tunable grating coupler with potential application in wavelength division multiplexing.

6.2 T u n i n g

The operation of grating couplers and reflectors can be greatly affected by fabrication tolerances. These variations result mainly from uncertainties in the grating fabrication (i.e. grating periodicity and modulation depth), and its effect on the waveguide parameters, but also from drifts due external influences. Some form of tuning is, therefore, essential for steering the device into operation at the appropriate wavelength. Although some limited amount of

tuning can be obtained through variations in the outer cladding index, by means of external parameters such as heat, pressure or electric field, a more significant effect can be expected by varying the grating periodicity. For gratings fabricated on the fibre surface, only small effects can be achieved by straining the fibre.

Instead of fabricating the grating on the fibre, it is possible to employ an external grating of the appropriate periodicity, pressed onto the flat fibre surface, close to the core, with a suitable index matching oily layer. Small rotation of the grating with respect to the fibre, results in limited tuning, by changing the effective periodicity as "seen" by the fibre, although for angles above 2° , the signal level appears to reduce considerably (1.45). Another more effective approach involves the use of a "fan"-shaped grating structure, in which the groove spacing (i.e. periodicity) varies continuously with position along its length. For a grating reflector configuration, such a grating can be scanned over the flat polished fibre section, changing the wavelength of operation. The same technique could be easily implemented with a polished, fused coupler block (see Fig.4.29.d), to realise a continuously tunable grating coupler. The use of a "fan"-shaped grating, though effective, appears to be somehow limited. The grating is usually fabricated lithographically (1.49), through a number of complicated masking processes, although fabrication by simpler interference methods has also been described (1.50). Additionally, the coupling efficiency is limited through

restrictions in the grating length of the polished coupler and loss, from the metallised surface of the external grating.

A simpler and potentially inexpensive alternative, could involve the use of an external grating replica on a thin silicone rubber membrane, attached to a piezoelectric ceramic and pressed against a flat fibre surface, in close proximity to the core. The grating periodicity could be varied either by pressing, or by stretching the rubber on the substantially harder fibre glass surface. Variations in the rubber parameters from temperature or pressure, may cause drifting in the grating characteristics. Some form of built-in control mechanism will, therefore, be required.

6.3 Concluding Comments

Even though the theory of grating couplers and reflectors has been completely analysed, their fibre device implementations have not yet fully proved their potential in narrow-band filtering. Some success has been obtained, in demonstrating the phenomenon of contradirectional coupling, but a lot of development is still required for improving the accuracy and versatility of the grating fabrication processes on optical fibres. Some form of tuning must be incorporated, to compensate for fabrication tolerances and drifts. Only then, will it be possible to fabricate long grating-on fibre lengths, weakly perturbed for sub- $\text{\AA}$ coupled

bandwidths and high reflectivities. For this purpose, long grating lengths, etched on the flat face of special D-shaped fibres, look a more promising alternative to polished fibre blocks, avoiding restrictions imposed by the fabrication of such blocks.

The successful fabrication and testing of the above fibre devices, clearly in the frontiers of today's technology, require large resources and "state of the art", sophisticated, and often expensive equipment, without which the fulfilment of the true potential of fibre device implementations of grating reflectors and couplers can never be realised.

R E F E R E N C E S

CHAPTER 1

- 1.1 "Fully Connected High-Speed Ti:LiNbO_3 Switch /
Modulator for Time-Division Multiplexing and Data
Encoding",
Korotky S. K., Eisenstein G., Alferness R. C.,
Veleska J. J., Buhr L. L., Harvey G. T., Read P. H.,
IEEE Journal Lightwave Technology, 3(1), Feb. 1985,
pp. 1-6 .
- 1.2 "6 Gbit/s Transmission over 30 km of Optical Fibre",
Chauck A. H., Bowers J. E., Cambell J. C.,
Electronics Letters, 22(11), May 1986, pp. 600-602.
- 1.3 "Current Status of Optical Communications Technology",
Midwinter J. E.,
IEEE Journal Lightwave Technology, 3(5), Oct. 1985,
pp. 927-930 .
- 1.4 "A Tutorial Review of Techniques for Coherent Optical
Fibre Transmission Systems",
Stanley I. W.,
IEEE Communications, 23(8), Aug. 1985, pp. 37-53 .

- 1.5 "Design and Fabrication of 1.5 μm Ridge Waveguide Distributed Feedback Lasers",
Nelson A. W., Westbrook L. D., Fiddymment P. J.,
IEE Proceedings, J , 132(1), Feb. 1985, pp. 12-19 .
- 1.6 "Wideband Optical Communication Systems, Part II,
Frequency Division Multiplexing",
Delange O. E.,
Proc. IEEE, 58(10), Oct. 1970, pp. 1683-1690 .
- 1.7 "Review and Status of Wavelength Division Multiplexing, Technology and its Application",
Ishio H., Minowa J., Nosu K.,
IEEE Journal Lightwave Technology, 2(4), Aug. 1984,
pp. 448-463 .
- 1.8 "Wavelength Multiplexing Components - A Review of Single-Mode Devices and their Applications",
Winzer G.,
IEEE Journal Lightwave Technology, 2(4), Aug. 1984,
pp. 369-378 .
- 1.9 "Optical Fibres in Local Area Networks",
Finley M. R.,
IEEE Communications, 22(8), Aug. 1984, pp. 22-35 .

- 1.10 "1.5-1.6 μm GaInAs/InP Dynamic-Single Mode (DSM) Laser with Distributed Bragg Reflector",
Koyama F., Suematsu Y., Arai S., Tanbun-ek T.,
IEEE Journal Quantum Electronics, 19(6), June 1983,
pp. 1042-1051.
- 1.11 "Viabilities of Wavelength-Division-Multiplexing Transmission System over an Optical Fiber Cable",
Stanley K. J.,
IEEE Communications, 26(5), July 1978, pp. 1082-1087 .
- 1.12 "Optical Demultiplexing Using a Silicon Echelette Grating",
Fujii Y., Aoyama K., Minowa J.,
IEEE Journal Quantum Electronics, 16(2), Feb.1980,
pp. 165-169 ,
and
"Wide Passband Grating Multiplexer for Multimode Fibres",
Hillerich B., Rode M., Weidel E.,
IEEE Journal Lightwave Technology, 3(3), June 1985,
pp. 590-594.
- 1.13 "Fibre-Optic Multifunction Device Using a Single GRIN-Rod lens for WDM Transmission Systems",
Tanaka T., Kishi S., Tsutsumi T.,
Applied Optics, 21(19), Oct. 1982, pp. 3423-3429 .

- 1.14 "Optical Grating Multiplexer in the 1.1-1.5 μm Wavelength Region",
Watanabe R., Nosu K., Fujii Y.,
Electronics Letters, 16(3), Jan. 1980, pp. 108-109 .
- 1.15 "A Four-Channel Lightwave Subsystem Using Wavelength Division Multiplexing",
Lipson J., Young G. A., Yeates P. D., Masland J. C.,
Wartonick S. A.,
IEEE Journal Lightwave Technology, 3(1), Feb. 1985,
pp. 16-19 .
- 1.16 "20-Channel Micro-Optic Grating Demultiplexer For 1.1-1.6 μm Band Using a Small Graded Index Rod Lens",
Seki M.,
Electronics Letters, 18(6), Mar. 1982, pp. 257-258 .
- 1.17 "Dielectric Multilayer Thin Film Filters for WDM Transmission Systems",
Minowa J., Fujii Y.,
IEEE Journal Lightwave Technology, 1(1), March 1983,
pp. 116-121 .
- 1.18 "Practical Two-Wavelength Multi-Demultiplexer: Design and Performance",
Fujii Y., Minowa J., Kanaka T.,
Applied Optics, 22(19), Oct. 1983, pp. 3090-3097 .

- 1.19 "Multireflection Optical Multi/Demultiplexer Using Interference Filters",
Nosu K., Ishio H., Hashimoto K.,
Electronics Letters, 15(14), July 1979, pp. 414-415 .
- 1.20 "Compact Wavelength Multiplexer Using Optical Fiber Pieces",
Miyauchi Y.,
Optics Letters, 5(7), July 1980, pp. 321-322 .
- 1.21 "Wavelength-Division Multi-Demultiplexers for Two-Channel Single-Mode Transmission Systems",
Reichelt A., Michel H., Rauscher W.,
IEEE Journal Lightwave Technology, 2(5), Oct. 85,
pp. 675-681 .
- 1.22 "Optical Multi/Demultiplexers for Single-Mode Fiber Transmission",
Watanabe R., Fujii Y., Nosu K., Minowa J.,
IEEE Journal Quantum Electronics, 17(6), June 1981,
pp. 974-981 .
- 1.23 "Tunable Optical Waveguide Directional Coupler Filter",
Alferness R.C., Schmidh R. V.,
Applied Physics Letters, 33(2), July 1978, pp. 161-163 .

- 1.24 "A Novel Integrated Optics Wavelength Filter in InGaAsP-InP",
Broberg B., Lindgren B. S., Oberg M. G., Jiang H.,
IEEE Journal Lightwave Technology, 4(2), Feb. 1986,
pp. 196-203 .
- 1.25 "Semiconductor Components For Monolithic Applications",
Garmine E. from "Integrated Optics" by Tamir T.,
Springer-Verlag, Berlin, 1982, ch.6 , pp. 254-255 .
- 1.26 "Low-Loss Single-Mode Optical Waveguides and Efficient High-Speed Modulators of $\text{LiNb}_x\text{Ta}_{1-x}\text{O}_3$ on LiTaO_3 ",
Hammer J. M., Phillips W.,
Applied Physics Letters, 24(11), June 1974, pp. 545-547 .
- 1.27 "Waveguide to Fibre Couplers",
Tamir T. from "Integrated Optics",
Springer-Verlag, Berlin, 1982, ch.3 ,pp. 126-128 ,
and
"Single-Mode Fiber-Film Directional Coupler",
Zhang M., Garmire E.,
IEEE Journal Lightwave Technology, 5(2), Feb. 1987,
pp. 260-267 .
- 1.28 "In Line Optical-Fibre Filter for Wavelength Multiplexing",
Whalen M. S., Walker K. L.,
Electronics Letters, 21(17), Aug. 1985, pp. 724-725 .

- 1.29 "Wavelength-Selective Directional Coupler Made of Non-Identical Single Mode Fibers",
Zengerle R., Leminger O. G.,
IEEE Journal Lightwave Technology, 4(7), July 1986,
pp. 823-827 .
- 1.30 "Analysis of a Tunable Single Mode Optical Fiber Coupler",
Digonnet M. J. F., Shaw H. J.,
IEEE Journal Quantum Electronics, 18(4), April 1982,
pp. 746-754 .
- 1.31 "Directional-Coupler Filter Using Dissimilar Optical Fibres",
Marcuse D.,
Electronics Letters, 21(17), Ag. 1985, pp. 726-727 .
- 1.32 "Optical Coupling in Coaxial Fibres",
Cozens J. R., Boucouvalas A. C., Al-Assam A., Lee M. J.,
Morris D. G.,
Electronics Letters, 18(15), July 1982, pp. 679-681 .
- 1.33 "Coaxial Optical Fiber Coupling",
Boucouvalas A. C.,
IEEE Journal Lightwave Technology, 3(5), Oct. 1985,
pp. 1151-1158 .

- 1.34 "Fibre Optic Spectral Filters Consisting of Concatenated Dual-Core Fibres",
Okamoto K., Noda J.,
Electronics Letters, 22(4), Feb. 1986, pp. 211-212 .
- 1.35 "Tapering of Single Mode Optical Fibres",
Boucouvalas A. C., Georgiou G.,
IEE Proceedings, J , 133(6), May 1986, pp. 385-392 .
- 1.36 "Methods for Fine-Tuning The Wavelength Response of Single-Mode-Optical Fibre Taper Filters",
Electronics Letters, 23(8), April 1987, pp.410-411 .
- 1.37 "Concatenated, Tapered Coaxial Couplers Filters",
Boucouvalas A. C., Georgiou G.,
IEE Proceedings, J , 134(3), June 1987, pp. 191-195 .
- 1.38 "All Fibre Wavelength Filters Using Concatenated Fused-Taper Couplers",
Yataki M. S., Payne D. N., Varnham M. P.,
Electronics Letters, 21(6), March 1985, pp. 248-249 .
- 1.39 "Efficient Wavelength Electro-Optic TE-TM Mode Converter/Wavelength Filter",
Alferness R. C.,
Applied Physics Letters, 36(7), April 1980, pp. 513-515 .

- 1.40 "Electro-Optic Waveguide TE—TM Mode Converter with Low Drive Voltage",
Alferness R. C., Buhl L. L.,
Optics Letters, 5(11), Nov. 1980, pp. 473-475 .
- 1.41 "Monolithic Integrated Microgratings and Photodiodes for Wavelength Demultiplexing",
Suhara T., Handa Y., Nishihara H., Koyama J.,
Applied Physics Letters, 40(2), Jan. 1982, pp. 120-122 .
- 1.42 "Grating Filters for Thin-Film Optical Waveguides",
Flanders D. C., Kogelnik H., Schmidt R. V., Shank C. V.,
Applied Physics Letters, 24(4), Feb. 1974, pp. 194-196 .
- 1.43 "Narrow-Band Grating Filters for Thin Film Optical Waveguides",
Schmidt R. V., Flanders D. C., Shank C. V., Stanley R. D.,
Applied Physics Letters, 25(11), Dec. 1974, pp. 651-652 .
- 1.44 "GaAs/GaAlAs Rib Waveguide Grating Filters for $\lambda=1.5 \mu\text{m}$ ",
Yi-Yan A., Carru H., Correc P., Chandouneau J. P.,
Dugrand L., Carre M.,
Electronics Letters, 23(12), June 1987, pp. 622-624 .
- 1.45 "A Single-Mode Fiber Evanescent Grating Reflector",
Sorin W. V., Shaw H. J.,
IEEE Journal Lightwave Technology, 3(5), Oct. 1985,
pp. 1041-1043 .

- 1.46 "High-Reflectivity Monomode Fibre Grating Filters",
Bennion I., Reid D. C. J., Rowe C. J., Stewart W. J.,
Electronics Letters, 22(6), March 1986, pp. 341-343 .
- 1.47 "High-Reflectivity Surface Relief Grating in Single-
Mode Optical Fibres",
Row C. J., Bennion I., Reid D. C. J.,
IEE Proceedings, J , 134(3), June 1987, pp. 197-202 .
- 1.48 "Demonstration of a Narrowband Bragg-Reflection Filter
in a Single-Mode Directional Coupler",
Whalen M. S., Divino M. D., Alferness R. C.,
Electronics Letters, 22(12), June 1986, pp. 681-682 .
- 1.49 "Wavelength-Tunable Single-Mode Fibre Grating Reflector",
Whalen M. S., Tennant D. M., Alferness R. C., Koren U.,
Bosworth R.,
Electronics Letters, 22(24), Nov. 1986, pp. 1307-1308 .
- 1.50 "Tunable Single-Mode Output of a Multimode Laser in a
Tunable Fibre Grating External Cavity",
Sorin W. V., Newton S. A.,
Electronics Letters, 23(8), April 1987, pp. 390-391 .
- 1.51 "Holographic Thin Film Couplers",
Kogelnik H., Sosnowski T. P.,
Bell System Technical Journal, 49(7), Sep. 1970,
pp. 1603-1608 .

- 1.52 "Beam Expansion in Linear Constant Period Gratings",
Walpita L. M., Pitt C. W.,
Applied Optics, 23(19), Oct. 1984, pp. 3434-3438 .
- 1.53 "Grating-Fiber Coupler as a High-Resolution Spectrometer",
Russell R. St.J., Ulrich R.,
Optics Letters, 10(6), June 1985, pp. 291-293 .
- 1.54 "Tunable Single-Mode Fiber Lasers",
Reekie L., Mears R. J., Poole S. B., Payne D. N.,
IEEE Journal Lightwave Technology, 4(7), July 1986,
pp. 956-960 .
- 1.55 "Narrow-Linewidth Fibre Laser with Integral Fibre Grating",
Jauncey I. M., Reekie L., Mears R. J., Payne D. N.,
Row C. J., Reid D. C. J., Bennion I., Edge C.,
Electronics Letters, 22(19), Sep. 1986, pp. 987-988 .
- 1.56 "Narrow-Linewidth Fibre Laser Operating at 1.55 μm ",
Jauncey I. M., Reekie L., Mears R. J., Rowe C. J.,
Optics Letters, 12(3), March 1987, pp. 164-165 .
- 1.57 "Fibre Bragg Reflector for Mode Selection and Line Narrowing of Injection Lasers",
Brinkmeyer E., Brennecke W., Zurn M., Ulrich R.,
Electronics Letters, 22(3), Jan. 1986, pp. 134-135 .

- 1.58 "Single-Mode Behaviour of a Multimode 1.55 μm Laser with a Fibre Grating External Cavity",
Park C., Rowe C. J., Buus J., Reid D. C., Carter A.,
Bennion I.,
Electronics Letters, 22(21), Oct. 1986, pp. 1132-1133 .
- 1.59 "Electro-Optic Distributed Bragg-Reflection Modulator for Integrated Optics",
An J. C., Cho Y., Matsuo Y.,
IEEE Journal Quantum Electronics, 13(4), April 1977,
pp. 206-208 .
- 1.60 "180° Turns in Integrated Optics",
Tietgen K. H., Kersten R. T.,
Optics Communications, 36(4), Feb. 1981, pp. 281-284 .
- 1.61 "High-Speed Pulse-Train Generation Using Single-Mode Fibre Recirculating Delay Lines",
Newton S. A., Howland R. S., Jackson K. P., Shaw H. J.,
Electronics Letters, 19(19), Sep. 1983, pp. 756-758 .
- 1.62 "Fibre-Optic Signal Processor with Applications to Matrix Vector Multiplication and Lattice Filtering",
Tur M., Goodman J. W., Moslehi B., Bowers J.E., Shaw H. J.
Optics Letters, 7(9), Sep. 1982, pp. 463-465 .

1.63 "Filter Response of Single-Mode Fibre Recirculating Delay Lines",

Bowers J. E., Newton S. A., Sorin W. V., Shaw H. J.,
Electronics Letters, 18(3), Feb. 1982, pp. 110-111 .

1.64 "Fiber-Optic Lattice Signal Processing",

Moslehi B., Goodman J. W., Tur M., Shaw H. J.,
IEEE Proceedings, 72(7), July 1984, pp. 909-930 .

1.65 "Backward wave couplers and reflectors"

Vassilopoulos C., Cozens J. R.,

Presented at the 4th International Symposium on
Optical and Optoelectronic Applied Science and
Engineering, the Hague, 1 April 1987.

To be published in the Conference Proceedings.

CHAPTER 2

- 2.1 "Directional Couplers Made of Nonidentical Asymmetric Slabs. Part I : Synchronous Couplers",
Marcuse D.,
Journal Lightwave Technology, 5(1), Jan. 1987 , pp. 113-118.
- 2.2 "Directional Couplers Made of Nonidentical Asymmetric Slabs. Part II : Grating-Assisted Couplers",
Marcuse D.,
Journal Lightwave Technology, 5(2), Feb. 1987 , pp. 268-273.
- 2.3 "Coupling Between Dielectric Waveguides",
by Marcuse D., from "Light Transmission Optics"
(Van Nostrand Reinhold , New York), 1982 , ch. 10 ,
pp. 415-438.
- 2.4 "Coupled Mode Theory",
Marcuse D., from "Theory of Dielectric Optical Waveguides",
(Academic Press, New York), 1974 , ch. 3 , pp. 95-131.
- 2.5 "Coupled Mode Theory for Guided Wave Optics",
Yariv A.,
Journal Quantum Electronics, 9(9), Sept. 1973 , pp. 919-933.

- 2.6 "Relation Between Normal Mode and Coupled Mode Analyses of Parallel Waveguides",
Marom E., Ramer O. G., Ruschin S.,
Journal Quantum Electronics, 20(12), Dec. 1984 ,
pp. 1311-1319.
- 2.7 "Accuracy of Directional Coupler Theory in Fibre or Integrated Optics Applications",
Yeh C., Manshadi F., Casey K. F., Johnston A.,
Journal Optical Society of America, 68(8), Aug. 1978 ,
pp. 1079-1083.
- 2.8 "Coupled Mode Theory of Parallel Waveguides",
Hardy A., Streifer W.,
Journal Lightwave Technology, 3(5), Oct. 1985 ,
pp. 1135-1146.
- 2.9 "Improved Coupled Mode Equations for Dielectric Guides",
Marcatili E. A. J.,
Journal Quantum Electronics, 22(6), June 1986 , pp. 988-993.
- 2.10 "Codirectional Coupling in a Periodic Waveguide",
by Yariv A., Yeh P., from "Optical Waves in Crystals",
(Wiley, New York), 1984 , ch. 11(5), pp. 436-439.
- 2.11 "Contradirectional Frequency Selective Couplers for Guided Wave Optics",
Yeh P., Taylor H.F.,
Applied Optics, 19(16), Aug. 1980 , pp. 2848-2855.

- 2.12 "An Analysis for Contradirectional-Coupler-Type Optical Grating Filters",
Imoto N.,
Journal Lightwave Technology, 3(4), Aug. 1985 , pp. 895-900.
- 2.13 "Frequency Selective Coupler for Integrated Optics Systems",
Elachi C., Yeh C.,
Optics Communications, 7(3), March 1973 , pp. 201-204.
- 2.14 "Electromagnetic Propagation in Periodic Media",
Yariv A., Yeh P., from "Optical Waves in Crystals",
(Wiley, New York), 1984 , ch. 6(6) , pp. 194-201.
- 2.15 "Introduction to Solid State Physics",
Kittel C.,
(Wiley, New York), 1971 , ch. 9 , pp. 309-318.
- 2.16 "Analysis of Optical Propagation in a Corrugated Dielectric Waveguide",
Sakuda K., Yariv A.,
Optics Communications, 8(5), May 1973 , pp. 1-4.
and "Periodic Waveguide-Bragg Reflection"
Yariv A., Yeh P., from "Optical Waves in Crystals",
(Wiley, New York), 1984 , ch. 11(4), pp. 429-436.

- 2.17 "Optical Directional Coupling with a Grating Overlay",
Syms R. R. A.,
Applied Optics, 24(5), March 1985 , pp. 717-726.
- 2.18 "The Coupling of Modes in Three Dielectric Slab
Waveguides",
Iwasaki K., Kurazono S., Itakura K.,
Electronics and Communications in Japan, 58(8), 1975 ,
pp. 100-108.
- 2.19 "Three Waveguide Couplers for Improved Sampling and
Filtering",
Haus H. A., Fonstad C. G.,
Journal Quantum Electronics, 17(12), Dec. 1981 ,
pp. 2321-2325.
- 2.20 Marcuse D., from "Light Transmission Optics",
(Van Nostrand Reinhold, New York), 1982, ch.8, pp. 305-322,
and "Theory of Dielectric Optical Waveguides",
(Academic, New York), 1974, ch.1, pp. 1-30.
- 2.21 "Theory of Dielectric Optical Waveguides",
Marcuse D.,
(Academic, New York), 1974, ch.1, pp. 49-59.
- 2.22 "Dielectric Rectangular Waveguide and Directional
Coupler for Integrated Optics"
Marcatili E. A. J.,
Bell System Technical Journal, Sep. 1969 , pp. 2071-2102

CHAPTER 3

3.1 "Backward Wave Optical Couplers for Sensing",

Cozens J. R., Vassilopoulos C.,

Journal of Optical Sensors, 1(3), May 1986, pp. 263-273 .

3.2 "Coaxial Fibre Sensors",

Attridge J. W., Cozens J. R., Leaver K. D., Webster N. L.,

Journal Lightwave Technology, 3(5), Oct. 1985, pp. 1084-1091.

3.3 "Guided-Wave Holographic Grating Beam Expander-Fabrication
and Performance",

Neuman V., Pitt C. W., Walpita L. M.,

Electronics Letters, 17(4), Feb. 1981, pp. 165-166.

CHAPTER 4

- 4.1 "Laser Enhanced Etching In KOH",
Gutfeld R. J., Hodgson R. T.,
Applied Physics Letters, 40(4), Feb. 1982 , pp. 352-354.
- 4.2 "Localised Laser Etching Of Compound Semiconductors
In Aqueous Solution",
Osgood R. M., Sanchez-Rubio A., Ehrlich D. J., Daneu V.,
Applied Physics Letters, 40(5), March 1982 , pp. 391-393.
- 4.3 "Grating Formation On Gallium Arsenide By One-Step
Laser Photochemical Etching",
Tsukada N., Sugata S., Saitoh H., Yamanaka K., Mita Y.,
Proceedings 2nd European Conference on Integrated Optics,
17-18 October 1983 , pp. 105-107
- 4.4 "Maskless Chemical Etching Of Submicrometer Gratings
In Single-Crystalline GaAs",
Podlesnik D. V., Gilgen H. H., Osgood R. M., Sanchez A.,
Applied Physics Letters, 43(12), Dec. 1983 , pp. 1083-1085.
- 4.5 "Selective Etching Of GaAs Crystals in $\text{H}_2\text{SO}_4\text{-H}_2\text{O-H}_2\text{O}$ ",
Iida S., Ito K.,
Journal of the Electrochemical Society, 118(5), 1971 ,
pp. 768-771.

4.6 "Optical Elements With Ultrahigh Spatial Frequency
Surface Corrugations",

Enger R. C., Case S. K.,

Applied Optics, 22(20), Oct. 1983 , pp. 3220-3228.

4.7 "Ion Beam Micromachining Of Integrated Optics
Components",

Garvin H. L., Garvine E., Somekh S., Stoll H., Yariv A.,

Applied Optics, 12(3), March 1973 , pp. 455-459.

4.8 Oriel Scientific Limited,

Technical Publication On Standard Sizes Of Commercially
Available Holographic Gratings.

4.9 "Formation Of Microgratings For III-V Semiconductor
Integrated Optoelectronics By High-Voltage Electron-
Beam Lithography",

McInerney J., Fice M. J., Ahmed H.,

Journal of Lightwave Technology, LT-4(10), Oct. 1986 ,
pp. 1494-1501 ,

"Fabrication Of First-Order Gratings For 1.5 μm DFB
Lasers By High-Voltage Electron-Beam Lithography",

Fice M. J., Ahmed H., Clements S.,

Electronics Letters, 23(11), May 1987 , pp.590-592.

- 4.10 "Fabrication Of Integrated Optical Elements Using
A Computer-Controlled Electron Beam"
Osrovsky D. B., Papuchon M., Roy A. M., Trotel J.,
Applied Optics, 13(3), March 1974 , pp. 636-641
- 4.11 "Embossed Optical Waveguides",
Ulrich R., Weber H. P., Chandross E. A., Tomlinson W. J.,
Franke E. A.,
Applied Physics Letters, 20 , 1972 , pp. 213-215.
- 4.12 "Embossing Technique For Fabricating Integrated Optical
Components In Hard Inorganic Waveguiding Materials",
Tiefenthalef K. , Lukosz W.,
Proceedings 2nd European Conference on Integrated Optics,
17-18 October 1983, pp. 108-111, and
Optics Letters, 8 , 1983 , pp. 537-539.
- 4.13 "Time-Resolved Measurements Of Stimulated Surface
Polariton Wave Scattering And Grating Formation In
Pulsed-Laser-Annealed Germanium",
Ehrlich D. J., Brueck S. R. J., Tsao J. Y.,
Applied Physics Letters, 41(7), Oct. 1982 , pp. 630-632.
- 4.14 "Narrow-Band Bragg Reflectors In Optical Fibers",
Kawasaki B. S., Hill K. O., Johnson D. C., Fujii Y.,
Optics Letters, 3(2), Aug. 1978 , pp. 66-68.

- 4.15 "Microposit 1300 Series Photoresist",
Shipley Chemicals Limited Technical Publication.
- 4.16 "Characterization Of Positive Photoresist",
Dill F. H., Hornberger W. P., Hauge P. S., Shaw J. M.,
IEEE Transactions on Electronic Devices, ED-22(7),
July 1975 , pp. 445-452.
- 4.17 "The Use Of Photoresist As A Holographic Recording
Medium",
Beesley M. J., Castledine J. G.,
Applied Optics, 9(12), Dec. 1970 , pp. 2720-2724.
- 4.18 "Optical Technique For Producing 0.1 μm Periodic
Surface Structures",
Shank C. V., Schmidt R. V.,
Applied Physics Letters, 23(3), Aug. 1973 , pp. 154-155.
- 4.19 "Simultaneous Exposure And Development Technique For
Making Gratings On Positive Photoresist",
Tsang W. T., Wang S.,
Applied Physics Letters, 24(4), Feb. 1974 , pp. 196-199.
- 4.20 "Photoresist Gratings On Reflecting Surfaces"
Kapon E., Katzir A.,
Journal of Applied Physics, 53(3), March 1982 , pp. 1387-1391

- 4.21 "Simple Versatile Method For Fabricating Coupled-Wave Gratings",
Mai X., Moshrefzadeh R., Gibson U. J., Stegeman G. I.,
Applied Optics, 24(19), Oct. 1985 , pp. 3155-3161.
- 4.22 "Optical Cleaning",
Coherent Ion Lasers Instruction Manual, Section 6 , pp. 1-4.
- 4.23 "Barium Silicate Films For Integrated Optical Circuits",
Goell J. E.,
Applied Optics, 12(4), April 1973 , pp. 737-742.
- 4.24 "Substrate Cleaning For Integrated Optical Waveguides",
Brandt G. B., Supertzi E. P., Henningsen T.,
Applied Optics, 12(12), Dec. 1973 , pp. 2898-2900.
- 4.25 "Solution-Deposited Thin Films As Passive And Active Light Guides",
Ulrich R., Weber H. P.,
Applied Optics, 11(2), Feb. 1972 , pp. 428-434.
- 4.26 "Oxide Layers Deposited From Organic Solutions",
by Schroeder H. in "Physics Of Thin Films",
Hass G., Thun R. E., (Academic, New York 1969), 5 ,
pp. 88-95.

4.27

"Ion And Plasma Assisted Etching Of Holographic Gratings",

Darbyshire D. A., Overbury A. P., Pitt C. W.,
Proceedings IPAT Conference, 1985 , pp. 147-158.

4.28 "Single-Mode Fibre Optic Directional Coupler"

Bergh R. A., Kotler G., Shaw H. J.,
Electronics Letters, 16(7), March 1980 , pp. 260-261.

4.29 "Automatic Manufacture Of Polished Single-Mode-Fibre Directional Coupler"

Nicholls S. T. ,
Electronics Letters, 21(19), Sept. 1985 , pp. 825-826.

4.30 "Monomode Fibre Directional Couplers",

Nayar B., Smith D.,
Optics Letters, 8 , 1983 , pp. 543-544.

4.31 "Preservation Of Polarisation In Optical-Fibre Waveguides With Elliptical Cores",

Dyott R. B., Cozens J. R., Morris D. G.,
Electronics Letters, 15(13), Jan. 1979 , pp. 380-382.

4.32 "Self-Locating Elliptically Cored Fibre With An Accessible Guiding Region",

Dyott R. B., Schrank P. F.,
Electronics Letters, 18(22), Oct. 1982 , pp. 980-981.

- 4.33 "Elliptical Dielectric Waveguides",
Yeh C.,
Journal Applied Physics, 33(11), Nov. 1962 , pp. 3235-3243.
- 4.34 "Optical Fibres And Dielectric Waveguides"
Marcuse D.,
"Light Transmission Optics", (Academic, New York 1982),
Ch. 8 , pp. 286-305.
- 4.35 "Silicon Dioxide Etch",
Micro-Image Technology Limited Technical Publication,
Particle Count ASTM F-312.
- 4.36 "Fabrication Of Twin-Rectangular-Cored Fibre Couplers",
Green M., Tate T.,
Electronics Letters, 23(11) , May 1987 , pp.593-595.
- 4.37 "Coaxial Optical Coupler",
Cozens J. R., Boucouvalas A. C.,
Electronics Letters, 18(3), Febr. 1982 , pp. 138-140.
- 4.38 "Low-Loss Single-Mode Optical Couplers",
Georgiou G., Boucouvalas A. C.,
IEE Proceedings J , 132(5), Oct. 1985 , pp. 297-302.
- 4.39 "Fabrication Of Single-Polarisation Single-Mode-Fibre
Couplers",
Kawachi M., Kawasaki B. S., Hill K. O., Eda Hiro T.,
Electronics Letters, 18(22) , Oct. 1982 , pp. 962-964.

- 4.40 "Polarisation-Holding Directional Coupler Made From Elliptically Cored Fibre Having A D-Section",
Dyott R. B., Bello J.,
Electronics Letters, 19(16), Aug. 1983 , p. 601.
- 4.41 "Polarisation Holding Directional Couplers Using D-Fibre",
Dyott R. B., Handerek V. A., Bello J.,
Proceedings SPIE, 497 , 1984 , pp. 23-27.
- 4.42 "Fused D-Fibre Couplers",
Handerek V. A., Dyott R. B.,
Proceedings SPIE, 574 , 1985 , pp. 108-115.
- 4.43 "Novel Method For Making Single-Mode Optical Fibre Directional Couplers",
Schoner G., Klement E., Schiffner G., Douklias N.,
Electronics Letters, 18(13), June 1982 , pp. 566-568.
- 4.44 "Polymerization Of Organosilicones In Microwave Discharges",
Wrobel A. M., Wertheimer M. R., Dib J., Schreiber L. P.,
Journal of Macromolecular Science-Chemistry, A14(3),
1980 , pp. 321-337.
- 4.45 "Generation Of Large Volume Microwave Plasmas",
Bosisio R. G., Wertheimer M. R., Weissflock C. F.,
Journal of Physics E: Scientific Instruments, 6 ,
1973 , pp. 628-630.

4.46 "Optical Properties Of Plasma Polymerised Organo-Silicone Films",

Wertheimer M. R., Klemberg J. E., Corriveau R.,
Canadian Journal of Physics, 60 , 1982 , pp. 628-631.

4.47 "Thin Organosilicone Films For Integrated Optics",

Tien P. K., Smolinsky G., Martin R. J.,
Applied Optics, 11(3), March 1972 , pp. 637-641

CHAPTER 5

- 5.1 "The Grating Coupler",
Tamir T., "Integrated Optics",
Topics in Applied Physics, vol. 7 ,
Springer-Verlag, Berlin, 1982, ch.3, pp. 90-101.
- 5.2 "Grating-Fiber Coupler High-Resolution Spectrometer",
Russell P. J., Ulrich R.,
Optics Letters, 10(6) , June 1985, pp. 291-293.
- 5.3 "Synchronous Mode-Locked Laser Configuration",
Yariv A., "Optical Electronics",
Holt-Saunders, New York, 1985, ch.6, p. 172.
- 5.4 "Organic Dye Lasers",
Yariv A., "Optical Electronics",
Holt-Saunders, New York, 1985, ch.7, pp. 217-221.
- 5.5 "Organic Dye Solution Laser",
Schafer F. P., Schmidh W., Volze J.,
Applied Physics Letters, 9(8), Oct. 1966, pp. 306-309.
- 5.6 "Stimulated Emission in Aromatic Organic Compounds",
Stockman P. L., Mallory W. R., Tittel K. F.,
Proc. IEEE, 52(5), March 1964 , pp. 318-320.

5.7 "Continuously Tunable Narrow-Band Organic Dye Lasers",
Soffer B. H., Mc Farland B. B.,
Applied Physics Letters, 10(10), May 1967, pp. 266-267.

5.8 "Design Considerations For Grating Couplers",
Tamir T., "Integrated Optics",
Topics in Applied Physics, vol. 7,
Springer-Verlag, Berlin, 1982 , ch. 3, pp. 111-118.

APPENDIX

EPO-TEK 301

SPECIFICATIONS:

Viscosity 100 cps

Curing Schedule: Room Temperature overnight

65 for 1 hour

Lap Shear Strength: 1700 psi

Refractive index: 1.538 - 1.540

Transmission: greater than 97 % for 320-900 nm

(Adhesive film thickness .0035)