

SURFACE PLASMA WAVE COUPLERS AS SENSORS.

by

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ABSTRACT

Optical sensing devices based on the excitation of surface plasma waves have been of much interest in recent years. In this thesis, the application of a number of surface plasma wave coupler structures as sensors is studied. The most commonly investigated structure consists of a thin metal film deposited on the base of a glass prism, in which the surface plasma wave propagating on the metal outer interface is excited by coupling from the evanescent field of light waves propagating in the prism. The surface plasma wave, which is largely distributed in the outer cladding, is shown to be a sensitive probe of variations in the refractive index of the metal film outer cladding. It is analytically shown that the sensing performance of the resulting device can be improved by introducing a dielectric buffer layer between the prism and the metal film. Comparison of the sensitivity of the buffered structure with that of a dielectric waveguide prism coupler, which has been suggested as an alternative, shows that the buffered surface plasma wave prism coupler is somewhat more sensitive.

The excitation of surface plasma waves by the guided mode of a dielectric waveguide in a directional coupler structure, and the application of the resulting device as a sensor are also studied. The coupling mechanism is analysed using the coupled mode theory. Coupling into surface plasma waves in a planar geometry has been experimentally investigated. Comparison with a similar structure introduced by Kreuwel et al reveals that the sensitivity of the structure examined in this thesis is comparable with that of the Kreuwel structure, while fabrication of the former is expected to be easier, possibly implying that it is a more attractive choice.

Finally surface plasma wave directional couplers of fibre geometry are considered. A potential fibre geometry comprises of a D-shaped fibre with the metal film deposited on the flat surface of the fibre. Analysis of this structure shows that the significant difference between the lateral dimensions of the fibre core and the metal film has the effect of significantly broadening the coupling, hence degrading the device sensitivity. Modifications to this geometry in order to overcome this difficulty are suggested. Attempts to experimentally observe the coupling in the D-fibre surface plasma wave coupler have, however, failed. A number of considerations which may have contributed to this are also analytically investigated. A coaxial fibre geometry is suggested as an alternative. Coupling between the guided mode of the dielectric rod and the surface plasma mode on the metallic tube in this structure is qualitatively shown to be relatively weak. Possible modifications which may enhance the coupling strength are also suggested. An important drawback associated with the coaxial geometry is, however, expected to be the small overall diameter of the structure, which limits its practicality.

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CHAPTER 1

INTRODUCTION.

Medical diagnosis, industrial process control, environment monitoring are all examples of many areas in which there is a pronounced need for fast, sensitive and cheap sensing devices. This is partly due to the fact that conventional laboratory analysis of the complicated chemical processes involved in some applications is generally time consuming, which not only puts strains on the cost effectiveness but also in some cases makes the information obtained useless.

Optical sensing devices, partly due to the advances in fibre optic technology, have attracted much interest in recent years. This has led to the development of numerous optical sensing devices, which are based on either new techniques or on the revival of some old ones.

Both optical and non-optical sensing techniques have been extensively reviewed by a number of researchers [Nylander 1985]. Fibre optic sensors, which may be considered to form an important category of optical sensors on their own, have also been thoroughly reviewed [Giallorenzi et al 1982]. In this chapter a brief outline of some of the major optical techniques is represented. The objective here is not to produce a complete literature survey but to establish the ideas which have led to the interest in the devices examined in the remainder of this thesis.

1.1.Optical sensors.

An optical sensing device can generally be defined as a device which transduces changes in a physical or a chemical parameter into an optical signal. Optical sensing devices can be made sensitive to a certain parameter by incorporating a material into the device, the optical properties (refractive index or extinction coefficient) or the thickness of which are sensitive to the parameter of interest. Some of the advantages of optical sensing devices over non-optical devices reviewed in the literature [Nylander 1985] are listed below.

1)Optical sensors are free of electrical interference.

2)Wavelength multiplexing in optical sensors enables simultaneous detection of a number of parameters by assigning each wavelength to a specific measurement.

3)Optical sensors can be used in environments in which electrical sensors may be dangerous, for example in presence of explosive gases.

4)Optical sensors can generally be used in direct contact with aqueous environments.

Optical sensing devices studied in this thesis are based on the excitation of surface plasma waves, which have attracted much interest in recent years. Excitation of surface plasma waves can be achieved by either light reflectance techniques or by coupling from the guided mode of a dielectric waveguide in a directional coupler structure. In the following, sensing devices based on these two techniques are briefly described.

1.1.1.1.Light reflectance techniques.

In a variety of optical sensing techniques, provided appropriate arrangements are made, variations in optical properties in the vicinity of a surface, referred to as the active surface, and hence the parameters influencing these properties can be directly monitored by measuring the resulting variations in the intensity of the light reflected from this surface (or from another surface placed in proximity to the active surface). Such techniques are categorized as light reflectance techniques. A number of sensing devices based on this technique are described below.

a)Brewster angle reflectometer sensors.

Brewster angle reflectometer sensors make use of the fact that the intensity of a p-polarized light reflected from an interface shows a minimum at the Brewster angle (fig.1.1.1). Application of such a device as, for example, a biosensor is based on the fact that appropriate choice of the interface enables coating of the surface by specific antibodies, the immobilization of which results in an increase in the intensity of the reflected light at Brewster angle. When this surface is brought in contact with a solution containing an appropriate type of antigen (corresponding to the precoated antibodies), the antigens bind to the antibodies, resulting in a further increase in the minimum reflected intensity [Lundstrom et al 1983, Wehlin et al 1984]. The final increase in the reflected intensity can therefore be a good measure of the antigen-antibody binding, in effect detecting presence of the antigens in the solution.

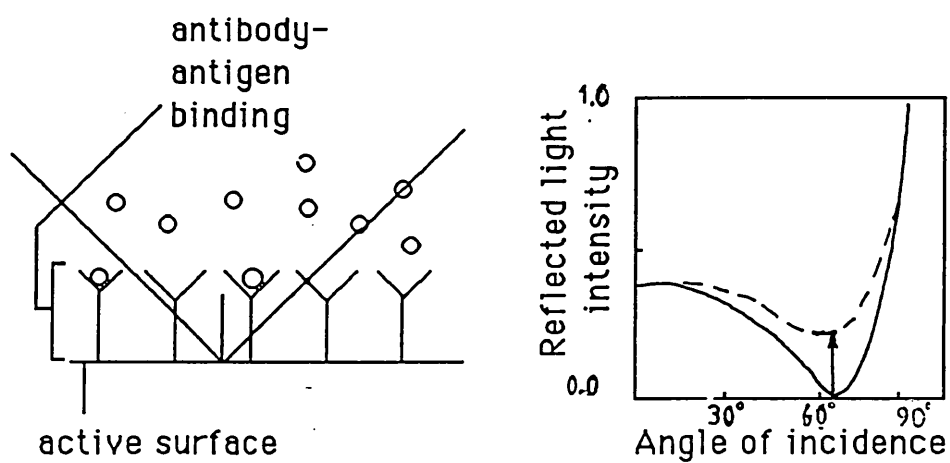


fig.1.1.1.Brewster angle reflectometry :at Brewster angle
P-polarized light shows a minimum in the reflectance
the depth of which is very sensitive to the buildup of
molecules of interest on the surface.

b) Surface plasma resonance sensors.

An attractive light reflectance sensing technique is based on the excitation of surface plasma waves. Surface plasma waves, first observed by Otto[1968] and extensively studied by a number of researchers, are a special type of surface electromagnetic wave which propagate on a metal-dielectric interface with their field peaking at the interface and exponentially decaying away from it. Surface plasma waves have a large fraction of their power in the vicinity of the metal surface and in the dielectric medium. This makes them very sensitive to changes in optical properties on the surface of the metal, and is the basis of many sensing applications of surface plasma waves.

Devices normally employed to excite surface plasma waves consist of either a thin metal film deposited on the base of a glass prism, referred to as the Kretschmann geometry [Kretschmann 1970] (fig.1.1.2(a)), or a thick metal film separated by a dielectric (air) gap from the prism, referred to as the Otto geometry [Otto 1968] (fig.1.1.2.(b)). In both of these geometries at angles of incidence larger than the critical angle the incident light is totally reflected from the base of the prism and is thus of a decaying (evanescent) nature inside the spacing region between the prism and the metal-dielectric interface. The surface plasma wave on the metal-dielectric interface can now be excited by coupling from the evanescent wave of the incident light. Maximum transfer of power into the surface plasma wave, as will be explained in chapter2, occurs at a certain angle of incidence, when the propagation velocity of the surface plasma wave is equal to that of the evanescent wave. The excitation of surface plasma waves, due to the absorption associated with the metal film, now appears as a reduction in intensity of the light reflected from the base of the prism, resulting in a resonance dip in the reflected light intensity versus the angle of incidence

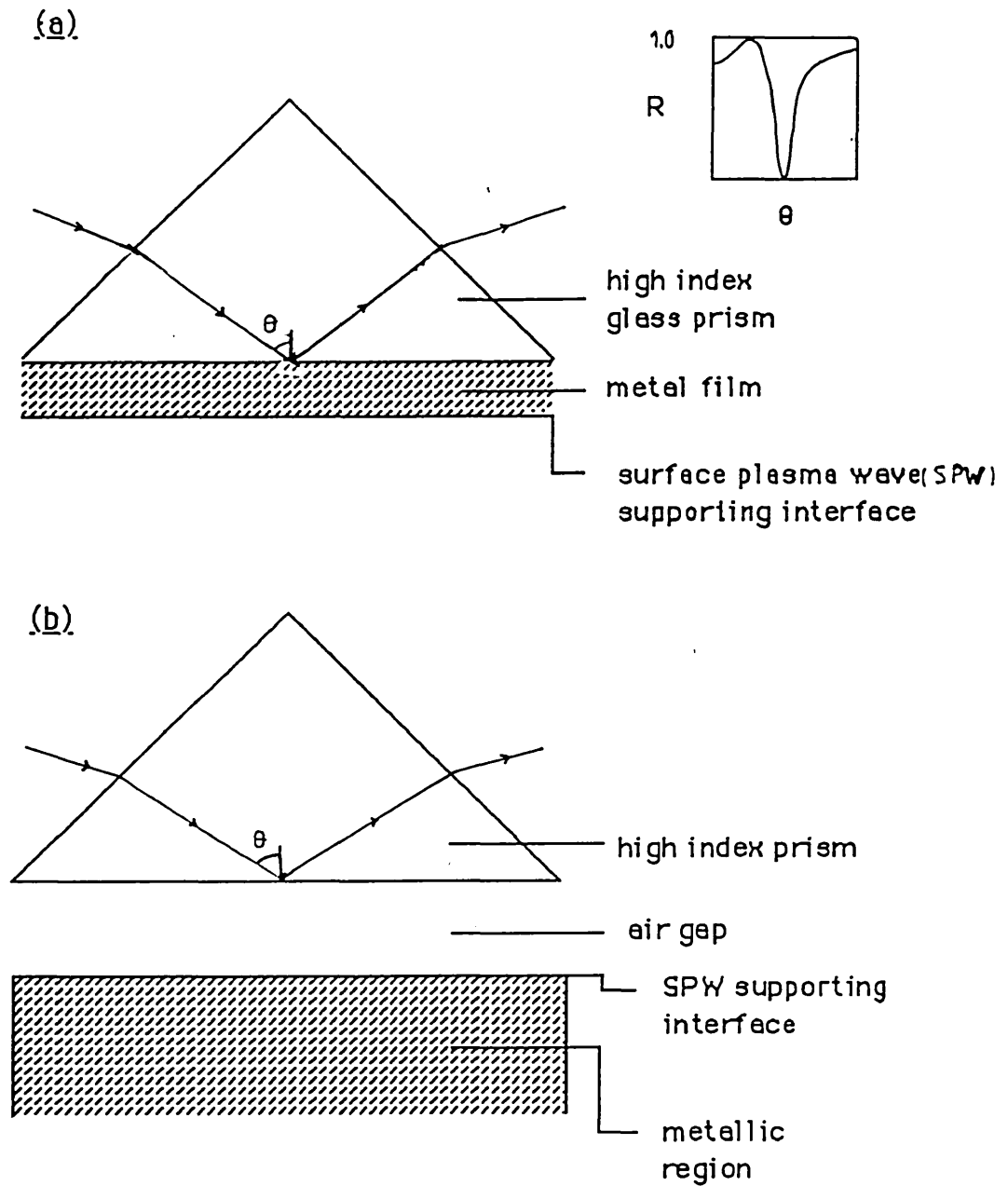


fig.1.1.2.SPW prism couplers: (a) the Kretschmann geometry , (b) the Otto geometry.

(fig.1.1.2). Excitation of surface plasma waves in this manner is commonly referred to as Attenuated Total Reflection (ATR).

The Kretschmann geometry is the arrangement commonly used in sensing applications. This is because introduction of the parameter to be measured into the spacing region of the Otto geometry, which is normally of an extremely small thickness (a few μm), is not free of practical complications.

Operation of the surface plasma resonance sensing devices is based on the fact that changes on the metal surface, having a drastic impact on the propagation velocity of the surface plasma wave, result in a substantial shift in the resonance.

Pockrand[1977] has reported detection of cadmium arachidate monolayers of thickness $26.8\text{\AA}$ formed on the surface of a silver film, using the Kretschmann geometry. The work by Pockrand has been extended by Yeatmann[1987] to a research on surface plasmon microscopy, in which very thin patterns formed on the surface of the silver film by, for example, deposition through a wire mesh are optically imaged using the resulting intensity variations of the reflected light.

Excitation of surface plasma waves using the Kretschmann geometry has also been employed by Leidberg et al[1983] to detect gas adsorbed by a thin layer of organic material formed on the outer surface of the metal film. The adsorption of the gas results in an increase in the thickness and the index of the polymer film. Leidberg et al have also utilized surface plasma wave excitation in this geometry in biosensing applications, in which binding of certain antigens to a layer of appropriate antibodies precoated on the surface of the metal film are detected by the resulting shift in the surface plasma resonance. A similar biosensor has also been studied by Flanagan[1984].

c)Dielectric waveguide resonance sensors.

A purely dielectric analogy to the surface plasma wave couplers of fig.1.1.2 has been suggested by Mason[1988]. In this structure, represented in fig.1.1.3, the surface plasma wave supporting metal film is replaced by a dielectric waveguide, the guided mode of which is excited in a similar manner by the incident light. This structure is referred to as the dielectric waveguide prism coupler. Excitation of the waveguide mode produces a resonant response which can be detected as a resonant dip in the intensity of the reflected light as a function of the incident angle, provided the dielectric waveguide is associated with a scattering loss mechanism. In the absence of an appreciable scattering loss the arrangement of fig.1.1.4 is devised in which excitation of the waveguide mode is associated with a resonance dip in the intensity of the reflected light passing through polarizer P2. This is achieved by aligning polarizer P1 such that equal amplitudes of the polarizations parallel and perpendicular to the plane of the waveguide are included in the incident light. Since the waveguide is generally birefringent, excitation of, for example, the TM-mode of the waveguide results in the corresponding polarization experiencing a phase shift of 360 degrees through the resonance, while the orthogonal polarization is hardly influenced. This results in a rotation by 90 degrees of the overall polarization of the reflected light relative to that of the incident light at the center of resonance. Therefore, alignment of polarisor P2 parallel to polarisor P1 would result in the intensity of the reflected light passing through P2 diminishing as the angle of incidence is scanned through the centre of the TM-mode resonance.

In the dielectric waveguide prism coupler used as a sensing device, it is the field of the waveguide mode which probes changes in the properties of the sensing medium. The field associated with the guided mode of a conventional dielectric waveguide is however generally confined to the core of the waveguide

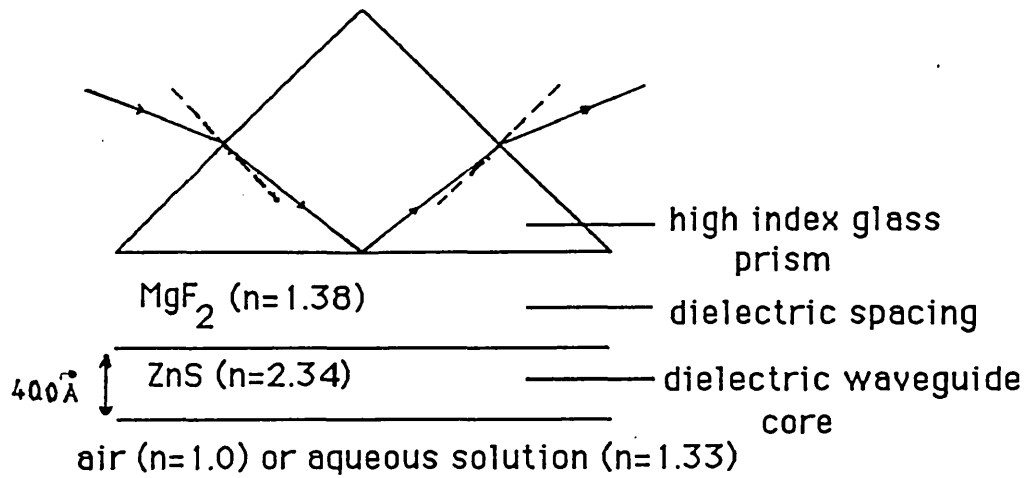


fig.1.1.3.Dielectric waveguide prism coupler.

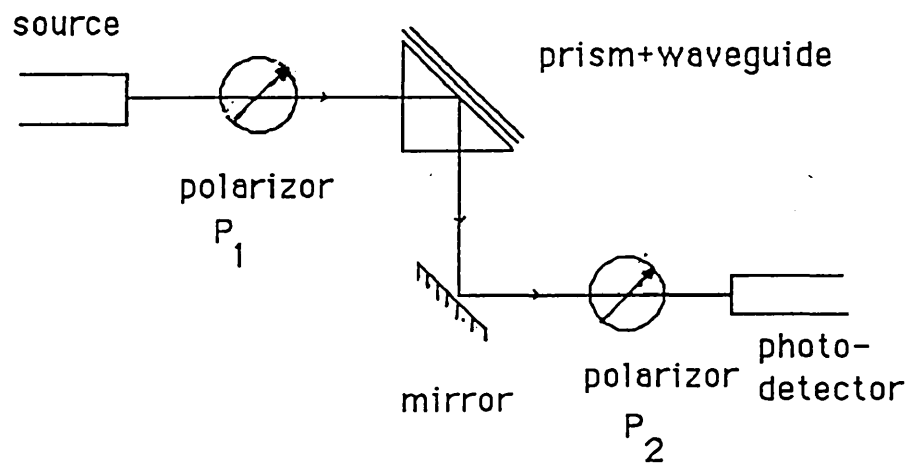


fig.1.1.4.The arrangement used to detect excitation of the waveguide mode in the waveguide prism coupler in the absence of scattering loss.

with a very small fraction in the sensing cladding. This implies that incorporation of such a waveguide in the dielectric waveguide prism coupler sensor would result in a poor sensing device.

As described by Mason, the design of the dielectric waveguide can, however, be optimised by appropriate choice of materials used for the cladding and the core of the waveguide and the thickness of the core. This is to increase the fraction of the field in the outer cladding of the waveguide (the sensing medium). The indices and the thickness of the waveguide indicated in fig.1.1.3 correspond to one such case.

1.1.2.Optical fibre sensors.

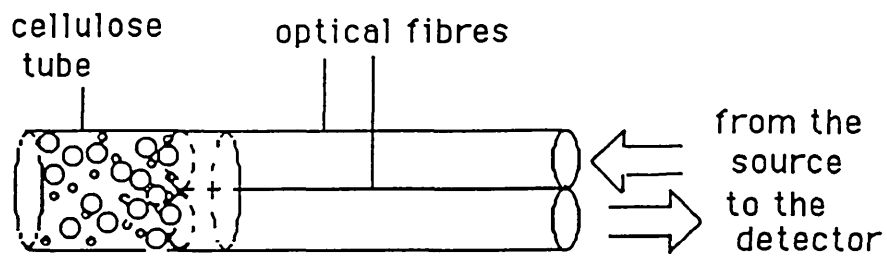
Advantages generally associated with optical fibre sensors can be summarized as follows;

1)Optical fibre sensors can be configured in arbitrary shapes, which makes the corresponding sensing devices geometrically versatile.

2)Light propagates in optical fibres over extremely long distances. Fibre optic devices are therefore an attractive choice for remote sensing applications.

3)They have the potential to be made very cheaply.

A straightforward technique which can be used in combination with optical fibres in sensing applications is light absorption. A configuration which uses this technique, suggested by Peterson et al[1980], is shown in fig.1.1.5. In this arrangement the ends of two optical fibres are inserted into one end of a cellulose tube, sealed at the other end, which is filled with polyacrylamide beads containing Ph sensitive phenol red, and polystyrene microspheres. Light from



○ : polyacrylamide beads+Ph sensitive phenol red.

• : polystyrene beads.

fig.1.1.5.A fibre optic Ph sensor, which uses partial absorption of light by the Ph sensitive phenol red.

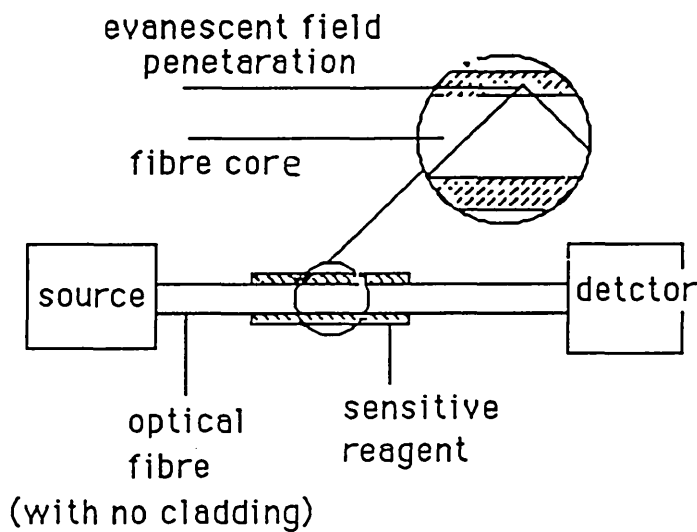


fig.1.1.6.Replacing a fibre cladding by an absorbing reagent selective to a chemical species forms a fibre optic sensor.

a tungsten source, launched into one of the fibres, is scattered by polystyrene particles, with certain wavelengths being absorbed by the Ph indicator. Absorption of light is now Ph sensitive, and hence is a measure of the Ph of a solution injected into the cellulose tube. The light scattered back down the other fibre is monitored at wavelengths 560nm corresponding to maximum absorption of light by the alkaline state of the Ph indicator and 600nm which is well removed from the absorption peak. The red light intensity can therefore be used as a reference. Variations in intensity of the green light (560nm) are shown to be a sensitive measure of the Ph over a range of 7.0 to 7.4, with a resolution of 0.01 Ph units.

Absorption of the light reflected at a surface, which as explained in section 1.1.1 can be used to monitor changes in optical properties on the surface, also form the basis of many optical fibre sensing devices. In an optical fibre which consists of a core surrounded by a cladding of lower refractive index, light propagates along the fibre as a result of total internal reflection at the core-cladding interface. Light also penetrates into the cladding by a distance which is normally a fraction of the optical wavelength. The penetration of the light propagating in the fibre forms an evanescent wave inside the cladding region. Replacing the fibre cladding by an absorbing reagent (fig.1.1.6) which is, for example, selective to certain chemical species now forms an optical fibre sensor, with the evanescent wave probing changes in the extinction coefficient of the reagent as a result of the species adsorption, causing a reduction in the intensity of the light remaining in the fibre. An advantage of such a device over devices described in section 1.1.1 is that the multiple reflection of the light at the fibre core interface, which now forms the active surface, increases sensitivity to reflectance changes. Ammonia sensors, using this technique, have been reported by Giuliani et al[1983].

Advances in monomode optical fibre technology have led to the development of another category of fibre optic sensing techniques based on optical fibre interferometers. Optical fibre interferometer sensors have been developed which can be used to sense parameters such as temperature, acoustic waves and magnetic fields [Giallorenzi 1982]. The arrangement shown in fig.1.1.7 is based on the Mach-Zehnder interferometry. In this arrangement a light beam is split with part of the beam transmitted using the reference fibre and the other part by the sensing fibre, which is exposed to the parameter of interest. The beams are then recombined at the output and on to a detector. The light propagating in the reference fibre is shifted by some phase modulation technique (e.g. a fibre stretcher [Jackson et al 1980]). The parameter of interest, influencing the light propagation in the sensor fibre, now results in a change of the phase difference between the two arms. The phase difference signal, which can thus be used to sense the parameter of interest, is now recovered at the output.

A practical difficulty associated with such optical fibre interferometer sensors is that in order to expose the evanescent field of the sensor fibre guided mode to the sensing environment, this fibre is required to be stripped of its cladding. This results in the sensing fibre, which is required to be monomode, being too small to handle and possibly fragile. Moreover, isolation of the two arms results in a relatively bulky arrangement. To overcome these difficulties attempts have been made to combine the two arms of the device in the same fibre. The cross-section of one such fibre arrangement, suggested by Attridge[1986], is shown in fig.1.1.8.

In this arrangement two monomode optical waveguides are placed in proximity to each other, and combined into a single fibre. The inner waveguide represents the reference arm of the interferometer, while the exposed wave-

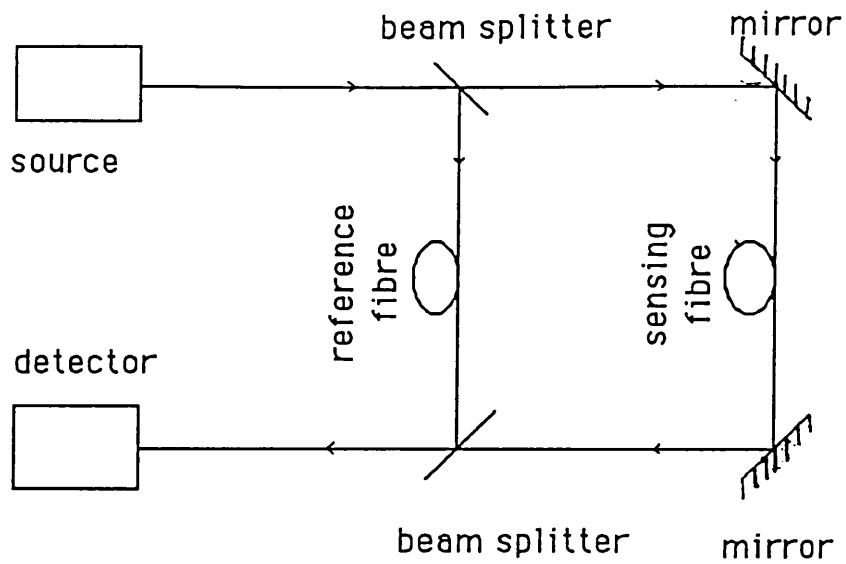


fig.1.1.7.Mach-Zehnder fibre optic interferometer as a sensor.

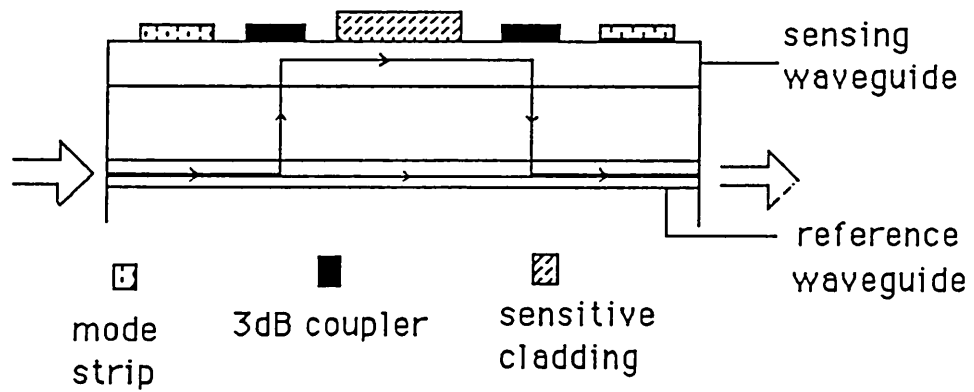


fig.1.1.8.Mach-Zehnder interferometer combined into a single fibre geometry.

uide acts as the sensing arm. The light launched into the reference waveguide is partially coupled into the sensing waveguide using the first 3dB coupler, which is formed over the region indicated in fig.1.1.8 by proper design of the waveguides and an appropriate choice of the outer cladding. The sensing is performed over the region covered with a material with a refractive index sensitive to the sensing parameter. The light in the sensing waveguide, having been influenced by the sensing parameter, is then recombined with the light remaining in the reference waveguide using an identical 3dB coupler near the output end.

1.1.3. Directional couplers as sensors.

A more simplified category of devices based on directional coupler arrangements are envisaged by making the actual coupling mechanism sensitive to the sensing parameter. A general configuration which can be employed in such applications is shown in fig.1.1.9. In such an arrangement the sensing region is infact the region over which coupling between the two waveguides occurs. Appropriate choice of the sensing waveguide outer cladding, the refractive index of which controls the coupling strength, allows its refractive index and hence the coupling mechanism to be sensitive to different sensing parameters.

In optical directional coupler sensors the sensing parameter is probed by the evanescent field of the guided mode of the sensing waveguide. The distribution of the field associated with the sensing waveguide, therefore, plays an important role in the sensitivity of the resulting device. Increasing the fractional field, or to be more precise the fractional power, in the sensing environment, as will be shown in details in later chapters, causes an improvement in the sensing performance of the device.

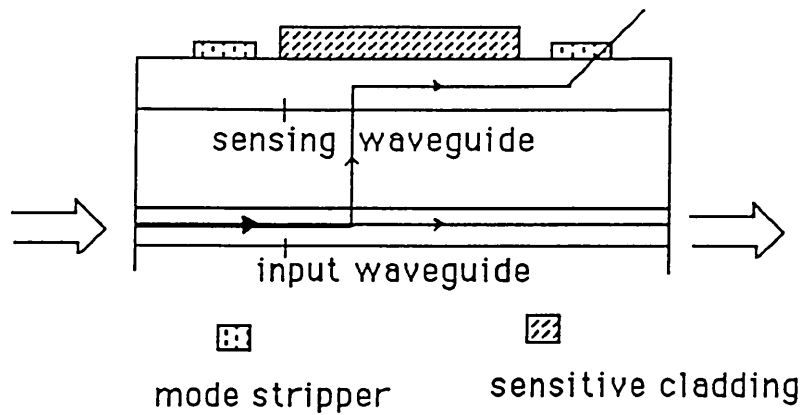


fig.1.1.9. Directional coupler sensor.

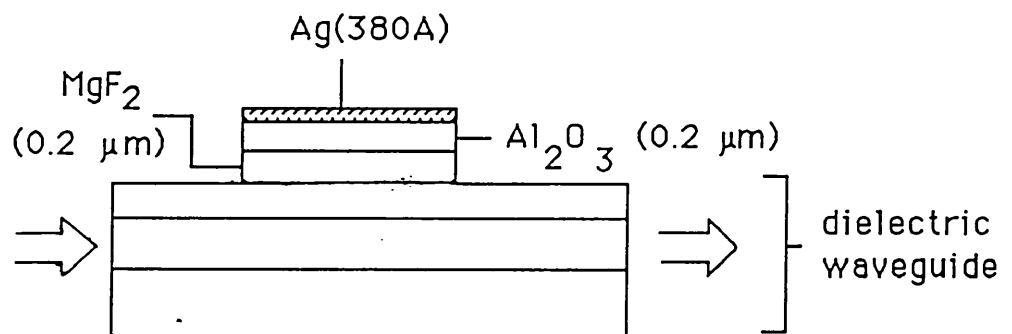


fig.1.1.10. Cross-section of the planar SPW directional coupler, studied by Kreuwel et al.

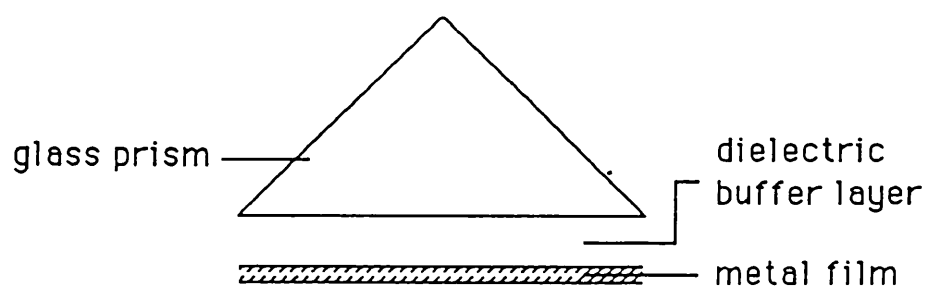


fig.1.1.11. Buffered surface plasma wave prism coupler.

Since, as will be shown later, surface plasma waves have a large fraction of their field in the dielectric medium and in the vicinity of the metal surface, replacing the sensing waveguide of the directional coupler sensors by a surface plasma wave supporting metal film is expected to result in considerably more sensitive devices. In such a device, it is now the coupling from the dielectric waveguide mode into the surface plasma wave which is sensitive to the sensing parameter. One such device has been reported by Kreuwel et al[1986]. The structure studied by Kreuwel et al is based on a planar geometry, the cross-section of which is shown in fig.1.1.10. It must also, in principle, be possible to devise surface plasma wave directional coupler sensing devices which are based on fibre geometries.

1.2. Structure of the thesis.

In this thesis, an alternative ATR configuration to the Kretschmann geometry is studied. This geometry, shown in fig.1.1.11, has already been introduced by Sarid et al[1982] in a study of nonlinear applications of surface plasma waves. It will be shown in chapter 2 that the introduction of the dielectric spacing layer between the prism and the metal film forming the alternative structure referred to as the buffered structure, is accompanied by a substantial increase in the sensing performance of the device.

Chapter 3 deals with the analysis and application of purely dielectric directional couplers as sensors. This is followed by a detailed analysis of the coupling mechanism between a dielectric waveguide and surface plasma waves in a surface plasma wave directional coupler (chapter 4).

The device examined by Kreuwel et al is of an unusual structure due to the presence of a high index aluminum oxide layer between the dielectric waveguide

and the metal film, the need for which has not been explained by Kreuwel et al. A more direct and simpler planar surface plasma wave directional coupler is experimentally studied in chapter 5. The basic differences between this structure and the one examined by Kreuwel et al are also presented in chapter 5.

Finally a number of fibre surface plasma wave couplers are introduced and studied in chapter 6.

CHAPTER 2

SURFACE PLASMA WAVE PRISM COUPLERS AS SENSORS

In this chapter, following a general background to surface plasma waves, excitation of surface plasma waves using the Kretschmann geometry (fig.1.1.2(a)), which is the most commonly used arrangement in sensing applications, and the application of the resulting device as a sensor are described. Analysis of this structure reveals that increasing the sharpness of the surface plasma resonance, which is expected to result in a more sensitive device, can be achieved by increasing the metal film thickness. Increasing the thickness of the metal film more than a certain value is, however, shown to be accompanied by a reduction in the depth of the resonance, which in turn may be considered a drawback.

Introduction of a dielectric layer between the prism and the metal film is subsequently shown to overcome the above constraints on the sensitivity of the device. The resulting device(fig.1.1.11), referred to as the buffered geometry, is shown to possess a superior overall sensitivity in certain applications.

Finally the sensing performance of the buffered surface plasma wave prism couplers relative to that of a dielectric waveguide prism coupler(fig.1.1.3), which has been suggested as a contender to surface plasma wave sensors, is briefly discussed.

2.1.General background.

Maxwell's Equations describing an electromagnetic wave travelling in an isotropic and non-magnetic medium, with the relative permittivity (ϵ), yield

the following scalar wave equation [Marcuse1972]^(a);

$$\nabla^2 \psi + \omega^2 \mu_0 \epsilon_0 \epsilon \psi = 0 \quad (2.1.1)$$

where ψ can be an electric or magnetic field component, with assumed time dependance of $\exp(j\omega t)$.

For waves travelling in the z-direction;

$$\psi = \hat{\psi} \exp(-j\beta z) \quad (2.1.2)$$

The wave equation can now be written in the following form;

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + (\epsilon k_0^2 - \beta^2) \psi = 0 \quad (2.1.3)$$

where

$$k_0^2 = \omega^2 \mu_0 \epsilon_0 \quad (2.1.4)$$

and β = propagation constant.

Consider the wave travelling parallel to the interface between two semi-infinite media, labelled (1) and (2), as shown in fig.2.1.1(a), with $x < 0$ and $x > 0$ defining the two media.

Since there is no structural variation in the y - direction, ie $\frac{\partial \psi}{\partial y} = 0$, equation (2.1.3) can be written in the following form;

$$\frac{\partial^2 \psi}{\partial x^2} + K_\nu^2 \psi = 0 \quad (2.1.5)$$

where $\nu = 1$ or 2 , corresponding to medium (1) or (2), and;

$$K_\nu^2 = (\epsilon_\nu k_0^2 - \beta^2) \quad (2.1.6)$$

The solutions of equation (2.1.5) can be described by the following expression;

$$\psi_\nu = A_\nu \exp(j K_\nu x) \quad (2.1.7)$$

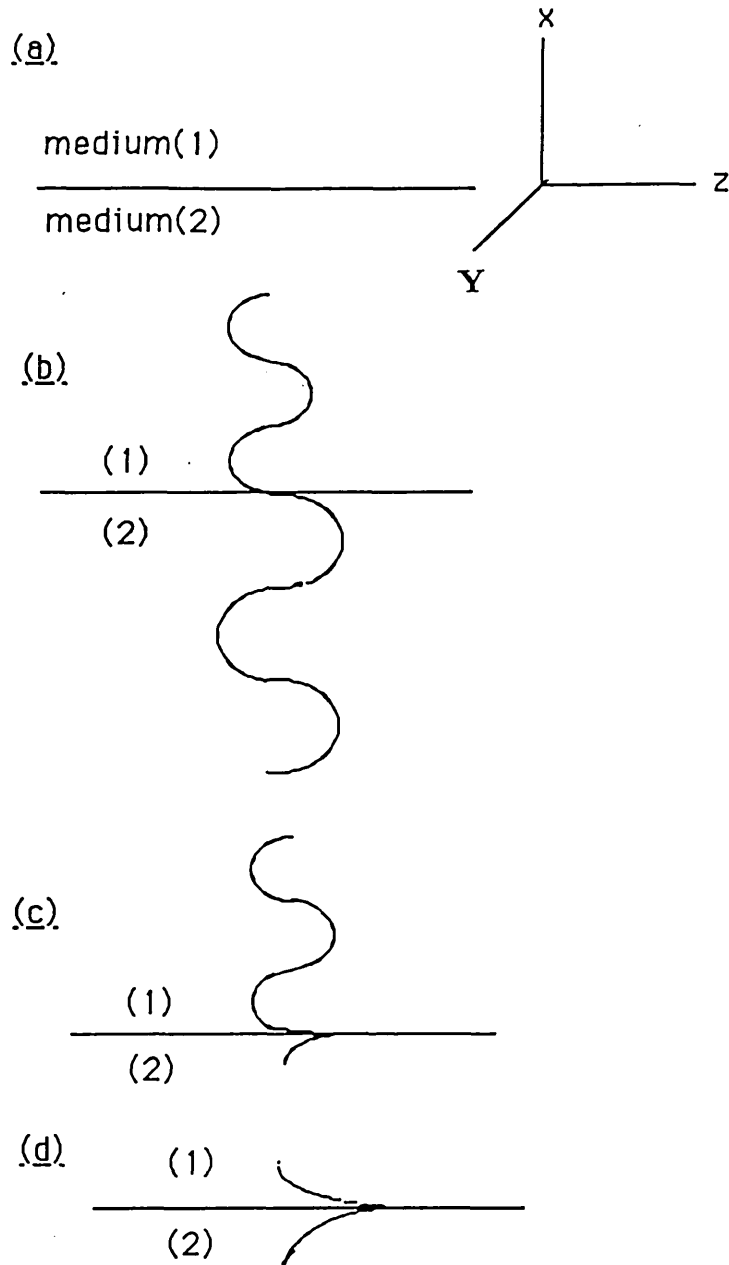


fig.2.1.1. Schematic representation of the interface between two semi-infinite media (a), and the field profiles corresponding to the light partially reflected from the interface (b), totally reflected from the interface (c), and the non-radiative surface mode (d)

Assuming both ϵ_1 and ϵ_2 to be real quantities, corresponding to lossless dielectric materials, three different ranges of solution can be considered, corresponding to the following situations;

(1) $\beta^2 < \epsilon_1 k_0^2$ and $\epsilon_2 k_0^2$: this range of solutions correspond to K_1 and K_2 both being real (equation (2.1.6)), resulting in oscillatory fields in both medium(1) and (2). The diagram in fig.2.1.1(b) is a schematic representation of the field corresponding to this range of solutions, which can describe a situation in which light incident from, for example, medium(1) is partially reflected from the interface, with the remainder refracted through.

(2) $\beta^2 < \epsilon_1 k_0^2$ and $\beta^2 > \epsilon_2 k_0^2$: this results in K_1 being real with K_2 purely imaginary, describing an oscillatory field in medium(1) and a decaying field in medium(2). The corresponding field is schematically shown in fig.2.1.1(c). This solution represents the incident light, from medium(1), being totally reflected from the interface.

(3) $\beta^2 > \epsilon_1 k_0^2$ and $\epsilon_2 k_0^2$: this condition leads to both K_1 and K_2 being imaginary and hence the field decays in both media, as shown in fig.2.1.1(d).

The electromagnetic waves represented by conditions(1) and (2) are referred to as radiative modes, while the one represented by condition(3) is called a non-radiative mode. In the following section, a more detailed analysis of the non-radiative modes reveals that these modes can only be of TM-nature and generally propagate on metal-dielectric interfaces. The electromagnetic waves corresponding to such modes are referred to as surface plasma waves.

Assuming one of the media, for example medium(2), to be a metal implies that ϵ_2 and β are complex. In such a case K_1 and K_2 are generally complex.

The category to which the corresponding solution belongs is now determined by the relative magnitudes of the real and the imaginary parts of K_1 and K_2 .

2.1.1. Surface plasma waves on a metal-dielectric interface.

Omitting the time and z -dependence (as will be the case all through the following analysis, unless otherwise stated), the fields of a TE-polarized non-radiative mode travelling parallel to the interface of fig.2.1.1(a) are described by the following expressions;

$$x \geq 0 :$$

$$E_y = A_1 \exp(j K_1 x) \quad (2.1.8)$$

$$H_x = \frac{-\beta}{\omega \mu_0} A_1 \exp(j K_1 x) \quad (2.1.9)$$

$$H_z = \frac{-K_1}{\omega \mu_0} A_1 \exp(j K_1 x) \quad (2.1.10)$$

$$x \leq 0 :$$

$$E_y = A_2 \exp(-j K_2 x) \quad (2.1.11)$$

$$H_x = \frac{-\beta}{\omega \mu_0} A_2 \exp(-j K_2 x) \quad (2.1.12)$$

$$H_z = \frac{K_2}{\omega \mu_0} A_2 \exp(-j K_2 x) \quad (2.1.13)$$

Applying the boundary conditions (ie. continuity of the tangential fields across the interface, in this case E_y and H_z), results in the following eigenvalue equation;

$$-K_1 = K_2 \quad (2.1.14)$$

or;

$$\epsilon_1 k_0^2 - \beta^2 = \epsilon_2 k_0^2 - \beta^2 \quad (2.1.15)$$

This equation has no solution, eliminating the possibility of the non-radiative mode being of a TE polarized nature.

The field components associated with a TM-polarized non-radiative mode, are described by the following expressions;

$$x \geq 0 :$$

$$H_y = B_1 \exp(j K_1 x) \quad (2.1.16)$$

$$E_x = \frac{\beta}{\omega \epsilon_1} B_1 \exp(j K_1 x) \quad (2.1.17)$$

$$E_z = \frac{K_1}{\omega \epsilon_1} B_1 \exp(j K_1 x) \quad (2.1.18)$$

$$x \leq 0 :$$

$$H_y = B_2 \exp(-j K_2 x) \quad (2.1.19)$$

$$E_x = \frac{\beta}{\omega \epsilon_2} B_2 \exp(-j K_2 x) \quad (2.1.20)$$

$$E_z = \frac{-K_2}{\omega \epsilon_2} B_2 \exp(-j K_2 x) \quad (2.1.21)$$

Applying the boundary conditions (continuity of the H_y and E_z components) results in the following eigenvalue equation;

$$-\frac{\epsilon_1}{K_1} = \frac{\epsilon_2}{K_2} \quad (2.1.22)$$

This equation can be rearranged into the following;

$$\left(\frac{\beta}{k_0}\right)^2 = \frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} = \epsilon_1 \left(\frac{\epsilon_2}{\epsilon_1 + \epsilon_2}\right) = \epsilon_2 \left(\frac{\epsilon_1}{\epsilon_1 + \epsilon_2}\right) \quad (2.1.23)$$

Assuming both media to be dielectric, implies their permittivities to be positive and real, resulting in $\frac{\epsilon_1}{(\epsilon_1 + \epsilon_2)}$ and $\frac{\epsilon_2}{(\epsilon_1 + \epsilon_2)}$ being smaller than unity. From equation (2.1.23), $\left(\frac{\beta}{k_0}\right)^2$ will now be less than both ϵ_1 and ϵ_2 . Therefore, from equation (2.1.6), it is concluded that K_1 and K_2 are both real. This corresponds to condition (1), describing a radiative mode.

However if, for example, ϵ_2 is a negative real quantity and larger, in magnitude, than ϵ_1 , from equation (2.1.23), $\frac{\beta}{k_0}$ will be positive and greater than ϵ_1 . Using equation (2.1.6), K_1 will now be purely imaginary. Since ϵ_2 is negative, again from equation (2.1.6), it is concluded that K_2 will also be purely imaginary. This situation describes a non-radiative mode.

In conclusion, the following is a necessary condition for the presence of a non-radiative mode on the interface;

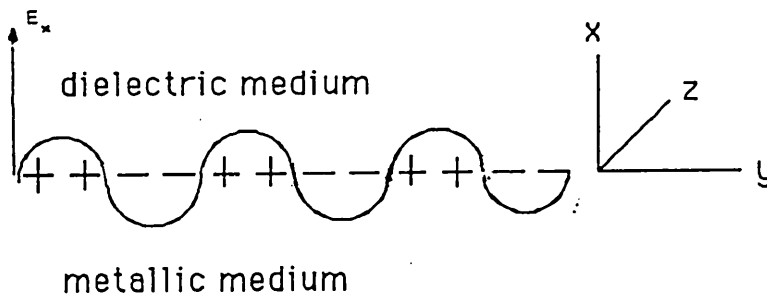
$$\left\{ \begin{array}{l} \epsilon_2 < 0 \\ |\epsilon_2| > \epsilon_1 \end{array} \right. \quad (2.1.24)$$

Most metals meet the above requirements for the material of medium (2) over a wide range of frequencies including the visible spectrum [Ordal et al 1983]. Non-radiative modes propagating on a metal-dielectric interface are referred to as surface plasma waves (modes). It is important to note that, since metals absorb light, their permittivities are complex quantities. This results in β , K_1 and K_2 also being of a complex nature. Analysis, however, reveals that K_1 and K_2 have imaginary parts which are significantly larger than their real parts. This implies that the surface plasma fields are generally decaying in both media, representing non-radiative modes. Since the fields associated with non-radiative surface plasma modes are maximum at the interface and exponentially decay away from the interface these modes can be referred to as being propagating on the interface. It is important to note that a complex propagation constant, $\beta = \beta_r + j\beta_i$, results in the following field variations in the z -direction;

$$\exp(-j\beta z) = \exp(-j\beta_r z) \exp(\beta_i z) \quad (2.1.25)$$

where β_i turns out to be a negative quantity and hence $\exp(\beta_i z)$ defines the loss associated with the surface plasma wave. In other words, the loss associated with surface plasma waves is determined by the imaginary part of the propagation constant β_i .

The generation of the surface plasma waves can be described qualitatively by the fact that the normal electric field component of the TM-light, E_x , generates charge dipoles on the surface of the metal, which can be considered to consist of a plasma of quasi-free electrons. Generation of these charge dipoles is schematically represented in the following diagram;



The oscillation of the dipoles now propagates along the interface as a surface plasma wave. The above description of surface plasma waves verifies that, since TE-light does not possess an electric field component perpendicular to the metal interface, it can not generate the charge dipoles, and hence surface plasma waves cannot be of a TE-nature.

It is notable that dielectric materials can also have a negative dielectric constant in the vicinity of their absorption band. Fig.2.1.2, reproduced from Boardman[1982] shows dielectric constants of two dielectric media (schematic). From this diagram it is concluded that, when the two media are placed adjacent to each other forming an interface, medium(1) is the surface active medium

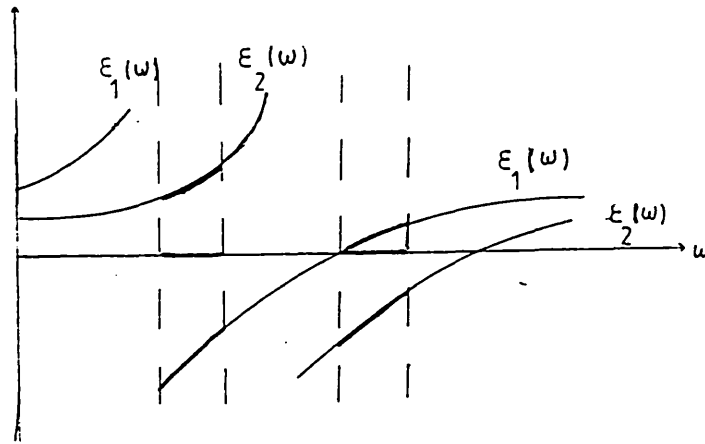


fig.2.1.2.Schematic representation of dielectric constants $\epsilon_1(\omega)$ and $\epsilon_2(\omega)$ of two dielectric materials. Condition (2.1.23) is satisfied in the frequency windows shown in bold.

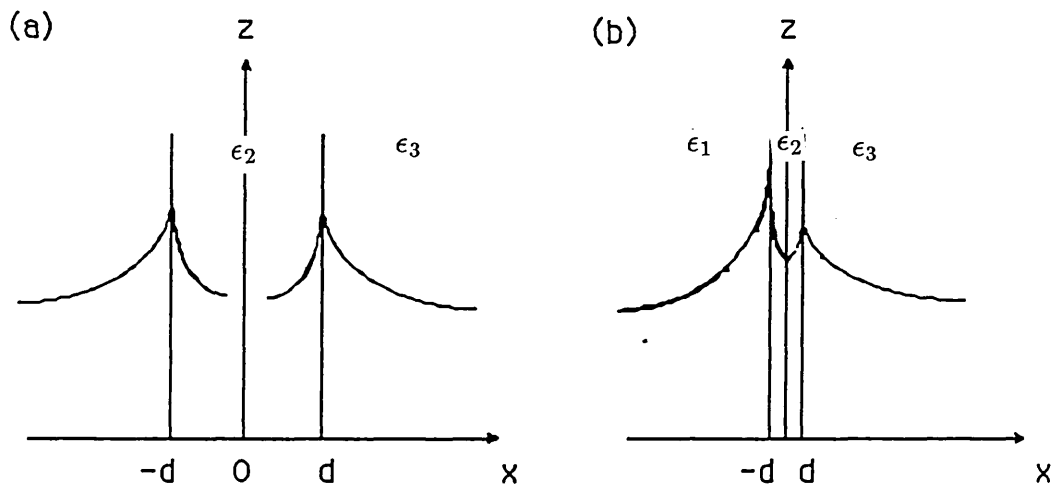


fig.2.1.3.Schematic representation of the H_y profiles of (a)surface plasma modes on a thick metal film (the modes on the two interfaces are isolated) and (b)surface plasma modes on a thin metal film (the modes on the two interfaces interact).

(negative permittivity) in the lower frequency window indicated by a bold line, while medium(2) is the surface active medium in the high frequency window.

2.1.2. Surface plasma waves on a metal film.

A metal film, surrounded by dielectric media, consists of two metal-dielectric interfaces, on either of which surface plasma waves can exist. Provided the metal film is sufficiently thick, fast decay of the fields of each mode inside the metal, implies that the two modes are essentially independent of each other. This is schematically shown in fig.2.1.3(a). However, as the film thickness is reduced to less than a certain value (approximately $1000\text{\AA}$ in the case of silver at a wavelength of $0.633\mu m$), the two modes of the isolated interfaces start to interact, as shown in fig.2.1.3(b). The resulting composite modes, as will be shown later, have symmetric and antisymmetric field distributions.

The field components associated with surface plasma waves on a metal film, which as explained for the case of surface plasma waves on a single metal-dielectric interface, are of a TM-polarized nature, can be described by the following expressions;

$$x \geq d :$$

$$H_y = A_1 \exp(j K_1 x) \quad (2.1.26)$$

$$E_x = \frac{\beta}{\omega \epsilon_1} A_1 \exp(j K_1 x) \quad (2.1.27)$$

$$E_z = \frac{K_1}{\omega \epsilon_1} A_1 \exp(j K_1 x) \quad (2.1.28)$$

$$-d \leq x \leq d :$$

$$H_y = A_2 \exp(j K_2 x) + B_2 \exp(-j K_2 x) \quad (2.1.29)$$

$$E_x = \frac{\beta}{\omega \epsilon_2} [A_2 \exp(j K_2 x) + B_2 \exp(-j K_2 x)] \quad (2.1.30)$$

$$E_z = \frac{K_2}{\omega \epsilon_2} [A_2 \exp(j K_2 x) - B_2 \exp(-j K_2 x)] \quad (2.1.31)$$

$$x \leq -d :$$

$$H_y = A_3 \exp(-j K_3 x) \quad (2.1.32)$$

$$E_x = \frac{\beta}{\omega \epsilon_3} A_3 \exp(-j K_3 x) \quad (2.1.33)$$

$$E_z = \frac{-K_3}{\omega \epsilon_3} A_3 \exp(-j K_3 x) \quad (2.1.34)$$

Applying the boundary conditions, at $x = d$ and $x = -d$, results in the following eigenvalue equation;

$$(\epsilon_2 K_1 + \epsilon_1 K_2)(\epsilon_3 K_2 + \epsilon_2 K_3) + (\epsilon_2 K_1 - \epsilon_1 K_2)(\epsilon_3 K_2 - \epsilon_2 K_3) \exp(2j K_2 d) = 0 \quad (2.1.35)$$

Analysis performed, at a wavelength of $0.633\mu m$, for a $300\text{\AA}$ silver film surrounded by dielectric materials of refractive index 1.45, shows that equation (2.1.35) has two solutions, corresponding to a symmetric and an antisymmetric field distribution. This is shown in fig.2.1.4. The metal is considered to have a refractive index; $n_m = 0.066 + j4.0$, corresponding to that of silver at $0.633\mu m$ [Johnson and Christy 1972].

The symmetric mode corresponds to a propagation constant with a smaller imaginary part. This is due to the fact that the symmetric mode has a smaller fraction of its total power inside the metal. For the example of fig.2.1.4, the symmetric mode has approximately 7 percent of its total power inside the metallic region compared to 24 percent in the case of the antisymmetric mode. The symmetric mode, which thus propagates over a longer distance before diminishing, is referred to as the long range mode, with the antisymmetric mode referred to as the short range mode.

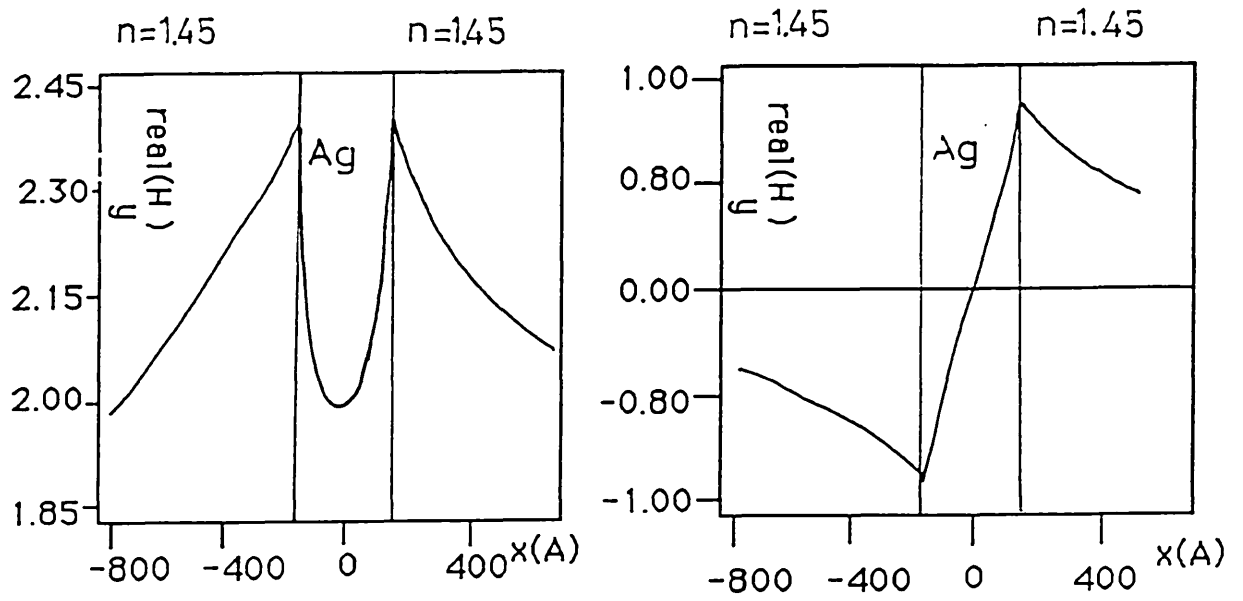


fig.2.1.4. The field profiles, $\text{real}(H_y)$, corresponding to the long range (symmetric) and the short range (anti-symmetric) surface plasma modes on a thin metal film. (wavelength = $0.633 \mu\text{m}$).

2.2.Surface plasma wave prism couplers and their application as sensors.

In the Kretschmann geometry, at angles of incidence larger than the critical angle, the field associated with the incident light is evanescent (decaying) inside the metal film. This evanescent field has a propagation velocity (V_P) along the base of the prism, which is determined by the angle of incidence (θ) and the refractive index of the prism (n_P) using the following expression.

$$V_P = \frac{\omega}{k_0 n_P \sin(\theta)} \quad (2.2.1)$$

The maximum transfer of power from the incident light into the surface plasma wave propagating on the metal outer interface, which perturbs the evanescent field, occurs at angle θ_r at which the propagation velocity of the evanescent field equals that of the surface plasma wave, which is defined as;

$$(V_P)_{SPW} = \frac{\omega}{\beta_r} \quad (2.2.2)$$

where β_r is the real part of the propagation constant of the surface plasma wave.

This leads to the following condition;

$$\frac{\beta_r}{k_0} = n_P \sin(\theta_r) \quad (2.2.3)$$

where, $\frac{\beta_r}{k_0}$ is referred to as the effective index of the surface plasma wave. The surface plasma wave and the evanescent field of the incident light are said to be phase matched under this circumstance.

From equation(2.2.3), it is concluded that in order to excite the surface plasma wave by the incident light, the prism refractive index, n_P , is required to be larger than the effective index of the surface plasma wave, $\frac{\beta_r}{k_0}$. Now, since

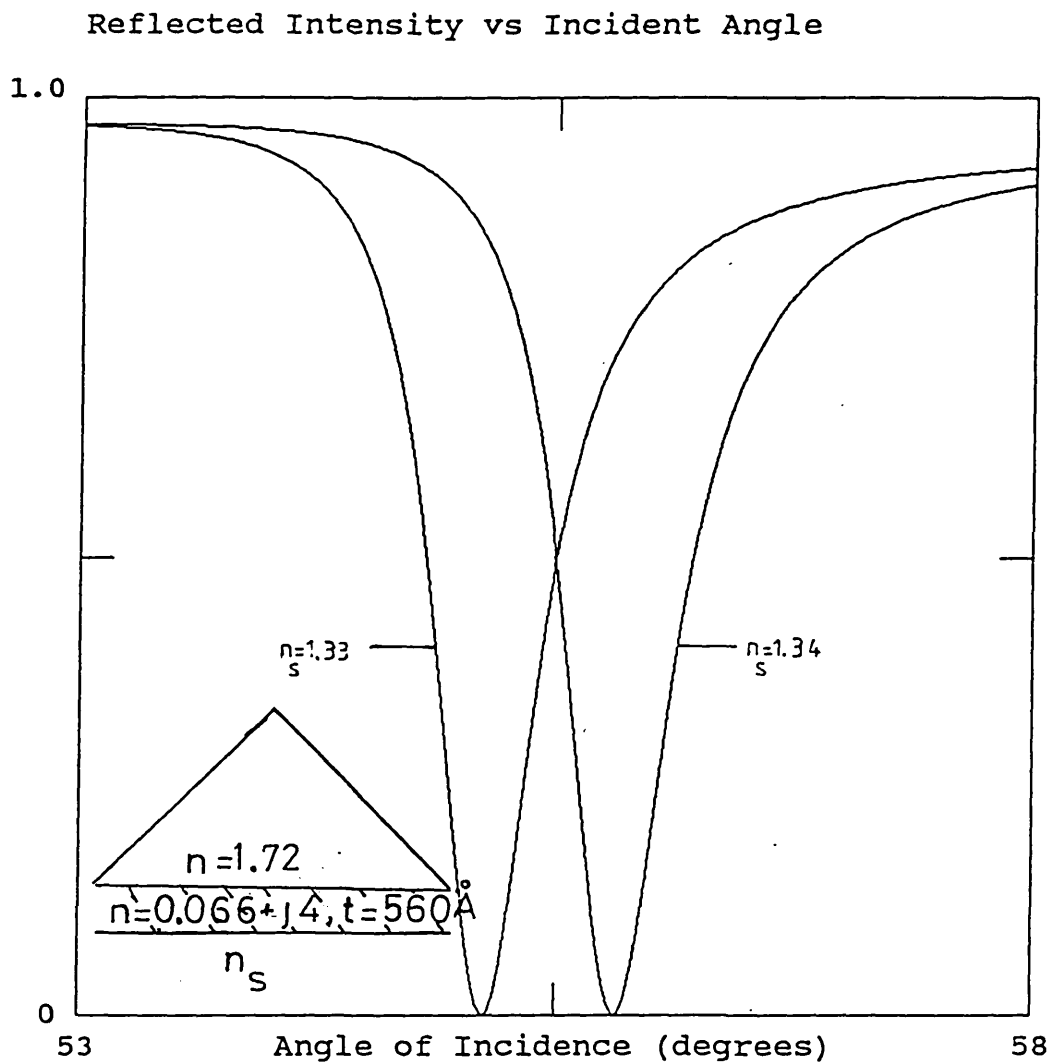


fig.2.2.1. Reflectivity versus the angle of incidence corresponding to the Kretschmann geometry shown above, and for different values of n_s . (wavelength = $0.633 \mu\text{m}$)

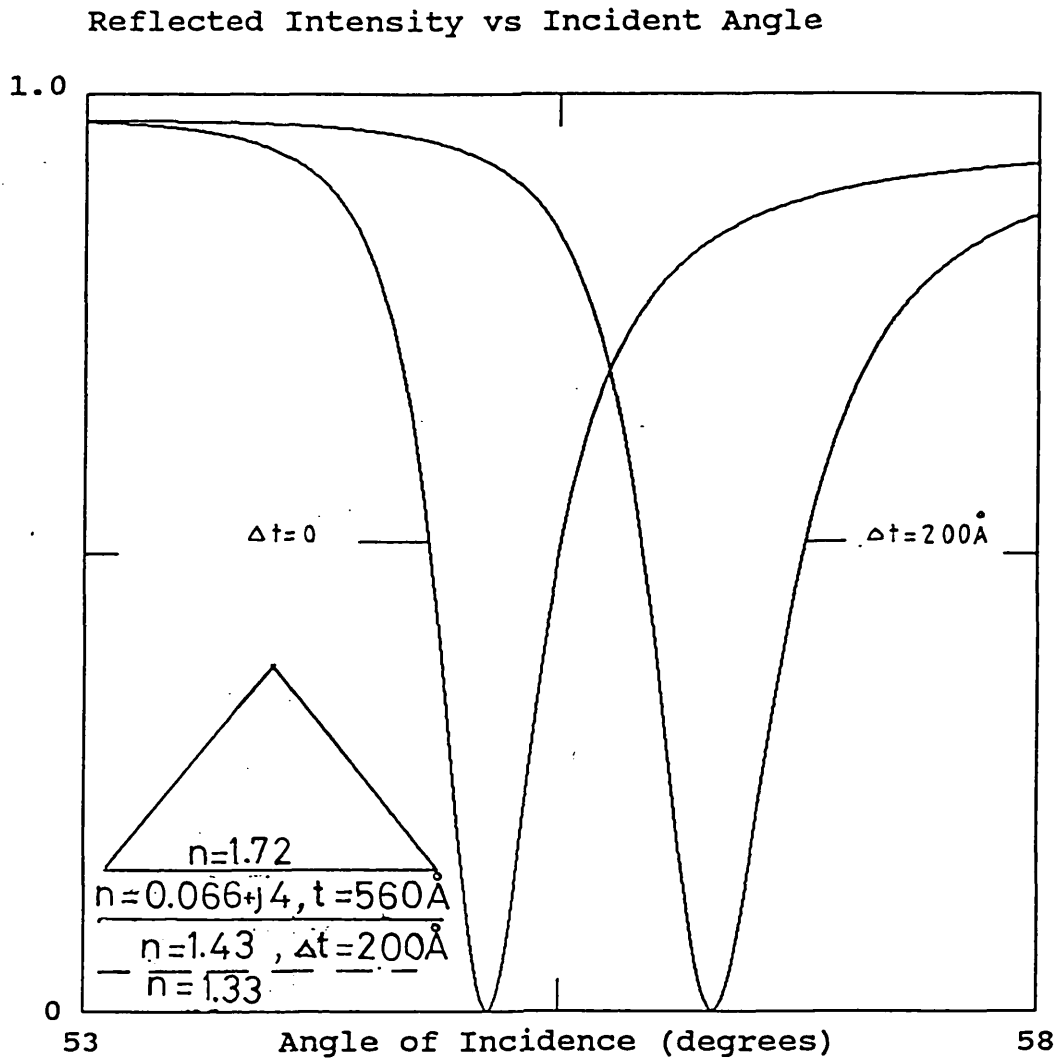


fig.2.2.2. Formation of a thin layer of thickness Δt and refractive index of 1.43 on the outer surface of the metal film causes an appreciable shift in the SP resonance. (wavelength = $0.633 \mu\text{m}$)

the effective index of the surface plasma wave propagating on a metal-dielectric interface is always larger than the refractive index of the dielectric medium, the surface plasma wave on the metal-prism interface, has an effective index larger than n_P , and hence cannot be excited by the incident light propagating in the prism.

The excitation of the surface plasma mode on the metal film outer interface appears as a dip in the reflectivity (from the prism base) versus the angle of incidence curve. This is shown in fig.2.2.1. The reflectivity is calculated using the plane wave analysis by Hansen[1968]. The dip in the reflectivity curve is referred to as the surface plasma resonant dip, with the angle of incidence θ_r , corresponding to the minimum in the reflectivity curve, referred to as the resonant angle.

Application of such a surface plasma wave coupler as a sensing device is based on the fact that variations in the refractive index, n_S , of the outer cladding of the metal film, referred to as the sensing medium (or sensing cladding), are associated with changes in the effective index of the surface plasma mode. From equation (2.2.3), it is clear that any change in the effective index of the surface plasma mode would now result in a shift in the resonant angle, θ_r . This is also shown in fig.2.2.1. The shift in the resonant angle can thus be used to deduce the values of changes in n_S , and hence the values of the variables which influence n_S . This can be implemented by either measuring the corresponding shift in θ_r or, as described by Nylander[1983], by fixing the angle θ somewhere in the middle of one of the slopes of the resonance curve and measuring the resulting variations in the intensity of the reflected light as n_S is varied.

The curves of fig.2.2.2 show that formation of a 200Å adlayer of refractive index 1.43 on the outer surface of the metal film, which is surrounded by an

aqueous medium (index=1.33), results in a substantial shift in the resonance dip. This suggests that the Kretschmann surface plasma wave coupler also has the potential to detect presence of thin adlayers formed on the surface of the metal.

Fig.2.2.3 shows a practical arrangement in which the metal film is deposited on a glass substrate, with the glass substrate brought in optical contact with the prism using a liquid of appropriate refractive index (the refractive index of the prism, contact liquid and the glass slide are nearly the same). The incident light now impinges on the glass slide- metal interface, reflects from this interface and emerges from the other side of the prism. The need for this arrangement arises from the fact that silver films tarnish upon exposure to atmosphere for a long time. This limits the life time of surface plasma wave sensors. Deposition of the silver film on the glass slide, however, allows fabrication of samples of the silver film in large quantities and at a relatively cheap cost.

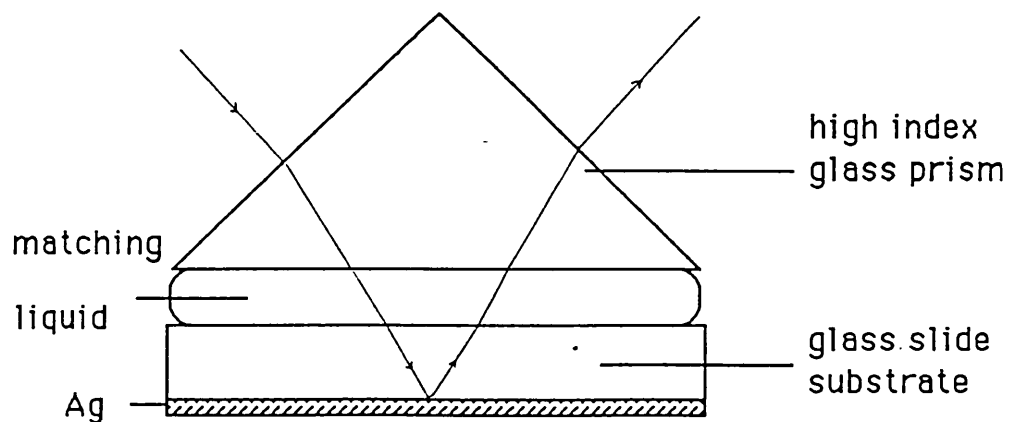


fig.2.2.3. In a practical arrangement the metal film deposited on a glass slide is brought in contact with the prism using a matching liquid of appropriate index.

The performance of a surface plasma wave coupler as a sensor is obviously a function of the sensitivity of the effective index of the surface plasma wave, $\frac{\beta_r}{k_0}$, to changes in n_S . The effective index of the surface plasma wave can, however, be approximated by;

$$\frac{\beta_r}{k_0} \sim \frac{P_1 n_1 + P_S n_S}{P_T} \quad (2.2.4)$$

where

n_1 =refractive index of the metal

n_S =refractive index of the sensing medium

P_1 =power in the metal

P_S =power in the sensing medium

P_T =total power

From (2.2.4), the following is deduced;

$$\frac{\partial(\frac{\beta_r}{k_0})}{\partial(n_S)} \sim \frac{n_1}{P_T} \frac{\partial P_1}{\partial n_S} + \frac{n_S}{P_T} \frac{\partial P_S}{\partial n_S} + \frac{P_S}{P_T} \quad (2.2.5)$$

But, for small changes in n_S , $\frac{\partial P_1}{\partial(n_S)}$ and $\frac{\partial P_S}{\partial(n_S)}$ can be neglected, resulting in the following approximate equation;

$$\frac{\partial(\frac{\beta_r}{k_0})}{\partial n_S} \sim \frac{P_S}{P_T} \quad (2.2.6)$$

An important conclusion drawn from equation (2.2.6) is that the sensitivity of $\frac{\beta_r}{k_0}$ (or θ_r) to n_S is a function of the fractional power distributed in the sensing medium. The effective index of the surface plasma mode propagating on the outer surface of the metal film in the Kretschmann structure, which has a very large fraction of its power confined to the metal film outer interface and inside the dielectric sensing cladding, is thus expected to be extremely sensitive to

variations in n_S . This suggests the possibility of devising very sensitive sensing devices based on the excitation of surface plasma waves using a Kretschmann structure. The strong confinement of the surface plasma power to the metal surface is shown in fig.2.2.4, which shows the surface plasma mode magnetic field intensity ($|H_y|^2$) profile of the corresponding surface plasma mode.

It is also obvious that increasing the sharpness of the surface plasma resonance in such a sensing device enables measurement of smaller shifts in the resonance as a result of variations in n_S , hence improving the sensing performance of the device.

Analysis shows that increasing the thickness of the metal film, which in fact defines the separation between the prism and the surface plasma wave supporting metal interface, results in an increase in the sharpness of the resonance. This is shown in fig.2.2.5. Increasing the separation thickness further than a particular value, $560\text{\AA}$ in the case of silver and at a wavelength of $0.633\mu m$, is however realised to result in a reduction in the depth of resonance. This is also shown in fig.2.2.5, and has been explained in the following manner.

Proximity of the high index prism to the surface plasma mode, propagating on the outer metal-dielectric interface, causes radiation of this mode into the prism, resulting in a loss mechanism represented by β_l , where β_l is in fact the modification to the imaginary part of the surface plasma wave propagation constant due to its perturbation by the prism.

Analysis shows that in order to obtain a maximum depth of resonance, ie zero minimum in the reflectivity, the radiation loss, β_l , is required to be equal

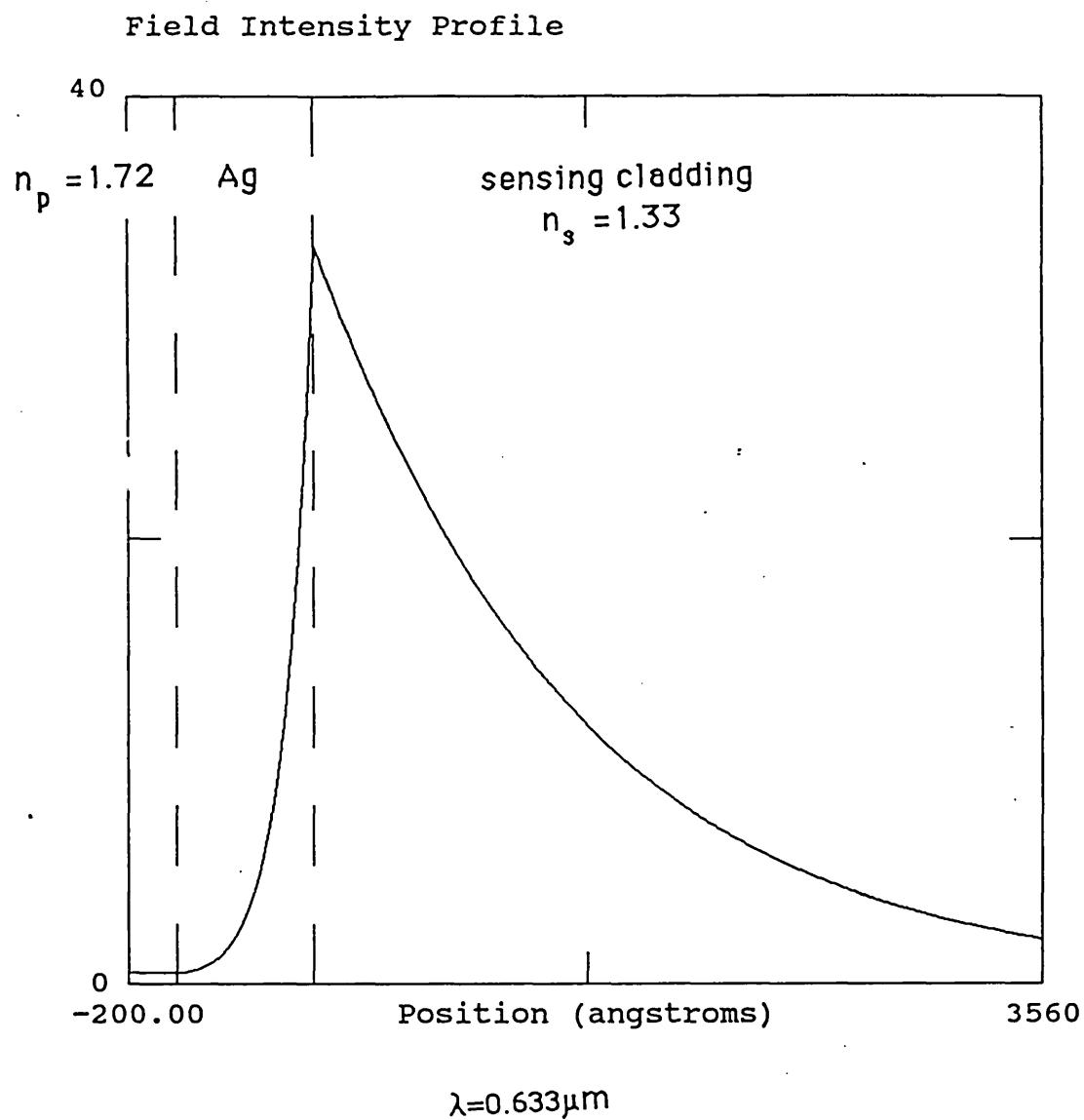
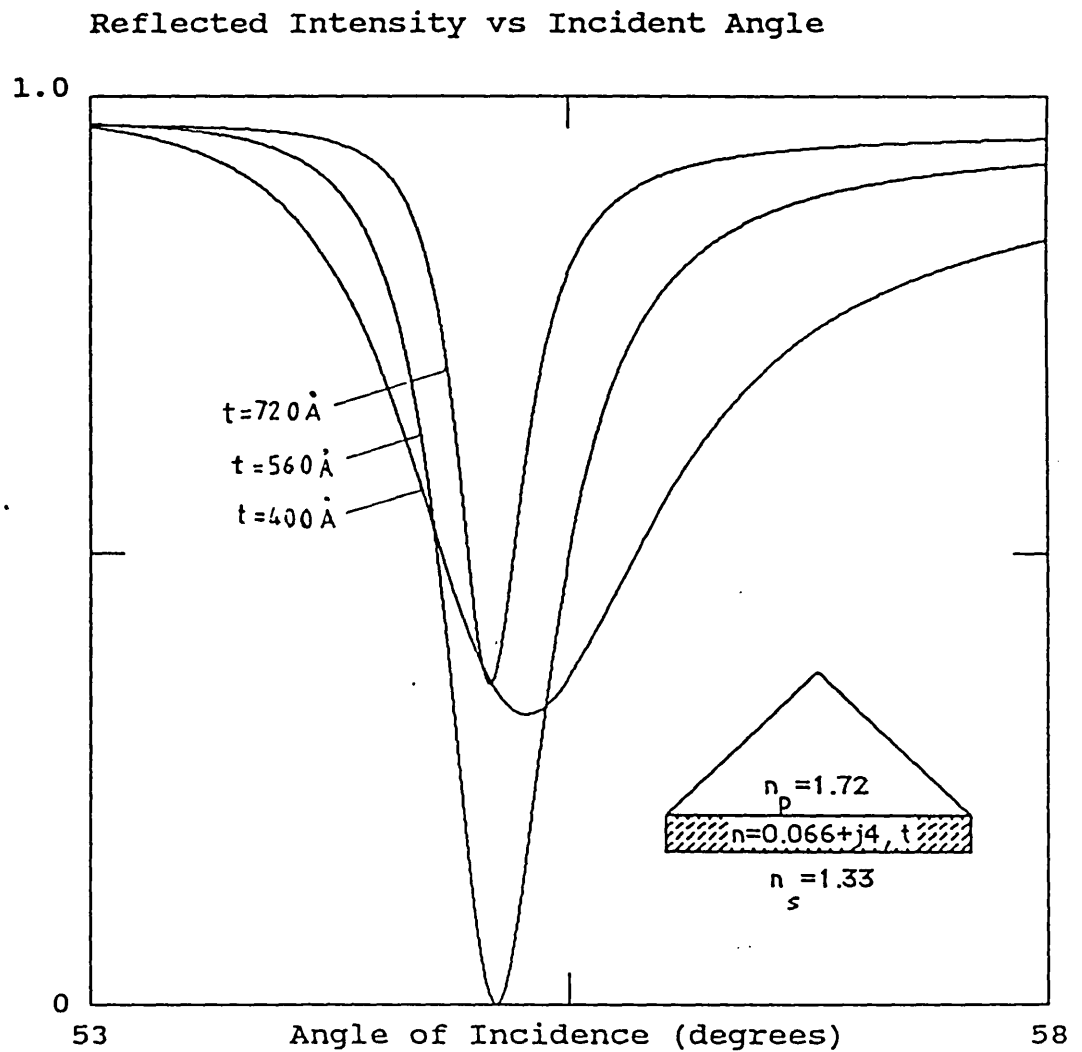


fig.2.2.4. The field intensity profile ($|H_y|^2$) of the SPW propagating on the outer surface of the metal film in the Kretschmann geometry.



$$\lambda = 0.633 \mu\text{m}$$

fig.2.2.5. Increasing the metal film thickness in the Kretschmann geometry sharpens the resonance, but for values of t larger than $560 \text{ \AA}$ it also reduces the resonance depth.

to the inherent loss associated with the surface plasma wave, β_i . This can be achieved by adjusting the thickness of the metal film which influences both β_i and β_t . This condition for the case considered so far, corresponding to a silver film at a wavelength of $0.633\mu m$, results in an optimum thickness of $560\text{\AA}$.

The reduction in the depth of resonance, which results in a weaker contrast between the maximum and minimum values of the reflected light intensity, may be considered as a drawback. This is because a large contrast would result in apparently more pronounced variations in the intensity of the reflected light as a result of changes in the sensing medium, which is generally the basis of sensing operation of this structure. It should, however, be noted that in most practical situations a maximum contrast, manifested by a maximum depth of resonance, is not essential. One application in which the contrast may play a significant role is the surface plasma microscopy [Yeatman 1987], in which the intensity variations may be required to be visually detected. In this work, however, for the sake of consistency, the sensing performance of devices based on different structures corresponding to the maximum depth of resonance are compared.

A technique devised here to overcome the above difficulty is to introduce a dielectric layer, referred to as the buffer layer, between the prism and the metal film (fig.1.1.11), which enables the sharpness of the resonance to be increased by increasing the thickness of the buffer layer. The possible resulting loss in the depth of resonance, due to the reduction in the radiation loss (β_t), can now be compensated for by adjusting the thickness of the metal film, which adjusts the inherent loss of the surface plasma mode, β_i , accordingly. In other words, for each value of the buffer thickness an optimum metal thickness exists for which β_t and β_i are identical and hence maximum depth of resonance is obtained.

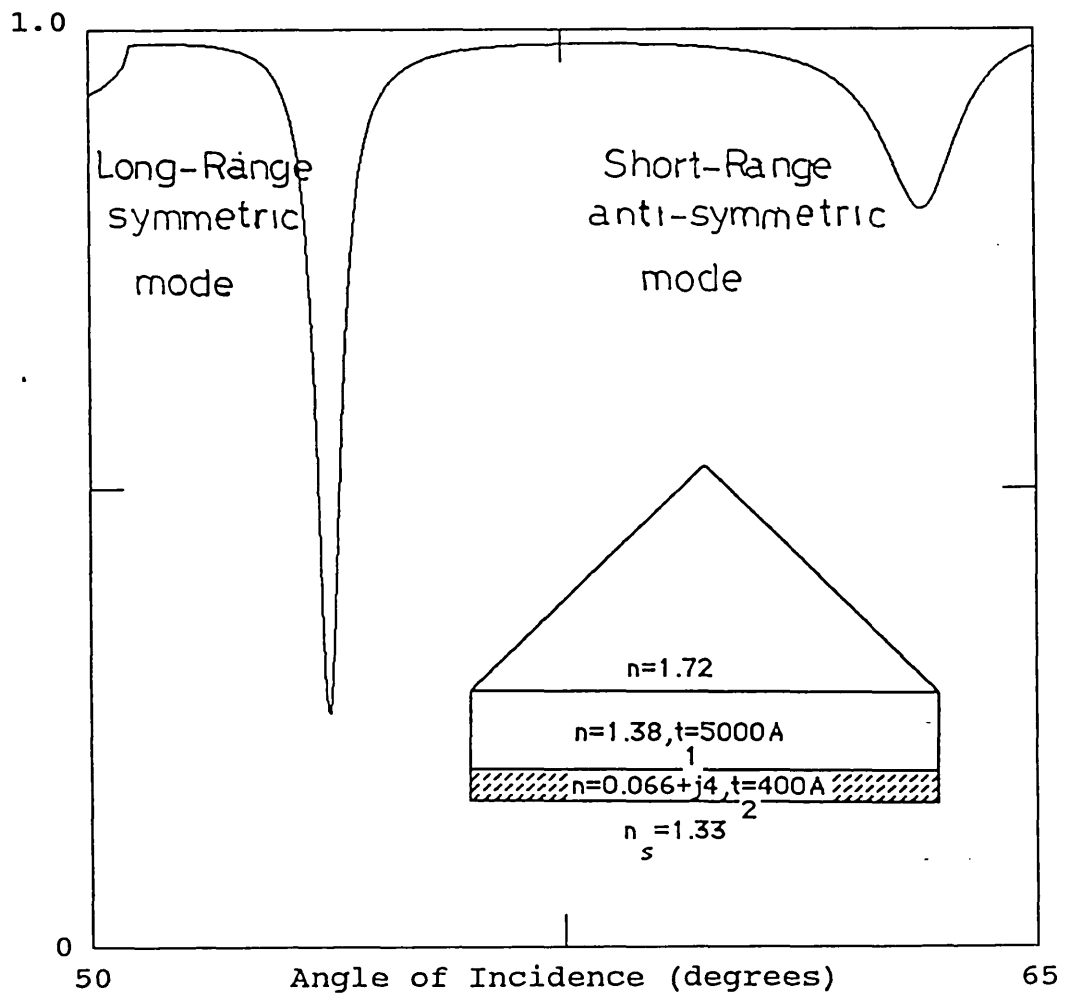
Fig.2.2.6(a) shows the reflectivity curve corresponding to a buffered geometry. The thickness of the buffer layer and the silver film are represented by t_1 and t_2 , respectively. The two resonance dips correspond to the long range and the short range surface plasma modes on the metal film, both of which, in this case, can be excited by the incident light. The long range mode, associated with a sharper resonance, is of more interest. The sharper resonance associated with the long range surface plasma mode is due to the fact that the width of the resonance for large values of buffer thickness, which is a requirement for a sharp resonance, is predominantly determined by the inherent loss, β_i . Therefore, the long range mode, associated with a smaller value of β_i , corresponds to a sharper resonance.

The magnetic field intensity profiles corresponding to the two surface plasma modes of the structure of interest, shown in fig.2.2.6(b), reveal that in contrast to the short range mode, the long range mode is largely distributed around the interface between the metal and the dielectric medium with the lower refractive index. The long range mode is therefore expected to be more sensitive to changes in the refractive index of this medium. This suggests that in the case of an asymmetric metal film, in order to secure the long range mode as the mode which is more sensitive to changes in the sensing medium, the sensing medium is required to be of a lower refractive index than the buffer layer. This requirement is satisfied in the example given here, which may correspond to certain applications. One such application is biosensing in which the sensing cladding is of an aqueous nature ($n=1.33$), with the buffer layer being a magnesium fluoride ($n=1.38$) layer.

The long range resonance dips for a number of buffer layer thicknesses are shown in fig.2.2.7(a). It is clearly shown that as the buffer layer thickness (t_1) is increased, the resonance tends to become sharper. The curves in fig.2.2.7(b)

2.2.6(a)

Reflected Intensity vs Incident Angle



(b)

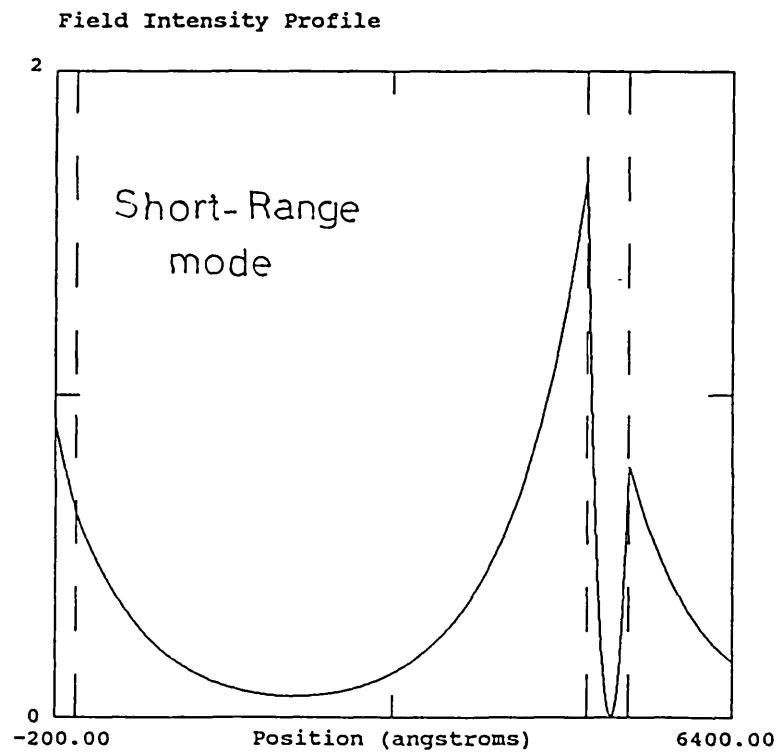
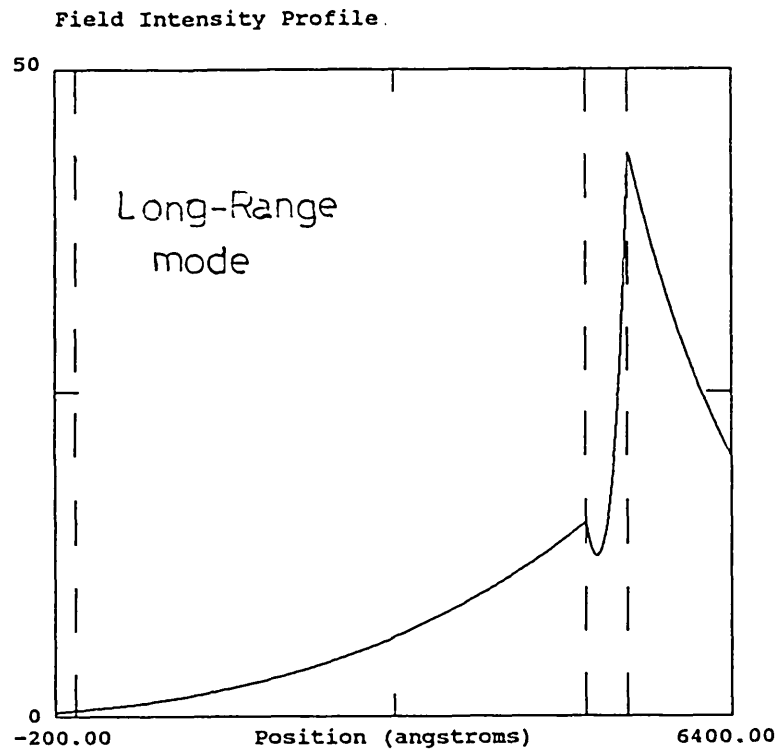
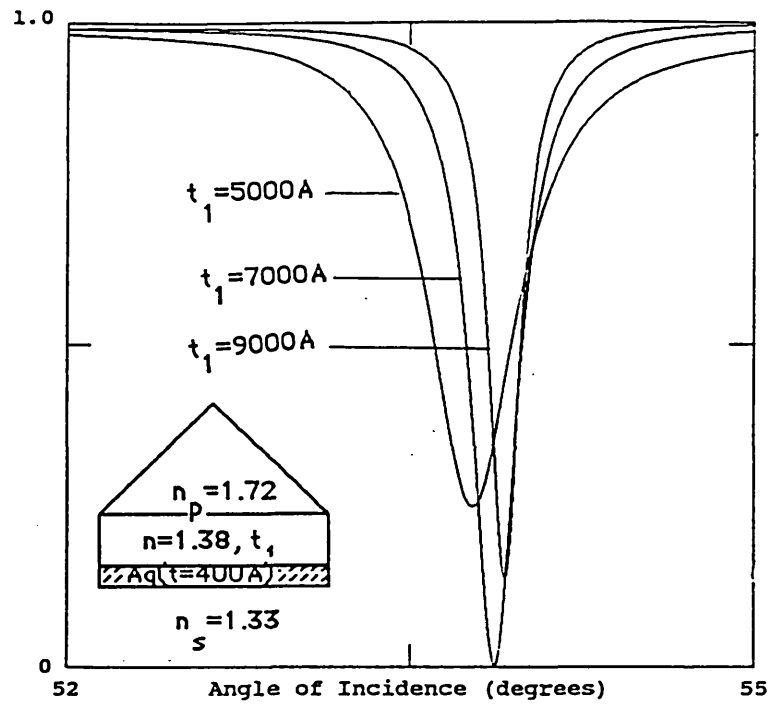


fig.2.2.6.Reflectivity versus angle of incidence corresponding to the buffered geometry(a), and the corresponding field intensity profiles(b). $\lambda=0.633\mu\text{m}$

(a) Reflected Intensity vs Incident Angle



(b) Reflected Intensity vs Incident Angle

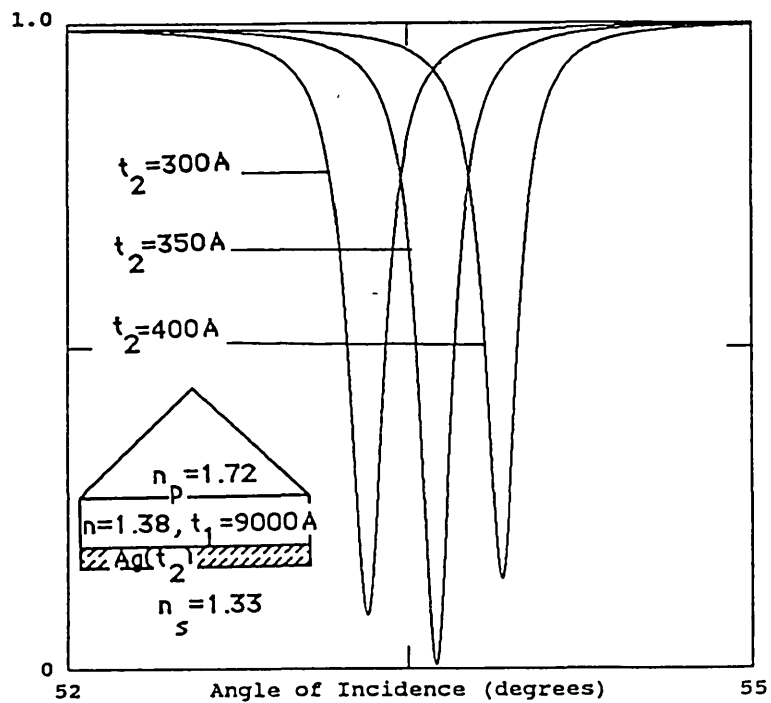


fig.2.2.7.(a) Increasing the thickness of the buffer layer sharpens the resonance, but may also reduce the resonance depth. (b) The depth of resonance can however be restored by adjusting the metal film thickness. $\lambda = 0.633 \mu\text{m}$

confirm that any loss in the depth of resonance, as a result of increasing t_1 , can be retrieved by adjusting the thickness of the metal film (t_2).

From the field intensity distributions of the surface plasma mode of the Kretschmann structure (fig.2.2.4) and that of the buffered structure (fig.2.2.6(b)) it is apparent that the long range surface plasma mode of the buffered geometry is distributed slightly more evenly around the two interfaces of the metal film. This characteristic, which is due to the fact that the surface plasma wave supporting metal film of the buffered geometry possesses a more symmetric index profile, suggests that the fractional surface plasma power in the sensing medium of the buffered geometry is slightly less than that of the Kretschmann geometry. This is confirmed by the curves of fig.2.2.8, in which the fraction of the surface plasma power confined to a region of thickness Δt of the sensing cladding adjacent to the metal interface, for both geometries are plotted as a function of Δt . Therefore, since the sensitivity of the effective index of the surface plasma mode to variations in the refractive index of the sensing medium (n_S) is determined by the fractional surface plasma mode power in the sensing cladding (equation(2.2.6)), sensing devices based on the Kretschmann structure may be expected to be of a superior performance.

The reflectivity curves of the two geometries and the corresponding shifts in the resonant dips as a result variations in n_S are shown in fig.2.2.9. These curves confirm that in the Kretschmann geometry, a larger shift in θ_r occurs as a result of the same change in n_S . However, it is also apparant that the improvement in the sharpness of the resonance, as a result of introducing the buffer layer, may be expected to make detection of smaller changes in n_S possible, implying a more sensitive device.

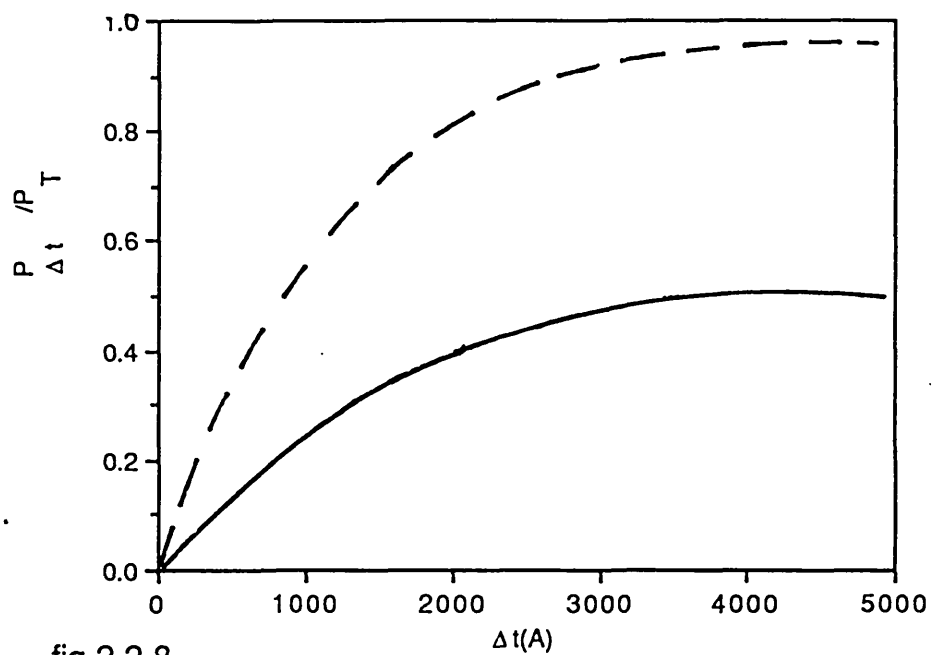


fig.2.2.8.

The % of SPW power in a region of thickness Δt of the sensing cladding adjacent to the metal surface of the Kretschmann (----) and the buffered(—)geometries.

(Buffered geometry: $t_{\text{buffer}}=9000\text{\AA}$, $t_{\text{Ag}}=350\text{\AA}$)

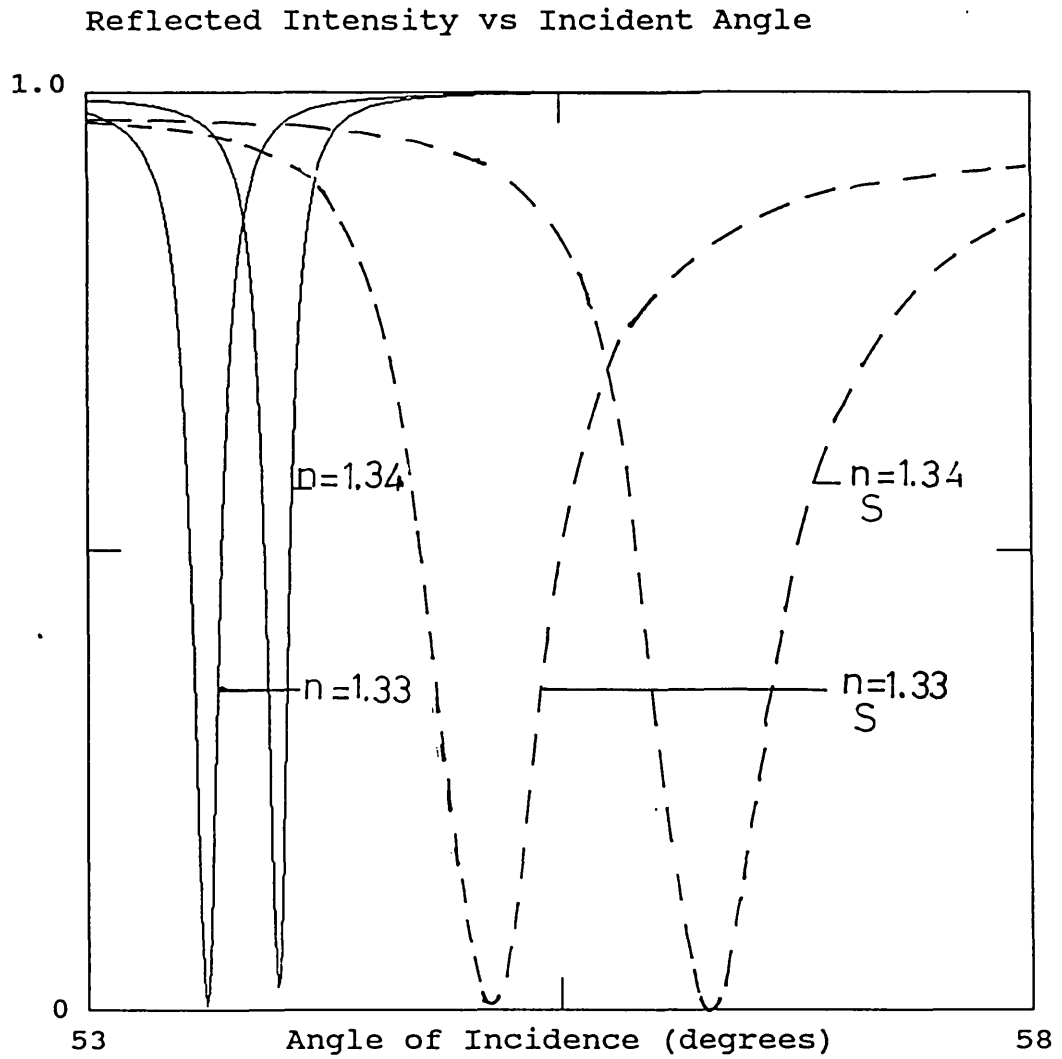


fig.2.2.9. Influence of variations in n_s on the reflectivity curves of the buffered geometry of fig.2.2.7(—) and the Kretschmann geometry of fig.2.2.1(----).

(Buffered geometry: $t_{\text{buffer}}=9000\text{\AA}$, $t_{\text{Ag}}=350\text{\AA}$)

To analytically compare the overall sensing performance of the two geometries, the sensitivity is defined by $\frac{1}{\Delta n_{min}}$, where Δn_{min} is the minimum change in n_s required to shift the resonance angle by a complete half power bandwidth. Fig.2.2.10, shows $\frac{1}{\Delta n_{min}}$ as a function of Δt , where Δt defines the thickness of, for example, an adlayer formed on the metal film outer surface. The continuous and the broken curves correspond to the Kretschmann and the buffered geometries, respectively. The thicknesses of the constituent layers of the buffered structure are also shown in this figure.

Fig.2.2.10 clearly shows that the buffered geometry is associated with larger values of $\frac{1}{\Delta n_{min}}$, suggesting that this geometry may form the basis of a superior sensing device.

From fig.2.2.10, it is also concluded that the sensing performance of the buffered structure may be further improved by increasing the thickness of the buffer layer. However it should be noted that for a buffer layer of thickness larger than $10000\text{\AA}$, to maintain maximum depth of resonance, the silver film is required to be thinner than $300\text{\AA}$. Silver films of such thickness may be of a relatively poor surface quality [Sennet and Scott 1950]. Surface roughness, present on the surface of very thin silver films, is however expected to result in scattering loss which would result in broadening of the surface plasma wave resonance and hence degrading of the sensing performance of the device. It may also be noted that for films of less than $60\text{\AA}$ in thickness the optical properties of, in effect, silver islands, which significantly differ from those of continuous films, do not satisfy condition (2.1.24) which is necessary for presence of surface plasma waves on a metal-dielectric interface (the real part of the silver permittivity measured by Inagaki et al[1986] for films of thickness less than $60\text{\AA}$ is a positive quantity).

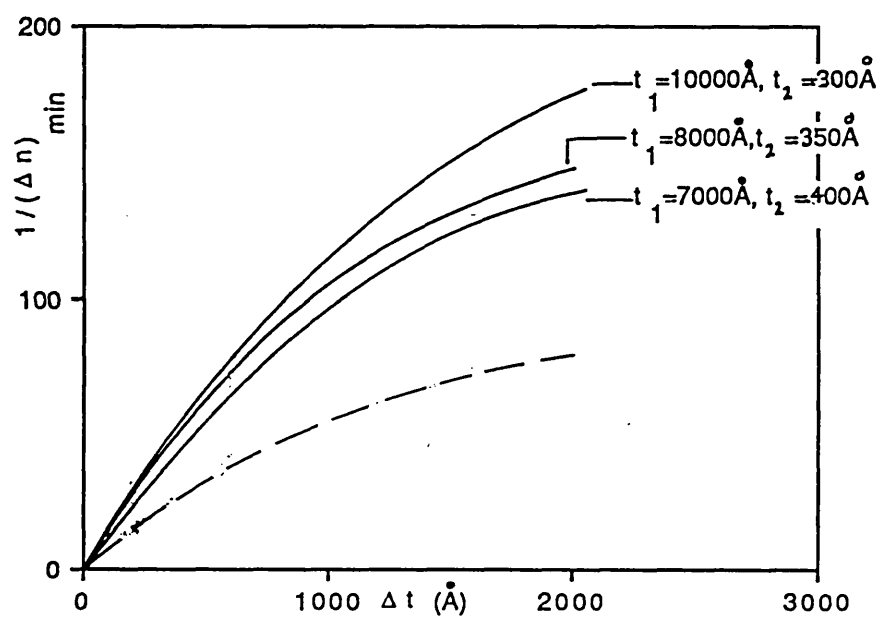


fig.2.2.10. The sensitivities of the buffered(—) and the Kretschmann(— —) geometries.

The above considerations put a practical limitation on the extent to which the performance of a buffered surface plasma wave coupler can be improved by increasing the buffer layer thickness.

It should also be noted that in certain applications it may be desired to detect formation of very thin adlayers on the metal outer surface while the outer cladding is formed by the ambient air [Pockrand 1978]. Under this circumstance the effective index of the surface plasma mode on the metal film outer interface, which probes the build up of the adlayer, will exceed the refractive index of the ambient air (approximately 1.0) by only a small amount, and hence will be less than the refractive index of the buffer layer (1.38). This implies that at the angle of incidence at which this surface plasma mode is excited, the light incident on the prism- buffer layer interface no longer totally reflects from this interface, and in fact refracts through into the buffer layer. The buffered structure, now, behaves like a Kretschmann structure. In other words, in such applications the concept of the buffered structure is meaningless, and the surface plasma resonance can no longer be sharpened by adjusting the buffer layer thickness.

2.3. Comparison with the dielectric waveguide prism coupler.

In the dielectric waveguide prism coupler of fig.1.1.3, the proximity of the high index prism to the dielectric waveguide allows the existence of electromagnetic fields in the guiding layer over a range of incident angles. Stronger perturbation of the waveguide mode by the prism, realised through thinner spacing layers, results in a broadening of this angular range. Conversely, for an isolated waveguide (ie. infinite spacing layer thickness) the resonance would be replaced by a delta response, corresponding to the guided mode of the isolated waveguide. From the above argument it is apparent that, theoretically, the sharpness of the waveguide resonance can be made infinitely sharp.

In surface plasma wave couplers, however, the sharpness of the surface plasma resonance is limited by the inherent loss of the surface plasma wave.

It is the possibility of increasing the sharpness of the waveguide resonance in the above manner which is suggested to enable fabrication of superior sensing devices based on the dielectric waveguide prism couplers [Mason 1988].

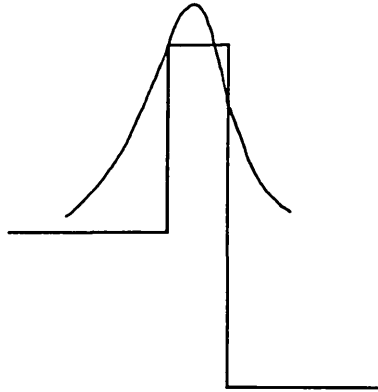
The major drawback with the dielectric waveguide prism coupler is the fact that the field associated with the waveguide mode (which is probing the sensing cladding) of a conventional waveguide is mainly confined to the guiding region (core), with very little field in the sensing cladding. Mason suggests that the fractional field in the sensing cladding and in the vicinity of the core-cladding interface can be significantly increased by increasing the index difference between the core and the claddings and reducing the thickness of the core substantially. One such structure consists of a $400\text{\AA}$ ZnS ($n=2.43$) layer as the core, in which more than 30 percent of the propagating power is distributed in an aqueous sensing cladding with the other cladding being MgF_2 ($n=1.38$).

However, increasing the fractional field in the above manner is realised to result in the effective index of the waveguide mode to be extremely sensitive to variations in thickness of the dielectric guiding layer. This is explained with the help of the field representation of an optimum waveguide (fig.2.3.1(a)) compared to that of a conventional waveguide (fig.2.3.1(b)). For the conventional waveguide the strong confinement of the field well inside the guiding layer makes the effective index of its guided mode somewhat insensitive to thickness variations. While in the case of the optimised waveguide strong perturbation of the field by the guiding layer boundaries make it very sensitive to thickness variations.

The waveguide thickness sensitivity limits the sharpness of the waveguide resonance attained using the waveguide prism coupler by causing the incident light to couple into the waveguide mode at slightly different positions on the structure and at different angles of incidence, resulting in a broader resonance. Mason suggests that thickness variations limit the angular width of the waveguide resonance for an optimum waveguide in a waveguide prism coupler to nearly 0.2 degrees [Mason 1988]^(a)

The angular width of the surface plasma resonance in the buffered geometry of the example in fig.2.2.7 is clearly comparable to the above value. It should also be noted that the surface plasma waves on the metal film of the buffered surface plasma wave coupler are not so susceptible to variations in the metal film thickness. For example, in the case of the optimised waveguide, a thickness variation of $1\text{\AA}$ results in a shift of 0.001 in the mode index of the dielectric waveguide, while such a thickness variation results in a change of only 0.0000007 in the surface plasma mode index on a $300\text{\AA}$ silver film surrounded by materials of refractive indices 1.38 and 1.33. This is due to the fact that in the case of the asymmetric metal film of the buffered structure examined here, the surface

(a)



(b)

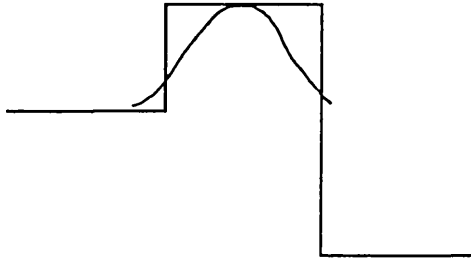


fig.2.3.1. Schematic representation of the field associated with an optimized dielectric waveguide(a), and that of a conventional waveguide(b).

plasma field is strongly confined to a single metal interface (the outer interface of the metal film).

In conclusion:

1) the width of the surface plasma resonance in the buffered geometry is comparable to that of the dielectric waveguide resonance in the dielectric waveguide prism coupler.

2) the fraction of the surface plasma resonance in the buffered surface plasma coupler (more than 45 percent) is larger than that of the optimised waveguide (30 percent).

It may, therefore, be concluded that the buffer surface plasma wave coupler is a more attractive sensing device compared to the dielectric waveguide prism coupler.

2.4. Conclusions.

The analysis and discussions in this chapter show that, as envisaged by other researchers, surface plasma wave prism couplers have enormous potential as sensing devices. As an illustration of the sensitivity of devices based on the surface plasma wave prism couplers -coverage of the silver film of the buffered structure of fig.2.2.7 (with $t_{Ag} = 300\text{\AA}$ and $t_{buffer} = 10000\text{\AA}$) with an adlayer of thickness of $20\text{\AA}$ and index of 1.45 (corresponding to, for example, an antibody-antigen layer) can easily be detected.

It has also been shown that the fact that a significant increase in the sharpness of the surface plasma resonance in the Kretschmann geometry is associated with an appreciable loss in the depth of resonance hinders possible

improvements to its performance. Introduction of a buffered surface plasma wave prism coupler, however, enables increasing the sharpness of the surface plasma resonance without loss of the resonance depth.

A contender to surface plasma wave prism couplers as sensors is the waveguide prism coupler, which enters the contest in virtue of its extremely sharp resonance, which compensates for its smaller fractional power in the sensing medium. However, considerations in section 2.3 show that the angular width of the surface plasma resonance in the buffered geometry is comparable to that of the waveguide resonance, while the buffered surface plasma wave coupler enjoys a larger fractional power distribution in the sensing medium, giving it a superior overall sensitivity.

From a practical point of view, since fabrication of the Kretschmann structure merely involves deposition of a single metallic layer on the base of the prism, devices based on this structure may possibly be the most commercially feasible of the structures considered in this chapter. This is further justified by taking into account that, as described by other researchers, devices based on the Kretschmann structure can still detect extremely small changes on the surface of the metal.

CHAPTER 3.

DIRECTIONAL COUPLERS AS SENSORS.

A number of optical sensing devices based on coupling of light between the guided modes of two dielectric waveguides in a directional coupler structure have been recently devised. Application of a coaxial optical fibre directional coupler geometry as a sensing device has been recently reported by Attridge et al[1985]. At present Cozens and Yi[1988] of Imperial College are investigating sensing devices based on an optical directional coupler comprising of two rectangular dielectric waveguides combined into a single fibre geometry.

As shown in the following diagram, a conventional optical directional coupler consists of two parallel dielectric waveguides placed in proximity to each other. The overlap of the fields of the guided modes of the two waveguides, now, results in the transfer of power, or coupling, between waveguide modes.

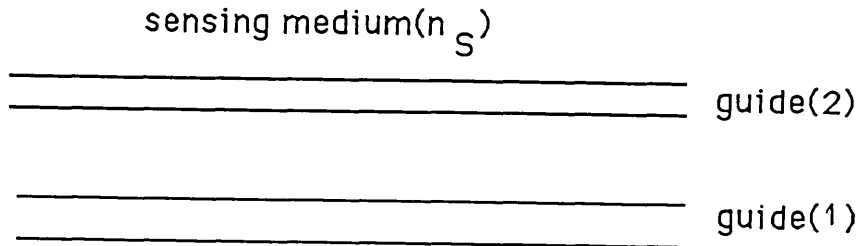


fig.3.1.The cross-section of a conventional directional coupler.

Since the coupling is a function of the parameters of the structure, including, for example, the refractive index n_s , such a directional coupler can be employed to deduce n_s , or changes in it, and hence the values of variables which influence n_s .

An exact analysis of the directional coupler structure reveals that the structure as a whole supports two normal modes, which possess symmetric and anti-symmetric field profiles [Yariv 1985]. The presence of the normal modes can be explained by the fact that as the two waveguides, each supporting a single guided mode, are brought into proximity to each other, the fields of the individual waveguides interact, resulting in two composite modes which are of symmetric and antisymmetric nature. Transfer of power between the two guides can now be considered as the interference between the normal modes of the structure. A directional coupler, therefore, resembles an interferometer, with the two waveguides representing the arms of the interferometer, virtually occupying the same space.

In the following analysis, the structure is treated as a combination of the two individual waveguides. It is then possible to define a coupling mechanism between the individual guided modes. This analysis is based on the coupled mode theory described by *Marcuse*[1972]^(b).

The formulation in section 3.1, upto equation (3.1.27) is of a general form, allowing for presence of loss. However, for simplicity and in order to establish a general understanding of the basic principles of the coupling mechanism, the examples considered in this chapter correspond to the case of lossless dielectric directional couplers of a slab geometry.

3.1. Coupled mode theory.

Consider a directional coupler consisting of the waveguides(1) and (2). The squares of the refractive indices of guides(1) and (2) have the profiles shown in

figures 3.1.1(a) and 3.1.1(b), and are described by functions $n_1^2(x)$ and $n_2^2(x)$, defined below;

$$n_1^2(x) = \begin{cases} n_3^2 & x < x_1 \\ n_1^2 & x_1 < x < x_2 \\ n_3^2 & x > x_2 \end{cases} \quad (3.1.1)$$

$$n_2^2(x) = \begin{cases} n_3^2 & x < x_3 \\ n_2^2 & x_3 < x < x_4 \\ n_S^2 & x_4 < x \end{cases} \quad (3.1.2)$$

The square of the refractive index of the structure as a whole, $n^2(x)$, represented in fig.3.1.1(c), can now be described by the following expression;

$$n^2(x) = (n_1^2(x) - n_3^2) + (n_2^2(x) - n_3^2) + n_3^2 \quad (3.1.3)$$

which is defined by;

$$n^2(x) = \begin{cases} n_3^2 & x < x_1 \\ n_1^2 & x_1 < x < x_2 \\ n_3^2 & x_2 < x < x_3 \\ n_2^2 & x_3 < x < x_4 \\ n_S^2 & x_4 < x \end{cases}$$

The field components of the guided mode of each guide in isolation are described by the following expressions;

$$E_\nu = \hat{E}_\nu(x, y) \exp j(\omega t - \beta_\nu z) \quad (3.1.4)$$

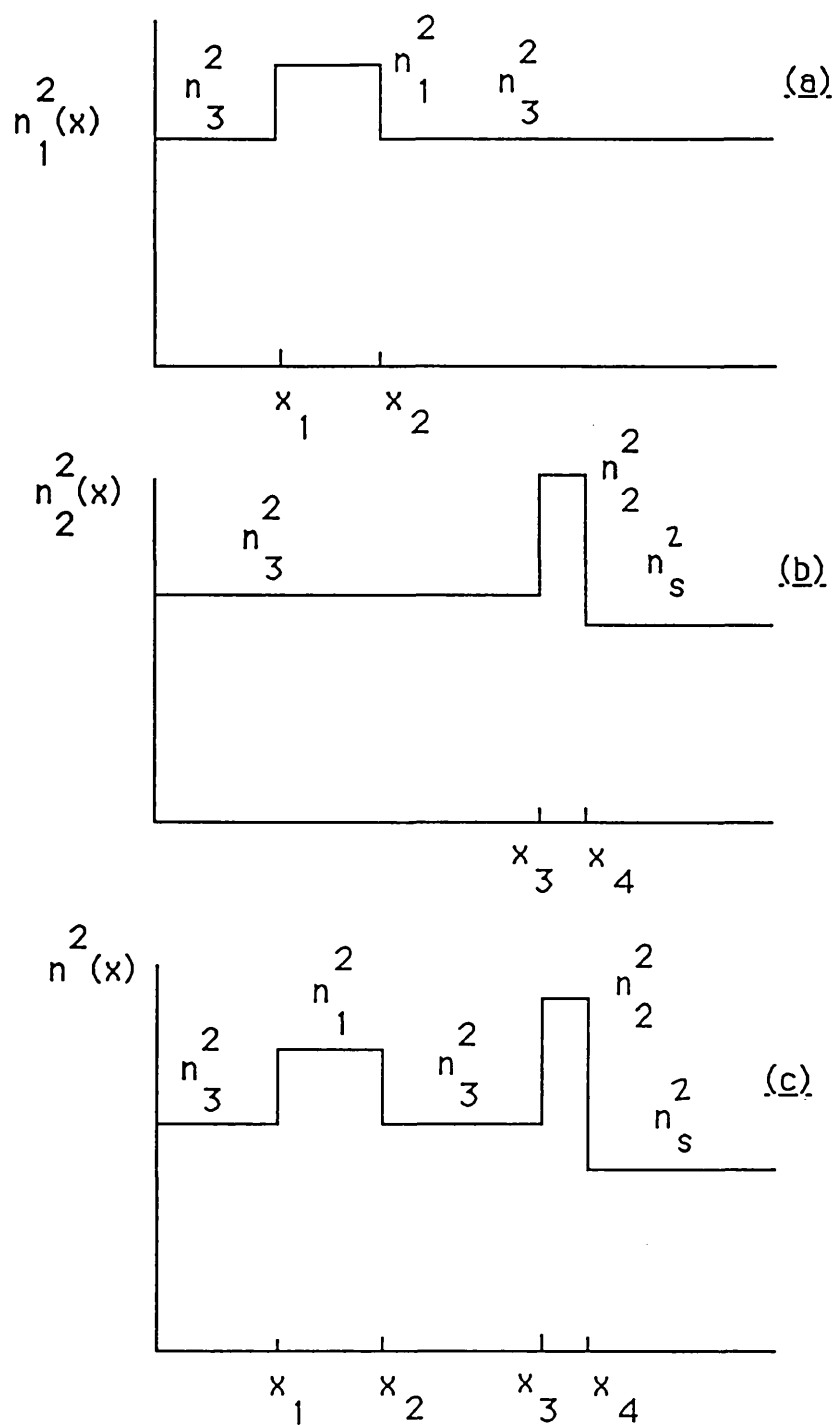


fig.3.1.1. The square of the refractive index profile of: (a) guide (1), (b) guide (2) and (c) the whole structure.

$$H_\nu = \hat{H}_\nu(x, y) \exp j(\omega t - \beta_\nu z) \quad (3.1.5)$$

where β_ν = propagation constants of the isolated guided modes, ω = angular frequency, and $\nu = 1$ or 2 , corresponding to guides(1) and (2) respectively.

The above fields satisfy Maxwell's Equations in the following form;

$$\nabla_t \times E_\nu - j\beta_\nu(\hat{Z} \times E_\nu) + j\omega\mu_0 H_\nu = 0 \quad (3.1.6)$$

$$\nabla_t \times H_\nu - j\beta_\nu(\hat{Z} \times H_\nu) - j\omega\epsilon_0 n_\nu^2(x) E_\nu = 0 \quad (3.1.7)$$

∇_t defines the transverse part of the operator ∇ and $\hat{Z}$ is a unit vector in the Z-direction.

Provided the two guides are not too close to each other, their proximity does not influence their individual guided modes significantly. The total fields, to a first approximation, can now be described by a superposition of the individual fields, in the following manner;

$$E = A_1(z)E_1 + A_2(z)E_2 \quad (3.1.8)$$

$$H = A_1(z)H_1 + A_2(z)H_2 \quad (3.1.9)$$

where allowance for variations with z is included in terms of $A_1(z)$ and $A_2(z)$.

Substituting equations (3.1.8) and (3.1.9) into Maxwell's Equations, results in the following;

$$\begin{aligned} & [\nabla_t \times E_1 - j\beta_1(\hat{Z} \times E_1)]A_1 + \frac{dA_1}{dz}(\hat{Z} \times E_1) \\ & + [\nabla_t \times E_2 - j\beta_2(\hat{Z} \times E_2)]A_2 + \frac{dA_2}{dz}(\hat{Z} \times E_2) \\ & + j\omega\mu_0 A_1 H_1 + j\omega\mu_0 A_2 H_2 = 0 \end{aligned} \quad (3.1.10)$$

$$\begin{aligned}
& [\nabla_t \times H_1 - j\beta_1(\hat{Z} \times H_1)]A_1 + \frac{dA_1}{dz}(\hat{Z} \times H_1) \\
& + [\nabla_t \times H_2 - j\beta_2(\hat{Z} \times H_2)]A_2 + \frac{dA_2}{dz}(\hat{Z} \times H_2) \\
& - j\omega\epsilon_0 n^2(x)A_1 E_1 - j\omega\epsilon_0 n^2(x)A_2 E_2 = 0
\end{aligned} \tag{3.1.11}$$

Using equations (3.1.6) and (3.1.7), and substituting for $n^2(x)$, the above equations are reduced to the following;

$$\frac{dA_1}{dz}(\hat{Z} \times E_1) + \frac{dA_2}{dz}(\hat{Z} \times E_2) = 0 \tag{3.1.12}$$

and

$$\begin{aligned}
& \frac{dA_1}{dz}(\hat{Z} \times H_1) + \frac{dA_2}{dz}(\hat{Z} \times H_2) \\
& - j\omega\epsilon_0(n_2^2(x) - n_3^2)A_1 E_1 - j\omega\epsilon_0(n_1^2(x) - n_3^2)A_2 E_2 = 0
\end{aligned} \tag{3.1.13}$$

To remove time dependance, the scalar product of (3.1.12) with H_1^- and (3.1.13) with E_1^- are taken. The negative superscripts indicate that β and ω are replaced by $-\beta$ and $-\omega$. The resulting equations are subtracted and integrated over an infinite cross-section, resulting in the following;

$$\begin{aligned}
& \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{dA_1}{dz} [E_1^- \cdot (\hat{Z} \times H_1) - H_1^- \cdot (\hat{Z} \times E_1)] \right. \\
& \quad \left. + \frac{dA_2}{dz} [E_1^- \cdot (\hat{Z} \times H_2) - H_1^- \cdot (\hat{Z} \times E_2)] \right. \\
& \quad \left. - j\omega\epsilon_0(n_1^2(x) - n_3^2)A_1 E_1^- E_1 - j\omega\epsilon_0(n_1^2(x) - n_3^2)A_2 E_1^- E_2 \right\} dx dy = 0
\end{aligned} \tag{3.1.14}$$

From definition (3.1.1), it is clear that $n_1^2(x) - n_3^2$ is non-zero only inside the region defined by the core of guide(1). In this region $n_1^2(x) - n_3^2$ is equal to $n_1^2 - n_3^2$. Similarly, from (3.1.2), $n_2^2(x) - n_3^2$ is non-zero inside the core and in the outer cladding of guide(2), for which $n_2^2(x) - n_3^2$ equals $n_2^2 - n_3^2$ and $n_s^2 - n_3^2$, respectively. Equation (3.1.14) can therefore be written in the following form;

$$\begin{aligned}
& \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{dA_1}{dz} [E_1^- \cdot (\hat{Z} \times H_1) - H_1^- \cdot (\hat{Z} \times E_1)] \right. \\
& \quad \left. + \frac{dA_2}{dz} [E_1^- \cdot (\hat{Z} \times H_2) - H_1^- \cdot (\hat{Z} \times E_2)] \right\} dx dy \\
& - j\omega\epsilon_0 \{ (n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_3}^{x_4} A_1 E_1^- E_1 dx dy + (n_S^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_4}^{\infty} A_1 E_1^- E_1 dx dy \\
& \quad + (n_1^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_1}^{x_2} A_2 E_1^- E_2 dx dy \} = 0 \tag{3.1.15}
\end{aligned}$$

Field components in this expression are ascribed orders of magnitude, according to their relative size, in the following manner. E_1 or H_1 (and E_1^- or H_1^-) in the region $x_1 < x < x_2$ (ie in the region defined by the core of guide(1)) and E_2 or H_2 (and E_2^- or H_2^-) in the region $x_3 < x < x_4$ (ie the region defined by the core of guide(2)) are considered to be zero order terms. Outside the above regions they are all of first order. Therefore the $E_1^- E_1$ term in $x_3 < x < x_4$, and $x_4 < x < \infty$ regions are of second order. Comparing orders of all the terms, $\frac{dA_1}{dz}$ and consequently $\frac{dA_2}{dz}$ are expected to be of first order. $E_1 \cdot (\hat{Z} \times H_2)$ is also a first order term, because wherever E_1 is of zero order, H_2 will be of second order and vice versa. Therefore $\frac{dA_2}{dz} [E_1^- \cdot (\hat{Z} \times H_2) - H_1^- \cdot (\hat{Z} \times E_2)]$ is a second order term. Neglecting all the second order terms in (3.1.15), the following equation is obtained.

$$\frac{dA_1}{dz} = jC_1 A_2 \exp j(\beta_1 - \beta_2)z \tag{3.1.16}$$

where

$$C_1 = -\omega\epsilon_0 \frac{(n_1^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_1}^{x_2} \hat{E}_1^- \cdot \hat{E}_2 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{Z} \cdot (\hat{E}_1^- \times \hat{H}_1 + \hat{E}_1 \times \hat{H}_1^-) dx dy} \tag{3.1.17}$$

Multiplying (3.1.12) and (3.1.13) by H_2^- and E_2^- respectively, and following the same procedure as above, the following expression, describing variations of A_2 with z in terms of A_1 is obtained.

$$\frac{dA_2}{dz} = jC_2 A_1 \exp -j(\beta_1 - \beta_2)z \tag{3.1.18}$$

where;

$$C_2 = -\omega\epsilon_0 \frac{(n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_3}^{x_4} \hat{E}_2^- \cdot \hat{E}_1 dx dy + (n_S^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_4}^{\infty} \hat{E}_2^- \cdot \hat{E}_1 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{Z} \cdot (\hat{E}_2^- \times \hat{H}_2 + \hat{E}_2 \times \hat{H}_2^-) dx dy} \quad (3.1.19)$$

Note that $E_2^- \cdot E_1$, in the $x_4 < x < \infty$ region, has not been neglected. This is because E_2 may be considered to be a zero order term in the vicinity of the core of guide(2), resulting in the product of E_2 and E_1 being a first order term in this region.

C_1 and C_2 , defined by (3.1.17) and (3.1.19), represent the strength of coupling between the guided modes of the two waveguides, and are referred to as the coupling coefficients. Equations (3.1.16) and (3.1.18) are the so called coupled wave equations, and by introduction of the wave amplitudes, ie;

$$a_\nu = A_\nu \exp(-j\beta z) \quad (3.1.20)$$

can be written in the following form.

$$\frac{\partial a_1}{\partial z} = -j\beta_1 a_1 + jC_1 a_2 \quad (3.1.21)$$

$$\frac{\partial a_2}{\partial z} = -j\beta_2 a_2 + jC_2 a_1 \quad (3.1.22)$$

Assuming that light is initially launched into guide(1), imposes the following initial conditions;

$$a_1(0) = 1$$

$$a_2(0) = 0$$

Using the above conditions, the following solutions for equations (3.1.21) and (3.1.22) are deduced;

$$a_1(z) = \exp -j \frac{(\beta_1 + \beta_2)z}{2} [\cos(Kz) + j \frac{(\beta_2 - \beta_1)}{2K} \sin(Kz)] \quad (3.1.23)$$

$$a_2(z) = \exp -j \frac{(\beta_1 + \beta_2)z}{2} [\frac{jC_2}{K} \sin(Kz)] \quad (3.1.24)$$

where

$$K = [(\frac{\Delta\beta}{2})^2 + C_1 C_2]^{1/2} \quad (3.1.25)$$

and

$$\Delta\beta = \beta_1 - \beta_2 \quad (3.1.26)$$

The power carried by guide (ν) ($\nu=1$ or 2) can generally be expressed by the following expression;

$$P_\nu(z) = \frac{1}{2} \text{real} \left\{ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A_\nu(z) E_\nu \times A_\nu^*(z) H_\nu^* dx dy \right\}$$

or

$$p_\nu(z) = A_\nu(z) A_\nu^*(z) \frac{1}{2} \text{real} \left\{ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_\nu \times H_\nu^* dx dy \right\}$$

Since $\int E_\nu \times H_\nu^* dx dy$ is independant of z , the general characteristics of $P_\nu(z)$ is simply described by $A_\nu(z) A_\nu^*(z)$.

To simplify the analysis, both guides are considered to be lossless. The impact of loss on coupling is left to be illustrated in the following chapter. Using (3.1.20) and (3.1.24), the following expressions, describing the power in the two guides, are derived;

$$P_2(z) = \frac{\sin^2 C [1 + (\frac{\Delta\beta}{2C})^2]^{1/2} z}{[1 + (\frac{\Delta\beta}{2C})^2]^{1/2}} \quad (3.1.27)$$

$$P_1(z) = 1 - P_2(z) \quad (3.1.28)$$

where $C = \sqrt{C_1 C_2}$ Equation (3.1.27) clearly indicates that coupling between the two guides is of a periodic nature. The distance between a maximum in one guide and the next maximum in the other guide is called the beatlength. This actually defines the length over which maximum power is transferred from one guide to the other, and is described by the following relationship;

$$Z = \frac{\pi}{2C [1 + (\frac{\Delta\beta}{2C})^2]^{1/2}} \quad (3.1.29)$$

From expression (3.1.27) it is also obvious that complete transfer of power occurs, only if $\Delta\beta = 0$. In this case the two guides are said to be phase matched. The beatlength corresponding to $\Delta\beta = 0$ is labelled L_B , and is equal to $\frac{\pi}{2C}$. Equation (3.1.27) and (3.1.29) suggest that, as $\Delta\beta$ is increased, both the extent of power transfer and the beatlength are reduced. This is shown in fig.3.1.2, which represents the power in guide(1) normalized to the input power, P_1 , versus $\frac{z}{L_B}$, for different values of $\Delta\beta$.

Fig.3.1.3 represents P_1 as a function of the mismatch represented by $\frac{\Delta\beta}{2C}$, for an interaction length equal to L_B .

The phase mismatch required for no power transfer into guide(2), is designated as $\Delta\beta_0$, and corresponds to the following;

$$C[1 + (\frac{\Delta\beta_0}{2C})^2]^{1/2} L_B = \pi \quad (3.1.30)$$

where $L_B = \frac{\pi}{2C}$, and hence:

$$\Delta\beta_0 = \sqrt{12}C \quad (3.1.31)$$

From equation (3.1.31) it is concluded that reducing the coupling strength, C , results in a smaller $\Delta\beta_0$, hence making the coupling curve of fig.3.1.3 sharper. It is clear that a sharper coupling curve implies that P_1 is more sensitive to changes in $\Delta\beta$. The influence of C on the sensitivity of P_1 to changes in $\Delta\beta$ can alternatively be explained by the fact that, as C is reduced, $\frac{\Delta\beta}{2C}$ becomes more significant, and hence, from equation (3.1.27), changes in $\Delta\beta$ will have a more significant impact on P_2 , and hence P_1 . In contrast, if C is very large, P_2 , and subsequently P_1 become insensitive to small changes in $\Delta\beta$ -a large $\Delta\beta$ is required to affect P_1 or P_2 appreciably.

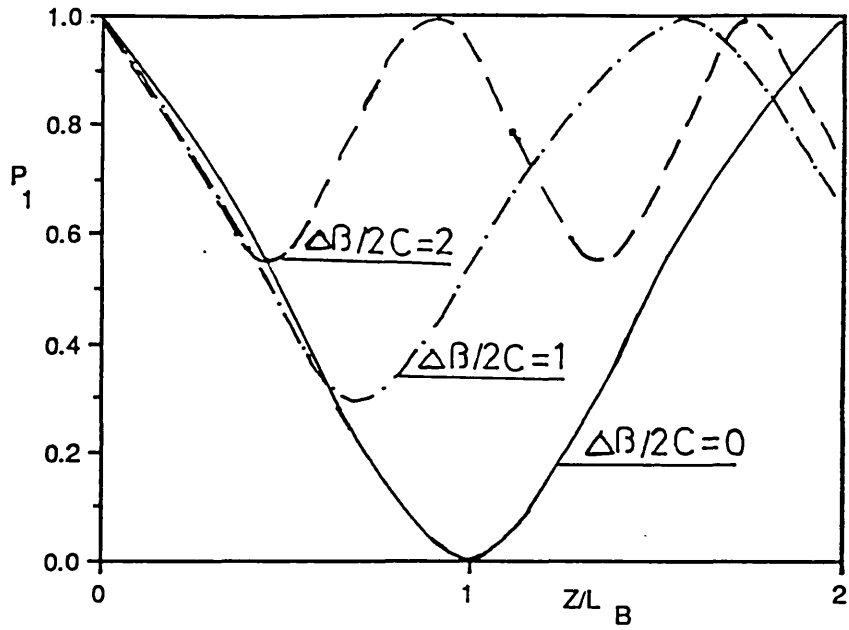


fig.3.1.2.

The normalized power in guide (1) as a function of Z/L_B for different values of the mismatch.

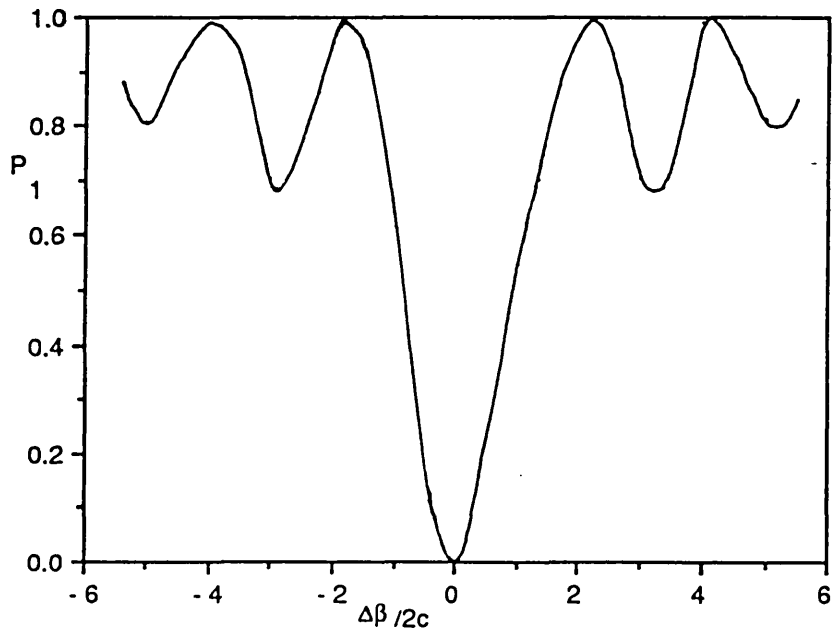


Fig.3.1.3.

The normalized power in guide(1) as a function of the mismatch represented by $(\Delta\beta/2C)$: $Z=L_B$.

It is important to note that, expression (3.1.29) suggests that a reduction in C is associated with an increase in the beatlength. Reducing the coupling strength can practically be achieved by increasing the separation between the two guides.

3.2. Operation of directional couplers as sensors.

In this section two modes of operation for the directional coupler as a sensing device are envisaged. The performance of the device and ways of improving its performance are then analytically investigated.

In the directional coupler of fig.3.1, varying the refractive index of the outer cladding of guide(2), n_S , causes the propagation constant of guide(2), β_2 , to change, with no significant influence on that of guide(1), β_1 . Therefore variations in $\Delta\beta$ can be implemented by changing n_S . Monochromatic power in guide(1), P_1 , having travelled through the interaction region, now varies with n_S as shown in fig.3.2.1. The interaction length is again considered to be equal to L_B . The approximately linear parts of this curve, shown in bold, can now be used to deduce changes in n_S by monitoring the corresponding variations in P_1 , and hence the device can be employed as a sensor monitoring parameters which influence n_S . This mode of operation, in which monochromatic light is launched into guide(1), is referred to as the monochromatic mode. Also, since the variations in n_S are probed by the guided mode of guide(2) this guide is referred to as the sensing guide, with guide(1) referred to as the input guide.

It is clear that, in this mode of operation, increasing the sharpness of the coupling curve would enable detection of smaller changes in n_S , hence resulting in a more sensitive device. A sharper coupling curve, in effect, implies an increase in the magnitude of changes in β_2 (or $\Delta\beta$) as a result of changing n_S ,

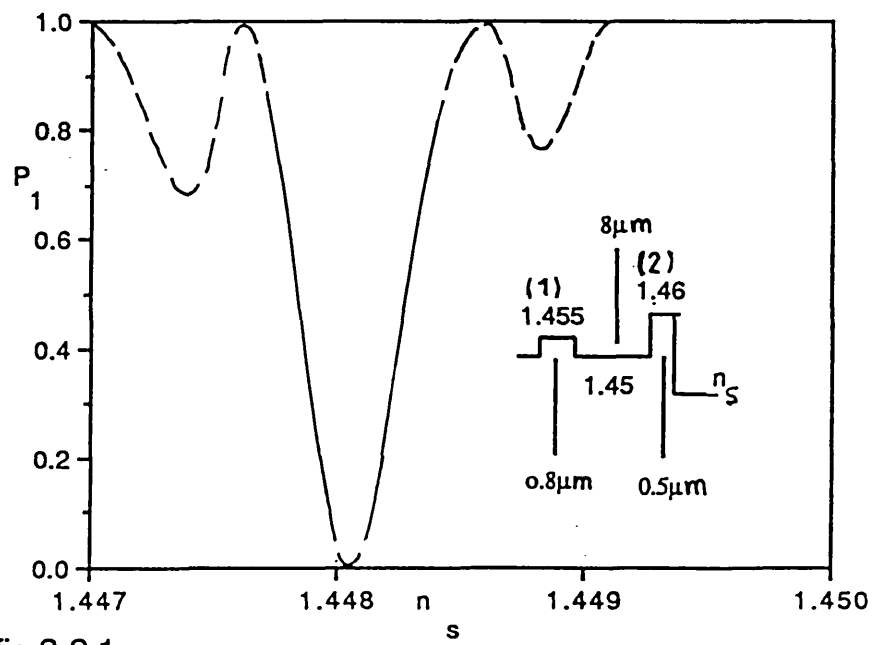


fig.3.2.1.

The normalized power in guide(1) versus n_s for the structure shown above.

which as explained for the case of surface plasma waves in chapter2 (equation 2.2.6), can be increased by increasing the fraction of the sensing waveguide mode power in the sensing medium.

Surface plasma waves propagating on metal films, as explained in chapter2, have a significant fraction of their total power distributed in the dielectric claddings of the metal. Therefore replacing guide(2) in the directional coupler of fig.3.1 with a surface plasma wave supporting metal film, brings about the possibility of devising a somewhat more sensitive device, based on the excitation of the surface plasma waves by the guided mode of the input guide (guide(1)).

A drawback with the monochromatic mode of operation of directional couplers as sensors is that variations in P_1 can only be used to measure values of n_s which correspond to the linear slopes of the coupling curve. This detectable range of values of n_s is however reduced as the device is made more sensitive by increasing the sharpness of the coupling curve. To overcome this difficulty the device can be operated in a broadband mode.

The broadband mode of operation is based on the fact that, since the interacting guides are very likely to have different dispersion characteristics, the transfer of power between the guided modes can be controlled by varying the wavelength of operation.

The dispersion characteristics of two dielectric waveguides are shown in fig.3.2.2(a)(page 76). At a certain frequency ω_m , corresponding to a wavelength λ_m , the two dispersion curves intersect, implying that the waveguides are phase matched ($\Delta\beta = 0$). Provided the interaction length equals the beat-length, L_B , all the light initially launched into the input guide couples into the guided mode of the sensing guide. As ω (or λ) is changed to say ω_1 (or λ_1), the mismatch $\Delta\beta_1$ results in a reduction in the extent of the transferred power.

Therefore, the power out of the input guide varies with the wavelength as shown in fig.3.2.2(b).

Now, changing the refractive index n_S , as explained before, causes the propagation constant of the sensing guide to change, with little influence on that of the input guide. This results in a shift in the phase matching wavelength (λ_m), as shown in fig.3.2.2(a) and (b). The value of the shift in the phase matching wavelength is therefore a measure of changes in n_S , and can be used to deduce values of parameters influencing n_S . It is clear that since in this mode of operation, the two waveguide modes can be phase matched by adjusting the wavelength of operation (independent of the value of n_S), the detection range of the device is not limited as in the monochromatic mode.

It is also clear that as the P_1 versus λ curve is sharpened, the number of resolvable wavelengths, and the corresponding indices, is increased, enabling detection of smaller changes in n_S . Therefore, in the broadband mode of operation, the sharpness of the coupling curve again plays a significant role in determining the sensitivity of the resulting sensing device.

One technique of increasing the sharpness of the P_1 versus λ curve would be to increase the thickness of the separation between the two waveguides. This, however, is accompanied by an increase in the beatlength, L_B . In order to maintain maximum transfer of power between the two waveguides, the interaction length is now required to be equal to L_B . Therefore, increasing the separation between the two waveguides must be accompanied by an increase in the interaction length, in some instances to an impractically long length. For example, reducing the half power bandwidth of the directional coupler of fig.3.2.2(b) to $10\text{\AA}$ must be accompanied by an interaction length of larger than

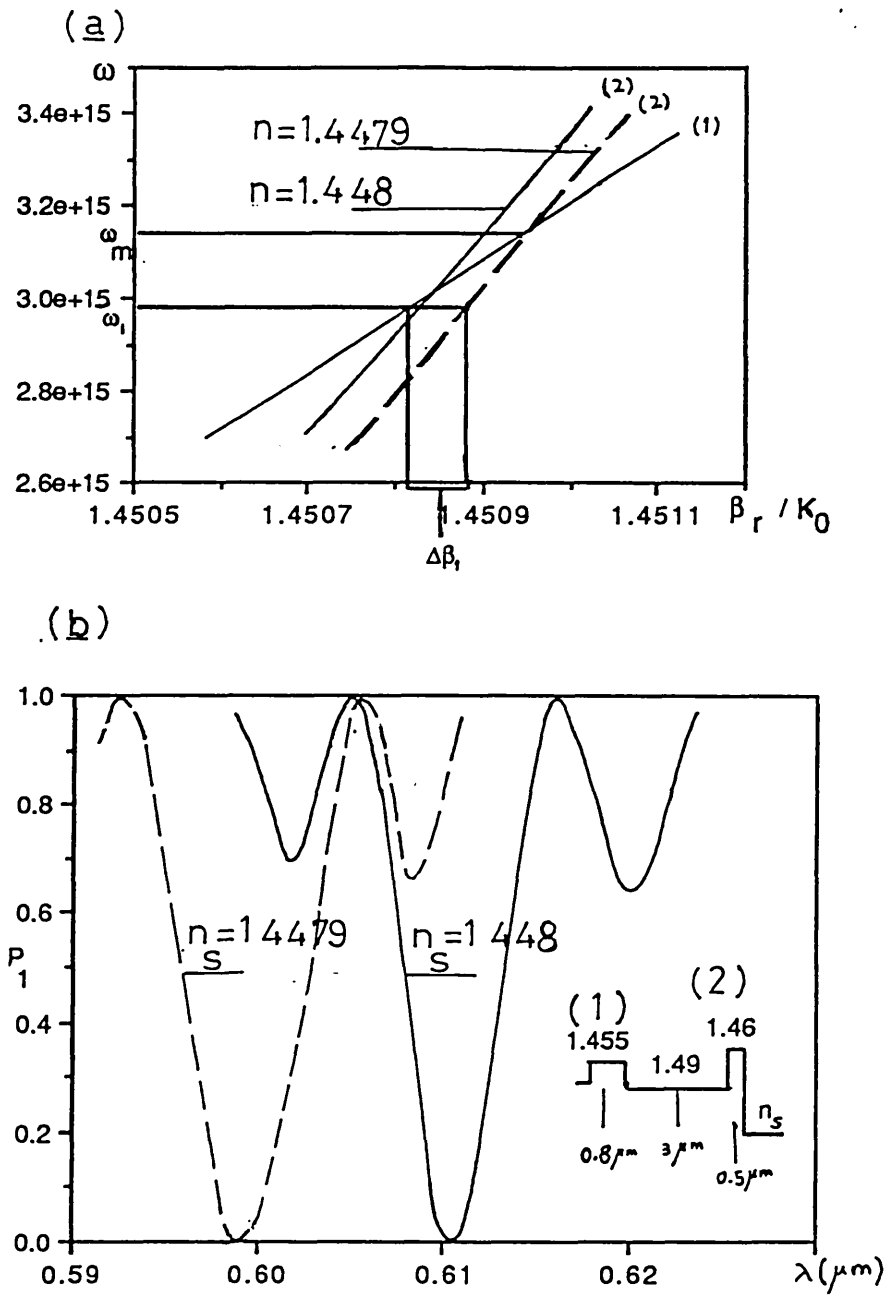


fig.3.2.2.

Dispersion curves(a), and power in guide(1) versus the wavelength(b).

12cm. Maintaining the uniformity of the structure over such a long length is not free of practical difficulties.

Alternatively as shown in fig.3.2.3, increasing the angle, θ , between the two dispersion curves, causes a larger mismatch ($\Delta\beta_2$ compared with $\Delta\beta_1$) as a result of the same frequency change $\Delta\omega$, hence implying a sharper coupling curve. A large value of θ , however, implies that the interacting waveguides have very different dispersion characteristics.

Examining dispersion characteristics of dielectric guiding structures reveals only small differences between them. Optical properties of metals, however, vary much more than those of dielectric materials with wavelength. Therefore the dispersion curve of the surface plasma wave, excited on the surface of a metal, is expected to significantly differ from that of the guided mode of a dielectric waveguide. In other words the angle between the dispersion characteristics of a surface plasma wave and the guided mode of a dielectric waveguide is likely to be large.

From the above argument, it can be concluded that sensing devices, based on coupling of the guided mode of a dielectric waveguide into a surface plasma wave are expected to be associated with sharper variations in P_1 as a function of wavelength, implying a more sensitive device.

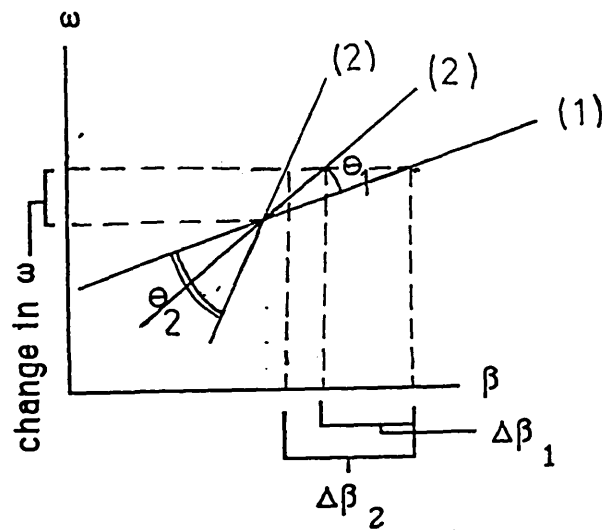


fig.3.2.3. Increasing the angle between the dispersion curves of guides (1) and (2) results in a larger mismatch ($\Delta\beta_1$ compared to $\Delta\beta_2$) as a result of the same frequency change, ie. a sharper coupling curve.

3.3. Conclusion

Following the formulation of coupling in a directional coupler structure, basic principles of coupling between the guided modes of two lossless dielectric waveguide in a directional coupler structure have been established.

Monochromatic and broadband modes of operating directional coupler structures as sensing devices have also been described.

From the analysis and discussions in this chapter, it can be concluded that the sensitivity of directional coupler sensing devices, whether operated in the monochromatic or the broadband mode, is expected to significantly improve by replacing the sensing guide, by a surface plasma wave supporting metal film.

These improvements are due to:

(1) the large distribution of the surface plasma wave power in the sensing medium.

(2) the dispersion characteristic of the surface plasma wave, being significantly different from that of a dielectric waveguide.

The resulting directional coupler is referred to as a surface plasma wave directional coupler, and is the main topic of investigation in the remainder of this thesis.

CHAPTER 4

SURFACE PLASMA WAVE DIRECTIONAL COUPLERS AS SENSORS.

In this chapter coupling between the guided mode of a dielectric waveguide and the surface plasma waves on a metal film in a surface plasma wave directional coupler is analytically studied. A basic surface plasma wave directional coupler arrangement is schematically represented in fig.4.1. This structure is analogous to the dielectric directional coupler of fig.3.1, with the sensing guide replaced by a surface plasma wave supporting metal film.

In this structure, it is the coupling between the guided mode of the dielectric waveguide and the surface plasma wave which is controlled by variations in n_S , forming the basis of the sensing application of the resulting device, with the surface plasma wave field probing the sensing medium.

The coupling formulation is again a general one, irrespective of the shape of the geometry involved. The examples considered, however, correspond to the simplified case of a planar (slab) geometry.

The basic difference between the surface plasma wave directional coupler and the purely dielectric directional coupler of the preceding chapter, is the significant loss associated with the surface plasma wave. The impact of loss on coupling is illustrated in section 4.1. In section 4.2, some design considerations,

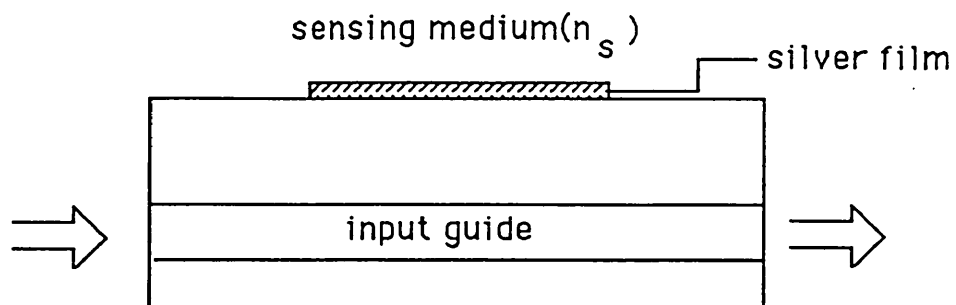


fig.4.1. Schematic representation of the surface plasma wave directional coupler.

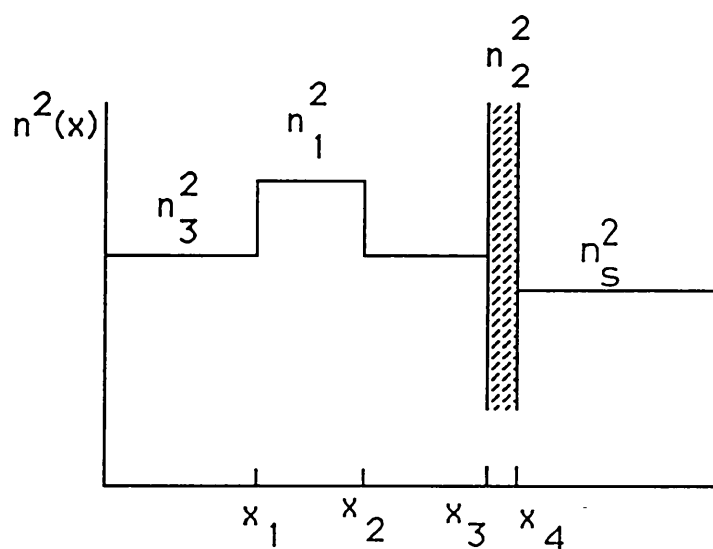


fig.4.1.1. The square of the refractive index profile of the surface plasma wave directional coupler.

to improve the performance of the surface plasma wave directional coupler as a sensor, are described.

4.1. Coupling between the guided mode of a dielectric waveguide and surface plasma waves.

The square of the refractive index profile of the surface plasma wave directional coupler can be represented by the schematic diagram of fig.4.1.1. The square of the refractive indices of the dielectric waveguide, the metal film, and the structure as a whole are represented by $n_1^2(x)$, $n_2^2(x)$ and $n^2(x)$, respectively, where $n_1^2(x)$, $n_2^2(x)$ and $n^2(x)$ are described by expressions (3.1.1), (3.1.2) and (3.1.3) of chapter 3.

Equation (3.1.15) of chapter 3, corresponds to a general case, and hence is also applicable to the lossy case of the surface plasma wave directional coupler. It is quoted here for reference;

$$\begin{aligned}
& \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{dA_1}{dz} [E_1^- \cdot (\hat{Z} \times H_1) - H_1^- \cdot (\hat{Z} \times E_1)] \right. \\
& + \frac{dA_2}{dz} [E_1^- \cdot (\hat{Z} \times H_2) - H_2^- \cdot (\hat{Z} \times E_2)] \Big\} dx dy \\
& - j\omega\epsilon_0 \left\{ (n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_3}^{x_4} A_1 E_1^- E_1 dx dy \right. \\
& + (n_1^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_1}^{x_2} A_2 E_1^- E_2 dx dy \\
& \left. + (n_S^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_4}^{\infty} E_1^- E_1 dx dy \right\} = 0 \tag{4.1.1}
\end{aligned}$$

Despite E_1 and E_1^- being first order terms in the $x_3 < x < x_4$ region, $(n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_3}^{x_4} E_1^- E_1 dx dy$ is not neglected here. This is due to the fact that n_2^2 , representing the permittivity of the metal, has a large real part relative to n_3^2 ,

and $n_2^2 - n_3^2$ is of an appreciable magnitude. Neglecting all other second order terms, as in chapter3, results in the following equation;

$$\frac{dA_1}{dz} = jC_1A_2 \exp j(\beta_1 - \beta_2)z + jK_{aa}A_1 \quad (4.1.2)$$

where

$$C_1 = -\omega\epsilon_0 \frac{(n_1^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_1}^{x_2} \hat{E}_1^- \cdot \hat{E}_2 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{Z} \cdot (\hat{E}_1^- \times \hat{H}_1 + \hat{E}_1 \times \hat{H}_1^-) dx dy} \quad (4.1.3)$$

and

$$K_{aa} = -\omega\epsilon_0 \frac{(n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_3}^{x_4} \hat{E}_1^- \cdot \hat{E}_1 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{Z} \cdot (\hat{E}_1^- \times \hat{H}_1 + \hat{E}_1 \times \hat{H}_1^-) dx dy} \quad (4.1.4)$$

Equation (3.1.18), describing variations of A_2 with z , in terms of A_1 , and equation (3.1.19), describing C_2 , retain their general form described in chapter3;

$$\frac{dA_2}{dz} = jC_2A_1 \exp -j(\beta_1 - \beta_2)z \quad (4.1.5)$$

where

$$C_2 = -\omega\epsilon_0 \frac{(n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_3}^{x_4} \hat{E}_2^- \cdot \hat{E}_1 dx dy + (n_2^2 - n_3^2) \int_{-\infty}^{\infty} \int_{x_4}^{\infty} \hat{E}_2^- \cdot \hat{E}_1 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{Z} \cdot (\hat{E}_2^- \times \hat{H}_2 + \hat{E}_2 \times \hat{H}_2^-) dx dy} \quad (4.1.6)$$

The permittivity of the metal film, n_2^2 , and hence the propagation constant of the surface plasma wave supported by the metal film, β_2 , and consequently C_1 , C_2 and K_{aa} are all complex quantities.

Introduction of the wave amplitudes (equation (3.1.20) of chapter3), results in the following coupled wave equations;

$$\frac{da_1}{dz} = -j(\beta_1 - K_{aa})a_1 + jC_1a_2 \quad (4.1.7)$$

$$\frac{da_2}{dz} = -j\beta_2a_2 + jC_2a_1 \quad (4.1.8)$$

Assuming that light is initially launched into the dielectric waveguide, implies the following initial condition;

$$a_1(0) = 1$$

$$a_2(0) = 0$$

Imposing the above conditions, the following solutions for equations (4.1.7) and (4.1.8) are obtained;

$$a_1(z) = \exp \frac{-j(\beta_1 - K_{aa} + \beta_2)z}{2} \left\{ \cos(Kz) - \frac{j(\beta_2 + \beta_1 - K_{aa})}{2K} \sin(Kz) \right\} \quad (4.1.9)$$

$$a_2(z) = \exp \frac{-j(\beta_1 - K_{aa} + \beta_2)z}{2} \left\{ \frac{jC_2}{K} \sin(Kz) \right\} \quad (4.1.10)$$

where;

$$K = \left[\left(\frac{\beta_1 - K_{aa} - \beta_2}{2} \right)^2 + C_1 C_2 \right]^{1/2} \quad (4.1.11)$$

These expressions are very similar to the expressions (3.1.23) to (3.1.24), describing the amplitudes in the two dielectric waveguides of a purely dielectric directional coupler. The only apparent difference is that the propagation constant of guide(1), β_1 , is replaced by, $\beta_1 - K_{aa}$. This suggests that K_{aa} defines the perturbation of the waveguide mode by the metal film, resulting in its propagation constant to be modified by an amount equal to K_{aa} .

The power carried in the waveguide and by the surface plasma wave are again described by $A_\nu \cdot A_\nu^*$, where $\nu=1$ or 2 , corresponding to the waveguide or the surface plasma mode.

Assuming;

$$K_{aa} = K_{aar} + jK_{aai}$$

and;

$$\beta_2 = \beta_r + j\beta_i$$

and using the following equation;

$$A_\nu = a_\nu \exp(j\beta_\nu z)$$

The power carried by the waveguide mode (P_1) and the surface plasma mode (P_2) can be described by the following expressions;

$$P_1(z) = \exp(-K_{aa}z) \exp(+\beta_i z) \left| \cos(Kz) + \frac{j(\beta_2 - \beta_1 + K_{aa})}{2K} \sin(Kz) \right|^2 \quad (4.1.12)$$

$$P_2(z) = \exp(-K_{aa}z) \exp(+\beta_i z) \left| \frac{jC_2}{K} \sin(Kz) \right|^2 \quad (4.1.13)$$

In the above expressions, $\left| \cos(Kz) + \frac{j(\beta_2 - \beta_1 + K_{aa})}{2K} \sin(Kz) \right|^2$ and $\left| \frac{jC_2}{K} \sin(Kz) \right|^2$, represent the oscillatory nature of the coupling, while the term, $\exp(-K_{aa}z)$, represents the absorption of the guided mode of the dielectric waveguide, due to the proximity of the metal film, and $\exp(\beta_i z)$, represents the attenuation associated with the surface plasma wave (note that β_i is a negative quantity). The attenuation terms result in a decay of P_1 and P_2 , as a function of z , which is superimposed on their oscillatory behaviour. This is shown in fig.4.1.2, which represents P_1 as a function of z . The corresponding parameters of the slab dielectric waveguide and the metal film are also shown in this figure. It is important to note that P_1 and P_2 , here, and in all the proceeding analysis and diagrams, are normalised to the initial power in the dielectric waveguide, $P_1(0)$.

The curve in fig.4.1.2 corresponds to the phase matched condition, which in this case is described by the following relationship;

$$\Delta\beta_R = \text{real}[(\beta_1 - K_{aa}) - \beta_2] = 0$$

Considering that the propagation constant of the waveguide mode is replaced by, $\beta_1 - K_{aa}$, the above definition of the phase matching condition agrees with the one stated in chapter3.

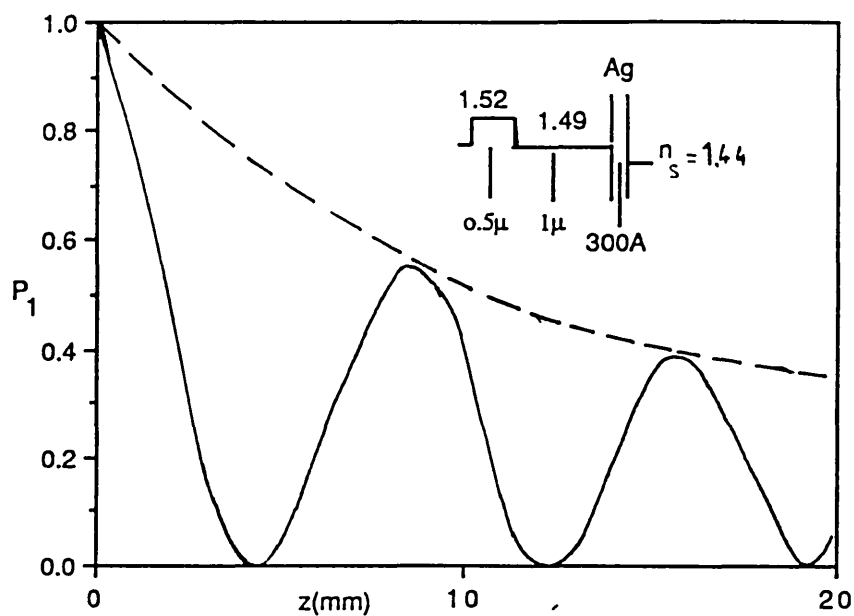


fig.4.1.2.

The normalized power in the dielectric waveguide as a function of the interaction length for strong coupling (thin separation) possesses an oscillatory nature.

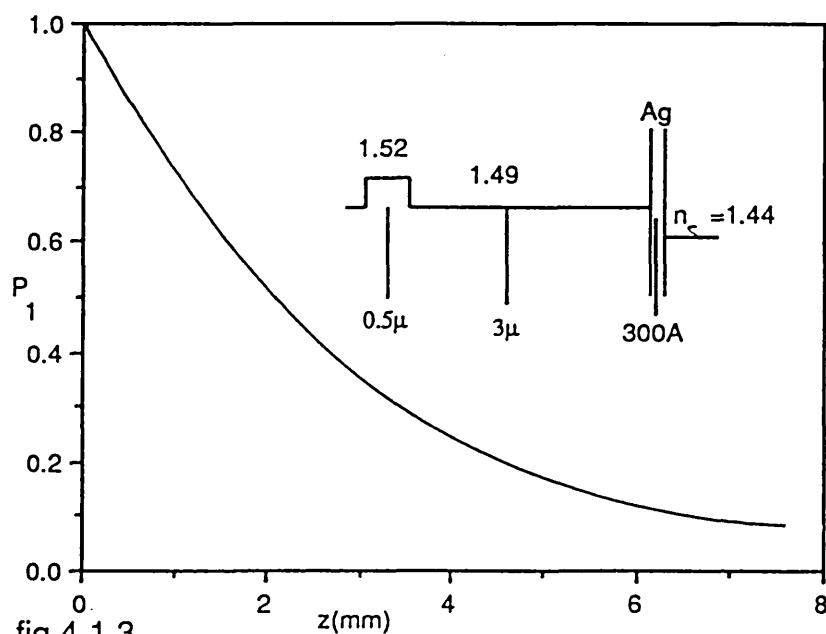


fig.4.1.3.

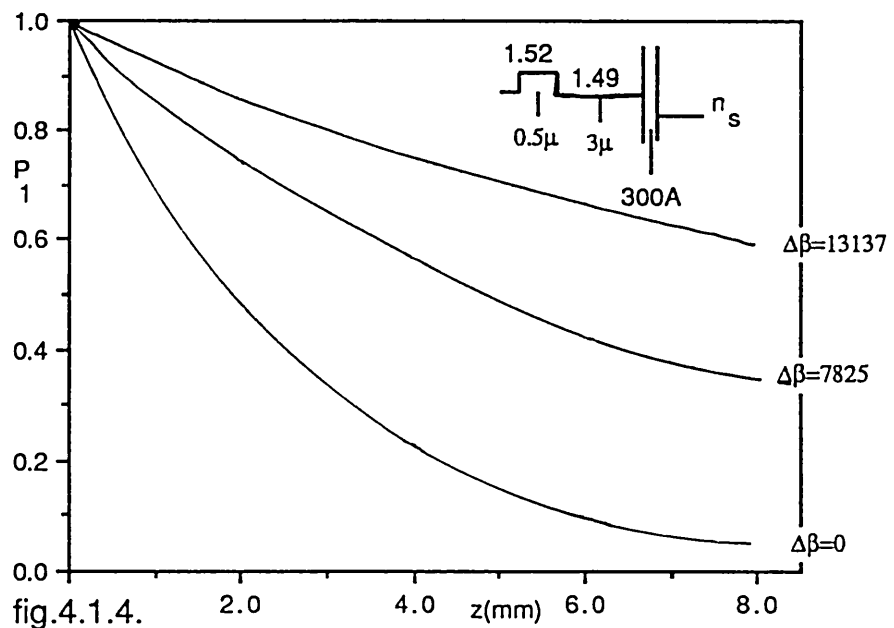
The normalized power in the dielectric waveguide versus the interaction length (z) for weak coupling.

The oscillatory nature of the coupling results in a beatlength, defined as in the case of the purely dielectric coupler. On the other hand, the decaying nature of the coupling results in a decay length, defined as the length over which $P_1(z)$ diminishes to $\frac{1}{e}$ of its initial value. Using equation (4.1.12), the decay length is hence defined by the following expression;

$$\text{decay length} = \frac{1}{\beta_i + K_{aai}}$$

As the separation between the waveguide and the metal film is increased, the perturbation of the waveguide mode by the metal, K_{aa} , and subsequently K_{aai} is reduced, until for a separation thickness of larger than a particular value K_{aai} becomes significantly smaller than β_i , in which case the decay length becomes very nearly equal to $\frac{1}{\beta_i}$. The decay length will now be independent of the thickness of the separation. Since an increase in the separation thickness is also accompanied by a reduction in the coupling strength, and hence the beatlength, increasing the separation thickness further than a particular value results in the beatlength, which defines the periodicity of $P_1(z)$, becoming larger than the decay length, which is now of a fixed value ($\frac{1}{\beta_i}$). For the case where the beatlength is appreciably larger than the decay length, the oscillatory nature of coupling disappears altogether, causing variations of $P_1(z)$ with z to be of a purely decaying nature. This is shown in fig.4.1.3, and implies that the waveguide mode power coupled into the surface plasma wave does not couple back into the waveguide mode.

P_1 versus z for a number of $\Delta\beta_r$ values are shown in fig.4.1.4. The curves in this figure reveal that introducing a mismatch, ie. $\Delta\beta_r \neq 0$, results in a slower decay of $P_1(z)$. This is due to the smaller transfer of power into the surface plasma mode.



The normalized power in the dielectric waveguide as a function of z for different values of mismatch. Variations in $\Delta\beta$ are implemented by varying values of n_s .

Similar to the case of the purely dielectric directional coupler, the variations in $\Delta\beta_r$ can be implemented by changes in the refractive index of the outer cladding of the metal film, n_S . This leads to the possibility of employing the surface plasma wave directional coupler as a sensor, to monitor variations in n_S . P_1 as a function of n_S , for different values of the interaction length, z , are shown in fig.4.1.5.

An interesting feature of the curves shown in fig.4.1.5 is that as z is increased, the flat part of the P_1 versus n_S curve is lowered. This is due to the absorption of the waveguide mode by the metal film in the absence of coupling, represented by $\exp(-k_{aa}z)$. The influence of K_{aa} on the coupling depth is illustrated in fig.4.1.6, in which the coupling curve corresponding to $K_{aa} = 0$ is compared with that corresponding to $K_{aa} \neq 0$. The flat part of the coupling curve corresponding to $K_{aa} = 0$ clearly corresponds to $P_1 = 1.0$.

To illustrate the overall impact of loss on the coupling mechanism in the surface plasma wave directional coupler, both K_{aa} and β_i are set to zero. The corresponding coupling curve together with a curve corresponding to K_{aa} and $\beta_i \neq 0$ are shown in fig.4.1.7(a). The elimination of β_i and K_{aa} has clearly resulted in a significantly sharper coupling curve, and a larger coupling depth (or contrast). It has also resulted in coupling being of an oscillatory nature, which is apparent from the presence of the side lobes in the corresponding coupling curve. This is also confirmed in fig.4.1.7(b), which shows an oscillatory variation of P_1 as a function of z for the lossless case and a decaying coupling characteristic for the case where loss is not omitted.

In conclusion, the loss associated with the metal film, manifesting itself in terms of K_{aa} and β_i , results in a reduction of the coupling depth and also

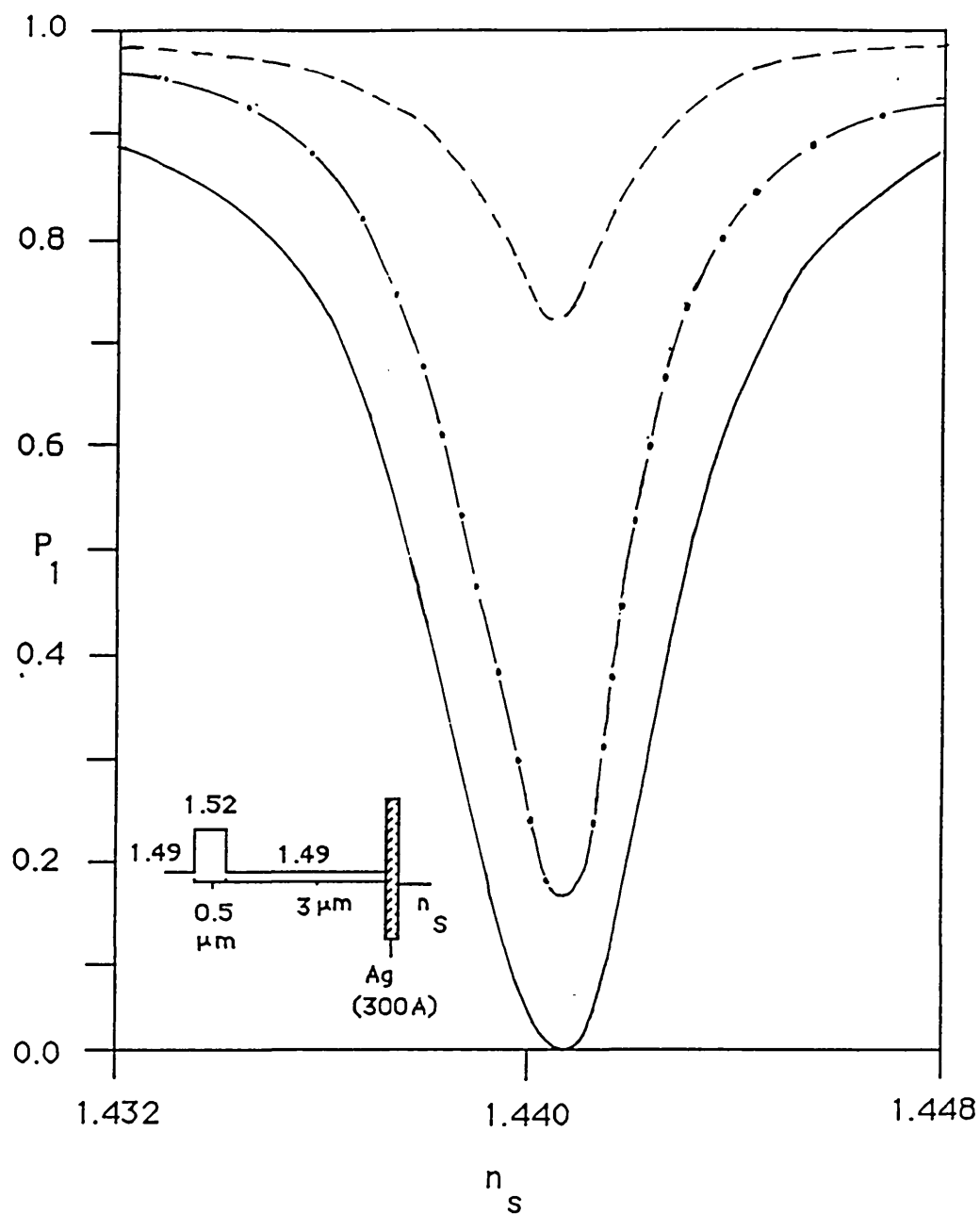


fig.4.1.5. The normalized power in the dielectric waveguide versus n_s for different values of the interaction length (z).

--- : $z = 1\text{mm}$
 - · - : $z = 5\text{mm}$
 — : $z = 12\text{mm}$

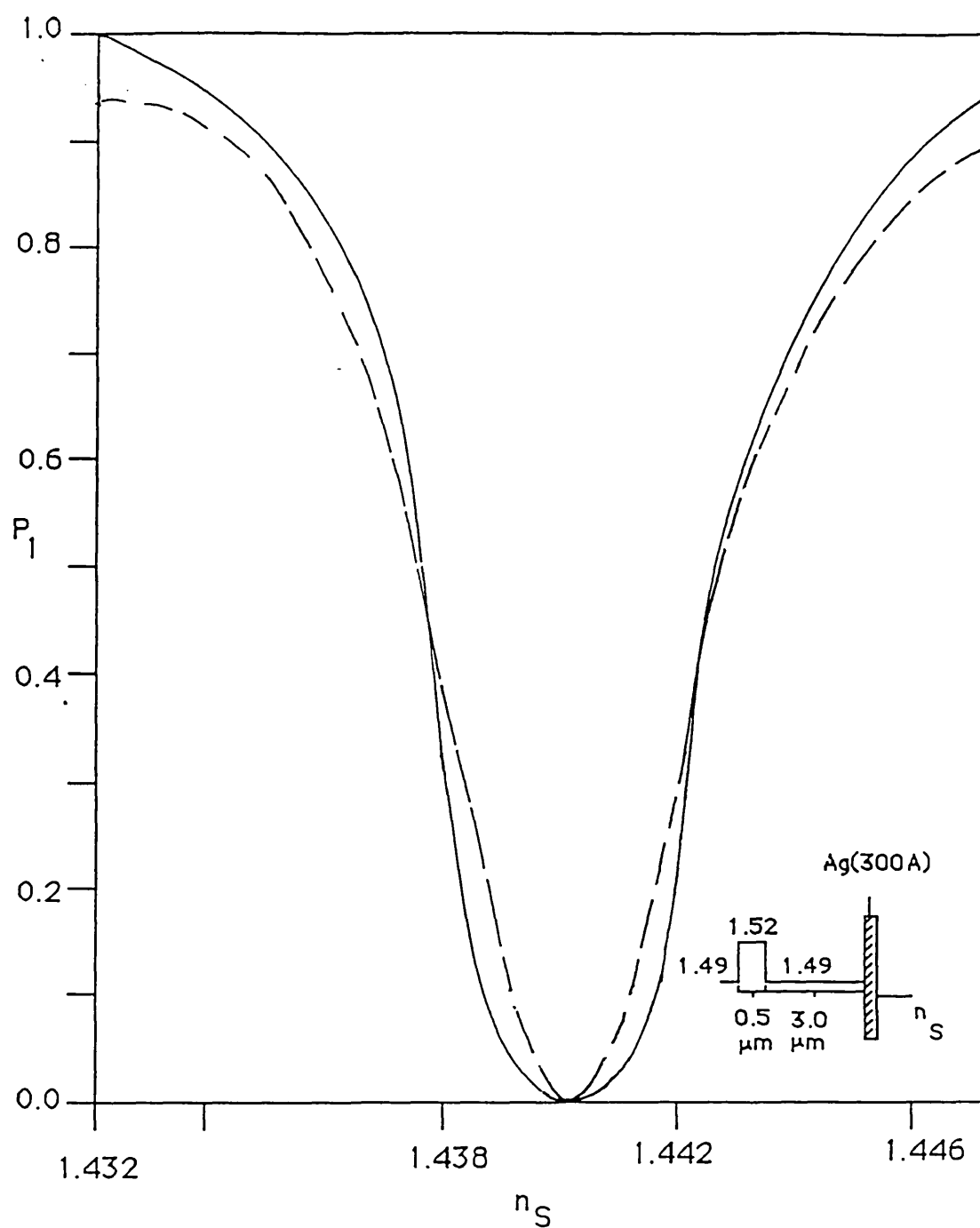
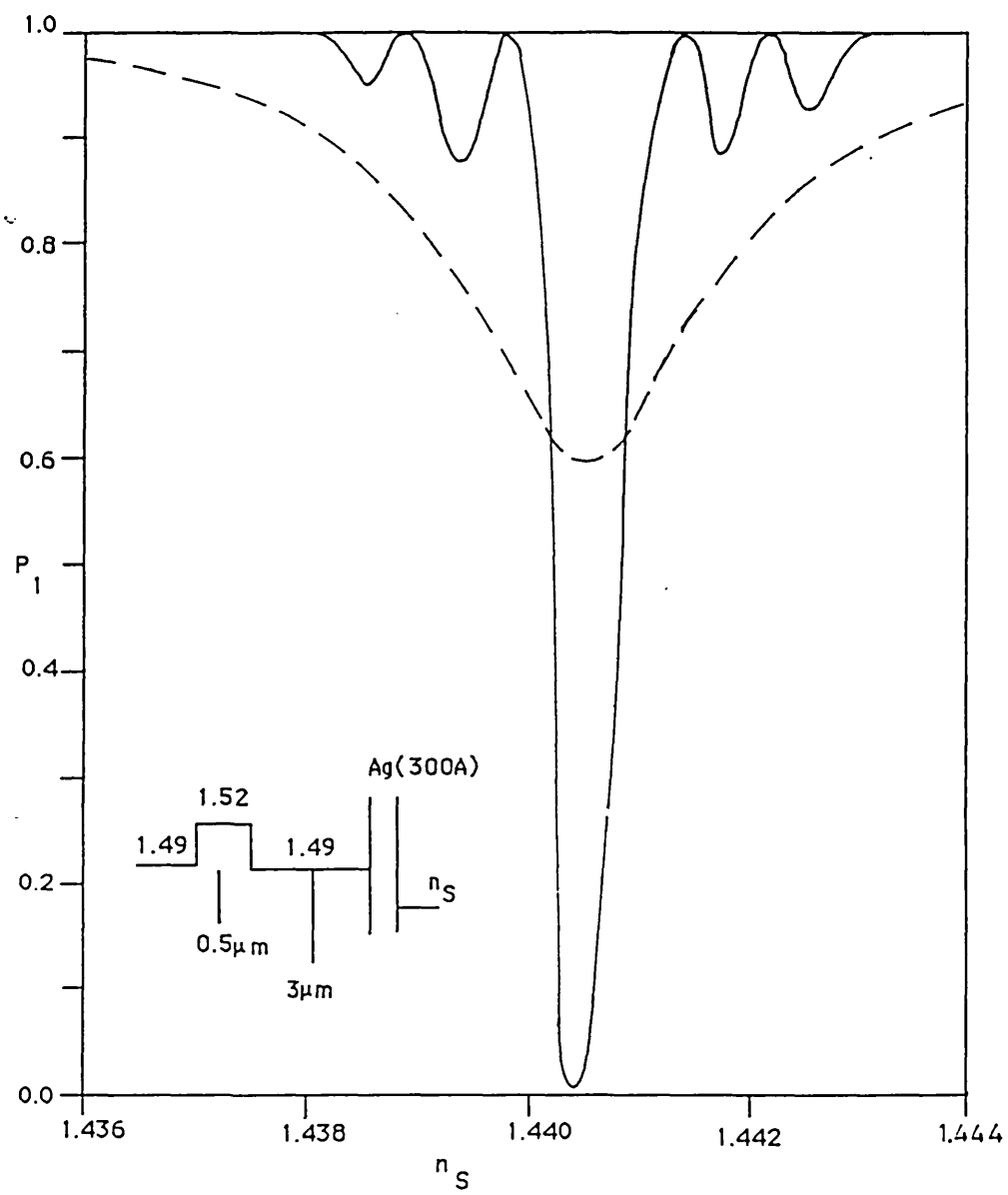


fig.4.1.6. Influence of K_{aa} on the coupling depth (contrast).
Interaction length is 12mm.

— : $K_{aa} = 0$
 - - - : $K_{aa} \neq 0$

4.1.7(a)



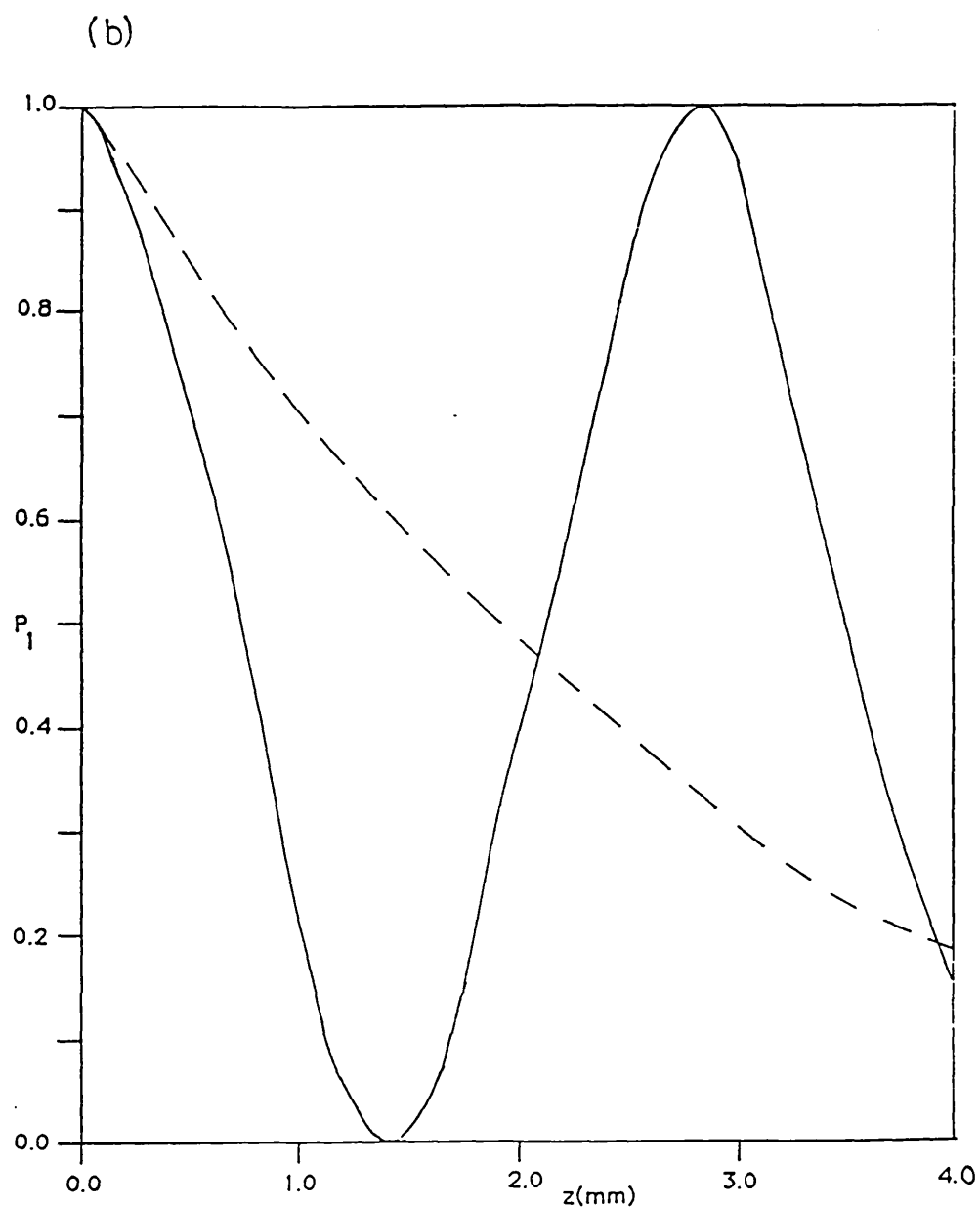


fig.4.1.7.Impact of loss on coupling:(a)the coupling curves corresponding to β_i and $K_{aa}=0$ (—) and $\neq 0$ (---), (b)the corresponding P_1 versus z curves.

broadening of the coupling curve. Both of these properties are undesirable, as far as sensing devices based on directional coupler structures are concerned.

Transfer of the waveguide mode power into the surface plasma wave, as a result of changing the wavelength of operation (broadband mode of operation), is represented by the coupling curves of fig.4.1.8. Variations in the refractive index of the sensing medium, n_s , are shown to result in a shift in the matching wavelength (λ_m), which is the basis of the sensing application of the directional coupler in this mode of operation.

4.2.Design considerations.

From the discussions presented in this chapter and chapter3 it can be concluded that the performance of the resulting sensing device can be improved by;

- 1) Minimizing the loss associated with the surface plasma mode, which results in an increase in the sharpness of the coupling curve.

- 2) Increasing the fractional surface plasma wave power in the sensing medium, which increases the sensitivity of the surface plasma wave propagation constant to variations in n_s .

In the remainder of this chapter, a number of design considerations to improve the sensing performance of the device are discussed.

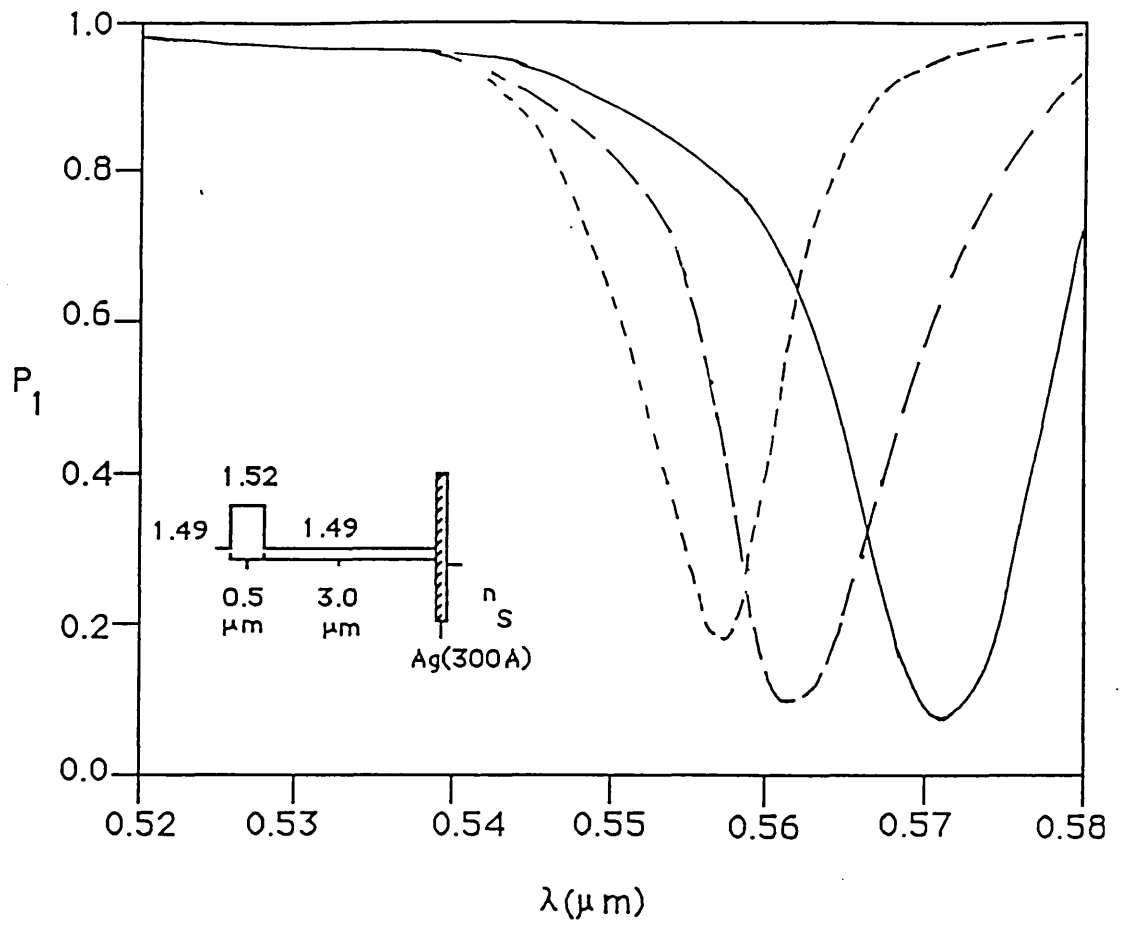


fig.4.1.8. Normalized power in guide (1), P_1 , versus the wavelength of operation, λ , for different values of n_s , and for an interaction length of 4.5cm.

----- $n_s = 1.417$
 -.-.-.- $n_s = 1.42$
 _____ $n_s = 1.423$

4.2.1.Choice of the metal

The choice of the metal is determined both by the magnitude of the imaginary part of its permittivity, which determines the loss associated with the surface plasma wave propagating on its surface, and its stability upon exposure to the atmosphere.

Silver, due to the small imaginary part of its permittivity, is expected to be a suitable choice. However, silver tarnishes upon prolonged exposure to atmosphere. A clearly visible tarnish takes several days to be formed on a thin (approximately $300\text{\AA}$ thick) silver film. The tarnishing is due to the formation of a sulphide layer, Ag_2S , on the surface of the silver [Burge et al 1969].

Formation of an Ag_2S layer, which differs significantly in its optical properties from pure silver ($n_{\text{Ag}_2\text{S}}=2.5-j0.4$ [Burge et al 1969]), behaving like a lossy dielectric material, implies that the surface plasma wave propagates on the $\text{Ag} - \text{Ag}_2\text{S}$ interface, with its power confined in the vicinity of this interface. Therefore, a certain fraction of the surface plasma wave power would now be distributed inside the Ag_2S layer, as schematically shown in the following diagram, causing a reduction in the fraction of the power which probes the sensing medium, hence reducing the device sensitivity.

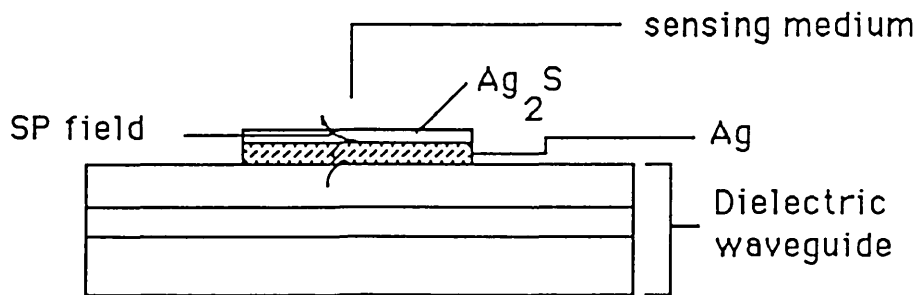


fig.4.2.1.The SP field is partially distributed inside the sulfide layer.

Gold is another choice, which is extremely stable in atmosphere. However its permittivity has a relatively large imaginary part[Ordal et al 1983].

Therefore, silver, due to the imaginary part of its permittivity being small and the fact that at room temperature it tarnishes at a very slow rate (measurements by Burge et al[1969] suggests that silver sulphide is formed at an initial rate of $0.6\text{\AA}$ per hour on the silver film, until a thickness of $2\text{\AA}$ is reached after which the growth rate drops to $4\text{\AA}$ per day), is thought to be stable enough for the fabrication of prototype devices, and hence is considered to represent the choice of the metal in this work.

4.2.2. Choice of the surface plasma mode.

As explained in chapter 2, a metal film can support two surface plasma modes of symmetric and antisymmetric field distributions, referred to as the long range and short range modes, respectively. Coupling into the long range mode, corresponding to a smaller loss (β_i), is expected to be sharper. This implies that, as far as sensing application of the surface plasma wave directional coupler is concerned, coupling into the long range mode is of more interest.

In most practical cases, the metal film has an asymmetric index distribution. For instance in the case of biological sensors, the sensing medium typically has a refractive index nearly equal to that of water (1.33), while the index of the other dielectric cladding generally belongs to a range of indices appreciably larger than that of water.

As shown in fig.4.2.2, the introduction of an asymmetry results in an uneven distribution of the surface plasma field across the dielectric-metal-dielectric layers. A large fraction of the field associated with the long range surface plasma

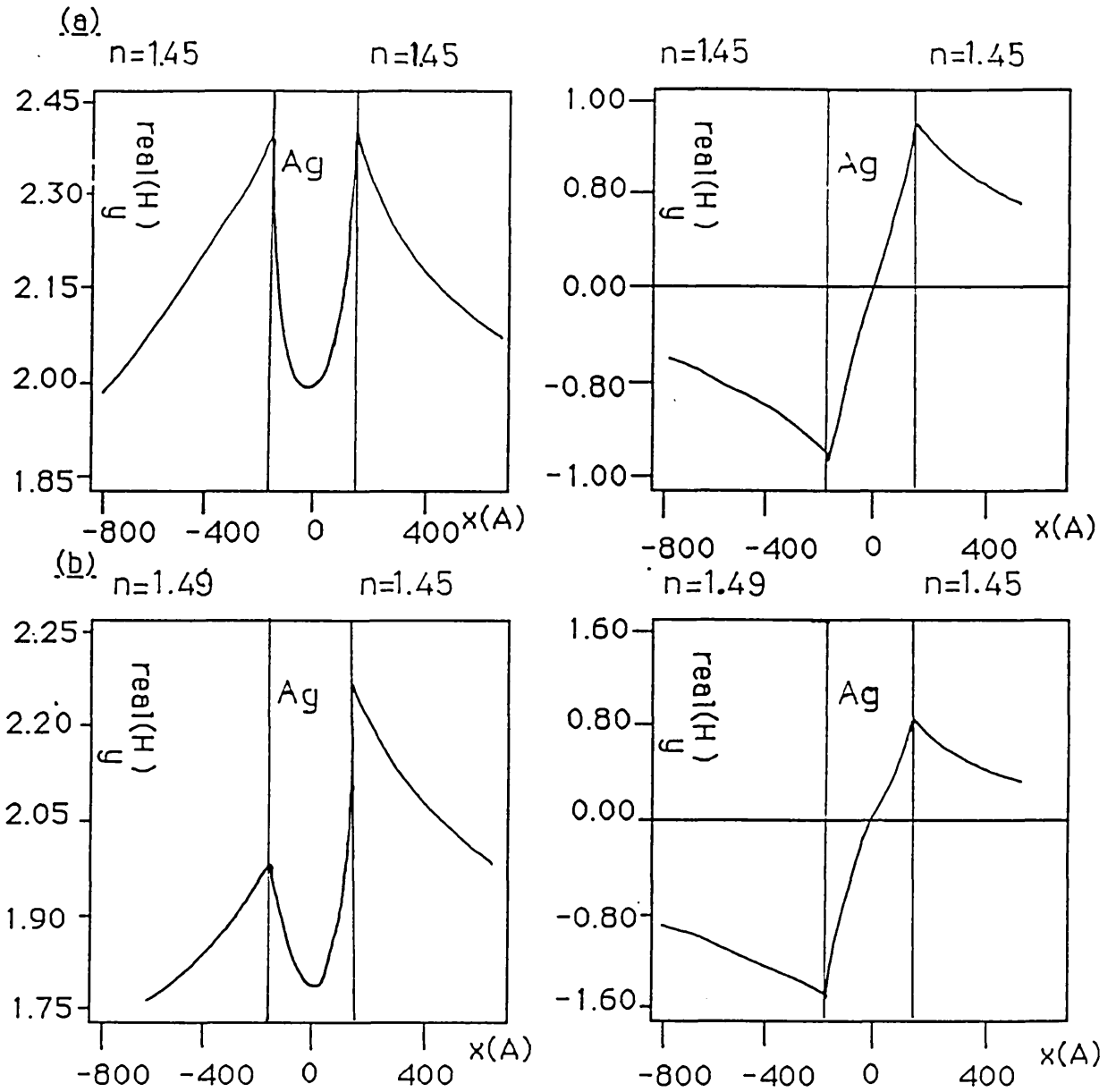


fig.4.2.2. Field profiles corresponding to the symmetric and anti-symmetric surface plasma modes of (a) a symmetric metal film, (b) an asymmetric metal film.

mode is now concentrated in the vicinity of the interface between the metal and the dielectric medium with the lower refractive index. The opposite is the case for the short range mode. This is due to the fact that the long range mode has a smaller effective index.

Therefore, to ensure the concentration of the long range mode around the metal-sensing medium interface, which makes coupling into this mode more sensitive to changes in the index of the sensing medium, the device is required to be designed such that the sensing medium is represented by the cladding of the smaller refractive index. In the case of biosensors, as mentioned earlier, this requirement is inherently met.

It should also be noted that comparison between the the long range surface plasma field profile of the symmetric metal film with that of the asymmetric film (fig.4.2.2) also suggests that increasing the asymmetry, resulting in the long range surface plasma mode being shifted more into the cladding of lower refractive index, is expected to improve the sensitivity of the propagation constant of this mode to variations in the refractive index of the sensing medium.

4.2.3.Thickness of the metal film.

Analysis shows that reducing the thickness of the metal film results in a decrease in the loss associated with the long range surface plasma mode. This is shown in fig.4.2.3. A reduction in the metal film thickness is thus expected to result in a sharper coupling curve.

However, reducing the thickness of the metal film is also accompanied by a reduction in the fraction of the long range surface plasma mode power in the sensing medium. This is shown in fig.4.2.4, which represents the fraction of

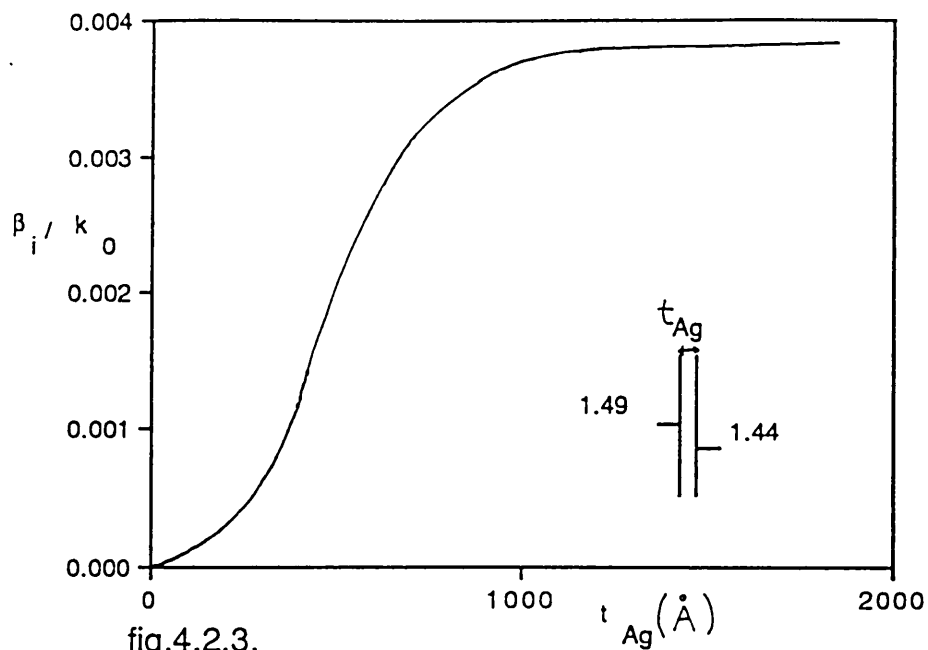


fig.4.2.3.

Influence of the metal film thickness over the loss associated with the long range surface plasma mode, β_i / k_0 .

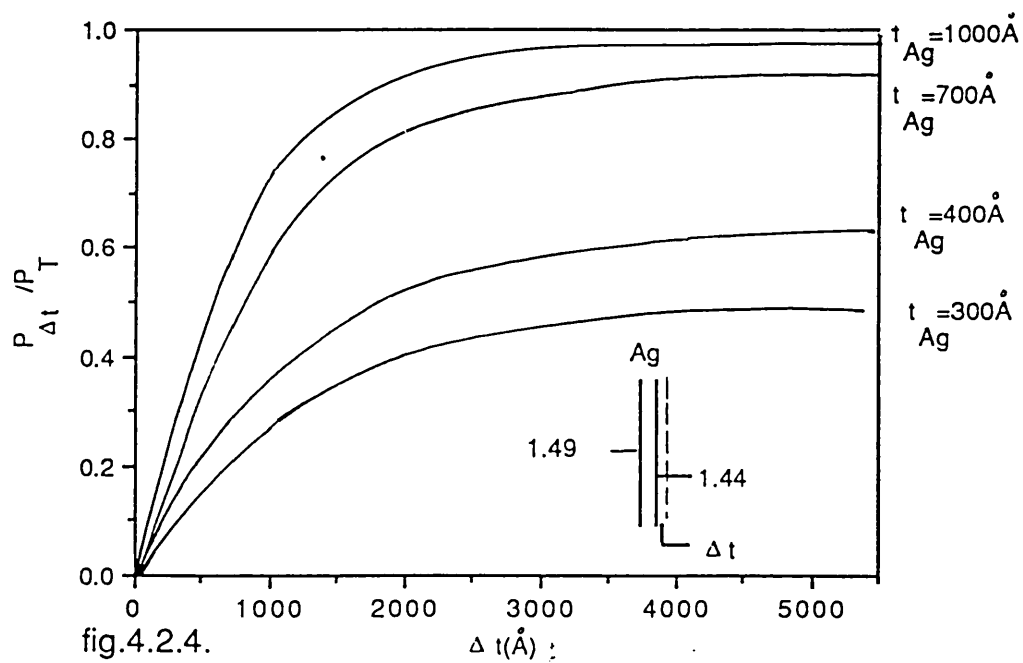


fig.4.2.4.

Fraction of the power associated with the long range SPW in the sensing region for different values of the metal film thickness .

the long range mode power in a sensing region of thickness Δt versus Δt , for different values of the metal film thickness. This implies that surface plasma wave directional coupler sensing devices which incorporate thicker metal films are expected to be more sensitive.

The sensitivity of the device, which as explained earlier can be determined by the sharpness of the coupling curve, is now expressed by the inverse of the half power bandwidth, $(\Delta n_s)_{BW}$.

The overall influence of the metal film thickness on the performance of the device is shown in fig.4.2.5, which represents $\frac{1}{(\Delta n_s)_{BW}}$ as a function of the metal film thickness. In the analysis performed to compute $(\Delta n_s)_{BW}$, variations in the metal film thickness are accompanied by adjustments to the refractive index of the core of the dielectric guide and the thickness of the separation between the waveguide and the silver film , to ensure the phase matching index and the strength of coupling at this index to be maintained for different values of the metal film thickness. This is an essential step to eliminate the possibility of these parameters affecting the sharpness of the coupling curve, as the metal film thickness is varied.

The curve of fig.4.2.5 reveals that an increase in the thickness of the metal film results in an overall broadening of coupling, hence reducing the sensitivity of the device. This indicates that, as the metal film thickness is varied, the loss associated with the surface plasma wave is the dominant factor in determining the sensitivity of the device.

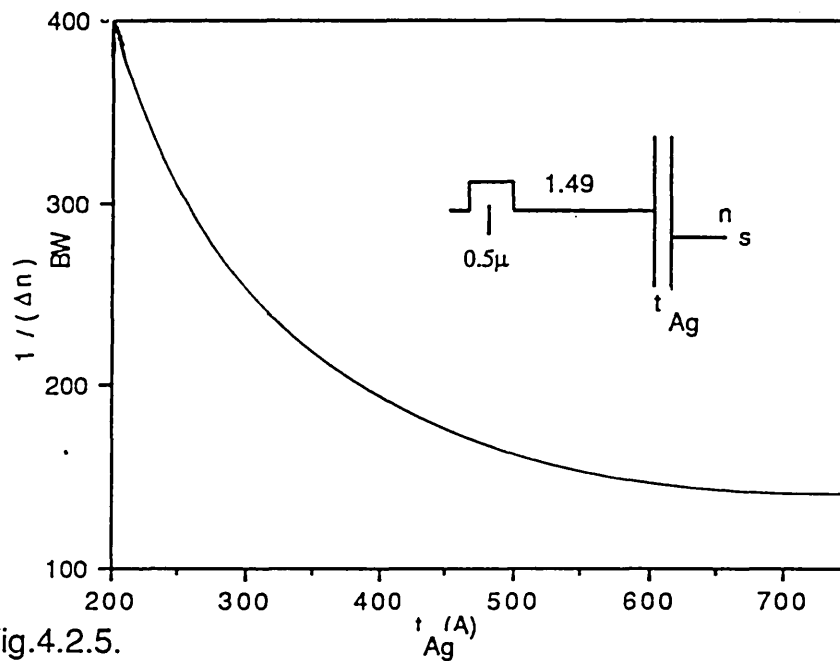


fig.4.2.5.

Increasing the thickness of the metal film results in a reduction in the sensitivity of the SPW directional coupler as a sensor, where sensitivity is defined in terms of the coupling sharpness $(\Delta n) \cdot BW$.

4.3. Conclusions.

In this chapter the impact of loss on coupling in a directional coupler structure has been established. The strong loss associated with the surface plasma waves has been shown to result in the coupling to be of a purely decaying nature, unless for strong coupling situations. It has also been shown that the loss results in a reduction in the contrast as well as the sharpness of the coupling curve (P_1 versus n_S), both of which are undesirable as far as the sensing performance of the resulting device is concerned. However, despite these drawbacks, the very large fraction of the surface plasma wave power in the sensing medium is thought to make sensing devices based on the surface plasma wave directional coupler an attractive choice.

Silver, in virtue of the small imaginary part of its permittivity, is expected to be the most suitable choice of metal. However, for a commercially feasible device instability of silver upon exposure to atmosphere may give rise to degrading of the device performance over a long period of time. Gold, due to its stability in atmosphere may be considered as an alternative. However, surface plasma waves propagating on a gold film are expected to be associated with larger attenuations, which result in broader coupling curves. Therefore, it may be concluded that since the device may be used as a disposable kit, or may be stored under vacuum conditions when not in use, silver may be a suitable choice.

It has also been shown that in order to ensure that the sensing medium is being probed by the long range surface plasma mode, which is associated with a smaller loss and hence a sharper coupling curve compared to the short range mode, the device is required to be designed such that the metal film sensing cladding has a refractive index lower than that of the other cladding.

The coupling (P_1 versus n_S) curve has also been shown to be made sharper by reducing the thickness of the metal film.

CHAPTER 5

A PLANAR WAVEGUIDE SURFACE PLASMA WAVE DIRECTIONAL COUPLER.

In this chapter, coupling in a planar waveguide surface plasma wave directional coupler, operated in the monochromatic mode, is experimentally investigated. This coupler consists of a slab dielectric waveguide on which a thin silver film is deposited. The silver film is separated from the core of the waveguide by a dielectric cladding layer.

P-polarized laser light is launched into the core of the waveguide using a high index prism (input prism), as shown in fig.5.1(page108). The transfer of power from the waveguide mode into the surface plasma wave, supported by the silver film, can now be implemented by varying the refractive index of the outer cladding of the silver film, n_S . The value of n_S corresponding to the maximum transfer of power is referred to as the phase matching index. The power remaining in the waveguide mode is coupled out of the waveguide using another high index prism (output prism), and can now be monitored as a function of n_S .

Continuous variation of n_S can be achieved by heating a liquid, the refractive index of which is temperature sensitive, placed on top of the silver film, forming its outer cladding. This liquid is referred to as the matching liquid. However, heating this medium in isolation is not feasible, and is very likely to influence the optical properties of the constituent layers of the dielectric waveguide, which, as will be discussed later, are selected to be made of polymers, the refractive indices of which are generally temperature sensitive. An obvious alternative would be to vary n_S by simply replacing the matching liquid. To

eliminate the tedious task of replacing this medium at small increments, and over a wide range of indices, which in fact may turn out to be unsuccessful, a relatively accurate knowledge of the range of indices in the vicinity of which the waveguide mode and the surface plasma wave are phase matched, is now required. This in turn requires prior knowledge of the optical properties and thicknesses of the constituent layers of the structure.

In addition, monochromatic operation of the directional coupler as a sensor may require phase matching of the waveguide mode and the surface plasma wave in the vicinity of a certain value of n_S . For instance, in biosensing applications, in which the binding of a certain type of antigens to appropriate antibodies, precoated on the outer surface of the metal film, are to be detected, the antigens are generally introduced into the system by an aqueous solution, which will now form the ambient medium. To detect the antigen-antibody binding, which in effect varies the thickness and the refractive index of the adlayer (previously made up of the antibodies), the phase matching is required to occur in the vicinity of the refractive index of the ambient aqueous medium, or the formation of the antigen-antibody adlayer would not result in an appreciable change in the intensity of the light remaining in the waveguide. To satisfy such application requirements, a relatively accurate design of the structure is required, which is again based on a prior knowledge of the optical properties of the constituent layers of the structure.

The literature on optical properties of polymers reveals the presence of some discrepancies in the measured values of the optical properties of these materials, e.g. $n_{pmma} = 1.498$ [Mason1988]^(b) and 1.486 [Swalen et al1977]. As

appreciated by Webber and McCarthy[1975], the literature on optical properties of silver also reveals significant discrepancies. For example the permitivity of silver measured by Schulz[1954] are significantly different from those by Hageman et al[1975] (Ordal et al[1983]). Such discrepancies may be attributed to the different measurement techniques used, or the influence of the conditions under which the films are deposited, which vary from operator to operator and plant to plant, some of which may be the pressure and nature of the residual gases in the deposition chamber, the temperature and cleanness of the substrate on which the films are deposited, the type of the boat from which the material is evaporated, and the rate of deposition.

From the above it may be concluded that the values ascribed to optical properties of polymers and metal films in the literature are not reliable, suggesting that these values are required to be measured independently.

Tien et al[1972] suggest a technique of measuring the refractive index and thickness of a polymer film by exciting the guided modes of such a film of several μm in thickness formed on top of a substrate, by coupling from light incident on the base of a high index prism placed on top of the film and separated from it by an air spacing. This work and a number of similar techniques described by other researchers [Ding et al 1983, Mason 1987] led the author to devise the structure shown in fig.5.2, referred to as a prism-waveguide-metal structure, in which the normal modes of the dielectric waveguide-metal (silver) combination can be excited by the light incident on the base of the prism. The information obtained regarding the propagation constants of the normal modes of the structure can now be used to experimentally deduce the value of the

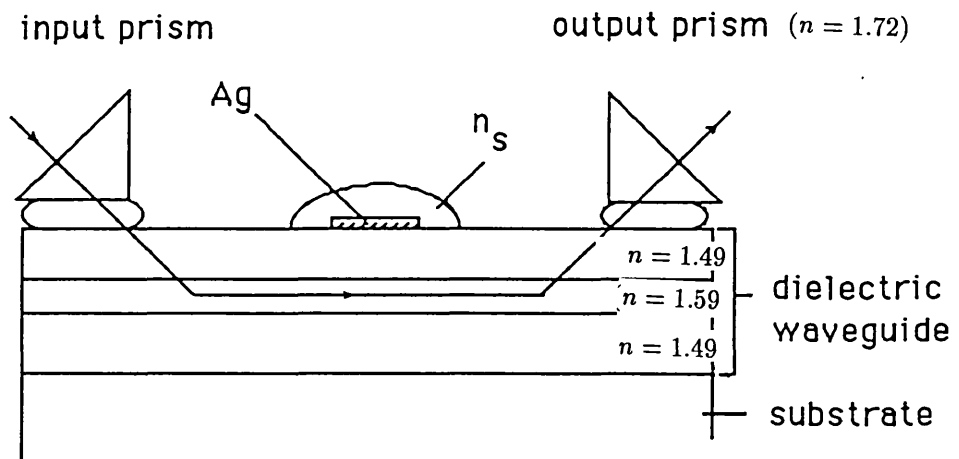


fig.5.1.Waveguide SPW directional coupler arrangement.

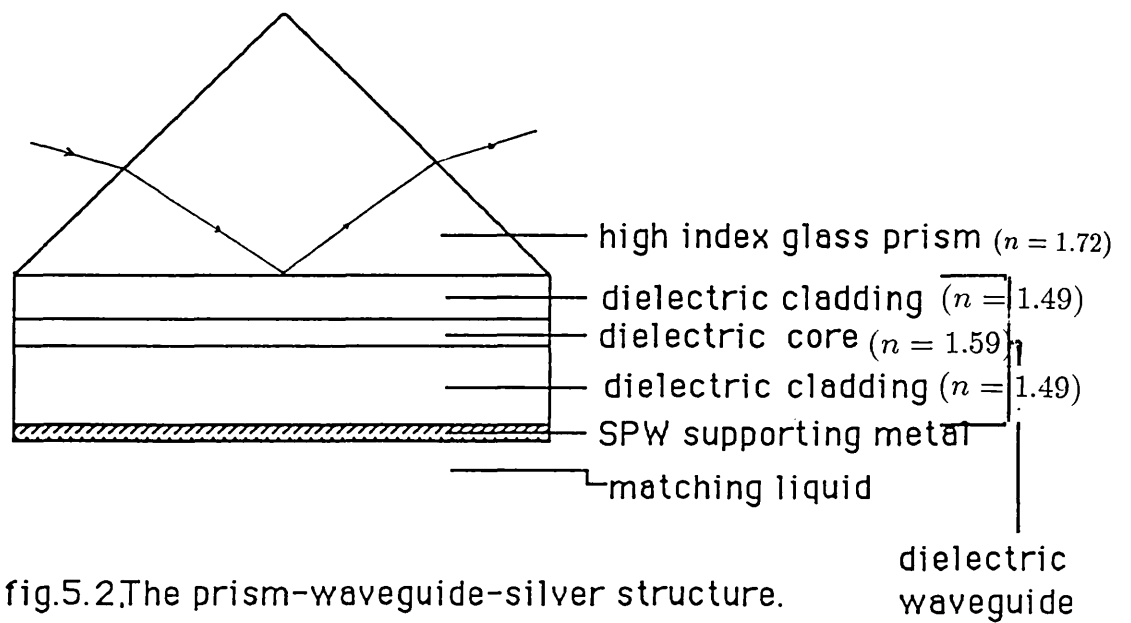


fig.5.2.The prism-waveguide-silver structure.

phase matching index for any particular surface plasma wave directional coupler structure with great ease, eliminating the need for the more tedious task of measuring optical properties of the constituent layers of the structure.

The prism-waveguide-metal structure can also be used to check if the directional coupler design satisfies the requirements of the specific application of interest, such as the phase matching index lying in a certain range of values.

It should also be noted that fabrication of the prism-waveguide-silver arrangement involves no further steps than that of the surface plasma wave directional coupler structure of interest, making the application of this arrangement for the above purpose attractive.

The application of the prism-waveguide-metal structure, to derive the phase matching index is described in the following section. This is followed by sections on fabrication of the surface plasma wave directional coupler (5.2) and the experimental observations (5.3). Finally the basic differences between the structure examined in this chapter and a similar structure devised by Kreuwel et al [1986], together with the possible advantages and disadvantages of the two structures are briefly discussed in section 5.4.

5.1. Prism-waveguide-metal structure.

The combination of the dielectric waveguide and the silver film supports two normal modes involving the long range surface plasma mode. The curves in the fig.5.1.1 represent the manner in which the effective indices of the isolated modes and those of the normal modes of a surface plasma wave directional coupler vary with n_s . From these curves it is apparent that the value of n_s corresponding to the isolated modes having identical effective indices (ie. the phase

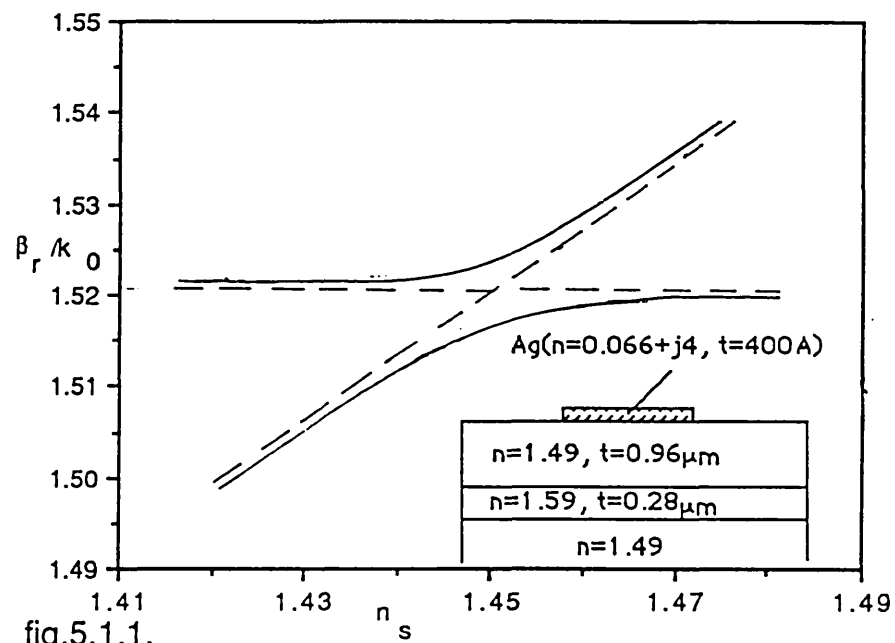


fig.5.1.1.

The effective indices of the isolated modes (---) and the normal modes (—) of a directional coupler structure as a function of n_s ($\lambda = 0.633\mu\text{m}$).

matching index), in fact, corresponds to the minimum difference between the effective indices of the normal modes. This suggests that the prism-waveguide-metal arrangement, in which the normal modes of the structure can be excited by the incident light, may be employed to deduce the phase matching index by comparing the effective indices of the normal modes as a function of n_S .

It is important to note that the proximity of the prism to the waveguide-silver combination modifies the effective indices of the normal modes. This can influence the value of n_S which corresponds to the minimum difference between normal mode effective indices, causing it to be different from the phase matching index in the structure of fig.5.1. The influence of the prism can however be reduced to a negligible value by increasing the thickness of the separation between the prism and the structure.

Excitation of the normal modes of the waveguide-silver structure by the incident light in the prism-waveguide-metal arrangement is similar to that of the surface plasma waves in the surface plasma wave prism couplers of chapter 2. At certain angles of incidence, the normal modes of the waveguide-silver combination propagate with the same velocity as that of the evanescent field of the incident waves, resulting in coupling from the evanescent field into the normal modes. Due to the absorption of the silver film, the excitation of these modes, which are partially distributed in the metallic region, appears as resonance dips in the intensity of the reflected light versus the angle of incidence.

The curves in fig.5.1.2 represent the reflectivity from the base of the prism as a function of the angle of incidence, for different values of n_S . The reflectivity curves are computed using the analysis by Hansen[1968]. The indices and

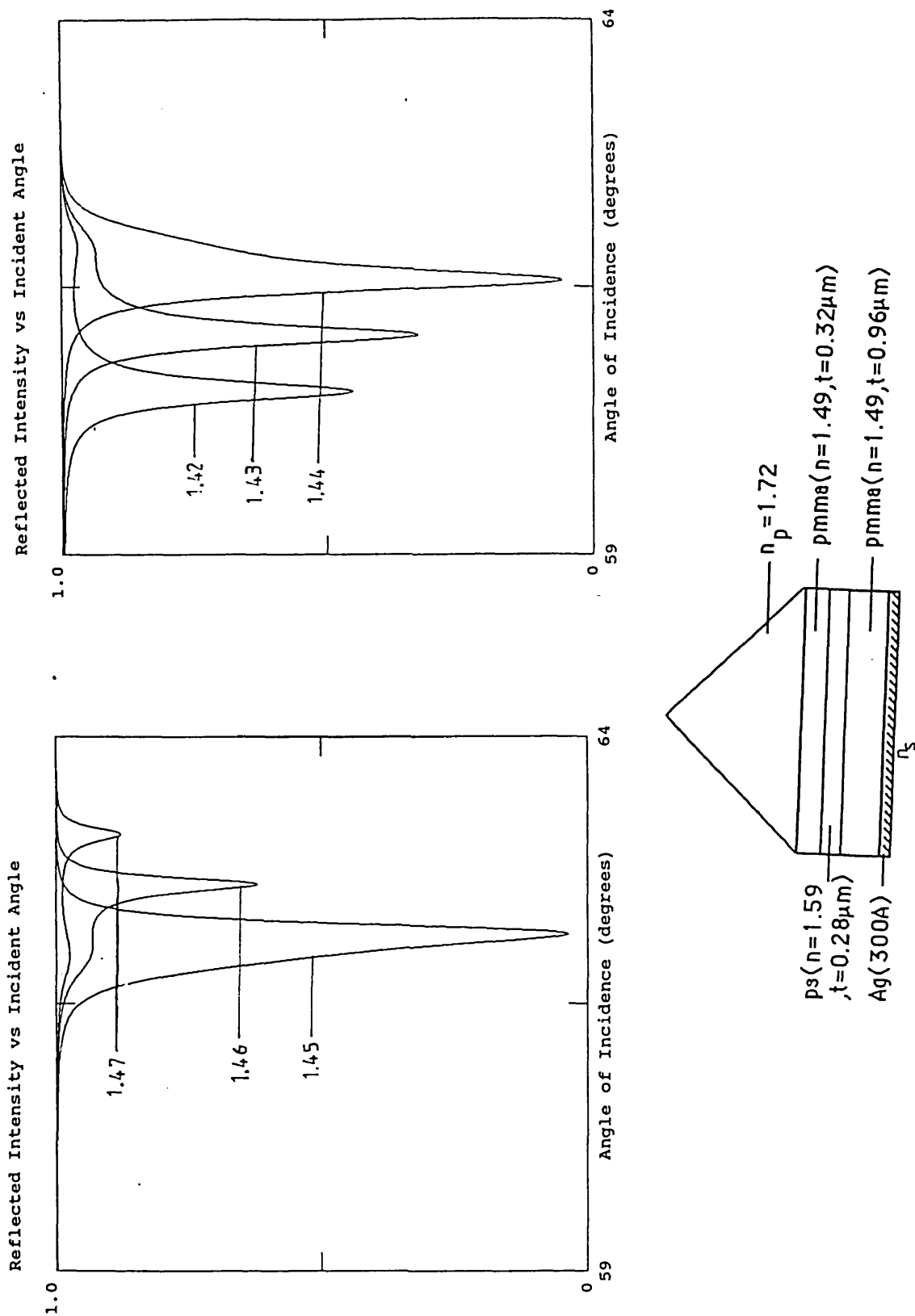


fig.5.1.2.Reflected intensity versus the angle of incidence for different values of n_s , and corresponding to the prism-waveguide-metal structure shown above.
 $\lambda = 0.633 \mu\text{m}$

thicknesses of the layers of the corresponding structure are also shown in this figure. The choice of indices of the dielectric waveguide core and claddings and the thickness of its core ensures that the waveguide supports a single mode.

The effective indices of the normal modes can now be defined by the following relationship;

$$\frac{\beta_r}{k_0} = n_p \sin(\theta_r) \quad (5.1.1)$$

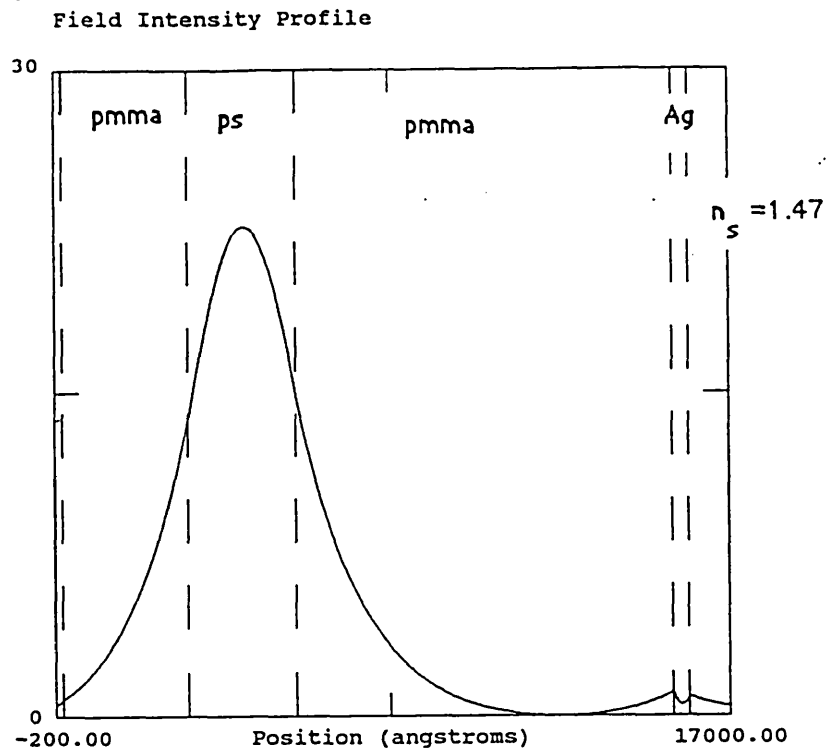
where, $\frac{\beta_r}{k_0}$ defines the effective indices of the normal modes, with n_p and θ_r representing the refractive index of the prism and the corresponding angles of resonance, respectively.

For an index of $n_S = 1.42$, two nearly distinct resonance dips are obtained, each of which corresponds to one of the normal modes of the coupler structure. As n_S is increased, the two dips get closer, until for values of n_S lying in the $1.44 < n_S < 1.45$ region they appear to coincide. Further increase of n_S causes the two dips to depart again.

From the curves of fig.5.1.2 it is concluded that $1.44 < n_S < 1.45$ defines a region at which the difference between the resonance angles corresponding to the two normal modes, and hence (from equation 5.1.1) the difference between the corresponding effective indices, approaches its minimum value. The phase matching index is therefore expected to lie in this range of values.

The reflectivity curves of fig.5.1.2 also indicate that the position of one of the resonance dips is very slightly influenced by the variation in n_S . Also, the field intensity profile at $n_S = 1.47$, and at the resonance angle $\theta_r = 61.979^\circ$, corresponding to this resonance (fig.5.1.3(a)), reveals that the mode corresponding to this resonance is mainly confined to the dielectric guiding region. Taking the above considerations into account, and considering that variations in n_S are

(a)



(b)

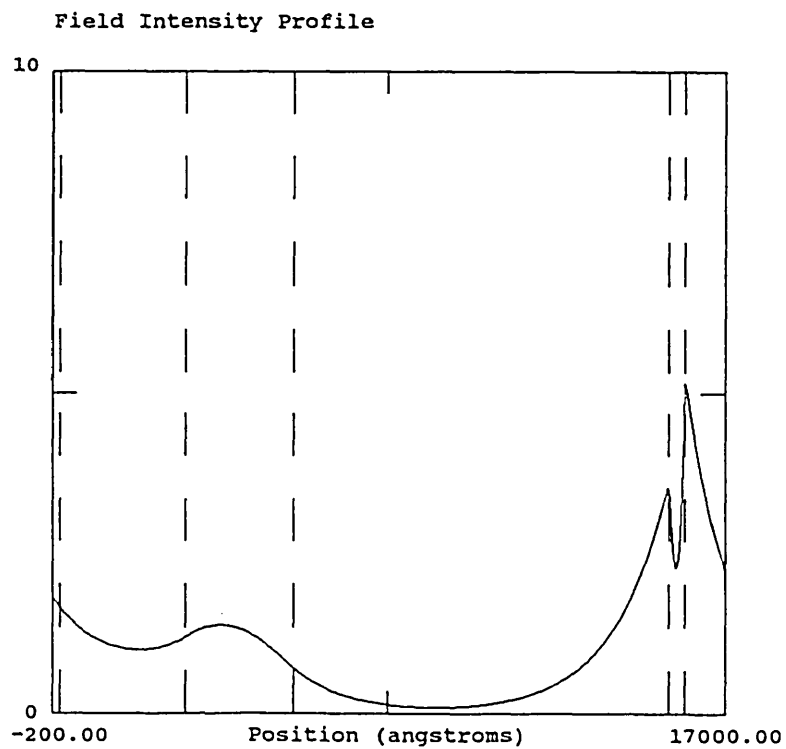


Fig.5.1.3.(a)Field intensity profile ($|H_y|^2$)corresponding to the waveguide resonance, and (b)that corresponding to the surface plasma resonance.
 $\lambda=0.633\mu\text{m}$

generally expected to have a negligible influence on the effective index of the dielectric waveguide mode, from this point on the normal mode corresponding to the above resonance is referred to as the waveguide resonance.

For completeness, we refer to the other resonance dip as the surface plasma resonance. The field intensity profile corresponding to this resonance ($\theta_r = 63.096^\circ$ at $n_S = 1.47$), shown in fig.5.1.3(b), which reveals that the corresponding mode is mainly confined to a region in the vicinity of the metal film, resembling a surface plasma mode, justifies this terminology.

Finally, consider the waveguide surface plasma wave directional coupler of fig.5.1, with its constituent layers having the same indices and thicknesses as those of the prism-waveguide-metal structure of fig.5.1.2. The normalized power out of the dielectric waveguide, P_1 , as a function of n_S , and for an interaction length of $200\mu m$, is shown in fig.5.1.8.

From this diagram it is clear that maximum transfer of power from the dielectric waveguide into the surface plasma wave, corresponding to the minimum in the coupling curve, occurs at approximately $n_S=1.45$, which is very nearly identical to the phase matching index deduced from the reflectivity curves of the prism-waveguide-metal structure. This confirms the validity of deducing the phase matching index from the reflectivity curves of the prism-waveguide-metal structure.

5.2.Fabrication.

Among numerous techniques of integrated optics waveguide fabrication reviewed by Tamir[1979], spin coating of polymer films appears to be the most suitable. This is due to the fact that virtually nonabsorbing, nonscattering films

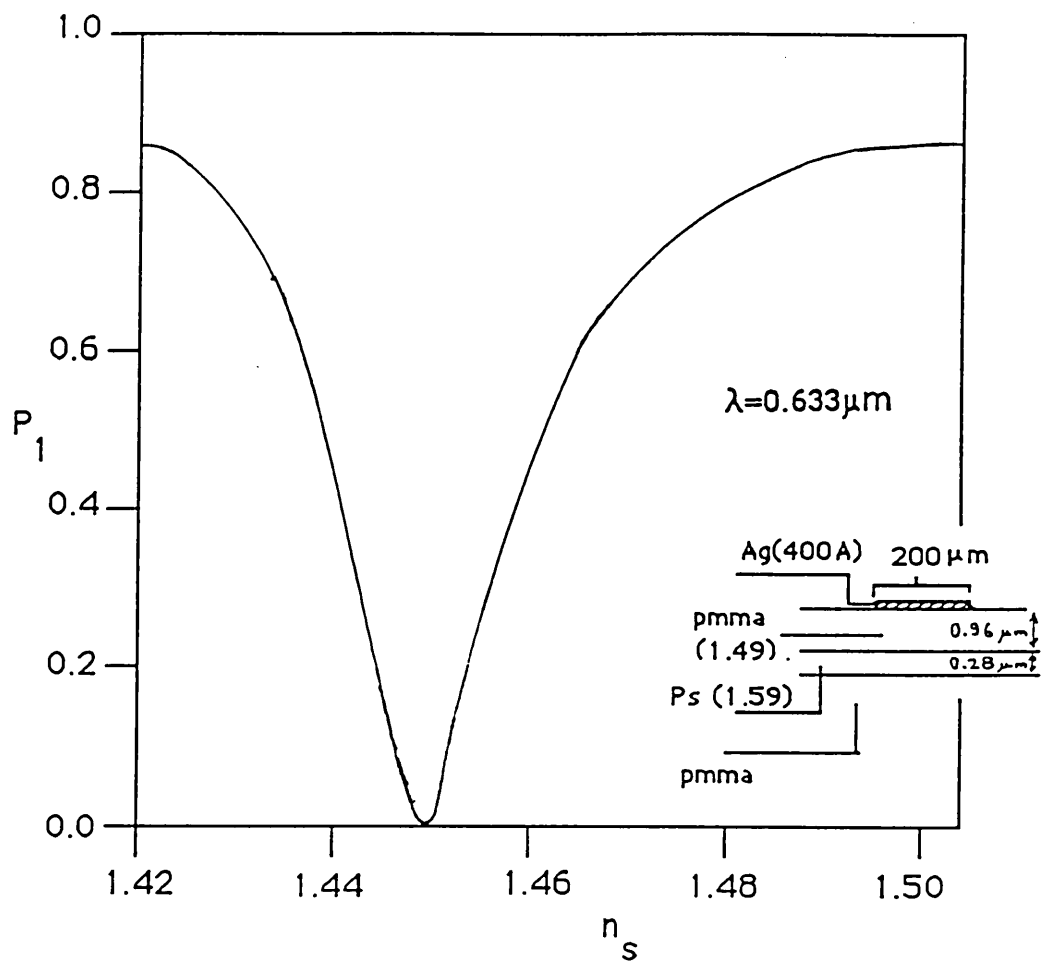


fig.5.1.8. The normalized power in the waveguide, P_1 , versus n_s .

of very smooth surface can be easily and quickly fabricated using this technique. The polymer films are, however, not very robust, deteriorate over a long time upon exposure to atmosphere and ultraviolet light, and can be attacked by a variety of solvents. These difficulties can however be partially overcome by covering the polymer with a thin layer of a robust material, such as magnesium fluoride.

Polystyrene (refractive index approximately equal to 1.59) and pmma (refractive index approximately equal to 1.49) are suitable materials for the core and the cladding regions of the waveguide, respectively.

Thin polymer films can be fabricated from solutions by a number of techniques, namely the horizontal flow method which involves covering the substrate with the polymer solution and then bringing it to a vertical position to drain off the excess solution, doctor blading in which the solution is spread over the substrate by moving a knife edge along the substrate, and spinning a few drops of the solution placed on the substrate [Swalen et al 1977]. Spinning which is expected to allow a more accurate control of the film thickness and results in more uniform films is the technique employed here.

In this work polymer films are deposited by spinning a solution of polymer with Xylene (boiling point=140 degrees centigrade) as the solvent, which is diluted to produce films of the required thickness.

The subsequent layers of the guiding structure can be spun on top of each other. To protect each layer against the solvent in the solution from which the subsequent layer is produced, each layer is hardened by baking it at 160°C for 30 minutes prior to spinning of the proceeding layer.

Initial attempts to spin a layer of pmma on top of polystyrene films have, however, failed. This is thought to be due to the relative softness of the polystyrene film, despite the baking process, which makes it prone to attacks by the solvent of the solution from which the pmma layer is spun. The profile of the structures formed by spinning polystyrene on top of a pmma layer and that formed by attempting to spin a layer of pmma on top of the resulting pmma-polystyrene combination are shown in figures 5.2.1(a) and 5.2.1(b), respectively. These profiles are measured using Talystep.

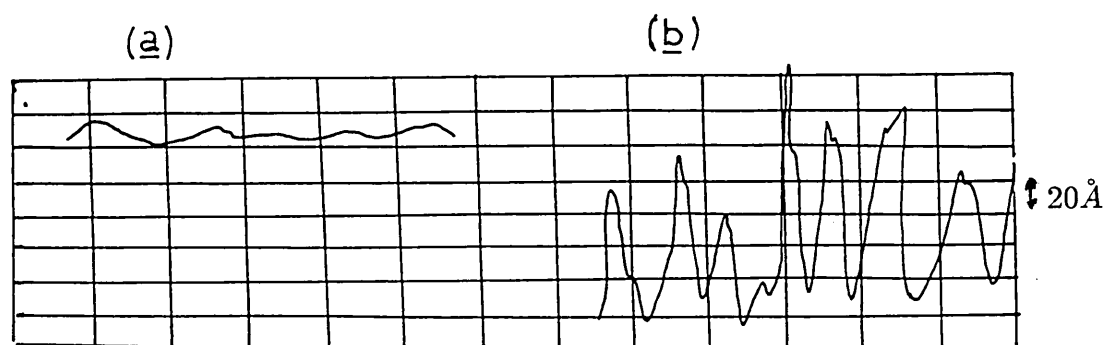


fig.5.2.1.(a)Profile of a ps layer deposited on top of a pmma layer, and (b) that corresponding to a layer of pmma formed on top of a ps layer, spinning of pmma on top of the ps film has damaged this layer leaving a very non-uniform film.

Fig.5.2.1(b) clearly indicates enormous irregularities caused as a result of spinning the pmma solution on top of the polystyrene.

The above difficulty is found to be overcome by glow discharging the polystyrene layer in oxygen, which is thought to harden the polystyrene, allowing the formation of the pmma layer without any appreciable damage to the polystyrene.

The thickness of the spun polymer films is found to be mainly sensitive to the speed with which the spinning is performed, and the concentration of the polymer in the solution from which the films are spun. The thickness of the films can be increased by reducing the spinning speed or alternatively increasing the concentration of the polymer in the solution. The latter technique is found to be more effective, enabling control of the film thickness over a wider range of values. However, spinning of a very concentrated solution results in films of poor surface quality. This is due to the evaporation of most of the small quantity of the solvent in a short time and prior to the termination of the spinning process, which results in spinning of a nearly hardened material, hence producing non-uniform films. To overcome this difficulty, a substantial increase in the concentration of the solution (in order to increase the thickness of the resulting film) has to be accompanied by an increase in the boiling temperature of the solvent, which would result in the slow evaporation of the solvent, hence avoiding spinning of a hardened material.

Another important observation is that the termination of the spinning process with a significant amount of the solvent present, causes non-uniformities in the resulting films, especially near the perimeter of the substrate. This is due to the deformation of the still 'wet' film, containing a large amount of the solvent, as a result of the solvent surface tension.

In summary, as the concentration of the polymer in the solution from which the films are spun is varied to control the thickness of the resulting films, the boiling temperature of the solvent is required to be adjusted accordingly, or non-uniform films may be produced.

A thin film formed on a reflective substrate, such as a polished silicon wafer, appears coloured provided its thickness is comparable to the wavelength of visible light. The colour of the film, which is due to constructive interference of the multiply reflected white light at the corresponding wavelength, is realised to be sensitive to small thickness variations, and in general non-uniformities of such a film. This characteristic, which has already been employed by Sandstrom et al [1985] to detect adsorption of monomolecular organic films as thin as $7\text{\AA}$ on a silicon dioxide layer, is used here for a quick inspection of the surface quality and thickness variations of the polymer film. Since the colour of the films change from red to blue as a result of thickness change of $250\text{\AA}$, film unevenness of order of $100\text{\AA}$, which is only a few percent of the required thicknesses, is easily detectable.

Very uniform pmma and polystyrene films, examined using the above technique, are produced from diluted solutions of solid polymers in Xylene. In both cases the concentration of the polymer in the solution is optimised to produce uniform films. The films fabricated in this manner are extremely reproducible.

Subsequent formation of pmma (0.32μ), polystyrene (0.28μ) and pmma (0.32μ) layers, which form the dielectric waveguide, with the polystyrene layer glow discharged in oxygen and all the layers baked as explained earlier, produces a structure with an overall thickness of very nearly $0.92\mu\text{m}$, which is equal to the sum of the thicknesses of the individual layers. In the same manner, subsequent

layers of pmma are spun on top of each other to produce an overall pmma layer of any required thickness.

Finally, to eliminate any possible contamination, the solutions are filtered through a $0.22\mu m$ microfilter immediately prior to the spinning process.

Having produced the dielectric waveguide in the above manner, a silver film of the required thickness can now be vacuum deposited on top of this structure over any required length (the length over which the silver film is deposited defines the interaction length), using an Edward vacuum deposition system. The silver films are produced from evaporation of a 99.9 percent silver powder, at pressures of less than 1×10^{-5} mmHg. The thickness of the silver films is monitored during the deposition process using a crystal thickness monitor.

5.3.Experimental observations.

The structure to be examined is fabricated on a high index glass slide, in the manner described in the preceding section. The glass substrate is then brought in optical contact with a high index prism using a liquid of an appropriate refractive index (di-iodomethane, with a refractive index of 1.74 at 0.633μ), as shown in fig.5.3.1. The final pmma layer is composed of three separate depositions, each $0.32\mu m$ thick.

The arrangement shown in fig.5.3.2 is used to monitor the intensity of the reflected light as a function of the incident angle, θ .

The matching liquid (a silicone based oil) is placed on top of the structure. Following the measurements with a certain matching liquid, the liquid is washed away using trichloroethane, and replaced by a liquid of different refractive index. This procedure is followed while the sample is still in position.

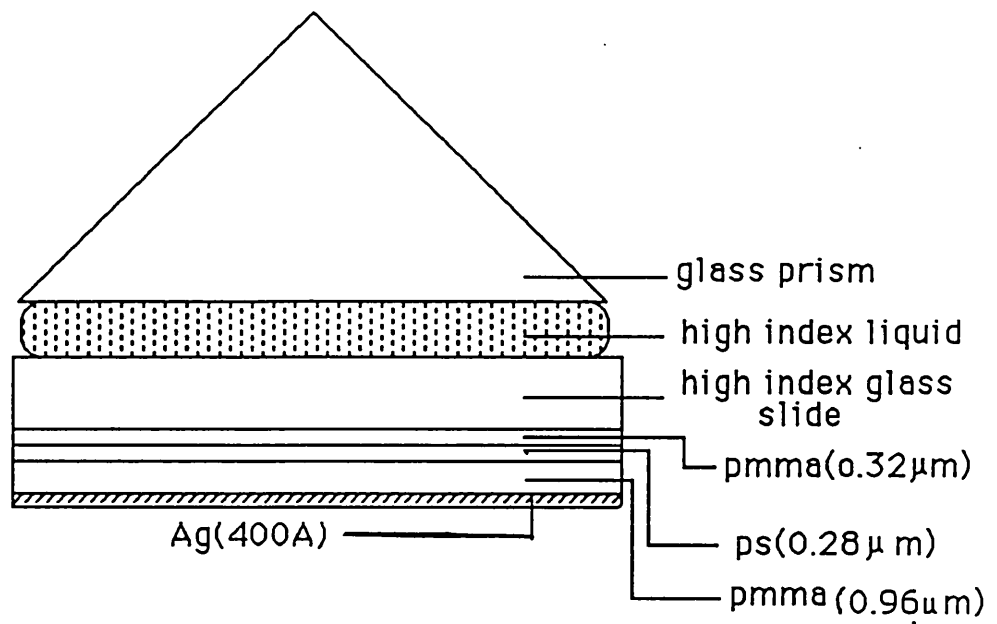


fig.5.3.1.The prism-waveguide-metal structure fabricated on a high index glass slide and brought in contact with a high index prism.

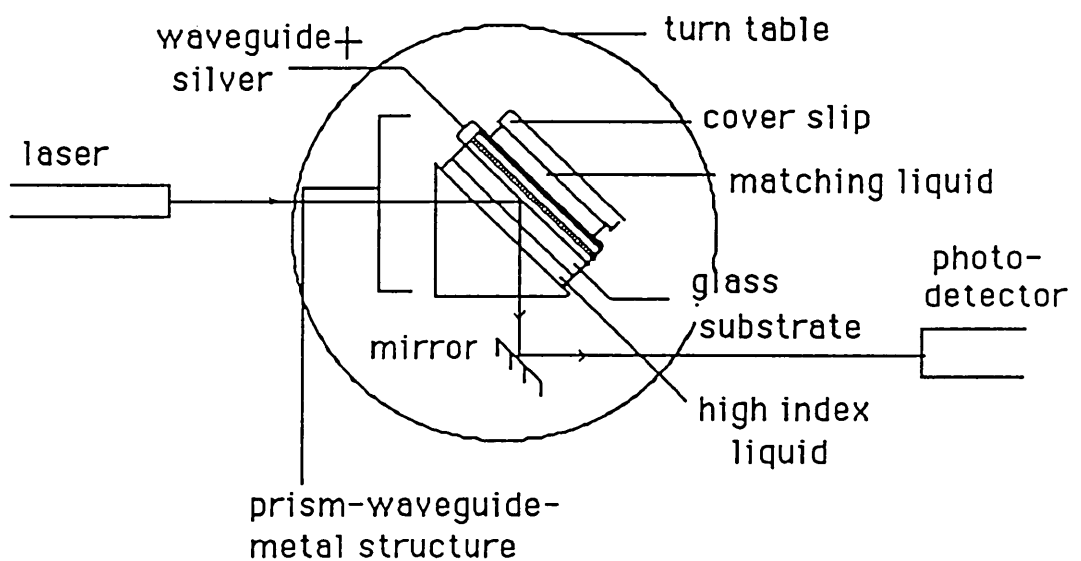


fig.5.3.2.The arrangement used to measure the intensity of the reflected light as a function of the angle of incidence.

The reflected light intensity versus the angle of incidence, measured for different values of n_S , are shown in fig.5.3.3. At $n_S = 1.417$ two distinct resonance dips, corresponding to the two normal modes of the structure, are observed. Adjustment of n_S brings the two dips closer to each other, till at a range of values of n_S between 1.427 and 1.441 they nearly coincide. The phase matching index, therefore, lies in the $1.427 < n_S < 1.441$ region. A clear increase in the depth of the waveguide resonance in this range of values of n_S is also observed, confirming an increase in the power transferred from the waveguide mode into the strongly attenuated surface plasma mode.

In summary, the general characteristics of the computed reflectivity curves of fig.5.1.2 are observed in the experimental curves of fig.5.3.3. However, the range of indices in which the phase matching index lies ($1.427 < n_S < 1.441$), is realised to be different from that deduced from the theoretical reflectivity curves ($1.44 < n_S < 1.45$). This confirms presence of inaccuracies in the theoretical model, which may be due to uncertainties in the assumed values of the optical properties of the constituent layers, taken from the literature or in the value of the thickness of the silver film

Following the deduction of the range of values of n_S in which the phase matching index lies, attempts are made to examine the coupling using the waveguide surface plasma wave directional coupler, shown in fig.5.1. Simultaneous fabrication of this structure and the prism- waveguide-metal structure of fig.5.3.1 ensures that both structures are produced under identical conditions.

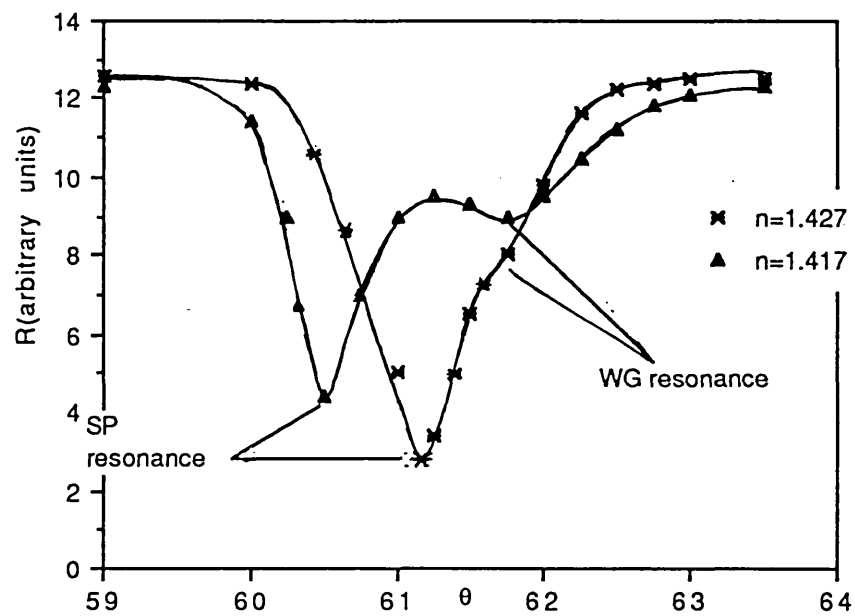
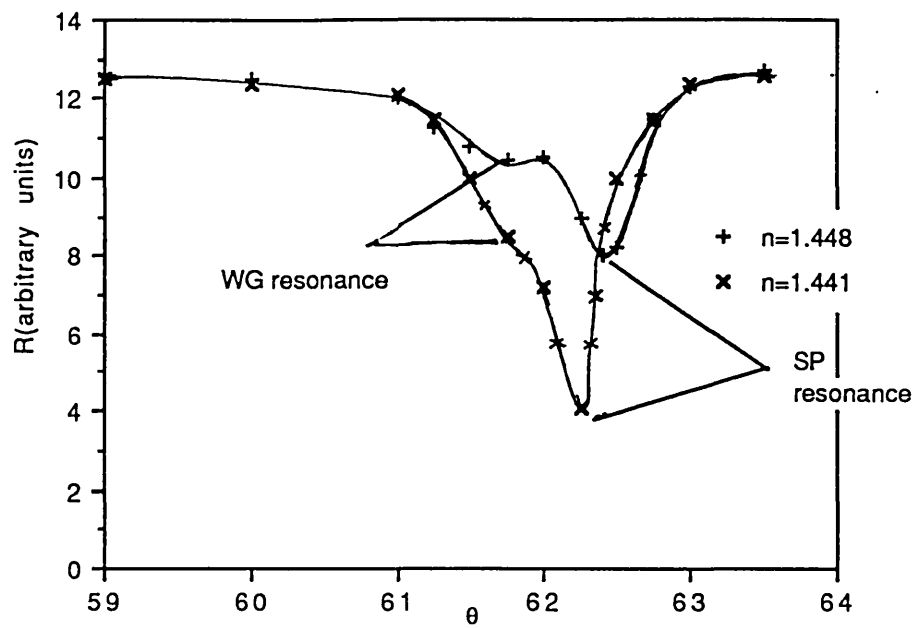


fig.5.3.3.

The measured reflected light intensity (R) versus the angle of incidence and for different values of n_s .
 $\lambda=0.633\mu\text{m}$

Monochromatic light is launched into the guided mode of the dielectric waveguide using the input prism, and having travelled through the interaction region, it is then coupled out of the waveguide using the output prism. Di-iodomethane is again used to make optical contact between the prisms and the dielectric waveguide.

To protect the polymer, which is attacked by di-iodomethane and possibly the matching liquid, a thin layer of magnesium fluoride (MgF_2) is deposited on the top surface of the polymer structure, every where apart from where it is already covered with silver.

An important consideration in the feasibility of employing magnesium fluoride as a protective layer is that the stress in magnesium fluoride films may cause formation of cracks in the resulting structures. This effect may be particularly pronounced when MgF_2 is deposited on top of relatively soft materials such as polymers. It was in fact observed that a MgF_2 film of a few 1000s of Å in thickness can not be totally removed once deposited on a $0.3\mu m$ thick polystyrene film, even when boiled in Xylene. This is despite the fact that hot Xylene is expected to dissolve polystyrene and hence remove the polystyrene film together with the magnesium fluoride overlayer. This suggests that the stress in MgF_2 film has actually partially pulled the polymer apart during the deposition process, allowing deposition of MgF_2 on the glass slide substrate and subsequently totally surrounding the polymer in some parts, preventing any contact between the Xylene and polystyrene.

The stress in MgF_2 films is however known to be reduced as the film thickness is reduced. Therefore, the formation of the cracks may be avoided by restricting the thickness of the MgF_2 films.

MgF_2 films of $1000\text{\AA}$ in thickness deposited on the polymer waveguide structure do not show any sign of cracks, when observed using an optical microscope of $\times 150$ magnification. Contact with di-iodomethane for approximately 60 minutes, however, results in formation of clear cracks. This is thought to be due to the presence of minute cracks on the fresh film which are porous to di-iodomethane, allowing di-iodomethane to reach and attack the polymer, hence increasing the size of the cracks. However, microscopic examination of magnesium fluoride films of approximately $500\text{\AA}$ in thickness deposited on the polymer structure shows no sign of any cracks even following contact with di-iodomethane for more than 24 hours. A $500\text{\AA}$ thick MgF_2 film is thus considered to be an effective protective layer.

Initial examination of the waveguide surface plasma wave directional coupler reveals that, even in the absence of the silver film, light launched into the guided mode of the dielectric waveguide, having travelled a distance of less than 0.8cm , is virtually totally diminished in intensity. This, if not restricting the practicality of the device, makes replacement of the matching liquid on the interaction region, which is located between the two prisms, difficult. The loss of the waveguide power in the absence of the silver film is attributed to the scattering loss associated with the waveguide, which may have occurred as a result of the following defects in the structure;

(1) Despite the precautions taken, the surface of each constituent layer of the dielectric waveguide is possibly attacked by the solvent in the solution from which the subsequent layer is produced, causing irregularities on the interfaces between the layers, resulting in the scattering of the light propagating in the structure. This effect can be minimised by reducing the number of the constituent layers.

A single thick and uniform layer of pmma can be spun from a more concentrated polymer solution, which contains a solvent of relatively high vapour pressure. The choice of the solvent with higher vapour pressure prevents the nearly total evaporation of the solvent prior to the termination of the spinning process, which would result in fabrication of a non-uniform film. Uniform pmma films of thickness as large as $1.06\mu\text{m}$ have been fabricated from a solution consisting of 10 percent pmma in Cellusolve Acetate solvent, spun at a speed of 4000 revolution per minute for 25 seconds. The relatively long duration of the spinning process is realised to be necessary to avoid 'wet' films, described earlier. Such a thick pmma layer can clearly replace the three $0.32\mu\text{m}$ thick pmma layers, which form the top dielectric cladding of the structure.

(2) The glow discharge of the polystyrene layer may have not been long enough to effectively protect this layer against attacks by the solvent of the solution from which the subsequent pmma layer is produced. This would result in an anomalous polystyrene-pmma interface, giving rise to a scattering loss mechanism.

To quantitatively examine the scattering loss the same arrangement as in fig.5.3.2 is used to measure the reflectivity as a function of the incident angle, in the absence of the silver film. In this case, assuming the polymers to be lossless, the presence of any resonance dip corresponding to the excitation of the waveguide mode, would be a direct result of the scattering loss associated with the dielectric waveguide. The depth of this resonance would now be a measure of the scattering loss. The impact of the glow discharge duration on the scattering loss can thus be monitored, by comparing the waveguide resonance depths corresponding to a number of samples, in which the polystyrene layer is glow discharged for different lengths of time.

The waveguide resonances corresponding to polymer guiding structures, consisting of a single top pmma layer of thickness $1.06\mu m$, with the polystyrene layer glow discharged for different lengths of time and in the absence of the silver film, are shown in figure 5.3.4, which represents the reflected light intensity versus the angle of incidence, for two such samples, with the corresponding glow discharge durations as indicated. A significant reduction in the depth of the waveguide resonance, and hence the corresponding waveguide scattering loss is obtained by increasing the glow discharge duration. This confirms the importance of the glow discharge duration on the scattering loss.

The prism-waveguide-metal structure, consisting of the single 1.06μ pmma layer, is then fabricated, with the polystyrene glow discharged long enough to minimise the scattering loss. The corresponding reflected light intensity versus the angle of incidence curves, measured for different values of n_S , are shown in fig.5.3.5. The expected features are clearly observed, with the phase matching index lying in the vicinity of $n_S = 1.446$.

Examination of the corresponding waveguide surface plasma wave directional coupler in the absence of the silver film shows that the light launched into the waveguide mode propagates over a distance longer than 1.5 cm. This is a clear improvement over the previous structure.

The silver film is $400\text{\AA}$ in thickness, and is deposited over a length of approximately $200\mu m$, which is equal to the theoretically computed interaction length, required in order to obtain a significant coupling depth.

Deposition of the silver film over such a short length is achieved using the masking arrangement described as follows. In this arrangement, a fibre of $200\mu m$ in diameter is used as a spacer between two cover slips. The cover slips are then secured in place using a liquid glue. The fibre is removed prior to the

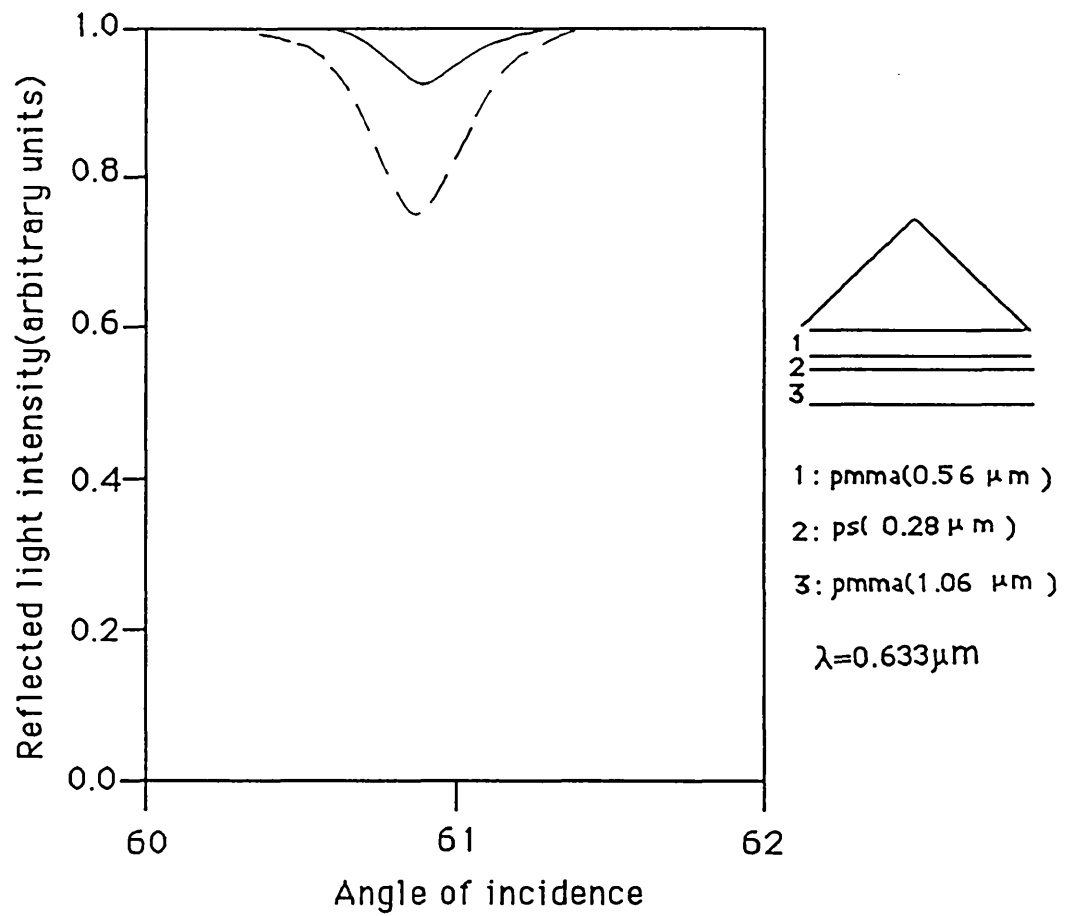


fig.5.3.4.Intensity of the reflected light versus the angle of incidence in the absence of the metal film and for different glow discharge durations.

- :glow discharged for 10 minutes at an average current of 60 mA & a voltage of 1.5KV.
- :glow discharged for 20 minutes at the same current and voltage.

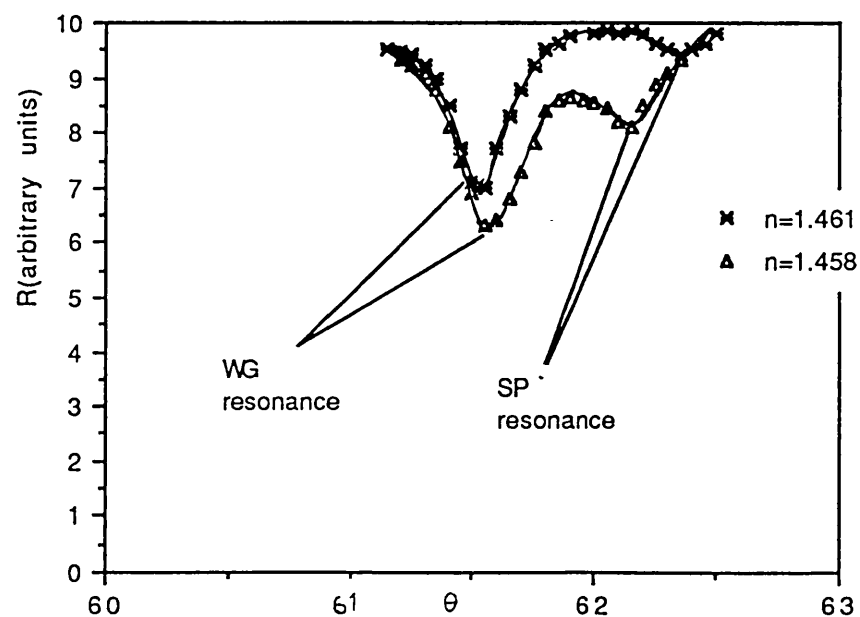
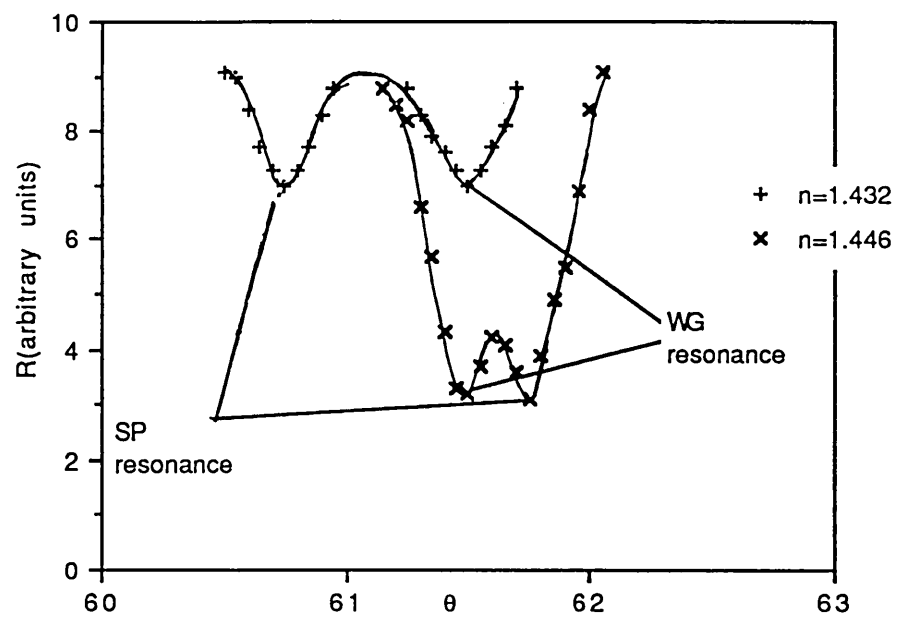


fig.5.3.5.

The measured reflected intensity (R) as a function of the angle of incidence and for different values of n_s . $\lambda=0.633\mu\text{m}$

setting of the glue. The cover slips are then placed in contact with the polymer structure, masking all of its area apart from the exposed $200\mu m$ region on which the silver film is to be deposited.

The $500\text{\AA}$ thick magnesium fluoride protective layer is then deposited all over the structure except where it is covered with the silver film. The silver film is masked during the magnesium fluoride deposition, by simply covering it with a fibre of $150\mu m$ in diameter.

The refractive index of the outer cladding of the silver film is varied by placing matching liquids of different refractive index over the interaction region. The intensity of the light out of the dielectric waveguide measured for different values of n_S is shown in fig.5.3.6. It should be noted that in the above measurements, the intensity of the light out of the waveguide is normalised to its value corresponding to the situation where no matching liquid is placed over the interaction region, ie. $n_S \sim 1.0$.

5.4.Conclusions.

The above observations confirm the presence of a coupling mechanism between the guided mode of the dielectric waveguide and the surface plasma mode in the planar surface plasma wave directional coupler of interest.

It has also been shown that the range of values of n_S which include the phase matching index can be deduced using the prism-waveguide-metal arrangement. The prism-waveguide-metal arrangement can therefore be used to check if the phase matching, corresponding to any particular design, occurs at the required value of n_S , satisfying the requirements of the specific application of interest. This eliminates the need to rely on an accurate theoretical model which

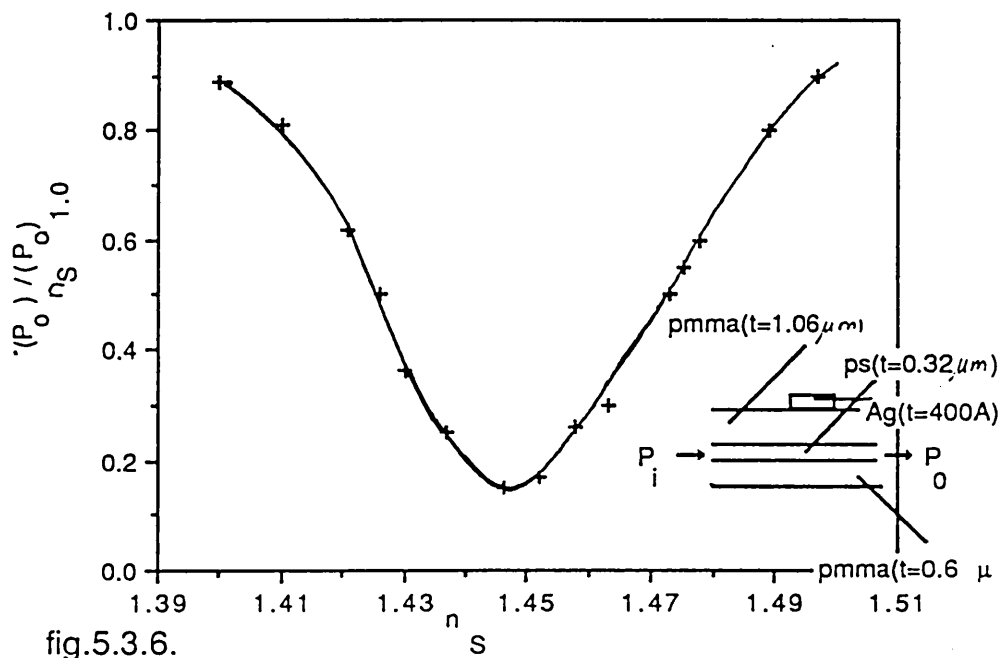


fig.5.3.6.

The measured power remaining in the waveguide versus n_s , normalized to the power corresponding $n_s = 1.0$. $\lambda = 0.633 \mu m$

would be based on a more tedious task of measuring the optical properties of the constituent layers.

A comparison of the experimental coupling curve of fig.5.3.6 with the theoretical curve shown in fig.5.1.8, however, reveals that the phase matching index (1.446) turns out to be quite close to its theoretically predicted value (1.45). It should be noted that in the structure of fig.5.3.1, which consists of a larger number of layers (3 layers of pmma forming the spacing between the waveguide core and the silver film), a larger difference between the experimental and the theoretical phase matching indices is obtained (theory; 1.45, experiment; 1.435). This confirms the validity of using the prism-waveguide-metal arrangement in certain structures, in which the uncertainties in properties of the constituent layer may be more significant.

A significant discrepancy between the experimental coupling curve of fig.5.3.6, and the corresponding theoretical curve (fig.5.1.8) is that the former is found to be substantially broader. This may be attributed to the inaccuracy of the assumed optical properties of the constituent layers of the theoretical model, which would result in inaccuracies in the field distributions and hence coupling strength. Also the silver film permittivity may possess a larger imaginary part than the value assumed for it in the theoretical model, resulting in a broader coupling curve.

The broadness of the coupling curve implies that the device is not particularly sensitive to small changes in n_S . For example, a change of 0.001 (1.475-1.474) in n_S is accompanied by a change of just over 3 percent in intensity of the output light.

The sharpness of the coupling curve can, however, be increased by weakening the coupling. This may be achieved by increasing the thickness of the separation between the waveguide and the silver film. However, a substantial increase in the separation thickness may require subsequent spinning of a number of pmma layers to form the separation. This, as explained earlier, is expected to be accompanied by an increase in the scattering loss.

Another parameter of the structure which influences the strength of coupling is the thickness of the dielectric waveguide core. This has the following opposing effects on the strength of coupling;

1) Increasing the thickness of the waveguide core results in a larger concentration of the waveguide field inside the core, causing an increase in the effective index of the waveguide mode and hence a faster decay of the waveguide evanescent field in the spacing layer, described by $\exp(-\gamma x)$, where $\gamma = ((\text{effective index})^2 - (n_{\text{spacing}})^2)^{1/2}$. This results in weaker perturbation of the waveguide mode by the silver film, which reduces the coupling strength.

2) An increase in the core thickness is also accompanied by an increase in the perturbation of the surface plasma field by the dielectric waveguide, which tends to increase the coupling strength.

However, analysis reveals that the coupling strength is predominantly determined by the perturbation of the waveguide mode by the silver film rather than that of the surface plasma mode by the waveguide. Therefore, increasing the thickness of the waveguide core has the overall effect of reducing the coupling strength and hence increasing the sharpness of the coupling curve.

A similar surface plasma wave directional coupler has been described by Kreuwel et al [1986]. The cross-section of this structure is shown in fig.1.1.10

(chapter1). The major difference between this structure and the structure examined in this chapter is the inclusion of an extra high index dielectric layer (Al_2O_3) between the dielectric waveguide and the silver film. In the remainder of this chapter the significance of the Al_2O_3 layer, which has not been discussed explicitly by Kreuwel et al, together with the possible resulting merits and disadvantages are discussed.

As explained in chapter4, in a surface plasma wave directional coupler, excitation of the long range surface plasma mode (accompanied by a smaller loss) is associated with a sharper coupling curve compared to that of the short range surface plasma mode, resulting in a more sensitive device. This leads to the following design requirements;

- 1) The waveguide mode is required to couple into the long range surface plasma mode.

- 2) The long range surface plasma power is required to be mainly distributed around the interface between the metal film and the sensing cladding, or the coupling into the long range mode will be somewhat insensitive to variations in the refractive index of the sensing cladding, resulting in a poor sensing device.

In the structure examined by Kreuwel et al, for an outer cladding of refractive index 1.44 or 1.45 (indices at which coupling between the waveguide mode and the surface plasma wave has been achieved in the experiments performed by Kreuwel et al), in the absence of the Al_2O_3 layer the long range surface plasma mode turns out to be mainly confined in the vicinity of the silver-inner cladding interface. This is shown in fig.5.4.1, which shows the field intensity profiles corresponding to both the long range and the short range surface plasma modes propagating on the metal film in this structure. The coupling into the

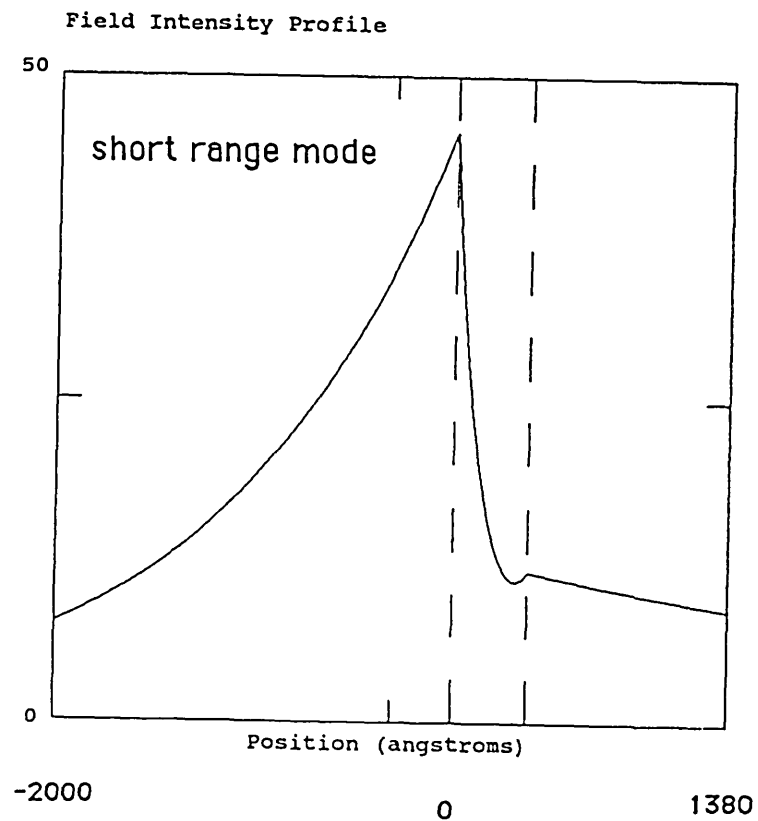
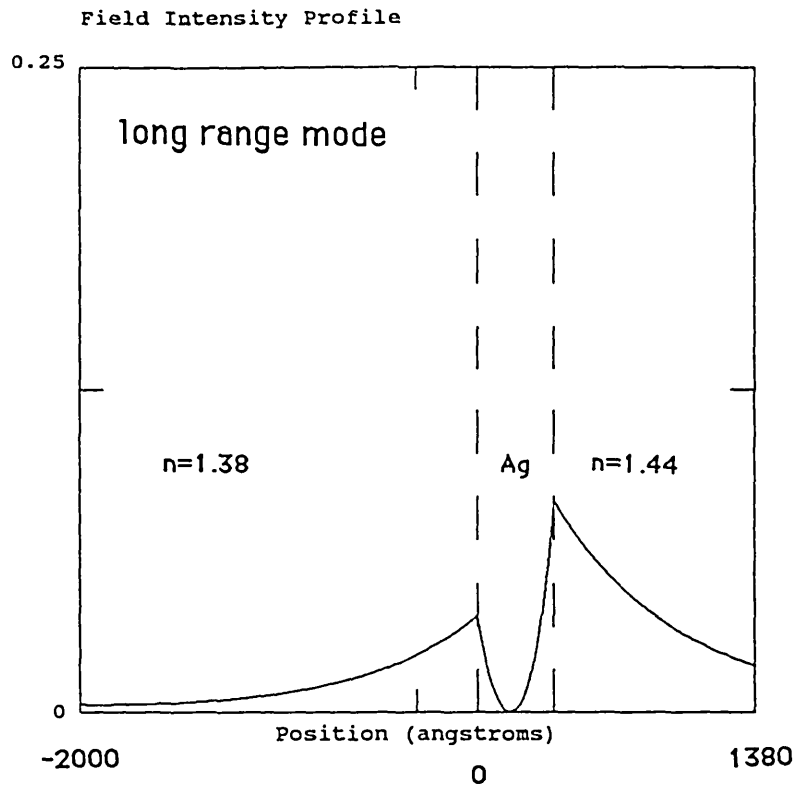


fig.5.4.1. The field intensity ($|H_y|^2$) profiles corresponding to (a) the long range SP mode and (b) the short range SP mode in the absence of the Al_2O_3 layer.

$\lambda = 0.633 \mu\text{m}$

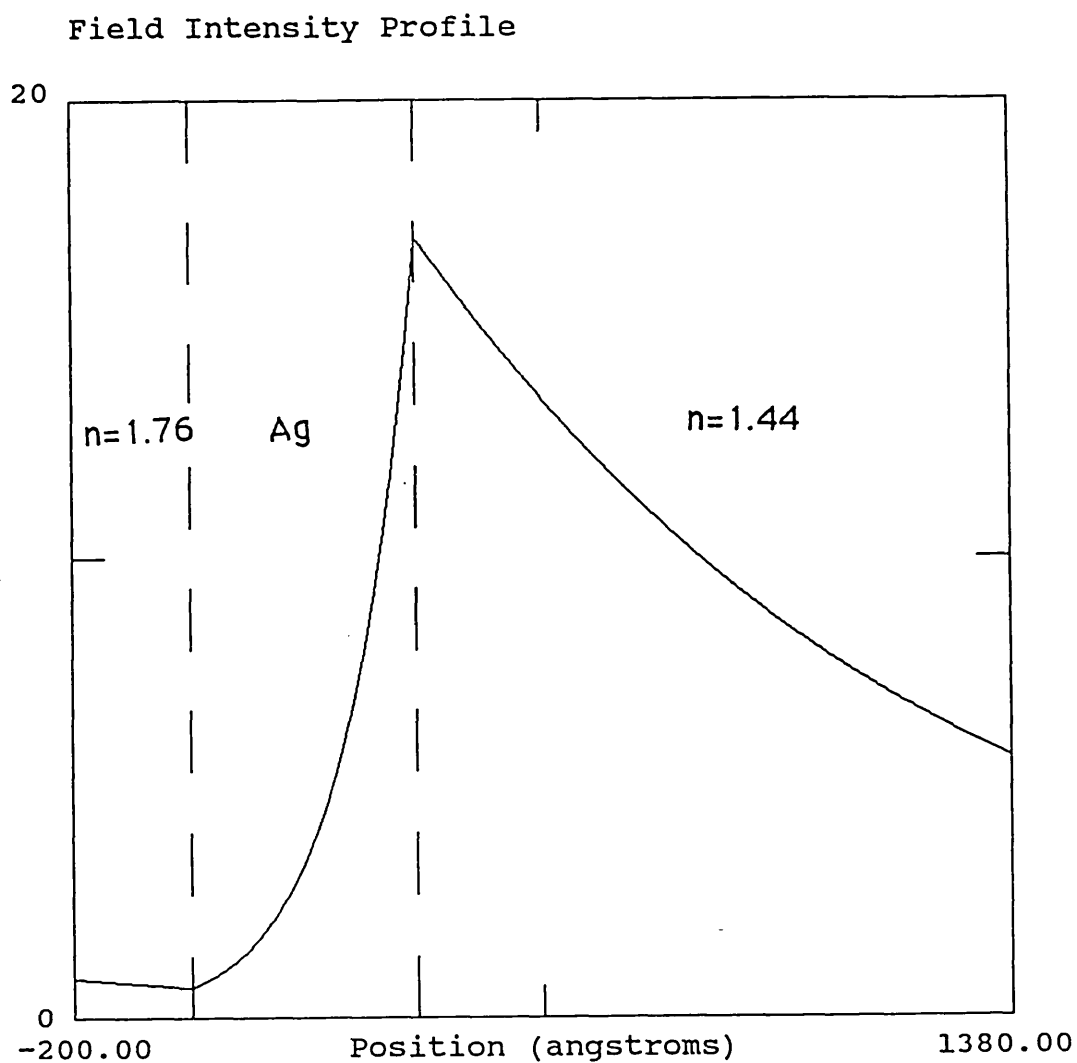


fig.5.4.2. Field intensity profile corresponding to the long range surface plasma mode, in presence of the Al_2O_3 layer. The Al_2O_3 layer causes the long range mode to be mainly confined to the metal film outer interface.
 $\lambda=0.633\mu\text{m}$

long range surface plasma mode would now be somewhat insensitive to variations in the refractive index of the outer sensing cladding. Introduction of the Al_2O_3 layer, however, causes the long range surface plasma mode to be mainly confined to the silver film outer interface (fig.5.4.2), resulting in a significant increase in the sensitivity of coupling into the long range mode to variation in the refractive index of the sensing cladding.

Another possible function of the Al_2O_3 layer is that this layer allows tuning of the long range surface plasma mode and any of the waveguide modes (the waveguide supports 4 TM guided modes [Kreuwel et al 1986]). Tuning of the surface plasma mode and a specific waveguide mode may be desired because, for example, the field of the waveguide fundamental mode, having the largest effective index, is mainly confined to the core with little field present in the claddings. This implies small perturbation of this mode by the silver film, resulting in weak coupling and hence a sharper coupling curve. It may, therefore, be of advantage to tune the surface plasma mode and the fundamental waveguide mode in the vicinity of the index of the sensing cladding.

To examine the influence of the Al_2O_3 layer on the tuning process in more detail, the equivalent prism-waveguide-metal structure, shown in fig.5.4.3, can be used. The reflectivity curves corresponding to the TM polarized incident light at a wavelength of $0.6328\mu m$ are shown in fig.5.4.4. The resonance dips in this curve correspond to the excitation of the waveguide and the surface plasma modes. The correspondence of the resonance dips to the waveguide and the long range surface plasma modes can be established using the corresponding field intensity profiles (fig.5.4.5). From the field profiles, it is clear that the resonance dips at resonance angles 66.468° , 65.777° , 64.633° and 63.090° correspond to the waveguide modes with increasing mode numbers, respectively, while the

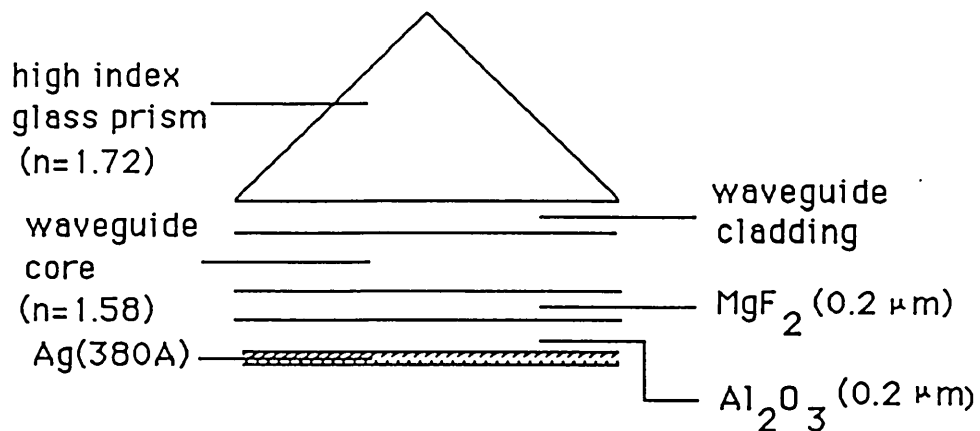


Fig.5.4.3. The prism-waveguide-metal structure corresponding to the structure examined by Kreuwel.

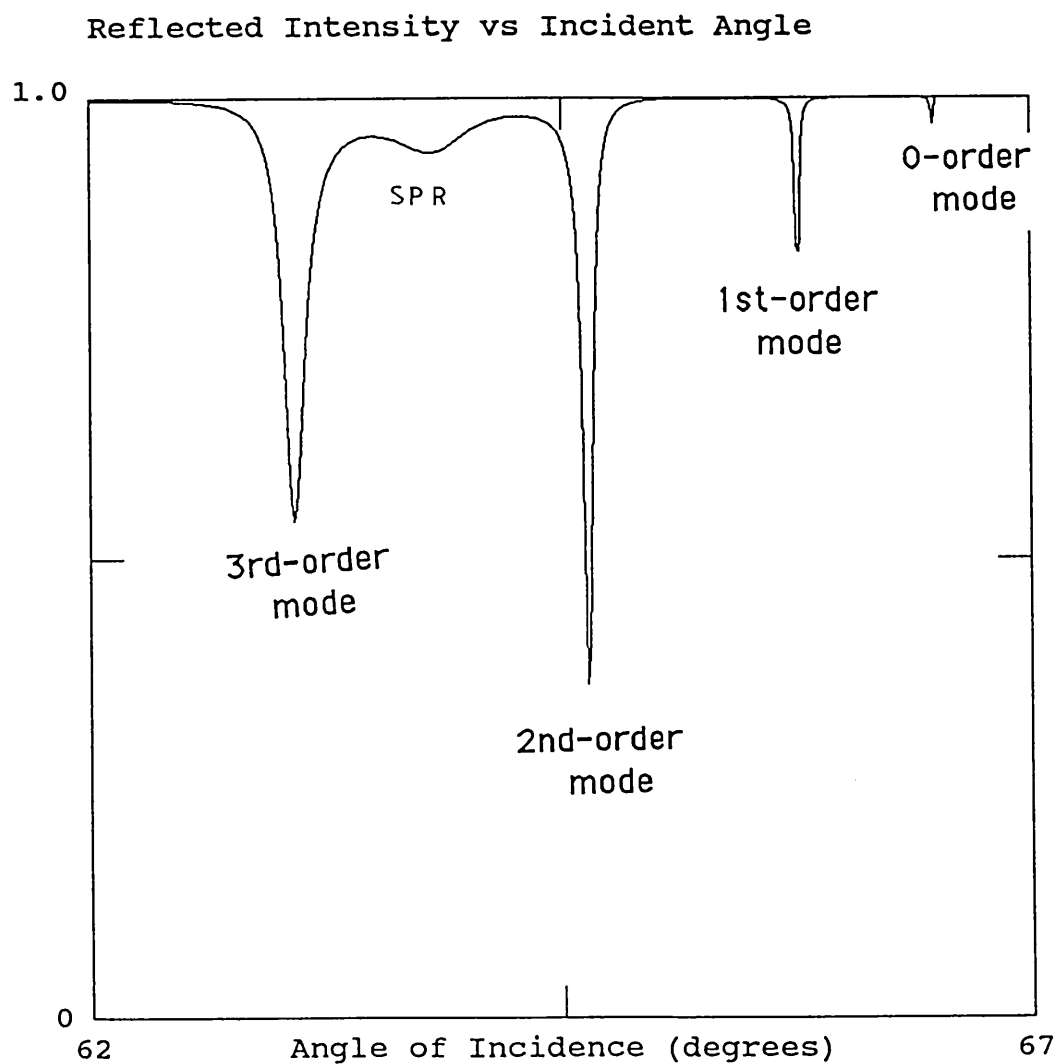
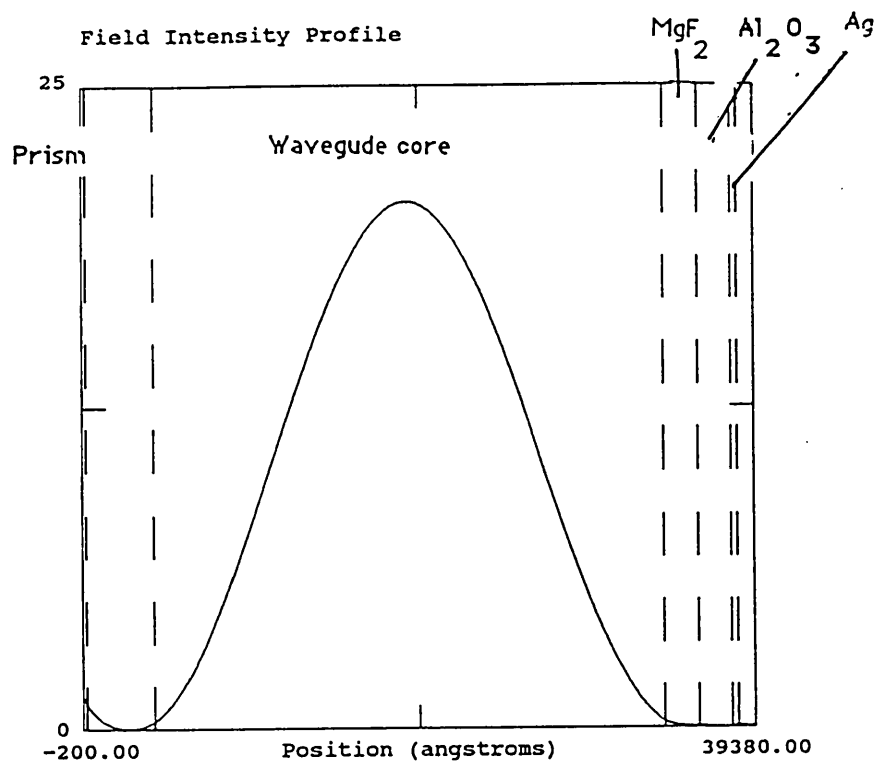
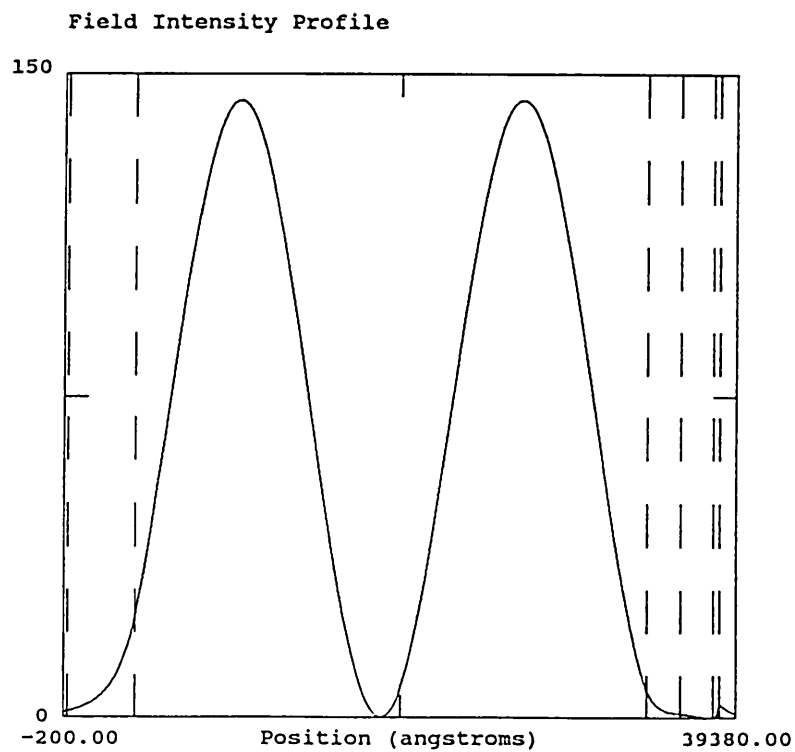


fig.5.4.4. The reflected intensity versus the incident angle corresponding to the structure of fig.5.4.3.

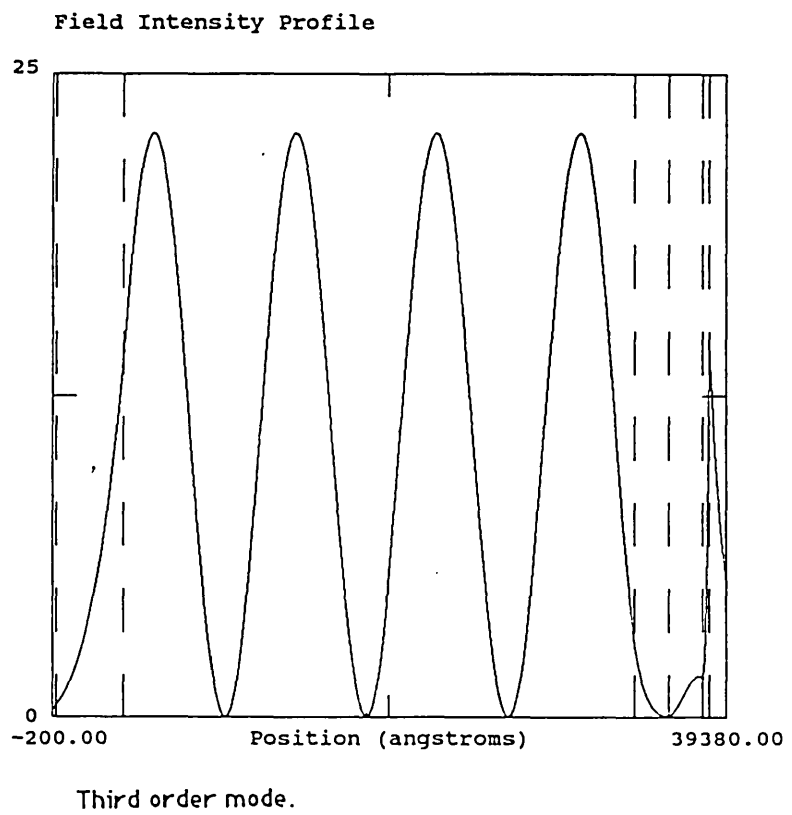
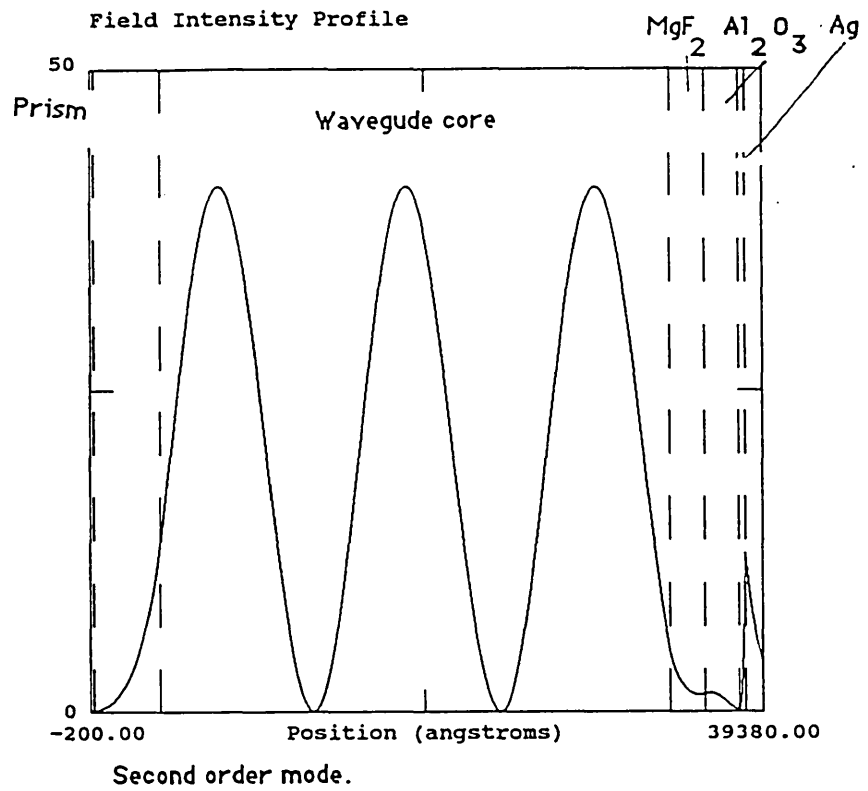
$$\lambda = 0.633 \mu\text{m}$$



Dielectric waveguide 0-order mode.



First order mode.



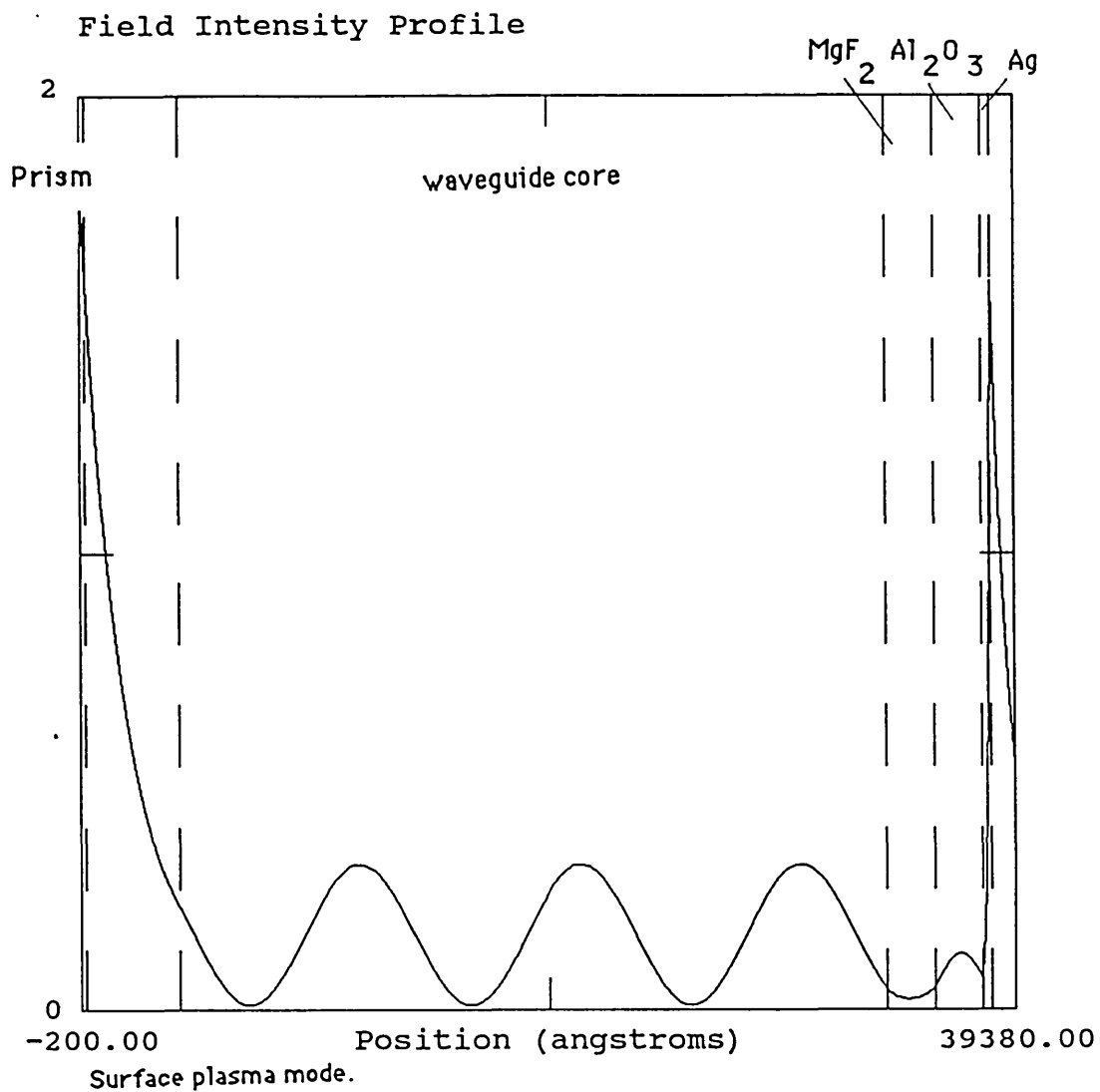


fig.5.4.5. The field intensity profiles corresponding to the waveguide modes and the long range SP mode.

resonance dip at the resonance angle of 63.809° corresponds to the long range surface plasma mode.

As explained earlier in this chapter, the surface plasma mode and the waveguide mode of interest are phase matched provided their corresponding resonance dips coincide. The proximity of the surface plasma resonance and the third order waveguide mode resonance (fig.5.4.4), therefore, implies significant coupling between this waveguide mode and the surface plasma mode.

The curves in fig.5.4.6 indicate that variations in the thickness of the Al_2O_3 layer, results in the surface plasma resonance being shifted closer to the third order mode, suggesting that the surface plasma mode can be tuned to any required waveguide mode by adjusting the Al_2O_3 layer thickness.

The Al_2O_3 layer, having a refractive index of approximately 1.76, also results in the silver film being highly asymmetric. This results in isolation of the surface plasma modes propagating on the two silver-dielectric interfaces, which now resemble surface plasma modes propagating on the single interfaces. Therefore, the long range surface plasma mode in the Kreuwel structure is expected to be more sensitive to changes in the refractive index of the outer sensing cladding compared to the long range surface plasma mode in the structure examined by the author, which is more evenly distributed in the vicinity of the two silver film interfaces. The curves of fig.5.4.7, which show the long range surface plasma fractional power in a region of thickness Δt of the sensing cladding adjacent to the metal film outer surface as a function of Δt for both structures, confirm this. From these curves it is apparent that more than 90 percent of the power associated with the surface plasma mode of the Kreuwel structure is distributed in the sensing medium, compared to just over 60 percent in the case of the structure examined in this chapter.

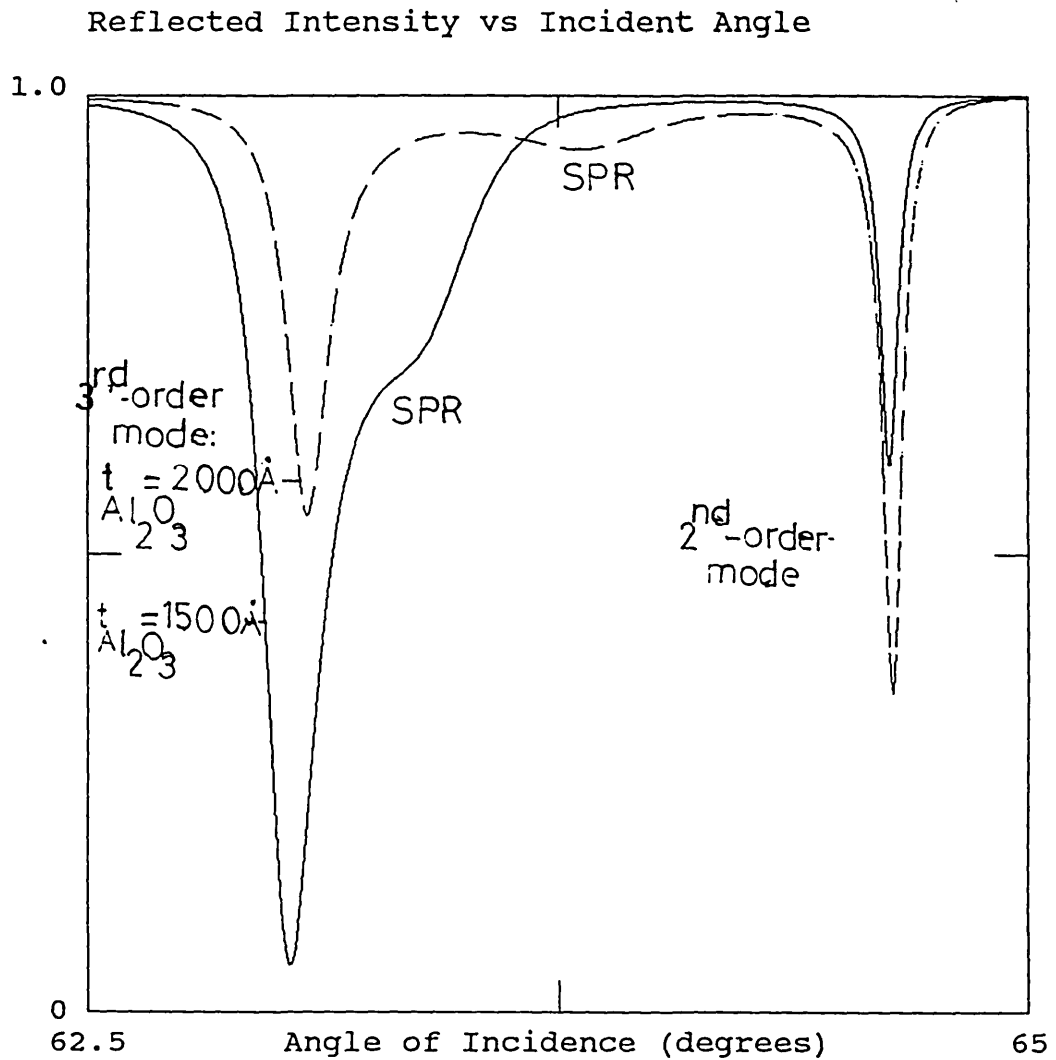


fig.5.4.6. Reflected intensity versus the angle of incidence for Al_2O_3 layers of thickness $0.15 \mu\text{m}$ (—) and $0.2 \mu\text{m}$ (---), showing the significance of this parameter in tuning the SP mode with any of the WG modes.
 $\lambda = 0.633 \mu\text{m}$

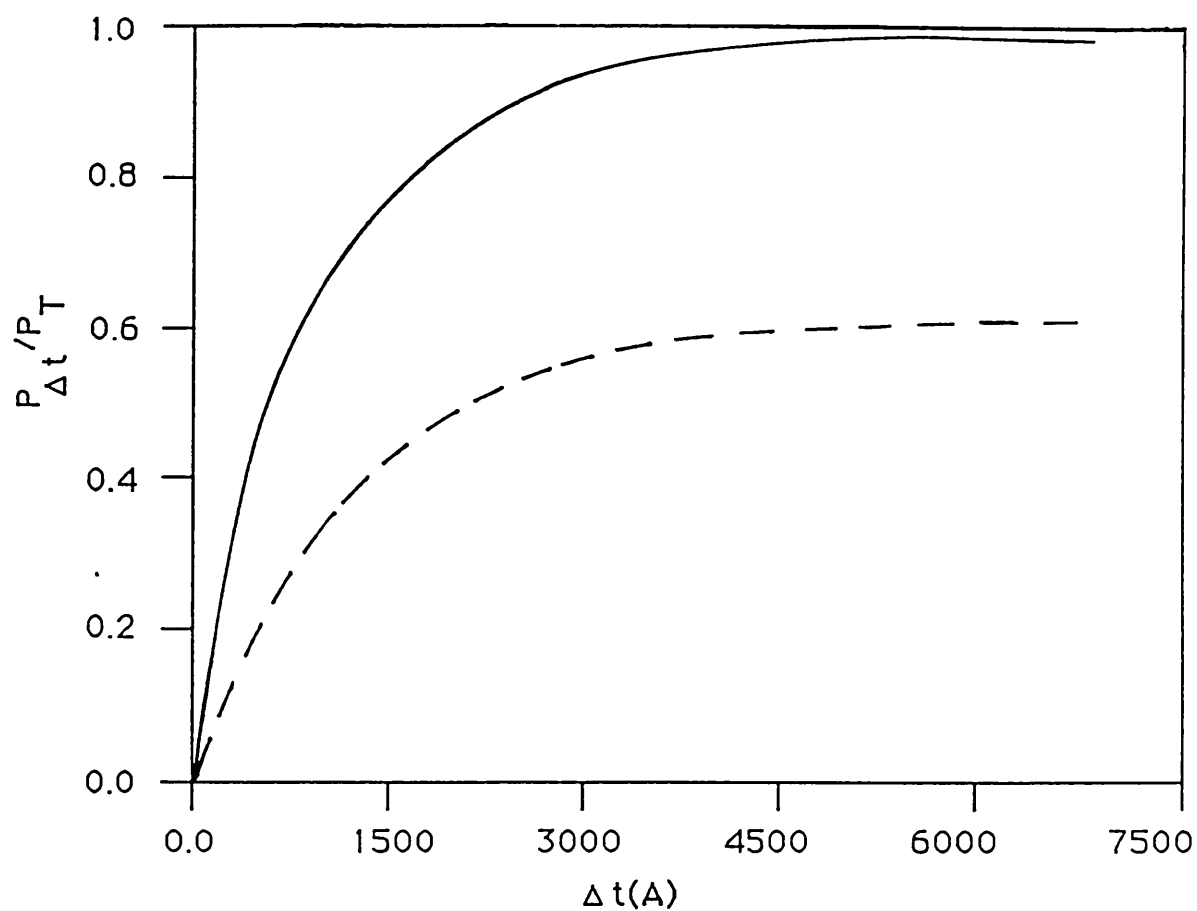


fig.5.4.7.The fractional SP power in a sensing region of thickness Δt corresponding to the Kreuwel structure(—) and the structure examined in this thesis (---).

Analysis, however, shows that the long range surface plasma mode in the Kreuwel structure also has a larger fraction of its power inside the metal, implying that the surface plasma mode, in this case, is associated with a larger loss (larger β_i). The imaginary part of the long range surface plasma mode propagation constant in the Kreuwel structure is computed to be 3 times larger than that of the long range surface plasma wave in the more symmetric structure of fig.5.1.8. A larger β_i , as explained in chapter 4, is expected to result in a broader coupling curve and hence a less sensitive device.

To compare the overall sensitivity performance of the Kreuwel structure with the structure examined in this chapter, a design of the latter, shown in fig.5.4.9, is considered in which the strength of coupling and consequently the coupling depth is identical to that of the Kreuwel structure. From the curves produced by Kreuwel et al (fig.5.4.8), it may be concluded that, at a wavelength of approximately $0.58\mu m$, in order to reduce the attenuation of the waveguide mode, due to coupling into the surface plasma mode, from 80 percent to nearly 0 percent, the refractive index of the sensing cladding is required to be varied by a value in the region of 0.01 (1.45-1.44: note that the curves corresponding to smaller increments are not present in the report by Kreuwel et al, and it is possible that smaller changes in the sensing cladding index can cause such a change in the attenuation), which is comparable to 0.009 (1.460-1.451) in the structure of fig.5.4.9. This suggests that a sensing device based on the Kreuwel structure is not particularly more sensitive. It should however be noted that the structure examined by the author is expected to be generally easier to fabricate, which in view of its sensitivity being comparable to that of the Kreuwel device, may make it a more attractive choice.

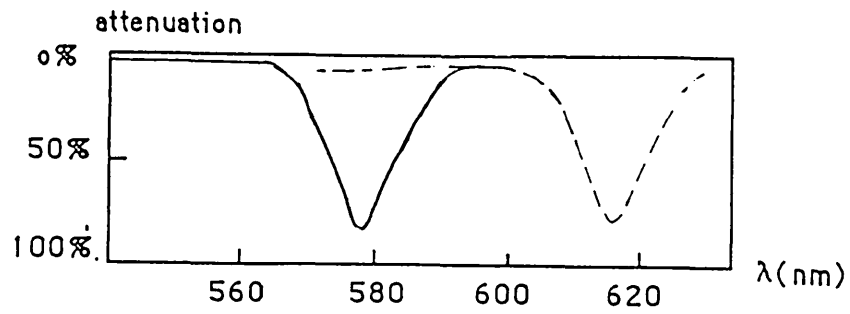


fig.5.4.8. Attenuation of the waveguide mode, due to coupling into the SPW, in the Kreuwel structure (Kreuwel et al 1986).

— : $n_s = 1.44$ (Theoretical curves)
 --- : $n_s = 1.45$

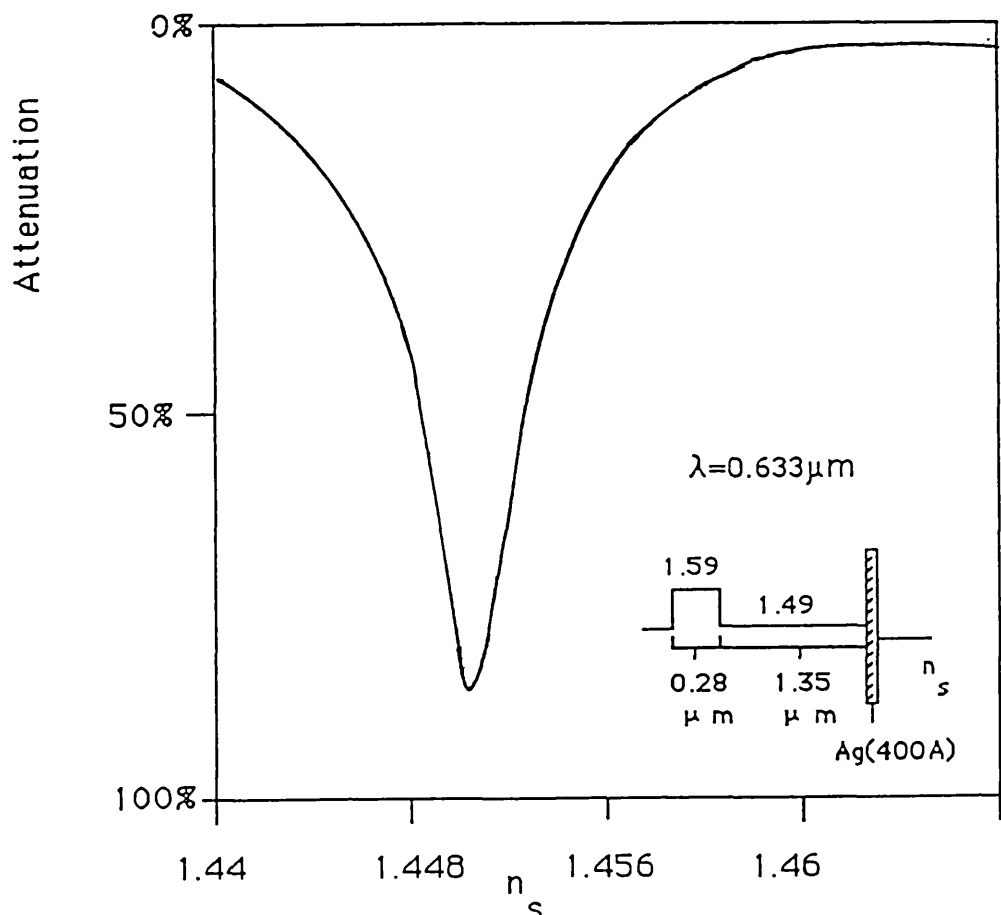


fig.5.4. 9. Attenuation of the waveguide mode due to coupling into the SPW, as a function of n_s , for the structure shown, which is of the type of directional coupler examined in this chapter. The separation thickness is adjusted such that the coupling strength in this structure and that examined by Kruwel are identical.

CHAPTER 6

FIBRE SURFACE PLASMA WAVE DIRECTIONAL COUPLERS AS SENSORS.

In this chapter a number of fibre surface plasma wave directional coupler and the possibility of employing them as a sensing device are studied.

Coupling between the guided mode of an optical fibre and surface plasma waves has been widely used in recent years [Parriaux et al 1981, Grauchmann et al 1983, for example]. The need for in-line fibre polarizers has risen from the fact that the insertion of bulk polarizing elements, such as planar surface plasma wave polarizing geometries [Wright et al 1979], into a fibre line is accompanied by a considerable fibre-planar waveguide coupling loss. A commonly used in-line fibre polarizer configuration based on excitation of surface plasma waves consists of a D-shaped fibre, the cladding of which is partially removed to expose the evanescent field of the fibre mode. A thick metal film is then brought in proximity to and separated from the flat surface of the fibre by a spacing dielectric layer of appropriate refractive index. The cross-section of such a geometry is shown in fig.6.1.1. With respect to the metal film, we can now define TM and TE polarized modes for the fibre, with the TM mode having its electric field perpendicular to the metal film and the TE mode representing the orthogonal polarization. Strong coupling of the fibre TM mode into the surface plasma mode can be achieved by a proper choice of the spacing layer refractive index, which results in the effective index of the fibre TM mode equaling that of the surface plasma mode on the metal-spacing layer interface. The TM mode is now associated with a significantly larger attenuation compared to the TE mode which is unable to excite the strongly attenuated surface plasma wave.

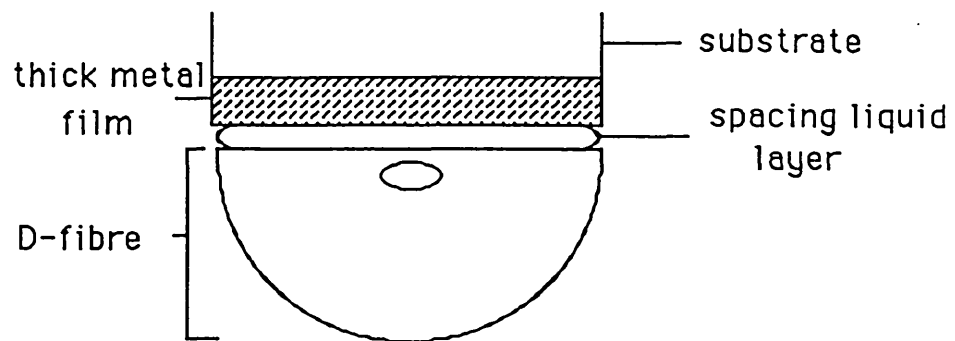


fig.6.1.1.The cross-section of the fibre SPW polarizer.

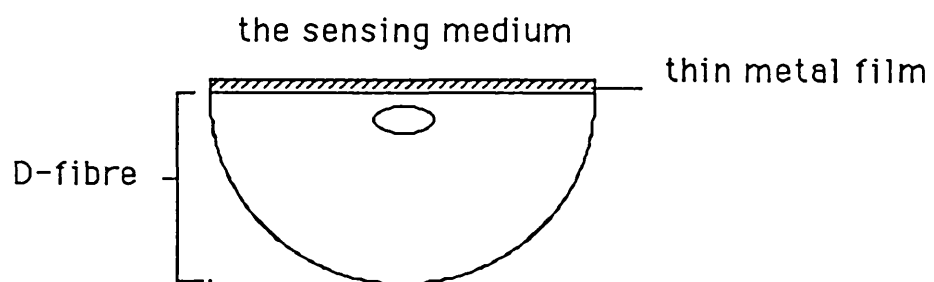


fig.6.1.2.D-fibre SPW coupler as a sensor.

It has also been suggested that any slight mismatch between the fibre TM mode and the surface plasma mode, due to deviation from the optimum refractive index of the spacing layer, can be compensated for by adjusting the spacing layer thickness, which results in modification of the effective indices of the fibre mode by the silver film and that of the surface plasma mode by the fibre core. The attenuation of the fibre TM mode relative to that of the TE mode is referred to as the extinction ratio, which is a quantitative measure of the polarizer performance. Another important parameter is the attenuation of the preferentially transmitted TE mode, referred to as the insertion loss, which is required to be minimized. In-line polarizers with extinction ratios in excess of 45dB and insertion losses less than 1dB have been reported using such a fibre configuration [Grauchmann et al 1983]. An important consideration in fibre polarizers has been the fact that the spacing layer is required to be of a small thickness (a few tenths of a μm), serving the following purposes;

- 1) A thin spacing layer results in tight coupling between the fibre mode and the surface plasma mode, hence causing the coupling to be very broad, eliminating the need for a tight phase matching of the fibre and the surface plasma modes.

- 2) In order to allow for any deviation from the optimum refractive index of the spacing layer to be compensated for by adjusting the thickness of the spacing layer, there is a need for strong perturbation of the interacting modes by each other, which necessitates a thin spacing layer.

In this chapter, application of a similar fibre structure as a sensing device is studied, in which a thin metal film is deposited directly on the flat surface of the fibre. The resulting device, referred to as a D-fibre surface plasma wave coupler in this thesis, is schematically shown in fig.6.1.2. In this structure, the

phase matching between the fibre mode and the surface plasma wave is achieved by adjusting the refractive index of the metal film outer cladding. The resulting device can therefore be employed as a sensor, detecting changes in the refractive index of the outer cladding. An important difference between the sensing fibre surface plasma wave coupler and its polarizing counter part is that in the former the coupling is required to be narrow, or the resulting device will not be of a high sensing performance. This in turn implies that there is a need for accurate control of the phase matching conditions.

The literature on fibre surface plasma wave couplers shows a lack of an extensive theoretical analysis. In this chapter, a somewhat more detailed analysis of the structure is presented, which takes into account the fact that the metal film; due to its very large lateral dimension, can in fact support a near continuum of surface plasma modes, which in this structure, due to the significant difference between the lateral dimension of the fibre core and that of the metal film has a significant impact on the shape of the coupling curve.

Attempts made to observe the corresponding coupling curve predicted by this model have however failed. A number of discrepancies and considerations which may have attributed to these unsuccessful attempts are briefly outlined and their impacts on the coupling analysed.

The analysis performed in this chapter also gives rise to certain implications regarding the fibre polarizers, which are discussed in section 6.1.5.

Finally an alternative fibre structure, based on a coaxial fibre geometry is suggested and qualitatively studied.

6.1 D-fibre surface plasma wave coupler.

The D-fibre surface plasma wave coupler, shown in fig.6.1.2, consists of a D-fibre, studied by Dyott and Schrank [1982], with the surface plasma wave supporting metal film deposited on the flat side of the fibre.

The elliptical core of the fibre can support two guided modes, with their transverse electric fields polarized along the major and the minor axes of the core, referred to as the odd (TE) and even (TM) modes, respectively.

A useful property of the D-fibre is that, when placed on a flat surface or held from one end, the fibre tends to bow with its flat side on the outside. This is due to the difference between the thermal expansion coefficients of the core and the cladding materials, which causes a strong stress to be developed in the fibre during its fabrication[Dyott and Schrank 1982]. This property can now be used to align the fibre in a desired orientation, allowing deposition of the silver film on its flat surface.

The combination of the elliptical core and a large difference between the indices of the core and the cladding of the fibre ($n_{core} = 1.4873$ and $n_{cladding} = 1.4523$) results in a strong birefringence[Dyott and Schrank 1982], ensuring negligible intermodal (TM-TE) coupling.

6.1.1. Approximate analytical model.

In this section coupling between the guided mode of the fibre and the surface plasma mode on the outer surface of the metal film deposited on the flat surface of the fibre is to be analysed using the coupled mode theory described in chapters 3 and 4. This analysis requires a knowledge of the field configurations of the fibre mode and that of the surface plasma mode. However, an exact

analysis of the field configuration of the guided mode of the elliptical core of the fibre is a tedious task. To simplify the analysis, the elliptical core of the fibre is approximated by a slab waveguide of the same refractive indices, as shown in fig.6.1.3(a).

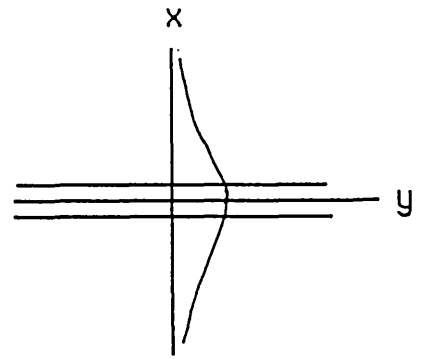
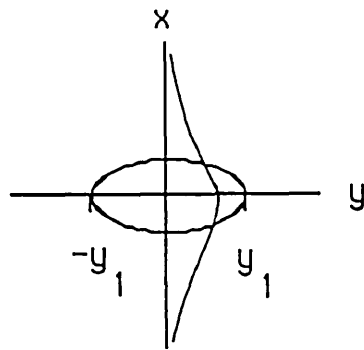
The thickness of the slab waveguide core can now be adjusted such that the propagation constant of the fibre and the slab waveguide TM modes are identical at the wavelength of interest. This implies that the transverse field of the the slab waveguide, now, quite accurately follows that of the fibre mode along the $y=0$ axis.

The field of the slab waveguide mode, however, laterally extends to infinity, while the confinement of the fibre core in the y -direction implies that the field associated with the fibre mode is laterally confined. To allow for this discrepancy the field associated with the slab waveguide is assumed to be terminated at positions corresponding to the lateral edges of the fibre core. In other words, the slab waveguide field is considered to have the following y - dependances;

$$\phi_2(y) = \begin{cases} 1 & \text{for } -y_1 < y < y_1 \text{ (fig.6.1.3(a))} \\ 0 & \text{for } y < -y_1 \text{ and } y > y_1 \end{cases} \quad (6.1.1)$$

The transverse dependance of the fields associated with the surface plasma wave supporting metal film of the D-fibre surface plasma wave coupler is now assumed to be identical to that of the fields associated with the surface plasma wave propagating on a laterally infinite metal film. However, since the metal film is also laterally confined, this time to the region defined by the flat surface

(a)



(b)

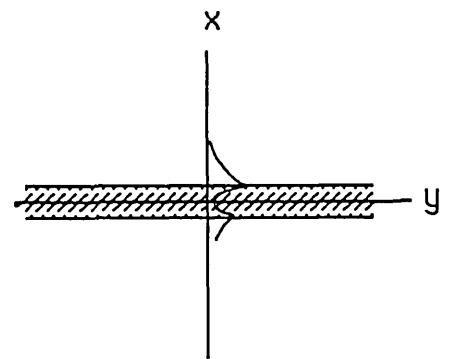
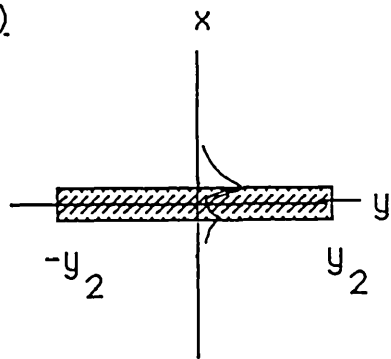


fig.6.1.3. Modelling of the fibre elliptical core by a dielectric slab waveguide(a), and the laterally confined metal film by a laterally infinite metal film(b).

of the fibre, the following y -dependance for the fields associated with the surface plasma wave can be defined.

$$\phi_2(y) = \begin{cases} 1 & \text{for } -y_2 < y < y_2 \\ 0 & \text{for } y < -y_2 \text{ and } y > y_2 \end{cases} \quad (6.1.2)$$

where $2y_2$ defines the lateral dimension of the metal film (fig.6.1.3(b)).

In summary, the fields associated with the fibre mode and the surface plasma wave propagating on the metal film are modelled so as to possess the same transverse dependances as the fields associated with the laterally infinite slab waveguide and metal film, respectively, with the lateral dependances described by equations (6.1.1) and (6.1.2).

Including the above lateral dependances into the expressions describing the coupling coefficients ((4.1.3) and (4.1.6)), results in the following;

$$C_1 = C_1(x) \frac{\int_{-\infty}^{\infty} \psi_1(y) \psi_2(y) dy}{\int_{-\infty}^{\infty} \psi_2^2(y) dy} = C_1(x) \frac{\int_{-y_2}^{y_1} dy}{\int_{-y_2}^{y_1} dy} = C_1(x) \frac{y_1}{y_2} \quad (6.1.3)$$

and

$$C_2 = C_2(x) \frac{\int_{-\infty}^{\infty} \psi_1(y) \psi_2(y) dy}{\int_{-\infty}^{\infty} \psi_1^2(y) dy} = C_2(x) \frac{\int_{-y_1}^{y_1} dy}{\int_{-y_1}^{y_1} dy} = C_2(x) \quad (6.1.4)$$

where $C_1(x)$ and $C_2(x)$, in fact, represent the coupling coefficients corresponding to the laterally infinite waveguide and metal film.

From the above expressions it can be concluded that the difference between the lateral dimension of the fibre core and that of the metal film has resulted in a reduction in the magnitude of C_2 by a factor equal to $\frac{y_1}{y_2}$, hence causing an overall reduction in the strength of coupling.

The power remaining in the fibre core in the structure of fig.6.1.2 can now be computed using expressions (4.1.12) and (4.1.13) of chapter 4.

An important consideration overlooked in the above analysis is that due to its large lateral dimension (approximately $50 \mu m$), the metal film can support a near continuum of surface plasma modes, which can be represented by rays propagating in different directions, parallel to the z-y plane, as shown in fig.6.1.4.

The rays representing the surface plasma modes can now be assumed to propagate in the corresponding directions with identical propagation constants, which are approximately equal to the propagation constant of the surface plasma mode propagating on a laterally infinite metal film of the same thickness. This propagation constant is designated as β_∞ .

The ray propagating in the z-direction represents the fundamental mode with other modes, propagating at angles to the z-direction, representing higher order modes.

To study the implications of coupling into a near continuum of surface plasma modes, let us consider the ray propagating at an angle θ_n to the z-direction (fig.6.1.5).

The ray propagate in this direction with a phase periodicity λ_n , where;

$$\lambda_n = \frac{2\pi}{(\beta_{real})_\infty} \quad (6.1.5)$$

and;

$$(\beta_{real})_\infty = \text{real part of } \beta_\infty$$

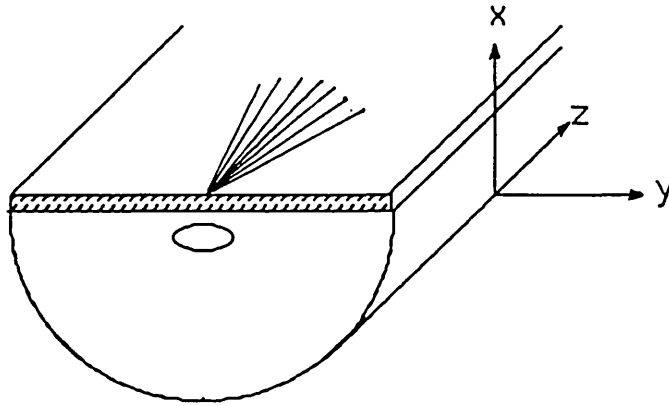


fig.6.1.4. Representing the near continuum of surface plasma modes by rays propagating in different directions.

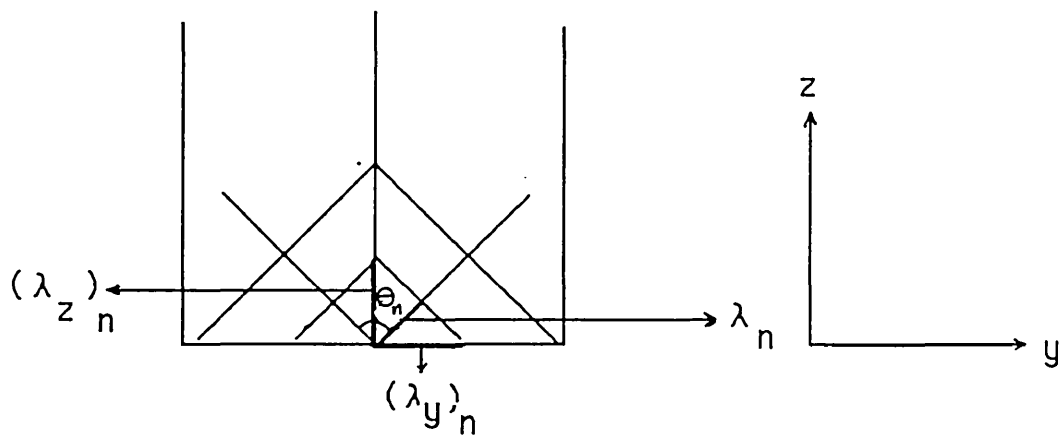


fig.6.1.5. The ray propagating at angle θ_n to the z direction.

Parameters $(\lambda_z)_n$ and $(\lambda_y)_n$ can also be defined, which represent the phase periodicities in the z - and y -directions, respectively, described by the following expressions;

$$(\lambda_z)_n = \frac{\lambda_n}{\cos(\theta_n)} \quad (6.1.6)$$

$$(\lambda_y)_n = \frac{\lambda_n}{\sin(\theta_n)} \quad (6.1.7)$$

The surface plasma modes propagate in the z -direction with a propagation constant represented by $(\beta_z)_n$, the real part of which is described by the following expression;

$$(\beta_{real_z})_n = \frac{2\pi}{(\lambda_z)_n} \quad (6.1.8)$$

Using equations (6.1.5), (6.1.6) and (6.1.8), we can write;

$$(\beta_{real_z})_n = (\beta_{real})_\infty \cos(\theta_n) \quad (6.1.9)$$

This leads to the following definition for the mismatch between the fibre mode and this surface plasma mode, which can be generalized to all surface plasma modes.

$$\Delta\beta_n = (\beta_{real_z})_n - \beta_{fibre} = (\beta_{real})_\infty \cos(\theta_n) - \beta_{fibre} \quad (6.1.10)$$

where β_{fibre} represents the propagation constant of the fibre mode.

For simplicity, the damping associated with all the surface plasma modes is assumed to be represented by the imaginary part of $\beta_\infty(\beta_i)$.

The rays propagating at angle θ_n to the z -direction also give rise to a standing wave in the y -direction, the periodicity of which is represented by $(\lambda_y)_n$. $(\lambda_y)_n$ now determines the lateral dependance of the fields, which can thus be represented by the following relationship;

$$\psi_2(y) = A \exp(j \frac{2\pi}{(\lambda_y)_n} y) + A \exp(-j \frac{2\pi}{(\lambda_y)_n} y) \quad (6.1.11)$$

where $\psi_2(y)$ represents the lateral dependance of the field.

The coupling coefficients, and hence the coupling strength, corresponding to each surface plasma mode can now be evaluated using the general expressions (4.1.3) and (4.1.6).

The field lateral dependances, which vary for different surface plasma modes, cause variations in the strength of coupling into different surface plasma modes. The impact of the variations in the lateral field dependances of the surface plasma modes on the coupling strength can be expressed in the following manner.

From equations (6.1.7) and (6.1.11) it is apparent that for low order surface plasma modes, corresponding to small values of θ_n , $(\lambda_y)_n$ is large and may be considerably larger than the lateral dimensions of the fibre core. This implies that, as shown in fig.6.1.6, the lateral variations corresponding to the low order modes, over the width of the fibre core, are negligible, resembling that of the fundamental surface plasma mode. Therefore, the overlap of the lateral dependances of the fields associated with the fibre mode and the lower order surface plasma modes and hence the strength of coupling into these modes are very nearly identical to that of the fundamental surface plasma mode.

As θ_n is increased, corresponding to higher order modes, $(\lambda_y)_n$ is reduced, resulting in more pronounced field lateral variations, as shown in fig.6.1.7. In the case of the higher order modes for which $(\lambda_y)_n$ is equal to or less than the width of the fibre core, the overlap of the lateral dependances of the fibre and the surface plasma fields decreases in magnitude significantly, causing a considerable reduction in the coupling strength.

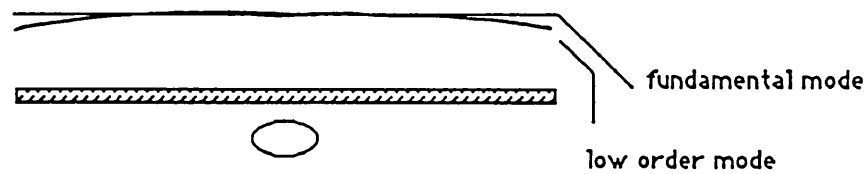


fig.6.1.6.The SPW field lateral dependences corresponding to low order modes are nearly identical to that of the fundamental mode, with a lateral phase periodicity significantly larger than the lateral dimension of the fibre core.

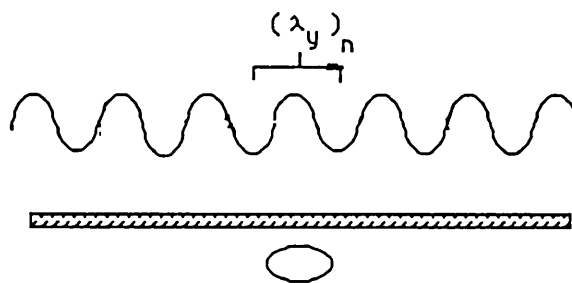


fig.6.1.7.The phase periodicity of lateral dependences of high order SP modes may be comparable to the lateral dimension of the fibre core.

The presence of a near continuum of surface plasma modes implies that, when operating the D-fibre surface plasma wave coupler as a sensor, as the index of the metal film outer cladding, n_S , is varied, at each value of n_S greater than or equal to $(n_S)_{pm}$ ($(n_S)_{pm}$ defines the value of n_S at which the fibre mode is phase matched with the fundamental surface plasma mode) there exists a surface plasma mode which is phase matched with the fibre mode $((\beta_{fundamental})_{real} \cos(\theta_n) = \beta_{fibre})$. This is because for these values of n_S the real part of the propagation constant of the surface plasma fundamental mode is larger than or equal to the propagation constant of the fibre mode. A value of θ_n can hence be defined which satisfies the phase matching condition.

However, increasing n_S is also accompanied by a reduction in the strength of coupling into the surface plasma modes. This is due to the following considerations;

- 1) Increasing n_S results in an increase in β_∞ , which determines the transverse distribution of the fields associated with the surface plasma modes, causing the fields to be more confined to the metal film in the x -direction, resulting in a smaller overlap of the fields in this direction.

- 2) For these values of n_S , phase matching occurs between the fibre mode and higher order surface plasma modes, for which, as explained earlier, due to the more pronounced lateral variations of the fields, the strength of coupling is reduced.

Having evaluated the coupling coefficients, the power remaining in the fibre mode normalized to the power initially launched into the fibre mode, can be computed using equations (4.1.12) and (4.1.13). The curves of fig.6.1.8 show the normalized power versus n_S for the previous model in which the metal film was assumed to support a single surface plasma mode (the fundamental mode)

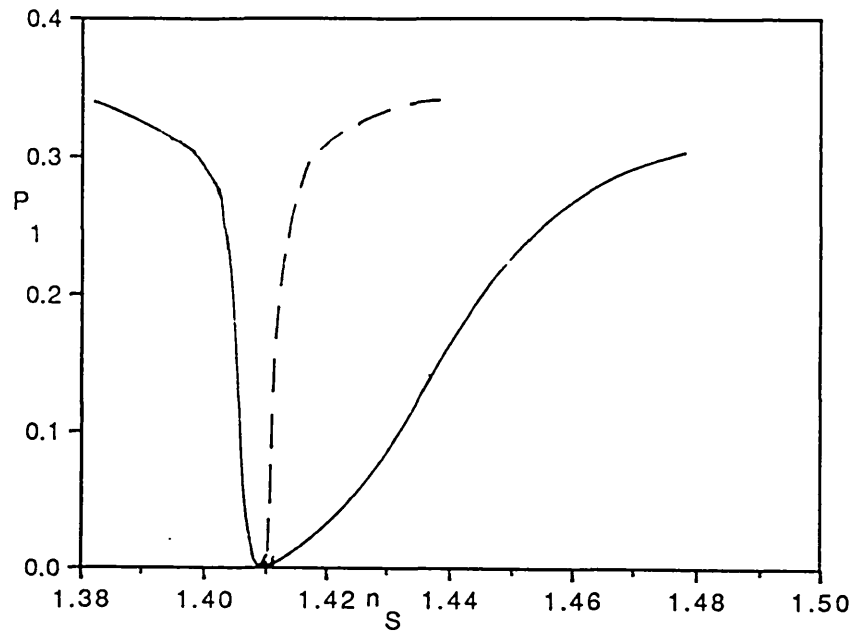


fig.6.1.8. The coupling curves corresponding to the D-fibre SPW coupler, when coupling into a continuum of SP-modes is taken into account(—), and when the the metal film is considered to support a single (fundamental) mode(— →).

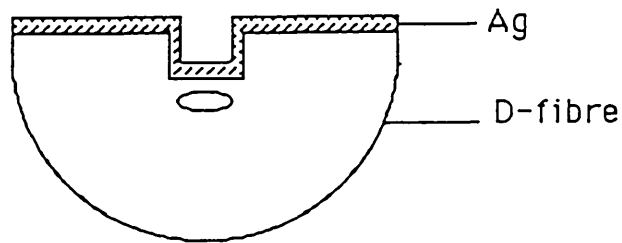


fig.6.1.9 .The cross-section of an alternative D-fibre SPW directional coupler, in which the discontinuity of the metal film results in lateral confinement of the metal film deposited on the surface closest to the fibre core

together with the coupling curve corresponding to the case where coupling into a near continuum of surface plasma modes is considered. These curves clearly indicate that taking into account the effect of coupling into a near continuum of modes has resulted in a significantly broader coupling curve.

As far as sensing applications of such a device are concerned, the significant increase in the broadness of the coupling curve degrades the sensitivity of the device.

One technique which may be envisaged to sharpen the coupling curve and hence improve the sensing performance of the device would be to devise a fibre structure shown in fig.6.1.9, in which the flat surface is discontinuous. In such a geometry, the transverse electric field of the fibre TM-mode is parallel to the metal film deposited on the vertical walls of the surface of the fibre. This implies that surface plasma modes cannot be excited on these regions of the metal film by the fibre TM-mode, resulting in the metal film deposited on the flat surface closest to the fibre core, in effect, being laterally confined to the width of this region, and hence unable to support a near continuum of surface plasma modes.

6.1.2.Design.

The following design of the D-fibre surface plasma wave coupler is based on its monochromatic mode of operation at a wavelength of $0.633\mu m$. The refractive indices of the core and the cladding of the D-fibre and the propagation constant of its guided modes are supplied by the manufacturers; $n_{core} = 1.4873$, $n_{clad} = 1.4523$ and $(\frac{\beta}{k_0})_{TM-mode} \simeq 1.4621$. The thickness of the equivalent slab waveguide, is then derived by adjusting its value such that the waveguide mode effective index equals that of the fibre TM-mode.

Fig.6.1.1 Q (page 170) represents the effective indices of the equivalent waveguide and the long-range surface plasma modes as a function of n_s and for different metal film thicknesses. It is clear that for silver films of thickness larger than $350\text{\AA}$, the phase matching index tends to be quite close to, if not less than, 1.40, which is the lowest refractive index attainable in the experiments performed.

Also, as discussed by Sennet and Scott [1950], depending on parameters such as the rate of deposition, silver films of less than a critical thickness tend to be discontinuous, consisting of isolated islands of silver. Even for thicknesses larger than the critical thickness, despite the fact that aggregates forming the film start to merge, there are still very distinct gaps present on the surface of silver films [Sennet and Scott]. The most immediate implication of a discontinuous film is that its optical properties are expected to differ significantly from the values deduced from the literature, which correspond to continuous and uniform films. This could result in significant inaccuracies in our theoretical analysis.

From the data produced by Sennet and Scott it can be concluded that for a deposition rate of approximately $10\text{\AA}$ per second, which is the rate employed by the author, the critical thickness turns out to be just over $100\text{\AA}$. However, they suggest that silver films are required to be as thick as $250\text{\AA}$ before their surface is free of any appreciable roughness.

The above considerations lead to the conclusion that the silver film thickness is required to lie in a region of 250 to $350\text{\AA}$.

The interaction length, defined by the length over which the fibre is covered with the silver film, and the separation between the fibre core and the silver film are very closely linked. The combination of these two parameters determines the depth and the sharpness of the coupling curve (P_1 versus n_s curve).

Analysis shows that a separation thickness of $2\text{ }\mu\text{m}$ with an interaction length of 1 cm results in the minimum value of P_1 being nearly zero, corresponding to a considerable contrast between the maximum and minimum value of P_1 .

6.1.3.Fabrication.

The first step in fabrication of the D-fibre surface plasma wave coupler is to adjust the thickness of the gap between the core and the flat surface of the fibre to a required value. This is accomplished by partially removing the fibre cladding using a solution containing hydrofluoric acid (HF), which dissolves the cladding material. This process is referred to as 'etching', and is performed at a constant temperature of 30°C .

The fibre is thoroughly cleaned prior to the etching process. The cleaning process involves; wiping the fibre using a lens tissue wetted in acetone (this is to remove large contaminations, such as dust particles), washing the fibre in an ultra-sonic bath using a high quality detergent 'micro soap' diluted in distilled water, followed by distilled water, and Iso-Propyl Alcohol (IPA) (these steps are to remove smaller contaminations). Finally the fibre is cleaned in an IPA reflux, which removes small organic contaminations.

To calibrate the etching process, the thickness of the gap between the fibre core and its flat surface is measured by observing the cross-section of the etched fibre for different etching durations, using a Scanning Electron Microscope. The cross-section of an etched fibre is shown in fig.6.1.11.

The flat surface of the fibre is observed to be slightly deformed and curved in the region immediately above the fibre core. This is due to the fact that the core is surrounded by a depressed cladding which is etched at a faster rate than the outer cladding. This implies that the metal film deposited on the fibre can

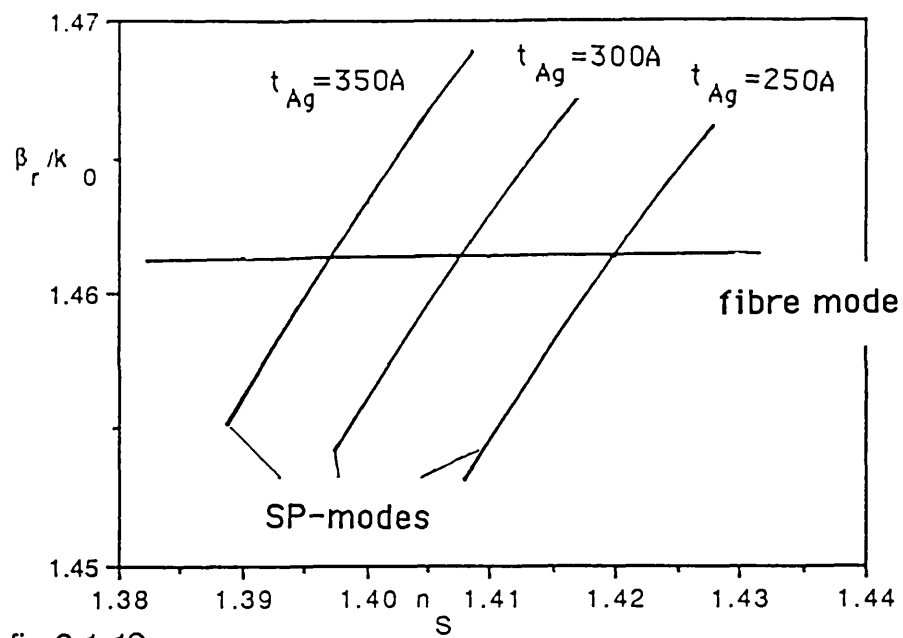


fig.6.1.10.

The effective indices of the fundamental SP-mode (for different metal film thicknesses) and the fibre TM-mode as a function of n_s .

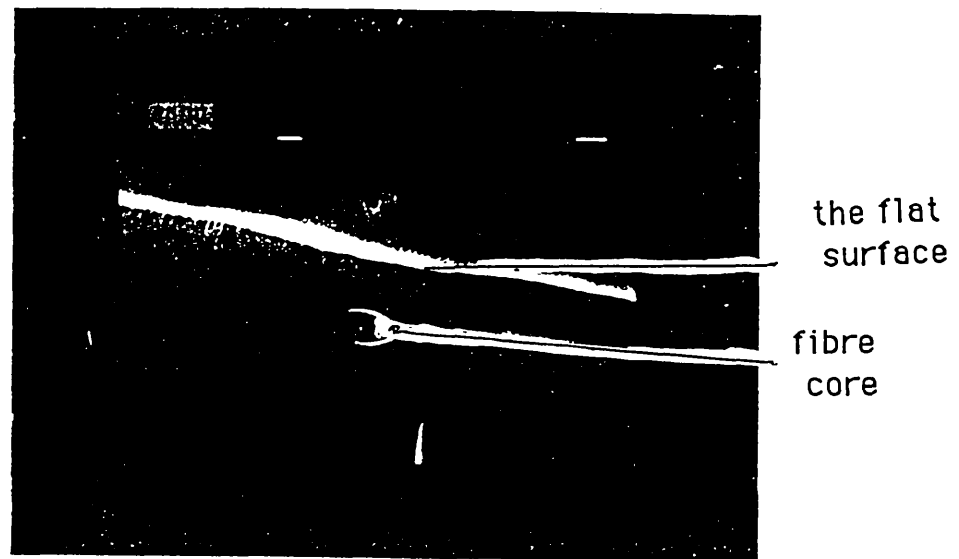


fig.6.1.11. The SEM micrograph of the cross-section of an etched D-fibre.

no longer be considered as a perfectly flat slab. This effect is however neglected, considering that the curvature on the etched fibre is shallow.

Following the etching process, the silver film is thermally deposited under vacuum condition on the flat surface of the etched fibre. To allow deposition of silver on the flat surface of the fibre, the fibre is laid on a curved metallic substrate. The natural curvature of the fibre now follows that of the substrate, with the fibre oriented with its flat surface on the outside and exposed to the evaporated silver.

Thickness calibration of a crystal monitor for the silver film deposited simultaneously on a flat glass slide, placed adjacent to the fibre and at the same distance from the evaporation source, is used to determine the thickness of the silver film on the fibre.

6.1.4. Experimental observations.

In this section coupling between the fibre TM-mode and the long-range surface plasma mode in the D-fibre surface plasma wave coupler is experimentally investigated. The device is operated in the monochromatic mode. A matching liquid is placed around the interaction region of the fibre. To phase match the waveguide mode and the surface plasma wave propagating on the silver film outer interface, the matching liquid, the refractive index of which is temperature sensitive, is heated. The experimental arrangement is shown in fig.6.1.12.

The natural orientation of the fibre is used to align the input end of the fibre (the end in which the laser light is launched) such that the minor axis of the fibre core is parallel to the electric field component of the linearly polarized

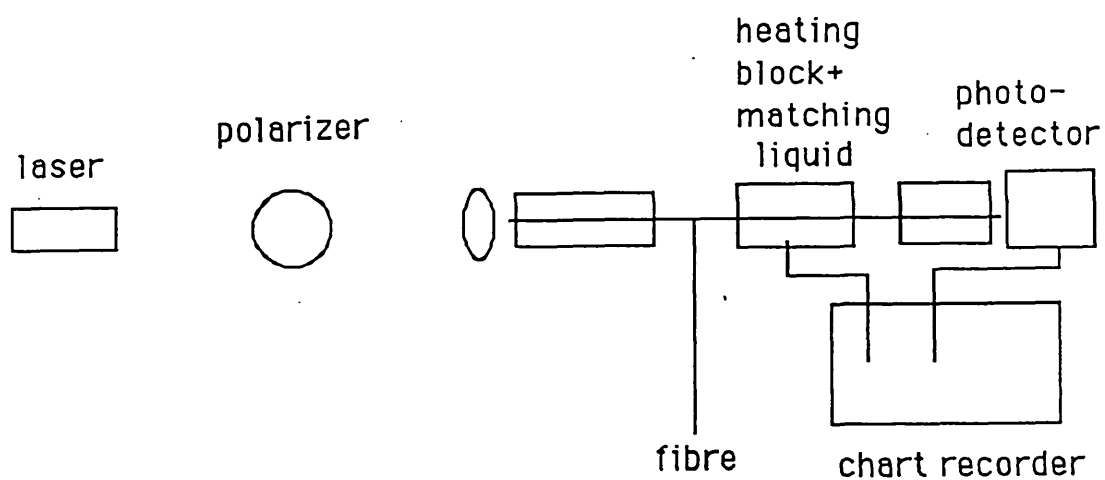


fig.6.1.12. The experimental arrangement.

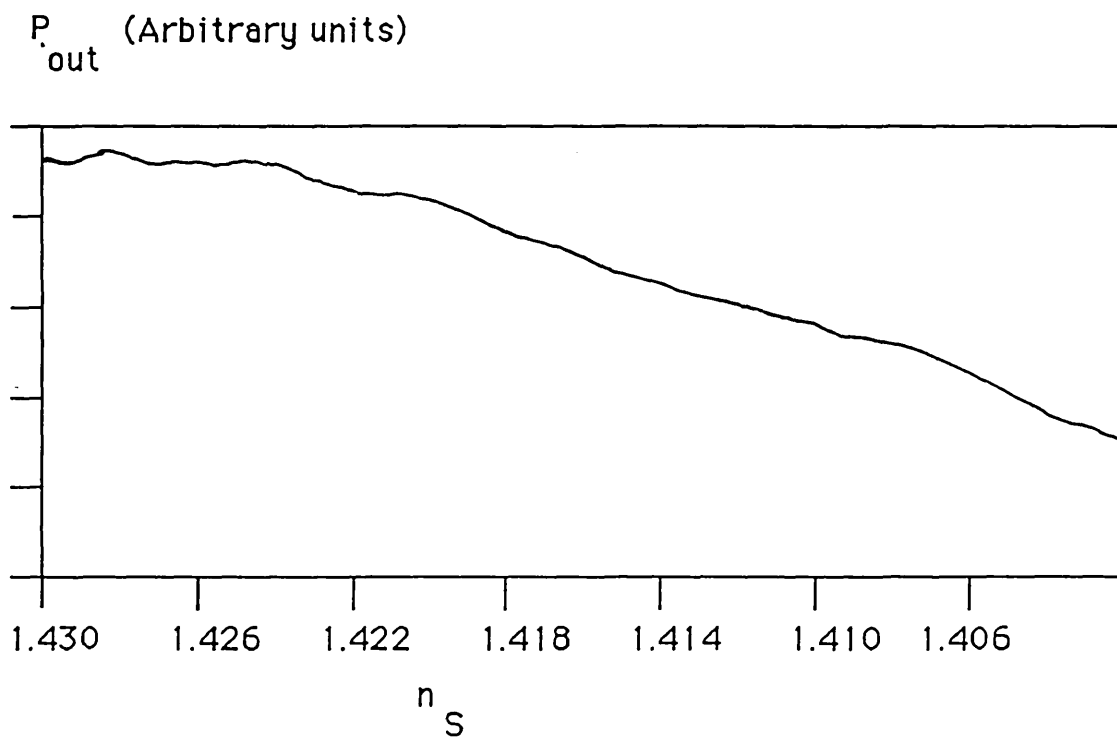


fig.6.1.13. The power remaining in the D-fibre core of the D-fibre SPW coupler, measured as a function of n_s . $\lambda=0.633\mu\text{m}$

input light. This ensures sole excitation of the fibre TM mode. Microscopic examination of the fibre end, while placed in position, using an Olympus travelling microscope reveals that the above alignment technique is quite accurate.

The interaction region of the fibre is surrounded by the matching liquid by passing it through a narrow groove cut in a copper block, which is then filled with the matching liquid. The copper block is placed on top of a heating element, used to heat the matching liquid. The temperature of the matching liquid is measured using a thermocouple arrangement, and is converted into changes in the refractive index.

Mode strip oils (refractive index of roughly 1.46) are placed near both ends of the fibre to shed any light possibly propagating in the fibre cladding. The photo-detector and the thermocouple outputs are connected to the $\checkmark$ - and $\times$ -inputs of the chart recorder.

The device is fabricated to the design specifications of section 6.1.2, ie. with a $2\mu\text{m}$ thick separation between the core and the flat surface of the fibre, and a silver film of thickness of nearly $300\text{\AA}$ deposited over 1cm of the etched region of the fibre.

The measured intensity of the light emerging from the output end of the fibre, corresponding to the TM-mode of the fibre, versus the refractive index of the matching liquid is shown in fig.6.1.13.

Despite covering a range of indices between 1.4 and 1.43, which is expected to cover the coupling range, only a gradual increase in intensity of the light emerging out of the fibre is observed.

6.1.5. Discussions and conclusions.

The lack of the predicted coupling curve in the experimental observations of the preceding section may be due to the presence of discrepancies between the D-fibre surface plasma wave coupler and the assumed theoretical model.

These discrepancies can be possibly attributed to the considerations mentioned and discussed in the following subsections.

1. Uncertainties in the indices of the fibre core and cladding.

It is very likely that the theoretical model used to compute the propagation constants of the fibre modes, which assumes the fibre core to be an ellipse with a step index profile, is far from accurate. It is in fact known that the core index is depressed in the middle and it is possible that it has a graded index profile. To allow for these uncertainties the refractive index assumed for the fibre core in the coupling analysis performed is adjusted.

Analysis show that an uncertainty of nearly 1 percent in the above parameter can result in a shift of 0.012 in the matching value of n_S , corresponding to the fibre mode and the fundamental surface plasma mode being phase matched. Such a discrepancy would result in the above value of n_S being 1.396, accounting for the lack of the leading edge of the coupling curve in the experimental index range.

2. Uncertainties in the assumed value of the silver film permittivity.

As discussed in chapter 5, the literature on optical properties of silver films reveals a very wide range of values ascribed to the silver permittivity. Therefore,

an independent measurement of the permittivity of the deposited silver film is thought to be a prudent step.

As described by Chen and Chen[1981], excitation of surface plasma waves on the silver film using a Kretschmann configuration, described in chapter 2, can be used to measure the optical properties and thickness of the silver film. In this technique, these properties can be deduced by fitting a theoretical surface plasma resonance curve to the measured curve. Here a similar technique is used.

A computer program is written, which evaluates three main characteristics of the surface plasma resonance curve of the Kretschmann geometry, namely the position, depth and the width of the resonance. These characteristics are computed as a function of the real and imaginary parts of the silver film permittivity (ϵ_r and ϵ_i). Fig.6.1.14 shows a set of three curves for values of ϵ_r and ϵ_i , which correspond to the measured depth, width and position of resonance.

Assumed thickness of the silver film, based on Talystep measurements, is then adjusted such that the three curves intersect at the same point. The values of ϵ_r and ϵ_i and the silver film thickness corresponding to this point correspond to a theoretical surface plasma resonance which very closely fit the measured curve. This is shown in fig.6.1.15. The silver permittivity measured using this technique turns out to be $-16.5+j0.9$, which lies in the range of values given in the literature, with the corresponding film thickness being $320\text{\AA}$ (instead of $300\text{\AA}$ measured using Talystep).

The coupling curve of a D-fibre surface plasma wave coupler with a separation thickness of $2.0\mu m$ and a silver film of $320\text{\AA}$ in thickness with a permittivity of $-16.5+j0.9$ and an interaction length of 1cm is shown in fig.6.1.16. From these curves it can be concluded that the measured thickness and permittivity of the silver film cause the matching value of n_S to shift from 1.408 to 1.404. Such a

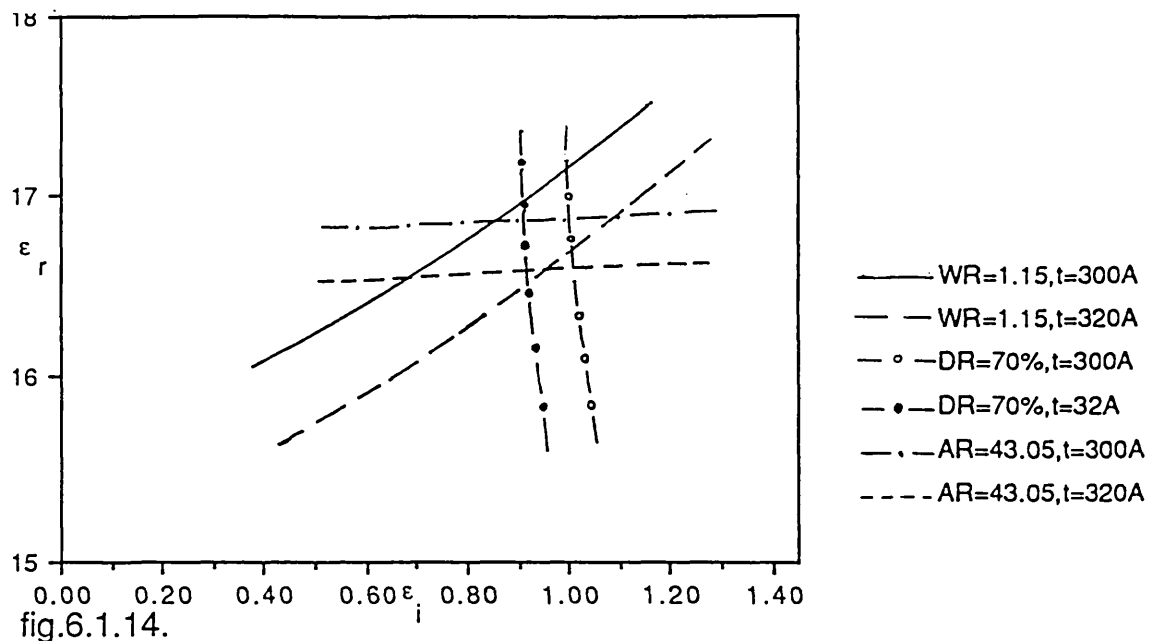


fig.6.1.14.

Computed values of ϵ_r versus ϵ_i corresponding to the measured values of the depth of resonance(DR), width of resonance(WR) and the angle of resonance(AR), for the metal film thicknesses(t) of 300 and 320A (wavelength=0.633 μ m).

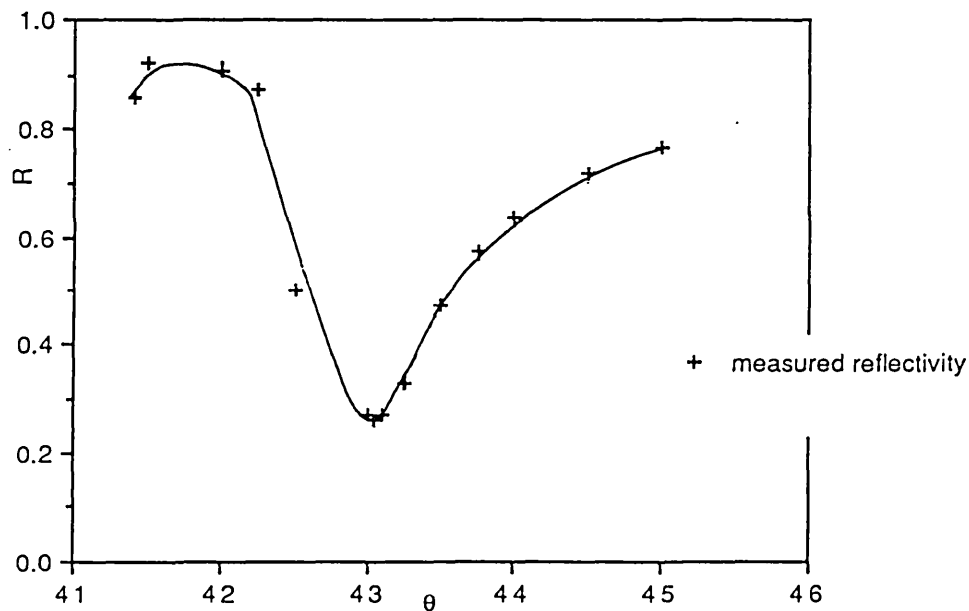


fig.6.1.15.

The theoretical SP resonance curve based on values of the silver film permittivity and thickness derived from fig.6.1.14 closely fit the experimental curve(+).

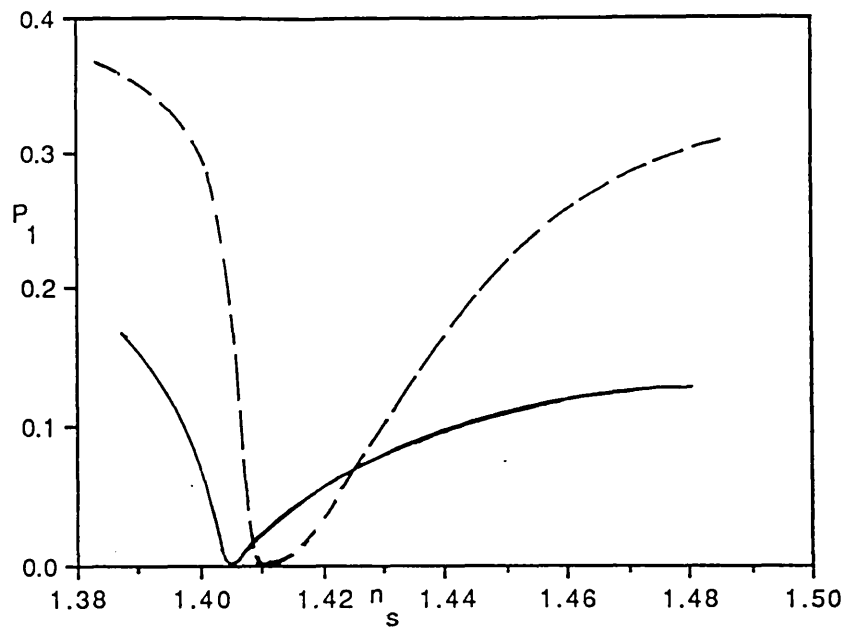


fig.6.1.16. The coupling curves corresponding to the metal permittivity of $-16.5+j0.9$ and thickness of 320A (—) and that corresponding to $-16.0+j0.53$ and 300A(---), ie the previously assumed values (wavelength=0.633 μ m).

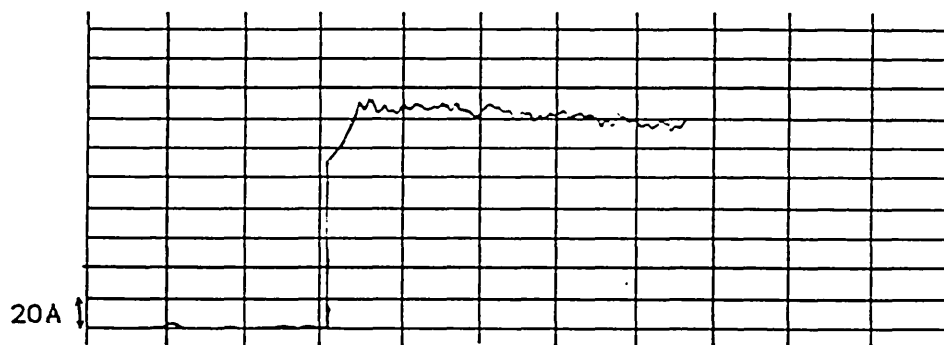


fig.6.1.17. The silver film profile, showing a surface roughness of nearly 10A peak to peak.

small shift in the value of $(n_s)_{pm}$ on its own does not however account for the lack of the predicted coupling curve in the experimental observations.

3.Surface roughness of the silver film.

Examination of the surface profile of a silver film deposited on a glass substrate using Talystep reveals the presence of surface roughness of more than $10\text{\AA}$ (peak to peak) on the top surface of the silver film. This is shown in fig.6.1.17.

However, Talystep in the mode of operation used in these measurements is not particularly sensitive to longitudinally fast varying variations on the surface of the film. Therefore, a more pronounced undetected surface roughness may be present. Moreover it is possible that due to slight misalignment of the fibre during the deposition process, the deposition of the silver on the fibre occurs at an oblique incidence. This is expected to result in a more pronounced surface roughness.

The influence of surface roughness can be analysed by modelling the surface roughness as a thin surface layer, referred to as the roughness layer, comprising of metallic regions and the voids formed as a result of the rough surface.

The permittivity of the roughness layer can now be calculated using the Maxwell-Garnet theory[Kovacs and Scott 1977]. According to the Maxwell-Garnet theory the effective permittivity of the roughness layer is a weighted average between the silver permittivity and that of the voids, and is described by the following equation;

$$\epsilon_e = \frac{\epsilon_D[\epsilon_m(1 + 2q) + 2\epsilon_D(1 - q)]}{[\epsilon_m(1 - q) + \epsilon_D(2 + q)]}$$

where ϵ_e =the effective permittivity, ϵ_D =permittivity of the dielectric constituent, ϵ_m =permittivity of the metallic constituent and q =the volume fraction of the metal constituent.

The curve shown in fig.6.1.18 represent the coupling curve corresponding to a D-fibre surface plasma wave coupler with a roughness layer of $10\text{\AA}$ in thickness. The q value is taken from a report by Kovacs and Scott[1977].

From the above curve, it is concluded that the surface roughness of this magnitude results in the phase matching index to be approximately 1.392, which lies outside the experimental range of indices, accounting for the lack of the coupling dip in the experimental observations.

4. Formation of silver sulphide on the silver film.

Formation of silver sulphide on silver films, as explained in chapter 4, is generally expected to occur at a very slow rate. The process of silver sulphide formation may however be speeded up as a result of raising the temperature of the surroundings, as is the case in the experiments performed.

Formation of a layer of silver sulphide, as explained in chapter 4, may have a substantial impact on the coupling of the fibre mode into the surface plasma mode.

The formation of a silver sulphide layer can be detected by measuring the reflectivity of the silver film which is reduced as a result of the silver sulphide formation. The reflectivity measurements on a number of identical, thick and opaque silver films, which are heated to different temperatures for different

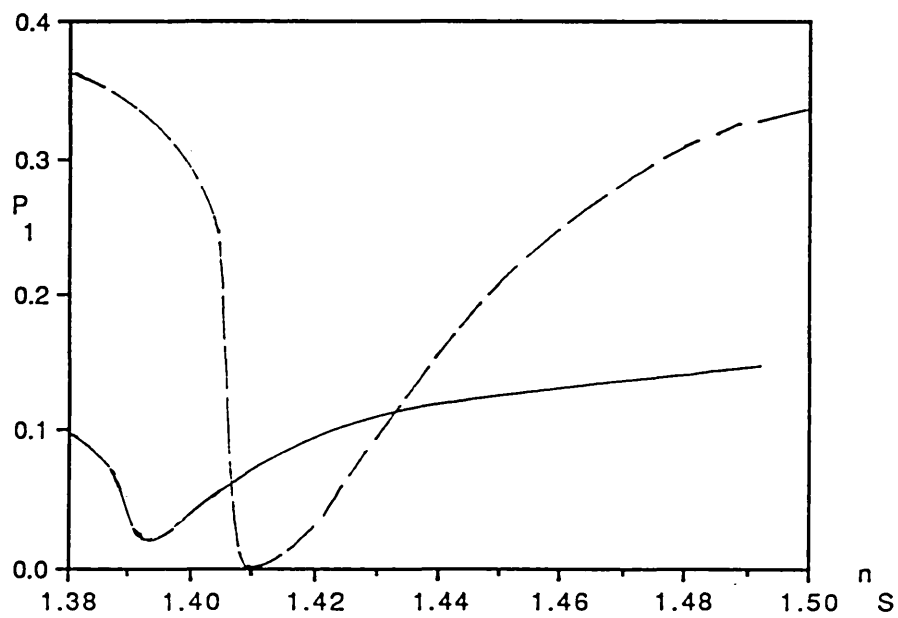


fig.6.1.18.

The coupling curve, assuming a roughness layer of thickness 10Å on the metal film(—), with $q=0.9$ (Kovacs and Scott[1977]), and that corresponding to the initially assumed parameters(---).

$\lambda=0.633\mu\text{m}$

lengths of time, are performed using a spectrometer. The corresponding reflectivities as a function of wavelength are then compared to that of an untreated sample which is exposed to atmosphere for a very short length of time.

The reflectivity measurements are shown in fig.6.1.19. It is clear from these curves that the sample has to be heated to a very high temperature (150 degrees centigrade) for a long time (6 hours) before any appreciable reduction in its reflectivity is observed. The reflectivity of samples heated to 60 degrees centigrade over an hour (the temperature to which the surrounding of the D-fibre was heated in the experiments of section 6.1.4), are realised to be only slightly worse than the fresh film, and are more reflective than samples exposed to atmosphere for 24 hours. However, according to Burge et al [1969], a silver sulphide layer of approximately $6\text{\AA}$ in thickness is expected to be formed on a sample exposed to atmosphere for 24 hours. Heating the silver films surroundings to 60 degrees centigrade is therefore expected to have caused formation of a silver sulphide layer of thickness less than $6\text{\AA}$.

The coupling curve corresponding to the D-fibre surface plasma wave coupler, with a $6\text{\AA}$ thick layer of silver sulphide formed on the silver film is shown in fig.6.1.20. The formation of the silver sulphide layer has caused the matching value of n_S to be shifted from 1.404 to 1.401. This shift on its own can not however explain absence of the leading edge of the coupling curve in the experimental observations.

Summary.

From the above discussions it may be concluded that a combination of the above uncertainties can cause the value of n_S at which the fibre mode and the fundamental surface plasma mode are phase matched to shift to a value less than 1.40. Under these circumstances, the leading edge of the coupling

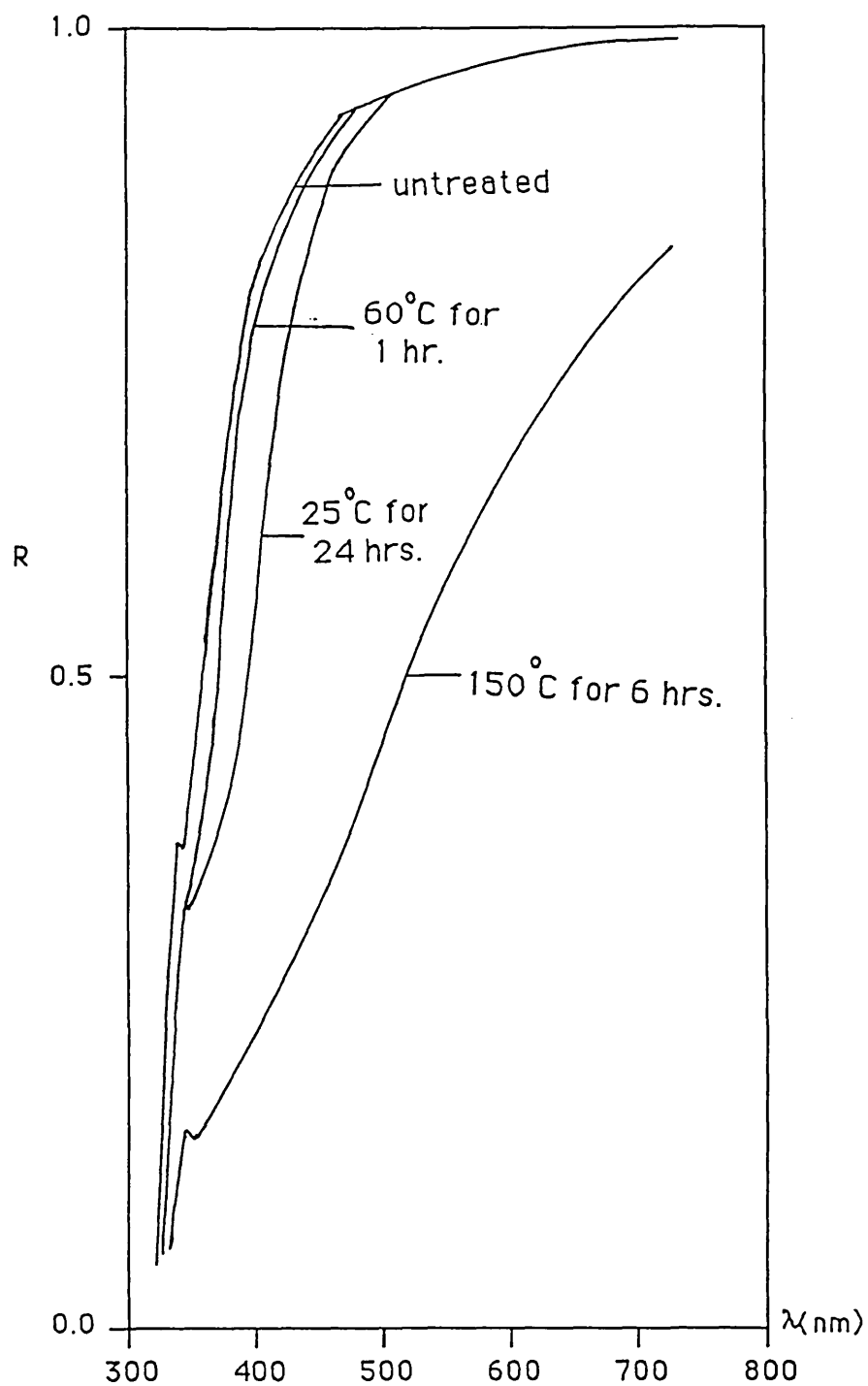


fig.6.1.19. Reflectivity from the surface of silver films versus wavelength measured for samples heated to different temperatures for different durations.

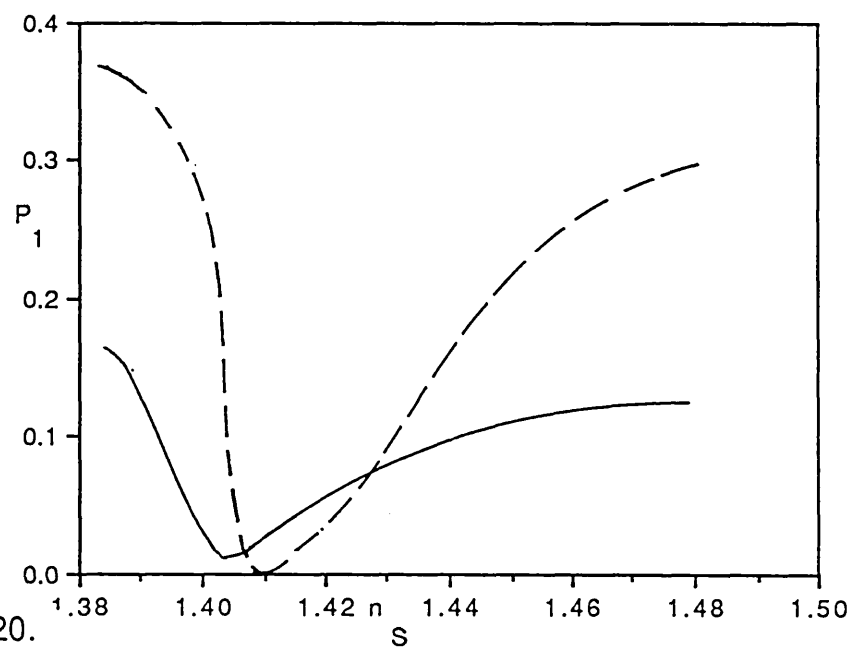


fig.6.1.20.

The coupling curve based on the assumption that a silver sulphide layer of thickness 6A is formed on the surface of the metal film(—) and that of the initially assumed structure(— —).

curve would be absent from the experimental curves, implying a mere gradual decrease in the intensity of light emerging out of the fibre as n_S is decreased. They also result in a reduction in the depth of coupling, causing the decrease in the output light intensity to appear more gradual. Moreover the discrepancies due to the roughness of the silver film are based on the measured roughness of the silver film deposited on a glass slide. The surface roughness of the silver film deposited on the etched fibre may, however, be more pronounced, due to possible roughness of the etched fibre, resulting in larger discrepancies.

6.1.6.A brief discussion on in-line fibre polarizers.

Broadening of the coupling curve of the D-fibre surface plasma wave coupler as a result of coupling into a continuum of surface plasma modes suggests strong attenuation of the fibre TM-mode compared to the TE-mode over a wide range of values of the refractive index of the metal outer cladding, n_S . Analysis of section 6.1.2 shows that for a device with a separation thickness of $1.3\mu m$ an extinction ratio of 50dB per centimetre is achieved over a range of values of n_S between 1.405 and 1.450.

The in-line fibre polarizers studied in the literature are generally of significantly smaller separation thicknesses. This would imply an even broader coupling curve. The broadness of the coupling curve suggests that a very precise phase matching between the fibre mode and the surface plasma modes is not an essential requirement in order to obtain a large extinction ratio. Research on a number of polarizers described in the literature, in which relatively large extinction ratios have been obtained in the absence of a precise tuning mechanism, justifies this argument. For instance, Dyott et al[1987] have fabricated polarizers with extinction ratios of nearly 20 dB per centimeter, by simply

coating the flat surface of a D-fibre with a thick layer of indium. They have attributed the large extinction ratio to phase matching attained by formation of a thin layer of indium oxide between the fibre and the indium layer, which may be considered as an unlikely cause of a precise tuning, particularly in view of the authors mentioning that this assumption is not based on a knowledge of the optical properties of indium oxide.

6.2.Coaxial fibre surface plasma wave coupler.

In this section an alternative fibre surface plasma wave coupler of a coaxial geometry is qualitatively analysed. Dielectric coaxial fibre directional couplers have been fabricated and employed as sensing devices in the department in which the author has been fulfilling this research. A surface plasma wave fibre coupler can be devised by replacing the dielectric tube in this structure by a metallic tube. The resulting structure is schematically shown in fig.6.2.1. Under appropriate conditions, the guided mode of the dielectric rod is expected to phase match and hence couple into a surface plasma mode supported by the metallic tube.

The dielectric rod, can be analysed using the weakly guiding approximation [Marcuse 1974]. This analysis is based on the assumption, valid in practice, that the core and the cladding have very nearly equal refractive indices.

The analysis by Marcuse suggests that the fields of the HE_{11} mode of the rod are essentially transverse, with the E_x component vanishing. This mode is therefore effectively linearly polarized.

To qualitatively examine the surface plasma modes supported by the metallic tube, the metallic tube might be considered as a flat metallic slab wrapped

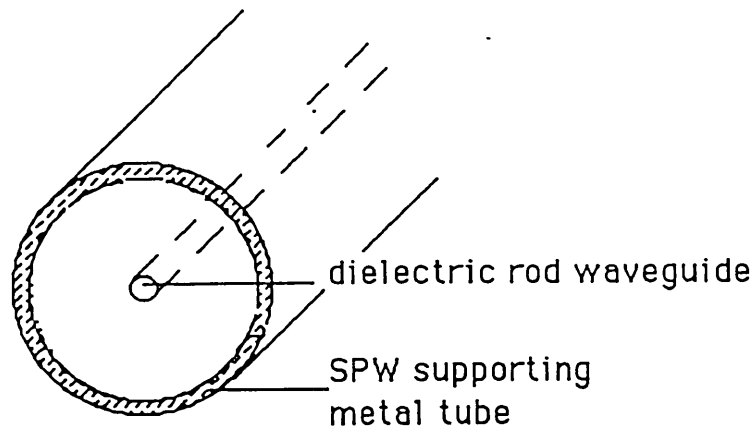


fig.6.2.1.Schematic representation of the coaxial fibre SPW directional coupler.

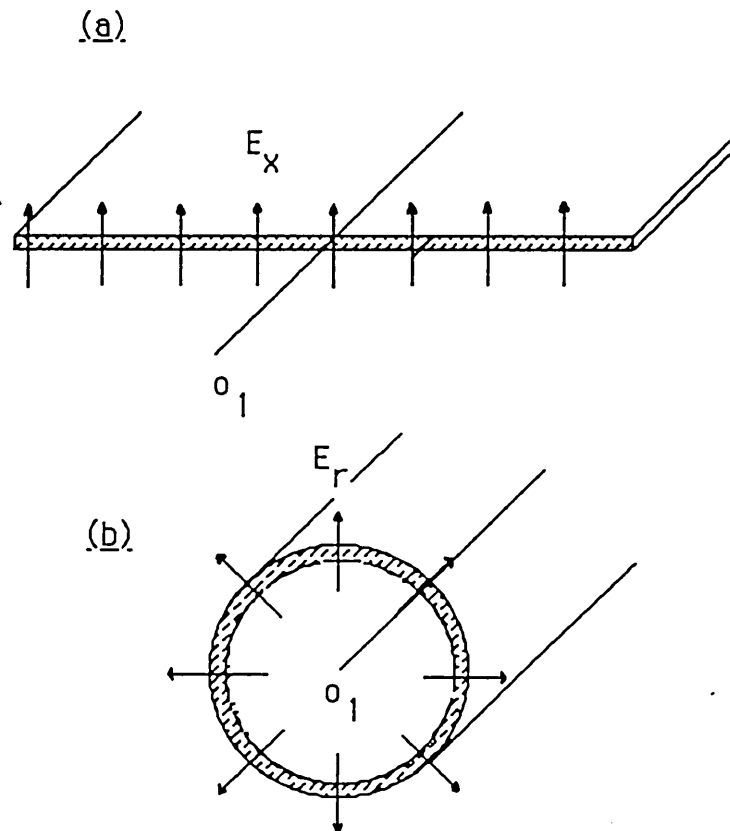


fig.6.2.2.Transformation of a metal slab (a) into a metallic tube (b), together with the expected vectorial representation of the corresponding fields.

around an axis. This is schematically shown in fig.6.2.2. The transformation of the metal slab into the tube geometry is expected to result in the transverse electric field component, E_x , of the surface plasma modes supported by the metallic slab to be transformed into the radial field component, E_r , of the surface plasma modes supported by the metallic tube. It can therefore be postulated that the E_r -field components, are pointing away from point O_1 in all directions, as shown in fig.6.2.2(b). This implies that the E_y and E_x -components are of the vectorial form shown in fig.6.2.3.

The strength of coupling between the guided mode of the dielectric rod and the surface plasma waves on the metallic tube is defined by the coupling coefficients expressed by equations (4.1.3) and (4.1.6) of chapter 4. Transforming these expressions into the cylindrical coordinates results in the following;

$$C_1 = -\omega\epsilon_0 \frac{(n_1^2 - n_4^2) \int_0^{+\infty} \int_0^{2\pi} \hat{E}_1 \cdot \hat{E}_2 r dr d\phi}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \hat{z} \cdot (\hat{E}_1 \times \hat{H}_1 + \hat{E}_1 \times \hat{H}_1) r dr d\phi} \quad (6.2.1)$$

$$C_2 = -\omega\epsilon_0 \frac{(n_3^2 - n_4^2) \int_0^{+\infty} \int_0^{2\pi} \hat{E}_2 \cdot \hat{E}_1 r dr d\phi}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \hat{z} \cdot (\hat{E}_2 \times \hat{H}_2 + \hat{E}_2 \times \hat{H}_2) r dr d\phi} \quad (6.2.2)$$

where E_1 and E_2 represent the electric fields of the dielectric rod and the surface plasma modes respectively. The scalar product $\hat{E}_1 \cdot \hat{E}_2$ is defined by;

$$\hat{E}_1 \cdot \hat{E}_2 = \hat{E}_{x1} \cdot \hat{E}_{x2} + \hat{E}_{y1} \cdot \hat{E}_{y2} + \hat{E}_{z1} \cdot \hat{E}_{z2} \quad (6.2.3)$$

where (E_x) 's and (E_y) 's are the transverse and (E_z) 's the longitudinal field components. The linear polarization of the guided mode of the rod eliminates the terms involving the product of the E_x -components.

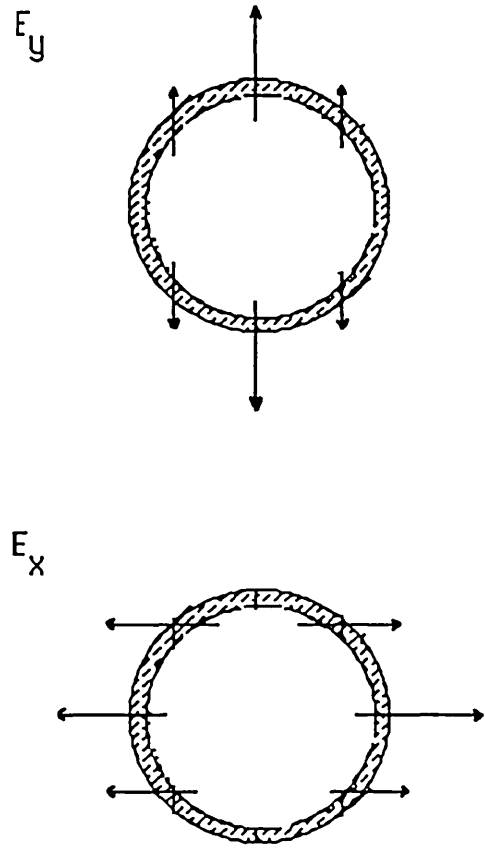


fig.6.2.3.The vectorial representation of the transverse fields of the SPW on a metallic tube resulting from the radial fields shown in fig.6.2.2.

Therefore, we can now write the following;

$$E_1 \cdot E_2 = E_{y1} \cdot E_{y2} + E_{z1} \cdot E_{z2} \quad (6.2.4)$$

We can also write;

$$\int_0^{2\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi = \int_0^{\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi + \int_{\pi}^{2\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi \quad (6.2.5)$$

However, the symmetry assumed for the electric fields of the surface plasma wave on the metallic tube (fig.6.2.3) implies that;

$$\int_0^{\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi = - \int_{\pi}^{2\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi \quad (6.2.6)$$

Substituting (6.2.6) into (6.2.5) results in the following;

$$\int_0^{2\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi = 0 \quad (6.2.7)$$

Therefore, the only term left in the numerator of C_1 is the term involving the product of the E_z -components.

However, the E_z -components of the guided mode of a dielectric waveguide are generally significantly smaller than the other field components. In fact they are generally omitted from the coupling analysis. This suggests that C_1 is generally expected to be of a small magnitude. In a similar manner C_2 can be shown to be a small quantity. The coupling between the guided mode of a dielectric rod and the surface plasma wave on a metallic tube is therefore expected to be relatively weak.

To enhance the coupling strength the gap between the rod and the metallic tube can be reduced. However, a reduction in the gap thickness may result in

the overall diameter of the structure, which is mainly determined by the rod diameter and the gap thickness, being unreasonably small.

The tedious analysis of the surface plasma waves on a metal tube, to verify the validity of the above assumptions, is not performed in this work. Instead the simplified case of a metallic rod is examined here, the fields of which, in view of the metallic rod being a special case of the metallic tube (with 0 inner diameter), is expected to behave in a similar manner to that of the metallic tube.

Ashley and Emerson [1974] have solved the eigenvalue equation describing the surface plasma modes on a metallic rod, for an aluminum rod of radius $80\text{\AA}$, and at a wide range of frequencies. They have considered the case of a perfect metal by neglecting the imaginary part of its permittivity. Although this eliminates the loss associated with the surface plasma mode, it produces useful information regarding the general characteristics of the corresponding field components. Ashley and Emerson have not however illustrated the manner in which the field components behave, which is of interest here. It is, therefore, necessary to derive the expressions describing the fields. The field characteristics can then be examined by substituting the propagation constants of the surface plasma modes, computed by Ashley and Emerson, in the field expressions. The field expressions are derived in the following manner.

It is convenient to perform the analysis on such geometries in the cylindrical coordinates. Transformation of the general wave equation into cylindrical coordinates, results in the following equation;

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \phi^2} - \gamma_z^2 \psi = 0 \quad (6.2.8)$$

Where:

ψ =longitudinal field components, E_z or H_z ,

$$\gamma_i = (\beta^2 - \epsilon_i k_0^2)^{1/2},$$

and $i = 3$ or 4 , corresponding to the metallic or the dielectric region respectively.

The variables of (6.2.8) can be seperated by introduction of;

$$\psi = AF(r) \exp(j\nu\phi) \quad (6.2.9)$$

Note that the $\exp j(\omega t - \beta z)$ has been omitted from the field expressions. Substituting (6.2.9) into (6.2.8), transforms the wave equation into the following;

$$\frac{d^2 F}{dr^2} + \frac{1}{r} \frac{dF}{dr} - (\gamma_i^2 + \frac{\nu^2}{r^2}) F = 0 \quad (6.2.10)$$

This equation is a well known differential equation, solutions of which are Bessel functions of the second kind, I and K . Defining the field components by I_ν inside and K_ν outside the metallic region, guarantees proper behaviour of the fields, which are to decay away from the metal-dielectric interface and with their peak value at the interface, representing non-radiative surface plasma modes.

The longitudinal field components of the surface plasma modes supported by the metallic rod are thus described by the following expressions;

$r \leq a_3$:

$$E_z = AI_\nu(\gamma_3 r) \exp(j\nu\phi) \quad (6.2.11)$$

$$H_z = BI_\nu(\gamma_3 r) \exp(j\nu\phi) \quad (6.2.12)$$

$r > a_3 :$

$$E_z = CK_\nu(\gamma_4 r) \exp(j\nu\phi) \quad (6.2.13)$$

$$H_z = DK_\nu(\gamma_4 r) \exp(j\nu\phi) \quad (6.2.14)$$

The radial and the angular field components, E_r and E_ϕ can now be described in terms of the longitudinal components.

Applying the boundary conditions, ie. continuity of the z - and the ϕ -components across the interface, results in the following eigenvalue equation;

$$\left[-\frac{K'_\nu(w)}{wK_\nu(w)} + \frac{I'_\nu(u)}{uI_\nu(u)}\right] \left[\frac{I'_\nu(u)}{uI_\nu(u)} - \frac{n_4^2}{n_3^2} \frac{K'_\nu(w)}{wK_\nu(w)}\right] = \left(\frac{\beta\nu}{k_0 n_3}\right)^2 \left[\frac{w^2 - u^2}{u^2 w^2}\right]^2 \quad (6.2.17)$$

where 'prime' represents differential of the function with respect to r , and;

$$u = \gamma_3 a_3$$

$$w = \gamma_4 a_4$$

This equation, although expressed in a different form, can be shown to be equivalent to the eigen value equation derived by Ashley and Emerson.

Ashley and Emerson have shown that the metallic rod supports a large number of surface plasma modes, depending on the diameter of the metal rod. Interpolating the propagation constants from the dispersion curves produced by Ashley and Emerson, the corresponding longitudinal and subsequently radial and angular field components are evaluated. The transverse electric field components, E_x and E_y , can now be computed in terms of the above field components.

Table 6.2.1 contains the transverse electric field components of the lowest order surface plasma mode, as a function of the angular coordinate, ϕ , evaluated at the surface of the metal rod ($r = a_3$), and at a wavelength of $0.62\mu m$. Figures

ϕ	E_x	E_y
0	0.0827	0
$\pi/4$	0.0585	0.0585
$\pi/2$	0	0.0827
$3\pi/4$	-0.0585	0.0585
π	-0.0827	0
$5\pi/4$	-0.0585	-0.0585
$3\pi/2$	0	-0.0827
$7\pi/4$	0.0585	-0.0585

.Table.6.2.1.The transverse electric field components of SPWs supported by an aluminum rod, evaluated at $r=a$.
 $(a=80\text{Å}, \epsilon_r=-7, \lambda=0.62\text{ }\mu\text{m}, n_{\text{cladding}}=1.0)$

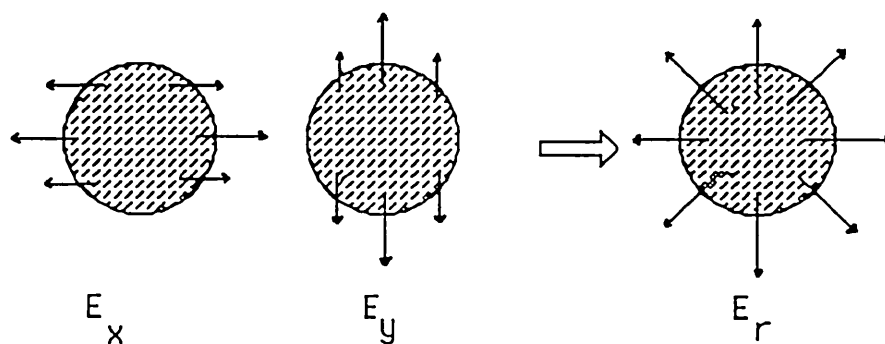


fig.6.2.4.The vectorial representation of the E_x, E_y and E_r components of the SPW supported by a metallic rod (based on the values in the above table).

6.2.4 shows a schematic vectorial representation of the transverse electric fields at the surface of the metallic rod, based on the data of table 6.2.1, which possess a similar symmetry to that shown in fig.6.2.3. Analysis of a number of higher order surface plasma modes supported by the metallic rod indicates that they possess field symmetries similar to that of the lowest order mode.

The design of the coaxial surface plasma wave coupler can however be modified in such a way as to increase the coupling strength. One such design would be to make the rod and the tube non-concentric, as shown in fig.6.2.5(a). The uneven coupling strength in such a geometry now results in the following;

$$\int_0^{\pi} \int_0^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} dr d\phi \neq \int_{\pi}^{2\pi} \int_0^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} dr d\phi \quad (6.2.18)$$

Hence;

$$\int_0^{2\pi} \int_{-\infty}^{\infty} \hat{E}_{y1} \cdot \hat{E}_{y2} r dr d\phi \neq 0 \quad (6.2.19)$$

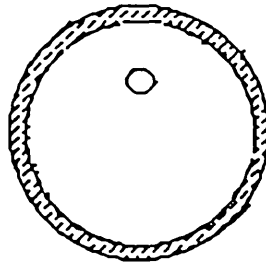
This implies that the terms in the coupling coefficient expressions, which include the product of the E_y components are non-zero, hence enhancing the coupling strength.

Replacing the metallic tube with a semi-tube, as shown in fig.6.2.5(b), also results in expression (6.2.19), again enhancing the coupling strength.

Conclusions.

The discussions on the coaxial surface plasma wave fibre coupler has shown that coupling between the guided mode of the dielectric rod waveguide and the surface plasma waves on the metallic tube is expected to be weak, imposing limitations on the practicality of this structure. A number of alternative coaxial geometries, in the form of a non-concentric coaxial structure or a coaxial

(a)



(b)

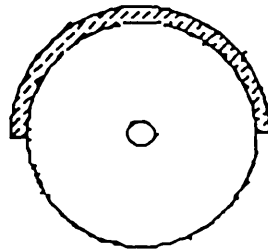


fig.6.2.5.The cross-section of alternative coaxial SPW couplers envisaged to increase the coupling strength.

structure comprising of a metallic semi-tube, have been suggested, in which the asymetry of the structure results in an increase in the coupling strength.

CHAPTER 7

CONCLUSIONS.

Surface plasma wave sensing devices based on Attenuated Total Reflection and directional coupler configurations have been investigated in this work. In the following, conclusions drawn from the theoretical analysis and the experimental observations presented in this thesis are outlined.

7.1. Surface plasma wave prism couplers (ATR configurations)

Introduction of a dielectric buffer layer into the Kretschmann ATR configuration, commonly used in sensing applications, has been shown to result in a somewhat more sensitive device, which may now be more sensitive than the rival dielectric waveguide prism coupler suggested by Mason. The high sensitivity of devices based on the resulting structure (buffered structure) is based on the fact that very sharp resonances can be achieved using this structure.

From a practical point of view sensors based on the Kretschmann geometry, which have a relatively high sensing performance, and are easier to fabricate (involving smaller number of layers), may be a more attractive choice.

It has also been suggested that it is possible to fabricate surface plasma wave prism couplers by depositing the silver film on a soda glass substrate in large quantities, which can then be mounted on a prism using the arrangement of fig.2.2.3, making the possibility of inexpensively manufacturing sensing devices based on this technique feasible.

7.1.1.Alternative mode of operation.

Surface plasma wave prism couplers can alternatively be operated by fixing the angle of incidence and varying the wavelength of the incident light. In this mode of operation the intensity of the reflected light possesses a resonant response as a function of the wavelength of operation, with the minimum reflected intensity corresponding to the so called phase matching wavelength at which the evanescent field of the incident light and the surface plasma wave propagate with identical propagation velocities. Variations in the refractive index of the sensing cladding and parameters influencing it now cause a shift in the phase matching wavelength. This is the basis of the sensing operation in this mode.

In principle the broadband operation of the device could also be used to determine the refractive index profile of a dielectric adlayer formed on the outer surface of the metal film. This is because the decay of the evanescent field of the surface plasma mode can now be scaled by the wavelength of the incident light. Also, assuming the adlayer to have a step refractive index profile, it is possible to determine both the refractive index and the thickness of the adlayer by examining the surface plasma resonances at two different wavelengths.

7.2.DirectionaI surface plasma wave couplers.

Monochromatic and broadband modes of operation for directional couplers as sensors have been described. The monochromatic mode has the advantage of involving a simpler detection mechanism, while in the broadband mode the fact that phase matching is achieved by adjusting the wavelength rather than the refractive index of the outer (sensing) cladding, relaxes the constraints on

the accuracy with which the index of this cladding is required in order to phase match the interacting waveguides.

Surface plasma wave couplers, due to the large fraction of the surface plasma power in the sensing cladding and the dispersion of the surface plasma modes significantly differing from that of dielectric waveguides, are expected to be associated with significantly larger sensitivities compared to purely dielectric directional couplers.

Monochromatic mode of operation of a planar surface plasma wave directional coupler has been experimentally investigated in this work. A comparison of this structure with a more complicated structure studied by Kreuwel et al suggests that the two structures have comparable sensitivities, while the structure examined in this work may be more practical in view of its simpler configuration.

7.2.1. Fibre surface plasma wave couplers.

In this work two different fibre surface plasma wave couplers, referred to as the D-fibre and coaxial surface plasma wave couplers have been studied. Analysis of the D-fibre surface plasma wave coupler has shown that the considerable difference between the lateral dimensions of the metal film and the fibre core in this geometry results in significant broadening of the coupling curve, degrading the sensing performance of the resulting sensing device. Modifications to this geometry in order to sharpen the coupling curve have been suggested. Attempts to observe the expected coupling characteristics have however failed. A number of possible explanations for this have also been presented.

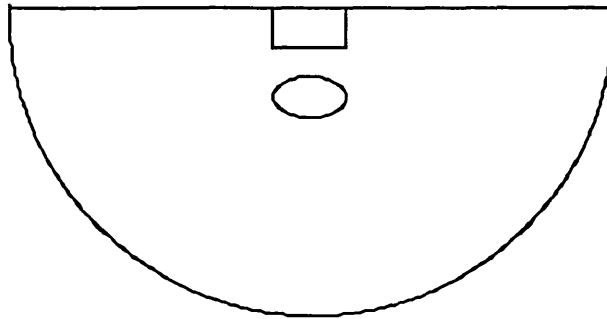
Coupling into surface plasma waves in a coaxial fibre geometry has been qualitatively shown to be weak, making employment of this geometry in sensing application, due to its very small dimensions required to enhance the coupling strength, impractical. Alternative coaxial geometries, in the form of non-concentric coaxial fibres or with the metal film being a semi-tube, have been suggested which may overcome this difficulty.

7.3. General remarks.

Of surface plasma wave coupler structures discussed in this thesis the prism couplers, which are thought to be the easiest to fabricate, are possibly the most attractive choice. Devices based on fibre geometries, enjoying advantages generally associated with fibre optic sensors, such as remote sensing, are also thought to be promising. The alternative coaxial geometries (fig.6.2.5), despite the enhanced coupling strength, are expected to be still of relatively small size. This may imply that, from a practical point of view, devices based on this geometry are not particularly feasible. The modified D-fibre geometry (fig.6.1.9) may, however, be worth considering. This geometry-with the discontinuity present on its flat surface-can possibly be fabricated by etching a twin cored fibre (fig.7.1(a)) all through its exposed core. Provided the material from which the exposed core is made of dissolves in the etching solution at a substantially faster rate compared to the surrounding cladding material, the etching will produce the geometry shown in fig.7.1(b), which resembles the required geometry.

It should be noted that, a significant drawback with surface plasma wave devices is that silver films, which are suggested as the most suitable choice of the metal, are not particularly stable in atmosphere. The silver film may be protected by a thin layer of a robust material. This would, however, result in

(a)



(b)

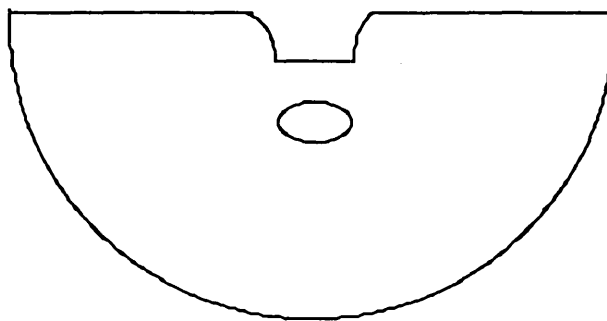


Fig.7.1.(a)The unetched twin cored fibre, (b) the etched twin cored fibre, resembling the fibre geometry of fig.6.1.9.

partial distribution of the surface plasma power in the protective layer, which degrades the sensing performance of the device. The protective layer would, therefore, be required to be as thin as possible. Another important difficulty is that noble metals such as silver generally have a poor adhesion to glass substrates, and can thus be damaged under relatively severe cleaning conditions. This suggests that surface plasma wave devices are not particularly robust. To overcome this difficulty the metal film can be deposited on a thin layer of the metal oxide precoated on the glass substrate, to which the metal has a better adhesion.

References:

Ashley J.C., and Emerson L.C.; "Dispersion relation for non-radiative surface plasmons on cylinders", *Surface Science*, vol.41, 1974, p.615-618.

Attridge J.W., Cozens J.R., Leaver K.D., and Webster N.L.; "Coaxial fibre sensors", *Journal of Light Wave Technology*, vol.LT-3, 1985, p.1084-1091.

Attridge J.W.; PhD thesis, "Fibre optic chemical sensing", Imperial College of Science and Technology, 1986, p.193.

Boardman A.D.; "Electromagnetic surface modes", Wiley, 1982, p.262.

Burge D.K., Bennett J.M., Peck R.L., and Bennett H.E.; "Growth of surface films on silver", *Surface Science*, vol.16, 1969, p.303-320.

Chen W.P., and Chen J.M.; "Use of surface plasma waves for determination of thickness and optical constants of thin metallic films", *JOSA*, vol.17, no.2, 1981, p.189-191.

Cozens J.R., and Gu Yi; personal correspondence, Imperial College of Science and Technology, 1988.

Ding T., and Gamire E.; "Measuring refractive index and thickness of thin films: a new technique", *Applied Optics*, vol.22, no.20, 1983, p.3177-3181.

Dyott R.B., and Schrank R.F.; "Self locating elliptically cored fibre with an accessible guiding region", *Elect. Lett.*, 1982, p.980-982.

Dyott R.B., Bello J., and Handerek V.A.; "Indium-coated D-shaped fibre polarizer", *Opt. Lett.*, vol.12, no.4, 1987, p.287-289.

Flanagan M.T., and Pantell R.H.; "Surface plasmon resonance and immunosensors", *Elect. Lett.*, vol.20, no.23, 1984, p.968-970.

Giallorenzi T., Bucaro J.A., Dandridge A., Sigel G.H., James JR., Cole H., Rasleigh S.C., and Priest R.G.,

Giuliani J.F., Wohltjen H., Jarvis N.L.; "Reversible optic waveguide sensor for ammonia vapours", *Opt. Lett.*, vol.8, p.54-56.

Grauchmann D., Petermann K., Staudigel L., and Weidel E.; "Fibre-optic polarizers with high extinction ratio", 9th European conference on optical communication, 1983, p.305-308.

Hageman H.J., Gudat W., and Kunz C., "Optical constants from infrared to X-ray region: Mg, Al, Cu, Ag, Au, Bi, C, and Al_2O_3 ", *JOSA*, vol.65, 1975, p.742.

Hansen N.W., "Electric fields produced by propagation of plane coherent electromagnetic radiation in a stratified medium", *JOSA*, vol.65, 1975, p.742.

Inagaki T., Goudonnet J.P., Royer P., and Arkawo E.T.; "Optical properties of silver island films in the attenuated-total-reflection geometry", *Applied Optics*, vol.25, no.20, 1986, p.3635-3639.

Johnson P.B., and Christy R.W.; "Optical constants of the noble metals", *Physical Review B*, vol.6, no.12, 1972, p.4370-4379.

Kovacs G.J., and Scott G.D.; "Optical excitation of surface plasma waves in layered media", *Physical Review B*, vol.16, no.4, 1977, p.1297-1311.

Kretschmann E.; "The determination of the optical constants of metals by excitation of surface plasmons.", *Z.Physik*, vol.241, 1971, p.313-324.

Kreuwel H.J.M., Popma Th.J.A., Lambeck P.V., and Gerritsma G.J.; "A surface plasmon waveguide sensor: a new type of chemical transducer based on optical phenomena", Proc. of the 2nd int. meeting on chemical sensors, 1986, p.7-10.

Liedberg B., Nylander C., and Ingemar L., "Surface plasmon resonance for gas detection and biosensing", Sensors and Actuators, vol.4, 1983, p.299-304.

Lundstrom K.I., Arwin H.R., Reike E., Sielaff G., and Hennrich N.; "Immunoassay methods without labels", 1983, European pat.73980-A.

Marcuse D.; "Light transmission optics", Van Nostrand Reinhold, 1972:

(a) p.4

(b) p.407

Marcuse D.; "Theory of dielectric optical waveguides", Academic press, 1974, p.60.

Mason W.D.; PhD thesis, "Prism coupler surface sensing", Imperial College of Science and Technology, 1988:

(a) p.170

(b) p.82

Nylander C.; "Chemical and biological sensors", J. Phys. E:Sci. Instrum., vol.18, 1985, p.736-749.

Ordal M.A., Long L.L., Bell R.J., Bell S.E., Bell R.R., Alexander R.W., and Ward C.A.; "Optical properties of the metals Al, Co, Cu, Au, Fe, Pb, Ni,

Pd, Pt, Ag, Ti, and W in the infrared and far infrared", *Applied Optics*, vol.22, no.7, 1983, p.1099-1119.

Otto A.; "Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection", *Z.Physik*, vol.216, p.398-410.

Parriaux O., Gidon S., and Cochet F.; "Fibre-optic polarizer using plasmon-guided wave resonance", 7th European conference on optical communication, 1981, p.6-1 to 6-3.

Peterson J.I., Goldstein S.R., Fitzgerald R.V., and Buckhold D.K., "Fibre optic Ph probe for physiological use", *Anal. Chem.*, vol.52, 1980, p.864-869.

Pockrand I., Swalen J.D., Gordon J.G., and Philpott M.R.; "Surface plasmon spectroscopy of organic monolayer Assemblies", *Surface Science*, vol.74, 1977, p.237-244.

Sandstrom T., Stenberg M., and Nygren H.; "Visual detection of organic monomolecular films by interference colors", *Applied Optics*, vol.24, no.4, 1985, p.472-478.

Sarid D., Deck R.T., Craig A.E., Hickernell R.K., Jameson S., and Fasano J.J.; "Optical field enhancement by long range surface plasma waves", *Applied Optics*, vol.21, 1982, p.3993-3995.

Schultz L.G.; "The optical constants of silver, gold, copper, and aluminum", *JOSA*, vol.44, 1954, p.357.

Sennet R.S., and Scott G.D.; "The structure of metal films and their optical properties", *JOSA*, vol.40, no.4, 1950, p.203-211.

Swalen J.D., Santo R., Tacke M., and Fischer J.; "Properties of polymeric thin films by integrated optical techniques", IBM J. Res. Dev., vol.21, 1977, p.168-175.

Tamir T.; "Integrated optics-topics in applied physics", vol.7, Springer Verlag, 1979, p.203-206.

Tien K., Smolinsky G., and Martin R.J.; "Thin organosilicon films for integrated optics", Applied Optics, vol.11, no.3, 1972, p.637-642.

Webber W.H., and McCarthy S.L.; "Surface plasmon resonance as a sensitive optical probe of metal film properties", Physical Review B, vol.12, no.12, 1975.

Wright S., De Oliveira A.D., and Wilson M.G.; "Optical waveguide polarizer with synchronous absorption", Elect. Lett., vol.15, no.17, 1979, p.510-512.

Yariv A.; "Optical electronics", Holt-Saunders International, 1985, p.445.

Yeatman E., Ash E.A., "Surface plasmon microscopy", Elect. Lett., vol.23, no.20, p.1091-1093.