Layout Optimization for Erbium-Doped Waveguide Amplifiers

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Abstract—The optical layout of erbium-doped waveguide amplifiers (EDWAs) based on spiral and folded spiral planar light-wave circuits is considered. It is shown that layouts may be ranked according to their ability to provide maximum gain within a given chip area and an optimum layout based on a spiral containing both straight and curved waveguide sections is identified from an initial set. The analysis is initially based on simple geometric principles. A detailed optical simulation is then carried out using an algorithm that links a five-level rate equation model with beam propagation by the method of lines. The results confirm the choice of optimum layout.

Index Terms—Erbium-doped waveguide amplifier (EDWA), optical amplifier.

I. INTRODUCTION

ERBIUM-DOPED waveguide amplifiers (EDWAs) may have advantages over erbium-doped fiber amplifiers (EDFAs) because of their potential for cost and size reduction and the possibility of integrating other components such as pump lasers and pump combiners.

It is well known that different host media allow different erbium doping levels [1], [2]. For example, ion-exchanged phosphate glasses allow sufficiently high doping that a high gain per unit length may be obtained. A useable overall gain may be obtained using a straight waveguide layout [3]–[6]. Sputtered phosphate glasses show similar behavior [7], as do sputtered multicomponent glasses [8], [9] and ion implanted alumina [10]. Unfortunately, planar lightwave circuits (PLCs) based on many of these materials systems are currently incompatible with the low-cost low-loss fiber pigtailling methods widely used with silica-on-silicon PLCs.

However, silicate glasses allow only relatively low erbium doping levels because of interactions that occur when Er^{3+} ions are closely spaced [2]. This effect appears to be independent of the deposition method used, which might be flame hydrolysis [11], plasma-enhanced chemical vapor deposition [12]–[15], or the sol-gel process [16], [17]. Most silica-based EDWAs demonstrated to date have had a much lower gain per unit length, so that a folded or spiral layout was required to achieve sufficient overall gain (e.g., [11]). Despite these contradictions, advanced EDWAs, such as lossless splitters that combine active and passive PLCs, are being developed in a number of materials systems [18]–[21].

In any dielectric waveguide system, radiation losses occur at bends. These losses rise rapidly for bend radii below a characteristic value, which depends on the confinement of the guide. For most PLCs, the confinement must be relatively weak for compatibility with optical fibers, so that the minimum bend radius is typically measured in millimeters. For weakly doped EDWAs, the challenge is, therefore, to develop optical layouts that allow a given length of amplifying waveguide to be arranged within a chip of reasonable size without reducing the gain by excessive bending loss.

Several criteria may be used to judge the utility of different optical layouts. Because silica-based EDWAs require complex hosts that are hard to deposit, we shall use the approach of minimizing chip area, because this is likely to maximize the number of individual chips obtained from a larger wafer that is separated into individual dies. However, other approaches, such as optimizing the aspect ratio of the chip, may also be important.

In this paper, we consider a number of different optical layouts for EDWAs and show that particular layouts offer quantifiable advantages. We base the discussion initially on simple geometric arguments, which are introduced in Section II. We confirm the results by simulation using a model for folded EDWAs [22]. This model combines rate equations developed for straight active guides with a beam propagation algorithm based on the method of lines. The model is reviewed briefly in Section III and applied to the different optical layouts in Section IV. The results show that the optimum structure is a spiral based on a mixture of curved and straight sections, using a series of waveguide intersections to extract the output; these conclusions are discussed in Section V.

II. GEOMETRIC CONSIDERATIONS

We begin by considering some simple geometries. The left-hand column of Fig. 1 shows several possible EDWA layouts, including bends of different radii to achieve a long path length in a compact chip. Ultimately, the bend radius might vary continuously, but here we restrict ourselves to layouts formed by cascaded right-angle bends and straight sections, for simplicity. The closest approach of neighboring guides is assumed to be limited to a minimum value δ , which is determined by the confinement of the guiding system. Typically, δ will be small compared with the minimum bend radius.

Layout 1A is a spiral with a central fold-back bend, which has been used in [11]. Clearly, the bend radius in the fold-back region is approximately half the radius elsewhere. Because radiation losses increase rapidly with curvature, we might expect any such loss to be concentrated in the fold-back region.

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Fig. 1. Layouts of folded spiral (1A and 1B) and spiral (2A and 2B) EDWAs.

Layout 2A shows a continuous spiral, which requires a number of waveguide intersections to allow the output to be taken from the edge of the chip. Right-angle crossings have been shown to cause extremely low loss in passive spirals [23], [24]. However, the layout still contains a bend of small radius near the exit and we would again expect any radiation loss to be concentrated in this region. The length of this section is approximately half that of the fold-back section in layout 1A, so we might expect any radiation losses to be lower.

Layouts 1B and 2B show modifications of 1A and 2A, respectively. In each case, additional straight guide sections have been inserted to allow the bend radius to be equalized as far as possible throughout the circuit. The aim of this strategy is to eliminate the tight bending regions likely to give rise to excessive radiation loss in layouts 1A and 2A and distribute the loss more evenly through the whole of the optical path. Layouts 1A and 2A require a square footprint and 1B and 2B require a rectangular one. Based on this simple argument, we might expect the order of merit of the different layouts to be, from worst to best, 1A, 1B, 2A, and 2B. The aim of the remainder of this paper is to demonstrate that this is, indeed, the case.

Even within such a restricted set of possibilities, there lies considerable complexity. For example, Fig. 2(a) shows a number of folded spiral circuits that fall within the general format of Layout 1A. If the restriction to right angle bends is removed, there are even more possibilities. After the first two circuits (labeled X and Y), the remainder consist of a primitive folded path (Z), combined with additional right-angle bends of large radius.

Some layouts that appear geometrically different actually have very similar path lengths and are marked with diagonal

linkages. In a comparison based purely on path length, it is only necessary to consider one of these alternatives. Other layouts have the entrance and exit guide lying at right angles to each other, which may be inconvenient. Therefore, we have restricted our attention to the third column of layouts, in which the entrance and exit guides are parallel and lie on opposite sides of the chip. In this column, the layout can be considered to consist of the primitive circuit Z combined with a number N of turns of a full circle. The primitive circuit has $N = 0$; the circuit below it has $N = 1/2$, and so on. We define the circuit with a particular value of N as the N th-order circuit.

When the separation δ between the guides tends to zero, the length of the path Z tends to $4r + 4\pi r$, where r is the minimum-bend radius. Similarly, the length of the full circle added to generate each subsequent circuit in the series is $4\pi r$. The total length L_N of the N th order circuit in Fig. 2(a) is, therefore, approximately given by

$$L_N \approx 4\{(1 + \pi) + \pi N\}r. \quad (1)$$

This approximate relation is illustrated in the right-hand column of Fig. 1. Most often, we will have an EDWA of fixed length L , which must be arranged into a compact chip. The minimum radius r_N of the N th order circuit is then

$$r_N \approx \frac{L}{4\{(1 + \pi) + \pi N\}}. \quad (2)$$

Similarly, the overall area A_N of the chip is approximately given by

$$A_N = 16r_N^2. \quad (3)$$

Fig. 2. Geometric possibilities of increasing complexity for (a) layout 1A and (b) layout 2A.

From (2) and (3), we can see that the minimum bend radius must decrease as the order of the circuit increases. Although this reduction allows the overall chip area to decrease, eventually the radius becomes small enough to cause unacceptable bending loss.

In a similar way, Fig. 2(b) shows a number of folded spiral circuits that fall within the general format of Layout 1B. Once again, an N th order circuit may be considered as being formed by the primitive circuit Z combined with N circular turns of guide, as shown in the right-hand side of Fig. 1. In this case, circuits with $N = 1/2, 3/2$, and so on, have the input and output guides emerging from the same side of the chip, while circuits with $N = 0, 1, 2$, and so on, have them on opposite sides.

In this case, similar approximations may be found for the minimum radius r_N and the chip area A_N . This process may be continued for layouts 1B and 2B and the relevant equations are grouped together in Table I. Note that layout 1B is a slightly special case, in that equations of different form are required for integer and noninteger values of N .

Table I highlights the similarities and differences between the four layouts. In each case, the minimum radius decreases as the

square root of the chip area. However, layout 2B has the largest minimum bend radius for a given chip area and, hence, is likely to have the lowest radiation loss.

When the waveguide separation δ is not negligible, expressions can again be derived for the optical path length L and the chip area A . Allowing an additional clear spacing of $\delta/2$ around the perimeter of the chip, we obtain for layout 1A, for example

$$L_N = r[4\{(1 + \pi) + \pi N\} + \delta \left[\frac{\pi}{2} + (2 + \pi)N + \pi N^2 \right]], \quad \text{for } N \text{ integer}$$

$$L_N = r[4\{(1 + \pi) + \pi N\} + \delta \left[\left(1 + \frac{\pi}{4}\right) + (2 + \pi)N + \pi N^2 \right]], \quad \text{for } N \text{ integer} + \frac{1}{2} \quad (4)$$

and

$$A_N = 16r^2 + 4(3 + 4N)r\delta + (4N^2 + 6N + 2)\delta^2, \quad \text{for all } N. \quad (5)$$

TABLE I
APPROXIMATE FORMULAS FOR MINIMUM BEND RADIUS AND CHIP AREA, FOR LAYOUTS OF TYPE 1A, 1B, 2A, AND 2B

Layout	Minimum bend radius r_N	Area A_N
1A	$L / [4\{(1 + \pi) + \pi N\}]$	$16 r_N^2$
2A	$L / [4\{(1 + 3\pi/4) + \pi N\}]$	$16 r_N^2$
1B	$L / [4\{(3/2 + 3\pi/4) + (1 + \pi/2)N\}]$	$8 r_N^2$ for N integer
	$L / [4\{(1 + 3\pi/4) + (1 + \pi/2)N\}]$	$8 r_N^2$ for N = integer + 1/2
2B	$L / [4\{(3/4 + \pi/2) + (1/2 + \pi/2)N\}]$	$6 r_N^2$

Fig. 3. Approximate (full line) and exact (data points) variation of minimum bend radius with chip area, for 30-cm-long EDWAs based on layouts 1A, 1B, 2A, and 2B. A guide separation of $\delta = 100 \mu\text{m}$ is assumed in the exact calculation.

It is simple to show that (4) and (5) simplify to (1) and (3), respectively, as $\delta \rightarrow 0$. Similar expressions may be derived for the remaining three layouts.

Because of the quadratic relations between A_N and r_N in Table I, the variations of minimum radius with chip area predicted by the approximate formulas are sets of points that lie on straight lines with a slope of 1/2 on a log-log plot. The intercept of this line differs from layout to layout, however. The full lines in Fig. 3 show these variations for an optical path length of 30 cm. The discrete data points show the result of the exact calculations, for a finite guide separation of $\delta = 100 \mu\text{m}$. The approximate variations agree well with the exact calculation for low-order circuits, which have relatively large bend radii. The agreement deteriorates as the order increases, when the circuit becomes so close packed that δ is a significant fraction of the bend radius. However, both calculations clearly demonstrate that layout 2B has the largest minimum bend radius for a given area; compared with layouts 1A and 2A, the minimum radius is increased by a factor of approximately $2/\sqrt{1.5} = 1.63$.

III. MODEL FOR FOLDED EDWAS

The layouts shown in Fig. 1 were simulated using a published model for folded EDWAs. Full details have been given in [22]; here we give a brief summary.

EDWAs are based on a three-level system, with level 1 ($^4I_{15/2}$), level 2 ($^4I_{13/2}$), and level 3 ($^4I_{11/2}$) being the ground, metastable, and pump levels, respectively. Absorption of pump radiation at 980-nm wavelength promotes electrons from level 1 to level 3. After decaying to level 2, these electrons provide signal gain at 1535 nm via transitions to level 1. At Er^{3+} densities above 10^{25} m^{-3} , ion-ion interactions allow nonradiative energy transfer between near neighbors through up conversion and cross relaxation involving level 4 ($^4I_{9/2}$) and level 5 ($^4F_{7/2}$). These processes can be modeled by a five-level set of rate equations, of the form [25], [26]

$$\begin{aligned}
 \frac{dN_1}{dt} &= -\sigma_{13}N_1v_gN_p + \{\sigma_{21}N_2 - \sigma_{12}N_1\}v_gN_s \\
 &\quad + \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_2} + K_2N_2^2 + K_3N_3^2 - C_{14}N_1N_4 \\
 \frac{dN_2}{dt} &= \{\sigma_{12}N_1 - \sigma_{21}N_2\}v_gN_s - \frac{N_2}{\tau_2} \\
 &\quad + \frac{N_3}{\tau_{32}} - 2K_2N_2^2 + 2C_{14}N_1N_4 \\
 \frac{dN_3}{dt} &= \sigma_{13}N_1v_gN_p - \frac{N_3}{\tau_{31}} - \frac{N_3}{\tau_{32}} \\
 &\quad - 2K_3N_3^2 + \frac{N_4}{\tau_4} \\
 \frac{dN_4}{dt} &= K_2N_2^2 - C_{14}N_1N_4 - \frac{N_4}{\tau_4} + \frac{N_5}{\tau_5} \\
 \frac{dN_5}{dt} &= K_3N_3^2 - \frac{N_5}{\tau_5}.
 \end{aligned} \tag{6}$$

Here, N_i is the density of the i th level and $\sum N_i = N_{\text{Er}}$ is the Er^{3+} ion density. N_p and N_s are the pump and signal photon densities, respectively. The constant σ_{13} is the cross section for pump absorption; the corresponding coefficient σ_{31} for pump emission is assumed to be negligible. The nonradiative decay path from level 3 is described by a lifetime τ_{32} . A further path from level 3 to level 1 has a lifetime τ_{31} . The cross sections for

TABLE II
COEFFICIENTS OF ERBIUM IONS USED IN THE NUMERICAL SIMULATIONS
(AFTER [22], [25], [26])

$\lambda_s = 1535 \text{ nm}$	$\tau_2 = 1 \times 10^{-2} \text{ sec}$
$\lambda_p = 980 \text{ nm}$	$\tau_{31} = 2 \times 10^{-1} \text{ sec}$
$\sigma_{12} = 5.36 \times 10^{-25} \text{ m}^2$	$\tau_{32} = 1 \times 10^{-5} \text{ sec}$
$\sigma_{21} = 5.41 \times 10^{-25} \text{ m}^2$	$\tau_4 = 1 \times 10^{-9} \text{ sec}$
$\sigma_{13} = 2.58 \times 10^{-25} \text{ m}^2$	$K_2 = K_3 = 3.5 \times 10^{-24} \text{ m}^3/\text{sec}$
$\sigma_{31} = 0 \times 10^{-25} \text{ m}^2$	$C_{14} = 3.5 \times 10^{-24} \text{ m}^3/\text{sec}$

signal absorption and emission are σ_{12} and σ_{21} , respectively. τ_2 , τ_4 , and τ_5 are lifetimes for levels 2, 4, and 5, respectively; K_2 and K_3 are up-conversion coefficients and C_{14} is a cross-relaxation coefficient. Suitable numerical values from the literature are given in Table II. $v_g \approx c/\sqrt{\epsilon_r'}$ is the group velocity, where c is the velocity of light and ϵ_r' is the relative dielectric constant of the host glass.

The electron populations in levels 1 and 2 give rise to pump-power absorption and signal-power gain coefficients a_p and g_s , given by

$$a_p = \sigma_{13}N_1 \quad g_s = \sigma_{21}N_2 - \sigma_{12}N_1. \quad (7)$$

In turn, these coefficients result in complex relative dielectric constants ϵ_{rp} and ϵ_{rs} of the doped material at the pump and signal wavelengths λ_p and λ_s , given by

$$\epsilon_{rp} = \epsilon_r' - j(\sqrt{\epsilon_r'}) \frac{a_p}{k_{0p}} \quad \epsilon_{rs} = \epsilon_r' + j(\sqrt{\epsilon_r'}) \frac{g_s}{k_{0s}}. \quad (8)$$

Here, $k_{0p} = 2\pi/\lambda_p$ and $k_{0s} = 2\pi/\lambda_s$.

We have modeled the propagation of optical fields in curved guides using the method of lines (MoL) [27]–[29] in cylindrical polar coordinates. Fig. 4(a) shows the geometry of a simple bend of radius R . For transverse electric (TE)-polarized fields, we assume the Helmholtz wave equation

$$\frac{\partial^2 E}{\partial r^2} + \frac{1}{r} \frac{\partial E}{\partial r} + \frac{1}{r^2} \frac{\partial^2 E}{\partial \phi^2} + k_0^2 \epsilon_r E = 0. \quad (9)$$

Here, $E(r, \phi)$ is the electric field, $\epsilon_r(r, \phi)$ is a relative dielectric constant and $k_0 = 2\pi/\lambda$. Substituting the new coordinates $x = r - R$ and $s = R\phi$, (9) reduces to

$$\frac{\partial^2 E}{\partial s^2} + \gamma^2 \frac{\partial^2 E}{\partial x^2} + C\gamma \frac{\partial E}{\partial x} + \gamma^2 k_0^2 \epsilon_r E = 0. \quad (10)$$

Here, $\gamma = 1 + Cx$ and $C = 1/R$. The overall window width W is now discretized in the x direction into a set of m lines separated by a distance $\Delta x = W/(m - 1)$. This process yields the matrix-vector differential equation

$$\frac{d^2 \underline{E}}{ds^2} + \{\underline{\gamma}^2 \underline{P} + C\gamma \underline{D} + \gamma^2 k_0^2 \underline{\epsilon}_r\} \underline{E} = 0. \quad (11)$$

Here, $\underline{E}(s)$ is a vector of size m containing values of E at each line. $\underline{\epsilon}_r$ is an $m \times m$ diagonal matrix of similar values of ϵ_r . $\underline{\gamma}$ is a diagonal matrix with elements $\gamma_{jj} = (1 + Cx_j)$, where x_j is the

coordinate of the j th line. $\underline{D}$ is an $m \times m$ matrix representing the discretized first derivative with respect to x and $\underline{P}$ is an $m \times m$ matrix representing the second derivative.

Ignoring backward-traveling waves and assuming that Δs is small, a field $\underline{E}(s + \Delta s)$ at a point along the path may be found in terms of an earlier field $\underline{E}(s)$ in the form

$$\underline{E}(s + \Delta s) = \underline{T} \exp \{-j\beta \Delta s\} \underline{T}^{-1} \underline{E}(s). \quad (12)$$

Here, β and $\underline{T}$ are the eigenvalue and eigenvector matrices, respectively, of a matrix $\underline{Q}$, which is given by

$$\underline{Q}^2 = \underline{\gamma}^2 \underline{P} + C\gamma \underline{D} + \gamma^2 k_0^2 \underline{\epsilon}_r. \quad (13)$$

To model curved EDWAs, the layout is first divided into cascaded bends of different radii, as shown in Fig. 4(b). Pump and signal field vectors $\underline{E}_p$ and $\underline{E}_s$ are computed at the input by solving the eigenvalue equation for a passive slab guide of core width w and core and cladding indexes $n_{\text{core}} = \sqrt{\epsilon_r'}$ and $n_{\text{cladd}} = \sqrt{\epsilon_r''}$, and discretizing the resulting field functions. Two MoL algorithms, with separate matrices $\underline{Q}_p^2$ and $\underline{Q}_s^2$, are then used to propagate the pump and signal vectors. At each step within a bend, the photon densities N_p and N_s are first calculated from $\underline{E}_p$ and $\underline{E}_s$ by solving a separate rate equation for each line in the core. These densities are used to evaluate ϵ_{rp} and ϵ_{rs} , so that the matrices $\underline{Q}_p^2$ and $\underline{Q}_s^2$ may be constructed. These matrices are decomposed into eigenvalue and eigenvector matrices $\underline{T}_{p,s}$, and $\beta_{p,s}$ and (12) is used to propagate each vector by a distance Δs . When $C = 0$, the model reduces to Cartesian coordinates and can simulate any straight guide sections.

Because the calculation window is finite (and for computational reasons, relatively small), reflections from the window walls must be suppressed. This aspect is particularly important in amplifier structures, because any calculation of the overall gain will otherwise be made inaccurate by the apparent reflection of radiated power back into the signal beam.

Edge reflections may be suppressed by modifying the top row of the matrix $\underline{Q}^2$ to mimic the action of a perfect absorber. We have used matrix elements based on a third-order rational series approximation to such an absorber [30]–[32]. A third-order approximation will typically only provide maximum attenuation for three distinct angles of incidence, giving a small finite reflection for intermediate angles. There is some flexibility in the choice of series coefficients. We have used coefficients derived from the L_a^∞ approximation [31], which has maximum absorption at 26.9° , 66.6° , and 87.0° . We have found this particular approximation to be particularly effective in absorbing radiation emitted from tight bends.

IV. SIMULATION RESULTS

Simulations of the different amplifier layouts shown in Fig. 1 were performed using the model in Section III. A step-index guide with a core width of $3.2 \mu\text{m}$ was assumed, with indexes of $n_{\text{core}} = 1.468$ and $n_{\text{cladd}} = 1.46$, respectively, so that the guide was just single-moded at 980 nm wavelength. The Er^{3+} concentration was $N_{\text{Er}} = 5 \times 10^{25} \text{ m}^{-3}$ and the input pump and signal intensities were 1 mW and $0.2 \mu\text{W}$ per square micron, respectively, averaged over the core. The window width

Fig. 4. Discretization used in MoL for (a) polar coordinates and (b) construction of overall layout using cascaded sections.

Fig. 5. Variation of overall gain with chip area, for layouts of type 1A and overall path lengths of 20, 30, and 40 cm.

was $W = 40 \mu\text{m}$, the line spacing was $\Delta x = 0.4 \mu\text{m}$, and the step size was $\Delta s = 0.3\text{--}5.0 \text{ mm}$. The core was centrally placed. Transverse fields derived from the equivalent passive guide were launched at the input and modal powers obtained after propagation were computed by evaluating overlap integrals with these fields. Initially, the effects of any waveguide intersections were ignored in considering Layouts 2A and 2B.

Fig. 5 shows the variation of overall gain with chip area for layout 1A, obtained for three different optical path lengths ($L = 20, 30$, and 40 cm). Each data point corresponds to a different value of N . The main difference between the three sets of data is that the gain increases with the path length. Other than that, a similar trend may be seen for each value of L . For large-area (or low-order) circuits, the overall gain is approximately independent of chip area, because the radius decreases so little when the chip packing is altered that little change in radiation loss occurs. As the area is reduced and the order increases, the gain suddenly falls dramatically. At this point, the circuit is now so compact that tight bends must be required. Previous simulations

Fig. 6. Variation of overall gain with chip area, for layouts 1A, 1B, 2A, and 2B and a fixed path length of 30 cm.

[22] have shown that this effect may be ascribed mainly to radiation of the signal, rather than radiation of the pump, modification of the core gain profile, or changes in the overlap of the signal beam with the gain distribution.

Fig. 6 shows the variation of overall gain with chip area for all four layouts (1A, 1B, 2A, and 2B) obtained for the same optical path length ($L = 30 \text{ cm}$). For each circuit type, a similar trend may again be seen. For large-area circuits, there is little to choose between any of the different layouts; each layout has an approximate gain of 15 dB, which would be obtained from a straight amplifier with these material parameters. This level of gain is suitable for many applications involving lossless splitters. As the area is reduced, differences between the layout become apparent. The abrupt fall in gain described above occurs at the largest area for layout 1A and at the smallest area for layout 2B. Layout 2B can, therefore, consistently provide the maximum gain for a given chip area.

To quantify this advantage, we consider the smallest chip area that can be adopted before the gain falls by 3 dB below the nominal value (i.e., before the gain falls to around 12 dB). For layout

TABLE III
PARAMETERS OF DIFFERENT LAYOUTS SIMULATED IN FIG. 7 (UPPER SET) AND FIG. 8 (LOWER)

Layout	Order N	Min. radius (mm)	Chip length (mm)	Chip width (mm)	Chip area (mm ²)	Gain (dB)
1A	5	3.69	15.98	15.88	253.7	7.11
1B	4	5.15	21.59	11.39	246.0	9.28
2A	5	3.75	16.15	16.20	261.6	11.62
2B	4.5	6.26	19.82	13.51	267.8	13.34
1A	5.5	3.42	14.86	14.96	222.4	2.98
1B	4.5	4.85	20.59	10.79	222.3	6.11
2A	5.5	3.47	15.14	15.19	229.9	10.14
2B	5	5.71	18.28	12.52	228.8	12.19

Fig. 7. Variation of gain with propagation distance for layouts 1A, 1B, 2A, and 2B, a fixed path length of 30 cm and a fixed chip area of $\approx 260 \text{ mm}^2$.

1A, this occurs at a chip area of $\approx 420 \text{ mm}^2$. For layout 2B, the corresponding value is $\approx 220 \text{ mm}^2$. Adoption of layout 2B instead of layout 1A can, therefore, result in a reduction in chip size of almost 50%. The advantage is, therefore, a significant one.

To understand this behavior, Fig. 7 shows the variation of gain with propagation distance, for layouts of types 1A, 1B, 2A, and 2B, assuming a fixed path length of 30 cm and a fixed chip area of $\approx 260 \text{ mm}^2$. Because of the discrete nature of the set of possible circuits, the areas differ slightly from layout to layout and full details of the dimensions and resulting performance are given in the upper four rows of Table III. For layouts 1A and 2A, the chip footprint is roughly a $16 \text{ mm} \times 16 \text{ mm}$ square and, for layouts 1B and 2B, it is a $22 \text{ mm} \times 12 \text{ mm}$ rectangle. Note that circuits of a given area involve different orders when realized using the different layouts.

For layout 1A, the gain initially rises steadily with propagation distance. Approximately halfway through the circuit, there is a sudden reduction in gain, when the central fold-back bends are reached. Similar behavior occurs for layout 2A. However, the abrupt fall in gain is now delayed until the tight bend near the output of the device. Furthermore, the reduction is approximately halved because the length of the tight-bending section is also halved. For layouts 1B and 2B, the gain near the input is slightly lowered compared with layouts 1A and 2A. However, because the abrupt changes are eliminated, the overall gain is increased considerably. The overall gain of layout 2B is approximately 6 dB higher than that of layout 1A, once again demonstrating the advantages of careful layout.

Fig. 8 shows a similar variation of gain with propagation distance for a chip area of $\approx 220 \text{ mm}^2$, and the lower four rows of Table III show the corresponding circuit parameters. The general trends are similar, but enhanced. For layout 1A, the radiation losses are so severe in the tight bending regions that the local gain actually becomes negative. However, a monotonic increase in gain with distance is still maintained in layout 2B. The overall gain of layout 2B is now approximately 9 dB higher than that of layout 1A, showing that careful layout becomes increasingly important as the chip area is reduced.

From Fig. 1, it should be clear that a circuit with layouts 2A or 2B and order N will have $N + 1$ orthogonal waveguide intersections, each of which must be crossed twice as the beam propagates around the optical circuit. It is, therefore, important to verify that the effects of introducing a potentially large number of intersections do not outweigh the advantages gained by optimizing bending losses.

The simulation of layout 2B was, therefore, repeated, modeling each intersection by assuming that the active guide is

Fig. 8. Variation of gain with propagation distance, for layouts 1A, 1B, 2A, and 2B, a fixed path length of 30 cm, and a fixed chip area of $\approx 220 \text{ mm}^2$.

Fig. 10. Variation of the reduction in gain due to guide intersections with propagation distance, for a layout of type 2B, a path length of 30 cm and a chip area of $\approx 220 \text{ mm}^2$.

Fig. 9. MoL model of waveguide intersections for layout 2B and order 5.

crossed at appropriate points along the optical path by passive guides of similar core dimension and refractive index. This model is somewhat unrealistic, because the intersecting guides themselves form part of the active circuit and will clearly be pumped at least to transparency under normal conditions. However, it gives a reasonable figure for the worst-case additional loss. The intersections were implemented by inserting additional lines defining refractive indexes appropriate for a passive intersecting core, as shown in Fig. 9. These lines were separated by considerably smaller values of Δs than elsewhere.

The calculations were performed for a 30-cm-long amplifier with the same parameters as before, coiled into a chip of 220-mm^2 area using layout 2B. In this case, the circuit is of order $N = 5$, which contains six orthogonal intersections that must each be crossed twice. Very little change was found from the previous calculation. To highlight the additional loss caused by the intersections, Fig. 10 shows only the variation with distance of the reduction in gain caused by the intersections.

As can be seen, the effect of the intersections is mainly to cause the gain to fall abruptly at regular intervals. For the majority of the circuit, each discrete drop in gain corresponds to a single intersection and each intersection is separated by roughly one turn of the spiral layout. There is also a more gradual re-

duction in gain between each intersection. Near the output of the device, there is a single, much larger fall in gain, because the active guide must cross six closely spaced guides to exit the spiral. The reduction in gain caused by each intersection (including both the abrupt and gradual contributions) varies from point to point, but is of the order of $0.015\text{--}0.02 \text{ dB}$ and the total reduction in gain is less than 0.2 dB . This figure is relatively insignificant compared with the gain advantage associated with layout 2B. The conclusions reached earlier are, therefore, qualitatively unaltered by the addition of even a moderately large number of waveguide intersections.

V. DISCUSSION

The optical layout of erbium-doped planar waveguide optical amplifiers based on spiral and folded spiral layouts has been considered. It has been shown that layouts may be ranked according to their ability to provide maximum gain within a given chip area, and an optimum layout is identified from an initial set. The best layout appears to be a spiral containing both straight and curved waveguide sections, in which the radii of curvature are equalized everywhere, as far as possible. The output is taken from the chip by orthogonal waveguide crossings, which do not appear to contribute significant loss. Clearly, the set of possible layouts may be enlarged (for example, to include more continuous bends or bend angles other than 90°). However, the results obtained even from the restricted set considered here confirm the effectiveness of a strategy that maximizes the minimum bend radius and minimizes the length of any tight-bending sections. Because the advantages appear significant, optimization of this general type will pay dividends in practical EDWAs.

The detailed simulation was carried out using a propagation algorithm based on rate equation modeling and the MoL. Clearly, a number of different rate equation models might have been used, including (for example) different numbers of levels, or different model coefficients. However, it is not considered that the conclusions above are model specific, so that adoption of a different model will still generate similar broad conclusions concerning the advantages of the different layouts.

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