Insertion loss reduction between single-mode fibers and diffused channel waveguides

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Methods of reducing the insertion loss between single-mode fibers and graded-index channel waveguides, namely, annealing and backdiffusion, are analyzed theoretically and compared. Mode mismatch and misalignment losses are calculated to determine the best method and the optimal conditions for their use. The main result of this paper is that, in the single-mode regime, there is no apparent advantage in using backdiffusion instead of the simpler annealing process, in contrast with the multimode case. In the coupling loss calculation, a numerical simulation of waveguide formation by potassium–sodium ion exchange in glass is used for illustration.

I. Introduction

With the development of efficient integrated optical devices for signal processing in the past few years, the problem of reducing the coupling loss between these devices and single-mode optical fibers has received increased attention. Three distinct experimental approaches have been demonstrated recently to achieve that goal. The methods used all rely on refractive-index profile modifications to match the mode of the channel guide to that of the fiber. The purpose of this paper is to compare theoretically the behavior of the mode shape under the first two of these methods, namely, annealing and backdiffusion, to understand better how they result in lower insertion losses. Also, we will be able to determine optimal conditions for their use, and their relative merits and limitations. The third method, a global index change reduction without size change, is discussed briefly to highlight its similarities with the other two. This study will be carried out with the help of a numerical simulation of the diffusion processes involved in these methods.

The only other contributions to coupling loss are the Fresnel loss and the alignment loss. These can be addressed separately by using antireflection coatings where necessary and by careful positioning of the fiber before bonding. The effect of misalignment on coupling loss in various cases of interest is also calculated.

II. Methodology

In this work we use a computer simulation of the formation of channel waveguides made by potassium–sodium ion exchange in glass, at a wavelength of 633 nm, as an example to calculate the mode mismatch loss in various cases of interest. This choice was made because of the availability to us of an extensive characterization of such waveguides. It does not limit the applicability of our result to other types of graded-index waveguide for which the diffusion parameters are known (LiNbO₃ based devices, for example).

Three contributions can be identified for the mode mismatch loss. Waveguide modes are smaller, more elliptical than the fiber modes and strongly asymmetric in the depth direction. The parameters of interest are listed in Table I. The power loss due to mode mismatch is evaluated by the following overlap integral between the amplitudes of the fiber mode \( \psi_f \) and the guided mode \( \psi_g \) (Ref. 5):

\[
I = \frac{\left( \int_{-\infty}^{\infty} dx dy \psi_f^* \psi_g \right)^2}{\left( \int_{-\infty}^{\infty} dx dy \psi_f^2 \right) \left( \int_{-\infty}^{\infty} dx dy \psi_g^2 \right)} .
\]  

To calculate the waveguide mode, a highly accurate Rayleigh-Ritz variational method was used, and only single-mode cases were considered. Once the mode is found, the mode size parameters \( w_i \) are obtained from the half-intensity contours (0.707 normalized amplitude contour of the \( E_y \) field of the TE₀₀ mode). It was verified in all cases that the waveguides remain single mode after the profile redistribution processes. For the fiber mode, a step-index fiber with a diameter of 4 \( \mu \)m and a relative index change of \( \Delta = 0.3\% \) is used. The normalized frequency of the fiber is \( V = 2.25 \) (in the single-mode regime), and its mode size, in the Gaussian mode approximation, is 2.3 \( \mu \)m (defined as
Table I. Definition of Size Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
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<tbody>
<tr>
<td>$a = w_i/w_f$</td>
<td>$e^{-1}$</td>
</tr>
<tr>
<td>$b = w_f/w_i$</td>
<td>$e^{-1}$</td>
</tr>
</tbody>
</table>

FIBER MODE FIELD

WAVEGUIDE MODE FIELD

the radius at which the field amplitude is equal to $e^{-1}$). This corresponds to a full width at half-maximum intensity of $w_f = 2.71 \mu m$.

To evaluate the integral in Eq. (1), the following approximation is used:

the waveguide mode is expressed by a simple function made up of a product of a Gaussian in the width ($y$) direction and a sum of two half-Gaussians in the depth ($x$) direction, using the mode size parameters defined previously to fix the size of the Gaussians, and centering the fiber mode on the maximum of the guided mode ($x = y = 0$):

$$
E_{\lambda}(x,y) = G(y)F(x),
$$

$$
G(y) = \exp\left[-\left(y^2/w_y^2\right)\right],
$$

$$
F(x) = \exp\left[-\left(x^2/4w_x^2\right)\right]; \quad x < 0
$$

$$
\exp\left[-\left(x^2/4w_x^2\right)\right]; \quad x > 0.
$$

Substituting these in Eq. (1) yields for the overlap

$$
I = \int \left( \frac{4}{w_f^2} + \frac{1}{w_y^2} \right)^{-1/2} + \left( \frac{4}{w_f^2} + \frac{1}{w_x^2} \right)^{-1/2} \right) w_f w_y w_x
$$

In general, the fiber mode is circular and larger than the guided mode. Therefore, the guided mode size must be increased ($w_f$ and $w_\perp \rightarrow w_f$), rendered less elliptical ($\epsilon \rightarrow 1$) and more symmetric ($\alpha \rightarrow 1$). In these limits $I \rightarrow 1$, and the mismatch loss becomes zero.

III. Annealing

In the first case, annealing, the initial channel is heated in the absence of a source of dopant. The result is that the waveguide dimensions increase and the magnitude of the index change decreases, because the dopant already in the glass diffuses over a greater

Fig. 1. (a) Refractive-index change contours normalized to the value found at the surface of the initial guide: $\Delta n_z = 0.09$ (substrate index 1.513). Case 1, annealing of initial guide with $D = 5 \mu m$ and $t = 48$ min. (b) Normalized amplitude contours of the fundamental TE mode of waveguides shown in (a) (amplitude maximum shown as +).
The effect on the diffusion continue at the same temperature (i.e., with the same diffusion coefficient). The effect on the index and mode profiles is shown in Fig. 3, and the resulting mode size parameters and mismatch loss in Fig. 4. As was desired, the initial ellipticity is smaller, and as was expected the minimum loss is much improved, reaching 0.08 dB/facet. In this instance, an inconveniently small mask aperture was needed (2 μm) to keep the waveguide single-mode at the long exchange time (2 h). However, the use of longer operating wavelengths (1.5 instead of 0.633 μm) would relax that requirement to a great extent.

It is interesting to note that in this case the ellipticity and asymmetry behave in the opposite way to what they did for the first case. This means that no predictions can be made about the effect of annealing on the behavior of these two parameters. We will come back to this in the conclusion.

IV. Backdiffusion

In the second method, backdiffusion, the goal is to symmetrize the index profile in the depth direction by diffusing the initial guide with a dopant which reduces the index. In our case, the potassium–sodium exchange is followed by sodium–potassium exchange to achieve this, a narrower mask aperture and longer exchange time were used at the same temperature (D = 2 μm, t = 120 min, yielding an effective depth of 2.8 μm).

The initial and annealed index and mode profiles are shown in Fig. 5 for the same initial guide as in Fig. 1. The increase in mode size (Fig. 6) is much faster in this case (note the time scale) because of the rapid reduction of the maximum value of index change which was originally located at the surface, and the first to be affected by the backdiffusion. As a result, the waveguide mode gets closer to cutoff and increases in size. However, there is little evidence of significant improvement in asymmetry. Also, the ellipticity decreases instead of increasing as was expected. The explanation of these findings is that the dominant mechanism seems to be the reduction of the maximum index change instead of the rearrangement of the profile shape.

Since the effect of backdiffusion is similar to that of annealing for that case, it is interesting to see how it
compares in the other case of the less elliptical initial waveguide. This is shown in Fig. 7, with the associated parameters in Fig. 8. Again, we see very little difference from annealing, and no evidence of decrease in asymmetry, in spite of the fact that the index profile is more symmetric.

This confirms our belief that the dominant mechanism of both annealing and backdiffusion is the reduction of the maximum index change which brings the waveguide mode closer to cutoff and enlarges its size in both directions (depth and width), regardless of the detailed shape modifications of the index profile. In Fig. 9, the maximum index change is plotted against both annealing time and backdiffusion time for the two initial guides considered, highlighting the similarity of the two methods. In view of this fact, these two methods can be considered equivalent, and also to the third method mentioned in Sec. I, namely, a global index change reduction without size change, which is obtained by reducing the amount of dopant available, but keeping the size of the index profile unchanged.5

Using the parameters calculated from Eq. (4), it becomes possible to evaluate Eq. (5) in any of the cases discussed above. This was done for the annealed waveguides, the backdiffused cases yielding essentially identical results, with the results plotted in Fig. 10. The first point to note is that the minimum coupling loss does not occur when the center of the fiber is aligned with the maximum of the guided mode but rather when it is displaced by ~0.2 μm toward the guide surface. A minimum loss of 0.05 dB is reached in this manner for case 2. Also, we see that the only effect of annealing is to shift the whole curve toward smaller values, without appreciable change of shape. Howev-

\[
I = \frac{4w_d w_f \exp \left[ \frac{-2.8x^2}{w_f^2 + w_d^2} \right]}{w_1 (w_f^2 + w_d^2)} \left[ \frac{w_d \exp \left[ \frac{-2.8x^2}{w_f^2 + 4w_d^2} \right]}{\sqrt{w_f^2 + 4w_d^2}} \right] \text{erfc} \left( \frac{-2.4x \sqrt{w_d}}{w_f \sqrt{w_f^2 + 4w_d^2}} \right) + \frac{w_f \exp \left[ \frac{-2.8x^2}{w_f^2 + 4w_d^2} \right]}{\sqrt{w_f^2 + 4w_d^2}} \text{erfc} \left( \frac{-2.4x \sqrt{w_d}}{w_f \sqrt{w_f^2 + 4w_d^2}} \right). \tag{5}
\]

Fig. 3. (a) Same as Fig. 1(a) for case 2: Annealing of initial guide with D = 2 μm and t = 120 min. (b) Same as Fig. 1(b) for case 2.
Fig. 4. Same as Fig. 2 for case 2.

Fig. 5. (a) Same as Fig. 1(a) for case 3: backdiffusion of initial guide with $D = 5 \mu m$ and $t = 48$ min. (b) Same as Fig. 1(b) for case 3.

Fig. 6. Same as Fig. 2 for case 3.
Fig. 7. (a) Same as Fig. 1(a) for case 4: backdiffusion of initial guide with $D = 2 \, \mu m$ and $t = 120 \, min$. (b) Same as Fig. 1(b) for case 4.

Fig. 8. Same as Fig. 2 for case 4.

Fig. 9. Maximum value of index change, normalized to the surface value of the initial guides ($\Delta n_s$), as a function of time for a, case 1; b, case 2; c, case 3; d, case 4.
er, this has the significant result of relaxing the alignment tolerance considerably. In case 2, for example, if the maximum allowable loss per facet is fixed at 0.25 dB, the acceptable offset in X and Y increases from ±0.2 μm to almost ±0.6 μm with annealing.

VI. Conclusion

In conclusion, it seems that a proper choice of the initial waveguide parameters is more important in determining the minimum loss obtainable with these methods than the choice of which method is used. Also, there does not seem to be a very good correlation between the changes in the refractive-index shape and those of the mode which it guides: backdiffusion symmetrizes the index profile to a great extent, but hardly affects the mode profile asymmetry, in total contrast to multimode cases where highly symmetrical field profiles have been achieved. Further, annealing is just as efficient as backdiffusion in moving the peak of the field profile away from the surface, thereby reducing propagation losses due to scattering.

Therefore, annealing of a properly designed channel waveguide may be the preferred method of mode mismatch loss reduction because of the relative simplicity of this experimental process over the other two discussed here. We have shown that mismatch losses as low as 0.05 dB/facet are possible with this method. We have also demonstrated clearly how the alignment tolerances are relaxed by annealing.

Finally, all the methods have the characteristic of burying the mode maximum away from the waveguide surface, a distinct disadvantage for active devices which rely on interactions between the modal field and perturbations generated near the surface of the substrate. This problem can be alleviated by tapering the mode size from the fiber joint to the active device region. On the other hand, for passive devices, the burial of the guide below the surface does not pose a problem and may in fact contribute to lower propagation losses because of reduced surface scattering. Fabricating such devices in glass would also reduce Fresnel losses to negligible levels (lower than 0.01 dB). This would make them competitive to all-fiber devices, which have poorer reproducibility and are less amenable to economical mass-production, as has been demonstrated for multimode devices already on the market.

References