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Smit, M.K.; Vreede, De, A.H.

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Adapting the mode profile of planar waveguides to single-mode fibers: a novel method

M. K. Smit and A. H. de Vreede

A novel method for coupling single-mode fibers to planar optical circuits with small waveguide dimensions is proposed. The method eliminates the need to apply microoptics or to adapt the waveguide dimensions within the planar circuit to the fiber dimensions. Alignment tolerances are comparable to those of fiber-fiber coupling. The low loss potential of the method is experimentally demonstrated for Al$_2$O$_3$ waveguides on silicon substrates.

Key words: Integrated optics, coupling.

I. Introduction

The problem of low cost coupling planar optical circuits with small waveguide dimensions to fibers has not yet been solved. Low cost solutions suffer from high coupling losses. To obtain low losses the planar mode profile must be matched to the fiber mode. This is most frequently being done with microoptical components. Alignment tolerances are in the submicron range resulting from the dimensions of the planar waveguide. The coupling problem is further aggravated by the strong ellipticity of the mode profile within most small size waveguides.

Although efficient coupling methods are presently applied industrially, they suffer from high fabrication costs. The cost of a pigtailed cleaved-mirror laser, for example, is many times the cost of the laserchip. It will be difficult, if not impossible, to reduce the coupling costs to the same order as future chip costs. The main problems are in the alignment and the packaging, where the relative positions have to be fixed within submicron precision under widely varying operating conditions.

The problem can be solved by creating a gradual local change of the planar waveguide geometry near the coupling region to adapt the mode profile to the fiber mode. In this approach the alignment and packaging costs will be reduced, the problem now lies in the reproducible fabrication of the nonplanar films, which are necessary for the adiabatic conversion of the mode profile. In this paper, another approach is proposed and experimentally tested, which allows for a fiber-matched output beam without having to adapt the transverse waveguide geometry.

II. Basic Principle

The prism coupler is widely used for experimental purposes. Coupling efficiency of the commonly applied configuration with a uniform tunneling gap is maximally 80% for Gaussian beams. Better coupling efficiencies can be obtained by applying a tapered tunneling layer, which yields a bell-shaped output beam, as shown in Fig. 1.

The width of the output beam is determined by the taper angle of the gap and will decrease monotonously to the transverse width of the guided mode if the taper angle is increased to 90°, corresponding to a perpendicular endface. A particular taper angle will thus exist for which the transverse width of the outgoing beam is matched to the width of a fiber mode. Consequently, it is possible to match the transverse width of the output beam of an arbitrary planar waveguide to a fiber mode by appropriately choosing this angle. The lateral width is determined by the lateral mode width, it is easily matched to the fiber mode by applying a planar taper.

The principle can be applied to couple light from a planar circuit to a fiber if a high index liquid is applied between the fiber and the waveguide. The index of this material has to be greater than the effective index of the mode, which is to be coupled out of the waveguide. Permanent connections can be made, in principle, with UV-hardening epoxies or low meltingpoint eutectics, if the optical and mechanical properties can...
be made sufficiently stable. In the following we will refer to the high index material as the prism material.

In the present paper, the potential of the above coupling principle is theoretically analyzed and experimentally demonstrated for the 633-nm wavelength. The latter wavelength was chosen because of the availability of accurate measurement equipment operating at this wavelength. The principle applies equally well to other wavelengths. The present experiments were designed for establishing the validity of the theoretical description given in the next section.

III. Coupler Analysis

A. Output Beam Shape

Two regimes should be distinguished in calculating the shape of the output beam. For small taper angles, evanescent field coupling will be the dominant mechanism. For large taper angles, the coupling region will become so short that evanescent coupling and diffraction effects are small and the coupling can be described as refraction of a parallel beam through a skew endface.

(1) In the evanescent coupling regime the radiated power is equal to the power leakage of the guided mode, so that the output beam shape can be computed by solving the differential equation describing the power decay of the guided mode from radiation leakage:

\[
\frac{dP(z)}{dz} = -2a(z)P(z). \tag{1}
\]

The attenuation coefficient \(a\) is dependent on thickness \(g\) of the tunneling layer and follows from the effective index as \(a(g) = -N''(g)k_0\), in which \(N''(g)\) is the imaginary part of effective index \(N\). The complex effective index of a prism loaded waveguide can be obtained numerically in several ways; we applied a transfer matrix method.\(^{10}\) The local attenuation coefficient \(a(z)\) follows from \(a(g)\) by substituting the (linear) dependence of \(g\) on \(z\). Numerical solution of eq. (1) yields the \(z\)-dependence \(P(z)\) of the guided power, from which power \(S(z)\) radiated per \(\mu m\) as follows:

\[
S(z) = -\frac{dP}{dz} \approx 2a(z)P(z). \tag{2}
\]

Figure 2 shows the beam shapes \(S(z)\) along the \(z\)-axis, radiating from the fundamental modes (TE and TM) in an aluminum-oxide waveguide on silicon substrate, as described in Sec. IV, for two different taper angles (1° and 2°).

The above computations are valid as long as the mode is able to adapt its profile adiabatically to the changing waveguide structure. This will be the case as long as the ray propagation angle \(\theta_m\) after reflection is smaller than the critical angle at the reflection interface, i.e., \(\theta_m = \theta_m + 2\theta_i < \theta_c\), in which \(\theta_c\) is the critical angle of the waveguide structure and \(\theta_m\) is the ray propagation angle corresponding to the guided mode. The reason for applying small sized waveguides is usually the requirement to keep the waveguide single-moded despite a relatively large index contrast. Critical angles in small-sized waveguides will therefore be large, in the order of 10 to 20°, and no problems should be expected in applying the above computation method until close to the end of the waveguide, where the mode approaches cutoff and \(\theta_m\) comes close to \(\theta_c\).

(2) In the refraction regime most of the guided power reaches the skew endface before being coupled out of the waveguide by evanescent coupling or diffraction. Computation of the beam shape in the refraction regime is straightforward. From Fig. 2, it is seen that the transition from the evanescent to the refraction regime...
Fig. 3. Refraction of a parallel beam through a skew endface.

starts before taper angles of 2°. For this taper angle not all of the guided power is coupled out of the waveguide before it becomes degenerate (at $z = z_e$ in Fig. 6(a)).

B. Output Beam Width

In the evanescent coupling regime effective width $w_s$ of the output beam, measured along the $z$-axis (see Fig. 3), is computed from

$$w_s = \frac{\int S(z)dz}{S_{max}}.$$  \hspace{1cm} (3)

Figure 4 shows the effective width as a function of the taper angle, for both polarizations. In the refraction regime $w_s$ follows directly from the effective mode width $w_m$ (Fig. 3):

$$w_s = w_i \cos \theta_t = w_m \cos \theta_t,$$  \hspace{1cm} (4)

in which $w_i$ is the beam width measured along the skew interface. The dotted curve in Fig. 4 shows the width computed according to this formula. The different predictions are close to each other. If we were able to correct for the truncation error, which can be observed in the beam shape for the 2° taper (see Fig. 2), the curves would come even closer for taper angles in excess of 1.5°.

The effective beam width $w_p$ follows from the assumption that the amplitude profiles match at the skew interface:

$$w_p = w_s \sin(\theta_p + \theta_t) \approx w_s \sin \theta_p.$$  \hspace{1cm} (5)

In this formula $\theta_p$ is the propagation angle at the output beam, which follows, both for the refraction and the evanescent coupling regime, from the field continuity conditions at the skew interface:

$$\theta_p = \arccos \left( \frac{N}{n_p} \cos \theta_t \right) - \theta_t = \arccos \left( \frac{N}{n_p} \right) - \theta_t,$$  \hspace{1cm} (6)

where $N$ is the mode index. For the waveguide configuration used in the present experiments $w_m \approx 0.30 \, \mu m$, with a negligible difference between the two polarizations. The radiation angle $\theta_p$ is approximately 25°. In the refraction regime an effective 5-μm width, which is representative for a fiber mode, requires a value $w_s \approx 12.5 \, \mu m$, from which a taper angle of 1° is computed through Eq. (4).

C. Coupling Efficiency

Coupling performance is determined by overall coupling loss $L$, which consists of two components:

$$L = L_r + L_m \quad (dB),$$  \hspace{1cm} (7)

where $L_r$ represents the reflection losses at the skew interface and at the fiber tip, and $L_m$ the loss from field mismatch between the output beam and the fiber mode.

(1) Reflection loss at the fiber tip is easily estimated using the Fresnel reflection formula, it can be eliminated by applying an appropriate antireflection coating. The reflection at the skew interface is more difficult to predict. In the evanescent coupling regime the mode will be able to adapt itself adiabatically to the changing waveguide geometry, and there will be no reflected field. In the refraction regime the loss will be dominated by Fresnel-like reflection which approaches 100% near grazing incidence.

For guided beams, however, the reflection deviates from plane wave reflection, a difference which increases with increasing incidence angle$^{11,12}$. The mechanism has been analysed for reflection at a plane normal to the propagation direction of the mode. The reflection of a guided wave at strongly skew interfaces has not yet been analysed theoretically. Therefore, we determined it experimentally, as will be discussed in Sec. V.

(2) Loss $L_m$ due to field mismatch can be computed by taking the overlap integral between the output beam and the fiber mode along the $z$-axis. For ease of computation, we approximated the fiber mode as a Gaussian beam. For the experimental waveguide configuration and a taper angle of 1°, the effective width of the TE-polarized beam was found to be 12.5 μm and that of the TM-polarized beam 13.5 μm, as can be seen from Fig. 4. Figure 5 shows the overlap of the square root of the corresponding beam profiles $S(z)$ with a Gaussian profile with 12.5-μm width, as a function of the $z$-coordinate of the Gaussian beam center.
From the figure it is seen that on proper alignment of the beam relative to the output beams a transverse coupling efficiency in excess of 94% can be obtained for the TE- and TM-polarized beams simultaneously. This corresponds to a 0.25-dB coupling loss to a Gaussian beam; coupling loss to a fiber mode is expected to be close to this value.

The coupling loss thus calculated accounts for the amplitude mismatch only. Because the two polarizations have a different propagation constant, it will not be possible to match their phases simultaneously. The resulting coupling loss can be estimated by comparing the difference in radiation angles within the prism material with the N.A. of the fiber.

In the aluminum-oxide waveguide system the angular difference between the two polarizations in a medium with \( n = 1.74 \) is in the order of \( 1.9^\circ \), both at short and long wavelengths (if the film thickness is adapted such as to keep the V-parameter at a fixed value of 2). If the fiber mode is approximated as a Gaussian beam, the effective N.A. of the fiber follows from \( \text{N.A.} = \lambda / (4\omega) \). For an effective fiber mode width \( \omega = 2.5 \) at 1.3-\( \mu \)m wavelength, the N.A. will be 2°. If the fiber alignment is centered between the radiation angles of the two polarizations, the angular misalignment will amount to 40% of the N.A. for each polarization. Assuming a Gaussian radiation pattern, an angular misalignment equaling the effective N.A. angle will cause a coupling loss of \( \sim 3 \) dB (for Gaussian beams the effective width comes close to the FWHM). Because the coupling losses reduce quadratically with decreasing misalignment angle, they are estimated to be in the order of 0.5 dB.

In conclusion, the anticipated excess loss from both amplitude and phase mismatch is expected to be well below 1 dB for the present experimental waveguide system. As the output beam closely resembles the fiber mode, the loss from residual misalignment will be the same as in the fiber to fiber coupling case.

IV. Experimental Results

The experimental waveguide structure was realized in a SiO\(_2\)/Al\(_2\)O\(_3\)/SiO\(_2\) layer stack on a silicon substrate. The waveguides were fabricated by RF-diode sputter depositing a 0.25-\( \mu \)m Al\(_2\)O\(_3\) film (\( n \approx 1.69 \)) on a thermally oxidized silicon substrate, as described by Smit et al.\(^{13,14} \) The lateral waveguide structure is produced by atom beam milling a 40-\( \mu \)m step into this layer. The etched structure is covered with a 0.6-\( \mu \)m RF-magnetron sputtered SiO\(_2\) layer (\( n = 1.46 \)) so that an embedded ridge guide structure is obtained, in which light can be coupled with a prism as described by Pasmooij et al.\(^{15} \) The end section of the waveguide is covered with an additional 0.4-\( \mu \)m SiO\(_2\). In this thick cover region we polished a spherical hole with a metal ball, as indicated in Fig. 6(a). Figure 7 shows an interference contrast micrograph of the tapered edge with a waveguide ending up in the taper region.

The taper angle \( \theta \), at the edge of the hole follows from the diameter of the hole, which can be measured with a microscope, as

\[
\theta = \arcsin \left( \sqrt{\frac{D_b}{D_h}} - \frac{\Delta}{D_b} \right) \tag{8}
\]

in which \( D_h \) is the diameter of the hole, \( D_b \) is the diameter of the polishing ball, and \( \Delta \), the offset of the waveguide axis relative to the hole center.

To determine the quality of the beam coupled out of the waveguide, we coupled light into the waveguide at the thin cover region and imaged the light distribution.
Fig. 7. Interference contrast micrograph of a tapered waveguide section, revealing polishing grooves. The waveguide at the left is 6 µm wide.

Fig. 8. (a) Transverse (—) and lateral (— —) intensity distribution at the coupling region, as imaged on the CCD camera. (b) Transverse intensity distribution radiating from the TE- (—) and TM-polarized (— —) fundamental modes.

coupled out of the tapered region on a CCD camera through a small high index prism, with a long working distance microscope objective. The prism (SF6 glass, n ≈ 1.74) was optically contacted to the waveguide structure with a high index liquid (CH3I2, n ≈ 1.74). Figure 8(a) gives an example of the transverse and the lateral light distributions measured with this setup, Figure 8(b) of the transverse profiles measured for the TE- and the TM-polarized mode. The widths of the measured transverse distributions are indicated in Fig. 4, showing good agreement between theory and experiment. The results shown are for TE-polarized light.

To determine reflection loss \( L_r \) at the skew interface, we slide the output prism in the direction of the input prism and record curves, as shown in Fig. 6(b), for taper angles ranging from 1.1 to 1.6°. From the left to the right, the flat zone corresponds to the region where the output beam is detected by the photodiode mounted on the prism. The dip at the left of this zone corresponds to the region where the output beam is no longer detected by the prism mounted diode. The zone farthest to the left corresponds to the region with a thin cover layer, where the guided power is coupled out of the waveguide in the usual way. The slope is the result of the waveguide attenuation. By comparing the extrapolated curve with the power level in the flat zone at the right, the reflection loss at the skew interface is seen to be <1 dB for both polarizations, which is a promising result. The low reflection loss indicates that evanescent coupling is still the dominant mechanism for taper angles up to 1.6°.

V. Conclusions

A novel method is proposed for coupling monomode fibers to planar optical circuits with small waveguide dimensions. It combines the alignment tolerance of butt-coupling with a good coupling efficiency, without the need to apply microlenses. The method applies to a variety of waveguide structures.

If the polishing is performed with a flat polishing process on a number of circuits parallel to each other, simultaneous coupling to a number of circuits seems feasible, which gives the method a potential for low cost production. The experimental results obtained with the surface quality as shown in Fig. 7 indicate that the polishing requirements are not critical.

Based on theoretical calculations, supported by experimental results, coupling losses are anticipated to be in the order of 1 to 2 dB (1-dB beam-shape mismatch loss and reflection losses in the order of 1/2 dB).

References


