Device Length Requirement in Slab Fiber Evanescent Coupler

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The effective device length of fiber–half coupler geometry has been investigated by the modal method, and the minimum device length required by the device operation for a slab/fiber evanescent coupler has been computed.

Slab/fiber evanescent couplers have been the main interest of many researchers [1–8] due to the variety of applications as an in-line component in optical fiber communication systems. Many devices such as tunable spectral filters, intensity modulators, and components in optical fiber sensor systems may be realized by slab/fiber evanescent coupler structures.

Evanescent coupling from an optical fiber to a slab waveguide has been experimentally investigated and tested for various materials and configurations by a number of researchers [1–3]. Most of the experimental devices were designed by using a fiber half-block that allows the fiber to expose its core outside. In these studies the overlay slab waveguide has been formed either by index oil on top of the fiber half-block or by a crystal slab attached to the quartz block [4]. The most frequently used crystal materials are $LiNOb_3$ and $ZnSe$, and various glasses have been tested as an overlay slab. In addition to those crystals, some polymers have been used to design electrically tunable devices [5]. These experimental results have proved that this kind of device can be exploited to realize crucial components of various tasks.

A theoretical model of this kind of devices was first introduced by Marcuse [6] for an optical fiber and infinite slab waveguide, which is not bounded in two dimensions but only one direction. This model uses coupled mode theory (CMT) in which each waveguide, namely, fiber and slab, is assumed to keep its respective mode and mode profile for all configurations. The separation distance between two waveguides is assumed constant in the propagation direction z in Marcuse's model. A loss factor has been added to accommodate the attenuation in the fiber mode due to coupling into the unbounded continuous slab modes. Therefore, at the end of the coupling region the power virtually vanishes at the optical fiber due to this loss factor. However, other researchers [1, 7] have extended the model by accom-

modating the curved shape of the fiber half-block, so the power couples back and forth between waveguides and then vanishes at some distance due to a weak coupling coefficient where the separation distance is large. In both cases the unbounded continuous-slab modes have been discretized by introducing artificial boundaries at some distance from the origin (center of the coupling region) such that the fields assume a zero value at these points. Results [1, 7] obtained by these models show good agreement for those configurations that have small index differences and shorter wavelengths.

On the other hand, these two waveguide structures can be regarded as a single waveguide. Dinleyici has adapted this approach and showed that this method can also be used to obtain the device characteristics for various geometries and configurations [8, 9]. However, this second model revealed that for most cases only one of the modes (ridge mode; mode obtained for whole structure) is confined in the coupling region. Therefore the dispersion characteristic of this ridge mode is responsible for the device behavior, as opposed to the CMT model, which utilizes the coupling of isolated modes of the slab and fiber.

Although these two approaches yield similar results for the configurations used in the experiments, these results deviate and contradict at some point, such as the resonance point and explanation of the device operation [8, 9]. One of these discrepancies is the device length requirement, which is of main interest in this paper. The device length requirement may be defined as the required propagation distance in the fiber axis such that it will allow the power in the fiber to be extracted effectively as imposed by the device operation. In this paper we investigate the device length requirements of these methods and compare the results for practical applications.

The CMT approach uses the fiber half-block geometry that makes a curved boundary between waveguides; however, in the ridge mode approach this boundary is a straight line. In order to determine the device length we need to find out where the coupling between the slab and the fiber modes is weak enough to neglect the coupling at any further points. The distance between these points is defined as the effective device length. In the following section the effective device lengths of various configurations are calculated.

Effective Device Length for Fiber Half-Block

A typical fiber half-block is shown in Figure 1. Here R is the radius of curvature that the fiber makes in the quartz block, and D, which is normalized with the radius of the fiber core, is the separation distance between the waveguides ($D = d/\rho$). The fiber cladding is removed to expose the core, and the core is brought in touch with the slab waveguide; therefore there is no offset between waveguides. Because of the symmetry in the device, the total effective device length is defined as L.

D is a function of z and increases parabolically with propagation in the z direction. It is clear that we need to define a value for D such that at any further points the coupling strength is negligible. This value will be dependent on the configuration of the whole structure. Marcuse et al. [10] have investigated perturbations on the modes of a circular fiber brought by a plane (infinite half-space) that limits the cladding. The structure resembles a D-fiber where the core is circular and the cladding has been cut out from one side.
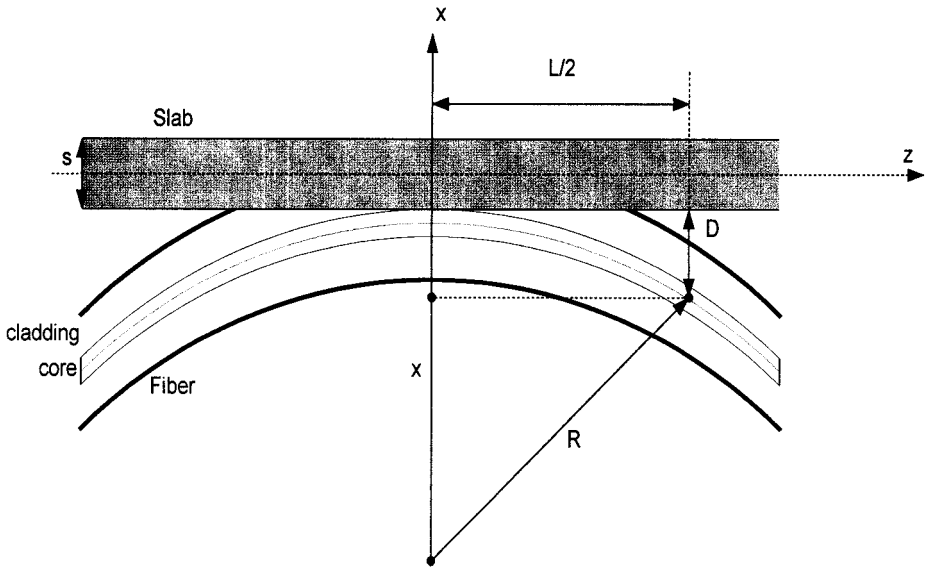
Figure 1. Fibre half-block geometry.

A mathematical model based on the modal expansion of the fields in various medium and matching these fields at the boundary is explained in Ref. [8]. We have used this technique to investigate slab/fiber structure [8, 9] and also the effect of the limiting plane on the circular fiber modes for various proximities. The bounded modes obtained by this method, which regards the whole structure as a single waveguide, are called ridge modes. These modes converge in either a slab mode or a fiber mode by increasing the separation between the slab and the fiber (i.e., waveguides are isolated or well separated), as shown in Figure 2.

Here, two different plots are obtained for the slab index greater than the index of the fiber core, and vice versa. The transverse propagation constant U is given by $U = \rho[(n_{core} 2\pi/\lambda)^2 - \beta^2]^{1/2}$ and in the case of the slab insolation, n_{core} is replaced by the slab core index (ρ is radius of the fiber core, n_{core} is the refractive index of the fiber core, and β is longitudinal propagation constant). P_{out} is obtained by decomposing the power of the first (input) fiber into the ridge modes and then repeating the procedure in reverse for the second (output) fiber. This geometry is depicted in Figure 3.

P_{out} and U converge the values of the isolated waveguide modes by an increase in the separation as shown in Figure 2.

Figure 4 shows the separation length required for a given V-number to convert the perturbed mode to the circular fiber mode. It is assumed that the ridge mode is converted to the isolated mode when the mode pattern (in power) of the ridge mode overlaps the isolated fiber mode's pattern more than 99%, which corresponds to almost -20 dB coupling loss. As the V-number increases, the power concentrates mostly in the core region of the fiber; therefore the mode field extends the cladding region very little, and D assumes smaller values in conjunction with the smaller V numbers.
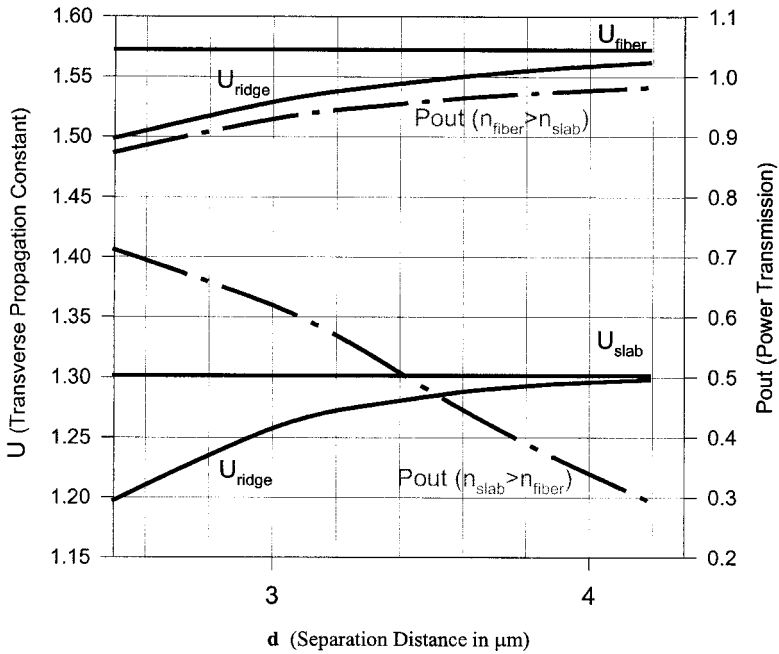
Figure 2. Convergence of ridge modes with increased separation.

For a given V number the effective device length can be described between the points after which the coupling coefficients are not sufficiently strong and effective. As an example, the following parameters are used to calculate the device length for the fiber half-coupler: $a = 2.5$ μm, $n_1 = 1.4646$, $n_2 = 1.46$, and $\lambda = 0.85$ μm. The V-number can be found to be 2.15. The corresponding D value, which is ~ 2, may be obtained from Figure 4. The actual value becomes $2a = 2 \times 2.5 = 5$ μm (which was normalized with the radius of the fiber core).

Referring to Figure 1, the effective device length L can be expressed as follows:
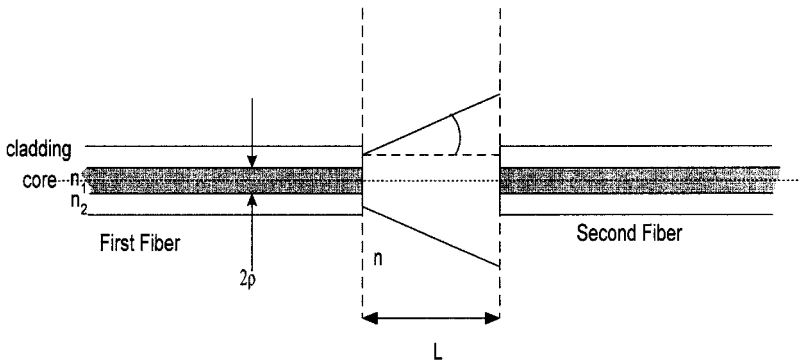
$$L \cong 2\sqrt{2\,RD\nu} \tag{1}$$

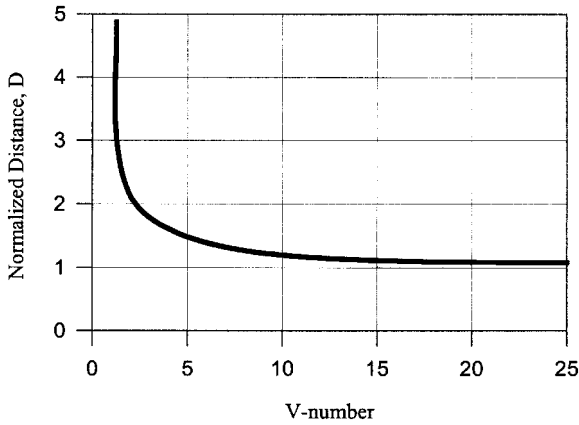**Figure 3.** Power coupling between two separated optical fibers.

Figure 4. Required separation distance for given V-number.

where R is the radius of curvature that the fiber makes. In this derivation, D is assumed to be much smaller than R ($D \ll R$). Figure 5 shows the effective device length as a function of the radius of curvature R.

As the radius of curvature increases, the boundary between two waveguides becomes flatter, and the effective device length approaches the device physical length. However, for larger values of R it is not possible to reach the fiber core for the circular core of ordinary fiber. Therefore many experimental devices are fabricated with the radius of curvature smaller than 100 cm, typically 50 cm. In Ref. [11] the effect of curvature on the transmission characteristic of the evanescent coupler has been investigated by the CMT method. This study has shown that the power couples in the shorter distances when the radius of curvature is increased. According to this study, it is not possible to extract the power completely from the fiber for $R = 50$ cm. This result is not precisely supported by the experimental results obtained by Andreev [1], who showed that it is possible to extract the entire power for $R = 50$ cm. However, as a general approach, the required radius of curvature is assumed to be about 50 cm, and the corresponding effective device
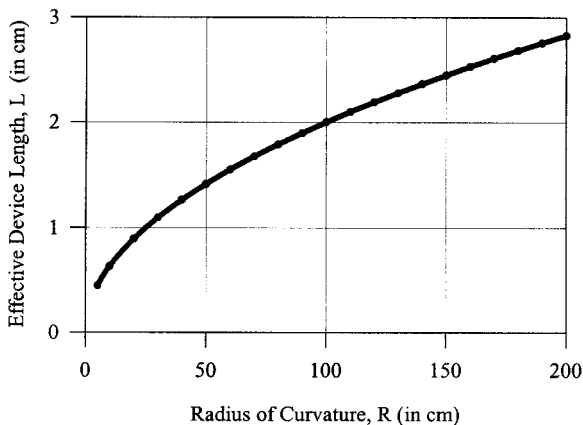

Figure 5. Effect of radius of curvature on the device length.

length can be computed, by the method explained above, to be ~ 1.5 cm. This length is long enough to allow complete extraction of the power. Consequently, studies using fiber half-couplers do not experience any trouble associated with the device length. On the other hand, there is no information about how small this length can be chosen, which is discussed in the next section.

Device Length Requirement in the Modal Method

Dinleyici [8, 9] has shown that the optical activities in the slab/fiber geometry can be explained by means of the ridge modes, which assume the whole structure as a single waveguide. Also, in most cases, only one of the ridge modes contributes significantly to the device performance. Therefore the device length calculation of the modal method differs significantly and conceptually from the CMT approach.

A fiber/slab coupler can be modeled by inserting the coupler between two optical fibers, as explained in Ref. [8] and shown in Figure 3, in order to obtain the power transfer characteristic. Since the whole device is fabricated from a single optical fiber, the coupler and input/output optical fibers are, in fact, the same optical medium. The field of the input optical fiber in the coupling region couples into the ridge mode(s), and excess power disperses into the slab waveguide region or unbounded continuum of modes. The power coupled into the ridge mode(s) is carried out to the output fiber without significant loss. However, the power dispersed into the unbounded slab modes (continuum of modes) is not supposed to reach the output fiber. Consequently, the problem is how to prevent the excess power from reaching the output fiber above a certain level and to calculate the device length accordingly.

The model, as shown in Figure 3, will be used to compute the required device length. Here we neglect the guidance effect of the slab on the unbounded continuous modes; therefore the excess power is assumed to radiate from the end-face of the first fiber, and some portion of this power is received by the output fiber. This assumption may be justified due to the fact that these three regions have the same optical property (refractive indices) and due to the continuum nature of unbounded modes.

Excess power will radiate and diffract from the end-face (tip) of the input fiber, and some portion of this power will be collected and guided by the output fiber. This diffracted pattern will be shaped by the mode field and the geometry of the fibers. By assuming a single-mode fiber, the field of the fundamental mode may be expressed in the form of a Gaussian beam, as suggested by Ref. [13], as follows:

$$E_y = A \exp\left(\frac{-r^2}{\omega_0}\right) \qquad \frac{\omega_0}{\rho} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \qquad (2)$$

where ω_0 is the mode spot size at the input fiber end and is given by the expression above as in Ref. [14] for a step-index fiber; ρ and V are fiber core radius and V-number, respectively.

Radiation of the Gaussian field at the circular fiber tip may be considered as a Fresnel diffraction from the Gaussian aperture. By calculating the mode spot size
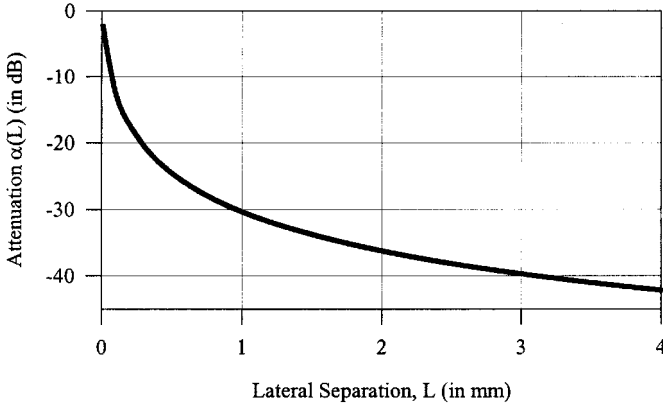
Figure 6. Attenuation caused by longitudinal separation.

ω_0 and the related Gaussian beam profile for a given configuration, the diffracted intensity can be expressed as follows:

$$I_0 = I_i \left(\frac{\omega_0}{\omega}\right)^2 \int_s \int \exp\left(\frac{-2r^2}{\omega^2}\right) da \tag{3}$$

where $\omega^2 = \omega_0^2 + \theta_0^2 L^2$ and $\theta_0 = \lambda/\pi\omega_0$, L is the longitudinal separation distance, and θ_0 is the diffraction angle. The mode spot size at the output fiber is approximated by the above relation, and the intensity is computed by the integral equation evaluated on the transverse plane at the output fiber.

The resultant attenuation $\alpha(L)$ becomes

$$\alpha(L) = \frac{\pi}{2}\left[1 - \exp\left(-2\frac{a^2}{\omega^2}\right)\right] \tag{4}$$

where a is the radius of the output fiber. The attenuation for the device having parameters $a = 2.5$ μm, $\lambda = 0.85$, $n1 = 1.4646$, and $n2 = 1.46$ is plotted versus separation distance in Figure 6. The V-number and the mode spot size at the input fiber are 2.143 and 3 μm, respectively.

At that point we need to decide how much excess power should be allowed to reach the second fiber in order to define the device length. For given configuration, 40 dB attenuation for the unwanted modes at the second fiber requires at least 3 mm device length.

Conclusion

We have found the effective device lengths of the fiber half-coupler for various radii of curvatures, as shown in Figure 5. Here the lengths are of the order of centimeters, while the prediction of modal analysis for the effective device length requirement is of the order of millimeters. Although the effective device length of the fiber half-coupler is about a thousand times greater than that calculated by the modal method, it should be noted that the modal method provides this result for

minimum distance requirement as imposed by this method's approach. However, as a result, it is probable that the experimental devices have more than enough effective interaction length.

The discrepancy between these two methods is conceptual [8, 9]. In the CMT, two modes couple back and forth while they propagate through the coupling region (beat length), and then the power mostly remains in one of the waveguides at the point where the coupling strength weakens due to the curved shape of the boundary. On the other hand, the modal method considers the entire waveguide as a single one and uses the dispersion characteristic of this mode to explain device operation. Here the modal method needs to dissipate the excess power before it reaches the second fiber, whereas the CMT needs to couple the power through the beat length. Therefore the device length requirements of these two methods are significantly different. On the other hand, the results obtained by the modal method may be considered as a minimum device length for a slab/fiber device.

In conclusion, the designed experimental devices have enough device length for proper operation. However, the effect of device length on device operation needs further experimental investigation. Also, these experiments will help to find the accuracy of estimations made by the CMT and modal methods.

References

1. Krassimir, P. P., and A. T. Andreev. 1994. Distributed coupling between a single-mode fiber and a planar waveguide. *J. Opt. Soc. Am. B* 11:826.
2. Johnstone, W., G. Thursby, D. Moodie, R. Varshrey, and B. Culshaw. 1992. Fiber optic wavelength channel selector with high resolution. *Electron. Lett.* 28:1364.
3. McCallion, K. W. Johnstone, and G. Fawcett. 1994. Tunable in-line fiber-optic bandpass filter. *Opt. Lett.* 19:542.
4. McCallion, K., and W. Johnstone. 1994. A tunable continuous-fiber-optic bandpass filter for sensor applications. In *10th Optical Fiber Sensor Conference*, 302.
5. Fawcett, G., W. Johnstone, I. Andonovic, D. J. Bone, T. G. Harvey, N. Carter, and T. G. Ryan. 1992. In-line fiber-optic intensity modulator using electro-optic polymer. *Electron. Lett.* 28:985.
6. Marcuse, D. 1989. Investigation of coupling between a fiber and infinite slab. 1989. *J. Lightwave Technol.* 7:122.
7. Zheng, S., L. N. Binh, and G. P. Simon. 1995. Light coupling and propagation in composite optical fiber-slab waveguide *J. Lightwave Technol.* 13:244.
8. Dinleyici, M. S., and D. B. Patterson. 1997. Vector modal solution of evanescent coupler. *J. Lightwave Technol.* 15:2316.
9. Dinleyici, M. S., and D. B. Patterson. 1998. Calculation of the wavelength filter properties of the fiber-slab waveguide structure using vector mode expansion. *J. Lightwave Technol.* 16:2034.
10. Marcuse. D., F. Ladouceur, and J. D. Love. 1992.Vector modes of D-shaped fibres *IEE Proc. J.* 139:117.
11. Zheng, S., G. P. Simon, and L. N. Binh, 1995. Analysis of couplers composed of a fiber half-block with a slab overlay: Effects of curvature of the fibre and asymmetry of the slab waveguide. *IEE Proc. Optoelectron.* 142(4).
12. Keiser, G. 1991. *Optical fiber communications*, 214. New York: McGraw-Hill.
13. Marcuse, D. 1978. Gaussian approximation of the fundamental modes of graded-index fibers. *J. Opt. Soc. Am.* 68:103.

14. Ohashi, M., N. Kuwaki, and N. Vesugi. 1987. Suitable definition of mode field diameter in view of splice loss evaluation. *Technol. Lett* 5:1676.

Biographies

M. S. Dinleyici was born in Turkey in 1963. He received his Ph.D. from Illinois Institute of Technology in 1997 and is now an assistant professor at the İzmir Institute of Technology, Turkey. His research interests include passive optical fiber component design and modeling and optical computing.