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Control of power-splitting ratio in asymmetric fused-tapered single-mode fiber couplers

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The extent of coupling in asymmetric fused-tapered single-mode fiber couplers is found to vary not only with the initial cladding diameters of the fibers to be tapered but also with the degree of fusion in the coupler. It is thus possible to optimize the coupling efficiency of dissimilar-fiber couplers by adjusting the degree of fusion without resort to etching the fibers. A simple slab-waveguide model is described that can account for these trends in coupler performance.

Fused-tapered single-mode 2 × 2 fiber couplers are available that have a flattened wavelength response and that are therefore useful in applications requiring a near-constant power-splitting ratio over a wide spectral range. Such couplers are fabricated by inducing an asymmetry in the constituent fibers, for example by pretapering one fiber before coupler fabrication,[1] by similarly pre-etching,[2] or indeed by using two unlike fibers.[2,3] In essence, all these methods produce an equivalent coupling structure; the single-mode fiber taper is a cladding-mode device, and the main differentiating factor among tapered fibers is therefore their overall diameter.

Couplers made from unlike fibers could also be useful for integrating systems having different fibers. For instance, in some fiber lasers pump light may need to be injected by a coupler at a wavelength that is well outside the single-mode range of the laser fiber. However, the use of a multimoded pump fiber would be problematical, requiring the launch and maintenance of only one pump mode in the fiber for efficient laser operation. One possible solution would be a coupler composed of two different fibers, the laser fiber and a fiber single-moded at the pump wavelength. It would be desirable for such a coupler to transfer the maximum possible pump light into the laser fiber, i.e., for the coupler not to show the wavelength-flattened response described above. This type of coupler response was attainable previously in unlike-fiber couplers only by differentially etching the fibers constituting the coupler in order to adjust the extent of cladding diameter asymmetry.[2]

The dependence of the maximum coupled power on the asymmetry in cladding diameters (for couplers made from fibers with similar cores) has been described in Refs. 1 and 2, where it was shown that the maximum coupled power decreases with increasing asymmetry. We demonstrate in this Letter that the maximum coupled power of an asymmetric coupler is also strongly dependent on the degree of fusion of the coupler and that it is possible to control the splitting ratio of an unlike-fiber coupler by adjustment of the degree of fusion, without resort to a differential etching or pretapering process before coupler fabrication.

The variety of potential applications for all types of asymmetric couplers underlines the importance of being able to model the behavior of these couplers in order to gain insight into their operation and hence to optimize their fabrication and performance. Unfortunately, previous models of the fused-tapered coupler can conveniently predict only the coupling coefficient,[4,5] whereas for asymmetric couplers it is the unequal excitation of the two lowest-order cladding modes of the tapered region of the coupler that determines the maximum coupled power and hence (with the coupling coefficient) the wavelength response. Since the determination of the maximum coupled power from existing models is somewhat involved, we outline a simple cladding-mode slab-waveguide model for the operation of asymmetric fiber couplers. Although this model is only qualitative and takes no account of the residual effects of the fiber cores in the coupler, it successfully predicts the experimental trends in maximum coupled power as the diameter asymmetry and the degree of fusion are varied.

Using conventional fabrication techniques, six 2 × 2 couplers were formed, couplers A, B, C, and F from fibers 1 and 2 and couplers D and E from fibers 1 and 3. Fiber 1 had a diameter of 80 μm, a N.A. of 0.22, and a cutoff wavelength λ_c of 675 nm; fiber 2 had a diameter of 100 μm, a N.A. of 0.14, and a λ_c of 525 nm; and fiber 3 had a diameter of 80 μm, a N.A. of 0.13, and a λ_c of 575 nm. Each fiber had a pure-silica cladding ($n = 1.458$). For each coupler, the progress of fabrication was monitored at a specific wavelength. For couplers A–D, tapering was stopped when all power returned to the launch fiber after one coupling cycle at a wavelength near 1 μm. Coupler D was then elongated through a further coupling cycle to give coupler E. Coupler F was similar to coupler A but was tapered through 11 successive coupling cycles at a wavelength of 800 nm. Figures 1 and 2 show the spectral logarithmic splitting ratios of the output powers of couplers A–C and D and E, respectively. The unusual behavior in the range below 650 nm is the result of launch fiber 1's being multimoded at these wavelengths. Figure 3 shows the variation of the maximum splitting ratio (m.s.r.) of coupler F at 800 nm with coupling cycle number. Un-

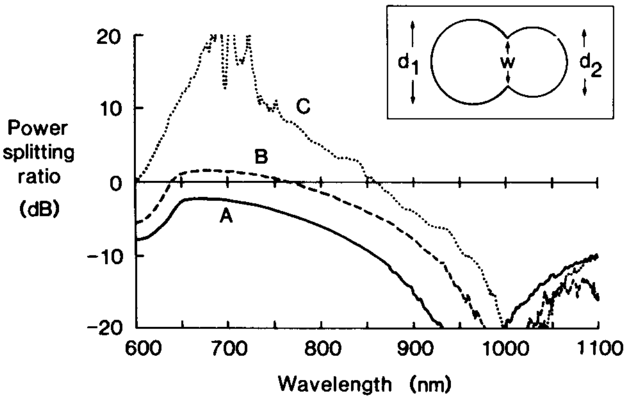

Fig. 1. Spectral power-splitting ratio [$=10\ \log_{10}(P_b/P_a)$, where a is the launch fiber] for different-diameter unlike-fiber couplers: A, with degree of fusion 0.58 and loss 0.05 dB; B, with degree of fusion 0.72 and loss 0.4 dB; and C, with degree of fusion 0.83 and loss 0.7 dB. Inset: schematic of the cross section of an asymmetric coupler; the degree of fusion is w/d_2.

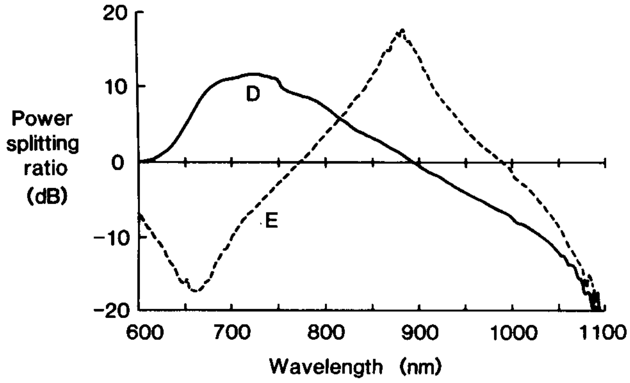

Fig. 2. Spectral power-splitting ratio for same-diameter unlike-fiber couplers D and E with degree of fusion 0.60 and loss 0.2 dB in each case.

polarized light was used throughout, and no polarization effects were observed.

After being characterized, the couplers were cleaved at the taper waist and the cross sections measured to determine each coupler's degree of fusion. To quantify this parameter, we define it to be the ratio of the width of the neck in the coupler cross section to the diameter of the smaller fiber in that cross section (w/d_2 in the inset of Fig. 1); the degree of fusion of coupler D is assumed to be that of coupler E. For each coupler, the degree of fusion and the loss are given in the figure caption.

Couplers A–C were fabricated from the same pair of unlike fibers. The main difference among these three couplers is their degree of fusion, which has an increasing trend from coupler A to coupler C. From Fig. 1 it is seen that the m.s.r. of these coupler shows a strong increasing dependence on the degree of fusion. Indeed, the spectral splitting ratio of coupler C approaches that expected for a standard symmetric coupler, with complete power transfer at certain wavelengths. Hence, by adjustment of the degree of fusion, it is possible to obtain efficient power transfer between fibers that have not been dimensionally tuned[6] by etching. That fibers 1 and 2 are not coincidentally dimensionally tuned without etching is demonstrated by the inefficient power transfer of coupler A. It should be noted, however, that well-fused couplers are more prone to loss than weakly fused couplers, as is demonstrated by couplers A–C.

The results of Refs. 1 and 2 show that the m.s.r. of an asymmetric coupler decreases rapidly as the coupler asymmetry increases. This trend is supported by the results shown in Figs. 1 and 2. The couplers made from the different-diameter fibers 1 and 2 exhibit only partial power transfer, except coupler C, for which the high m.s.r. is due to the degree of fusion effect. However, coupler E, which was made from different fibers with equal cladding diameters, displays almost complete power transfer, as is routinely achieved in symmetric couplers, although the degree of fusion is similar to that of coupler A. This extent of coupling is a consequence of the cladding-mode nature of the single-mode fiber taper, so the tapered region of coupler E is essentially equivalent to that of a symmetric coupler. The less-than-complete power transfer in coupler D is probably the result of a residual core effect, since coupler D was not tapered as far as coupler *F*.[7] We are justified in comparing the peak splitting ratios of couplers D and E even though they lie at different wavelengths, as we have found little variation in the size of the splitting ratio peaks of our couplers when each peak's wavelength position is changed by continued tapering. The wavelength-band restriction observed elsewhere[8] in dissimilar-fiber couplers is absent in our couplers; this is probably because the asymmetry due to differences between the residual cores is less pronounced in the fibers used here compared with those used in Ref. 8 and also because we have not accentuated the effects of these core differences by etching down the fibers' cladding diameters.

Figure 3 shows the variation of m.s.r. with coupling-cycle number for coupler F. The absolute coupler width will decrease as the coupler is tapered further, thus altering the nature of the cladding waveguide region as well as its length. From Fig. 3 it appears that there is clearly little dependence of the m.s.r. on the coupler width once coupling commences.

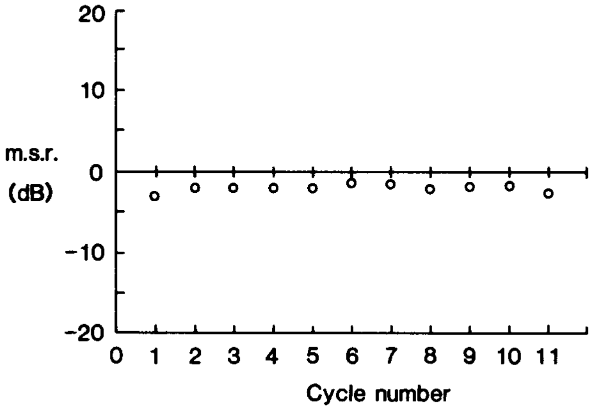

Fig. 3. Variation of m.s.r. with coupling-cycle number for coupler F with a degree of fusion of 0.60.

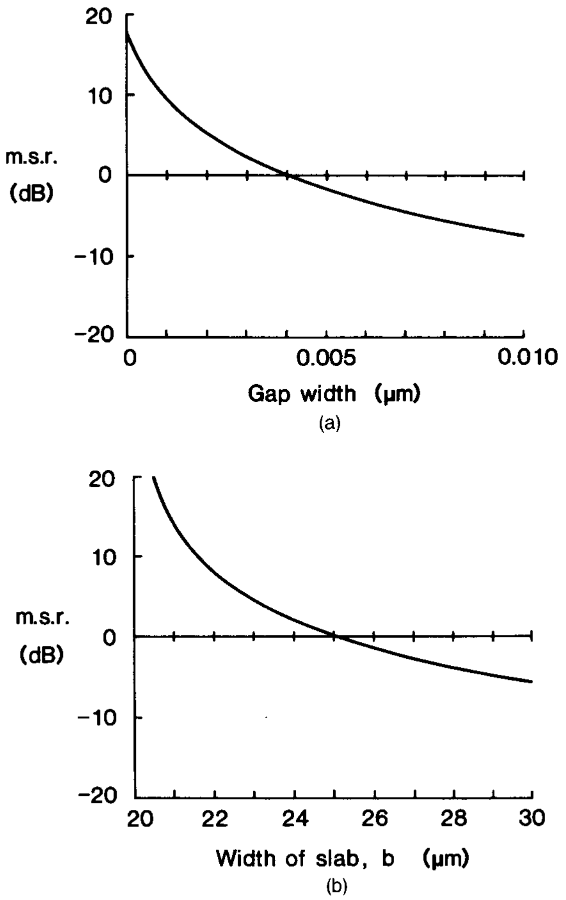

Fig. 4. Variation of m.s.r. for the slab model at a wavelength of 700 nm and with slab a 20 μm wide, with (a) gap width for slab b 25 μm wide; (b) width of slab b for a gap 0.004 μm wide.

A simple model is used to predict the above trends in coupler performance. The waist region of the coupler is represented by an asymmetric two-slab waveguide, with a gap separating the two slabs, a and b. The slab widths represent the tapered fiber cladding diameters, while the gap represents the degree of fusion (a smaller gap corresponds to a greater degree of fusion). The slabs and the surrounding medium are taken to have refractive indices $n_1 = 1.458$ and $n_2 = 1.000$, respectively.

For simplicity we assume a loss-free model. The electric field distributions E_1 and E_2 of the two lowest-order modes of the waveguide are computed for the wavelength of interest. The field distribution E_a representing the input field in slab a is taken to be that superposition of E_1 and E_2 that maximizes the power in slab a; the distribution E_b corresponding to maximum power in the other slab will then be the superposition of E_1 and E_2 that is orthogonal to E_a.

The modes E_1 and E_2 excited by the input field E_a are propagated a distance l (representing the interaction length of the coupler) along the waveguide with propagation constants β_1 and β_2, respectively. The resulting field is then overlapped with E_a and E_b, and the overlaps are squared to give the output powers and hence the splitting ratio. The distance l is chosen to maximize this splitting ratio and so to give the m.s.r.

The asymmetry in slab widths gives rise to an unequal excitation by the input field of the two lowest-order modes of the waveguide, which directly limits the coupling efficiency. Figure 4(a) shows the variation of the m.s.r. with the gap width at a wavelength of 700 nm, where slab a is 20 μm and slab b is 25 μm wide. The m.s.r. decreases with increasing gap width, a trend consistent with the decrease in m.s.r. with decreasing degree of fusion as found in the real couplers of Fig. 1. Figure 4(b) shows the variation of the m.s.r. with the slab-width asymmetry, where the gap width is fixed at 0.004 μm, the wavelength is again 700 nm, and slab a is fixed at 20 μm while slab b is varied from 20 to 30 μm. The m.s.r. is found to decrease with increasing asymmetry, which is again consistent with the experimental trend discussed above. For a given ratio of slab widths with no gap, it is found that the absolute size of the two-slab waveguide has a negligible effect on the m.s.r., as would be expected for a highly multimoded (large V) waveguide. This is verified by the results in Fig. 3.

In this Letter we have shown that the operation of asymmetric couplers depends not only on the level of asymmetry but also on the degree of fusion of the fibers. It has been shown both experimentally (using unlike fibers with comparable cores) and for a simple slab-waveguide model that the maximum power transfer in asymmetric couplers decreases with increasing asymmetry but increases with increasing degree of fusion, even though the model is a cladding-mode model and cannot account for core effects in either the waist or the tapered regions of the coupler. Knowledge of the above trends in the behavior of such couplers allows for more flexibility in their fabrication. For instance, if a coupler fabrication rig always yields the same degree of fusion, then we require good control (by etching or pretapering) over the initial fiber diameters to achieve a given maximum power transfer. On the other hand, if we have two fibers with suitable initial diameters, then control over the degree of fusion of the coupler should be sufficient to produce the required power transfer without the need to etch or pretaper the fibers.

References

1. D. B. Mortimore, Electron. Lett. **21**, 742 (1985).
2. R. G. Lamont, K. O. Hill, and D. C. Johnson, in *Digest of Topical Meeting on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1985), p. 78.
3. R. G. Lamont, K. O. Hill, and D. C. Johnson, Opt. Lett. **10**, 46 (1985).
4. F. P. Payne, C. D. Hussey, and M. S. Yataki, Electron. Lett. **21**, 561 (1985).
5. K. S. Chiang, Electron. Lett. **22**, 1221 (1986).
6. K. O. Hill, D. C. Johnson, F. Bilodeau, and S. Faucher, in *Digest of Topical Meeting on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1987), p. 116.
7. M. N. McLandrich, Electron. Lett. **24**, 8 (1988).
8. K. O. Hill, D. C. Johnson, and R. G. Lamont, in *Digest of European Conference on Optical Communication* (Instituto Internazionale delle Comunicazioni, Genoa, 1985), p. 567.