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Practical tuning mechanism for fused-tapered couplers

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The axial twisting of a fused-tapered single-mode fiber coupler causes optical decoupling, which can change the power-splitting ratio of the coupler. Twisting of the coupling region causes a redistribution of the modal fields away from the coupler axis as a result of an effective refractive-index change. A simple analytical expression is derived that describes this decoupling effect. An environmentally stable package is implemented that allows a coupler's response to be tuned through all possible values.

The fused-tapered single-mode fiber coupler is a popular component for many fiber applications, as it is simple to fabricate and is environmentally stable.[1] However, no practical method of tuning the power-splitting ratio of tapered couplers has been found. It is known that an induced bend in a tapered coupler will affect the coupler's splitting ratio,[2,3] but this effect has not been successfully exploited in a practical device. This is in contrast to the polished coupler, which finds widespread laboratory use as an adjustable power splitter.[4]

We have found that the splitting ratio of a tapered coupler can also be tuned by inducing an axial twist in the coupler and that this tuning is the result of a decoupling effect. By twisting a coupler that has been tapered through many coupling cycles during fabrication, some important trends in the behavior of twisted couplers have been determined. From an analysis of the twisted coupler, a simple equation that describes the decoupling effect is derived. A prototype packaging container for fused-tapered couplers is described that is temperature and vibration insensitive and that allows the power splitting of the coupler to be readily tuned between 0 and 100% at the operating wavelength.

A fused-tapered single-mode fiber coupler (coupler 1) was made in the conventional manner[1] and was tapered through one complete coupling cycle at 870 nm, i.e., the optical power returns completely to the throughput fiber at this wavelength. After fabrication, but without being packaged, the coupler was subjected to various degrees of twisting and was characterized. To avoid the effects of bends, care was taken to ensure that the coupler remained taut; and by positioning adhesive tabs along the untapered fibers we confirmed that all the twisting was absorbed by the tapered region alone.

Figure 1 shows the variation of the logarithmic splitting ratio of the output powers of the coupler with the amount of twist at a wavelength of 870 nm. The splitting ratio was seen to vary across all possible values, from no power coupled to all the power coupled, over 480° of twist in either sense. This variation was found to be reversible as the coupler was untwisted. The coupler insertion loss of 0.1 dB suffered no significant change at any stage.

Figure 2 shows the spectral splitting ratio of the coupler for different degrees of twist, the amount of twist increasing from curve (a) to curve (c). The features of the graph shift toward the longer wavelengths with increasing twist, which is the opposite of what happens as tapering proceeds during coupler fabrication, and we conclude that twisting a coupler induces decoupling rather than further coupling. Twisting clearly has a pronounced effect on the coupler, since the coupling strength at 870 nm is halved as the power transfers from one fiber to the other over the 480° twist.

The coupler suffered many 480° twisting–untwisting cycles without degradation. The coupler was finally destroyed after approximately eight consecutive revolutions of twist in the same sense. In a fatigue test, a similar coupler underwent more than 9000 tuning cycles without twist-induced degradation. Tapered couplers are clearly robust enough for twist tuning to have practical applications.

A second coupler (coupler 2) was tapered through one coupling cycle, as was coupler 1, but was fabricated under a larger tapering tension. This resulted in a longer, less strongly fused coupler than coupler 1. (In this Letter the strength, or degree, of fusion refers to

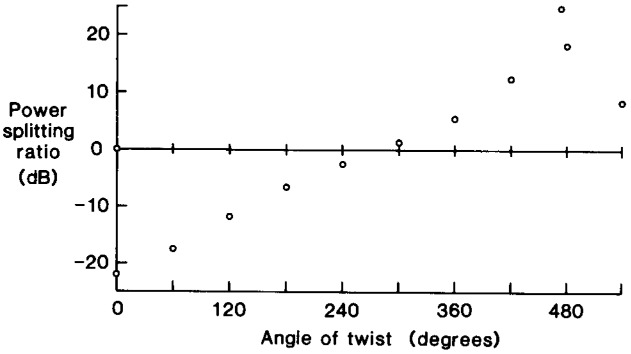

Fig. 1. Variation of the power-splitting ratio [$=10\log_{10}(P_b/P_a)$, where a is the launch fiber] at 870 nm of coupler 1, as a function of the axial twist angle.

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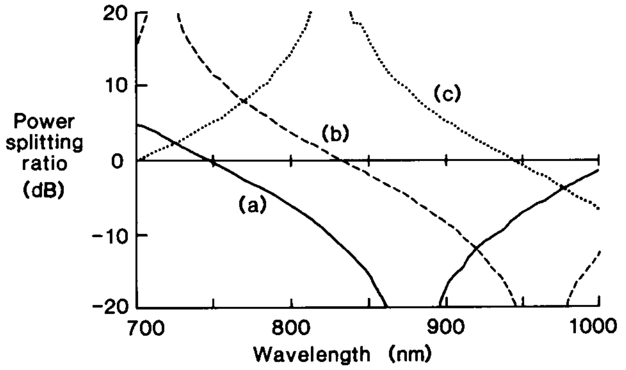

Fig. 2. Spectral power-splitting ratio of coupler 1 under progressively increasing amounts of twist: (a) for 0°, (b) for 240°, (c) for 480°.

the geometry of the coupler's cross section.) In this case the coupler required two revolutions of twist to tune across the full range of splitting ratios at the operating wavelength of 850 nm. A number of similar couplers were twisted, and all exhibited similar properties, demonstrating the reproducibility of the tuning effect.

A further coupler (coupler 3) was fabricated with a degree of fusion similar to that of coupler 2 but was tapered through 10 coupling cycles at a wavelength of 810 nm. Figure 3 shows the variation of the splitting ratio of this coupler with the amount of twist. This coupler required more twisting (4.4 revolutions) to tune across the whole range of splitting ratios than did couplers 1 and 2, leading to the remarkable result that the greater the number of coupling cycles the coupler is tapered through, the less sensitive the coupler is to the effects of twisting. By continuing to twist the coupler, we found that this sensitivity increases as the coupler is twisted further from the untwisted position. These trends in the tuning sensitivity were confirmed by using a five-cycle coupler that was similarly tested.

It is now well established that the waist region of a fused coupler behaves as a composite multimode optical waveguide and that coupling is a result of interference between the two lowest-order modes in this region.[5] Coupling behavior is determined by the propagation constants of these two modes. In order to model the behavior of a twisted coupler, we express the modal fields in the waist region as functions of a set of twisted rectangular coordinates (x, y, z). When the wave equation is transformed into these coordinates it can be written in terms of an effective refractive index n_{eff} induced by the twist as follows:

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + (k^2 {n_{\mathrm{eff}}}^2 - \beta^2)E = 0, \tag{1}$$

where

$${n_{\mathrm{eff}}}^2 = \left[1 + \frac{(x^2 + y^2)}{c^2}\right] {n_0}^2, \tag{2}$$

x and y are transverse coordinates, $2\pi c$ is the twist pitch, and n_0 is the actual refractive-index distribution. The approximations are made that the waist region is highly multimoded and is narrow in comparison with the twist pitch. The effective index in Eq. (2) arises in a manner similar to that for the familiar effective index used in the treatment of bends in optical waveguides.[6]

Qualitatively, the increase in the effective index toward the edges of the coupler when the coupler is twisted causes a redistribution of the modal fields in the coupler away from the longitudinal axis. This reduces the field overlap between the two sides of the coupler, and hence decoupling takes place.

To derive a zeroth-order expression for the effects of a twist on a coupler, we represent the waist region of an untwisted coupler by a rectangular metal waveguide (this approximates a coupler waist that is highly multimoded and strongly fused), and the change in effective index resulting from an axial twist is treated by using perturbation theory. The changes in the propagation constants of the two lowest-order modes of this waveguide can then be calculated, and the following simple equation describing the effects of twisting can be derived:

$$T^2 = 32 \frac{N_0}{9} (N_0 - N), \tag{3}$$

where N_0 is the number of coupling cycles of the untwisted coupler at the wavelength of interest and N is the number of coupling cycles at the same wavelength after the coupler has been subjected to a total of T revolutions of twist. Although there is no explicit wavelength dependence in this equation, it should be noted that N_0 is a spectrally varying quantity.

Couplers 1 and 2 described above were tapered through an $N_0 = 1$ coupling cycle at the wavelength of interest and then tuned to an $N = 0.5$ coupling cycle. According to Eq. (3) this requires $T = 1.33$ twists, i.e., 480° of twist. This is exactly that needed to half-decouple coupler 1 and less than that needed to half-decouple coupler 2, which was less strongly fused and hence differed more from the modeling waveguide than did coupler 1.

By differentiating Eq. (3), the differential sensitiv-

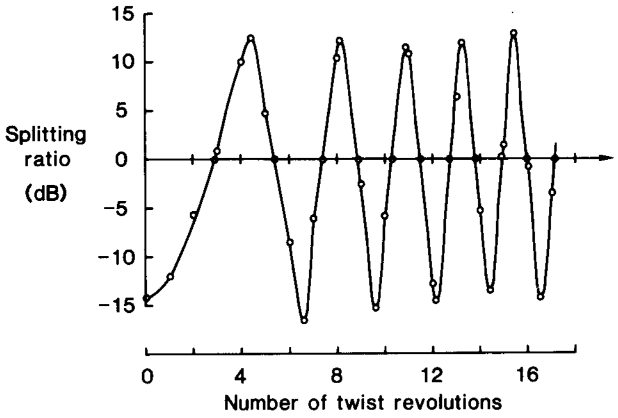

Fig. 3. Variation of the power-splitting ratio of 810 nm of coupler 3 as a function of the number of axial twist revolutions.

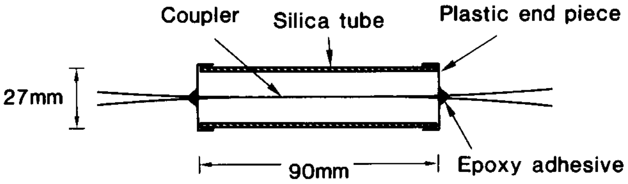

Fig. 4. Construction of a simple tunable coupler package.

ity of the coupler's splitting ratio to twisting can be expressed as

$$-\frac{\mathrm{d}N}{\mathrm{d}T}=\frac{9T}{16N_0}, \tag{4}$$

which decreases with the number of coupling cycles N_0 in the untwisted coupler and increases with the amount of twist T. Hence Eq. (3) correctly predicts the trends in the twist sensitivity of coupler 3 discussed above. The theory also provides a reasonable quantitative approximation to experiment for this coupler, considering the simplicity of our model.

An investigation was made into the design of a practical tuning package for fused-tapered couplers to utilize the twisting effect. After coupler 2 was fabricated it was packaged in a prototype cylindrical container consisting of a silica tube with plastic endpieces. In each endpiece a 1-mm hole was drilled, through which the fibers were threaded. After coupler fabrication the package was assembled around the coupler, and the coupler ports were fixed in the endpieces with epoxy adhesive while the coupler was kept taut between them (Fig. 4). The endpieces were free to rotate on the silica tube, and this provided the twisting mechanism.

To test the environmental stability of the packaged coupler, the coupler was tuned so that power emerged from both output ports and was then subjected to changes in external temperature. A change in temperature from 0 to 60°C gave rise to a 0.45% change in the fraction of the input power coupled, and the coupler insertion loss of 0.2 dB suffered negligible change. The packaged coupler was struck vigorously and dropped onto the bench from a height of 20 mm and suffered a coupled-power variation with an amplitude of typically 0.4%, and at no stage greater than 0.9%, owing to vibration of the coupler.

A further coupler was mounted in a similar package, which was then filled with a viscous uncured silicone elastomer (Dow-Corning Sylgard 182) to assist in the mechanical protection of the coupler. The tunability of the coupler was little changed by the addition of the elastomer; however, the temperature sensitivity of the coupler was increased to a 0.8% change in the fraction of power coupled per 20°C change in temperature. This increased temperature sensitivity is almost certainly due to the thermally induced change in the elastomer refractive index.

We have demonstrated that fused-tapered single-mode fiber couplers can be tuned with low loss across all splitting ratios by twisting. This process is reversible and repeatable without degrading the coupler performance (one coupler has been tested through more than 9000 tuning cycles without degradation). It has been shown experimentally (i) that tuning is a result of a decoupling effect, (ii) that this effect is so strong that one to two twist revolutions are sufficient to tune a one-cycle coupler across all splitting ratios, (iii) that sensitivity to twisting increases with the degree of fusion of the coupler, (iv) that the sensitivity decreases as the number of cycles that a coupler is tapered through increases, and (v) that the differential sensitivity increases as the coupler is twisted away from the untwisted position. A zeroth-order analytical expression has been derived, using an effective refractive-index method, that correctly predicts all the above features of twist-tuned couplers except feature (iii), which would require a more sophisticated model. A simple, controllable, and environmentally stable tuning package has been described, which should provide the basis for the design of a practical tunable tapered coupler.

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