All-fiber polarizer based on a null taper coupler

T. A. Birks, D. O. Culverhouse, S. G. Farwell, and P. St. J. Russell

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

Received March 22, 1995

An entirely new type of single-mode all-fiber polarizer is reported. The polarizer is based on a narrow circularly fused null taper coupler, which was twisted through 45° after being made. The polarizing effect is due to the excitation of hybrid second modes in the coupler waist. An extinction ratio of 15 dB and an insertion loss of 0.2 dB have been obtained, with scope for further improvement.

We report here a new type of all-fiber polarizer based on a null coupler.[1] This is a fused taper coupler made from two single-mode fibers that are so dissimilar that the maximum coupled power is zero; it is an extreme example of the wavelength-flattened coupler.[2] Thus a passive null coupler does not function as a beam splitter at all. Two different fibers can be used, or a pair of identical fibers can be made dissimilar by stretching (pretapering) one before the coupler is made. Either way, one fiber guides light with a larger propagation constant than the other; we describe this as the larger fiber and the other as the smaller fiber, which is literally the case with the pretaper technique.

An ideal null coupler is a perfectly adiabatic device; light in the larger fiber evolves into just the fundamental mode of the multimode cladding–air waveguide at the narrow coupler waist, whereas light in the other fiber evolves into just the second-order mode at the waist (Fig. 1). In both cases, at the exit of the coupler the light returns to the output end of whichever fiber it was originally launched into. This behavior has been described as mode splitting[3] and arises from the properties of the coupler's taper transitions. Such changes in mode symmetry are permitted because the coupler itself is not symmetric, so symmetry arguments cannot be applied. We have successfully used the null coupler as the basis of an all-fiber acousto-optic device, in which an acoustic wave couples light between the modes of the coupler waist.[1]

In fact each input fiber can carry two modes in its core—the two polarization states of the "single" mode—making four available modes in all. Each input mode evolves adiabatically into just one mode of the coupler waist. Where the cross section of the waist is noncircular, or the residual fiber cores are significant, the four corresponding modes in the waist are LP modes. However, if the waist is circular and the residual cores are truly negligible (as can be the case when the waist is very narrow), the four modes evolve in turn into a set of HE_{11}^{x}, HE_{11}^{y}, TE_{01}, and HE_{21}^{e} hybrid modes, as required by the circular symmetry.[4] We determine this evolution by assuming strict adiabaticity: light initially in the *n*th mode (in order of decreasing propagation constant) remains in the *n*th local mode throughout the device, whatever form that local mode may take. The evolution process and the field patterns of the modes are depicted schematically in Fig. 2, which was prepared in accordance with Ref. 5.

The TE_{01} and HE_{21}^{e} modes are two members of a family of second-order modes that includes the HE_{21}^{o} and TM_{01} modes, also depicted in Fig. 2. The latter two modes are not normally excited in the coupler waist, and any light coupled to them is lost (both remain cladding modes at the output of the coupler and are stripped by the fibers' coatings). However, the HE_{21}^{o} mode is just the HE_{21}^{e} mode rotated through 45° and is degenerate with it. If the coupler is twisted through an odd multiple of 45°, the HE_{21}^{e} mode becomes an HE_{21}^{o} mode relative to the output fibers, and so any light in it is lost. In contrast, the circularly symmetric TE_{01} mode is unaffected by the twist, and any light in it is returned to the smaller fiber without loss. Since the HE_{21}^{e} and TE_{01} modes are excited by light of different polarizations in the smaller fiber, the twisted null coupler acts as a polarizer for light in that fiber.

Light entering the larger fiber is of no interest here. The function of the larger fiber in the polarizer is simply to supply a destination, or dump, for the uninteresting HE_{11} modes of the coupler waist.

Because polarizer action (and the required twist angle of 45°) is determined only by circular symmetry, the polarizer should have a response as broad as the useful wavelength range of the single-mode fiber itself. Note that there is no metal or other polarization-sensitive overlayer in this structure; the lost polarization is finally absorbed in the fiber coating downstream of the coupler.

We used light with a wavelength of 633 nm for our experiments, because polarization optics are readily available for this wavelength and it enabled us to see

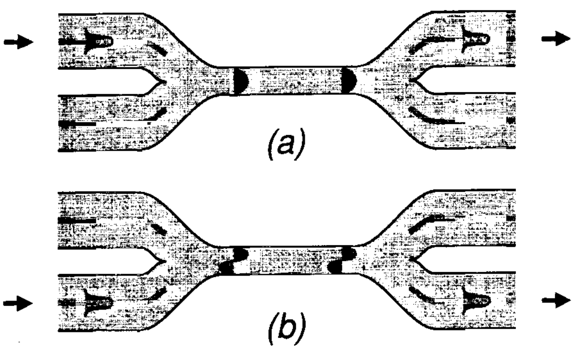

Fig. 1. Evolution of light through a null coupler when launched (a) into the larger fiber and (b) into the smaller fiber.

0146-9592/95/121371-03$6.00/0

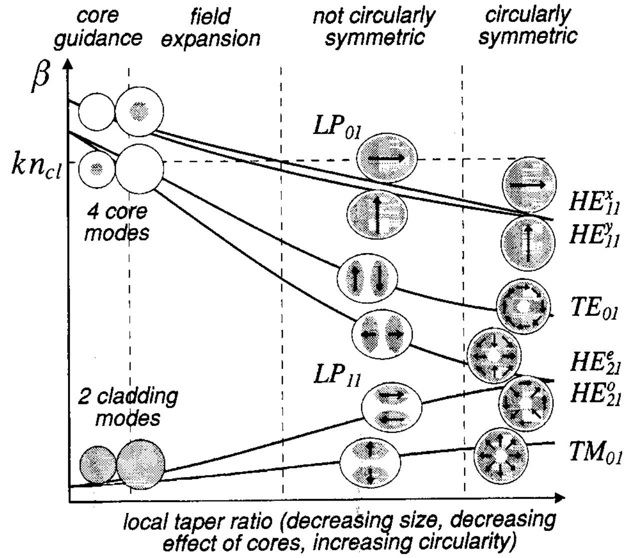

Fig. 2. Propagation constants β of the six lowest-order modes along a null taper coupler as functions of the local taper ratio. Also shown are the modal electric-field distributions where the fibers are separate at one end of the coupler (left-hand side; each picture represents two polarization states), within the coupler where the cladding–air waveguide is not circularly symmetric (middle), and at the waist of a narrow coupler where the waveguide is circularly symmetric (right-hand side). This figure is highly schematic; in particular, the field patterns are not to scale, and the β variations are illustrative only.

the relevant mode field patterns. We made a null coupler by pretapering one piece of single-mode fiber to reduce its diameter by 25% before elongating it with another (untreated) piece of the fiber to form the coupler. The coupler was stretched until the waist diameter was 2 μm; the length of the waist was 25 mm. The excess loss of the coupler was 0.2 dB, and the maximum splitting ratio was 1:4000, experimentally justifying the theoretical assumption of strict adiabaticity.

One end of the coupler was held at the center of a rotation stage, the other end being held fixed. Light from a polarized He–Ne laser was launched, via a bulk-optic half-wave plate and a fiber polarization controller, into one input of the null coupler. The light emerging from the corresponding output was monitored. The end of the coupler that was held in the rotation stage was used as the output, so that the input fibers were not disturbed when the coupler was twisted.

For input light in the fiber that was not pretapered, twisting had no effect. However, for input light in the pretapered fiber there was twist-dependent loss that was maximum for odd multiples of 45° twist. This loss was also dependent on the polarization state of the input light. The polarization controller was adjusted to maximize the loss, and the variation of output power with twist angle was measured. The orthogonal polarization state was then launched into the coupler by rotation of the half-wave plate, and the measurement was repeated. Both measurements are plotted in Fig. 3.

When the coupler was twisted through 45°, one input state of polarization in the pretapered fiber was substantially lost, while the other polarization was unaffected. For light in the pretapered fiber, the twisted coupler therefore acted as an all-fiber polarizer, with an insertion loss of 0.2 dB and an extinction ratio of 15 dB. Although this extinction ratio is not particularly large, its ratio with the insertion loss compares favorably with that of other types of fiber polarizer—an arbitrarily large extinction ratio can be obtained by concatenating polarizers, but the insertion loss will increase in proportion. Furthermore, the extinction ratio can be reduced by twisting the coupler through a different angle, yielding a variable-extinction polarizer for any application requiring such a device.

The maximum extinction ratio of this design of polarizer can be increased by making the coupler waist more circularly symmetric, for example, by making the coupler waist even narrower. The insertion loss of 0.2 dB can readily be improved; losses of less than 0.05 dB are routinely obtained for fused couplers, including narrow null couplers.

The polarizing behavior supports the assumption that a very narrow coupler waist is effectively circularly symmetric and so supports hybrid second modes. We confirmed this by cleaving the coupler at its waist, after the input polarization had been adjusted to give maximum loss in the twisted coupler. The emerging far-field pattern was ring shaped, as expected for a pure hybrid second mode. When a sheet polarizer was placed in the path of the emerging light, a two-lobed pattern resulted. As the sheet was rotated in one sense, the pattern rotated in the opposite sense. This is exactly what would be expected for an HE^{e}_{21} mode, as can be appreciated by examining Fig. 2 and taking field components in one direction. After we rotated the half-wave plate to give the orthogonal input polarization, there was a similar ring-shaped far-field pattern. However, with the sheet polarizer, a two-lobed pattern resulted that this time rotated in the same sense as the sheet, as expected for a TE_{01} mode. These two modes could be distinguished from the HE^{o}_{21} and TM_{01}

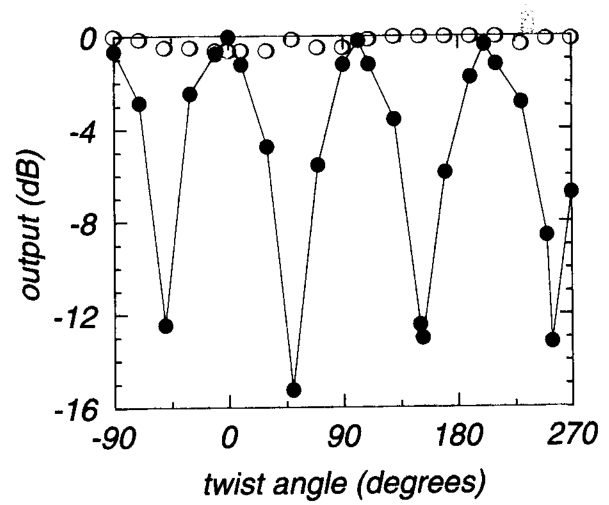

Fig. 3. Optical output power in the pretapered fiber of a null coupler with a 2-μm waist as a function of twist angle for input light polarized to give maximum loss (filled circles) and for light in the orthogonal state of polarization (open circles).

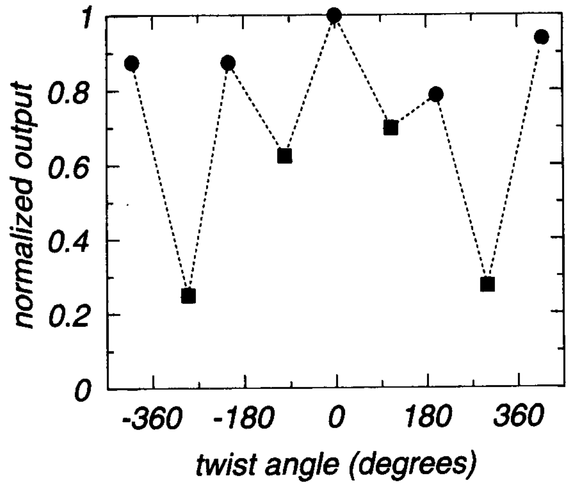

Fig. 4. Optical output power in the pretapered fiber of a null coupler with a 10-μm waist as a function of twist angle. Only the local maxima (circles) and minima (squares) of the oscillatory response are shown. This response is polarization independent.

modes by consideration of the absolute orientation of the lobes when the sheet polarizer is at 45°, thus verifying our understanding of the narrow null coupler.

The cleaved coupler waist was examined by scanning electron microscopy; the waist was indeed circular in cross section, with a diameter of 2 μm, as expected. A null coupler that is not so narrow behaves quite differently. Although the residual fiber cores in the waist of such a coupler have little effect on the guidance of light, they are still large enough to break circular symmetry. Also, in a wider waist the cross section is more likely to be slightly elliptical instead of perfectly circular. Thus the second modes in the waist more closely resemble the familiar LP_{11} modes than the hybrid modes. Figure 4 is a plot of output power versus twist for a null coupler with a waist of diameter 10 μm; the response was oscillatory, but only maxima and minima are plotted. The loss was polarization independent, the twist angle required for maximum loss was slightly greater than 90°, and the maximum loss increases with twist. This is characteristic of coupling between nondegenerate LP_{11} modes, as can be seen by rotation of the LP mode patterns shown in Fig. 2. When the coupler's waist was cleaved, the far-field pattern was a typical two-lobed LP_{11} pattern, with the nodal line perpendicular to the plane of the coupler.

We have demonstrated an entirely new type of all-fiber polarizer. The device is a narrow circularly fused null coupler that is twisted on its axis through 45°. The measured insertion loss of 0.2 dB can potentially be reduced to less that 0.05 dB simply by making the coupler less lossy. The measured extinction ratio of 15 dB is adjustable downward and can be improved by making the coupler waist more perfectly circularly symmetric. The polarizing effect is due to the excitation of hybrid second modes in the coupler waist. Since the effect is purely geometric, with no metal or other polarization-sensitive overlayers involved, the polarizer should function over the whole range of wavelengths for which the fiber is single mode.

This research was partly supported by the U.S. Department of the Air Force through the European Office of Aerospace Research and Development, London.

References

1. T. A. Birks, S. G. Farwell, P. St. J. Russell, and C. N. Pannell, Opt. Lett. **19**, 1964 (1994).
2. D. B. Mortimore, Electron. Lett. **21**, 742 (1985).
3. W. K. Burns and A. F. Milton, IEEE J. Quantum Electron. **QE-11**, 32 (1975).
4. A. W. Snyder and J. D. Love, *Optical Waveguide Theory* (Chapman & Hall, London, 1983), pp. 633–634.
5. Ref. 4, pp. 288, 319, 385, 634–636. Note that Fig. 18-3(a) is incorrect.