Single-mode-fiber 1 × N directional coupler

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We report the development of an adjustable single-mode-fiber multiterminal directional coupler that exhibits efficient coupling and uniform terminal output over a wide range of coupling coefficients. The device is made using a new technique that employs silicon V-groove substrates in the fabrication of arrays of evanescently coupled taps on single-mode fibers. The coupler is highly directional and polarization independent and exhibits excess loss as low as 0.09 dB per terminal in a 1 × 7 device. The fabrication technique may be extended to produce devices having large numbers of terminals. Applications include use in fiber data-bus systems and as a tapped delay line for broadband signal processing.

Introduction

Single-mode fiber is finding increasing use in a variety of sensing, signal-processing, and data-transmission applications. As a result, there is an increasing need for high-quality components capable of coupling two or more such fibers. For example, when single-mode fiber is to be used as a broadband data bus, it is important to be able efficiently to tap a small amount of the propagating signal and distribute it uniformly to a number of remote terminals.

Most existing single-mode-fiber directional couplers are four-port (two-fiber) devices that operate by means of the evanescent field coupling that occurs if the two fiber cores are physically close to each other. This proximity is achieved in these and similar devices by removing part of the fiber cladding, usually either by chemical etching[1,2] or by mechanical polishing.[3] A single-mode multiterminal directional coupler was first realized using a straightforward extension of the encapsulated etching technique.[4] In this Letter, we describe a new multiterminal coupler based on the mechanical polishing technique, which uses arrays of silicon V grooves to align and position precisely a series of single-mode-fiber taps. Like the four-port version of the polished coupler, this device offers adjustable coupling over a wide range, polarization independence, and low excess loss. Furthermore, the coupler exhibits excellent output uniformity that can be extended to a large number of terminals.

Fabrication and Operation

The coupler consists of two arrays of polished fibers that are mated through a thin layer of index-matching oil to form an array of evanescently coupled taps. Each fiber array is mounted on a substrate consisting of a silicon wafer bonded on a curved (typically 60-cm-radius) surface of a rectangular quartz block. The wafer has been anisotropically etched to form an array of V grooves whose spacing and depth are determined with submicrometer precision by using photolithographic planar processing techniques.[5] Each N-fiber array is fabricated by epoxy bonding subsequent turns of an N-turn coil into adjacent grooves of the silicon substrate. It is then processed by grinding in a plane defined by four quartz feet that have been mounted at the corners of the curved quartz surface. A portion of the cladding of the fiber (as well as some silicon and epoxy) is removed where the curved surface containing the fiber array intersects the grinding plane. After a substantial amount of the cladding has been removed, the array is polished until 90–99% of the input light can be coupled out of any one of the fibers by index-matching oil. At this point, the cores of the curved fibers are several micrometers below the surface (the exact distance depends on the wavelength and fiber curvature) yet are exposed enough to achieve the weak coupling desired in this device. The N-turn coil of one such array is then cut to form a terminal array of N separate polished fibers.

A 1 × N directional coupler is formed by mating the terminal array with an uncut but otherwise identical array of polished taps on a single continuous fiber (Fig. 1). A thin layer of index-matching oil inserted between the contacting surfaces increases the evanescent coupling and allows the two substrates to slide smoothly over each other. The device can then be easily adjusted to align each fiber of the terminal array with a corresponding tap of the continuous fiber. Since the strength of the coupling depends on the proximity of the fiber cores, the coupling coefficient can be adjusted by translation of one array with respect to the other. The precise spacing provided by the V-groove substrates ensures that the coupling at all taps will be reasonably uniform. The device is a 1 × N directional coupler in that a portion of any signal injected into the continuous fiber will be uniformly distributed among the N fibers of the terminal array. Likewise, a signal injected at any one of the N terminals will be directionally coupled back into the continuous fiber loop.

The coupler is mounted in a holder that holds the lower substrate fixed while the upper substrate may be positioned by micrometers that force it against spring-loaded dowels for lateral adjustability. This

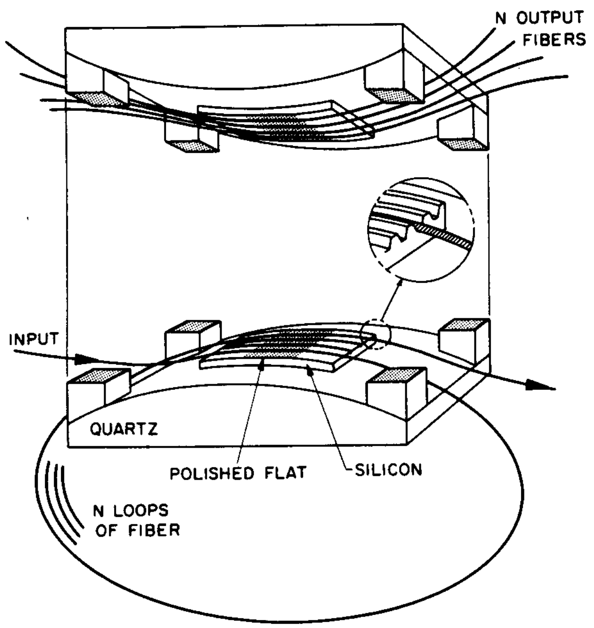

Fig. 1. Exploded view of 1 × N directional coupler. The N-fiber terminal array (above) is mated with the corresponding tap array on the continuous fiber coil (below) to achieve coupling.

allows the user to adjust both the parallelism and the relative offset of corresponding fibers in the two arrays. In this way, the coupling coefficients at all taps can be adjusted simultaneously to the same value, with the maximum coupling occurring when the fibers in the two arrays are exactly superposed. To ensure intimate contact between the polished regions of the two substrates, a small pressure plate may be used on the upper substrate to counteract any upward component of force that may be due to the micrometers and the spring loading.

Performance

The uniformity and the adjustability of the coupler were demonstrated by coupling a laser source into the continuous fiber coil and measuring both the coupled power at each terminal and the uncoupled power through the device. The coupling uniformity and the excess loss were then determined with the coupler adjusted for a variety of coupling coefficients. Figure 2 shows the results of such a test for a typical 1 × 4 coupler at a source wavelength of 633 nm. This device uses ITT single-mode fiber (4-μm core) bonded in V-groove arrays having a 500-μm groove period. The upper substrate was laterally offset relative to the lower substrate (as described earlier) to obtain five different mean coupling strengths, each of which corresponded to a different amount of offset (core-to-core distance) between corresponding fibers in the two arrays. The output uniformity was measured for each of these mean coupling strengths, which ranged from −49.5 dB (0.001%) to −11.1 dB (7.8%). The maximum deviation from the mean coupling coefficient was 1.9 dB (Fig. 2). The average excess loss was 0.18 dB per terminal. Devices having larger numbers of terminals have also been made. A seven-terminal device has exhibited coupling uniformity of ±1.6 dB with an excess loss of 0.09 dB per terminal.

Measurements of coupler directivity and polarization dependence were performed as described in Ref. 6. The coupling directivity was found to exceed 60 dB in all cases. The maximum variation in the coupling coefficient $\Delta\kappa/\kappa$ that was due to a change of the input polarization was approximately 0.005. These values are in agreement with theoretical and experimental values given for standard two-fiber couplers of this type.[6]

Discussion

As expected, this multiterminal coupler exhibits the desirable properties associated with the standard two-fiber polished coupler. The present output uniformity can be further improved by properly identifying the sources of error. Even if the coupling at all taps is identical, the output will monotonically decrease at successive terminals because of tapping and other losses, such as those that are due to scattering. The power output at the Nth terminal is given by

$$P_N = (1 - \alpha)^N (1 - \kappa)^{N-1} \kappa P_0, \tag{1}$$

where κ is the coupling coefficient and α is the excess loss per tap. For small α and κ, the expression can be expanded to give the ratio between the outputs of the Nth and the first terminals:

$$\begin{aligned} P_N/P_1 = {} & 1 - (N - 1)(\alpha + \kappa) + (N - 1)^2 \alpha\kappa \\ & + \tfrac{1}{2} (N - 1)(N - 2)(\alpha^2 + \kappa^2) + \ldots \end{aligned} \tag{2}$$

If α and κ are sufficiently small, the output nonuniformity that is due to these losses may be insignificant, even for devices having large numbers of terminals. For the 1 × 4 coupler presented here ($\alpha = 0.042$), the predicted difference between the first and last terminal outputs in the case of the strongest mean coupling ($\kappa = 0.078$) is 31% (1.6 dB). However, the unformity measurements do not show such a monotonic decrease in

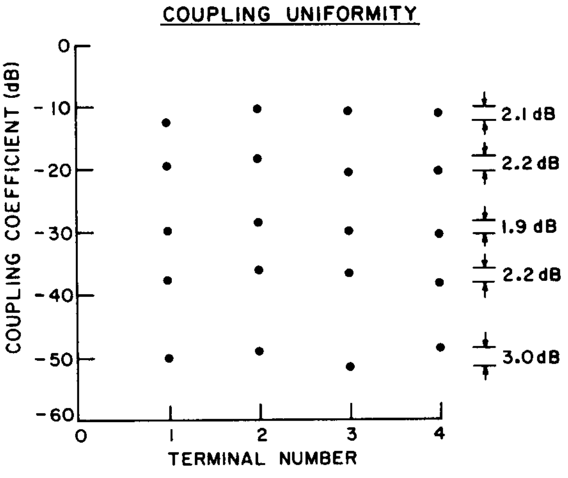

Fig. 2. Terminal output uniformity for five different adjustments of the mean coupling coefficient. The average excess loss is 0.18 dB per terminal.

output with terminal number. In fact, the fourth output is stronger than the first, and the deviation between the strongest and weakest terminal outputs exceeds the value predicted by Eq. (2) by 0.5 dB. In this case, therefore, the uniformity is predominantly limited by factors other than tapping or scattering loss, such as coupling nonuniformities caused by variations in the core-to-core spacing from one tap site to another. Where these losses do limit the uniformity, they can be compensated for (to first order) by polishing later taps closer to the core for increased coupling.

In devices such as the 1 × N coupler in which the maximum coupling is weak, the minimum core-to-core spacing at each tap is at least 3 or 4 core radii. In this case, the expression for the coupling coefficient[6] can be simplified and written as

$$\kappa = 2R\left(\frac{\lambda}{2\pi n_1 a}\right)^2\left(\frac{u}{V}\right)^4\frac{\exp\left[-v\left(\frac{h}{a}-2\right)\right]}{h}, \tag{3}$$

where R is the fiber radius of curvature, λ is the wavelength, n_1 is the core index, a is the core radius, and u and v are the transverse-mode parameters satisfying $u^2 + v^2 = V^2$, where V is the normalized frequency. The core-to-core spacing is h and is given by

$$h = (h_0{}^2 + y^2)^{1/2}, \tag{4}$$

where h_0 is the minimum (vertical) core-to-core spacing when the fibers are superposed ($y = 0$) and y is the lateral offset in the horizontal plane. By using these expressions and a maximum mean coupling coefficient of 7.8% for the 1 × 4 device, the minimum core-to-core separation h_0 is determined to be approximately 9.5 μm. When used with our uniformity data, these equations indicate that the variation in fiber separation among the taps is at most 0.6 μm of vertical offset and 3.3 μm of lateral offset. Since our photolithography is accurate to better than a micrometer in the horizontal plane, it is likely that most of the error is due to variations in the more-sensitive vertical spacing. These variations may be due to minor photolithography and processing variations, nonconcentricity of the fiber cores, polishing nonuniformities, and the presence of particles in the V grooves under the fibers. It is expected that further improvements in output uniformity and reduction of excess loss will be achieved as the fabrication and polishing techniques are refined.

It is important to note that, since the taps on the continuous fiber coil occur in series, the device can also be used as a tapped delay line to perform any of a large family of signal-processing functions. The continuous fiber tap array can be mated with a standard coupler half to form a variable-delay line.[7] If the terminal outputs of the 1 × N coupler are simultaneously summed, the device can be used as a transversal filter that selectively passes modulation at frequencies corresponding to the reciprocal tap spacing and higher harmonics.[8] For example, the device described here has a tap spacing of about 50 cm (2.5-nsec delay) and if used as a filter would have a fundamental passband at 400 MHz. This tap spacing was chosen for convenience and can be made much shorter (several hundred picoseconds when the present design is used) to reach a higher fundamental frequency. Since single-mode fiber filters exhibit large numbers of uniform overtones,[9] filtering at frequencies of tens of gigahertz may be accomplished.

Summary

We have presented a new technique for fabricating arrays of evanescently coupled taps on single-mode fibers. These arrays have been used to form an adjustable multiterminal directional coupler that exhibits efficient, uniform power distribution over a wide range of coupling coefficients. The fabrication technique also represents a new way of making fiber tapped delay lines for high-speed signal processing as well as a means for the eventual mass production of standard polished coupler halves.

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