Polished coupler and resonator fabrication

Robert P. Dahlgren
The Charles Stark Draper Laboratory, Inc.
555 Technology Square, Cambridge, Massachusetts 02139
Tel: (617) 258-1158 Fax: (617) 258-1131

Robert E. Sutherland
Micracor Inc., 43 Nagog Park
Acton, Massachusetts 01720
Tel: (508) 371-2114 Fax: (508) 371-3095

Abstract

Polished coupler technology has developed several niches for prototype and breadboard applications, particularly for birefringent fiber. Applications include variable splitting ratio couplers, ultralow-loss devices, resonant rings and cavities, and evanescent-field-based devices. This paper will discuss the processing of polished couplers, including coupler substrate preparation, principal axis alignment, fiber-to-groove bonding, and substrate polishing. Coupler assembly, including adjustable, adhesive-bonded, optical contact bonded (OCB) designs, and resonator assembly will be described. Data from several spliced and spliceless resonators will be presented, including single-eigenstate-of-polarization, polarization rotating, and high-finesse devices.

Introduction

Several approaches have been developed for the coupling of single-mode optical fiber,[1] such as polished, etched, micro-optic, fused, and integrated optic. One of the first practical and widely-used techniques was the polished coupler,[2] which enabled a number of fiber-optic sensors to be demonstrated. More recently, high-performance fused coupler devices that exhibit ruggedness have been developed by the fiber gyro community.[3,4] In the future, fused couplers will be increasingly used in commercial and military photonic instruments, and are already widely used in fiber-based telecom and CATV systems. It is the authors' opinion that polished coupler technology will continue to find applications in prototype development, adjustable coupling situations, resonant cavities, and evanescent sensors and devices.

Lapped coupler technology is becoming mature; products are being developed for high performance, not high reliability or full environment. It is well suited for fabrication of couplers from birefringent fiber because the polished surface provides a good reference to align the principal axes. The interested reader is referred to References 5 and 6 to review some of the alternate fabrication approaches. While fused couplers are starting to be employed in resonators,[4] assembly losses need be reduced to the 0.01-dB level to produce rings with finesse >1000, comparable to the champion-polished resonators[7,8] reported to date.

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Substrate Preparation

The processing begins with the fabrication of a substrate to act as a receptacle for the fiber during polishing. For optical contact bonded (OCB) couplers, substrates are made from $20 \times 6 \times 12$ mm blocks of Corning 7740 Pyrex. The choice of a relatively soft block material is such that the fiber polishes slightly slower than the substrate. This will ensure that the polished fiber surface will protrude a fraction of a micron above the block surface, and will be in the intimate contact required by optical contacting.

First, a curved groove having a 30-cm radius is cut into the substrate, having precisely controlled width, depth, and surface finish. It is important to have a consistently close fit between the fiber and the groove walls to minimize the quantity of the epoxy in the finished device; this produces superior flatness during polishing. To obtain consistent grooves, a novel fixture has been built to generate the grooves in the substrates. Figure 1 illustrates the construction of the computer-controlled groove generator. With this technique, groove width can be controlled to $\pm 10\ \mu m$ and depth variation is $<1\ \mu m$.

Commercially-available epoxy mixed with a thixotropic compound is used to bond the fiber into the groove. Careful preparation, degassing, application, and quality control of the adhesive and cure cycle is crucial to get consistent bonding and polishing characteristics. An acousto-optic technique[9] is used for identification and orientation of the birefringent principal axes; the fast axis of the birefringent fiber is aligned parallel to the substrate surface within ± 0.5 deg. Figure 2 shows a magnified view of a typical groove cross section with a polished PANDA fiber showing one stress rod polished away.

Substrate Polishing

Grinding is performed on a 30-cm diameter ungrooved cast iron polishing wheel as indicated in Table 1. The polishing jig incorporates an integral conditioning ring and an Invar receptacle for the substrate, which moves up and down with respect to the conditioning ring on a precision piston arrangement, as shown in Figure 3. The receptacle has been designed to permit storage of the fiber pigtails during polishing, and holds the coilform for spliceless resonator polishing. A special waxing procedure attaches the substrate(s) and blocking material to the Invar receptacle with minimal strain. Grinding begins with an aluminum oxide compound and deionized water mixture that permits rapid material removal. Grinding and polishing pressure is controlled with a load-cell test prior to grinding, which measures the downward force on the central piston assembly of the polishing jig. Subsequently, a finely ground surface is achieved with cerium oxide, leaving roughly 25 μm remaining to the core. To ascertain this dimension, the minor axis of the elliptical polished fiber surface[10] is measured to estimate polishing depth.

The polishing process is optimized to produce a very smooth surface, free from stress and subsurface damage.[11] The traditional technique of polishing with a pitch polishing pad has been replaced by a Polytron pad material[12] with a high degree of success. When properly conditioned, synthetic polishing pad materials produce excellent surface quality and flatness, and works well with colloidal silica polishing suspensions. The Boron-doped stress rods polish at a slightly higher rate than the cladding, which results in a sub-μm depression when polished. Progress of polishing is known by visualization of that stress-rod depression by Nomarski and/or Mirau microscopy. After the upper stress rod is observed to be polished away, there is approximately 3 μm remaining to the core

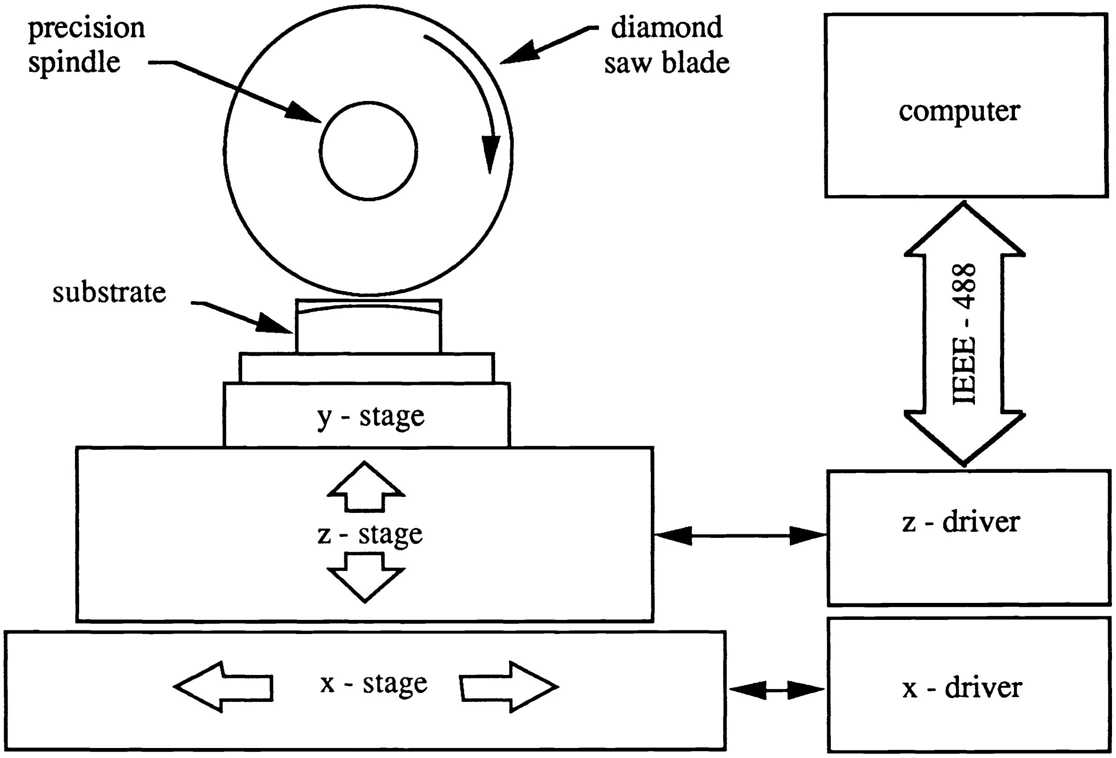

Figure 1. Computer-controlled groove generator.

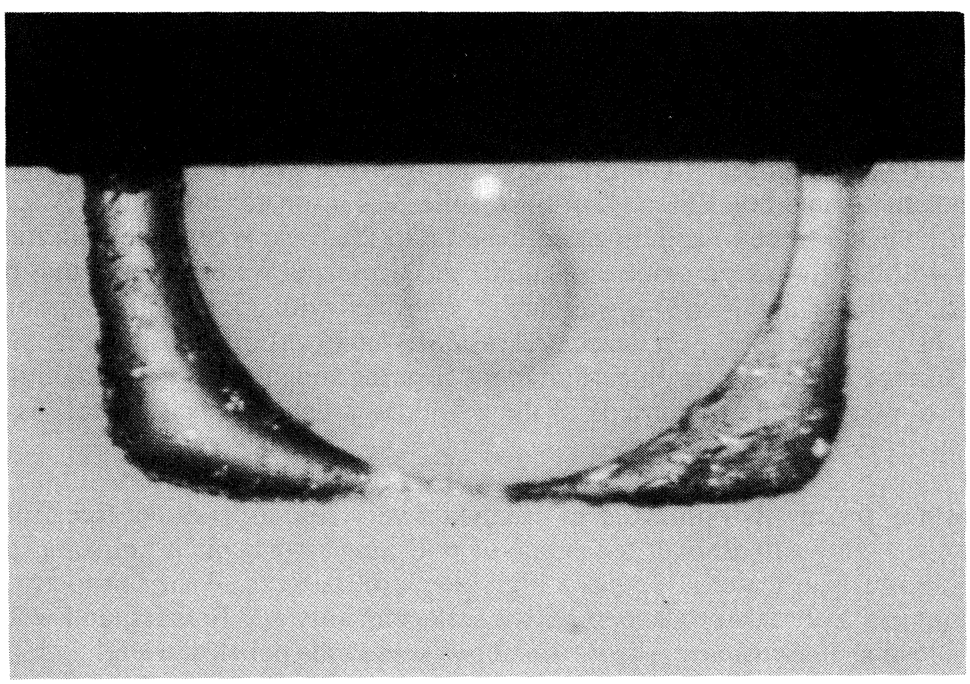

Figure 2. Groove and polished PANDA fiber cross section.

Table 1. Polishing process.

PROCESS STEP	POLISH PAD	POLISH COMPOUND	CONC:DI WATER	SPEED rpm	PRESS. g/mm^2	TIME min
Grind	Cast Iron	3 mm Al_2O_3	1:6	30-35	3	15-30
Lap	Polytron	3 mm CeO_2	1:8	30-35	3	30
Polish	Polytron	Syton™	pH ≈ 11	30-35	3	AR
Finish	Polytron	Syton™	pH ≈ 11	5-10	0.2	4 h

boundary. After that point, the polishing pressure and speed are reduced to produce a superior finish at a reduced removal rate.

An oil drop test[13] is used during the final stages of polishing to serve as an indicator to remaining polishing time, and to characterize the final core-to-surface proximity. It has been found that a flatness of $\lambda/15$ is sufficient to permit optical contact bonding. The selection of materials and process produces a substrate with a fiber that protrudes approximately 250 Å above the substrate surface. The surface roughness has been characterized to be 20 Å rms, measured over several mm^2, as verified by a Zygo phase-stepping interferometer.

Coupler Assembly

The cleaning of the polished substrates follows the guidelines in Reference 14, and is crucial to successful assembly. Three methods have been used to attach polished half-couplers, namely index-matching oil, UV-cured adhesive, and optical contact bonding. To make an adjustable coupler, the blocks are cleaned and assembled in diffuse white light; if a zeroth-order (black) fringe is observed, the gap is sufficiently small to permit coupling. The mated substrates are placed into an alignment fixture, and the fibers are aligned atop one another under high magnification. Index-matching oil, the refractive index of which is equal to the cladding, is wicked in between the assembled half-couplers by capillary action. Fine adjustment is performed with a dual-channel optical power meter and a laser source. Alternately, a controlled-index UV-curable adhesive is used in lieu of the oil, and the coupler may be removed from the fixture after curing; both of these methods produce couplers with splitting ratios that are highly temperature sensitive. Figure 4 depicts a pair of substrates with an incomplete OCB between them, clearly illustrating the fringe pattern or "Newton's rings" associated with two nonflat surfaces in close proximity. Since these are substrates made for adjustable devices, there is a slightly convex crown on the surface and only the central region and fibers are bonded.

For high-performance devices, OCB is used to get a permanent attachment of the substrates without any intermediate materials. The glass blocks used are twice the thickness of the adjustable devices, with greatly improved flatness. The coupler substrates are cleaned, mated, and the fiber cores are aligned actively as before, only in a special OCB fixture. Once the coupler is optimized, a slight pressure initiates the OCB, which proceeds rapidly across the entire block surface. As the bond commences, a slight shift in the splitting ratio, typically <5%, is observed. The shift is repeatable, and the blocks can be debonded with a heat gun and the shift may be compensated for. The strength of the bond increases with time to form a permanent bond after one week;[15] it is routinely possible to

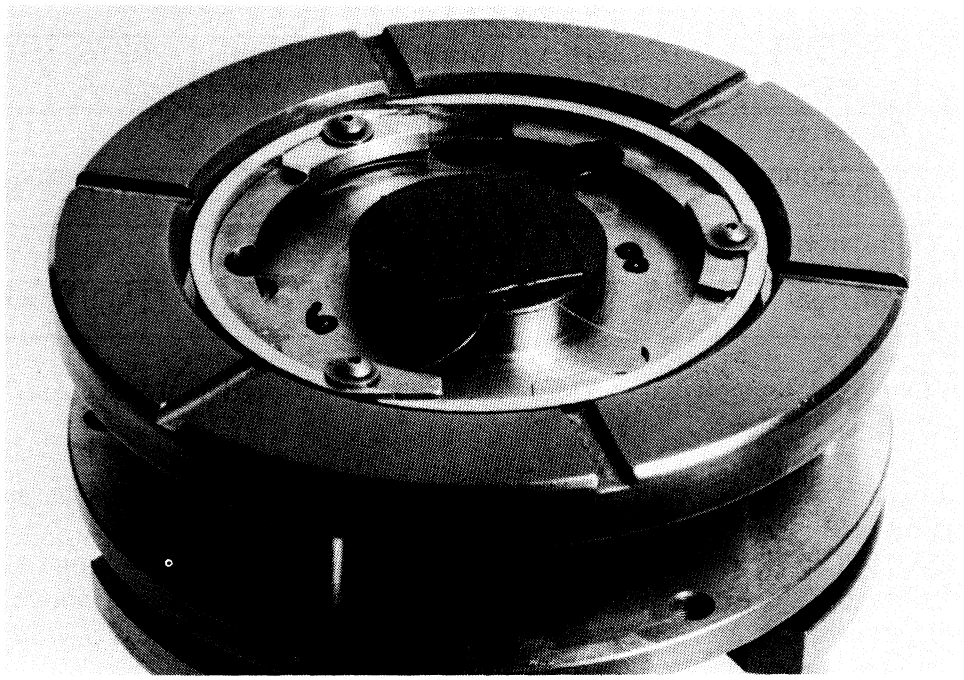

Figure 3. Face of polishing jig showing conditioning ring and substrates.

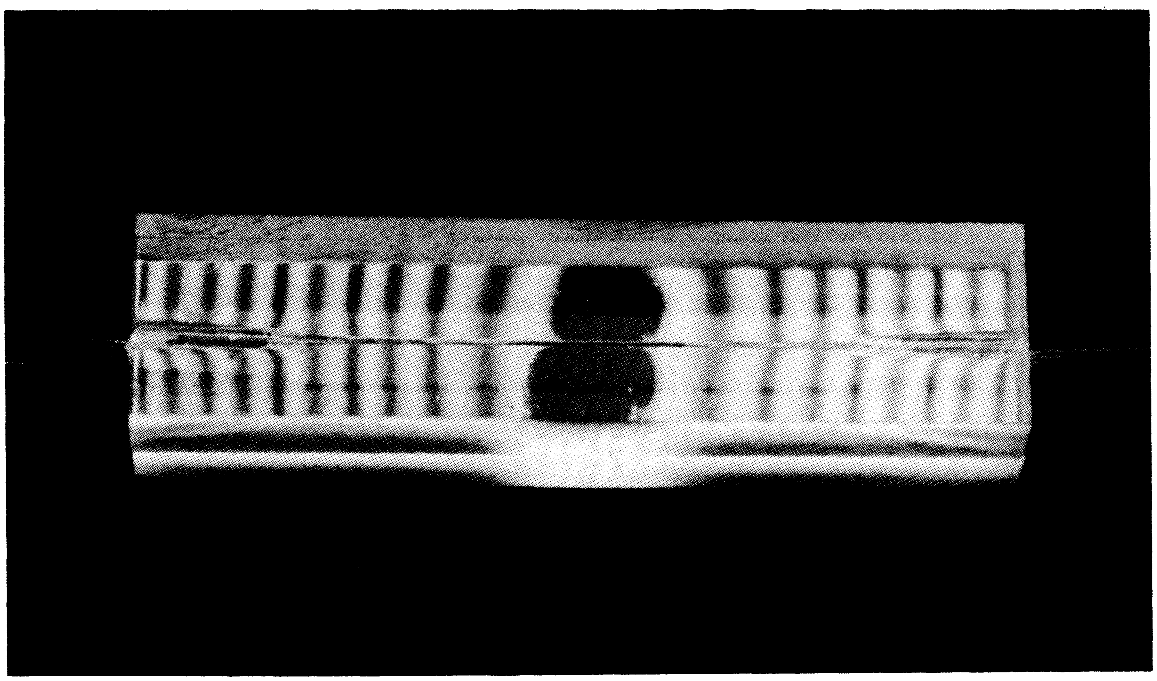

Figure 4. Coupler with incomplete optical contact bond.

obtain a stable OCB over nearly 100% of the surface when using the thicker substrate blocks. Typical OCB coupler loss is <0.1 dB, and polarization crosstalk is below 20 dB.

Resonator Assembly

Fiber coils are wound out of Fujikura polarization-preserving or polarizing fiber on a custom-made coil winding machine. The coils were all bobbin-wound with low tension, with the exception of the 400-m coil, which was quadropole-wound. Assembled resonators were made with an electric arc splicer with a typical loss of -0.03 dB per splice. The various resonators listed in Table 2 were assembled in different ways: (i) spliceless rings were made with substrates polished right on the fiber coil pigtails; (ii) the coupler was fabricated separately, then spliced to a coil; (iii) the polished half-couplers were spliced onto the coil, then assembled and adjusted. Figure 5 shows a variable PM coupler in its adjustable fixture which has been spliced to a 20-m coil to form a spliced resonator.

Table 2. Polished Coupler Ring Resonators

RING TYPE	TYPE	LENGTH	FINESSE	LINEWIDTH kHz fwhm	% DIP DEPTH	CROSS-TALK dB
Spliceless	adj.	20	320	31 see Fig. 6	93	-25
Spliced	adj.	20	72	139	98	-20
" see Fig. 5	adj.	20	145	69	99	-20
Short FSR	adj.	400	65	7	85	-30
PM/PZ	adj.	27	27	260	98	-25
90° splice	adj.	≈20	23.1	≈450	91	<-20
PM/PZ	OCB	24	25	350	98	<-20
Spliceless	OCB	≈20	80	≈130	98	<-20

To characterize the resonators, a tunable diode-pumped Nd:YAG laser was used as a source that had a wavelength $\lambda = 1319$ nm. To optimize resonator performance and maximize dip depth, the coupler splitting ratio is adjusted to equal the sum of the resonator losses,[16] where the losses are expressed as fractional intensity transmission. Figure 6 shows the transfer function of a spliceless PM resonator with symmetric, high finesse dips. Consistently low cross coupling, dip symmetry, and dip depth can be achieved for standard resonator designs with OCB or adjustable couplers. PM resonators of several topologies were demonstrated, one spliceless design with finesse in excess of 300, and the 400-m cavity having linewidth below 7 kHz. Initial testing of spliceless PZ fiber resonators[17] required fabrication of couplers out of PZ fiber, which was met with great difficulty. Alternate single-eigenstate-of-polarization resonators have been recently demonstrated, including a 90-deg splice design after Reference 4 and a polarizing-ring resonator,[18] which is being used in an RFOG breadboard.

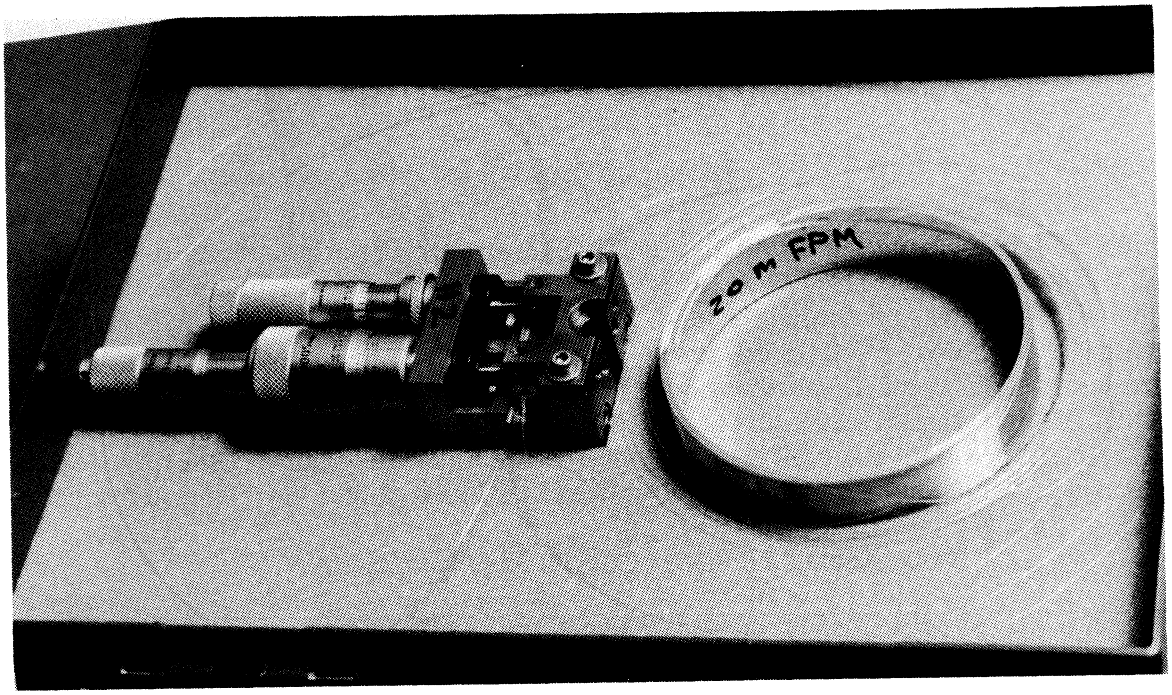

Figure 5. Spliced variable PM fiber resonator assembly.

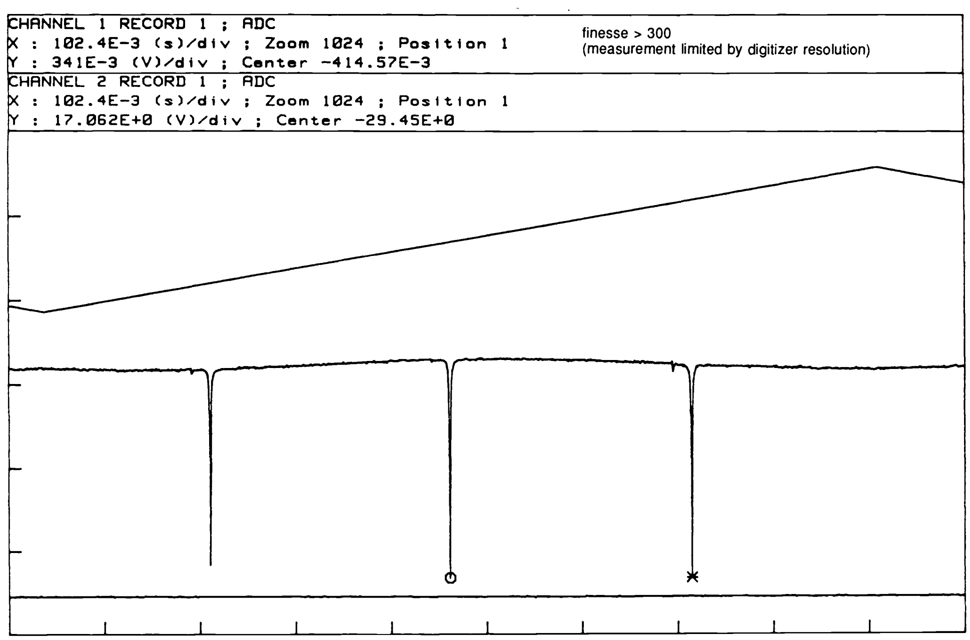

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Figure 6. Resonant dips and zero light level.

Conclusion

While fused coupler technology is dominating the nonbirefringent fixed-splitting-ratio communications market, polished coupler technology still retains several key niches. Prototypes and experiments that need variable coupling, preservation of polarization, and have relaxed environmental requirements will have a need for lapped couplers. Assemblies of polished couplers and special evanescent-based devices will continue to be valuable research tools in optical physics, sensors, and communications experiments. Devices fabricated under this project are being used in RFOG experiments and Brillouin scattering physics studies.

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References

1. A. K. Agarwal, "Review of optical fiber couplers," *Fiber and Integrated Optics*, Vol. 6, No. 1, pg. 27-53, (1985).

2. R. A. Bergh, G. Kotler, and H. J. Shaw, "Single-mode fibre optic directional coupler," *Electronics Letters*, Vol. 16, No. 7, pg. 260-261, (1980).

3. K. Sakuma, "Fiber optic gyro productization at JAE," Fiber Optic Gyro 15th Anniversary Conference, S. Ezekiel ed., *Proc. SPIE*, Vol. 1165, pg. 8-16, (Boston, 1991).

4. G. A. Sanders, R. Y. Liu, and L. K. Strandjord, "Progress in interferometer and resonator fiber optic gyroscopes," OFS'8, F. Leonberger ed., *IEEE/LEOS*, pg. 26-29, (Monterey, 1992).

5. L. Li, A. Kerr, and I. P. Giles, "Single-mode optical fibre tunable couplers," Fiber Optics Components and Reliability, P. M. Kopera and D. K. Paul ed., *Proc. SPIE*, Vol. 1580, pg. 205-215, (Boston, 1991).

6. V. Annovazzi-Lodi, and S. Donati, "Technology of lapped optical-fiber couplers," *Journal of Optical Communications*, Vol. 11, No. 3, pg. 107-112, (1989).

7. R. Dahlgren, and O. Laznicka, "Ultra-High Finesse Polarization-Maintaining Fiber Resonator," Fiber Optic and Laser Sensors VII, E. Udd and R. DePaula ed., *Proc. SPIE*, Vol. 1169, pg. 382-387, (Boston, 1989).

8. C. Yue, J. Peng, Y. Liao, and B. Zhou, "Fibre Ring Resonator with Finesse of 1260," *Electronic Letters*, Vol. 24, No. 10, pg. 622-3, (1988).

9. S. L. A. Carrara, B. Y. Kim, and H. J. Shaw, "Elasto-optic alignment of birefringent axes in polarization-holding optical fiber," *Optics Letters*, Vol. 11, No. 7, pg. 470-472, (1986).

10. A. Kumar, S. Pilevar, and K. Thyagarajan, "Measurements on variation of birefringence with depth of polishing in elliptic core fibers," *Optics Communications*, Vol. 72, No. 3,4, pg. 187-189, (1989).

11. P. P. Hed, and D. F. Edwards, "Optical glass fabrication technology. 2: Relationship between surface roughness and subsurface damage," *Applied Optics*, Vol. 26, No. 21, pg. 4677-4680, (1987).

12. A. Lindquist, "Pitch, Polytron, and Polyurethane: a comparison," *Applied Optics*, Vol. 25, No. 21, pg. 3796-3797, (1986).

13. M. J. F. Diggonet, J. R. Feth, and L. F. Stokes, "Measurement of the core proximity in polished fiber substrates and couplers," *Optics Letters*, Vol. 10, No. 9, pg. 463-465, (1985).

14. J. M. Bennett, and L. Mattsson, "chapter 8; Cleaning and Inspection of Surfaces," in *Surface Roughness and Scattering*, (1990) Optical Society of America.

15. S. S. Kachkin, and Y. V. Lisitsyn, "Optical-contact bonding strength of glass components," *Soviet Journal of Optical Technology*, Vol. 47, No. 3, pg. 159-160, (1980).

16. L. Stokes, M. Chodorow, and H. Shaw, "Sensitive all-single-mode-fiber resonant ring interferometer," *IEEE Journal of Lightwave Technology*, Vol. 1, No. 1, pg. 110-115, (1983).

17. T. J. Kaiser, D. Cardarelli, and J. Walsh, "Experimental developments in the RFOG," Fiber Optic and Laser Sensors VIII, R. DePaula and E. Udd ed., *Proc. SPIE*, Vol. 1367, pg. 121-126, (San José, 1990).

18. R. P. Dahlgren, and R. E. Sutherland, "Single-polarization fiber-optic resonator for gyro applications," Fiber Optic Gyros: 15th Anniversary Conference, S. Ezekiel and E. Udd ed., *Proc. SPIE*, Vol. 1585, pg. 128-135, (Boston, 1991).