AT&T BELL LABORATORIES TECHNICAL JOURNAL
Vol. 63, No. 3, March 1984
Printed in U.S.A.

Single GRIN-Lens Directional Couplers

By F. H. LEVINSON* and S. W. GRANLUND†

(Manuscript received June 10, 1983)

Two types of small, rugged, gradient-index (GRIN) rod-lens directional couplers have been made. One is a three-port directional coupler and the other is an asymmetric four-port coupler. Each coupler can have various splitting ratios from 1:1 to 20:1. Excess insertion loss is less than 1.0 dB, and directivity is greater than 30 dB for the three-port couplers, while these same figures are 1.2 dB and 40 dB for the asymmetric four-port couplers. The couplers are stable between −40 and +80°C.

I. INTRODUCTION

Several designs for directional couplers that use gradient index (GRIN) rod lenses have been published; many of these are discussed in the review by Uchida and Kobayashi.[1] We report the results of two multimode fiber coupler designs. The first is a three-port directional coupler similar to that of Nishimoto et al.,[2] described in Ref. 1. Our design, however, incorporates a single GRIN lens and a unique angled mirror for performing the power division. The other coupler is an asymmetric four-port that is useful in fiber networking applications. Waveguide and notched fiber manifestations of this coupler exist.[3,4] This GRIN-lens design is more flexible and useful for a wide range of fibers and applications. The three-port coupler is described first since its fabrication, performance, and stability are similar to that of the asymmetric four-port. Following this, details specific to the four-port coupler are presented.

* AT&T Bell Laboratories; present affiliation Bell Communications Research, Inc. † AT&T Bell Laboratories.

II. THREE-PORT DIRECTIONAL COUPLER

2.1 Design

The upper portion of Fig. 1 presents the design of the three-port directional coupler with a 1:1 or 3 dB splitting ratio. Light from fiber 1 passes through the quarter-pitch lens and is collimated at the end face. Collimated light from a GRIN lens is not normally parallel to the lens axis, but is usually at an angle related to the distance of fiber 1 from the lens axis. Any change in the direction of this beam, other than 180 degrees, after reflection from the lens end-face mirror results in a positional change when the beam is refocused back to the original plane of incidence. In this way, the part of the light from fiber 1 that strikes the portion of end face covered by the fixed mirror (evaporated Au deposited directly on the lens) is reflected symmetrically about the lens axis and refocused into fiber 2. The remaining light is reflected off the tilted mirror and can be refocused into fiber 3 by precise angular adjustment of that mirror.

2.2 Fabrication

The assembly of the three-port device is accomplished in two independent steps. First, an array of three fibers is brought near the lens and permanently set with its position adjusted for optimum light

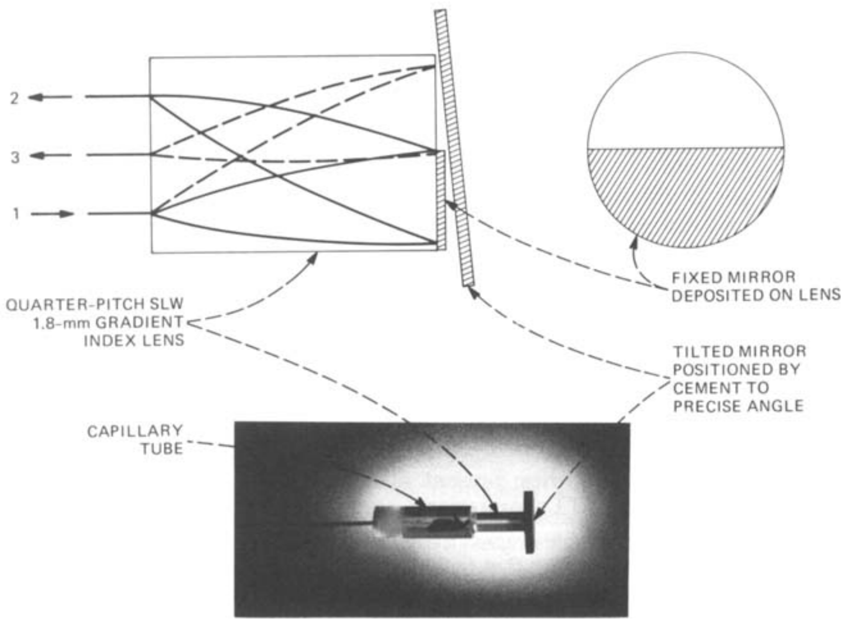


Fig. 1—Schematic diagram of GRIN-lens three-port directional coupler and photograph of a finished device.

coupling between the input fiber and either of the two output fibers. Next, a mirror is brought near the lens end face. After the lens-mirror joint is filled with an optical cement, which has an index similar to that of the fiber and GRIN lens, the mirror is angularly adjusted and permanently set for optimum coupling between the input fiber and the remaining output fiber. An angle of ~1.3° is typical for a SLW 1.8-mm *Selfoc** lens and fibers with outer diameters (ODs) of 125 μm. An important aspect of this two-step assembly process is the independent alignment of the fibers, which results in optimum coupling. The lower portion of Fig. 1 contains a photograph of a completed miniature three-port directional coupler. The overall length of this device is 1.5 cm; however, couplers as short as 1 cm were fabricated.

An additional step can be taken to compensate for the cement's shrinkage during curing by increasing the tilted mirror's angle and the fibers' distance from the lens before curing by an amount proportional to the shrinkage. However, cement shrinkage during curing is small, and when a device is made (using 50/125-μm fiber) without compensating for cement shrinkage during cure, a degradation of at most 0.1–0.2 dB results.

2.3 Performance characteristics

A flexibility inherent in both the three-port and four-port coupler designs is the change in the splitting ratio that results from varying the area of the end-face mirrors. As Nishimoto et al. reported,[2] we have found a fan-shaped mirror to be the best approach in order to minimize modal sensitivity of the coupler. Couplers have been fabricated with splitting ratios of 1:1, 5:1, 10:1, and 20:1.

The coupler loss and crosstalk measurements were made using either a $\lambda = 0.87$-μm or $\lambda = 1.3$-μm Light Emitting Diode (LED) light source and a calibrated optical power meter. Light from the LED was coupled to a length of fiber that includes a mandrel wrap to provide a steady-state mode excitation. This fiber was then spliced to the device fiber pigtail and the signal level (after a mandrel wrap) on the output fibers (P_{out}) were recorded. Following the necessary optical power measurements, the input fiber was broken to obtain the input-power zero point (P_{in}). The insertion loss of a particular channel is defined to be 10 log (P_{out}/P_{in}). The excess insertion loss is defined to be that portion of the insertion loss that is not attributable to the power division. For example, if a three-port coupler is designed to split the input power equally between the two outputs, then, ideally, each output port would have a 3-dB insertion loss. If each port shows a 3.8-dB insertion loss, then the coupler has a 0.8-dB excess insertion loss.

The excess insertion loss of the experimental coupler models was

* Registered trademark of Nippon Sheet Glass.

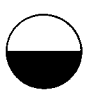
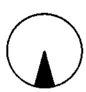
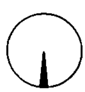
between 0.6 and 1.0 dB (see Table I). As a result, although couplers with splitting ratios higher than 20:1 are possible, there is little performance improvement in excess insertion loss to be realized on the high reflection channel over that of a 20:1 coupler. Minimum excess insertion loss in the coupler appears to be attributable to the following sources: 0.2 dB from lens aberration,[5] 0.1-dB Au mirror loss,[6] and 0.3-dB misalignment and cement curing losses.

The directivity of the three-port coupler was measured by determining the coupler's insertion loss between fibers 2 and 3 (see Fig. 1), while the end of fiber 1 was immersed in index matching fluid. An average of 32 dB was found for a 1:1 splitting-ratio coupler, and the directivity increases with increasing splitting ratio. The dominant source of this crosstalk is the light from fiber 2 or 3 that is reflected by the fiber 1-cement interface and refocused back into fibers 3 or 2, respectively. A reflection also occurs at the lens-cement interface, but this is not properly focused and as such does not significantly contribute to the crosstalk. Using the simple fresnel formula with a fiber index, n_f, of $\sim$1.46 and a cement index, n_c, of $\sim$1.56,

$$R = (n_F - n_C)/(n_F + n_C)^2 = 0.11\% \quad \text{or} \quad 29.6 \text{ dB}.$$

Practical directivity values are better than this because we are making two passes through a 50-percent transmission mirror (3-dB coupler case), and hence, this provides an additional 6 dB of directivity. Some of our best 3-dB couplers have approached this theoretical limit of 35 dB.

Table I—Insertion losses for three-port directional couplers

SPLITTING RATIO	MIRROR SHAPE	INSERTION LOSS IN DECIBELS* THEORETICAL	ACTUAL*	EXCESS
1:1		3.0/3.0	3.8/3.8	0.8
5:1		7.8/0.8	8.8/1.7	0.9
10:1		10.4/0.4	10.0/1.4	0.8
20:1		13.02/0.2	13.0/1.0	0.8

*ACTUAL LOSSES OF MORE THAN 20 DEVICES SHOW APPROXIMATELY 0.3-dB VARIATION ABOUT THESE MEANS.

The couplers can also be constructed with relatively good spectral independence. Longer wavelengths increase the GRIN-lens focal length, but this sensitivity can be reduced by optimizing for an average of the system wavelengths. For example, using 50-μm core multimode fiber in a dual wavelength system at $\lambda = 0.87$ μm and 1.3 μm, a focus set for $\lambda = 1.05$-μm degrades the performance of the coupler by less than 0.2 dB.

2.4 Temperature stability

Temperature stability of the coupler was investigated, and variations in performance of <0.2 dB were observed over the range −40 to +80 °C. Devices were subjected to 100 hours of cycling, 1 hour at each extreme. Figure 2 shows the stability of the coupler for the 1 → 2 and 1 → 3 channels. The plotted data are from 100 cycles of a device between −40 and +80 °C. The hatch-shaded region is the performance of the fixed-mirror channel, while the dot-shaded region is the performance of the tilted-mirror channel. The ±0.1-dB variation of the fixed-mirror reflection is attributed to lateral cure strains in the fiber-lens joint. The ±0.2-dB insertion loss variation in the light reflected from the tilted mirror is the sum of two separable small shifts, the ±0.1-dB variation of the fiber-lens joint is still present, and an additional ±0.1 dB is attributable to the thermal expansion and contraction of the cement wedge at the mirror. For a mirror bonded at a 1.3-degree angle

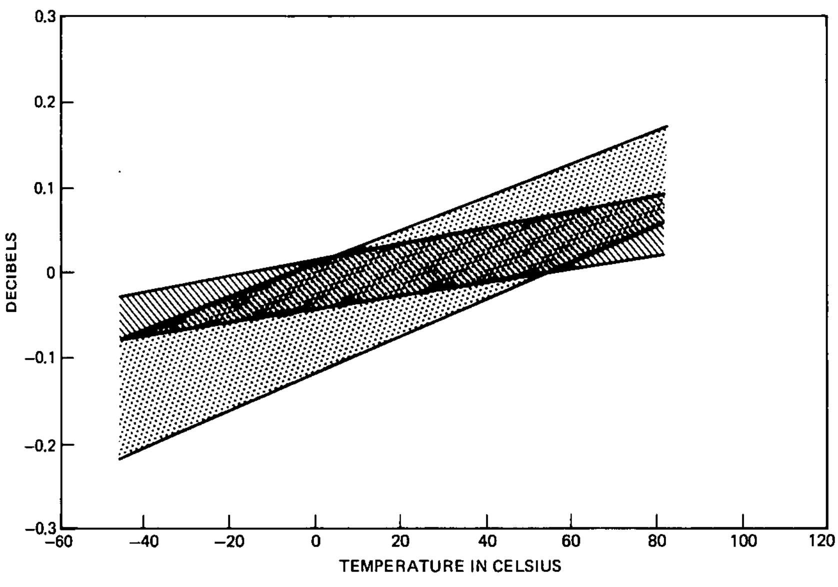


Fig. 2—Plot of coupler excess loss variation versus temperature. The hatch-shaded region is the coupler performance for the fixed mirror channel; the dot-shaded region is for the tilted mirror.

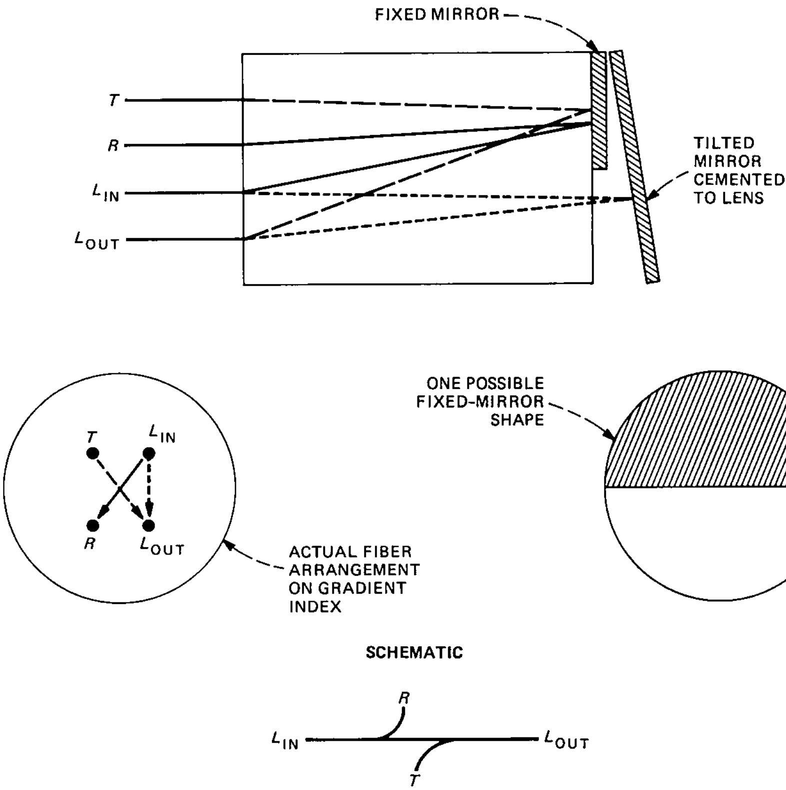


Fig. 3—Schematic diagram of GRIN-lens asymmetric four-port coupler.

to a 1.8-mm diameter lens, there is a thickness variation of 41 μm. If the cement has an average thermal expansion coefficient of 100×10^{-6} mm/mm/°C, the angle can vary by ±0.6 percent, which translates to a ~±1-μm shift of the focal point in the focal plane or a ±0.1-dB variation with temperature. As for the improved performance at higher temperature, we believe it can be attributed to thermal relaxation of the curing stresses and cement contraction that disturbed the original alignments.

III. FOUR-PORT DESIGN

Figure 3 gives the design of an asymmetric four-port coupler. This component couples light passively on a throughput [line in (L_{in}) → line out (L_{out})] channel; a portion of the signal is also tapped. The same modes of the input fiber, L_{in}, which are diverted to the R (receiver) fiber, are available to be refilled with modes from the T (transmitter) fiber. This data-bus transceiver coupler allows for the

Table II—Insertion losses for four-port directional couplers

Device	Channel	Insertion Loss (dB) Theoretical	Actual
1	$L_{in} \rightarrow R$	7.8	8.8
	$T \rightarrow L_{out}$	7.8	10.3
	$L_{in} \rightarrow L_{out}$	0.8	1.7
	$T \rightarrow R$		46.5
	excess		1.2
2	$L_{in} \rightarrow R$	3.0	3.8
	$T \rightarrow L_{out}$	3.0	4.2
	$L_{in} \rightarrow L_{out}$	3.0	4.0
	$T \rightarrow R$		43.5
	excess		1.0
3	$L_{in} \rightarrow R$	0.8	1.6
	$T \rightarrow L_{out}$	0.8	1.8
	$L_{in} \rightarrow L_{out}$	7.8	7.0
	$T \rightarrow R$		42.0
	excess		0.6

"listen while talking" function important to the *Ethernet** or Carrier-Sense Multiple-Access with Collision Detection (CSMA/CD) local-area network protocol since the T and R fibers are optically isolated by more than 40 dB. In addition to being useful in CSMA/CD-based fiber networks, these couplers are also important in fiber-optic fail-safe nodes.[7]

The one difference in fabrication lies in the arrangement of the fibers on the GRIN-lens face. In the three-port coupler the fibers are held in a close-packed triangular array; in the asymmetric four-port coupler they must be held on the corners of a square (actually, a rhombus will do). This is because the $L_{in} \rightarrow R$ and $T \rightarrow L_{out}$ couplings are achieved simultaneously by reflections from the fixed mirror when the four fibers are arranged symmetrically about the GRIN-lens axis (see Fig. 3). The $L_{in} \rightarrow L_{out}$ coupling is made using a tilted mirror similar to that described in the three-port coupler. High isolation between the T and R ports results because the remaining portion of the beam from fiber T is directed (by the tilted mirror) far from fiber R.

Since the coupler is so very similar to the three-port coupler previously described, it is not surprising that its performance is the same as far as its temperature stability and wavelength insensitivity. Excess insertion losses less than 1.0 dB are obtained for this coupler as well. Table II summarizes the performance for three different splitting ratios of this coupler.

Consistent asymmetric four-port coupler performance is (at present)

* Registered trademark of Xerox Corporation.

somewhat more difficult to achieve because of the simultaneous $L_{in} \rightarrow R$ and $T \rightarrow L_{out}$ alignment condition required by the device. This condition is easier to meet if a larger core fiber is used at the receiver port. Such large core fibers are common in receiver designs to promote better coupling. For the asymmetric four-port, such a fiber choice allows for the four fibers to be on the corners of the square with a lower precision and still not affect the overall excess insertion loss of the device.

This occurs in the following way. Alignment of the square fiber array is made by optimizing light from $T \rightarrow L_{out}$. Then the light from $L_{in} \rightarrow R$ is checked. When port R is a large fiber, all that is required for excellent coupling is that the image of L_{in} falls somewhere inside the R fiber core area. If a 50/125-μm fiber is used at the input and an 80/125-μm fiber is at port R, then this fiber pair can have a $\pm$15-μm error with respect to the T/L_{out} pair and the corners of the square. The losses in Table II are for the case where all four ports are 50/125-μm fiber. An average of 0.2-dB improvement is seen for the case of a large core 80/125-μm fiber at the R port.

IV. CONCLUSION

Small, ~1-cm, three- and four-port directional couplers have been designed for independent alignment of the fibers, for freedom in splitting-ratio variation, and for a certain degree of spectral independence. These couplers have also been tested for stable operation between −40 and +80 °C.

These GRIN-lens couplers typically exhibit 0.8-dB excess insertion loss. The splitting ratio of the coupler can be varied by changing the area of a deposited Au mirror on the lens end face. Fiber-optic local-area network transceivers can be constructed using the asymmetric four-port coupler.

REFERENCES

1. T. Uchida and K. Kobayashi, "Micro-Optic Circuitry for Fiber Communications," in "Japan Annual Reviews in Electronics, Computer and Telecommunications, Optical Devices and Fibers, 1982," Y. Suematsu, ed.
2. H. Nishimoto et al. (title and paper in Japanese), Proceedings of the National Conference on Optical and Radio-Wave Electronics, IECE Japan, 1980, p. 301.
3. E. Weidel and J. Guttmann, "Asymmetric T-Couplers for Fiber-Optic Data Buses," Electron. Lett., *16,* No. 17 (August 1980), p. 673.
4. A. D. De Oliveira and M. G. F. Wilson, "Stripe Waveguide Y-Intersection as Efficient Coupler for Multimode Optical Communications Systems," Electron. Lett., *17,* No. 2 (January 1981), p. 100.
5. T. W. Cline and R. B. Jander, "Wave-Front Aberration Measurements on GRIN Rod Lenses," Appl. Opt., *21,* No. 6 (March 1982), pp. 1035–41.
6. *American Institute of Physics Handbook,* 3rd ed., D. E. Gray, ed., New York: McGraw Hill, 1972, pp. 6–157.
7. A. Albanese, "Fail-Safe Nodes for Lightwave Digital Networks," B.S.T.J., *61,* No. 2 (February 1982), p. 247.

AUTHORS

Stephen W. Granlund, B.S. (Physics), 1980, Moravian College, Bethlehem, PA; AT&T Bell Laboratories, 1980—. At AT&T Bell Laboratories, Mr. Granlund is currently working on the development and reliability of various fiber-optic components.

Frank Levinson, B.S. (Mathematics and Physics), 1975, Butler University, Indianapolis, IN; M.S., 1978 and Ph.D. 1980 (Astronomy), University of Virginia; AT&T Bell Laboratories, 1980–1983. Now a member of the Central Services Organization of the Reginal Bell Operating Companies. Mr. Levinson has done research and development on fiber-optic couplers, hybrid optical transceivers, and other fiber components suitable for fiber-optic local-area networks. In September of 1983 he joined the CSO as a member of the Communications Sciences Department, where he is involved in fiber-optic local- and metropolitan-area network hardware and systems research. Member, Optical Society of America and IEEE.