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OPTICAL ROTORS— LIGHTWAVE TRANSMISSION ACROSS ROTATING INTERFACES

Introduction

The rapid evolution of lightwave technology into today's communication networks, military systems, and industrial applications has spawned a new generation of optical components. One such device, the optical rotor, provides for the transmission of photonic signals across a rotating interface. Low-loss optical rotors for fiber-optic systems are cost-effective while providing significant improvements in transmission quality compared to conventional electrical systems that use slip-ring technology.

Optical rotors are envisioned to have broad applications in lightwave systems. The initial market for optical rotors has been in military lightwave uses, where the primary application is shipboard lightwave cable systems deployed and recovered from a reel on board a ship. An optical rotor, mounted on the reel axis, allows the direct transmission of photonic signals from the rotating reeled system to the shipboard equipment. Other potential applications are fiber-controlled remotely operated vehicles (ROVs); military fire control systems such as those for tank turrets, helicopters, and shipboard munitions; industrial process controls; robotic systems; and monitoring fiber systems during installation. The in-process monitoring of fiber during cabling operations can be easily accomplished using an optical rotor at the fiber supply pool.

Several advances in optical rotor technology have resulted from developments in the Lightwave Systems Design Department at AT&T Bell Laboratories, Whippany, New Jersey. A high-performance, dual-fiber optical rotor for multimode lightguide systems was developed in 1984.¹ Subsequent developments have generated innovations for a multifiber optical rotor for multimode fibers² and for single-mode optical rotor technology. Although multimode fiber rotors have been developed to satisfy initial lightwave applications, the future market demand will be for single-mode fiber lightguide rotors.

Optical rotors provide several advantages over the conventional alternative which uses electrical slip rings for signal transmission across rotating interfaces. Optical transmission features increased bandwidth, low noise, and low crosstalk, and eliminates electromagnetic interference and electrical ground problems. In addition, optical rotors allow significant reductions in the size and weight from the slip-ring hardware, while remaining a cost-effective alternative for signal transmission.

The performance of optical rotors is generally characterized in terms of mean insertion loss, dispersion, and crosstalk (multifiber rotors). In addition, the rotational variation (over 360° rotation of the rotor) results in an optical level variation. In digitally encoded lightwave transmission, bit errors may be introduced if inadequate detection range is present in the optical receiver.

Principles of Operation

The fundamental component of the optical rotor is a small, cylindrical optical device call the graded-index (GRIN) lens. Like a graded-index fiber, its index of refraction pro-

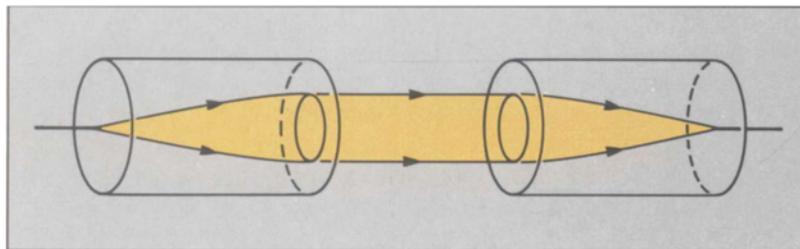
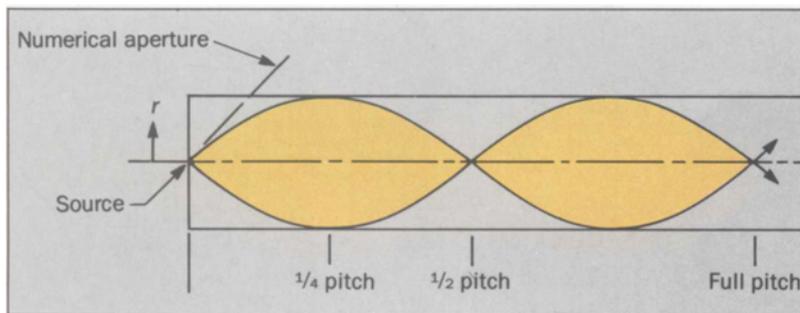


Figure 1. Light transmission through a GRIN lens.

Figure 2. A collimating pair.

file is approximately quadratic; therefore, it guides light in the same manner.³ When compared with a conventional lens, the cylindrical shape of a GRIN lens (0.5 to 5 mm in diameter) simplifies the interface to fiber.

If a point source of light is placed against the face of a GRIN lens, the light will be guided in the manner shown in Figure 1. If the lens is cut to its "1/4-pitch" length, then a collimated beam will be produced at the exiting face. In this situation, the 1/4-pitch distance is effectively the focal length. Assuming that the end of a fiber core can be approximated by a point source, a 1/4-pitch GRIN lens can be used as a collimator. A pair of transmitting and receiving collimators will form the basic unit for light transmission across an interface (Figure 2). A single-channel optical rotor is achieved by rotating one of the collimators in this configuration about its optical axis.

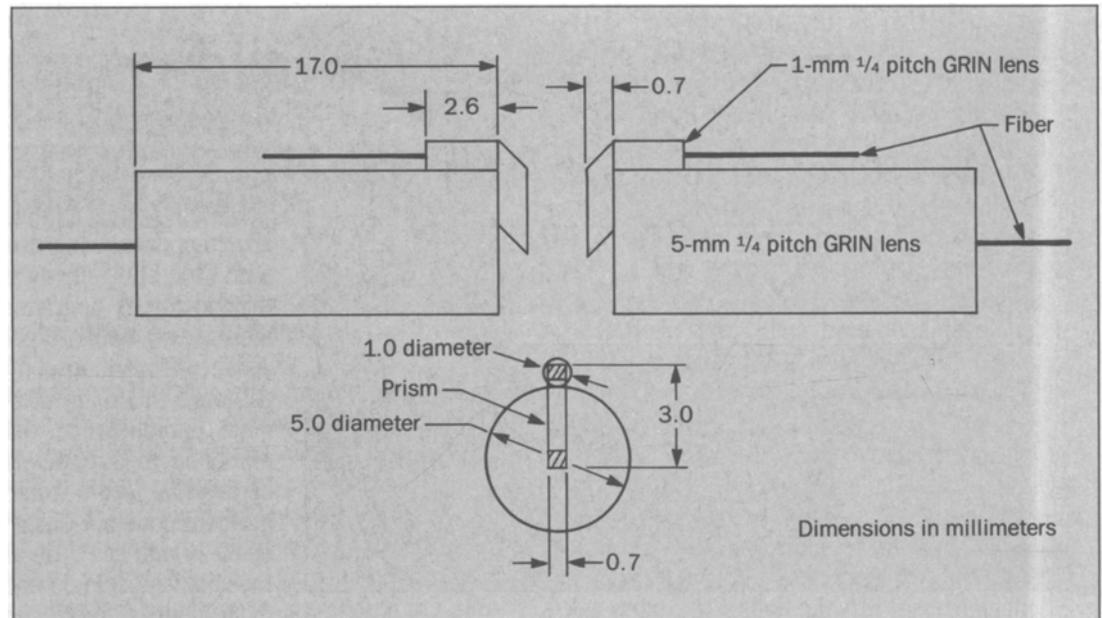
Parenthetically, it is true that the same idea can be achieved by simply transmitting directly from fiber to fiber. However, this configuration is highly sensitive to transverse misalignment⁴ (an offset of about one-third the fiber core radius yields a 1-dB loss) while the GRIN lens to GRIN lens combination can accommodate reasonable mechanical tolerances with little effect. Also, the fiber-to-fiber coupling is quickly degraded as end separation increases (a separation of several core radii reduces transmission by approximately 1 dB). Although the input fiber to a GRIN lens is not quite a point source, the resultant quasi-collimated beam is relatively immune to end separation. (For a value of the refractive index gradient constant equal to 0.11, a separation of up to 20 mm has little or no effect.) However, these advantages do not come gratis. A multi-mode fiber-to-fiber coupling can tolerate several degrees of angular misalignment before it sustains a signal strength loss of 1 dB, while for a GRIN lens to GRIN lens combination (depending primarily on the focal length), a 1-dB degradation is realized at misalignments of several tenths of a degree.

In short, the GRIN lens to GRIN lens coupling is less sensitive to lateral misalignment and end separation but it is more sensitive to angular misalignment when compared with fiber-to-fiber coupling. By using the GRIN lens instead of direct fiber coupling, we trade off the tolerance requirements on lateral and axial alignment against those on angular alignment. The GRIN lens approach requires a stringent angular alignment.

Dual-Fiber Optical Rotor

As mentioned earlier, a one-fiber optical rotor is relatively easy to fabricate.

Figure 3. Dual-fiber optical rotor.



Unfortunately, an optical rotor with more than one fiber presents many geometrical and practical problems, especially if the input and output fibers are identical (i.e., same core diameter and numerical aperture) and low loss is required.

The design of a two-fiber rotor is shown in Figure 3. By attaching a second smaller GRIN lens to the body of the main lens of a one-fiber rotary joint, so that the two end faces of the lenses are in line with each other, and attaching a rhomboid prism to these faces, so that the end faces of the prism coincide with the center of these lenses, a second off-axis channel transmission is possible. Like the first channel, this second channel can be transmitted through a rotating joint. Therefore, a two-independent-channel optical rotor is obtained. The important factor here is that the collimated

beam of the smaller lens must be much smaller than that of the main lens. This will assure lower losses as well as lower crosstalk between the channels, since the end face of the prism will obstruct a portion of the main lens.

The dual-fiber optical rotor described above is limited to two channels. This is true because there is only one central axis of rotation, and only one off-axis channel can be guided onto that axis without introducing large losses. Therefore, a totally different approach was used to realize a multifiber rotor. This approach is described below.

Multifiber Optical Rotor. If the first fiber is centered on the axis of rotation, as in the single-fiber optical rotor, there is a portion configuring the remaining off-axis fibers. Consider the beginnings of a two-fiber optical rotor with one on-axis and one off-axis fiber as

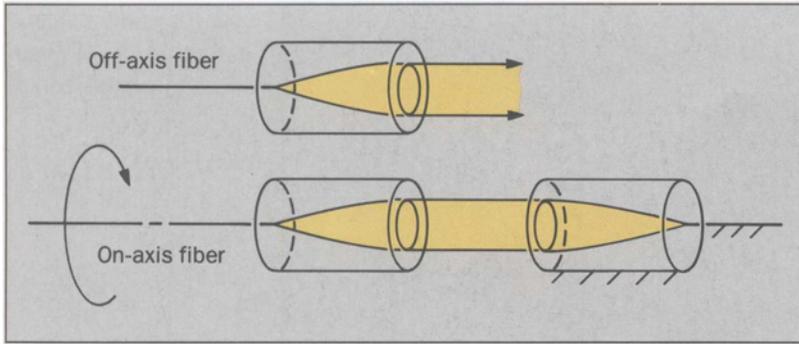
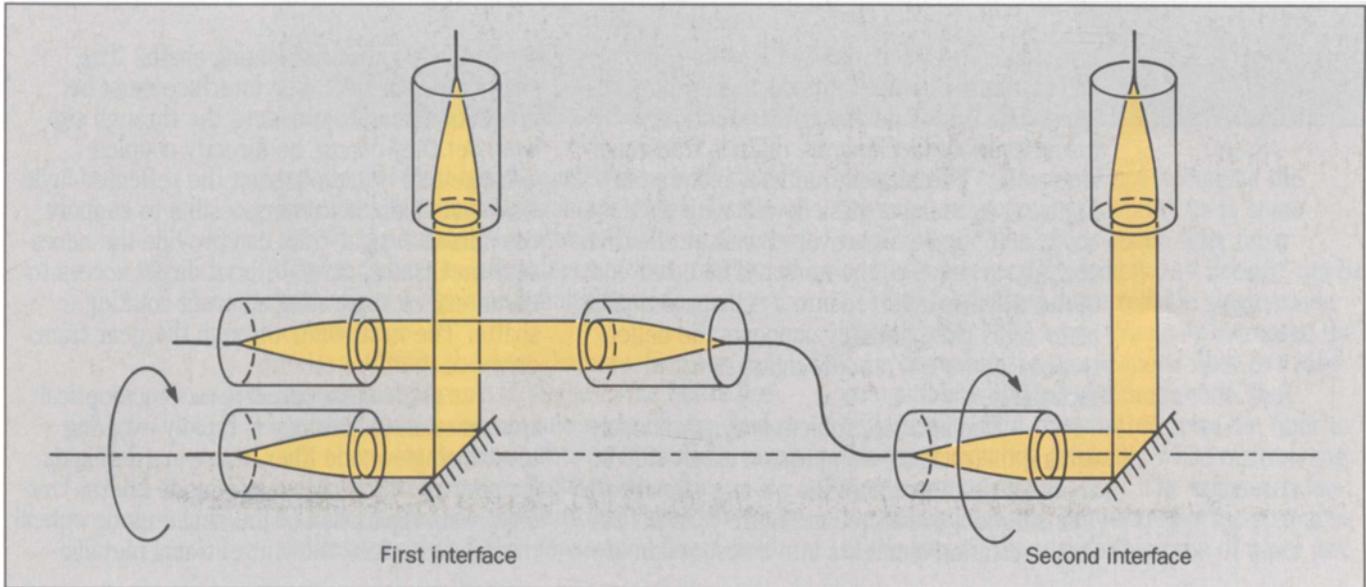


Figure 4. Two rotating fibers.

shown in Figure 4. First, instead of directly coupling the rotating on-axis signal across the interface into a fixed on-axis fiber as shown in the figure, reflect the signal 90° with a mirror. Now a collimator can be correctly positioned to receive the reflected signal. This is demonstrated in Figure 5. Second, allow the off-axis signal to pass through the interface and be cap-

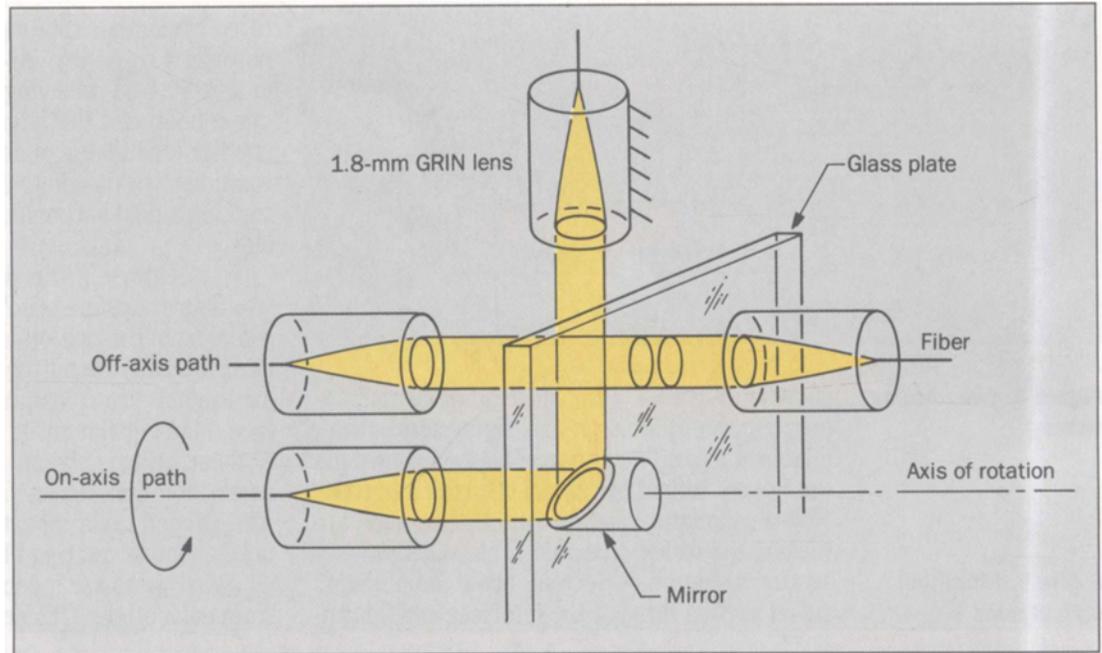
Figure 5. Multifiber optical rotor.



tured by another rotating off-axis lens. This is possible if these two off-axis lenses are rotating in unison. The receiving lens focuses the light into a fiber, and the fiber guides the light to another lens that is positioned on the axis of rotation. At this point, the sole remaining rotating signal is coupled into a fixed receiving lens.

However, this device is not limited to two fibers. If there are N rotating fibers, the signal from the one on-axis fiber is reflected as described above and the remaining $N - 1$ off-axis signals are transmitted across the interface to an equal number of rotating lenses. One of these off-axis signals is then guided to the axis of rotation, leaving $N - 2$ off-axis signals. This procedure is repeated at each interface until only one rotating fiber remains. Note that all signal paths are independent and isolated from each other. This ensures the absence of

Figure 6. Rotary interface.



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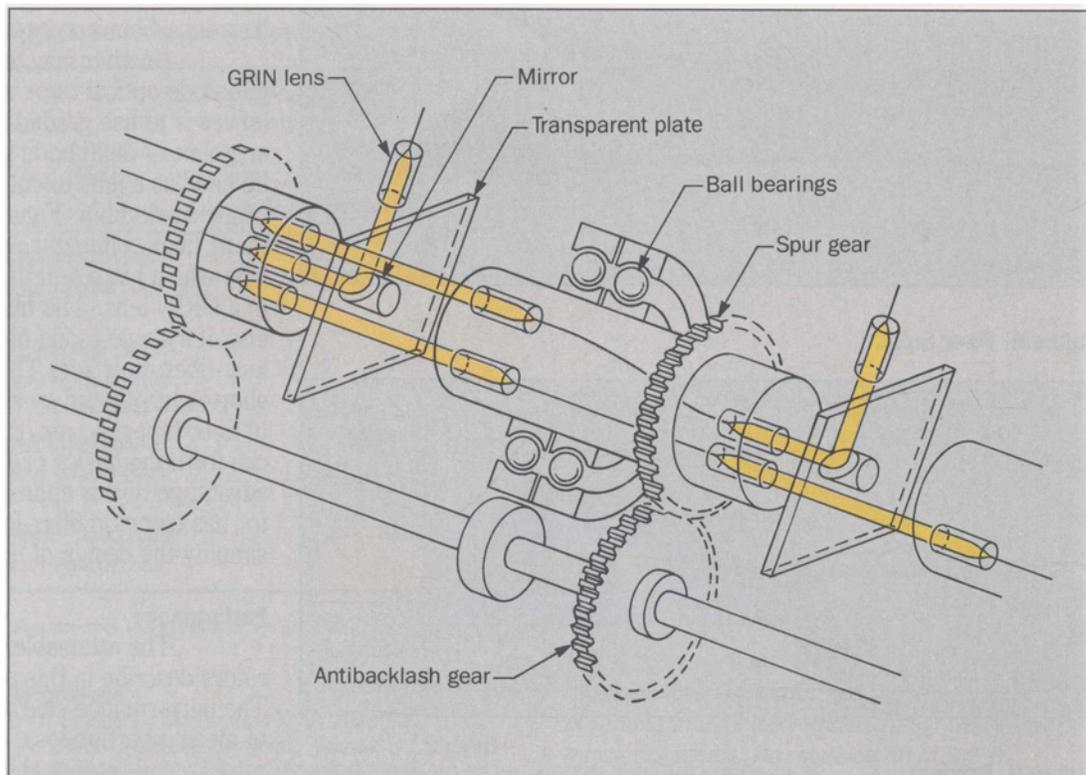
crosstalk. The discontinuity between rotating and stationary components does present problems. The first is mounting the stationary mirror without blocking the off-axis transmission paths. The present method, pictured in Figure 6, is to use a glass dowel, with one face cut at a 45° angle and covered with a reflective coating, to serve as the mirror. The other end of the dowel is inserted into a transparent glass plate. This plate not only supports the deflector, but allows the off-axis signal to travel through it.

The second problem is synchronously driving the rotating elements on either side of an interface to maintain the off-axis signal path. The solution, presented in Figure 7, is to first fix the rotating elements into a succession of

accurately positioned rotating shafts. The shafts on each side of an interface must be driven in unison to preserve the through signals, yet they cannot be directly coupled because this would obstruct the reflected light-wave path and make it impossible to support the mirror. A gear train can provide the necessary mechanical drive without direct access to the interface separating adjacent rotating shafts. The first shaft, through the gear train, drives each of the others.

Single-Mode Optical Rotor. Since optical transmission technology is rapidly evolving toward single-mode fiber, there are demands for optical rotors with single-mode fibers. One important application of the single-mode optical rotor is to replace the conventional metallic

Figure 7. Partial schematic of the multifiber optical rotor.



waveguide joint which is used in aircraft radar antennas to transmit gigahertz-range signals across the rotating interface. The optical rotor approach has the advantages of low cost, small size, light weight, and multifrequency operation.

Since the core diameter and the numerical aperture of single-mode fibers are smaller than those of multimode fibers, there are stringent requirements on lateral and angular tolerances on the single-mode rotor. Furthermore, the conventional approach using collimators with GRIN lenses and fibers held

together by epoxies will not withstand the adverse environmental conditions in some applications. The single-mode fiber taper recently invented by Amitay and Presby⁵ can be used to fabricate a more reliable single-mode optical rotor. The taper gradually increases the core diameter of a single-mode fiber to a size compatible with that of a multimode fiber (Figure 8). Light transmitted from the fiber to the taper expands gradually while maintaining single-mode transmission. The expansion factor depends on the diameter and the structure of the taper. A pair with this type of taper can

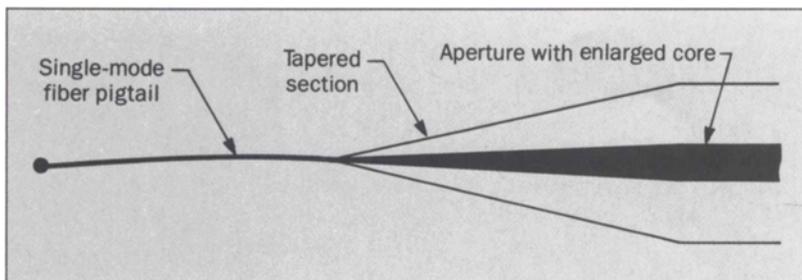


Figure 8. Fiber taper.

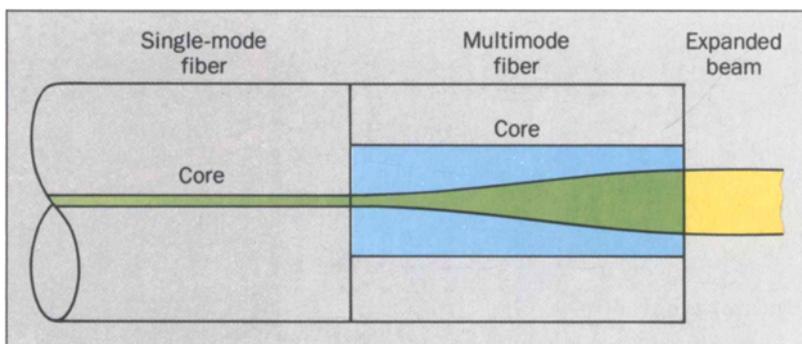


Figure 9. Graded-index fiber lens.

be used in coupling signals between two single-mode fibers. Since the beam waist of the light gets expanded, the coupling loss due to the lateral misalignment is reduced. However, the coupling loss due to angular misalignment becomes very sensitive. The reduction in lateral sensitivity and the increase in angular sensitivity are similar to those experienced in coupling between a pair of single-mode fiber collimators using discrete lenses.

Hence, the taper approach also requires as stringent angular control as does the discrete lens approach. The advantages of a taper approach in an optical rotor application are mechanical stability and a wider operating temperature range, since the rotor does not

have lens-fiber epoxy joints.

Another way to fabricate a rugged single-mode optical rotor without using discrete lenses is to use graded-index fiber lenses.⁶ A segment of multimode graded-index fiber can be used as a lens to collimate the light from a single-mode fiber. Figure 9 depicts a single-mode fiber collimator using a multimode fiber lens which has a length equivalent to a $1/4$ pitch of a GRIN lens. The fiber lens is fused to the end of a single-mode fiber to provide a stable lens-fiber interface. This collimator has a shorter length and smaller diameter than those of fiber taper. A pair of single-mode collimators can form the basics of an optical rotor. The advantage of this approach is that the collimator has common fiber-lens diameters that simplify the design of the rotor.

Performance

The attainable performance of the rotors describe in this paper is given in Table I. The performance characterization is in terms of mean insertion loss, crosstalk (multifiber rotors), and rotational variation.

Summary

The fiber-optic rotors presented here are unique and have been implemented for some initial system applications. However, all of the above devices employ on-axis transmission, which limits the number of channels. Even in the multichannel rotor, the loss increases as the number of channels increases. Therefore, the future will lie in the development of a low-loss, off-axis optical rotor which has a structure similar to that of an electrical slip ring. The optical rotor structures can then be stacked together to provide multichannel capability without increasing loss.

Table I. Summary of Achievable Performance

Type	Mean insertion loss* (dB)			Rotational variation (dB)	Crosstalk (dB)
	First channel	Second channel	Nth channel		
Multimode single-fiber optical rotor	2	N/A†	N/A	± 0.2	N/A
Multimode dual-fiber optical rotor	4	4	N/A	± 0.5	-40
Multimode multi-fiber optical rotor	2	3	$N + 1$	± 0.2	N/A
Single-mode single-fiber optical rotor	2	N/A	N/A	± 0.5	N/A

*Mean insertion loss includes the loss of connectors.

†Not applicable.

References

1. Y. C. Shi, L. Klafter, and E. E. Harstead, "Dual-Fiber Optical Rotary Joint," *Journal of Lightwave Technology*, Vol. LT-3, 1985, pp. 999-1004.
2. E. E. Harstead, Y. C. Shi, and L. Klafter, "Low-loss, Multifiber Optical Rotary Joint," Optical Fiber Communication Conference, 1986, *Technical Digest*, pp. 70-71.
3. Nippon Sheet Glass Co., "The Theory and Design of the Selfoc Lens," 1982.
4. T. C. Chu and A. K. McCormick, "Measurements of Loss Due to Offset, End Separation, and Angular Misalignment in Graded Index Fibers Excited by an Incoherent Source," *Bell System Technical Journal*, Vol. 57, No. 3, March 1978, pp. 595-602.
5. N. Amitay et al., "Single-mode optical taper for self-aligned beam expansion," *Electronics Letters*, 1986, pp. 702-703.
6. W. L. Emkey and C. J. Jack, "Analysis and Evaluations of Graded Index Fiber Lens," Optical Fiber Communications Conference, 1987, *Technical Digest*, p. 112.

Biographies (continued)

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