9.0 PROJECT #9: MULTIMODE INTENSITY SENSORS

(Est. Time Required: 3:00 hrs.)

The projects undertaken up to this point have explored the basic properties of fibers, fiber communication components, and analog communication links. Another important fiber application is sensor technology. In this project, multimode fiber sensors are examined, which exploit light-guiding capabilities and optical properties of multimode fibers. A variety of sensors will be examined that measure a number of different physical parameters. What these fiber sensors have in common is that they all measure the intensity of the light returned by the fiber from a discrete sensor element. On the other hand, single-mode fiber sensors, which measure the phase changes of the light carried by a single-mode fiber, will be studied in **Project #10**. The multimode sensors illustrated in this project represent only a small sample of the many intensity sensors that have been designed or are in use. Instructors of advanced students may choose to design and construct sensors other than those presented.

9.1 FIBER OPTIC SENSORS

The unique properties of optical fibers allow innovative approaches to the design of optical sensors. Optical fibers are non-conducting and immune to electromagnetic and radio frequency interference. The low attenuation coefficients of fibers allow sensitive electronic equipment to be located remotely. The availability of fiber optics gives the system engineer great flexibility in sensor design. Fiber optic sensors are used in a wide variety of applications ranging from simple counters and limit switches to measurements requiring high precision and accuracy.[1-3]

Fiber optic sensors are currently being used in a wide variety of areas, such as biology, chemistry and engineering, to name but a few. Biosensors measure the formation of a fluorescent complex, allowing fast and efficient analysis of hazardous materials remotely, using computerized data acquisition systems.[4-6] Chemical sensors detect and monitor flow rates of heavy metals in water, among other applications.[7] There are also fiber optic sensors, which monitor the integrity and safety of civil structures, such as bridges.[8-9]

One of the many advantages of fiber optic sensors is their environmental versatility. They may be found in such varied and adverse conditions as aqueous systems, ultra-high vacuum environments (such as deep space), and extreme temperature settings (like combustion or plasma labs). In addition, they can be used in hazardous environments such as toxic, mutagenic and nuclear sites. There is a promising future for fiber optic sensor design and technology. Indeed, whereas the twentieth century was the era of copper technology, the twenty-first will be the era of fiber optic technology.

Fiber optic sensors can be classified into two general categories, intensity sensors and phase sensors. These two classes of sensors differ in construction, sensitivity, dynamic range, signal transmission, and detection schemes. Phase sensors use single-mode fibers that employ an interferometer to extract phase information from the sensor. They will be explored in **Project #10**: "Single-Mode Interferometric Sensors."

Intensity sensors use multimode fibers and small transducers, which make measurements at specific points along the light path. (A **transducer** is a device that converts one physical parameter into another, making the measurement of the first parameter easier. The transducer in a fiber optic intensity sensor converts a physical parameter into a change in the amount of light that is transmitted.) Optical power is transmitted to the sensor, the physical parameter being measured causes the transducer to change the amount of light passed by the sensor, and the power is then returned to the detector. Depending on the type of intensity modulation used, multimode intensity sensors are subdivided into two major groups, hybrid sensors and internal effect sensors. Hybrid sensors treat the fiber as a light pipe, transmitting the light to a remote sensor, which is generally a miniaturized device at the end of the fiber. Hybrid sensors allow a broad range of modulation schemes, which include conventional non-fiber optical sensors. However, internal effect sensors use the fiber itself as the transducer, with the parameter being measured causing a modulation of the light-guiding properties of the fiber.

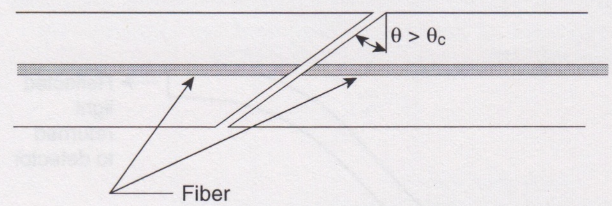

Figure 9.1. Liquid level sensor: θ_c is the critical angle for total internal reflection at a glass-air interface in the glass fiber.

9.2 HYBRID SENSORS

The simplest sensor acts as an on-off switch to detect the presence or absence of a stimulus at the sensor site. An example of this, shown in **Fig. 9.1**, is a liquid level sensor that detects the presence or absence of liquid in the gap between two fiber ends. As shown in the figure, the fiber ends are cut at an angle so that the angle of the fiber end is greater than the critical angle for total internal reflection of the central ray of the beam transmitted by the fiber. When a liquid is present in the gap between the fiber ends, the glass-air interface at which total internal reflection occurs is eliminated and the index of the glass is nearly matched by the liquid. Light is no longer totally internally reflected and optical power is transmitted from one fiber end to the other.

Another, more sophisticated hybrid sensor is the pressure sensor, illustrated in **Fig. 9.2**, which uses the photoelastic effect to monitor the pressure in a glass transducer.[10] Pressure applied to the glass causes stress-induced birefringence, resulting in a change of the polarization of the beam transmitted through the transducer. The polarizer, P in **Fig. 9.2**, causes the light incident on the glass to be polarized at an angle of 45° with respect to the applied stress, S. The stress-induced birefringence causes the plane of the polarization to change from linear to elliptical. A second polarizer, A, acts as an analyzer selecting the component of the transmitted beam perpendicular to the original linear polarization. For the configuration shown, the optical power transmitted by the sensor is[11]

$$I = I_0 \sin^2 (\pi t S/f), \quad (9\text{-}1)$$

where t is the thickness of the glass transducer, S is the applied stress, and $f = 2tS_0$, where S_0 is the stress required to make the transmitted power through the transducer go from a maximum to a minimum. It is called the material fringe value. Typical values for f are in the range of 0.2-0.3 MPa-m. This type of sensor has been used to measure pressures of up to 21 MPa (3,000 psi) with a resolution of better than $\Delta P/P = 10^{-4}$.

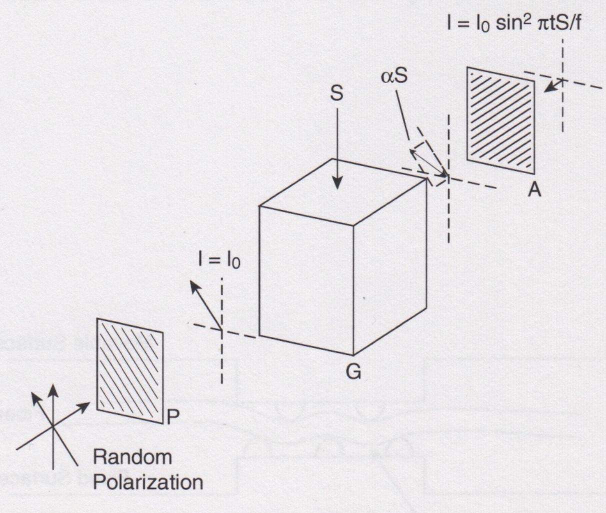

Figure 9.2. Pressure sensor using the photoelastic effect: unpolarized light is polarized, at an angle of 45° with respect to the stress axis, S. Stress causes birefringence, which causes the polarization of the light to change. The analyzer, A, selects the perpendicular component of the beam.

The previous two examples use high-quality low-loss multimode transmission fibers that allow remote measurements to be made at long distances. In addition, fiber sensors can use lower-technology fiber bundles. An example is the proximity sensor, which uses a bifurcated (Y-branched) fiber bundle as shown in **Fig. 9.3**.

Optical power is launched in one arm of the fiber bundle. It is reflected from a surface at the output end of the fiber to the second arm of the bundle. The reflected light is transmitted to a detector. The amount of light returned to the detector depends on the distance between the end of the bundle and the surface being monitored.

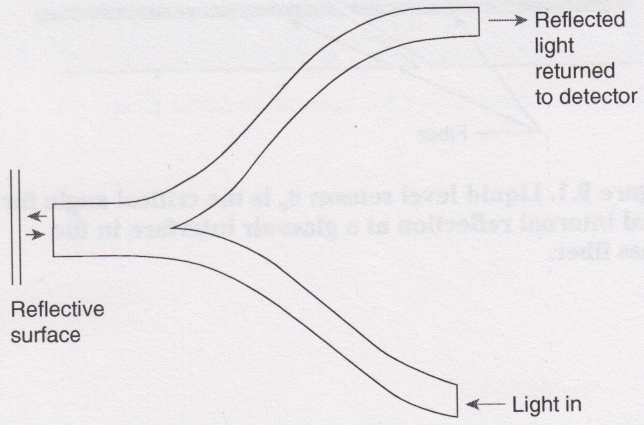

Figure 9.3. Proximity sensor in a bifurcated fiber bundle.

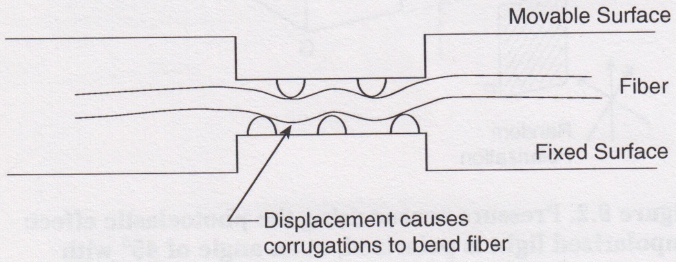

Figure 9.4. Microbend strain sensor: structural strain causes corrugations to bend the fiber, causing loss.

9.3 INTERNAL EFFECT SENSORS

Internal effect sensors use various modulation schemes to perturb the fiber. The fiber thus becomes both the transmission medium and the transducer. The modulation effects used in these sensors include microbending loss, modal intensity modulation (mode filtering is used to detect redistribution of the optical power due to mode coupling caused by mechanical deformation of the fiber), and internally generated thermal radiation.[2]

As an example of the sensors that can be designed, **Fig. 9.4** shows a displacement sensor that uses microbending loss.[12] Optical power is coupled from guided modes to the cladding when the fiber is bent. The displacement sensor has a fiber placed between two corrugated plates and the optical loss is measured as a function of the displacement of the two corrugated plates with respect to each other.

These examples of multimode fiber optic intensity sensors represent only a small part of the large number of fiber optic sensors that have been investigated or developed.

9.4 REFERENCES

1. T. G. Giallorenzi, et al., "Optical fiber sensor technology"; IEEE Journal on Quantum Electronics QE-18, 626 (1982)
2. S. K. Yao and C. K. Asawa, "Fiber optic intensity sensors"; IEEE Journal on Selected Areas in Communications SAC-l, 562 (1983) and references therein
3. Proceedings of the SPIE, Fiber Optic and Laser Sensors, Vol. 412 (1983), Vol. 478 (1984), Vol. 566 (1985), Vol. 586 (1985)
4. D.L. Wise and L.B. Wingard, Ed., *Fiber Optic Biosensors,* Humana Press (NJ), 1991
5. O.S. Wolfbeis, Ed., *Fiber Optic Chemical Sensors and Biosensors,* CRC Press Inc. (Boca Raton FL.), 1991
6. J.P. Golden et al., "An evanescent wave biosensor using tapered fiber optic probes", Optical Engineering, 31(7), pp. 1458-1462 (1992)
7. K.J. Ewing et al., "Detection of trace levels of Mercury in aqueous systems via a fiber optic probe", SPIE Symposium on Optical Tools for Manufacturing and Advance Automation, Technical Conference #2068, Environmental Sensors, Sept. 7-10 (1993)
8. M.A. Davis et al., "Distributed fiber Bragg Grating strain sensing in reinforced concrete structural components", J. Cement and Concrete Composites, (August 1996)
9. K.H. Wanser et al., "Novel fiber devices and sensors

based on multimode fiber Bragg Gratings", Proc. OFS-10, Glasgow, p. 265 (1994)

10. E. Hecht, *Optics*, Addison-Wesley (San Francisco), 2002

11. W.B. Spillman, Jr., "Multimode fiber-optic pressure sensor based on the photoelastic effect," Optic Letters 7, 388 (1982)

12. C.K. Asawa, S.K. Yao, R.C. Stearns, N.L. Mota, and J.W. Downs, "High sensitivity fiber optic strain sensor for measuring structural distortion," Electronics Letters 18, 362 (1982)

9.5 PARTS LIST

Cat#	Description	Qty.
F-MLD	100/140 MM Fiber, 50 meters	1
R-30025	1.5 mW HeNe Laser	1
ULM-TILT	Laser Mount	1
340-RC	Clamp	1
41	Short Rod	1
F-CL1	Fiber Cleaver	1
F-STR-175	Fiber Stripper	1
F-916	Fiber Coupler (without lens)	1
FPH-S	Fiber Chuck	1
M-20X	20X Objective Lens	1
FP-1A	Fiber Positioner	2
F-BLX	Allen Wrench Set	1
SK-25A	Screw Kit, ¼-20	1
VPH-2	Post Holder, 2"	7
SPV-2	Post, 2"	7
1918-C	Power Meter	1
918D-SL-OD3	Low Power Detector, Silicon	1
FP3-FH1	Bare Fiber Holder	1
818-FA2	Bare Fiber Holder Mount	1
FM-1	Mode Scrambler	1
05657-00	Epoxy	1
F- TK1L	160 Lapping Sheets	1
FK-LS	Liquid-Level Sensor Assembly	1
FK-PS	Pressure Sensor Assembly Base	1
FK-GT	Glass Transducer	4
FK-GR25P	NSG 0.25-p GRIN-Lens (without filter)	2
FK-POL	Polarizer Sheet	1
423	Translation Stage	1
SM-13	Micrometer, 13 mm	1
MPC	Collar	3
777-1	Bifurcated fiber bundle	1
IMIC-1	Fiber Inspection Microscope	1

Additional equipment required: Laboratory weight set for the pressure sensor, Kimwipe XL, tape, pipette, and toothpick.

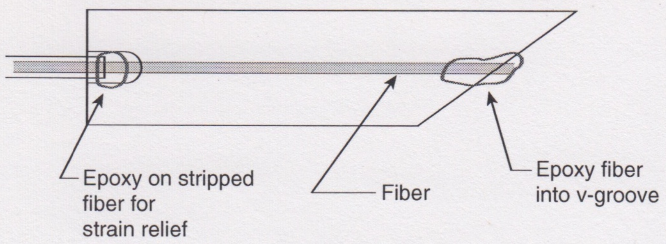

Figure 9.5. Epoxy the fibers into the recessed area and the v-groove of the angled pieces of the Liquid-Level Sensor (FK-LS).

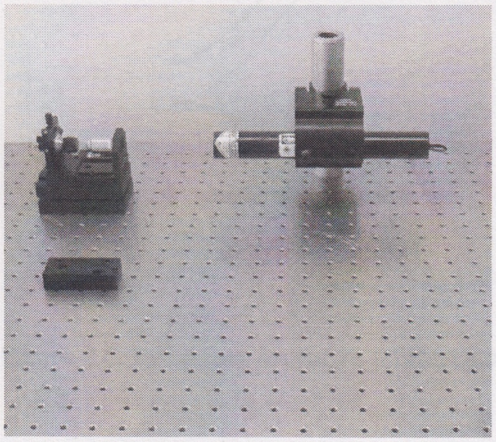

Figure 9.6. Laboratory set-up of the liquid-level sensor.

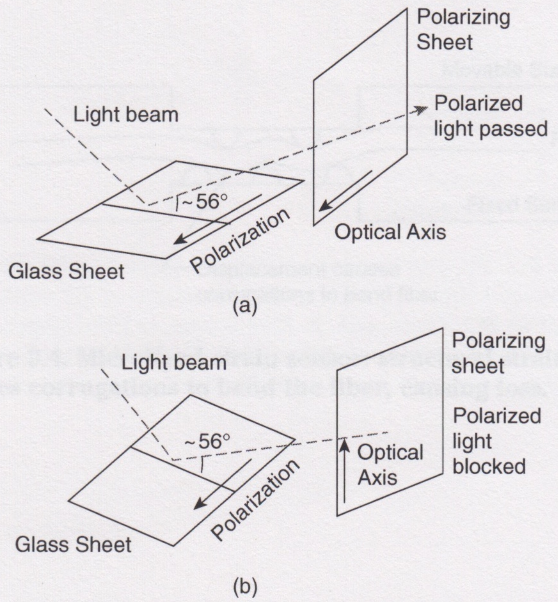

Figure 9.7. Determination of the optical axis of a polarizer: a) optical axis parallel to the plane of polarization. b) optical axis perpendicular to the plane of polarization.

9.6 INSTRUCTION SET

9.6.1 Liquid-Level SENSOR

1. Strip both ends of an F-MLD fiber. Lay the fiber in the grooves of the liquid-level sensor inserts. There is a recessed area at the end of the insert into which the jacketed end of the fiber may be set for strain relief. Tape may be used to hold the fiber in place while performing the following procedure.

2. Use the 05657-00 Epoxy to mount the fibers in the grooves as shown in **Fig. 9.5**. Be sure that this includes part of the jacketed fiber in the recessed area. The epoxy cures completely in about one hour.

3. Polish the fiber ends following the same general technique used to in **Project #6**, (see **Section 6.5.2, Steps 6-11**). Use a pipette to dispense a small amount of water, a couple of drops, on the lapping sheet.

4. Place the insert on the sensor assembly base. Slide the inserts against the rail so that the fibers will be aligned with each other. Adjust the spacing between the fiber ends to about 1/2 mm. The actual spacing required depends on the surface tension and viscosity of the liquid that will be used.

5. Couple the light from the HeNe laser into one of the fibers. Place the end of the other fiber in the FP3-FH1 Bare Fiber Holder. Connect to the 918D-SL-OD3 detector using the FP3-FH1 and an 818-FA2. Record the optical power input of the sensor before applying the liquid. This value can be as low as microwatts. The complete laboratory set-up for this sensor is shown in **Fig. 9.6**.

6. Immerse the sensor in a liquid bath or place a drop of liquid between the fibers in the gap in the sensor. The liquid can be glycerin, water, alcohol, or acetone, which will dissolve the epoxy. Record the optical power output through the sensor.

7. Calculate the ratio of power between the on and off states of the sensor. Express in dB. (Which liquid is expected to provide the greatest ratio?)

9.6.2 PRESSURE SENSOR

1. Determine the optical axis of the FK-POL Polarizing Sheet. *View the polarizing sheet at an angle of ~56°. The glare from a sheet of glass will be polarized in a plane parallel to the glass sheet (see Reference 4 for a description of this phenomenon). The glare will be a maximum when the optical axis is parallel to the plane of polarization (***Fig. 9.7a***) and a minimum when the optical axis is perpendicular to the plane of polarization (***Fig. 9.7b***).*

2. Cut two pieces from the polarizing sheet so that the axis of polarization is at an angle of 45° to the sides. Cut the pieces to fit the ends of the FK-GT Glass Transducer.

3. Epoxy a thin film on the smooth clear side of the glass transducer. (Note: be sure that there are no bubbles in the epoxy). A wooden toothpick is an excellent device as an applicator. Dip the toothpick into the epoxy, make sure that the excess epoxy is removed, role the epoxy gently and slowly on the transducer. Remove any excess epoxy from the edges of the transducer. If the polarization axes of the polarizer and the analyzer are crossed with respect to each other, the sensor will exhibit sine^2 stress dependence (see **Eq. 9-1**). If the polarization axes are parallel, the pressure sensor will yield a cosine^2 stress dependence. Crossed polarizers are preferred for commercial devices, because the highest pressures give

the largest signals, and a large amplification can be used to detect small stresses in a dark background. On the other hand, parallel polarizers are recommended for a student laboratory, because this makes the optical alignment of the sensor easier. (Why?)

4. Glue two .25 pitch GRIN-rod lenses, FK-GR25P, into the grooves in the pressure sensor assembly base (see **Fig. 9.8**). Be sure that the ends of the lenses do not extend into the central portion of the sensor, which is occupied by the glass transducer.

5. Strip and cleave two lengths of F-MLD fiber. Couple HeNe laser light into one of the fibers using the F-916 Fiber Coupler. Mount each fiber into the FP-1A Fiber Positioner as shown in the laboratory set-up of **Fig. 9.9**. The pressure sensor assembly should be mounted on posts to provide the proper height for coupling light through the sensor. Maximize the fiber-to-fiber coupling through the assembly.

6. Place the glass transducer in the pressure sensor assembly. Again maximize the fiber-to-fiber coupling. (This is the answer to the "Why?" question at the end of Step 3 above.)

7. Bring the lever arm down on top of the transducer. Adjust the setscrew so that the lever arm is horizontal when it rests on the glass. Add weight to the end of the lever arm. Monitor the optical power through the sensor as a function of applied weight. Calculate the pressure in the glass from the applied force, the cross-sectional area of the glass, and the mechanical advantage of the lever arm:

$$P = mg \times (d_2/d_1)/A \qquad (9\text{-}2)$$

where m is the mass applied to the lever arm, g is the acceleration due to gravity, d_2 is the distance from the pivot point to the end of the lever where the weight is applied, and d_1 is the distance from the pivot point to the pressure point.

8. Plot the power transmitted by the sensor as a function of applied pressure. Compare this with a cosine^2 curve. Find the pressure at which the transmitted power goes through a minimum. Use this to calculate the fringe constant of the glass from **Eq. 9-1**.

9.6.3 PROXIMITY SENSOR

1. Insert an 8-32 setscrew into each of three SPV-2 posts. Screw an MPC Collar onto each setscrew. Insert each of the three ends of the 777-1 Dual Fiber Bundle into each collar. Gently tighten each setscrew. Do not over tighten. The laboratory set-up for this sensor is shown in **Fig. 9.10**.

2. Mount one of the single ends in a VPH-2 Post Holder and illuminate this end with a HeNe laser. This sensor can also be constructed using a white-light source if you have a high-power lamp, which can be focused onto the end of the fiber bundle.

3. Fasten a VPH-2 post holder to the 423 Translation Stage and place the post with the common end of the fiber bundle into this holder. Set up a card (a white surface) so that the HeNe output of the fiber bundle shines on the card, or mount the translation stage so that the output shines on a wall. In either case, the fiber bundle needs to be mounted so that it is able to actually make contact with the surface to be measured.

4. Light reflected by the surface being monitored will reflect back into the fiber bundle and will go to the other end. Mount this end in a VPH-2 post holder coupling the

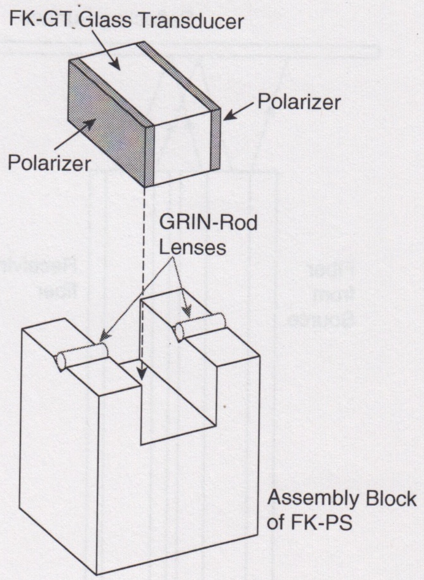

Figure 9.8. Place the 0.25 pitch GRIN rod lenses in the pressure sensor assembly (FK-PS).

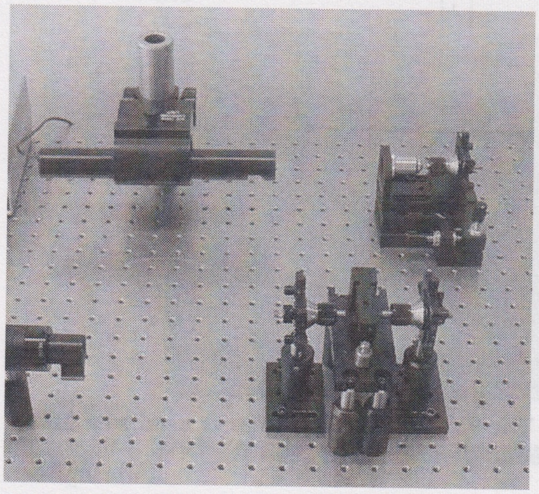

Figure 9.9. Laboratory set-up for pressure sensor assembly.

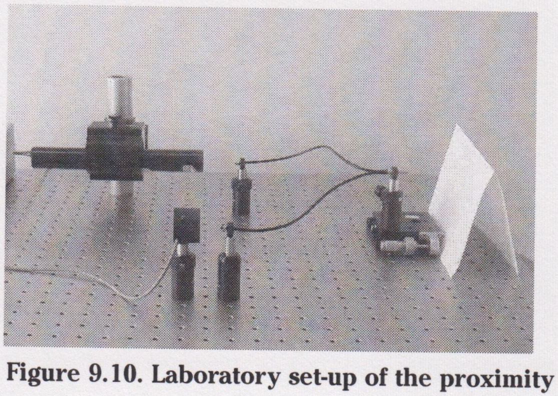

Figure 9.10. Laboratory set-up of the proximity sensor.

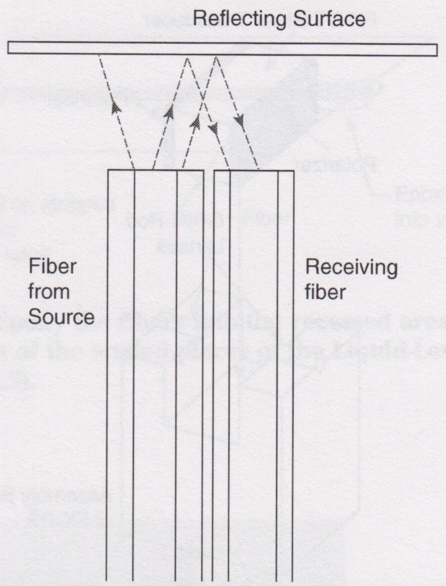

Figure 9.11. Drawing showing light emitted by one fiber, reflected by the near-by surface, and received by a neighboring fiber. Repeat this drawing for different fiber-to-surface distances.

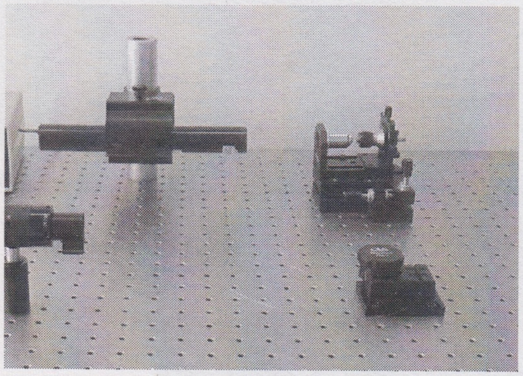

Figure 9.12. The FM-1 Mode Scrambler is used as a fiber optic microbend displacement sensor.

output light into the 918D-SL-OD3 detector and power meter. Vary the distance between fiber end face and reflector and record data.

5. Measure the reflected output power as a function of distance. Also, plot this power as a function of $1/d^2$.

6. Find the power where linear $1/d^2$ dependence begins. This is the distance that the finite diameter of the fiber core is no longer significant in determining the amount of reflected light the fiber bundle accepts. Why does the amount of reflected power accepted by the fiber bundle drop from a maximum as the distance, d, gets very small? (**HINT:** Draw the light cone from the fiber bundle incident on the surface being monitored and the cone of acceptance of the neighboring fiber which detects the light as in **Fig. 9.11**. Vary the distance between the fiber end faces and the reflecting surface.)

7. Estimate the smallest positional resolution of this sensor.

9.6.4. MICROBEND DISPLACEMENT SENSOR

1. The FM-1 Mode Scrambler, which was used in Projects #2 and #6 is an example of a displacement sensor. Rotate the knob on the FM-l to fully separate the corrugated surfaces.

2. Strip and cleave both ends of F-MLD fiber. Launch light into a segment of F-MLD fiber using the HeNe laser and the F-916 coupler. The laboratory set-up for this sensor is shown in **Fig. 9.12**.

3. Place the jacketed fiber in the slot between the corrugated surfaces.

4. Rotate the knob until the corrugated surfaces just contact the fiber. Note the knob position. (**Note:** each major graduation on the knob represents a 25 micron displacement, while the smaller graduations mark 12.5 micron displacements).

5. Record and plot the power output from the fiber as a function of displacement. The fiber has a soft buffer, so some period of stabilization may be needed after you set the displacement for the transmitted power to come to equilibrium, approximately 30 seconds. In an actual sensor system, the knob-controlled displacement would be replaced by having the corrugated surfaces attached to two surfaces whose relative position is to be measured.