A Practical Optical Modulator and Link for Antennas

JERRY C. WYSS, MEMBER, IEEE, AND STEPHEN T. SHEERAN

Abstract—**This paper describes a practical application of a technique for coupling an antenna to a receiver using a passive fiber-optic link. This technique should avoid pickup and electromagnetic perturbations normally associated with the use of electrically conductive cables. Laser light (632.8 nm) is modulated at the antenna by an electrooptic lithium-tantalate crystal and is then transmitted with a fiber-optic cable to the receiver electronics. Using an avalanche photodiode, the amplitude modulated optical signal is converted to an electrical signal. The crystal is mounted directly on an antenna without amplifiers or other electrically powered components. Using a broad-band antenna with fields generated in an anechoic chamber and a standard TEM cell, the frequency response as measured dropped 3 dB per 1.0 GHz from 100 MHz to at least 2.0 GHz, with a signal-to-noise ratio of 5 dB with a 1.0-V/m field and a 1.0-kHz bandwidth. A dynamic range of at least 60 dB is shown.**

Key Words—**Antenna, electromagnetic interference, electrooptics, fiber-optic link, optical fibers, electrooptic modulator.**

I. Introduction

IN THE precise measurement of electromagnetic fields, signals gathered by an antenna are usually fed to the receiver electronics using conductive cables. These cables can degrade the system response characteristics in a number of ways, including: 1) acting as an antenna itself, causing unwanted pickup; 2) directly perturbing the local field; and 3) greatly attenuating the received signal, requiring the receiver to be located close to the antenna. To avoid these electrical cable problems, a prototype fiber-optical link and modulator has been constructed and tested between the antenna probe and receiver electronics.

There are basically two types of fiber-optical systems that have been used as links between antennas and receivers: 1) active systems where batteries, amplifiers, and other active components are located in a box at the antenna, and 2) passive systems that have no electrically powered components at the antenna. A number of active systems have been described in the literature (a selection of some of the devices are cited in [1]–[4]). The active systems have the advantage of increased sensitivity through amplification, but have the disadvantage of requiring a power source at the antenna. Also, the active components near the antenna could conceivably perturb the field being measured.

Various passive systems have been proposed to overcome the limitations of the active systems [5]–[8].[1] Passive systems, which have no electrically powered components at the antenna, do not require a battery nor an external power source. The only electrically conducting component of the system exposed to the field to be measured is the antenna itself, while all the other components, such as the modulating crystal, lenses, polarizers, and mounting supports, are nonconducting dielectrics. This makes the system relatively nonperturbing except for the antenna which could be well characterized. The disadvantages of passive systems include: 1) lower sensitivity, 2) potentially poor thermal stability, and 3) usually, the necessity to use small-core single-mode fibers which can require special optics and special connectors.

Bassen and Peterson [5] have proposed two types of passive system: 1) a design based on a bulk-modulation crystal, and 2) an integrated-optics modulator scheme. While a bulk modulator system is easier to fabricate than the integrated optics system, the bulk modulator has poorer sensitivity (1 V/m versus ~1 mV/m for the integrated optics) [6], [7]. This paper describes the latest results in a passive modulator and link based on the bulk-modulator design. The theory of the system as well as the experimental approach and results will be presented. Results using an earlier system where tests were made using a signal generator instead of actual electric fields have been reported earlier [9], [10].

II. Theory

The theory of electrooptical modulators has been adequately described in the literature [11]; therefore, the following is a brief description as to the theory's application to a passive bulk modulator and fiber-optic link for antenna systems. Fig. 1 shows an idealized optical modulator setup that can be used with an antenna system. A linearly polarized laser becomes elliptically polarized with a Babinet compensator. A single-mode fiber transmits the light to a crystal connected to a dipole antenna. The crystal modulates the laser polarization as a function of the antenna voltage. A linear polarization analyzer at 135° converts the polarization modulation into an amplitude modulation which is received by the detector. The second crystal, oriented with its fast axis at 180°, is used to improve the temperature stability of the system.

The polarization of the laser light traveling through the system in Fig. 1 can be described by a single parameter Γ, which can be defined as the phase difference between

Manuscript received June 14, 1984; revised October 19, 1984

J. C. Wyss was with the Electromagnetic Fields Division, Center for Electronics and Electrical Engineering, National Bureau of Standards, U.S. Department of Commerce, Boulder, CO 80303. He is now with the General Research Corporation, Santa Barbara, CA 93111.

S. T. Sheeran is with the Electromagnetic Fields Division, Center for Electronics and Electrical Engineering, National Bureau of Standards, U.S. Department of Commerce, Boulder, CO 80303.

[1]The technique in [8] could be used to make an electric-field probe.

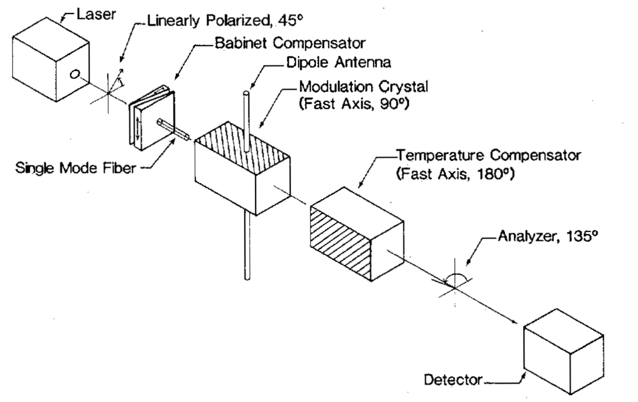


Fig. 1. An ideal modulator system for use with an antenna is shown.

the vertical and horizontal polarization components of the laser light. As an example, if $\Gamma = 0$, then the vertical and horizontal components are in phase, and the light is linearly polarized at 45° with respect to the two axes. As polarization of the light changes from linear to elliptical, Γ will correspondingly change. From Chen [13], Γ can be used to mathematically describe the modulator shown in Fig. 1 by the following equation:

$$I = \frac{I_o}{2}\{1 - \cos \Gamma\} \tag{1}$$

where I_o and I represent the input and output laser intensities, respectively. The parameter Γ can be further broken down into three elements

$$\Gamma = \frac{\pi V}{V_{1/2}} + \alpha + \beta \tag{2}$$

where V represents the voltage applied to the crystal, $V_{1/2}$ represents the half-wave voltage (the voltage needed to provide a π-radians polarization shift), α represents the sum of all the temperature-dependent phase shifts due to the temperature-dependent birefringence of the two crystals, and β represents the sum of all the nontemperature-dependent static phase shifts due to all the other components (Babinet compensator, single-mode fiber, and also the nontemperature-dependent static birefringence of the two crystals). As mentioned earlier, a second nonmodulating crystal is used to reduce the temperature dependence of the system, or mathematically to reduce α to zero (see Chen [13]). We will therefore set $\alpha = 0$.

The second term of (2) can be adjusted to any value using the Babinet compensator and polarization rotator. If β is made to equal $\pi/2$ and α is neglected, then (2) can be substituted into (1), and by a simple trigonometric identity, the result yields

$$I = \frac{I_o}{2}\left\{1 + \sin \frac{\pi V}{V_{1/2}}\right\}. \tag{3}$$

If V is taken to be much less than $V_{1/2}/\pi$, then (3) can be expanded in a power series. Neglecting cubic and higher terms yields

$$I = \frac{I_o}{2}\left\{1 + \frac{\pi V}{V_{1/2}}\right\}. \tag{4}$$

The final problem is to relate the electromagnetic field E detected by the antenna to the crystal voltage V. In the system proposed here, a dipole antenna is used where each element has length h. Using the analysis of Bassen and Peterson [5], the antenna voltage will then be

$$V_a = 2Eh \tag{5}$$

where E represents the magnitude of the electric field along the direction of the dipole. The simplest model for coupling from the antenna to the crystal is to assume capacitive coupling between them, as described by Bassen and Peterson [5]. If the antenna has a capacitance C_a and the crystal has a capacitance C_x, then

$$V = \frac{C_a}{C_a + C_x} V_a. \tag{6}$$

Substituting (5) into (6) and then (6) into (4) yields

$$I = \frac{I_o}{2}\left\{1 + \frac{2\pi C_a hE}{V_{1/2}(C_a + C_x)}\right\}. \tag{7}$$

Using a 15-cm long dipole (h = 7.5 cm) with a 5-mm diameter yields a $C_a \approx 4.3$ pF. Using a 1-mm × 1-mm × 1-cm lithium-tantalate crystal with a dielectric constant of 98 [14] yields $C_x \approx 8.7$ pF. With $V_{1/2} = 284$ V [14], substituting these values into (7) yields

$$I = \frac{I_o}{2}\left\{1 + 5.49 \times 10^{-4}\,\mathrm{E}\right\} \tag{8}$$

where E is taken in volts per meter. Thus a 1-V/m field would produce a modulation of 0.05 percent, which should be detectable using narrow-band detection techniques.

III. Experimental Design

The experimental setup is shown in Fig. 2. A linearly polarized single-mode He–Ne laser (λ = 632.8 nm) is mounted on an optical bench and is used as the light source for the modulator. The laser light, expanded with a 3× telescope, goes through the Babinet compensator and the polarization rotator and then is focused onto a 30-m long single-mode fiber using a 20× microscope lens. The fiber, which has a 6.9-μm fiber mode size, guides the laser light to the antenna assembly, where the beam is collimated with a lens so that it passes through the crystals and the polarization analyzer (see Fig. 3). A second lens focuses the laser light onto the return multimode fiber. The two crystals are made of lithium tantalate and are each 1 cm long by 1 mm by 1 mm. The polarization analyzer is made of plastic-sheet polaroid material. The collimating and focusing lenses are graded-index micro lenses.

The alignment of the fiber cables, lenses, crystals, and polaroids is very critical. The single-mode fiber is first mounted in a conventional multimode otpical-fiber ferrule using the techniques specified by the manufacturer [15]. The ferrule was first modified by drilling two holes on either side of the face. After the fiber has been glued and polished in place, two delrin rods (2 mm long × 0.4 mm diameter) are glued in the extra holes to provide mechan-

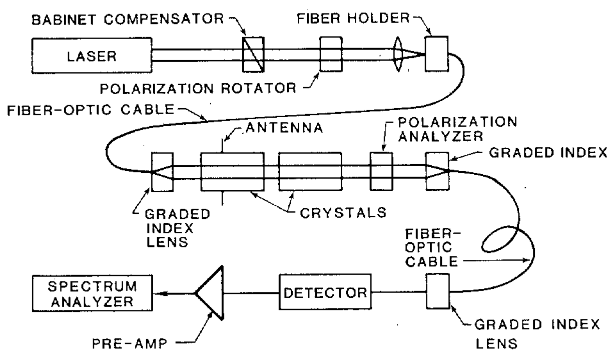


Fig. 2. The experimental setup for the fiber optically linked antenna system.

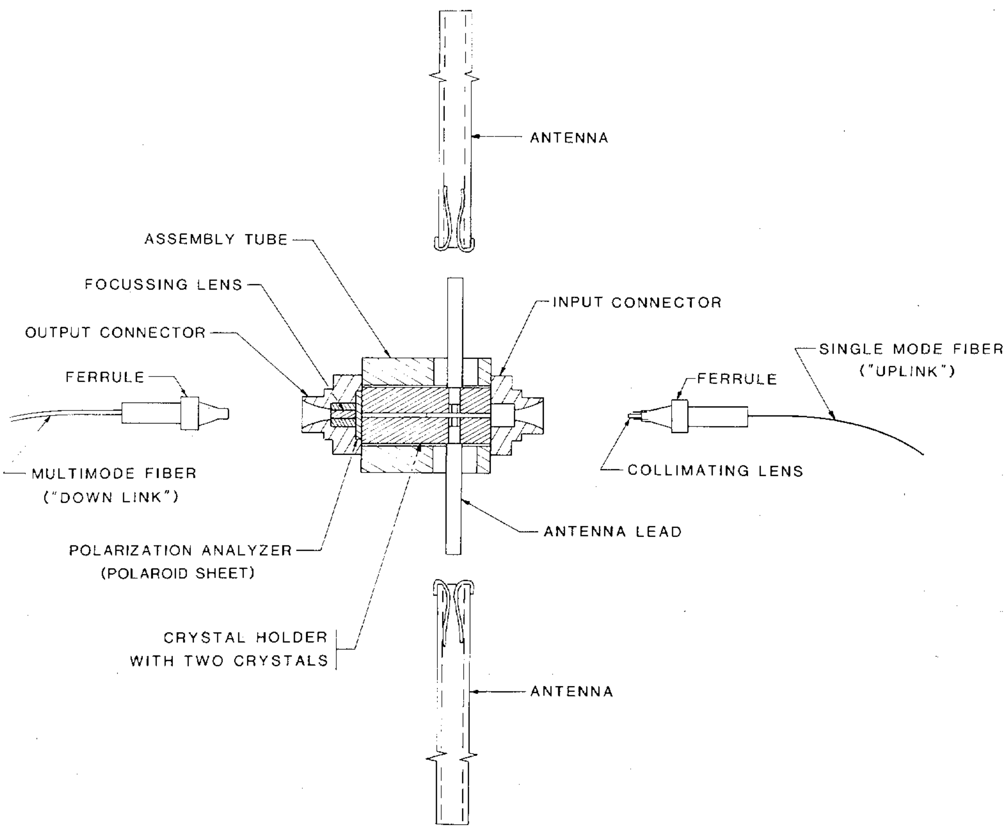


Fig. 3. Cross-sectional view of the antenna-crystal assembly showing fiber-cable ferrules, connectors, crystals, lenses, antennas, and polarization analyzer.

ical support for the collimating lens. To align the collimating lens, laser light is focused onto the input end of the fiber and is observed to come out of the bare output end. The collimating lens, held in an X–Y–Z translator, is positioned at the output such that the output beam is now collimated to better than a 1-cm spot at 3 m away from the lens. With the lens optimally centered on the fiber core, the lens is epoxied to the ferrule and to the delrin support rods. Using this procedure results in a beam size through both crystals of less than 0.5 mm in diameter. Since the crystals provide a 1-mm diameter clear opening, it is only necessary to center the beam to ± 0.25 mm. The ferrule with the fiber and collimating lens glued in place is held on the antenna assembly using a connector that has been centered on the crystals to ± 0.25 mm.

The two crystals are mounted in a nylon rod which has two side holes for antenna leads. A 15-cm broad-band resistivity loaded antenna is used [16], [17]. This antenna was chosen because it has a broad (0.1–5.0 GHz) frequency range. Thus the frequency response of the optical system could be tested over a large range without changing antenna elements. As shown in Fig. 3, the 3-cm long brass antenna leads are threaded into the nylon crystal holder for mechanical support. Spring-loaded rods mounted in the tips of the brass rods make electrical contact with the crystal. The antennas are slipped onto the brass rods and covered by a teflon protector. The sheet polaroid is glued onto the return fiber connector and is oriented at 135° with respect to the horzontal optical axis of the crystals (see Fig. 1). The return connector, centered on the axis of the crystals, also holds a focusing lens.

The downlink fiber is a large-core (50-μm) multimode fiber (30 m long) that is fitted with standard fiber-cable ferrules at both ends. One end plugs into the return fiber connector on the antenna assembly, while the other end plugs into a fiber connector attached to a focusing lens and a fast, broad-band, silicon avalanche photodiode. With a gain–bandwidth product of over 200 GHz, the photodiode is well suited for the present system. Its electrical output is fed to a low-noise high-gain preamplifier which drives a spectrum amplifier. Two different preamplifiers are used: one that is sensitive from 10–1000 MHz, and a second which is sensitive from 0.8–2.0 GHz. The output of the He–Ne laser is rated at 1 mW, but its output here was measured to be 0.75 mW. After traveling through all of the optical modulator and link system, the laser power is reduced to 0.015 mW hitting the avalanche photodiode. This corresponds to a loss of -17 dB in the laser power through the system.

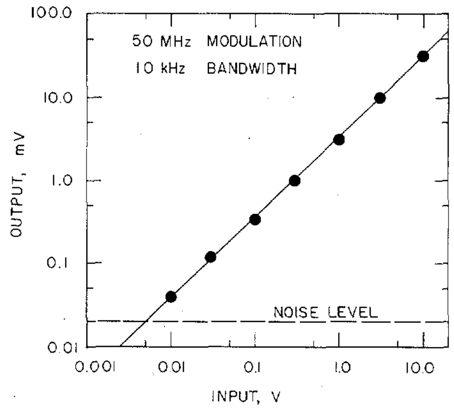


Fig. 4. Input voltage at crystal versus output voltage measured on a spectrum analyzer with a 10-kHz bandwidth.

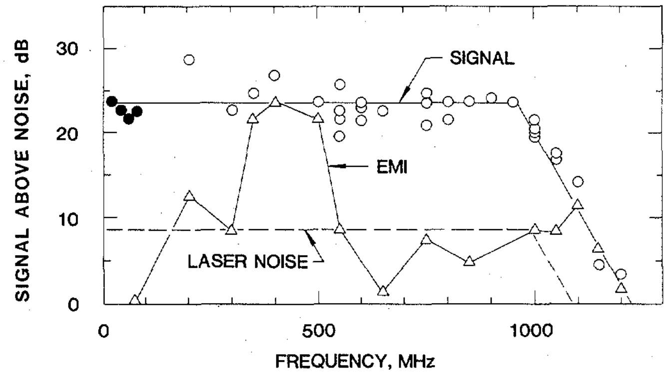


Fig. 5. The signal above noise is plotted for the initial low-frequency setup.

IV. Results

In the first experiments, the linearity and dynamic range of the system were tested. A signal generator set at 50 MHz was directly connected to the brass antenna leads using a 50-Ω input, 200-Ω output balun transformer with a 200-Ω resistor on the crystal side. With the spectrum analyzer set for 10-kHz bandwidth and centered on 50 MHz, the signal generator level was adjusted to provide between 0.01–10.0 V (peak-to-peak) at the antenna crystal. The signal measured on the spectrum analyzer is shown in Fig. 4 and indicates good linearity over a 60-dB range. (This result was previously reported [9], but it is shown here for completeness.) The dashed line on the curve represents the noise level of the system which is mostly due to fluctuations in the He–Ne laser intensity.

Equation (4) can be used to calculate the minimum detectable modulation of the system using the results of Fig. 4. (Equation (4) is used instead of (8) because the signal is directly applied to the crystal through a transmission line. When free fields are used, (8) becomes applicable.) If $V \cong 10$ mV is taken to the the minimum voltage, and if $V_{1/2} = 284$ V [4], then (4) yields a minimum detectable modulation of 0.01 percent, which is reasonable, considering the narrow-band (10-kHz) bandwidth detection used. Higher harmonics of the modulated output were searched for by turning the spectrum analyzer to the higher frequency settings. No harmonics were observed above the noise, indicating that if they existed they must be at least 45 dB below the fundamental.

The temperature dependence of the two-crystal system was qualitatively compared to a system without the second temperature compensating crystal. Simple tests using a heat gun showed that the second crystal greatly reduces the temperature-dependent birefringence term α of (2). If the two crystals are identical and at the same temperature, then α would be zero.

To test the frequency response of the system with the dipole attached, the antenna assembly was placed in a TEM cell (10–100 MHz) and in an anechoic-chamber room (200–2000 MHz) where the system was illuminated with a signal of 10 V/m. In the first set of experiments, the preamplifier frequency range was 10–1000 MHz, and the spectrum-analyzer bandwidth was set at 1 kHz. As shown in Fig. 5, the results show about a 15 dB S/N ratio. The circles represent the signal, and the triangles represent electromagnetic interference (EMI) which resulted from the direct electrical pickup of the signal by the unshielded photodiode with the laser beam blocked. While the dashed line represents noise due to the laser, the zero decibel level represents the noise level of the system with the laser beam blocked. Much of the scatter in the signal is due to mechanical instability in the first fiber-cable positioner used to hold the input end of the uplink fiber. The roll-off above 1000 MHz was due to the frequency response of the preamplifier. This first set of experiments show that the system has an essentially flat response from 10 to 1000 MHz.

To test at higher frequencies, the 10–1000-MHz pream-

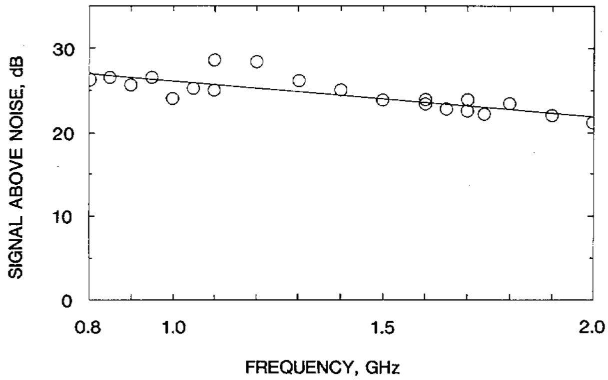


Fig. 6. Signal above noise for improved higher frequency system.

plifier was replaced with a 0.8–2.0 GHz preamplifier (see Fig. 2). In addition, the photodiode was electrically shielded to prevent the unwanted EMI, and the mechanical stability of the system was improved to increase the laser-light throughput and reproducibility. The results over the frequency range of 0.8–2.0 GHz are shown in Fig. 6. In this graph, the zero decibel level was taken to be the laser noise level. No EMI was observed. Measured in the anechoic chamber using 10 V/m and a 1-kHz spectrum-analyzer bandwidth, the average signal-to-noise ratio is now 25 dB, which is a 10-dB improvement over the previous setup. It is also now clear that the sensitivity drops at about 3 dB/GHz. With a 1-V/m field intensity, the sensitivity would still be better than 5 dB.

The results of Fig. 6 can be used with (8) to calculate the minimum detectable modulation that was measured. Using $E_{\min} = 1$ V/m, the minimum detectable modulation is found to be 0.05 percent at 1-kHz bandwidth. Converting to a 10-kHz bandwidth yields an effective modulation value of 0.16 percent, which is about 16 times worse than the value calculated from Fig. 4. This loss of sensitivity is probably due to the addition of the dipole antennas and the downlink fiber cable with its additional optical components. Future improvements in the optical design may result in improved sensitivity.

V. Conclusions

A laboratory (as contrasted to a field-portable) optical modulator and optical link have been designed and tested which will have the ability to replace metallic or high-resistance cables between antennas and receiver electronics. This passive system requires no batteries or power at the antenna and, thus, it will be useful for long-term unattended remote applications. Using long fiber-optical data links, the antenna is completely electrically isolated from the receiver. The receiver electronics can be well protected from hazardous high-field situations. Using a short 15-cm dipole, the system has been shown to have a usable response from 0.1 to 2.0 GHz, with a 60-dB dynamic linear-response range, and with a minimum sensitivity of better than 1.0 V/m with a 1-kHz bandwidth.

In future work, the temperature stability of the system will be thoroughly investigated. Using a higher frequency preamplifier, the upper frequency range of the system will be determined. To make a field portable device, the visible gas-phase He–Ne laser will be replaced with a more compact and rugged infrared solid-state laser.

Acknowledgment

We would like to acknowledge the continued help and advice from G. Day. We would also like to thank H. I. Bassen for loaning us his prototype optical modulator device. E. Kim graciously measured the core size of the single-mode fiber. We would like to acknowledge the efforts of M. Kanda, A. Ondrejka, and D. Melquist who contributed to the initial studies and designs of a previous (unpublished) version of this optical modulator.

References

[1] E. B. Larsen, J. R. Andrews, and E. E. Baldwin, "Sensitive isotropic antenna with fiber-optic link to a conventional receiver," Nat. Bur. Stand., Washington, DC, Rep. NBSIR 75-819, Sept. 1976.

[2] H. I. Bassen and R. J. Hoss, "An optically linked telemetry system for use with electromagnetic-field measurement probes," *IEEE Trans. Electromag. Compat.*, vol. EMC-20, pp. 483–488, 1978.

[3] H. Bassen, W. Herman, and R. Hoss, "EM probe with fiber optic telemetry system," *Microwave J.*, pp. 35–47, Apr. 1977.

[4] K. Münter, "An isolated sensor determining the poynting vector in the near field of a radiating antenna,"in *Conf. on Precision Electromagnetic Measurements*, Boulder, CO, IEEE Cat. 82, CH 1737-6, June 1982, pp. P-14–P-15.

[5] H. Bassen and R. Peterson, "Complete measurement of electromagnetic fields with electro-optical crystals," in *Biological Effects of Electromagnetic Waves, Selected Pap. USNC/URSI Annu. Meet., 1975*, HEW publication (FDA) 77-8011, pp. 310–323, 1975.

[6] C. H. Bulmer, W. K. Burns, and R. P. Moeller, "Linear interferometric waveguide modulator for electromagnetic-field detection," *Opt. Lett.*, vol. 5, p. 176, 1980.

[7] S. K. Yao, T. Findakley, R. Cordero-Iannerella, S. Thaniyavarn, G. Hayward, and B. Chen, "Electromagnetic sensor using integrated optic channel waveguide modulator and polarization preserving fibers," *Fiber Optic and Laser Sensors*, Emery L. Moore, O. Glenn Ramer, Ed., in *Proc. SPIE*, vol. 412, 1983, pp. 178–184.

[8] C. C. Ku, R. P. DePaula, J. Jarzynski, and J. A. Bucaro, "High frequency response of a single mode fiber optical phase modulator utilizing a piezoelectric plastic jacket," *Fiber Optic and Laser Sensors*, Emery L. Moore, O. Glenn Ramer, Eds., *Proc. SPIE*, vol. 412, pp. 178–184, 1983.

[9] J. C. Wyss, M. Kanda, D. Melquist, and A. Ondrejka, "Optical modulator and link for broadband antennas," *Conf. Precision Electromagnetic Measurements*, Boulder, CO, IEEE Cat. 82 CH 1737-6, pp. P-16–P-17, June 1982.

[10] J. C. Wyss and S. Sheeran, "Fiber-optical modulator and link for broadband antennas," in *Conf. on Lasers and Electro-Optics, Technical Digest*, Baltimore, MD, May 1983, pp. 152–154.

[11] I. P. Kaminow, Ed., *An Introduction to Electrooptic Devices*. New York: Academic, 1974.

[12] T. Tamir, Ed., "Integrated Optics," in *Topics in Applied Physics*, vol. 7, 2nd ed. Berlin, Germany: Springer, 1979.

[13] F. S. Chen, "Modulators for optical communications," *Proc. IEEE*, vol. 58, pp. 1440–1457, 1970.

[14] P. V. Lenzo, E. H. Turner, E. G. Spencer, and A. A. Ballman, "Electrooptical coefficients and elastic-wave propagation in single-domain ferroelectric Lithium Tantalate," *Appl. Phys. Lett.*, vol. 8, p. 81, 1966.

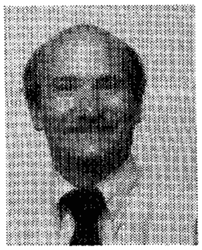
[15] T. Bowen, "Low cost connectors for single optical fibers," AMP Inc., Harrisburg, PA, Tech. Note, 1978.

[16] M. Kanda, "The characteristics of a relatively short broadband linear antenna with tapered resistive loading," *Int. IEEE/AP-S Symp. Dig.*, June 1977.

[17] M. Kanda, "A relatively short cylindrical broadband antenna with tapered resistive loading for picosecond pulse measurements," *IEEE Trans. Antennas Propagat.*, vol. AP-26, pp. 439–447, 1978.

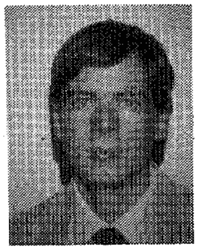
Jerry C. Wyss (M'84) received the B.S., M.A., and Ph.D. degrees in physics from the University of California, Santa Barbara.

From 1980 to 1984, he was a Post-Doctoral Research Associate and then a Staff Member with the National Bureau of Standards, Boulder, CO. As



the Project Leader on photonics probes for electromagnetic field measurements, he designed and developed, along with coworkers, the photonic EM probe described in this issue. He also was responsible for other EMI projects. In May 1984, he joined the Advanced Technologies Division of the General Research Corporation in Santa Barbara, CA. As the Project Leader of the electromagnetic fields, photonic sensor program, he has been developing and seeking new techniques for measuring electromagnetic fields using optical techniques. He has been working closely with Dr. Gail T. Flesher, one of the founders of the photonics program at General Research Corporation.

Dr. Wyss is a member of the Optical Society of America and the American Physical Society.



Stephen T. Sheeran was born in Boulder, CO, on June 13, 1960. He received the B.S. degree in mechanical engineering from the University of Colorado, Boulder, in May 1984. Topics of study included machine design, production automation, and robotics.

While an undergraduate student, he worked at the National Bureau of Standards, Boulder, CO, in both the Time and Frequency and Electromagnetic Fields Divisions in the capacity of engineering aid, designing instruments used in a variety of experimental situations, including an electrooptic probe described in this issue. Mr. Sheeran is presently with the Electromagnetic Fields Division designing and supervising construction of mechanical systems used in measurements of electromagnetic fields.