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Electro-Optic and Magneto-Optic Sensors for High-Power Microwave Applications

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Tests are described using fiber-attached, all-dielectric sensors for the noninvasive detection of electric and magnetic fields. The sensors utilize nonlinear optical materials (electro-optic and magneto-optic crystals) and are tested in a variety of radio frequency and high-power microwave sources.

KEYWORDS: Electro-optic, HPM, Magneto-optic, Probe, Sensor

1. Introduction

We have been developing fiber-attached, all-dielectric sensors for the measurement and characterization of radio frequency (RF) and high-power microwave (HPM) fields.[1,3–5] Conventional field probes are typically composed of dipole or loop antenna elements. Because of their metallic structure, they can perturb the very fields they measure as well as cause undesirable beam reflections. Physically smaller probes can reduce these effects but are easily saturated and must be restricted to lower field strengths (typically $<$1,000 V/m). An attractive alternative to metallic probes is the use of all-dielectric sensors composed of nonlinear optical materials. These sensors have large intrinsic bandwidths (dc to terahertz) and measure the amplitude, phase, and direction of an applied field. Electro-optic (EO) sensors are based on electric field-induced birefringence (Pockels effect) in an EO crystal, whereas magneto-optic (MO) sensors are based on magnetically induced polarization rotation (Faraday effect) in an MO crystal. In both cases, the fields are detected optically, using fiber-optic cables with no metallic elements. In Ref. 3, we describe a low-noise, robust EO sensor configuration that is accommodating and practical for actual field testing applications. In this report, we discuss recent field testing measurements with this sensor at an HPM test site. We also describe preliminary data with our recently developed MO sensor in both static and RF magnetic fields.

2. Field Tests with EO Sensor

Figure 1(a) shows a single-axis EO sensor head. A laser is sent to an EO crystal via an input optical fiber. The crystal is placed between two sheet polarizers, and the intensity of the laser is modulated when the crystal is exposed to an external electric field. The modulation

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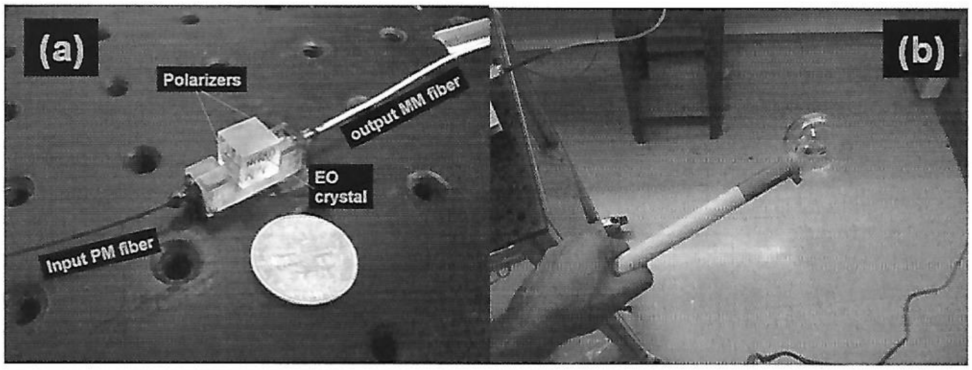

Fig. 1. (a) Single-axis EO sensor head; (b) three-axis EO sensor head.

depth of the beam intensity is directly proportional to the applied field, allowing the field to be directly measured (within a proportionality factor) using a photodetector located remotely at the end of the output fiber. In Fig. 1(b), three single-axis sensors were arranged with the modulation axes of the crystals placed in orthogonal directions to form a three-axis E-field sensor. The sensor heads and fibers were placed in a ruggedized housing to accommodate field use. Because the three-axis sensor head is all dielectric and produces all-optical signals, there is no cross talk or interference as in antennas or other metallic-based field probes.

Tests with our EO sensor were carried out in a variety of indoor and outdoor conditions. Figures 2(a) shows our test setup with the three-axis EO sensor in the near field of a d-band radar horn. Power levels up to 1 MW were used during the testing. Because of their dielectric structure and with half-wave retardation fields E_π of the order 1 MV/m, EO sensors are ideally suited for near-field testing of HPM. Time domain traces of the vector components of the applied field, shown in Fig. 2(b), demonstrate the vertical polarization of the radiating field. In Fig. 2(c), the EO sensor was used to perform a spatial map of a 1-GHz continuous-wave (CW) electric field from a double-ridged horn antenna powered by a 20-W amplifier. The total beam power derived from the sensor data (obtained by integrating E^2 across the surface area of the horn) was 18.7 W, indicating a 0.27-dB insertion loss from the horn. The peak electric field (at the center of the horn) was measured to be 850 V/m, indicating a gain figure of 5 dBi. Both insertion loss and gain data measured by our sensor are consistent with the specifications provided by the horn vendor. In Fig. 2(d), the electric field was measured as a function of distance z from the horn. The near-field to far-field boundary can be derived from the point at which the data deviate from their $1/z$ dependence. This occurs at $z = 12$ cm, which is consistent with the calculated value (13 cm) based on the horn dimensions and the frequency of the field.

Factors determining the sensitivity and minimum detectable field include optical intensity and polarization noise in the laser and fiber, as well as Johnson and shot noise in the photodetector amplifier. The design of the EO sensor has been optimized to eliminate optical noise,[3] allowing very long optical fibers to be used with little or no loss of sensitivity. In HPM applications, the use of long optical fibers is critical. For example, in Fig. 3 our EO sensor was placed in front of a d-band radar horn [Fig. 3(a)] and a 3 × 3 phase array antenna [Fig. 3(b)]. To minimize electrical noise and protect the readout instrumentation from stray or reflected HPM fields, it was necessary to collect data remotely in a shielded

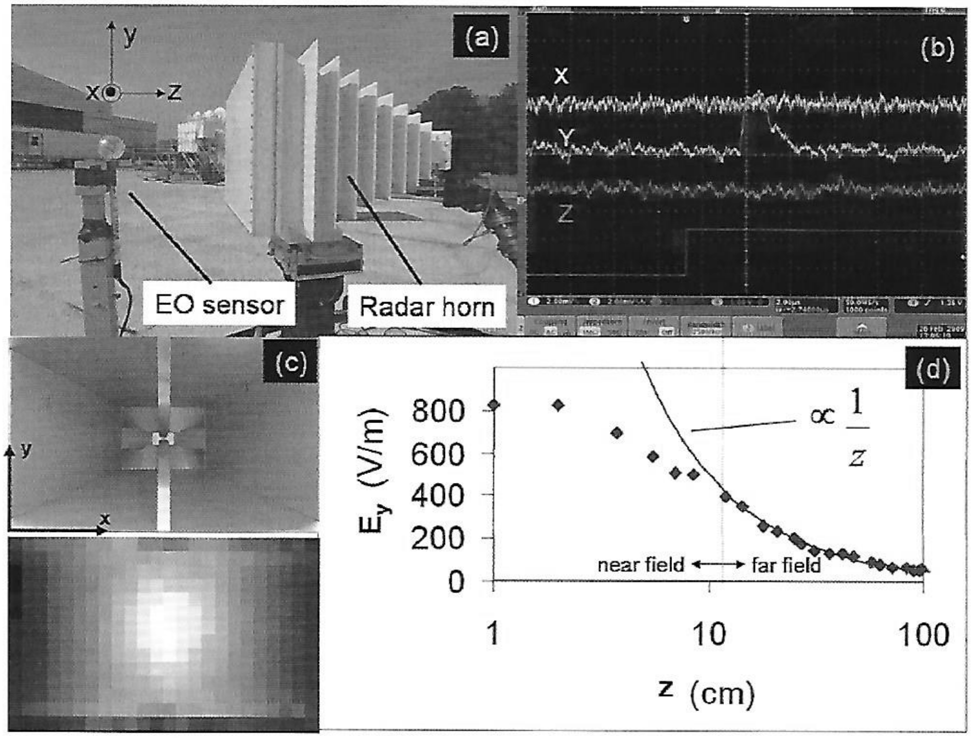

Fig. 2. (a) Near-field measurements of a 1-MW d-band radar horn (courtesy of the Naval Electromagnetic Radiation Facility at the Naval Air Warfare Center, Aircraft Division, Pax River); (b) time domain traces from three-axis EO sensor, revealing y-axis polarization of radar horn E-field; (c) near-field mapping of double-ridged horn antenna; and (d) far-field measurement of double-ridged horn.

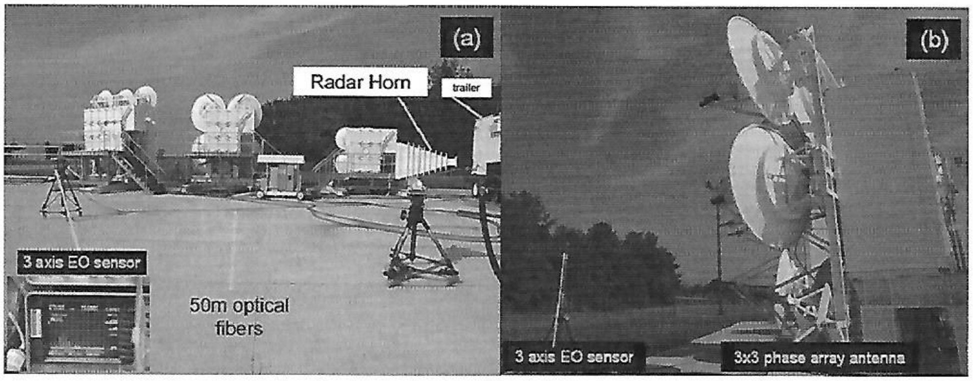

Fig. 3. Three-axis EO sensor used in HPM measurements (courtesy of the Naval Electromagnetic Radiation Facility at the Naval Air Warfare Center, Aircraft Division, Pax River); using 50-m-long optical fibers to carry the optical signal from the sensor head to a shielded trailer: (a) far field of a d-band radar horn and (b) focus of a 3 × 3 phase array antenna.

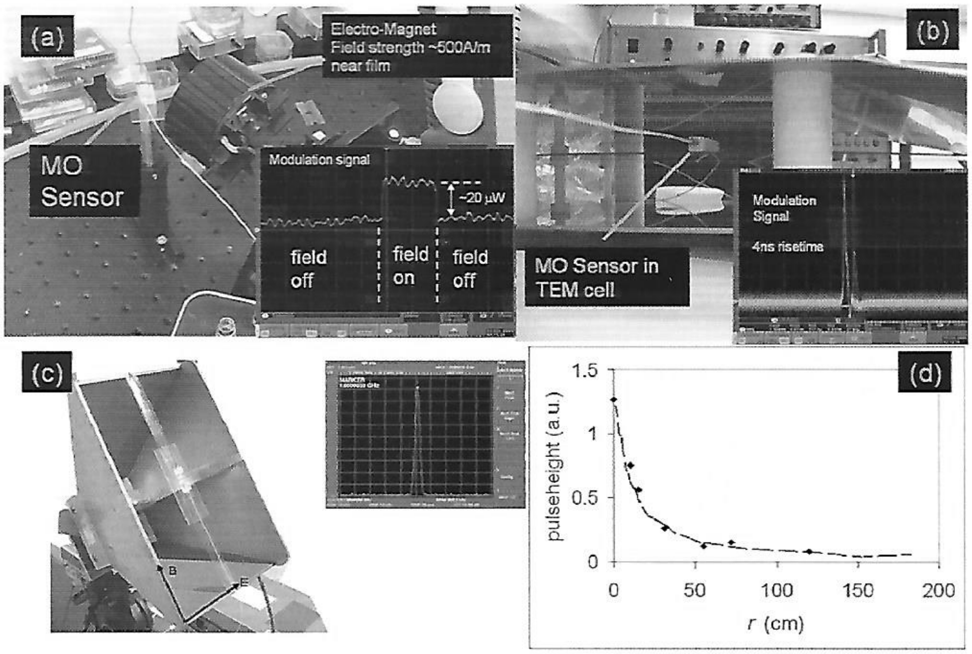

Fig. 4. Magnetic field detection and measurements using an MO sensor: (a) static field from an electromagnet ($B \sim 500$ A/m), (b) 4-ns rise time pulsed field in a TEM cell ($B \sim 100$ A/m), (c) near field of double-ridged horn antenna ($B \sim 2$ A/m), and (d) far-field measurement of double-ridged horn.

trailer [shown in Fig. 3(a)]. This was accomplished using 50-m-long optical fibers to carry the optical modulation signal from the sensor head to the trailer.

Besides optical noise, the EO sensor also carries Johnson and shot noise from the transimpedance amplifier of the photodetector. Because the amplitude of this noise increases with measurement bandwidth, optimal sensitivity is achieved in CW fields using a spectrum analyzer set at a narrow span (e.g., <500 kHz). For transient signals, more-broadband instruments such as oscilloscopes can be used. However, for subnanosecond timescale signals, sensitivity will not be as high as in the CW case, unless some type of filtering can be used to reduce the measurement bandwidth. The minimum detectable field is defined as the electric field value in which the modulation signal is equal to the noise level, divided by the square root of the measurement bandwidth. This provides one with a sensitivity figure that is more or less independent of the measurement instrument. Currently, the minimum detectable field of our EO sensor is less than 1 mV/m-$\text{Hz}^{1/2}$.

3. Preliminary Results with MO Sensor

Our magnetic field sensor is based on the platform identical to that of our EO sensor shown in Fig. 1, with the EO crystal replaced with a suitable MO material. By design, the laser, optical fibers, and readout instruments are identical to that of the EO sensor so that both sensors can share instrumentation and be combined into an integrated (electric + magnetic field) sensor. The MO material currently used is an iron garnet thick film, because of its large Verdet constant and its transmissivity at 1,550 nm (wavelength used for EO sensor). As in the EO sensor, the MO material is placed between two polarizers. When a magnetic field is applied to the material, the transmitted laser power is polarimetrically modulated, with a modulation depth proportional to the magnetic field strength. Like EO sensors, MO sensors have very large half-wave retardation fields, B_π ~50 kA/m, making them ideally suited for high-power applications. Initial laboratory tests were conducted with the MO sensor placed in a variety of magnetic fields and are summarized in Figure 4. In Fig. 4(a), the MO sensor was used to measure a static magnetic field from an electromagnet ($B = 500$ A/m). In Fig. 4(b) the sensor was placed in a TEM cell to which a 4-ns voltage pulse was applied ($B \sim 100$ A/m). In Fig. 4(c), the MO sensor was placed in a 1-GHz CW field from a double-ridged horn antenna ($B \sim 2$ A/m). The responsivities (modulation depth per applied field) were similar in the three different fields, indicating that the sensor can be used in both low and high frequencies. However, more detailed frequency response measurements show resonance-like behavior at ~500 MHz.

The sources of noise with the MO sensor are identical to there of the EO sensor, i.e., optical intensity noise, phase noise, electrical Johnson, and shot noise. The (bandwidth-normalized) minimum detectable magnetic field was measured to be 0.25 μA/m-Hz$^{1/2}$.

4. Conclusions

Our fiber-optic EO and MO sensors have demonstrated measurement capability of microwave and RF fields generated by a variety of sources in a variety of test conditions. The minimum detectable fields were 1 mV/m-Hz$^{1/2}$ for the EO sensor and 0.25 μA/m-Hz$^{1/2}$ for the MO sensor. Future work will consist of testing the MO sensor at actual HPM test facilities and integrating EO and MO sensors into a single electromagnetic sensorhead.

5. Acknowledgment

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References

[1] Garzarella, A., R.J. Hinton, S.B. Qadri, and D.H. Wu, Appl. Phys. Lett. **92**, 22111 (2008).

[2] Garzarella, A., S.B. Qadri, T.J. Wieting, D.H. Wu, and R.J. Hinton, Opt. Lett. **32**, 964 (2007).

[3] Garzarella, A., S.B. Qadri, and D.H. Wu, Appl. Phys. Lett. **94**, 22113 (2009).

[4] Garzarella, A., S.B. Qadri, D.H. Wu, and R.J. Hinton, Appl. Opt, **46**, 26, 6636 (2007).

[5] Garzarella, A., D.H. Wu, and R.J. Hinton, "Progress in High Sensitivity Electro-optic Field Sensors," CLEO/QELS Conference, May 6–11, 2007.

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Dr. Anthony Garzarella received his Ph.D. in experimental physics at Temple University in 1996, where he worked on nuclear radiation detectors using superconducting thin films. From 1996 to 2003 he worked as a process engineer in the semiconductor and flat panel industries, specializing in surface preparation, wet chemical etching, and optoelectronic assembly. In 2004, he returned to experimental physics and currently is at the Naval Research Laboratory in Washington D.C., where he works on electromagnetic radiation detection and measurement using nonlinear optical materials.

Dr. Dong Ho Wu had been a research staff member at the Korea Standards Research Institute and studied at the Korea Advanced Institute of Science and Technology before he pursued his graduate study in the United States. He received his Ph.D. degree in condensed matter physics from Tufts University in February 1991. He briefly stayed at Northeastern University as a postdoctoral fellow and then joined GTE Laboratories, Waltham, Massachusetts, in 1991, as a member of the technical staff. A few months later he became a research faculty member at the University of Maryland and remained until he joined the Naval Research Laboratory in 2001 as a Research Scientist. Currently he is also Adjunct Professor of Physics at Temple University. He has contributed to the understanding of the electrodynamics of superconductors and the properties of nonlinear optical materials. He has also carried out several research projects for the development of electromagnetic field sensors, terahertz detectors, and terahertz sources. He has published three book contributions and more than 60 papers in peer-reviewed journals.