Non Intrusive Electromagnetic Sensors for Ultra Wideband Applications Using Electro-Optic and Magneto-Optic Materials

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Abstract—We have developed and tested fiber optic electric and magnetic field sensors for ultra wideband (UWB) applications. The sensors are based on nonlinear effects in electro-optic (EO) and magneto-optic (MO) crystals. Unlike conventional antenna-based probes, EO and MO sensors are composed of all-dielectric materials and do not perturb the very fields that they measure. The sensors are small in size (less than 5mm in diameter), allowing them to be used in confined spaces and can be used with over 50 meters of optical fibers. These features make the sensor very well-suited for UWB applications and attractive for potential commercial use.

I. INTRODUCTION

In tests and measurements of UWB signals, there is a need for compact, high bandwidth, nonintrusive sensors that are capable of measuring the amplitude, phase, and polarization of the electromagnetic signal in both open and confined spaces. Conventional sensors, such as D-dot and B-dot probes, have several limitations in this regard. Firstly, because they are metallic in structure, they perturb the very fields that they measure. This introduces complications when attempting to determine the amplitude, phase and polarization of the fields. It is especially problematic if the UWB signal is to be measured within an enclosed metallic structure, since the resonant frequencies of the structure and the reverberations of the electromagnetic signal are greatly affected by the presence of metallic objects within [1]. Secondly, D-dot and B-dot probes do not measure the fields themselves, but rather their time derivatives. Thus in order to obtain the true transient characteristics of the field, intervening signal processing is necessary. In impulsive applications where the transients ring between positive and negative values, studying the detailed transient behavior is intrinsically problematic at the zero slope points, since the time-derivative based signal levels falls below the noise floor. Thirdly, in high power applications, great care must be taken in the positioning and placement of metallic probes, since they may cause beam reflections that can present safety hazards to both personnel and instrumentation. Ideally, field sensors should be nonintrusive, while still measuring the true amplitude, phase and polarization of the fields. Thus, there is great motivation to develop nonintrusive sensors that can simply be placed in anywhere in an electromagnetic field (avoiding costly set-up time) and directly measure amplitude, phase and polarization in real time (avoiding costly signal processing).

II. SENSOR DEVELOPMENT

In contrast to conventional metallic probes, sensors based on nonlinear optical materials can be constructed using all-dielectric material. Optical signals through electro-optic (EO) and magneto-optic (MO) crystals are modulated by external electric and magnetic fields respectively, with modulation depths directly proportional to the respective fields. This,
along with their large intrinsic bandwidths (up to THz frequencies) makes them very well suited for measuring true, unperturbed waveforms of UWB signals. Also, because of their small size (5mm in diameter) they may be used for measuring fields in either open spaces or small cavities. Our EO sensor head is shown in Figure 1. A laser is sent to a Potassium Dideuterium Phosphate (KDP) crystal via a polarization maintaining optical fiber and input polarizer P1. The state of polarization of the laser is modulated by an external field directed along the optic axis of the crystal. By analyzing the beam exiting the crystal with polarizer P2, the modulation of polarization is converted to a modulation of beam intensity. The modulated light is coupled into an output fiber and converted to an electrical signal using a photodetector. The resulting voltage signal directly replicates the transient of the external field (to within a proportionality factor) and can be instantly read on a readout instrument such as an oscilloscope or spectrum analyzer. Many types of EO and MO materials as well as many optical components (such as lasers, optical fibers, lenses, etc.) were investigated and chosen to optimize sensitivity and stability of the sensors. A quasi-longitudinal orientation of a KDP crystal allows the EO sensor to be used with over 50 meters of optical fiber with little or no added phase noise [2]. Because the iron garnet crystals used in MO sensors are not birefringent, they are not susceptible to such phase noise and can be directly used with the long fibers without special modifications. Apart from interchanging the EO crystal with an MO crystal, our MO sensor head is virtually identical to the EO sensor shown in Fig. 1. Because of this, our EO and MO sensors can easily be integrated into a single sensor head that can simultaneously measure electric and magnetic fields, powered by a common optical engine, and utilizing identical photodetectors and readout instruments.

III. RESULTS AND DISCUSSION

Tests were performed with our EO and MO sensors in electromagnetic fields generated by a variety of sources, including radar horns, phase array antennas, Marx generators, and GTEM cells [3]. An example of the data collected by our sensors is shown in Figure 2, where an integrated EO/MO sensor was placed alongside a B-dot probe inside a high power electromagnetic pulser (Fig. 2a). The signals measured by the MO sensor component (Fig. 2b) showed nearly identical transient behavior as the B-dot probe, but with greater detail (i.e. less noise) in regions where $\frac{dB}{dt} = 0$. Furthermore, the integrated sensor also measures the electric field simultaneously, while being nonintrusive and about 100 times smaller in size than the B-dot sensor. Figure 3a shows...
our EO sensor and a D-dot sensor placed in front of a Marx Generator. In Fig. 3b, we have overlaid the transient signals outputted by both sensors. As in the case with the MO and B-dot sensors, general agreement is observed, except in regions in which the time derivative of the field becomes zero. Figure 4 shows the frequency response of the EO sensor from 1 to 20 GHz, using a double ridged horn antenna and a continuous wave power supply. The frequency response of the sensor is consistent with the calculated frequency response of the applied field (based on gain data of horn antenna). The 20 GHz maximum frequency was not limited by the sensor itself, but rather by the available instrumentation (power source and photodetector). With photodetectors bandwidths in excess of 50GHz becoming increasingly available from commercial vendors, utilizing EO and MO sensors for UWB applications is becoming much more feasible. In configuring the sensors for high frequency applications, the crystal length \( L \) along the optical path becomes an important parameter. Although nonlinear mechanisms such as the EO effect occur up to THz frequencies, the sensor exhibits a much lower bandwidth due to the finite laser transit time through the crystal. Therefore \( L \) must be chosen such that this transit time is much less than the transient characteristics of the external field. That is \( L \ll c/(nf) \), where \( c \) is the speed of light, \( n \) is the refractive index of the crystal and \( f \) is the characteristic frequency of the external field. Theoretically, the 3 dB bandwidth of the sensor is inversely proportional to \( L \), while sensitivity is directly proportional to \( L \). Thus sensitivity is compromised when a higher bandwidth is sought. The crystal used in Fig. 4 has a length of 4mm and a (theoretical) 3 dB bandwidth of 30 GHz. To extend its operating range to 50-60 GHz, its length can simply be reduced to 2mm. To offset some of the sensitivity loss associated with shorter crystal length, the laser power can be increased.

**IV. CONCLUSIONS**

Although sensors configured for UWB will be much less sensitive than their counterparts at RF and microwave frequencies, their frequency response will be flatter and their dynamic range will be larger. The current sensitivities are of the order 1 mV/m-Hz\(^{1/2}\) for our EO sensors, and 1\( \mu \)A/m-Hz\(^{1/2}\) for our MO sensors. The maximum detectable fields are determined by the half wave retardation fields \((E_0, B_0)\) and are of the order \(10^6\) V/m (EO) and 50 kA/m (MO). Because of the intrinsic advantages discussed herein, EO and MO sensors are currently being employed in a variety of military applications, and may soon be available for more commercial use.

*This material is based upon work supported by the Test Resource Management Center (TMRC) and Evaluation/Science & Technology (T&E/S&T) program and by the T&E/S&T program. This Project is funded by the T&E/S&T program through the U.S. Army Program Executive Office for Simulation, Training and Instrumentation (PEO STRI). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the TMRC, T&E/S&T or PEO STRI programs.*

**REFERENCES**


[3] Courtesy of NERF at the Naval Air Warfare Center, Aviation Division, Patuxent River, MD