Advantages and potentialities of electro-optic sensors for an ultra wide bandwidth characterization of radiated or guided electric fields

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Abstract: We present different electro-optic sensors dedicated to the vectorial measurement of high frequency electric fields either guided [1] or radiated in free space (e.g. field radiated by antennas [2]). These sensors are based on organic and inorganic electro-optic crystals, isotropic and anisotropic, these latter ones being used as amplitude modulator or as polarization state modulator for a laser beam passing through them. We follow by a discussion on the main advantages and the performances of the developed electro-optic sensors.

Keywords: Electric field sensor, electro-optic, high frequency, ultra wide bandwidth

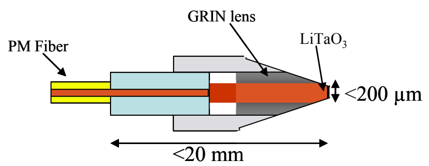
1. Introduction

Guided or radiated electric (E) fields are usually characterized using metallic probes or dipole antennas, respectively. This kind of measurement presents important limitations: a relatively narrow frequency bandwidth, a quite low spatial resolution and a significant disturbance of the signal to be measured. The presented electro-optic (EO) sensors are fully dielectric, thus minimizing the perturbation that they induce on the signal to be measured. They are based on the Pockels' effect which consists in a modification of the refractive indices of an EO crystal induced by an applied E field. Their transversal spatial resolution depends on the shape of the laser beam inside the EO crystal and can be of the order of 10µm. The geometry, permittivity, and refractive indices of the crystal determine the bandwidth of the sensor and the softening factor between outer and inner E fields. The selectivity to E field components is directly linked to the modification of the eigen dielectric axis of the EO crystal induced by the applied E field. Whereas anisotropic crystals (e.g. $LiTaO_3$ or DAST) allow to measure one component of the E field, isotropic crystals (ZnTe) can provide a two-component E field measurement. Finally, we have used two types of modulation in order to exploit the Pockels' effect: our EO sensors are either based on polarization state modulation or on amplitude modulation [3]. During the conference, we will also focus our talk on the advantages of E-field measurements using EO sensors compared to other techniques like antennas, bolometers, infrared thermography, …

2. Polarization state modulation

The principle of EO sensors based on polarization state modulation is the following: a linear polarization of a laser beam making an angle of 45° with the eigen dielectric axes of the EO crystal is subjected to a rotation directly proportional to the applied electric field when an adequate treatment of the polarization is realized after the laser beam has crossed the crystal. Our first probes were based on a lithium tantalate crystal ($LiTaO_3$) and were pigtailed in order to get handy probes. As the useful information is transported by the polarization, we use a polarization maintaining fibre to carry the beam to the crystal and back. A gradient index (GRIN) lens focalise the beam on a multilayer dielectric mirror on the backside of the crystal (see Figure 1). To reduce the induced perturbation of the EO sensor on the signal to be measured, and also to get a homogeneous E field inside the crystal, we have recently given a conic shape to our probes. Moreover, such conic-shape EO probes are perfectly suited for guided wave measurements on integrated circuits like MMIC for example. A schematic diagram of such probes is given in Figure 1.

a)



b)

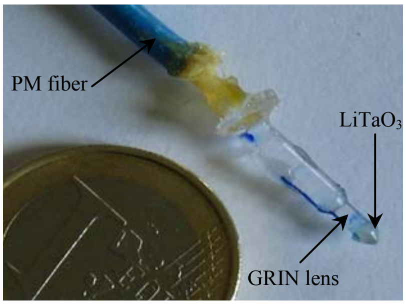


Figure 1: Schematic (a) and picture (b) of a fully dielectric conic-shape EO sensor.

To further reduce the perturbation induced by this latter probe due to the high permittivity of $LiTaO_3$ ($\varepsilon_r \sim 42$), and also to increase the sensitivity, a pigtailed EO probe using a DAST [4] crystal has been realized. This organic crystal presents very high EO coefficients (r_{11}=47pm/V @ 1550nm) and a very low permittivity (ε_{rz}=3). The sensitivity to the ambient E field has been increased by a factor of 10 compared to the $LiTaO_3$ probe. A comparison between inner-crystal E-field responses of $LiTaO_3$ and DAST probes is given in Figure 2. Points correspond to the measures while solid and dash lines represent a theoretical fit including the noise floor.

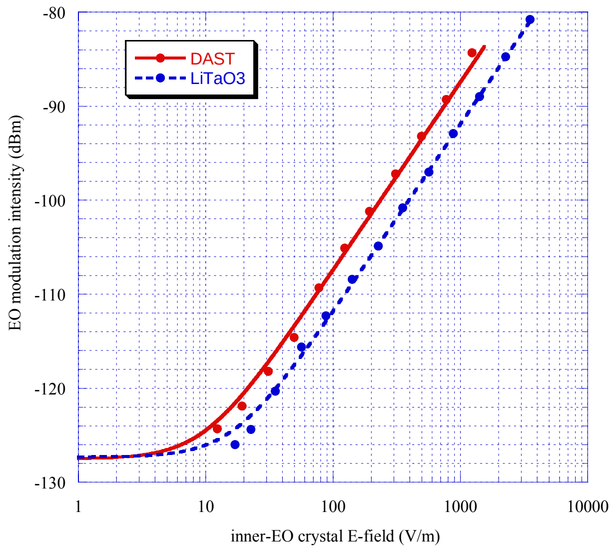


Figure 2: Comparison between inner-crystal E-field responses of 10-GHz bandwidth $LiTaO_3$ and DAST probes measured using a spectrum analyzer at 612 kHz with a 30-Hz resolution bandwidth.

The intrinsic bandwidth of the developed probes covers the frequency range from DC up to 20 GHz. For the recently developed ~9-GHz-bandwidth DAST probe, we have obtained a preliminary minimum measurable inner-crystal E field of ~ $1 V.m^{-1}.Hz^{-1/2}$. During the conference, we will present their complete characterization. Let us remark that these sensors, either based on $LiTaO_3$ or DAST, are sensitive to a unique E field component transverse to the symmetry axis of the probes.

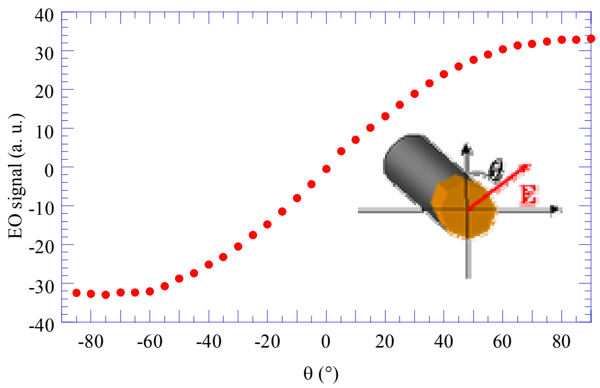


Figure 3: Measured selectivity of a $LiTaO_3$ probe to one component of the E-field.

As shown on Figure 3, the EO signal vanishes for a 90° rotation of the sensor and is inverted for a 180° rotation. To get an EO sensor that probes simultaneously two E field components, an isotropic EO crystal is required [5]. We will also present during the conference our first 2-components E field measurement with a zinc telluride (ZnTe) EO crystal [6]. Some studies have already addressed the problematic of vectorial E field measurements in the last few years. A mapping of the three components of the electric field radiated by a patch antenna has been obtained using different EO probes to successively characterize each E field component [2]. Another solution that consists in using different laser beams passing through the same EO crystal has been also proposed [7,8]. However, in these two experimental developments of vectorial electric field analysis, the different components of the electric field are not measured at the same time or at the same location, respectively. Moreover, the practical implementation of the second technique is rather complex. We present here a very simple 2-components electric field measurement technique using a single isotropic EO crystal and a single laser probe beam. We have theoretically demonstrated in Ref [5] that only isotropic EO crystals potentially allow the simultaneous measurement of two orthogonally electric field components in the simplest experimental configuration where a single laser probe beam passes through a single EO crystal. Due to the submission of a patent deposit, the details of the method will not be presented here. Nevertheless, we give some first results demonstrating the method and showing the accuracy of the method. Using two planar electrodes mounted on a rotation stage, we applied an E field transverse to the EO probe. We performed some measurements for three different values (see Table 1) of the angle γ_E between the direction of the applied E field and the vertical in the laboratory referential (see schematic appearing on the right-hand side of Table 1).

applied value of γ_E	measured value of γ_E
62°	62.4°
105°	104.1°
115°	116.3°

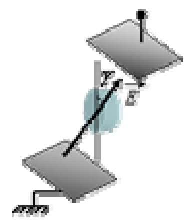


Table 1: Results of first measurements of the direction of the transverse E field.

Let us remark that an uncertainty of 0.5° has to be considered on the applied value of γ_E due to the resolution of the rotation stage. The uncertainty on the measured value of γ_E, linked to the method we have developed, is of the order of 1°. These uncertainties are in very good agreement with the difference that is observed between the applied and measured values of γ_E. A ZnTe-based pigtailed EO sensor dedicated to this simultaneous 2-components probing is currently in fabrication.

3. Amplitude modulation

Like many organic EO polymer, DR1-PMMA constitutes an EO material of major interest due to its low cost, its low permittivity [9] and its easiness of spin-coating over almost any substrate [9][10]. Using EO polymers, a few studies have already reported on EO detection of short pulses [11] and asymmetric Fabry-Pérot cavities (FPC) have been used to detect high frequency signals (1.2 GHz) [12]. However, a poling under huge E-field (~MV/m) is required to align the DR1 molecules and in turn to get a non-centrosymmetric material. Both poling and spin-coating cannot be done for thick samples. Therefore, an optical resonant microcavity built around the EO polymer is necessary to increase the interaction length of the laser probe beam with the EO polymer. Consequently, we have built a symmetric organic microcavity based on a 16-µm-thick DR1-PMMA layer embedded in a high finesse Fabry-Pérot cavity (FPC) with optimal orientation of DR1 molecules, parallel to the faces of the microcavity (see Fig. 4).

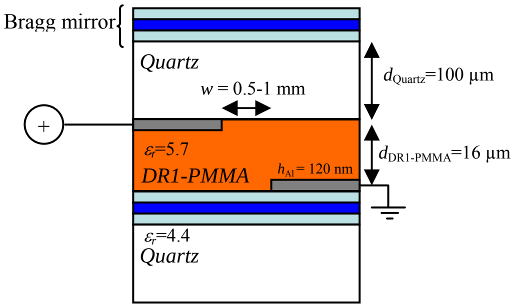


Figure 4: Schematic of the realized organic EO microcavity

This optimal orientation has been carried out by lateral poling, thanks to the use of two planar Al-electrodes, and a r_{33} value of 2.5 pm/V±0.7 pm/V has been obtained. Even if only a rough estimation of r_{33} has been achieved due to the uncertainties on the applied E field (10 %), its value is consistent with results published in the literature [13,14] and consequently validates the method employed for the poling of the EO polymer. The two Bragg mirrors deposited on the quartz wafers present a high reflectivity (99.7% @ 1555 nm) and the resulting finesse F of the microcavity is 480.

When the laser wavelength λ corresponds to a working point situated on one side of a transmission peak of the FPC, any modification of the FPC refractive index leads to a displacement of the peak and in turn to a modification of the transmitted optical power. The modulation of the transmitted laser beam is maximal when the working point corresponds to the inflexion point of the FPC optical response. This optimal modulation depth d_{max} is given by equation:

$$d_{max} = \frac{\pi\sqrt{3(2F/\pi)^2 - 1}\, L_{DR1}\, n_e^3\, r_{33}\, E}{2\lambda_{max}} \qquad (1)$$

L_{DR1} is the thickness of the EO polymer, λ_{max} is the optimal wavelength and n_e is the refractive index seen by the optical beam which linear polarization is parallel to the DR1 molecules. Finally, E is the amplitude of the inner-cavity E field.

Figure 5b shows the transmission T of the FPC versus the laser wavelength and exhibits high wavelength selectivity. The associated modulation depth, normalized to its maximum value, is represented in Fig. 5a. In both figures, dots represent the measurement while the dash lines are theoretical fits.

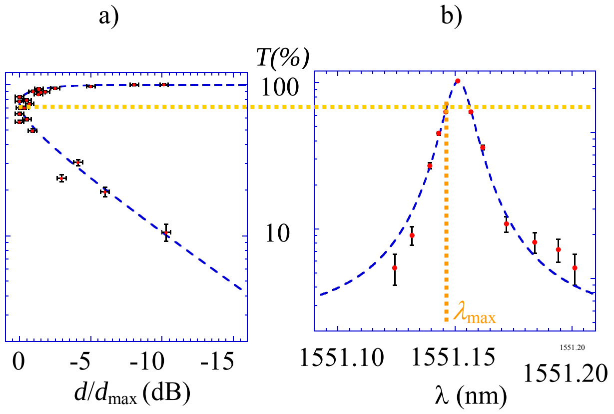


Figure 5: Measured and theoretical transmission of the cavity (b) and associated normalized modulation depth (a).

Once chosen the optimum working wavelength, linearity measurements have been performed using a coplanar waveguide to apply the E field to the EO microprobe. The measurement setup is very simple and consists only in a DFB laser linearly polarized along the direction of the poled molecules, the organic EO microcavity and an optical receiver connected to a spectrum analyzer.

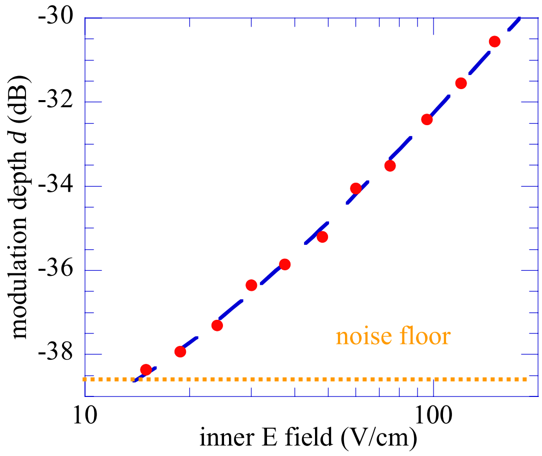


Figure 6: Response of the cavity to electric field measured @ 500 kHz with a 30 Hz resolution bandwidth: experimental data (dots) and theoretical fit (dash line).

The response of the EO microprobe to the E field is plotted in Fig. 6. We observe an excellent agreement between the measurement and the theoretical fit. This latter one corresponds to a linear response of the EO microprobe and takes the noise floor into account. A minimum detectable field of 14V/cm is obtained leading to a sensitivity of 2 $V.cm^{-1}.Hz^{-1/2}$ with only a 16µm-thick layer of polymer. This result validates the poling method. This EO microprobe presents also a very low invasiveness thanks to its shape and to the use of the low permittivity materials for its fabrication.

4. Conclusion

A wide variety of EO sensors dedicated to measurements performed either in free space or in guided propagation are addressed in this paper. These sensors use organic and inorganic EO crystals, isotropic and anisotropic crystals and they are based either on polarization state modulation or on amplitude modulation. Probes using polarization state modulation are pigtailed and long distance remote sensing can be performed: distances up to a few tens of metres have been used between the EO probe and the measurement setup. They present also ultra wide intrinsic bandwidths from quasi DC up to a few tens of GHz. Their fully dielectric conception leads to a very low invasiveness and their high lateral spatial resolution (~10 µm) is at least as good as the one obtained with infrared thermography. Moreover, they present a rather good sensitivity ($0.2V.m^{-1}.Hz^{-1/2}$ for most sensitive probes) perfectly suited for the characterisation of high power microwaves. Whereas $LiTaO_3$-based EO sensors are very selective and present a complete rejection of orthogonal E-field components, the EO sensors based on the use of isotropic crystals allow to measure simultaneously two orthogonal components of the E field. Contrary to the vectorial EO probes already published in the literature, our vectorial E field sensor uses a single laser beam and a single EO crystal. Concerning the amplitude modulation, the realized microprobe permits to validate the employed poling technique and constitutes a promising way to design EO sensors. Only a very thin layer of polymer is actually needed thanks to cavity effect that leads to a huge enhancement of the interaction path. Another advantage of this technique is linked to the extremely simple experimental setup that is required as compared to the one dedicated to polarization state modulation. All the presented measurement setups are A3-sized. Therefore the different systems are fully portable.

5. Aknowledgment

The authors would like to acknowledge the DGA (French Military Programs Management and Procurement Agency) for their support.

6. References

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7. Glossary

E: Electric

EO: Electro-optic

FPC: Fabry-Pérot cavity