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OPTICAL SENSORS: IMPROVEMENT OF ENVIRONMENTAL STABILITY

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Abstract – The paper presents a theoretical analysis and experimental verification of the temperature effects in electro-optic sensor with cubic crystals and naturaly birefringent crystals. New compensation methods, based on an optimal optical alignment, have been proposed and experimentally verified.

Keywords: optical sensors, birefringence, measurement accuracy

1. INTRODUCTION

Recent interest in measurement of high frequency electric fields has been generated primarily by an increasing number of mobile and hand held electromagnetic radiating devices and concomitant electromagnetic compatibility and exposure concern. On the other end of the spectrum, at dc and extra-low frequencies (ELF), it is electrostatic and space charge hazard that increases the need for an accurate and reliable electric field measurements. Although a wide range of conventional sensors is available at present, ranging from potential probes for DC fields up to dipole probes for high frequency fields [1][2], optical sensors play an important role primarily due to their passive and nonperturbing nature and high measurement accuracy. This is particularly important for the near field measurements at high frequencies [3] and dc field measurements in the presence of space charge [4]. However, optical probes generally suffer from a low measurement resolution and limited environmental, particularly temperature, stability [2].

In this paper we present a novel compensation method which was used to improve environmental, particularly temperature, stability of bulk electro-optic sensors. The method was analysed using Jones calculus and the results were experimentally verified for commonly used Bismuth Germanate and Lithium Niobate electro-optic crystals.

2. THEORETICAL ANALYSIS

Most of the bulk optical sensors are based on the polarimetric optical scheme (Fig. 1), which, in contrast to interferometric optical schemes, provides a better compromise between optical complexity and measurement sensitivity [2]. Cubic crystals of point symmetry $\bar{4}3m$ are normally used for AC field sensor because they do not poses natural birefringence and consequently offer a better temperature stability [7]. These crystals also have a lower permitivity, hence provide a higher measurement resolution when used in air. Still, they do not have sufficiently low conductivity needed for DC and ELF field measurements [5], where they are replaced by much less stable Lithium Niobate [4].

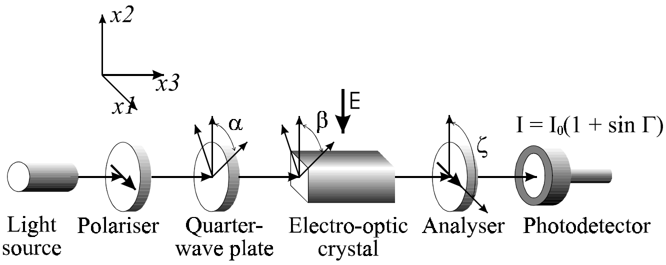

Fig. 1 Polarimetric optical scheme

Generally, changes in the output intensity of the sensor caused by the temperature variations can be characterised by a temperature coefficient α_T defined as

$$\alpha_T = \frac{1}{I_0}\frac{\partial I_0}{\partial T} \approx \frac{\partial \Gamma}{\partial T} \tag{1}$$

where I_0 is the light intensity at photodetector without electric field (Fig. 1), Γ $(= 2\pi n^3 rEl/\lambda)$ is the phase retardation of the electrooptic crystal due to electric field E, and T is the temperature. Here, n is the refractive index, r is the electrooptic coefficient, λ is the wavelength of the light and l is the length of the crystal traversed by the light. Taking into account that the internal electric field in the crystal E_r $(= E_0/(1+\varepsilon_r - d))$ depends on the crystal permitivity ε_r and depolarisation factor d [6], the equation (1) becomes:

$$\alpha_T \approx \frac{2\pi}{\lambda} n^3 r \frac{E_0 l}{1+d\varepsilon_r - d} \cdot \left(\frac{3}{n}\frac{dn}{dT} + \frac{1}{r}\frac{dr}{dT} + \right.$$

$$\left. + \frac{1}{l}\frac{dl}{dT} - \frac{1}{\lambda}\frac{d\lambda}{dT} - \frac{d}{1+d\varepsilon_r - d}\frac{d\varepsilon_r}{dT} \right) \tag{2}$$

As reported for cubic crystals [7], the temperature dependency of the electrooptic coefficient r is too small to cause any noticeable change in the sensor output. We have experimentally established in our laboratory that the temperature change in the permitivity ε_r and dimension l, hence the depolarisation factor d, are also very low and do not have any significant effect on a practical application. The temperature dependency of refractive index n is generally of the order of $10^{-5}/^0C$, changing the sensor output for $\approx 1\%$ for the temperature change from 0 to 100 ^{0}C. This leaves the quarter-wave plate to be the only component that could contribute to the temperature instability of the sensor with cubic crystal (Fig. 1). The best temperature stability is achieved with zero-order quartz quarter-wave plates with a typical value of $\partial\gamma/\partial T = 2.2\cdot 10^{-4}$ rad/K, where γ is the phase retardation of the quarter-wave plate (ideally $\pi/2$). This change is several orders of magnitude higher than in cubic crystals. Hence, following the procedure in ref. [6] and with $\Gamma << 1$, $\gamma \approx \pi/2$ and $\partial\Gamma/\partial T << \partial\gamma/\partial T$, the overall temperature change of the output of the sensor is

$$a_T = \sin(\gamma + \Gamma)\left(\frac{\partial\gamma}{\partial T} + \frac{\partial\Gamma}{\partial T}\right) \approx \frac{\partial\gamma}{\partial T} \tag{3}$$

suggesting that the quarter-wave plate is the major contributor to the temperature instability of the sensor. The temperature effects of the quarter-wave plate can be minimised by positioning the plate and analyser. If the analyser is aligned along the fast axis of the quarter-wave plate, when $\alpha = \pi/4$, $\beta = \pi/2$ and $\zeta = \pi/4$ as shown in Fig. 1, the overall temperature change of the output of the sensor becomes:

$$a_T = \frac{1}{2}\frac{\partial\gamma}{\partial T}\left(\sin(\gamma + \Gamma) - \sin(\gamma - \Gamma)\right) +$$

$$+ \frac{1}{2}\frac{\partial\Gamma}{\partial T}\left(\sin(\gamma + \Gamma) + \sin(\gamma - \Gamma)\right) \approx \frac{\partial\Gamma}{\partial T} \tag{4}$$

In this case the temperature dependence of the sensor is given by the temperature dependence of the phase retardation Γ in the crystal, which is much smaller than that of the quarter-wave plate.

Electro-optic crystal of Lithium Niobate, identified as the most suitable crystal for DC and extra low frequency measurements, is a naturally anisotropic crystal and its temperature stability is affected by the associated natural birefringence. It also exhibits a pyroelectric effect, which further compounds the temperature stability. Both of these effects can be minimised, theoretically even removed, by a perfect alignment of the light along the optical axis. In the real situation, however, misalignment has to be expected to some extend. It can be due to mechanical disturbances and vibration, due to the bad parallelism of the quarter-wave plate and the crystal, due to the finite precision of the crystal cut, or solely due to the alignment accuracy.

From the geometry of the index ellipsoid it is not difficult to show that the natural birefringence Δn in Lithium Niobate depends on the misalignment α as [6]

$$\Delta n = \frac{n_0 n_e}{\sqrt{n_e^2 \cos^2(\alpha) + n_0^2 \sin^2(\alpha)}} - n_0 \tag{5}$$

where n_e and n_0 are extraordinary and ordinary refractive indices, respectively [7]. Consequently, the sensor output, as a function of natural birefringence (zero electric field), is

$$I = I_0\left(1 + \sin\Gamma_{nb}\right) = I_0\left(1 + \sin\left(\frac{l\Delta n}{\lambda}2\pi\right)\right) \tag{6}$$

where Γ_{nb} is the phase retardation due to the natural birefringence, l is the length of the crystal traversed by the light and λ is the wavelength of the light. Applying the equation (1), the temperature stability of the sensor output due to the natural birefringence is found to be

$$\alpha_T = \frac{2\pi}{\lambda}\left(\Delta n\frac{dl}{dT} + l\frac{d\Delta n}{dT}\right)\cos\left(\frac{l\Delta n}{\lambda}2\pi\right) \approx$$

$$\approx \frac{2\pi}{\lambda}\left(\Delta n\frac{dl}{dT} + l\frac{d\Delta n}{dT}\right) \tag{7}$$

It is evident from equation (7) that the temperature coefficient α_T decreases with wavelength, but also that the natural birefringence can cause a very strong temperature instability of the sensor. For example, a misalignment of the crystal optical axis of only 0.1^0 at a wavelength of 1310 nm provides $\alpha_T = 10^{-7}$ rad/K. To avoid the effects of natural birefringence the crystal has to be aligned along the optical axis with precision better than 0.01^0.

Additionally, Lithium Niobate exhibits a very strong pyroelectric effect [7]. A temperature change of only 1 ^{0}C can induce internal electric field of magnitude 10^5 V/m in the direction of optical axis, which, at least theoretically, should not affect the sensor output. However, due to always-present non-uniformity of the pyroelectric field caused by the structural inhomogeneity in the crystal, the perpendicular component E_{12} of the pyroelectric field was observed in our laboratory in all the samples of Lithium Niobate. It was experimentally established that E_{12} is proportional to the inhomogeneity α_i of the crystal and the longitudinal component of the electric field E_3 as (Fig. 1)

$$E_{12} = \alpha_i \cdot E_3 \tag{8}$$

By adjusting the analyser in Fig. 1 it is possible to suppress the pyroelectric field component E_{12} so that it will not influence the sensor output. The measured field is then perpendicular to this suppressed component of the pyroelectric field.

3. EXPERIMENTAL RESULTS

The sensing crystal of Bismuth Germanate and a low order quarter-wave plate at a wavelength of 850 nm were used in the polarimetric set-up (Fig. 1) to verify the temperature stability of the electro-optic sensor with cubic crystals. Fig. 2 shows the output of the sensor as a function of temperature for two cases: i) analyser at 45^0 to the quarter-wave plate eigenaxis, and ii) analyser parallel to the quarter-wave plate eigenaxis.

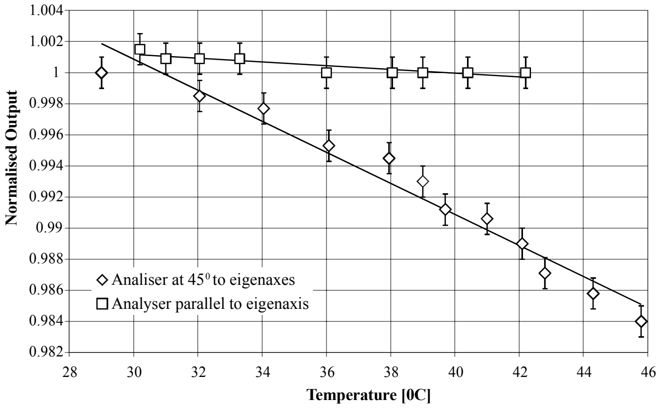

Fig. 2 Experimental results

As shown, a strong temperature dependency of the output was observed when the analyser was aligned a 45^0 to the quarter-wave plate eigenaxis. The measured temperature coefficient α_T of the sensor was 10^{-3}. The estimated temperature coefficient of the quarter-wave plate $\partial\gamma/\partial T$ was 10^{-3} rad/K. With the analyser parallel to the quarter-wave plate eigenaxis, the temperature stability has been improved by a factor >10.

The sensing crystal of Lithium Niobate and a Quartz quarter-wave plate were used to assess the effect of misalignment on the temperature stability of the sensor with anisotropic crystals. The temperature was changed between 20 ^{0}C and 48 ^{0}C. Table 1 summarises the effect of quartger-wave plate, the electro-optic effect and the natural birefringence. The phase retardation α_i induced by the electric field of 10 V/m is shown in Table 1 for comparison. It becomes apparent that the temperature stability of the sensor is, as expected, mainly due to the temperature effects of the quarter-wave plate and natural birefringence, and that the accuracy of alignment is very important in suppressing them.

Table 1 Temperature effects

	Quarter-wave plate	**Crystal natural birefringence**		**Electro-optic effect**
	Quartz	**0.1^0**	**0.01^0**	**10 V/m**
Γ	-	-	-	$0.7.10^{-6}$ rad
α_T	5.10^{-4} rad/K	10^{-5} rad/K	10^{-7} rad/K	$3.6.10^{-4}$ rad/(V/m)

4. CONCLUSION

It has been shown that the temperature dependency of the quarter-wave plate can introduce a large error in measurement with the electro-optic sensor based on cubic crystals. A method of quarter-wave plate temperature compensation, based on an optimal alignment of the crystal and the analyser with respect to the quarter-wave plate, has been described and experimentally verified.

Natural birefringence and pyroelectric effect in the crystal of Lithium Niobate were found to be a source of strong temperature instability of the electro-optic sensor with anisotropic crystals. Theoretically, both effects can be suppressed by aligning the light beam along the crystal's optical axis. In order to suppress these effects to a practically acceptable level, the alignment has to be better than 0.01^0.

REFERENCES

[1] J.A. Cross, "Electrostatic principles, problems and applications", Adam Highler, IOP Publishing Limited, Bristol chapters 2, 3, 1987;

[2] F. Cecelja, "Experimental dosimetry for high frequencies", Journal of Measurement and Control (U.K.), vol. 31, pp. 179-184, 1998

[3] F. Cecelja, "Electro-optic sensor for near-field measurement", IEEE Trans. on instrum. and measurements, Vol. 48, No. 2, pp. 650-653, 1999

[4] F. Cecelja, M. Bordovsky, B. Balachandran, "Lithium Niobate sensor for measurement of DC electric fields", IEEE trans. on inst. and meas., vol. 50, No. 2, 2001

[5] M. Bordovsky, F. Cecelja, W. Balachandran, "Comparative study of cubic crystals in bulk electro-optic sensor for DC and extra-low frequency measurements", Proc. SPIE, vol. 2839, pp. 166-173, 1996

[6] M. Bordovsky, "Electro-optic electric field sensor for DC and extra-low-frequency measurement", - Ph.D thesis, British Library, London, 1998

[7] A. Yariv, "Optical waves in crystals - propagation and control of laser radiation", New York: John Eilley & Sons, 1984