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NON-PERTURBING SENSOR FOR MEASUREMENT OF DC FIELDS IN THE PRESENCE OF SPACE CHARGE

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Abstract − The paper presents theoretical analysis and experimental verification of an electro-optic sensor for measurements DC electric fields in space charge environment. Effects of both unipolar and bipolar charge were investigated. In both cases the sensor output is linearly dependent on the intensity of measured electric field and independent of the space charge density. The achieved measurement resolution is 100 V/m with a dynamic range of 80 dB and a temperature stability of 0.1 %/^{0}C for temperatures near 20 ^{0}C.

Keywords: space charge, electric field measurement, Pockel's effect, linear electro-optic effect.

1. INTRODUCTION

The dipole probes with diode or thermocouple square-law sensing elements are commonly used today for measurements of ac electric fields [1]. DC electric fields, however, are measured mainly using potential probes of field meters utilising the principle of electric induction. To avoid the spurious offsets, drifts and charge effects the sensor output is usually modulated by mechanically rotating or vibrating the sensor forming the known rotating vane field meter or vibrating fork field meter, respectively.

Electro-optic effect has also been successfully utilised for electric field measurements at both low and high frequencies [2][3]. Measurement at extra-low frequencies and dc field measurements in the presence of space charge were considerably less considered. The only reported dc field probes [4][5] also utilise mechanical rotation of the sensing crystal to avoid charge deposition on the sensing crystal and/or probe.

Along with the natural birefringences and optical activity as main limiting factors for an accurate dc electro-optic sensor [6], effects of internal and external space charge are the main design criteria for dc field sensors. Consequently, highly resistive crystals, which do not exhibit photoconductive effect, are required to prevent generation and migration of internal space charge. The problem of external space charge, unipolar or bipolar, can be formulated as an electrostatic problem. This charge tends to deposit on the dielectric surface of the probe altering internal electric field in the sensing crystal, hence the measurement accuracy.

In this paper, we present the design of a non-perturbing, all-dielectric electro-optic sensor for measurement of dc electric fields without the need for mechanical rotation of the sensing head. Final calibration results are also presented.

2. SENSOR DESIGN AND CRYSTAL SELECTION

The sensor makes the use of linear electro-optic (Pockel's) effect deployed in a polarimetric optical scheme (Fig. 1). The principle of operation of the polarimetric optical scheme can be found elsewhere [3]. It is sufficient to say that a high-quality polariser and a quarter-wave plate were used to provide a circularly polarised light with an ellipticity error less than 1%. Traversing the sensing crystal, the polarisation of the light is modulated by the perpendicular electric field component, due to electro-optic effect. The second polariser (analyser) transduces the change in the concomitant ellepticity into the change in optical intensity. The output signal is monitored by a low-drift photodetector 1.

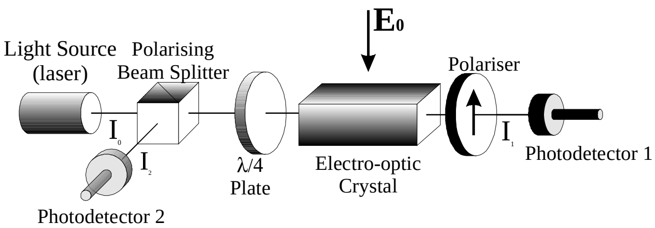

Fig. 1 Electric field probe

Under the effect of a dc or sufficiently low frequency electric field, the free charge carriers in the sensing crystal start to drift and to accumulate on the crystal boundaries. The accumulated space charge generates an electric field with orientation opposite to the original electric field with tendency to balance it to zero. The speed of this process depends on the density of space charge which is proportional to crystal conductivity. With the charge relaxation time defined as $\tau = \varepsilon_0 \varepsilon_r / \sigma$, where σ is the specific conductivity of the crystal, ε_0 and ε_r are permitivity of vacuum and relative permitivity of the crystal, respectively, the crystal of Lithium Niobate $LiNbO_3$ with its $\tau = 7 \times 10^6$ s was found to be the most suitable crystal for this application. It has to be said that cubic crystal of Bismuth Germanate $Bi_4Ge_3O_{12}$, although with significantly lower charge relaxation time (248 s), is another attractive choice primarily due to the environmental stability it offers.

The photoconductivity is another potential source of free charge inside the crystal. The electron excitation energy is supplied by a flux of photons with energy $h\nu$, where ν is the frequency of the light and h is Plank's constant. Hence, in a crystal without impurities the bandgap of the material is of primary interest as it determines the absorption edge. As Lithium Niobate have critical wavelength of 350 nm, if it operates at a wavelength of 1310 nm, the photoconductive effect is negligible.

2. EFFECTS OF EXTERNAL SPACE CHARGE

When a dielectric probe is placed in an uniform electric field, the probes becomes polarised and the electric field around the probe is distorted due to the difference between the permitivity of the probe and the surrounding environment. As a consequence, the environmental charged particles, if present, will move along the field lines: the positively charged particles in the direction of the electric field intensity and the negatively charged particles in the opposite direction. Inevitably, some of the drifting charged particles will hit the surface of the probe. Assuming a very low surface conductivity of the crystal, some of the charged particles will stay attached on the surface [7]. This process of charging will continue until the attractive force acting upon the particles caused by the original field is equal to the repulsive force of the deposited charge. The deposited charge on the surface, however, change the intensity of the internal electric field, hence altering the measurement sensitivity.

Assuming that the space charge contribution to the measured electric field is negligible, the potential of the electric field around a dielectric crystal can be calculated using the Laplace equation. An analytical solution for both internal and external electric field was found for a fully symmetrical probe (dielectric ball) and for Pauthenier charging process with no migration of the surface charge [8].

A detailed analysis of the solution shows that in the bipolar environment with both positively and negatively charged particles, the internal electric field in the crystal $\mathbf{E_{in}}$ is related to the measured electric field $\mathbf{E_0}$ as:

$$\mathbf{E_{in}} = \frac{3}{2}\mathbf{E_0} \qquad (1)$$

The equation (1) shows that the internal electric field is directly proportional to the external field and amplified by 3/2, and it is uniform and independent on the dielectric property of the crystal. It must be said that this equilibrium is achieved in a finite time, which depends on the mobility of the ions in the charged environment and on the crystal permitivity.

While in the bipolar environment the charge deposition affects both hemisphere of the probe, in the unipolar environment this is limited on one hemisphere only. As such, the internal field is no longer uniform, and, using a polar coordinate system (r, θ, ϕ) (see Fig. 2), it has a general form

$$E_{in}(\theta, r) = C(\theta, r)E_0 \qquad (2)$$

where E_{in} is the electric field component inside the crystal, C is a constant for a given position (θ, r), and E_0 is the measured external field. The constant C can be obtained from the mathematical model once the deposited charge distribution is known. We used step-by-step layers of the deposition negatively charged particles. In each iteration the charge was deposited only in areas with positive electric field intensity. The deposited charge density was proportional to the radial component of the electric field on the surface of the crystal. There is no charge deposition allowed if the radial component of the electric field was equal or less than 0 V/m. A detailed analysis shows that internal electric field in the crystal varies from $1.1 \cdot E_0$ near to the deposited surface to $0.7 \cdot E_0$ on the opposite side of the crystal. But internal field keeps the same direction as external.

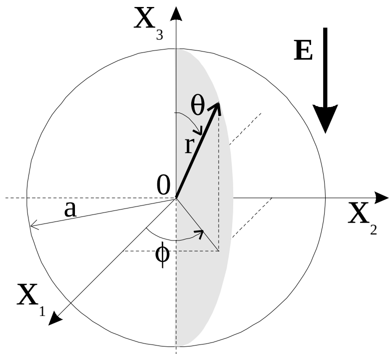

Fig. 2 Polar coordinate system of the ball-shaped dielectric probe

As an illustration, the TABLE 1 shows the values of the electric field in the middle of the probe exposed to a uniform electric field of 1 V/m. The electric field intensity E_{in3} was calculated for two different permitivities of the probe: $\varepsilon_r = 4$ (Bismuth Germanate) and $\varepsilon_r = 85$ (Lithium Niobate). The values of E_{in3} in an environment without space charge and in bipolar environment are shown for comparison. Method 1 refers to the simulation in which the already deposited charge is not allowed to leave the surface of the probe, whereas the method 2 allows the charge detachment. Both methods gave very similar results showing that the constant $C(r, \theta)$ is a function of the relative permitivity ε_r, in contrast to the bipolar environment where it depends only on the external electric field. In TABLE 1, E_{in0} is the internal electric field without any space charge and E_{bi} is the internal electric field in a bipolar environment.

TABLE 1 The calculated values of the internal electric field E(0,0) in the centre of the dielectric probe

ε_r	**E(0,0) Meth od 1**	**E(0,0) Meth od 2**	**E_{in0} No deposition**	**Ebi /Ein0**
4	-0.81	0.805	0.5	3
85	-0.106	-0.101	0.034	44

3. EXPERIMENTAL MEASUREMENTS

The experimental work aimed to investigate the possibility of using the sensor in the space charge environment. The experimental set-up is shown in Fig. 3. The electric field was generated by two parallel plates wide enough to provide a uniform field across the crystal. The positive ions were generated by a sharp needle maintained at a positive potential and placed in the middle of the aperture of the ground plate. The negative ions were generated by the negative corona discharge at the needle placed in the middle of the aperture of the negative high voltage electrode. The electric field contribution due to the high potential of the needle was considered to be negligible.

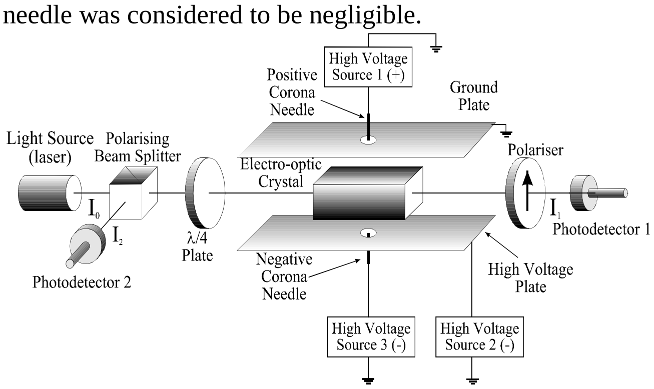

Fig.3 The experimental set-up for measurement in space charge environment

One of the main problems experienced during the measurement was drift of the zero output level. This drift was caused mostly by an uncorrelated long-term drift of the photodetector, and, to a lesser extend, by laser power fluctuations. It was, therefore, necessary to define the zero level before each measurement. Direct light output to the photodetector 2 was used for this purpose. In the case of space charge measurements, the zero level was defined always after neutralizing the sensing crystal by an AC corona discharge and waiting until the output was stable.

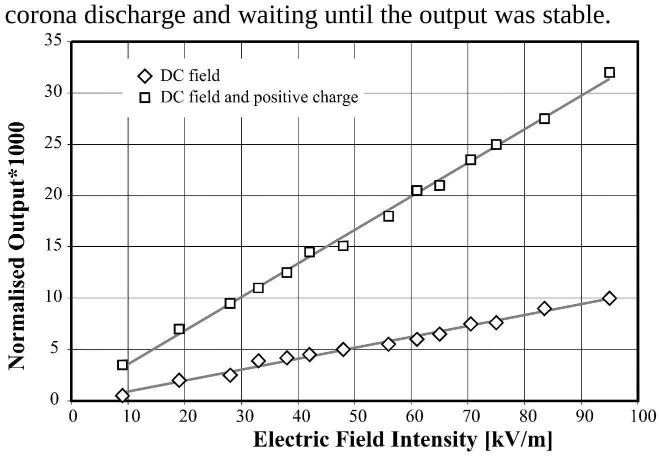

Fig. 4 Normalised output as a function of applied electric field for the DC field sensor with Lithium Niobate crystal in both unipolar and environment without space charge

Fig. 4 shows the normalised output of the sensor with Lithium Niobate in both the unipolar environment and the environment without space charge. It is apparent that in both cases the sensor output is linear and proportional to the applied electric field. It is also apparent that the output with the bipolar charge is in agreement with the theoretical results within the experimental error. However, while the field was decreased, the sensor output did not follow expected values due to accumulated charge on the crystal.

TABLE 2 shows the slope of the transfer characteristic for different corona currents. The space charge density was assumed to be proportional to the current I_{SPCest} between the electrodes. The slopes are found to be equal within the experimental error. This leads to the conclusion that in the performed experiments the sensor response was not influenced by the space charge density, as suggested by the theoretical analysis.

TABLE 2 Measured slopes of transfer characteristics for different space charge density

I_C [µA]	2	4	8	14
I_{SPCest} [µA]	0.23	0.3	0.34	0.43
Slope [m/kV]	0.338	0.314	0.352	0.33

The experimental results in bipolar environment are shown in Fig. 5. The experiments were carried out by switching on the DC field, then the positive ion generator, and finally the negative ion generator. It is apparent from Fig. 5 that the results do not correspond to the prediction fully. The measured ratio of the internal electric field in the bipolar environment to that in the environment without the space charge was 38. The difference to that given in Fig. 5 was attributed to the rectangular shape of the crystal, while the theoretical results were obtained for a ball. Consequently, in the charge equilibrium the surface charge density exceeds predicted equilibrium. Additionally, the sensor output was not very stable during the experiment due to the fact that the bipolar charging was preceded by unipolar charging and concomitant release of excessive charge deposited during the first stage of the unipolar charging. Still, the experiments show that the sensor transfer characteristic is linear and independent on the space charge density. As the mentioned difference is attributed by the type and shape of the sensing crystal, in practice this difference can be easily solved by the sensor calibration, as long as the charge density is low enough not to influence the measured field.

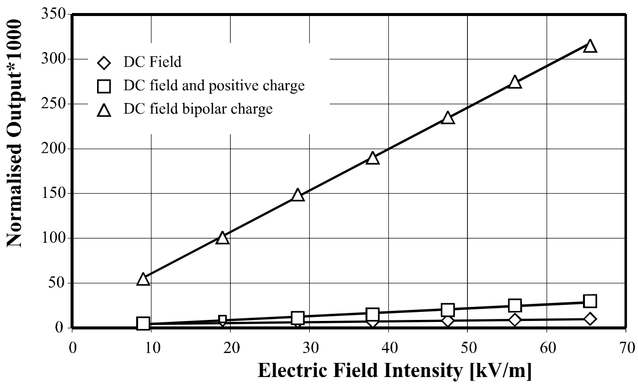

Fig. 5 Normalised output as a function of applied electric field for the DC field sensor with in bipolar, unipolar and environment without space charge

4. CONCLUSION

The theoretical analysis and the experiments with Lithium Niobate in unipolar environment confirmed that the sensor output is a linear function of the measured electric field and independent on the space charge density. It is therefore possible to measure electric field in the unipolar environment once the probe is calibrated and the space charge density is low enough not to influence the measured field. The measurement in the bipolar environment was found theoretically possible. However, a detailed experimental confirmation is still underway.

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