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Sensitive electro-optic sensor using $KTa_{1-x}Nb_xO_3$ crystal

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ABSTRACT

$KTa_{1-x}Nb_xO_3$ (KTN) is well-known as a crystal having very large EO coefficients. High-quality KTN crystal growth technology has been recently developed, and several applications of KTN are being investigated. We tried to use KTN to make an electric field sensor and, studied its electro-optic properties for this purpose. The modulation depth of the sensor was about 20 times deeper than that of the ZnTe sensor used in our previous system in the frequency range from DC to 1.5 MHz.

1. Introduction

There are many objects to be measured: the human body, animals, plants, circuits, and the earth. Information from an object under test is detected by placing a sensor (transducer) between the object and a receiving circuit. A sensor senses physical and chemical quantities and converts them into electrical signals. The object under test, however, does not necessarily have a proper circuit ground line. This means there may be common-mode noise in the signals detected by the receiving circuit. One method of obtaining a large common-mode rejection ratio (CMRR) is to insulate the receiving circuit from the object under test. In particular, the object under test can be electrically isolated from the receiving circuit, making the CMRR large, by using an electro-optic (EO) sensor.

We previously reported on the development of EO probe systems [1,2] and an intra-body communication system [3] using EO sensors. The EO sensors of these systems were made from cadmium telluride (CdTe) and zinc telluride (ZnTe). The modulation depths of these crystals were not so large. There is a thought of fabricating a waveguide-type EO sensor in order to obtain a large modulation depth. The problem with this sort of sensor is the cost.

$KTa_{1-x}Nb_xO_3$ (KTN) is a crystal with very large EO coefficients [4]. Until recently, it was extremely difficult to grow a large homogeneous crystal, but high-quality KTN crystal growth technology has been developed [5]. This development has opened up the possibility of useful new KTN applications, and so far, a beam scanner system [6] and a variable focal-length lens system [7] have been reported.

In this study, we used KTN to make an electric field sensor for making waveform measurements and studied its electro-optic properties for this purpose. The modulation depth of KTN is about 20 times deeper than that of ZnTe in the frequency range from DC to 1.5 MHz. The next section explains the merits of an EO sensor system. The succeeding section describes the electro-optic properties of KTN. Finally, we show the results of experiment on a fabricated KTN sensor.

2. EO sensor system

Various sensors outputting electrical signals have been developed. Sensors are placed between an object under test and a receiving circuit, as shown in Fig. 1. The signal detected by the sensor, V_{SIG}, is transmitted to the receiving circuit via a signal and circuit ground line (Fig. 2). There are two kinds of noise on transmission lines: differential-mode noise, V_{DN}, and common-mode noise, V_{CN}. As for differential-mode noise, the signal line voltage is inverted to the circuit ground line voltage ($V_1 = -V_2$). Magnitudes

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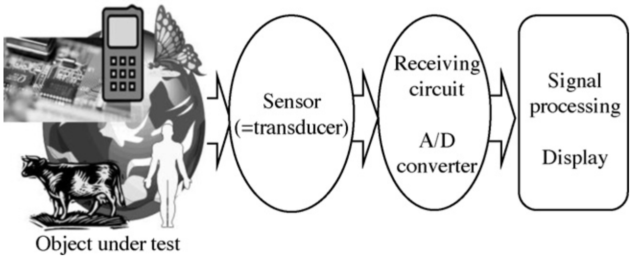

Fig. 1. Concept of sensor system.

are equal and phase difference is a π radian. The differential-mode noise has the same characteristics as those of the detected signal, V_{SIG}, and for that reason, it is also called normal-mode noise. As for common-mode noise, the signal line voltage is the same as that of the circuit ground line voltage ($V_1 = V_2$). Magnitudes are equal and phase difference is 0 radian. It is reported that the noise generated from DC-to-DC converters used in electric equipment is the common-mode noise. The common-mode currents return to the earth ground via the parasitic impedances. The common-mode currents generate electromagnetic field noises with equal magnitude and phase, so it is difficult to cancel them [8]. The CMRR for a V_{SIG} of 0 V and for a V_{DN} of 0 V is given by

$$\mathrm{CMRR} = \frac{V_{CN}}{V'_{12}} = \frac{V_{CN}}{V'_1 - V'_2} = \left(\frac{Z_{SE}}{Z_s + Z_{SE}} - \frac{Z_{GE}}{Z_G + Z_{GE}}\right)^{-1} \quad (1)$$

To obtain a large CMRR, we need to balance the impedance of the signal line and circuit ground line, as expressed in Eq. (2)

$$\frac{Z_{SE}}{Z_s + Z_{SE}} = \frac{Z_{GE}}{Z_G + Z_{GE}} \quad (2)$$

However, there is not necessarily a proper circuit ground line near the signal line for the object under test. In such a case, the impedance balance between signal line and circuit ground line deteriorates and the CMRR becomes lower. That means electrical sensor based systems are affected by common-mode noise.

Another approach to obtaining a large CMRR ($Z_S, Z_G \to \infty$) is to insulate the receiving circuit from the object under test. One way of electrically isolating an object under test from the receiving circuit is to use an EO sensor. Such an EO sensor system can measure signals precisely without the effect of common-mode noise. We have developed EO sensor heads for “low-invasive” measurement systems (Fig. 3). The contactless EO sensor system (a) can be used for making internal node measurements of integrated circuits [1],

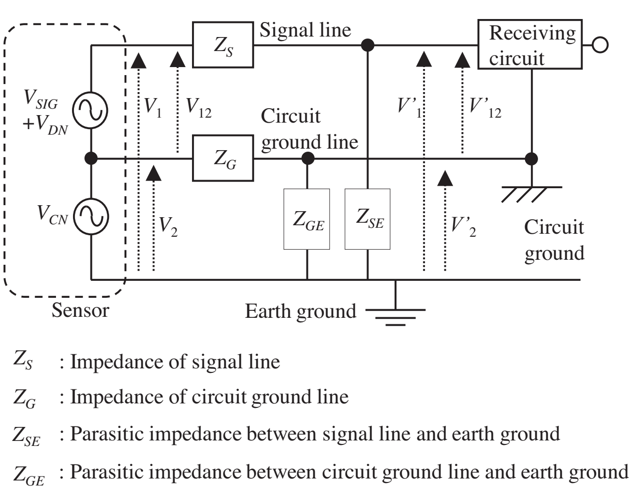

Fig. 2. Common-mode and differential-mode noise on transmission line.

whereas the contact EO sensor system (b) can be used for measuring waveforms from printed circuit boards [2]. Moreover, the concept of intra-body communication, in which the human body is the transmission medium, has been investigated for the purpose of developing useful ubiquitous computing services. In this type communication, the signal line is the human body and the ground line is parasitic capacitance between human body, and the earth ground [9]. The transmission channel's impedance balance is extremely degraded under these circumstances. A near-field sensor head for the intra-body communication system is shown in Fig. 3(c). It was reported that using an EO sensor enables 10-Mbps intra-body communications to be achieved [3]. This means that the EO sensor can overcome the large amounts of common-mode noise generated in intra-body communication.

3. Electro-optic properties KTN crystal

KTN is a mixture or solid solution of $KNbO_3$ (KN) and $KTaO_3$ (KT). Above its Curie point, it has a cubic crystal structure; it is optically isotropic, with a refractive index and has the Kerr effect. The electro-optic properties are characterized by three Kerr constants, g_{11}, g_{12}, and g_{44}, in accordance with the cubic centrosymmetric space group $m3m$ of the perovskite structure (Fig. 4). Potassium (K) is placed at the corner position of the cube, and Niobium (Nb) or tantalum (Ta) is placed in the center of the cube. When an electric field E is applied in the z direction, the optical indicatrix and the change in refractive indexes n_x, n_y, and n_z are described by [4]

$$\frac{x^2}{(n_0 - (n_0^3/2)g_{12}P^2)^2} + \frac{y^2}{(n_0 - (n_0^3/2)g_{12}P^2)^2} + \frac{z^2}{(n_0 - (n_0^3/2)g_{11}P^2)^2} = 1 \quad n_x = n_y = n_0 - \frac{n_0^3}{2}g_{12}P^2, \quad n_z = n_0 - \frac{n_0^3}{2}g_{11}P^2 \quad (3)$$

Here, n_0 is the refractive index without the electric field, and P is the induced dielectric polarization by the electric field E. When the relative dielectric constant ε_r is extremely large ($\varepsilon_r \gg 1$), P can be expressed [10]

$$P^2 = (\varepsilon - \varepsilon_0)^2 E^2 = \varepsilon_0^2(\varepsilon_r - 1)^2 E^2 \simeq \varepsilon^2 E^2 \quad (\varepsilon_r \gg 1) \quad (4)$$

ε is the static dielectric constant, and ε_0 is the vacuum permittivity. When laser light propagates in the x direction, it is subject to an induced phase retardation Γ in the EO crystal that is described by

$$\Gamma = \frac{2\pi}{\lambda}\int_0^L (n_y - n_z)dx = \frac{\pi n_0^3(g_{11} - g_{12})\varepsilon^2 L V^2}{\lambda d^2} = \pi\left(\frac{V}{V_\pi}\right)^2 \quad (5)$$

where λ is the vacuum wavelength of light, d is the electrode gap distance, L is the crystal length, V is the voltage applied to the crystal, and g_{ij} is the Kerr constant. V_π [10] is the half-wave voltage required to produce a π phase retardation in the EO crystal and it is expressed as

$$V_\pi^2 = \frac{\lambda d^2}{n_0^3(g_{11} - g_{12})\varepsilon^2 L} \quad (6)$$

If the relative dielectric constant ε_r is large, the half-wave voltage is small, and the sensitivity of the sensor will be high. The relative dielectric constant ε_r obeys the Curie–Weiss law [4],

$$\varepsilon_r \propto \frac{1}{T - T_c} \quad (7)$$

where T is temperature, and T_C is paraelectric Curie temperature. Eq. (7) means that the relative dielectric constant ε_r increases sharply around T_C. To obtain a large ε_r, we kept the temperature of the KTN at a few degrees above T_C in our experimental setup.

The light transmittance ratio concerning the modulation depth can be measured using crossed polarizers as shown in Fig. 5. The