Simple optical transformer system for intense electric field and voltage sensing

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Abstract: This paper presents a quite simple and efficient optical transformer system for high-voltage measurements. Compact and concise electro-optic sensors measure intense electric fields emitted from 50 kV of a spherical surface. We present two distinct types of optical sensors, one suitable for contacting and the other suitable for non-contacting sensing geometry. The properties of each sensor, including the design, operation principle, linearity and sensitivity, for intense electrical signals are discussed. The voltage sensing capability of the proposed optical transformer, from the measured electric fields, was evaluated and calibrated in a field simulation based on a finite element method and by a commercial potential transformer.

Keywords: optical voltage transformer, high-voltage measurement, Pockels effect, electro-optic sensor

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Photonic-based high-voltage measurement systems—widely called OPT (optical potential transformer) systems—have garnered much attention as an alternate solution against traditional oil-insulated electrical transformers [1, 2, 3, 4, 5]. OPT systems are based on the Pockels (or EO. i.e., electro-optic) effect, which generally shows significantly lower sensitivity levels to electric fields compared to electrical schemes. However, most EO materials are highly robust against intense electromagnetic fields having high damage threshold levels. Moreover, EO media generally hold the excellent linearity of the Pockels effect close to the damage level. Hence, the feature of a wide dynamic range without saturation or failure has been a main advantage of OPTs, especially for high-voltage sensing applications.

Another main feature of OPTs is their immunity against electrical and electromagnetic environments. EO media and related sensor embodiments have no conductance due to their all-dielectric dielectric characteristic. These sensors can be coupled into lengthy optical fibers to secure the galvanic and spatial isolation of high-voltage and observation systems without electromagnetic interference. Unlike conventional capacitive- or inductive-type PTs, which transform the high voltage down to the handy lower levels, OPT systems deliver the voltage information exclusively in the form of modulated light. The higher voltage levels only increase the light modulation depth without changing the average optical power going to the observer system. This type of photonic modulation scheme offers a safer working environment with very wide dynamic ranges as well as noise-rectified features.

In this paper, we present a simple and compact OPT system. The optical sensors designed and implemented here are simple and light so as to be mounted directly on or above the surface of high-voltage electrode. First, the design and operation principle of each sensor to detect the electric fields emanating from the electrode are discussed. The electric fields measured at various locations above the spherical electrode are compared with those which are calculated with those determined by the finite-element method (FEM). The dynamic fields from a 50 kV AC surface are then converted to voltages which are compared to those of a conventional PT method.

2 Optical potential transformer system

The complete OPT measurement system for a high-voltage electrode is illustrated in Fig. 1. The photo in the figure is a 50 kV, 60 Hz AC voltage-generation system which has a spherical electrode with a diameter of 100 mm. Intense electric field flux is formed from the electrode to the ground. All of the fields are bent between the electrodes, except those on or above the sphere apex, where the fields radiate only vertically.

The implemented EO sensors are sensitive in only certain directions of electric fields. In this case, we positioned the EO sensors on or above the apex to measure

Fig. 1. 50 kV AC voltage-generation system with an EO probe (top) and its associated OPT system (bottom).

only the vertical field components. The EO sensors are mated to a few meters (or longer if necessary) of totally enclosed 1550 nm fiber-optic link. Details of the optical parts—from the polarization-controlled laser, the optical link which circulates from the EO sensor, to the photo detector—are discussed in our previous work [6]. The electric fields are demodulated in electrical signals at the detector and read through a lock-amplifier in the voltage unit. Meanwhile, a commercial PT system, used to calibrate the OPT system, also monitors the voltage on the spherical electrode.

3 Design of EO sensors

The refractive indices of optical crystals can be modeled as an index ellipsoid. Fig. 2(a) shows the index ellipsoid for LiTaO₃ crystals. It has two ordinary (n_o) and one extraordinary (n_e) refractive indices. We set their orientation as $n_x = n_y = n_o$ and $n_z = n_e$.

Fig. 2. EO properties of the LiTaO₃ crystal: (a) positive uniaxial ($n_x = n_y < n_z$) index ellipsoid, (b) x- and z-cut wafers, (c) EO modulated index ellipsoid for the x-cut wafer (d) EO modulated index ellipsoid for the z-cut wafer.

The refractive indices of LiTaO₃ become modulated when the crystal is exposed to electric fields. The amount of index modulation primarily depends on the direction of the electric field applied and the EO tensor of the crystal. The complicated tensor analysis can be greatly simplified by dicing a bulk LiTaO₃ crystal along the y - z plane (x -cut) and the x - y plane (z -cut), as shown in Fig. 2(b). For the x -cut LiTaO₃ wafer, its index ellipsoid is most efficiently modulated when an electric field is applied only along its n_e axis. The index ellipsoid is then simplified as shown in Fig. 2(c) and as expressed by Eq. (1).

$$\left(\frac{1}{n_o^2} + r_{13}E_z\right)x^2 + \left(\frac{1}{n_e^2} + r_{33}E_z\right)z^2 = 1 \quad (1)$$

The known birefringence and EO parameters of the LiTaO₃ crystal at 1558 nm are $n_e = 2.1224$, $n_o = 2.1186$, $r_{33} = 27.4$ (pm/V), and $r_{13} = 6.92$ (pm/V) [7]. In practice, $r_{33}E_z \ll n_e$, $r_{13}E_z \ll n_o$; and because $dn = -(1/2)n^3d(1/n^2)$, the birefringence perturbed by the applied E_z can be re-expressed as Eq. (2).

$$n_o(E_z) = n_o - \frac{1}{2}n_o^3r_{13}E_z, \quad n_e(E_z) = n_e - \frac{1}{2}n_e^3r_{33}E_z \quad (2)$$

For alternate time-varying electric fields, the electrically induced birefringence levels for the x -cut LiTaO₃ wafer along the x and z axes are denoted as $\Delta n_x(E_z)$ and $\Delta n_z(E_z)$, respectively, in Fig. 2(c). The corresponding induced terms are $\pm n_o^3r_{13}E_z/2$ and $\pm n_e^3r_{33}E_z/2$. Because of the EO coefficient difference ($r_{33} > r_{13}$), the x -cut LiTaO₃ wafer would theoretically have four times stronger sensitivity over the z -cut one. However, the z -cut LiTaO₃ wafer does not show birefringence, instead showing only a modulation term of $\pm n_o^3r_{13}E_z/2$, as illustrated in Fig. 2(d). In general, the x -cut wafers are preferably used for LiTaO₃ due to their superior EO coefficients.

The x -cut scheme must specify the n_e direction and set it along the electric field direction to maximize the EO modulation term. In addition, the static birefringence ($n_e - n_o$) in the x -cut wafer often need to be removed using a compensator. In case of the z -cut wafer, it has no cumbersome birefringence and its n_e direction is quite straightforward as it is normal to the wafer. Because of these merits, the z -cut LiTaO₃ sensor should be also suitable for intense field sensing despite of its relatively lower EO characteristics. We present both x - and z -cut sensors and compare their characteristics for intense electric fields from the 50 kV electrode.

The LiTaO₃ wafers in Fig. 2(b) are 1.5 mm × 1.5 mm × 0.5 mm in size. Both wafers can serve as field sensors, either horizontally or vertically with respect to the apex of the spherical electrode, as shown in Fig. 3. For the LiTaO₃ sensor with the x -cut wafer shown in Fig. 3(a), the laser beam travels to the wafer tip through the optical fiber along the y -direction. If we set the laser polarization so that it is aligned only along either the n_z or the n_x axis using a polarization controller, the laser beam will experience only a single and exclusive refractive index change, which is $\Delta n_x(E_z)$ or $\Delta n_z(E_z)$. For instance, as the n_e value of the x -cut wafer in Fig. 3(c) is set along the E_z direction, if the laser polarization is linear and also set along to the z - (or x -) direction, the laser beam undergoes only n_e (or n_o) throughout the wafer. We utilized this ‘birefringence-free’ condition to implement a ‘thick-interferometric’ type of EO sensor [6].

Fig. 3. EO sensors used to measure vertical electric fields from the electrode apex: (a) a non-touch scheme with an x -cut sensor, and (b) a touch scheme with a z -cut sensor.

The basic idea is to use the interference of the laser beam reflected at both sides of the surfaces of the wafer. The refractive index difference at the interface of the fiber-LiTaO₃ causes the primary reflection coefficient about 0.17. To maximize the interference fringes, the secondary reflection coefficient at the interface of LiTaO₃-air needs to be comparable with respect to that of the primary one. The second LiTaO₃ surface at the air side is coated with highly reflective film to maximize the reflection at the secondary interface. However, only some portion of this reflected beam gets coupled back to the fiber core because of the beam divergence within the LiTaO₃ wafer. In our case, this secondary reflected and coupled beam is in charge of EO modulation and it is about two times greater than the first reflected one. The secondary beam has additional phase retardation with respect to the first one, which is readily controllable with laser wavelength. Thus, the clear interferometric fringe patterns can be obtained as in Fig. 4.

Fig. 4. Reflectance fringes of x -cut (solid and dashed lines) and z -cut (dotted line) LiTaO₃ wafers with a temperature-tunable laser.

The black solid and red dashed lines in Fig. 4 denote the reflectance fringes of the x -cut sensor wafer due to the distinct reflective indices of n_e and n_o . The contrast of the fringes is maximized when the polarization is set along the z - or the x -axis. Thus, the wafer has binary fringe patterns depending on the polarization status applied to the wafer. On the other hand, the reflectance fringe of the z -cut

sensor wafer always shows a single status, as represented by the blue dotted line in Fig. 4, as the beam, with any polarization, is influenced by an identical reflective index of n_o . The reflected beam at the first interface (fiber to front LiTaO₃ surface) is not modulated. However, the phase of the beam reflected at the second interface (back LiTaO₃ surface to air) is modulated because the refractive index within the wafer changes the phase-retardation characteristics of the beam upon exposure to an electric field. The latter reflection is in charge of ‘fringe modulation’ for *x*-cut LiTaO₃ wafers in Fig. 4. To maximize this modulation, it is highly recommended to set both the electric field and the laser polarization along the *z*-direction, as this condition causes efficient field-induced refractive index modulation, $\Delta n_z(E_z)$, as illustrated in Fig. 2(c). Such refractive index modulation ‘shakes’ the fringes in Fig. 4. Thus, the EO modulation efficiency heavily depends on where the laser is running on the fringes. It is desirable to set the laser wavelength at a position where the fringe’s slope is steep for good modulation efficiency. In case of EO modulators (EOM), which modulate light with huge scale, the intermediate operating point is preferred because of the best linearity. In case of EO sensing, the modulation amount is so minute compared to that of EOM. Thus, the linearity is maintained even operating below ‘the intermediate point’. Both 0.15 and 0.1 points have good EO modulation slopes but the 0.1 points shows less laser-induced noise because of delivering less light to the detector.

The points a_1 , a_2 and a_3 are good laser wavelength biases for the ‘ n_e fringes’ in *x*-cut LiTaO₃ wafers, as the slope is fairly steep and reflects fewer photons, offering good EO signals with low laser-induced noise. The red dashed fringe in Fig. 4 should be avoided because the field-induced refractive index modulation, $\Delta n_x(E_z)$, is approximately four times less than $\Delta n_z(E_z)$. A *z*-cut LiTaO₃ wafer always has only one type of fringe because there is no birefringence. The points b_1 and b_2 are good laser wavelength biases for *z*-cut wafers. Although *z*-cut wafers generally show weaker signals compared to *x*-cut wafers, they are more convenient to use due to their free-birefringence condition. In addition, they can measure the field normal to the wafer surface, whereas *x*-cut wafers do this along the surface instead.

4 OPT performance with EO sensors

EO sensors do not measure voltage signals directly. Instead, they detect the electric fields which are formed between electrodes. For high-voltage system shown in Fig. 1, intense electric fields emerge from the 50 kV spherical electrode and flow to the electrical ground on the floor. The field flux is curved, except at the apex of the electrode. To characterize the vertical electric fields depending on the sensing distance from the electrode, the sensing scheme shown in Fig. 3(a) is used. The *x*-cut sensor is assembled with a dielectric support to adapt it as a positionable field probe. The electrode with a 50 mm diameter yields a potential of 50 kV on its surface. This 50 kV is down-transformed to 82.951 V through the electrical PT in Fig. 1. The electric fields measured with the sensor are also read in voltage through a lock-in amplifier.

Fig. 5(a) shows the EO/PT voltage ratio and the absolute EO voltage signal for a distance from the surface up to 6 electrode radii. Each instance of field data at

various distances is an average of 100 measured points. The type A uncertainty (shown at a 10× magnified scale for convenience) with a 95% confidence level is presented along with the data. The EO voltage signals are RMS values of 60 Hz sine waves and they can be readily observed using an oscilloscope as shown in Fig. 5(b).

Fig. 5. Performance of x -cut LiTaO_3 sensor: (a) EO voltage response versus the distance from the 50 kV electrode, and (b) 60 Hz temporal response at a distance of one radius.

We can assume that a virtual point charge ($\equiv Q$) generates radial fields from the origin to the surface of the electrode ($\equiv r_s = 50$ mm). The voltage and E field at the distance r from a point charge Q are $V(r) = \frac{Q}{4\pi\epsilon r}$ and $E(r) = \frac{Q}{4\pi\epsilon r^2} \hat{r}$. For the electrode in Fig. 1, the voltage at r_s ($\equiv V_s$) is known instead of Q . Then, E field at r ($r \geq r_s$) is $E(r) = \frac{r_s}{r^2} V_s \hat{r} = (\frac{r_s}{r})^2 E_s \hat{r}$, where E_s is E field at r_s .

Having E_s measured by the EO sensor, the $E(r)$ values calculated by the simple analytical expression match up fairly well with the measured ones as shown in Fig. 5(a). Thus, by measuring the fields at an arbitrary distance from the electrode apex, the voltage at the electrode can be extracted if the sensor's linearity is assured. The linearity was evaluated in Fig. 6 for both x - and z -cut wafer sensors. The blue and red lines show the degrees of linearity of x - and z -cut sensors at a level as high as 50 kV in 2 kV steps, respectively. The x -cut sensor was horizontally positioned 50 mm above the surface and the z -cut sensor was imprinted vertically

on the surface. Both sensors show excellent linearity (linearity errors: $<0.2\%$ and $<0.6\%$ for the x - and z -cut sensors) and type A uncertainty characteristics.

Fig. 6. Linearity of x - and z -cut LiTaO_3 sensors with type A uncertainty (The uncertainty bar is exaggerated ten times for convenience).

Using an x -cut sensor is advantageous for detecting fields above the surface, whereas when using a z -cut one is more accessible to be directly attached to the surface, as demonstrated in Fig. 3. The x -cut sensor would theoretically have four times stronger sensitivity over the z -cut sensor. Although z -cut sensors have lower levels of sensitivity owing to the lower EO coefficients, they can be readily mounted onto an electrode surface on the apex or at any other location using an optical adhesive if necessary.

The x -cut sensor can be utilized for extremely high voltage measurements. The stronger electric fields from the higher voltage supply can be mitigated to moderate levels by lifting the sensor. In other words, the slope of the blue line (measured at $r = 50 \text{ mm}$) in Fig. 6 can be lowered adaptively by increasing r in Eq. (4). For instance, if $r = 266 \text{ mm}$, the electric field strength at the sensor position will be mitigated by ten times with the same potential. Thus, EO sensors at a new position would show similar performance levels up to 500 kV as if the voltage axis in Fig. 6 is accordingly rescaled by ten times.

It is also known that the linearity of an EO sensor is feasible up to the $\sim \text{MV/m}$ scale without failure caused by damage [8]. The absolute field level on the surface can be calculated, and we simulated the field distribution of our 50 kV system using finite-element method (FEM) software, in this case COMSOL Multiphysics [9]. First, we simplified the voltage-generation structure to two-dimension problem and confined the analysis area to 1 m (width) $\times$ 2 m (height) around the system. Nearly ten thousand mesh elements were used, and the computation time was less than ten minutes to create the field distribution in Fig. 7. The computer used had two quad-core Intel Xeon CPUs and 12 GB of memory. The vertical electric field on the surface apex is $\sim 157 \text{ kV/m}$ with 50 kV of DC potential on the electrode. Allowing the assumption that the linearity is feasible up to the $\sim \text{MV/m}$ scale, these EO sensors can measure a voltage system of a few hundreds kVs , which covers most industrial applications.

Fig. 7. Electric field flux and equipotential lines from the high AC voltage generator.

5 Conclusion

We have presented an optical transformer system for high AC voltage measurements up to 50 kV. The implemented sensors and system are designed to be quite compact and cost-effective. These EO sensors have a compact and lumped scheme and thus can be usable at arbitrary distances from the electrode apex. The voltage on the electrode system was evaluated by electro-optic sensors which measure the electric field from the electrode. The voltage and field strength levels on the electrode surface were characterized by an electrical potential transformer and a numerical field simulator to validate the performance of the proposed optical potential transformer system. The system also shows good stability and a wide dynamic sensing range that covers 50 kV applications and beyond.

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