DIRECTLY HIGH VOLTAGE MEASURING SYSTEM BASED ON POCKELS EFFECT

A. Kumada*and K. Hidaka
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku , Tokyo 113-8656, Japan
*Email: <kumada@hvg.t.u-tokyo.ac.jp>

Abstract: A new optical high voltage measuring system using a Pockels crystal in a longitudinal modulation arrangement is presented. The maximum measurable voltage for conventional Pockels sensors has been limited by the half-wavelength voltage, $V\pi$. In the new system, two-wavelength dual laser system is introduced to expand measurable voltage up to 1 MV which corresponds to the least common multiple of $V\pi$ for each light. The system consists of eight bars of 10×10×120mm^3 $Bi_4Ge_3O_{12}$ (BGO) crystal which are arranged in a series, laser diode (LD) sources of 1300 nm and 1550 nm wavelengths, an optical multiplexer, an optical demultiplexer, two O/E converters, and optical fibers. Prior to the assembling a prototype of the system, the thermal dependence of the sensitivity of BGO bars is also measured. The sensitivity of BGO bar shows little thermal dependence and agrees with each other within 10 % variability. The measured results for dc, ac, lightning impulse, and step voltages by the prototype system are presented and compared with the predicted values. Although not-negligible gyration of the light is recognized in case of measuring higher than $V\pi$, the system shows an advantage of directly measuring voltage up to 300 kV without any potential divider in a wide frequency bandwidth.
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1 INTRODUCTION

New techniques developed in electronics and optical field including fiber optic technology bring new contributions to measure the voltage and electric field [1,2]. The Pockels voltage sensor has been widely introduced to electrical power transmission and distribution systems and some advantages of the optical voltage measuring techniques are reported in [3].

The main problem measuring the high-voltage directly using electro-optic sensors is the sensitivity of them which is usually too high in comparison with the measured voltage. The conventional solution is to use capacitive or resistive voltage dividers to obtain small part of the total voltage on the sensor. The authors have developed a multi-segment type Pockels sensor for measuring over 250kV, which has such a structure that 8 slices of Pockels crystal are placed in series with a certain SF6 gas layer, and capacitive divided potential is measured by Pockels effect [4,5]. However, the outputs of capacitive dividers are generally influenced by stray capacitances between surrounding apparatus.

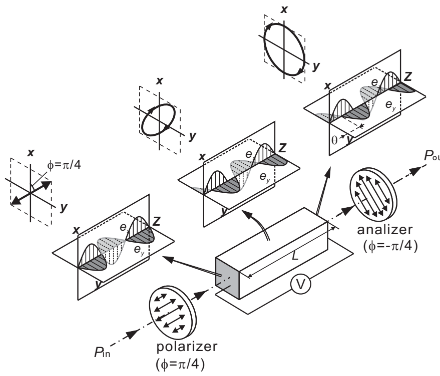


Figure 1: Principle

In this paper, a Pockels sensor for directly measuring high voltage over 300 kV is developed by utilizing a two-wavelength dual laser system.

2 MEASURING SYSTEM

2.1 Pockels Effect

The electro-optic effect can be expressed by the change in the index ellipsoid that certain materials exhibit when an electric field is applied [2]. Figure 1 shows the polarization change of the light which propagates in the Pockels crystal in longitudinal modulation arrangement, where the applied electric field and the light beam direction are in parallel. The linearly polarized incident light enters Pockels crystal and propagates along z-axis of it. The polarization status is changed due to the Pockels effect of the crystal. The phase retardation, θ, between two orthogonal light components of the output light is given by the function of the integration of the electric field;

$$\theta = \frac{2\pi}{\lambda} n_o{}^3 r_{41} \int E_z dz = \frac{2\pi}{\lambda} n_o{}^3 r_{41} V \qquad (1)$$

where λ is the wavelength of the light, n_o is the ordinary refractive index of the Pockels crystal, r_{41} is the Pockels constant, V is the potential difference between the end faces of the Pockels crystal. An additional retardation of θ_0 is

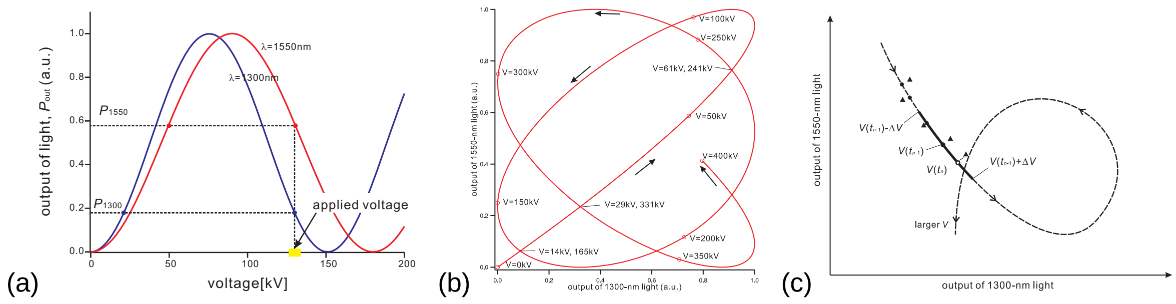


Figure 2: Relationship between light outputs and application voltage, (a) *P-V* curves, (b)Relationship between P_{1300} and P_{1550}, (c) Calculation of application voltage.

superimposed to θ by natural birefringence of optical components or by a retardation plate.

When the transmitted light is detected by an analyzer whose direction is perpendicular to that of the polarizer, the detected light intensity P_{out} is given by

$$P_{out} = \frac{P_{in}}{2}\{1-\cos(\theta+\theta_0)\} = \frac{P_{in}}{2}\left\{1-\sin\left(\pi\frac{V}{V_\pi}+\frac{\pi}{2}+\theta_0\right)\right\} \quad (2)$$

where V_π is the half-wave voltage defined as the value of V at which θ reaches π, and is given by

$$V_\pi = \frac{\lambda}{2n_o^3 r_{41}}. \quad (3)$$

2.2 Expansion of Measurable Voltage

When a voltage higher than V_π is applied to the Pockels crystal, it is difficult to estimate the applied voltage uniquely from the detected light intensity, which changes as a sinusoidal function of the applied voltage as expressed in Eq.(2). This was the main problem for measuring the high-voltage directly using Pockels sensors.

To expand the measurable voltage, double-wavelength lights are utilized. Two lights of different wavelength, which are mixed by an optical multiplexer, propagate in the Pockels crystal, and the transmitted lights are separated into each wavelength light by an optical demultiplexer, and are monitored simultaneously. Due to the availability of the optical components, 1300 nm and 1550 nm lights are used in this study.

As V_π depends on the wavelength of the light, the P_{out}-V characteristic curves (*P-V* curves) are different as shown in Fig. 2(a). It is possible to calculate the applied voltage uniquely from these two detected signals even when a voltage higher than V_π is applied. The calculation process is as follows:

1. Applying a known high voltage to the Pockels crystal as described later in subsection 3.3, *P-V* curves for both wavelengths shown in Fig 2(a) are obtained experimentally.

2. From each *P-V* curve, the relationship curve between the outputs of 1300-nm, P_{1300}, and 1550-nm light, P_{1550}, can be parametrized by using parameter V. Figure 2(b) shows an example of the trajectory curve between P_{1300} and P_{1550}, for various V. In this figure the half-wave voltages are tentatively set at 75.5kV for 1300nm light and 90kV for 1550nm light and natural birefringence is set to be negligibly small.

3. When an unknown voltage is applied to the Pockels crystal, both light outputs P_{1300} and P_{1550} are monitored. As noise is superimposed on the measured value, the measured combination (P_{1300} ,P_{1550}) sometimes deviates from the trajectory curve. Therefore, the parameter V, which expresses the nearest point on the trajectory curve from the measured point in P_{1300} - P_{1550} plane is selected as the calculated voltage.

The relationship curve crosses by themselves at certain points. For example, the combination of P_{1300} and P_{1550} takes the same values at V = 14 kV and 165 kV in Fig. 2(b). To calculate uniquely the application voltage from the light outputs, the time-continuity of the voltage is taken into account. That means, the increment/decrement of the measured voltage from the shortly before measured one is assumed to be limited to a certain value ΔV.

2.3 High Voltage Measuring System

Figures 3(a) and (b) show the schematic diagram of the measuring system, and the photograph of the Pockels voltage sensor, respectively. It consists of laser diode (LD) sources of 1300 nm and 1550 nm wavelengths, an optical multiplexer, an optical demultiplexer, two O/E converters, optical fibers, and Pockels voltage sensor. The Pockels voltage sensor consists of eight bars of BGO crystal, two polarized beam splitters (PBS) and two plates of glass with transparent conductive coat as the transparent electrodes. The sizes of BGO bars are 10 x 10 x 120mm^3 , and are arranged in a series in order that the total length of the BGO bar is long enough for being applied high

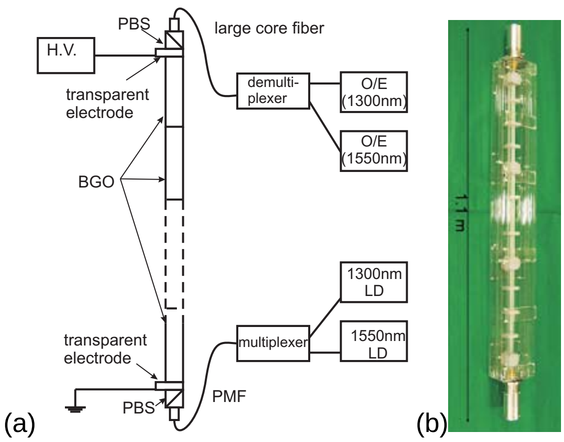


Figure 3: High Voltage Measuring System; (a) Schematic diagram, (b) Photograph

voltage. The transparent electrodes are placed on the both ends of the connected bar of BGO. One transparent electrode is grounded directly or grounded via a modulation ac power source. The other electrode is applied to the high voltage to be measured.

The lights of 1300 nm and 1550 nm wavelengths combined with an optical multiplexer, pass through a polarization maintaining fiber (PMF) and enter the Pockels sensor. The linearly polarized incident light propagates in BGO crystal. The transmitted light through a PBS is detected by a PBS and divided into each wavelength component by an optical demultiplexier. The outputs of each component are monitored by O/E converters.

3 EXPERIMENTAL RESULTS

3.1 Thermal Stability of BGO

The natural birefringence and the sensitivity π / V_{π} for each bar of BGO were measured by ac modulation technique: Single BGO-bar sensors are assembled as shown in Fig.4, where a BGO bar and a pair of PBS were placed in a thermostatic bath. 50Hz-modulation voltage of 500 V in its peak value is applied to an end of BGO and dc voltage of 0.8 kV to 2.0 kV is applied to the other end of BGO. From the ratio between the 50Hz-frequency component and dc component of the output light intensity, the sensitivity π / V_{π} and the natural birefringence can be calculated [7].

Figures 5(a) and (b) show the thermal dependences of the sensitivity and the natural birefringence of BGO bars for 1300-nm light. As No. 1-bar was examined in thermally unstable condition, the measured points of the sensitivity vary widely. The sensitivity of other bars measured in stable condition show little thermal dependence. The individual difference of the natural birefringence depending on temperature is as large as tens of milliradian.

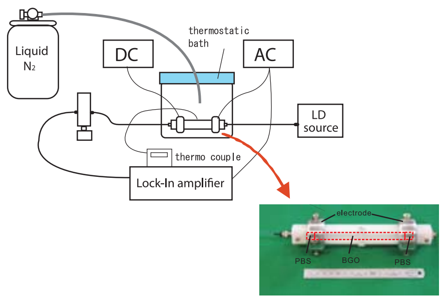


Figure 4: Arrangement for measuring the sensitivity and the natural birefringence of BGO.

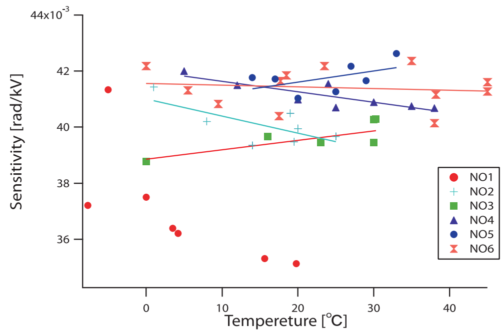


Figure 5: Sensitivity of BGO bars for 1300 nm light.

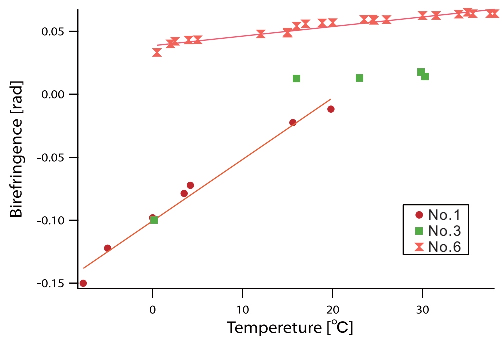


Figure 6: Natural birefringence of BGO bars for 1300 nm light.

The half wavelength voltages of BGO bars for 1300 nm and 1550 nm are calculated to be 75.5 and 90 kV, respectively.

3.2 Ac Voltage Measurement

50-Hz ac voltage of 50 kV to 200 kV in its peak value was applied to the measuring system. Typical waveforms of the light outputs are plotted by red and blued lines in Fig. 7 together with the output of a reference resistive divider, which are plotted by green line. As the applied voltage exceeds the half-wave voltage, the light output rises and falls for certain times in a single cycle. When the applied voltage is high, some spikes are observed in the waveforms of light output as shown in Fig. 7(b). These are electromagnetic noise caused by partial discharges on metallic parts of the measuring system.

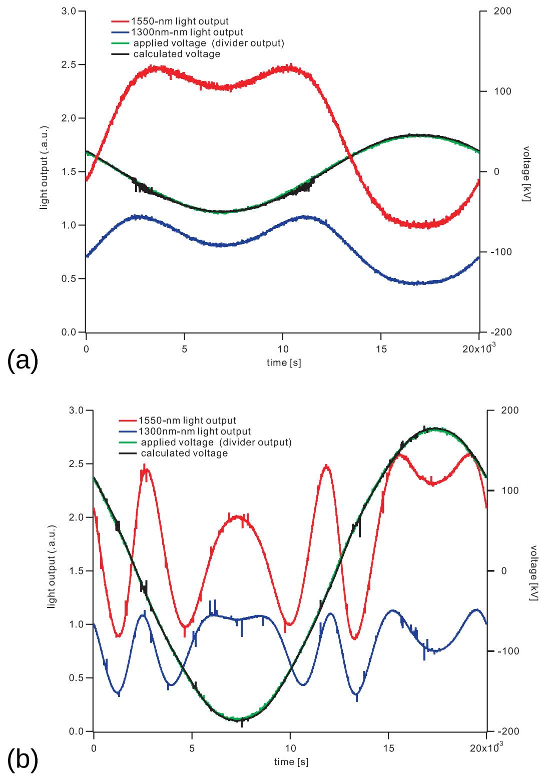


Figure 7: AC voltage measurement under (a) 50kV- and (b) 180kV- voltage application.

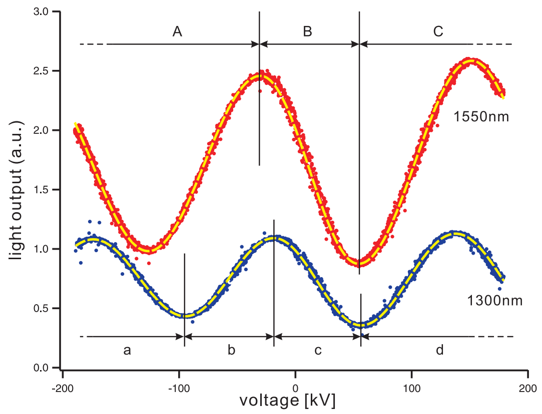


Figure 8: *P-V* curve derived from light outputs shown in Fig. 7 (b).

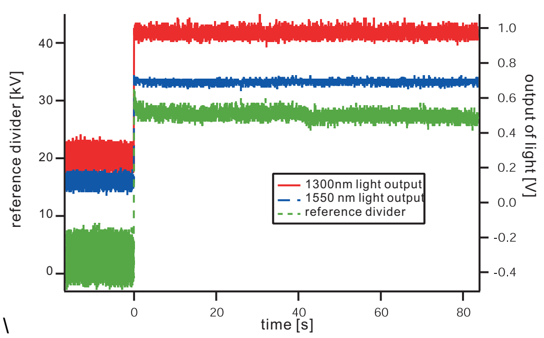


Figure 9: DC voltage measurement under (a) 50kV- and (b) 180kV- voltage application.

Figure 8 shows *P-V* curve derived from light outputs shown in Fig. 7(b). The light output seemingly changes as a sinusoidal function of the applied voltage. But it is difficult to fit the entire measured data onto a unique sinusoidal function, because the amplitude increases several percent per 100kV.

As plotted by broken lines in Fig. 8, three and four piecewise sinusoidal functions are tentatively utilized to express P_{1300}-V and P_{1550}-V characteristics, respectively. $V\pi$s of piecewise fitting functions for P_{1300}-V characteristics are 74 to 80 kV, and those for P_{1550}-V characteristics are 84 to 96 kV.

Using the calculation process described in Subsection 2.2, the applied voltage waveforms are inversely calculated from the light outputs with the *P-V* curve shown in Fig. 8, and plotted by black lines in Fig. 7. The calculated voltage waveforms coincide well with the reference outputs of the resistive divider.

3.3 Dc Voltage measurement

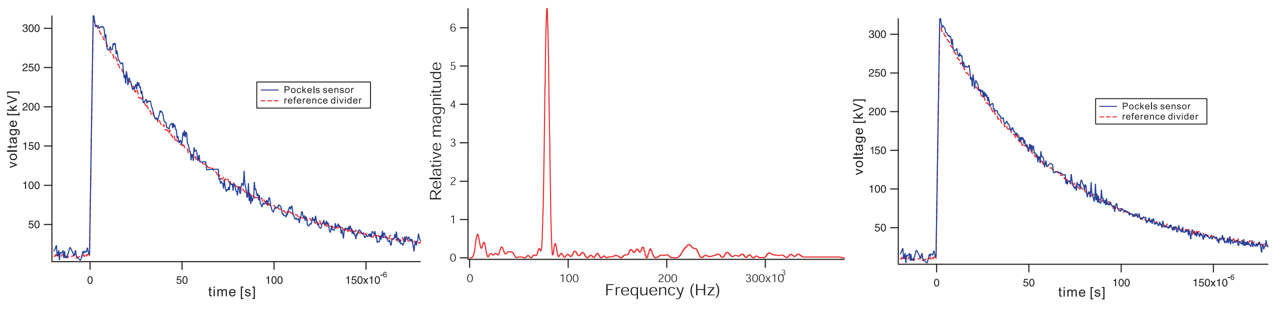
Since the system developed in this study adopts longitudinal modulation arrangement of Pockels crystal, it is possible to measure dc voltages without any modification. Dc measurement was performed by applying dc 30 kV for more than 1 hour. The light outputs followed well with the application voltage over 1 hour.

Figure 9 shows an example of the response characteristics when the step voltage was applied. The instabilities observed in the waveforms of the light outputs are caused by several factors: drift of the output intensity of the light sources, gradual settlement of the fiber, mechanical vibrations, etc. In future work, a more stable light source and a less sensitive fiber will be applied to the system in order to improve its performance.

3.4 Lightning Impulse Voltage Measurement

A lightning impulse voltage (1.2/50 μs) was applied to the measuring system. A typical waveform obtained from the measurement is shown in Fig. 10(a). In this figure, an oscillatory component of around 80 kHz appears after the voltage application. This is attributed to mechanical vibrations of the Pockels crystal caused by the piezoelectric effect.

By applying digital filter to the measured waveforms [4], it is possible to eliminate this oscillation. The filtering procedure is as follows. Firstly, oscillation waveform is extracted by taking the difference between the measured waveforms and the smoothed waveform by quadratic exponential function. The oscillation waveform is transformed in the frequency domain as demonstrated in Fig. 10(b) by performing fast Fourier transformation (FFT). The power spectrum



(a) (b) (c)

Figure 10: Impulse voltage measurement, (a) Calibrated voltage waveform, (b) Spectrum of oscillatory component, (c) Voltage waveform with digital filter processing

around 80 kHz, which is caused by the above mentioned piezoelectric effect, is eliminated down to the level of neighbour spectrum. This filtered oscillation waveform is added back to the subtraction quadratic exponential function. Figure 10(c) shows the waveform after FFT digital filtering. The oscillation component due to the piezoelectric effect is successfully removed.

For a Pockels measuring apparatus, it is desired to have small mechanical vibration. It has been successfully realized with sliced crystals [8] or a tapered crystal [9]. As a future work, such technique would be introduced into this measuring system.

3.5 Steep-front Square Voltage Measurement

Pockels voltage sensor is expected theoretically to have a wide frequency response up to GHz. Steep-front square voltage of 16 ns in rise-time and 50 kV in the maximum voltage were applied to the single BGO-bar sensor. The osicillatory component in the sensor output due to the piezoelectric effect is removed by the digital filtering in the same manner for the case of lightning impulse voltage measurement.

Figure 11 shows the sensor output after FFT digital filtering compared with a measured waveform by a capacitive divider. The time delay between the outputs of the reference capacitive divider and of the Pockels sensor is about 25 ns, which corresponds to the travelling time of light in an 8-m optical fiber.

4 DISCUSSION

The prehension of accurate *P-V* characteristics is necessary for this measuring system to achieve reliable high voltage measurement. As noted in subsection 2.2, the measured *P-V* curves shown in Fig. 8 have variation in the amplitudes.

This phenomenon can be explained in terms of the gyration in BGO. $Bi_4Ge_3O_{12}$ belongs to $\bar{4}3m$ point

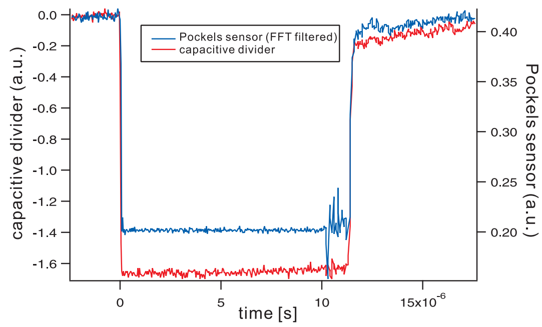


Figure 11: Steep-front square voltage measurement with digital filter.

group and exhibits not only the Pockels effect but also the Faraday effect [10] and piezogyration effect [11].

When an electric field $\boldsymbol{E} = (E_x, E_y, E_z)^T$ and a magnetic field $\boldsymbol{H} = (H_x, H_y, H_z)^T$ are simultaneously applied to a BGO crystal, electrooptic phase retardation θ and magnetooptic rotation angle ϕ_F will be produced simultaneously. The rotation angle ϕ_F is given by

$$\phi_F = V_{ver\,det} H_Z L \,, \qquad (4)$$

where L is the crystal length, and V_{verdet} is the Verdet constant, which is 30.8 [rad/(Tm)] for 635-nm light. When the AC voltage measurement was conducted with applying 200kV to the measuring system described in subsection 3.2, the magnetic field around the Pockels crystal was measured to be less than 3mT corresponding to ϕ_F of 0.1 rad at most.

On the other hand, the mechanical strain $\boldsymbol{S} = -(0, 0, 0, c_{44}e_{41}E_x, c_{44}e_{41}E_y, c_{44}e_{41}E_z)^T$ is generated due to the inverse piezoelectric effect of BGO under the application of an electric field, where c_{44} is a compliance coefficient and e_{41} is a piezoelectric coefficient [12]. By the piezogyration effect, the rotation angle ϕ_P

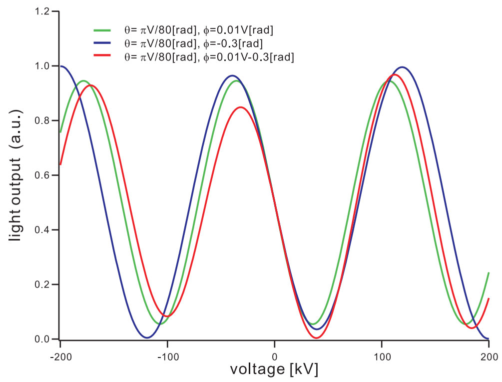


Figure 12: Influence of gyration on *P-V* curve.

$$\phi_P = \frac{\pi L}{\lambda n_o} g$$
$$= \frac{\pi L}{\lambda n_o} 2 w_{44} c_{44} e_{41} (E_x s_2 s_3 + E_y s_3 s_1 + E_z s_1 s_2), \quad (5)$$

is produced, where g is the scalar parameter of gyration, w_{44} is a piezogyration coefficient, and s_i are components of the unit vector of wave propagation.

When the propagation direction of the light is not aligned precisely to the crystal axis, ϕ_P takes a certain value almost linearly associated with the applied voltage. Thus, it is possible to assume the rotation angle $\phi = \phi_F + \phi_P \approx k_1 V + k_2$ is produced in the BGO crystal.

The resulting field for a beam of circularly polarized light passing through a crystal, where phase retardation θ and rotation angle ϕ are produced, and a polarizer is

$$\begin{pmatrix} E_{ox} \\ E_{oy} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} A & B \\ -B & A^* \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} E_{ix} \\ 0 \end{pmatrix},$$
$$A = \cos\Theta + j\frac{\theta}{2\Theta}\sin\Theta, \quad B = \frac{\phi}{\Theta}\sin\Theta \quad (6)$$

where A, B are the Jones matrix components for the crystal [10,13] and $\Theta = \sqrt{(\theta/2)^2 + \phi^2}$ is referred to as the resultant field induced phase retardation. The light intensity P_{out} emerging from the crystal is

$$P_{out} = \frac{P_{in}}{2}\left\{(\cos\Theta - \frac{\theta}{2\Theta}\sin\Theta)^2 + (\frac{\phi}{\Theta}\sin\Theta)^2\right\}. \quad (7)$$

Figure 12 shows calculated *P-V* curves for various k_1 and k_2. In some case, the amplitude of *P-V* curve changes almost 10% per 100 kV.

The maximum measurable voltage for this system is theoretically given by the least common multiple of the half-wave voltages of the lights. For this system, it exceeds 1.3 MV, and is possibly expanded to be a certain MV by choosing suitable combination of the laser wavelength.

5 CONCLUSION

A new optical high voltage measuring system using a Pockels crystal in a longitudinal modulation arrangement is presented. In the new system, two-wavelength dual laser system is introduced to expand measurable voltage over the half wave voltage.

In this study, the measured results for dc, ac, lightning impulse, and step voltages by the prototype system are presented. Although not-negligible gyration of the light is recognized in case of measuring higher than $V\pi$, the applied voltage is calculated uniquely from the detected optical outputs.

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