Light Intensity Measurement of Kerr Effect Using Photodiode and High Speed Camera in Propylene Carbonate Under Applied DC Electric Fields

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Abstract. Light intensity is a resultant of Kerr effect measurement which later can be translated to electric field as well as charge density distributions in dielectric liquid. The light intensity can be measured either with photodiode or camera but measurement with both detectors has not been done yet. This study focuses on the comparison of light intensity measurement using Kerr effect with simultaneous detectors of photodiode and high speed camera. Hence, a pair of parallel electrodes is used in the experiment under high DC electric field. Propylene carbonate is used as the test liquid with Kerr constant, \( B = 1.41 \times 10^{-12} \text{ mV}^{-2} \). From the measurement results obtained, the light intensities from both detectors were compared and showed significant results as compared to the predicted light intensity ratio.

1. Introduction

Kerr effect is an optical measurement method which is well established in measuring electric field and space charge distributions in dielectric liquids [1]–[3]. The measurement technique is based on the optical phase retardation due to the dielectric anisotropy induced by the electric field. In other words, anisotropic materials become when there is application of high electric field. Kerr effect has demonstrated the usefulness of its measurement system for quantifying electric field in dielectric liquids. One of the measurement techniques is based on defining the fringe pattern from a one-shot image which then calculate the electric field and the space charge distributions in the test liquid [4], [5]. The technique allows a direct observation of the light intensity distribution which depicts a nonuniform electric field distribution across the electrodes. However, by incorrectly assigning of number of the fringes will give an erroneous electric field distribution result. Besides, the light intensity of the Kerr experiment can be measured by using the single photodiode or array of photodetectors [6], [7]. For instance, [7] reported that the array of eight positions of photodetector was able to record the light intensity continuously between a 3 mm gap apart at a given time under impulse voltage. This continuous measurement minimises the error of measurements from the repeated tests by using the camera when there are errors in peak voltage, wave-front time and the half-peak time of the impulse voltage. In comparison, the array photodetector is a good detector type for continuous time measurement whereas the camera is good for spatial and temporal measurement.

Initial study has been done in [8] to verify the reliability and sensitivity of the measurement by using photodiode and high speed camera. The measurements were done separately and comparison of theoretical and measurement results was done at end of the study. In this paper, the light intensity measurement of Kerr effect using both photodiode and camera simultaneously is introduced with improved experimental setup. The study considered the parallel electrodes with 2.1 mm gap and propylene carbonate is used as the test liquid under DC voltages. As a result, comparison between pixel arrays and photodiode measurements is presented. Moreover, the relationship of the measurement and calculated values of transmitted light intensity as a function of applied electric fields is presented at the end of this paper.
2. Kerr Effect

Kerr effect is an electro-optical effect that was first observed by John Kerr in 1877. Under high electric fields, dielectric liquids become birefringent, or the refractive index of the substance changes. The light wave that oscillates parallel to the electric field is called extraordinary beam, \( n_{\parallel} \), light wave that oscillates perpendicular to the electric field is known as the normal beam, \( n_{\perp} \). The corresponding refractive indices of \( n_{\parallel} \) and \( n_{\perp} \) are directly proportional to the square of the applied electric field, \( E \) defined in equation (1) [4].

\[
\frac{c}{n_{\parallel}} - \frac{c}{n_{\perp}} = n_{\parallel} - n_{\perp} = B\lambda_0 E^2
\]  

(1)

where \( c \) is speed of the light, \( \lambda_0 \) is wavelength of free space and \( B \) is liquid Kerr constant. The difference in refractive indices of \( n_{\parallel} \) and \( n_{\perp} \) can be determined by measuring the resultant optical phase shift, \( \Delta \theta \) that can be related by:

\[
\Delta \theta = 2\pi B L E^2 = \pi \left( \frac{E}{E_m} \right)^2 \text{ where, } E_m = \frac{1}{\sqrt{2BL}}
\]  

(2)

\( E_m \) is the electric field magnitude at the first maximum light which depends on the liquid Kerr constant, \( B \) and the length of the electrode, \( L \). Measurement of the optical phase shift is difficult to be measured directly. However, it can be determined from the light intensity measurement of the transmitted light through the dielectric material. For example, Figure 1 shows the optical measurement system using one polarizer and one analyzer positioned perpendicular to each other with the dielectric liquid placed in the middle. By having such configuration, the light transmitted from the system is given by:

\[
\frac{I}{I_m} = \cos^2(\theta_p - \theta_a) - \sin 2(\theta_k - \theta_p) \sin 2(\theta_k - \theta_a) \sin^2 \left( \frac{\Delta \theta}{2} \right)
\]  

(3)

where \( I \) is the magnitude of the transmitted incident light, \( I_m \) is the magnitude of the maximum incident light, \( \theta_p \) and \( \theta_a \) are the angle set for the polarizer and analyser from the \( x \)-axis respectively, and \( \theta_k \) is the electric field direction from the \( x \)-axis.

![Figure 1. Optical measurement method of Kerr effect.](image)

3. Experimental Setup

Generally, the overall system consists of three main parts namely optical components, high voltage source and detectors. In this experimental setup, both a high speed camera and a photodiode are used in the tests to capture the output intensity of the transmitted light. The optical measurement configuration consists of the 7 mW, 633 nm He-Ne laser, an expander and polarisers are attached on an optical bench for easy mounting and positioning. A polariser, Polariser-1 is set at \( +\frac{\pi}{4} \) after the expander to reduce half of the incident light intensity from the laser and an iri diaphragm is used to
limit the beam of transmitted light at the middle of the electrodes. The second polariser, Polariser-2 is set at +45°, while the analyser is set at -45° relatively to the applied electric field axis. The linear polarised light from the Polariser-1 will pass through the test cell becomes elliptically polarised light. Then, the elliptically polarised light is converted back to the linearly polarised light as it passes through the analyser. A beam splitter is used to split the output light into two beams while a lens is used to focus the output light onto the photodiode and the camera as illustrated in Figure 2.

Figure 2. Experimental Kerr setup with photodiode and camera.

4. Image Processing

4.1 Region of Interest (ROI)

In the study, the central region between the two electrodes is observed. As shown in Figure 3, the positive and negative electrodes are presented in the dark black intensity with the bright intensity between them is gap across the electrodes. Knowing the gap is 2.1 mm with 470 pixels across, the total imaging area is 8.45 mm x 6.76 mm as the resolution of the high speed camera is 1280 x 1024. As illustrated in the Figure 3, diameter of the laser beam is, $\phi_a = 24.3$ mm that covers most of the electrodes height. Using the iris diaphragm, the measurement area for the photodiode is limit to $\phi_b = 13$ mm of diameter. Meanwhile, the lens focused the output of light beam onto small area between the gap producing height of $h_2 \cong 5.7$ mm. Hence, the measurement area is ROI$_1 = 2.1$ mm x 13 mm and ROI$_2 = 2.1$ mm x 5.7 mm for photodiode and high speed camera respectively as shown in Figure 3.

4.2 Mean Images and Averaging Filter Techniques

The experiments is optical measurement method that compose several optical components that susceptible to light refraction and diffraction along the system. Thus, this interferences produced noises to the measurement system. One of the interference was from the scattering light effect of the laser that travels along all the optical components as well as the liquid. Furthermore, measurements were recorded by the high speed camera which also can produce electronically optical noise. For example, the total images recorded from the high speed camera is 1000 images which equal to 1 ms per image. By determining a mean intensity from a total of 1000 ms images could reduce the time-varying noise produced in the system. It can be calculated by using equation (4) as follows.
$$I_{\text{mean}(x,y)} = \frac{1}{n} \left( \sum_{i=1}^{n} I_{i(x,y)} \right)$$

(4)

Where $I_{\text{mean}(x,y)}$ = mean intensity of $n$-images, $n$= total number of images and $I_{i(x,y)}$= intensity of $i$-image.

Additionally, image smoothing can be done using averaging filter technique. In the averaging filter technique, pixel in the centre of the arrays is set to the average value of all the pixels in the arrays. The example of 3 by 3 array for averaging filter technique for an image is shown in Figure 4.

Figure 5 shows the mean intensity of $n$-images. It is found that by determining the mean intensity of the images did not improve the image quality. Hence, the averaging filter technique has been applied to enhance the images. Figure 6 shows the images of the filtered $n$-images. In the study, 3 by 3 array of the averaging filter technique is applied. This is because having larger array reduces more noise but less detail is kept.
Figure 5. Mean intensity images for $n = 1, 30, 50, 100, 200, 500$ and $1000$.

Figure 6. Mean and filtered images for $n = 1, 30, 50, 100, 200, 500$ and $1000$ number of images.
As depicted in Figure 5 and Figure 6, there is not much different of intensity result between the mean image technique and the averaging filter technique. However, both methods have improved the quality of the images for further analysis. Besides, both methods valid only for steady state condition as assumed there is least difference between 1 ms interval of image.

5. Comparison of Light Intensity Measurement using Photodiode and High Speed Camera

Experiment for determining the relationship between the transmitted light intensity and the applied electric field has been performed. Figure 7 shows the measurement results of light intensity ratio of propylene carbonate over the predicted theory under DC applied electric fields. With the absence of electric field, both measurements of photodiode and high speed camera showed there was no light has transmitted through the optical components and hence the light pattern is uniformly dark. It is also found that both measurements showed the transmitted light intensity increased and reached the first light maxima at $2.11 \times 10^6 \text{ Vm}^{-1}$ with the increased of electric fields.

As shown in Figure 7, measurement results from photodiode followed the predicted Kerr effect curve. Although, there was small error margins between the measurement results and the predicted values, the first maxima intensity ratio still achieved at the maxima electric field. After more enhanced fields applied to the system, the intensity ratio reduced to low intensity magnitudes. In contrast, the ratio of light intensity measurement using the camera did not show a good agreement with the Kerr curve theory. Apart from the disagreement, the light intensity ratio still reached the first light maxima at the first maxima of electric field. Two primary factors that could contribute to the measurement errors the sensitivity of the camera’s sensors and light scattering effect in optical system [9]. Thus, error margins of the light intensity ratio due to measurement sensitivity were presented in Figure 8.

![Figure 7. Light intensity ratio of the photodiode and camera measurements.](image-url)
Figure 8. Standard deviation between the intensity ratio measurement and Kerr effect curve.

6. Light Intensity Ratio Distribution in Propylene Carbonate

Figure 9 shows the light intensity distributions in propylene carbonate measured in every 2 minutes test under various applied DC voltages ranges from zero to 4.6 kV over 2.1 mm gap. Figure 9(a) shows the zero intensity as no voltage applied into the system. When $0.24 \times 10^6$ Vm$^{-1}$ field is applied to the system, slightly change of intensity magnitude can be observed near the negative electrode which is shown in Figure 9(b). After increasing the applied electric fields to $0.66 \times 10^6$ Vm$^{-1}$, the light intensity became visible and slightly higher at the negative electrode as depicted in Figure 9(c) and Figure 9(d). During this low field conditions, the positive charges were moved towards the negative electrodes. Later, it can be observed that distribution of light intensity has increased near the positive electrode as the applied fields increased. Figure 9(e) to Figure 9(h) show the light intensity distributions at positive electrode increased from $0.95 \times 10^6$ Vm$^{-1}$ to larger magnitude at $1.6 \times 10^6$ Vm$^{-1}$ of applied field. This is caused by the accumulation of negative charges near the positive electrode. With further increased of applied fields up to $2.19 \times 10^6$ Vm$^{-1}$, more intense of light was recorded across the gap which showed in Figure 9(i) to Figure 9(l).

7. Conclusion

Comparison of light intensity measurement using photodiode and high speed camera has been validated against the Kerr effect curve. The measurement of photodiode and camera followed the Kerr curve until it reached the maximum intensity at $E_m \approx 2.11 \times 10^6$ Vm$^{-1}$. Measurement results from the high speed camera showed a margin of error happened as the electric field increased until the first maximum electric field is believed caused by the measurement sensitivity and light scattering effect in the system. Nonetheless, from the results obtained using the approximation of pixel count method, the light intensity ratio relative to applied electric field can be used to determine the electric field distribution and charge density distribution in future study.
Figure 9. Intensity ratio distributions in propylene carbonate under various DC applied fields.
8. References

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