Second-Harmonic Imaging of Flexoelectric Polarization in Various Liquid Crystal Cells

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ABSTRACT

Since the flexoelectric polarization of LCs attracts much attention in the LCD industry, we visualize the flexoelectric polarization in nematic LCs with SHG microscopy. The observed flexoelectric polarization is induced by applying an electric field to various nematic LCs with positive or negative dielectric anisotropy in several types of cells.

1 INTRODUCTION

Even-order nonlinear optical (NLO) effects allow us to probe symmetry breaking in the material structure owing to their forbidden nature in centrosymmetric systems. Among them, the lowest even-order NLO effect that is optical second harmonic generation (SHG), provides a powerful tool for studying the induced polarization in the light-transmitting media. One of local polarizations found in liquid crystals (LCs) called the flexoelectric polarization results from a coupling of elastic deformation and electric dipoles[1]. The flexoelectric effect has been attracting much attention in the LC device industry. For example, it is known that the optical flickering due to the flexoelectric effect is significant in the fringe-field switching (FFS) mode displays and deteriorates the image quality of the device[2]. Thus, we have visualized the flexoelectric polarization in LCs with SHG microscopy[3].

Here, we have visualized the flexoelectric polarization with SHG in nematic LCs in which SHG is forbidden because of their inversion symmetry. We induced the flexoelectric polarization by applying an external electric field to nematic LCs in various types of cells and succeeded in visualizing resultant polarization by SH microscopy. This method sholud be advantageous in evaluating the performance of the industrial LCDs, which are susceptible to the design of devices and LC materials.

2 EXPERIMENT

2.1 Sample

As the liquid crystal sample, 5CB (TCI) was used as a p-type nematic liquid crystal (NLC), and MBBA (TCI), some other compounds and their mixtures, all of which were provided by JNC corporation,, were used as an n-type NLC. These LCs were evaluated after injected into IPS, FFS, TN, wedge and homeotropic cells. The thickness of the IPS cell is 5 μm, and the line and space of the comb electrode is L/S = 10/10 μm.

2.2 SHG microsope

A schematic drawing of the experimental setup for SHG microscopy is shown in Fig. 1. A transmission SHG microscope based on an inverted microscope (Eclipse Ti, Nikon) was constructed for SH imaging. We used pulse light from a fs-Ti: sapphire oscillator (Vitesse, Coherent) with a wavelength of 800 nm and a repetition frequency of 80 MHz as the fundamental light. The fundamental light that has passed through a scanning optical system consisting of a 2-axis galvano scanner and an f-θ lens is incident on the sample placed on the microscope stage. The SH light generated by the sample was collected with an objective lens. After removing the fundamental light with filters, the image was taken with an Electron Multiplying CCD (iXon3, Andor) connected to the left port. A photon counting head (Hamamatsu) attached to the right port was used to measure extremely weak SH signals.

2.3 Simulation of Flexoelectric Polarization Distribution

In order to verify the origin of the SH image, we calculate the distribution of the flexoelectric polarization in an IPS cell. First, it is necessary to cal-

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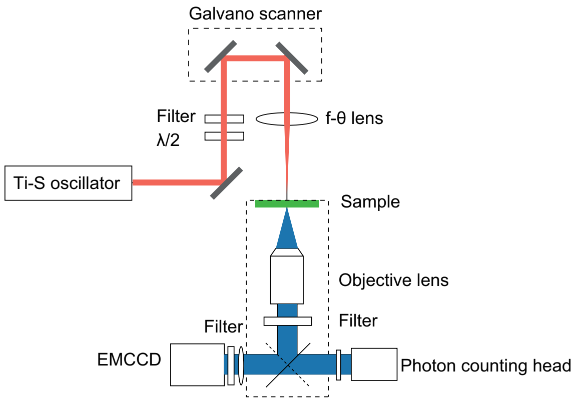

Fig. 1 Optical setup for SHG microscopy.

culate the liquid crystal alignment when an electric field is applied to the IPS cell. The flexoelectric polarization is then calculated from the obtained director distribution.

In the case of n-type IPS cells, the deformation of the NLC can be approximated only by in-plane rotation, hence the LC alignment can be calculated from the electrostatic field and the Euler-Lagrange equation for LC alignment field[4]. All simulations of n-type IPS cells were calculated with COMSOL Multiphysics®5.4 (COMSOL inc.). On the other hand, in the case of p-type IPS cells, orientational change of the NLC by the applied electric field is complicated. Thus, we used a LC simulator, LCDMaster/2D (SINTECH, Inc.), to calculate the LC orientation. Using the derived director, the distribution of flexoelectric polarization was calculated with MATLAB (MathWorks).

3 RESULTS AND DISCUSSION

3.1 SH Imaging of Various Liquid Crystal Cells

First, we observed the flexoelectric polarization in an IPS cell of 5CB under an electric field with a SHG microscope. While no SH image was observed in the absence of electric field, the SH image did appear with increasing amplitude of the applied square wave (frequency: 1 kHz). Figure 2 shows the SH images of 5CB in the IPS cell obtained by applying a square wave with the amplitude of 50 V. The polarized direction of fundamental light was perpendicular to the interdigitated fingers, the SH light was observed along the fingers (Fig. 2(a)). While the polarized direction of fundamental light changed to parallel the fingers, the SH light appeared at the tip of the fingers (Fig. 2(b)). This corresponds to flexoelectric polarization caused by splay and bend deformation between the pair of interdigitated electrodes (Fig. 2(a)) and between the tips of the interdigitated electrodes and the terminal strip of another electrode (Fig. 2(b)).

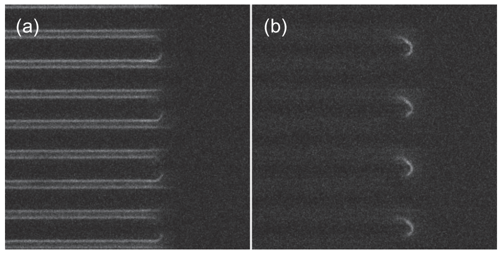

Fig. 2 SH micrographs taken for 5CB in an in-plane electrode cell by applying a square wave with amplitude of 50 V. The incident polarization is (a) vertical and (b) horizontal.

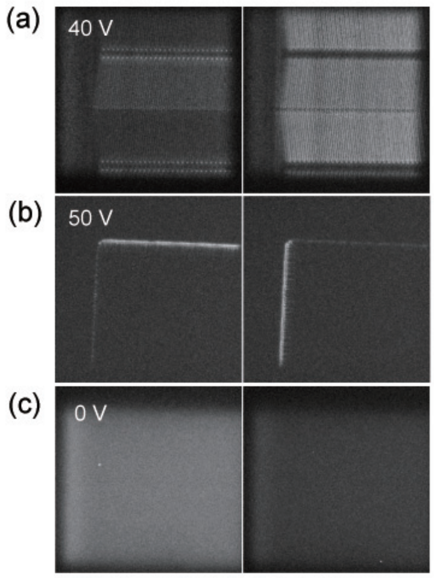

Fig. 3 SH micrographs of 5CB for various liquid crystal cells. (A) n-type mixture in an FFS cell with a voltage of 40 V, (b) 5CB in a TN cell with a voltage of 50 V, and (c) 5CB in a wedge cell without an electric field. The incident polarization is vertical (left column) and horizontal (right column).

Figure 3 shows the results of SHG imaging using various types of liquid crystal cells. In FFS, which operates almost on the same principle as IPS, the flexoelectric effect is known to affect the display quality. As expected, it is possible to observe an SH image probably due to flexoelectric polarization (Fig. 3(a)). The SH signal intensity of an FFS cell varies depending on the liquid crystal material; the liquid crystal material giving larger flicker showed stronger SH signal. Meanwhile, the flexoelectric effect in TN cells is ordinary not considered. However, it is possible to obtain an SHG image from a TN cell under an electric field as shown in Fig. 3(b). Finally, the SH image of 5CB in a wedge cell (homogeneous alignment) is shown in Fig. 3(c). Splay deformation caused by the wedge cell induced the flexoelectric polarization.

3.2 Simulation of Flexoelectric Polarization Distribution

We compared the flexoelectric polarization observed in the n-type IPS cell with the simulation results. Figure 4 shows steady results when 5 V is applied to the IPS cell. As shown in Fig. 4(d), the flexoelectric polarization spreads from the electrode edge to the inside of the LC. This result is consistent with the flexoelectric polarization image observed by the SHG microscopy. The magnitude of flexoelectric polarization increased when the applied voltage was raised to 50 V.

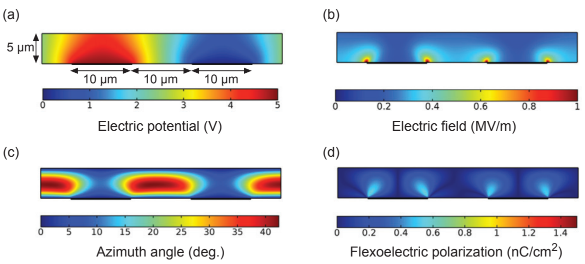

Fig. 4 Simulation results of an IPS cell with n-type nematic liquid crystals. (a) Electric potential, (b) Electric field, (c) Azimuth angle of the director and (d) Flexoelectric polarization.

Next, we simulated flexoelectric polarization in an IPS cell with p-type NLC. When the applied voltage was low, the same result as in the n-type was obtained. However, when a high voltage that could not be applied in an IPS display was applied, we have found characteristic results that do not appear in the n-type IPS cell. Figure 5 shows the simulation results of an IPS cell with p-type nematic liquid crystals at an applied voltage of 50 V. As can be seen from the director distribution shown in Fig. 5 (a)-(c), the disclination line is formed at the center of the electrode. The presence of a disclination line at the center of the electrode at high voltage was confirmed with a polarizing microscope. However, the flexoelectric polarization induced at the electrode center shown in Fig. 5 (d) has not been observed in the SH image (Fig. 2). Vector component analysis of the flexoelectric polarization induced in the center of the electrode revealed that the main component of this polarization is z (cell thickness direction) component. For this reason, we infer that this flexoelectric polarization cannot be detected in the current setup, and only the polarization appearing at the electrode edge is imaged. The next step will be to capture this polarization by improving our SHG microscope.

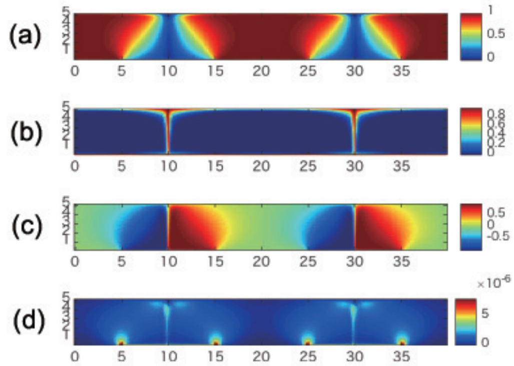

Fig. 5 Simulation results of an IPS cell with p-type nematic liquid crystals at an applied voltage of 50V. (a) x component (n_x), (b) y component (n_y), (c) z component (n_z) of director and (d) Flexoelectric polarization(|P| [C/m^2]).

4 CONCLUSIONS

The flexoelectric polarization of nematic liquid crystal was visualized by SHG microscopy. We have verified that flexoelectric polarization is widely observed in various liquid crystal cells, and not limited to IPS and FFS. Moreover, it was confirmed from the simulation of flexoelectric polarization that the SH image corresponds to flexoelectric polarization. In p-type IPS cells, we have found that flexoelectric polarization is induced by a defect line in the center of the electrode. However, it is necessary to improve the setup to verify this polarization. This SHG method should be advantageous in evaluating the performance of the industrial LCDs, which are susceptible to the design of devices and LC materials. In the future, we would like to establish an evaluation method for local flexoelectric coefficients applying this method.

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