Acousto-optical effect induced by ultrasound pulses in a nematic liquid-crystal film

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The reorientation of the director of a homeotropically aligned nematic liquid-crystal film subjected to ultrasound pulses is discussed. The relationship is investigated for the first time, to our knowledge, between the transmitted optical power and the high-frequency (approximately megahertz) pulsed ultrasound intensity. It is evident that there exists a power law governing the ultrasound-intensity-dependent optical transmission. However, the data indicate no existence of a characteristic threshold for the acousto-optical effect. Our results suggest that acoustic streaming, known to be responsible for acousto-optical effects in cw ultrasound experiments, should also play a similarly important role in the case involving a pulsed ultrasound field. © 2001 Optical Society of America

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1. Introduction

Previous attempts have been made to explain the phenomenon of acousto-optic effects in liquid crystals (LC's) based on several mechanisms proposed by both theoretical and experimental approaches. Some researchers suggest that, just like the Fréedericksz transition that is well known to occur in a LC film for an applied electric or magnetic field with a strength beyond a certain value, molecular reorientation under periodic compression results from a threshold effect caused by nonlinear stresses.[1,2] However, recent experiments revealed no characteristic thresholds and concluded that the apparent thresholds reported earlier may be attributed to the inferior sensitivity limit of the instruments.[3,4] According to a better accepted treatise that is supported by a number of experimental efforts, the acousto-optic effects of a LC are believed to be involved with the generation of the acoustic streaming arising from the gradients of the acoustic pressure within the nematic mesophase.[5–10]

Since the previous publication by the authors of the first visual observation of the acousto-optic effects induced by ultrasound pulses instead of by a continuous acoustic wave in the megahertz-frequency range,[11] there seems to have been only one study on acousto-optic effects concerning the interaction of an ultrasonic field with a pure nematic LC.[12] Extending our previous effort at merely the observation of birefringence patterns, we report in this paper what is, to our knowledge, the first quantitative observation of acousto-optic effects induced by ultrasound pulses in a nematic LC film.

2. Experiment

The LC cell is composed of a free-circular-edged layer of the homeotropically aligned nematic LC MBBA, i.e., *p*-methoxybenzylidene-*p*-*n*-butylaniline (Merck Ltd.) sandwiched between two pieces of cover glass treated with the surfactant DMOAP.[13] The sample has a diameter of 5 mm and a thickness of 200 μm, as determined by a Mylar spacer. The cell was examined by conoscopy before adoption for an experiment.

The 2-MHz or 0.5-μs ultrasound was generated from a Matec ultrasound pulse generator connected to both a triggering source and an oscilloscope. Peak-to-peak voltages of up to 460 V can be made with the instrument. The pulse width was fixed to be 2.5 μs, with a repetition rate ranging from 50 to 500 Hz. The LC cell was horizontally immersed in a temperature-controlled water bath and was 5 cm below a piezoelectric transducer with a diameter of 2.5 cm. The ultrasound pulses were incident at an angle of 55° from the normal onto the cell between two crossed linear polarizers. The plane of incidence of the ultrasound pulses was oriented at an angle of 45°

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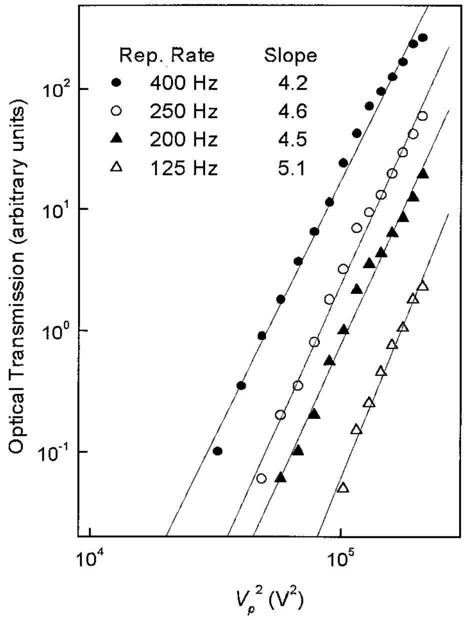


Fig. 1. Plot of optical transmission vs. peak-to-peak pulse voltage of the ultrasound.

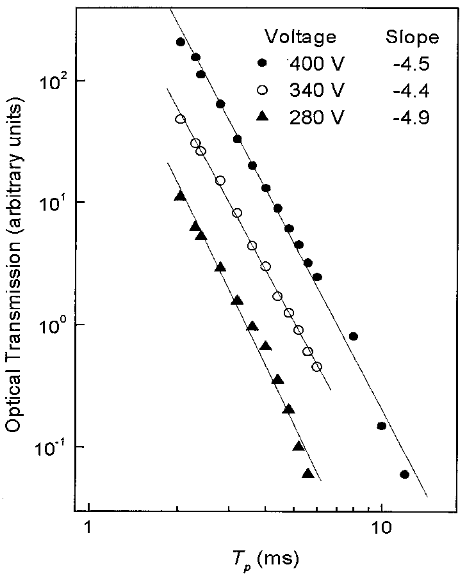


Fig. 2. Plot of optical transmission vs. repetition rate. The cell temperature is 22.4 °C.

with respect to the transmission axes of these polarizers. This configuration yields no detectable signals of a transmitted He–Ne laser (Uniphase 1125P) beam in the absence of the acoustic excitation as read with a dual-channel power meter (Newport 2835-C) interfaced with a computer. Although the domain fringe pattern induced by high-frequency ultrasound pulses changed for different incidence angles of the ultrasound, as reported in the authors' previous work,[11] a laser beam 0.8 mm in diameter was set to pass through the geometric center of the nematic sample throughout the experiment. The center also gives the central maximum of fringe brightness for an incidence angle of 55° of ultrasound pulses. See Fig. 2(h) in Ref. 11.

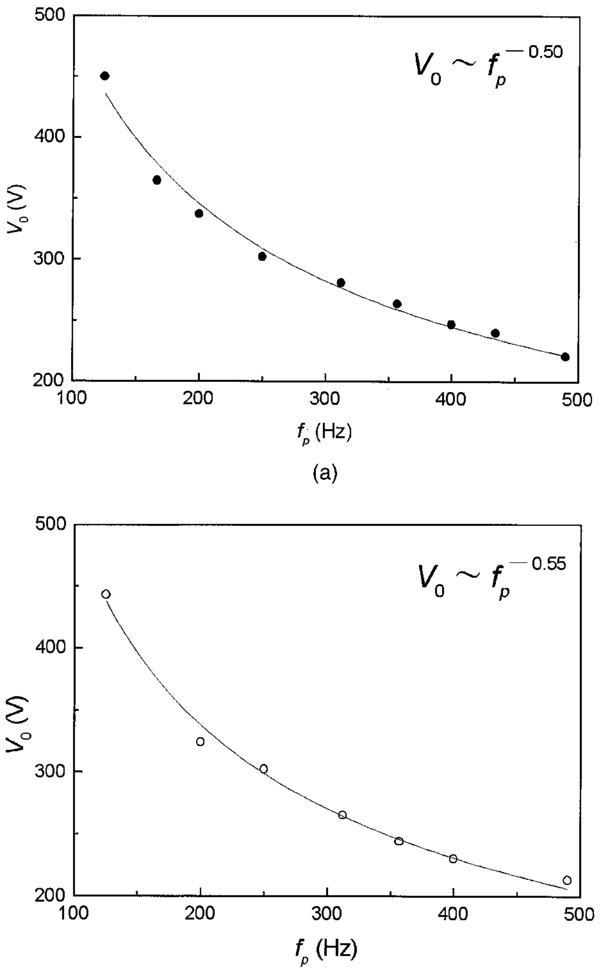
3. Results and Discussion

The power of the transmitted laser beam passing through the sample layer between crossed linear polarizers, I, was measured as a function of the repetition rate f_p and peak-to-peak pulse voltage V_p of the ultrasound for various cell temperatures. The control of water temperature with a temperature controller gives a desired equilibrium temperature of the cell.

The optical transmittance measured increases monotonously with the peak-to-peak pulse voltage V_p. Figure 1 shows a log-to-log plot of the transmitted light power against the square of V_p for a fixed sample temperature of 22.2 °C for various pulse repetition rates. Note that the amplitude of the incident ultrasound is proportional to V_p and the ultrasound intensity is therefore proportional to V_p^2. The straight lines shown in the figure were acquired by means of a linear least-squares analysis; they yield a power law for optical transmission induced by ultrasound pulses in a nematic LC film between crossed polarizers. Several models suggested previously for the physical mechanisms, responsible for the destabilizing torque under continuous compression of a nematic, show that the theoretical optical transmission is, as a rule, proportional to the fourth power of the acoustic intensity.[14] We can see from Fig. 1 that the acoustic intensity exponents deduced from fitting the experimental data are close to the theoretically ideal value of 4, as indicated in previous research based on acoustic streaming in a continuous ultrasonic beam.[5–10] Instead of use of a continuous ultrasonic beam to acoustoexcite the LC sample, a similar power law can be expected through accumulative interactions with the ultrasound pulses, as illustrated in Fig. 1 and suggested by the general trend that the exponent for a higher repetition rate is closer to the value of 4. It should be noted that the true relationship between these quantities is more complicated and that the diversity among the exponents is partially attributed to the complexity of the spatial inhomogeneity of the acoustic field and many other experimental conditions.[14]

Figure 2 reveals another power law for repetition period (T_p) independence. The results shed light on an ideally possible value of -4, giving the optical transmission as proportional to f_p^4. Consider the intensity of pulsed ultrasound J, which is defined as the average rate of energy flux through a unit area perpendicular to the acoustic propagation direction. Let E denote the ultrasound energy and ΔA the areal element. Then we obtain $J = E/\Delta t \Delta A \sim V_p^2/T_p = V_p^2 f_p$. The fourth-power-order dependence of the optical transmission on the ratio V_p^2/T_p implies that the optical transmission is, indeed, proportional to the fourth-power order of the ultrasound intensity.

We studied the peak-to-peak pulse voltage dependence of optical transmission for 11 different pulse



(a)

(b)

Fig. 3. Relationship between the peak-to-peak pulse voltage and the pulse repetition rate for an optical transmission of 2.5×10^{-3}. The cell temperatures are (a) 23.6 °C, (b) 23.5 °C.

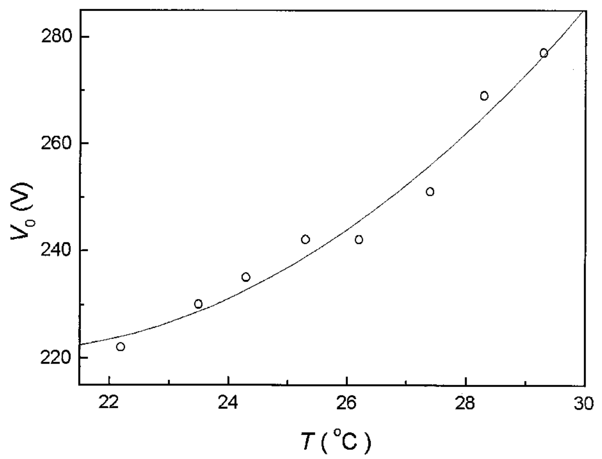


Fig. 4. Temperature dependence of the excitation voltage required for yielding an optical transmission of 2.5×10^{-3}. The pulse repetition rate of the ultrasound is 400 Hz.

repetition rates from 50 to 490.2 Hz. (As $f_p = 50$ Hz, no transmitted light can be detected even at the maximum excitation voltage of 460 V.) Our data reveal no evidence of a characteristic threshold. It is seen above that, to reach the same level of the optical transmission, a higher peak-to-peak voltage V_p is required for the lower range of pulse repetition rates. This is confirmed even for the least detectable transmission. Now define V_0 as the required voltage that leads to an optical transmission of 2.5×10^{-3}; i.e., a reliable, minimum value corresponding to the sensitivity limit of our measuring system. Figures 3(a) and 3(b) display a relationship between V_0 and f_p. The exponent deduced by means of a least-squares fit in both figures is very close to -0.5, indicating that V_0 is roughly inversely proportional to the square root of the repetition rate for a fixed optical transmission to be produced. This relationship is consistent with the basic concept that the optical transmission is dependent on the ultrasound intensity, given by the multiplication of f_p and the square of V_0.

An investigation of the optical transmission of the nematic sample at various temperatures between 20 and 30 °C, with the repetition rate kept fixed, demonstrates that the optical transmission decreases with increasing temperature for a constant peak-to-peak pulse voltage. This seems to imply that the propagation of ultrasound pulses in the high-frequency range in a denser LC matter is more significant than in a less dense sample. The results show a discrepancy with those of Letcher *et al.*, who carried out a similar study on 8CB under the excitation of a continuous ultrasonic wave.[8] The distinct behaviors may well be explained by the different regimes of acoustic intensity.

Figures 4 and 5 illustrate the acousto-optic effect induced by ultrasound pulses at various sample temperatures. As shown in Fig. 4, obtained for a constant pulse repetition rate at 400 Hz, the voltage V_0 increases with the elevation of temperature, indicating that a certain amount of reorientation of the LC direction axis requires that more ultrasound intensity be applied on the sample at a higher tempera-

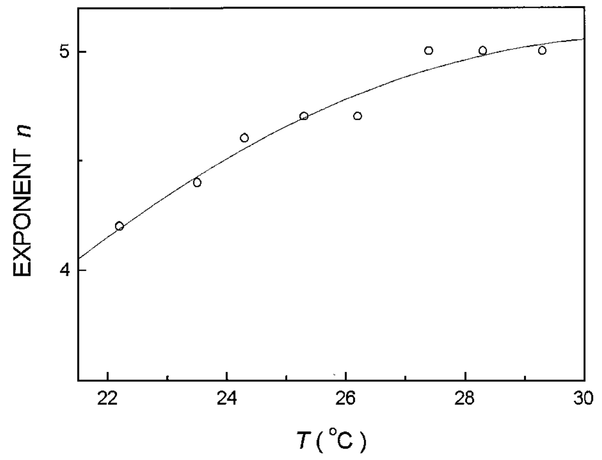


Fig. 5. Exponent n as a function of the cell temperature as in the relation $I \sim (V_p{}^2)^n$ for a fixed pulse repetition rate of 400 Hz.

ture. In Fig. 5 the exponent n in the relationship $I \sim (V_p{}^2)^n$ is plotted versus the temperature of the nematic LC film for a fixed pulse repetition rate of 400 Hz. It grows from 4 to 5 with increasing temperature in our case study. The figure indicates that the exponent increases with elevated temperature and seems to gradually approach a saturated value at higher temperatures in the nematic range.

4. Conclusion

In summary, we have investigated for the first time, to our knowledge, the acousto-optic effect in a free-circular-edged LC film induced by obliquely incident ultrasound pulses instead of the continuous acoustic wave in the high-frequency range. The measurements performed show a power-law dependence of the optical transmission on the ultrasound intensity. The exponent in the power law agrees with the theoretical value of 4 suggested by the mechanisms involving the acoustic streaming. Such a dependence has previously been observed in cw ultrasound experiments.[5–10] Our data also reveal no characteristic thresholds for acousto-optic effects, even in a pulsed ultrasonic field. All of the new results point toward the underlying mechanism—acoustic streaming—through accumulative acoustointeractions. Although practical applications in acoustic imaging with LC cells may still seem remote, the understanding of the acousto-optical effect is potentially useful for applications in transducers and optical measurement devices and in the development of new LC light valves and spatial light modulators.

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