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Ultrasound sensing using the acousto-optic effect in polymer dispersed liquid crystals

O. Trushkevych, T. J. R. Eriksson, S.N. Ramadas, S. Dixon, and R. S. Edwards

Department of Physics, University of Warwick, Coventry, CV4 7AL,

UK[a)]

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Acousto-optic effects are demonstrated in polymer dispersed liquid crystal (PDLC) films, showing promise for applications in ultrasound sensing. The PDLC films are used to image two displacement profiles of an air-coupled flexural transducers resonant modes at 295 kHz and 730 kHz. Results are confirmed using laser vibrometry. The regions on the transducers with the largest displacements are clearly imaged by the PDLC films, with the resolution agreeing well with laser vibrometry scanning. Imaging takes significantly less time than a scanning system (switching time of a few seconds, as compared to 8 hours for laser vibrometry). Heating effects are carefully monitored using thermal imaging, and are found not to be the main cause of PDLC clearing.

[a)]Electronic mail: r.s.edwards@warwick.ac.uk

The field of acoustics is of fundamental importance, allowing extraction of material properties such as elastic constants, flaw and crack detection in components and structures, and detection of phase transitions in single crystals[1,2]. Measurements can use a variety of different acoustic wavemodes, including bulk (longitudinal, shear) and surface acoustic waves (SAWs)[3]. Ultrasonics is in common use in non-destructive testing (NDT), where waves with frequencies typically between 50 kHz and 10 MHz are used for e.g. monitoring safety-critical components and structures such as rail tracks, pipelines and nuclear waste containers for the presence of defects. NDT is continually growing in importance as the existing infrastructure ages, and as new challenges arise. Incremental improvements to NDT are insufficient and novel disruptive technologies and approaches must be introduced[4].

The acousto-optic effect in liquid crystals (LCs)[5] shows promise for large area ultrasound sensing and visualisation without the need for scanning[6–10], offering the potential to bring the step-change NDT requires. Ultrasound sensors using a thick layer of aligned nematic LC for detecting longitudinal waves have been developed for holography and medical imaging (acoustography,[11–13]). However, they are optimised for use at a single frequency (3.3 MHz) and can only be used at oblique incidence. They also have large thickness (> 200 μm), which is generally undesirable in LC devices as it leads to high cost and slow operation due to backflows during relaxation in the LC layer[10].

Recently, acoustic clearing (becoming transparent under the influence of an acoustic field) in polymer dispersed LC (PDLC) has been reported using SAWs at 18.74 MHz[14,15]. PDLCs are thin (~ 20 μm) films in which LC droplets are held in a polymer matrix[16,17], primarily using nematic LCs[5]. These are birefringent fluids with ordinary and extraordinary refractive indexes n_o and n_e. The refractive index of the polymer matrix is usually chosen to be the same as that of the LC in its aligned state, n_o. Without application of an external field the direction of alignment of the LC in these droplets varies randomly from droplet to droplet due to the way the films are produced (no preferential direction is set), and hence the effective refractive index of the droplets has random values between n_o and n_e, producing strong scattering of light and a 'milky' appearance. The LC in the droplets can be aligned if an external field is applied, at which point the PDLC film becomes optically homogeneous and transparent. Such clearing using acoustic waves is highly promising in a variety of applications, including visualisation of acoustic fields for ultrasonic imaging.

For longitudinal acoustic (pressure) waves in aligned LC layers with thickness d, three

wavelength regimes (short ($\lambda \ll d$), long ($\lambda \gg d$) and intermediate ($\lambda \sim d$)) exist, depending on the viscous wavelength[6],

$$\lambda = 2\sqrt{\frac{\pi\eta}{f}} \tag{1}$$

where f is acoustic frequency and η is the kinematic viscosity of the LC. Within the long and short wavelength regimes the acousto-optic effect does not depend on the frequency of the exciting ultrasound, as long as this is higher than the relaxation of the LC layer[6]. In addition, the reorientation angle of the LC depends on the acoustic intensity.

It is expected that PDLC films will behave similarly. The dependence on acoustic intensity will lead to a "grey-scale" response to the acoustic field, and the lack of frequency dependence in the short and long wavelength regimes will give a broadband sensor. For PDLC, the LC droplet diameter δ takes the role of the LC layer thickness d. The work in[14,18] uses 70%wt of LC E7 in an optically curable monomer NOA65, with an expected droplet size of $\geqslant 1$ μm[19]. For the reported frequency of ultrasound, 18.74 MHz, the viscous wavelength is about 5 μm, which is of the same order of magnitude as the droplet size, and hence the previous work is in the intermediate regime.

This paper aims to demonstrate the practical importance of PDLC films for ultrasound sensing and their promise for applications. We work within the long wavelength regime in order to operate at typical ultrasonic frequencies used in NDT, and to measure in the regime which is best understood in LCs, allowing prediction of the expected acousto-optic effect. Such a comparison cannot be direct, however, as in PDLC new considerations relating to surface effects, anchoring strength, droplet size, shape and distribution are of importance. The chosen demonstration application is that of ultrasonic transducer characterisation. A type of flexural transducer, consisting of a piezoelectric element rigidly bonded to the back of of a metal cap, was used. The transducers operate at a resonant vibration mode of the cap (plate vibration[20]), and are routinely used for air-coupled ultrasonics [21]. Their vibrational behaviour at resonance consists of areas with large displacement along with nodal points and/or lines (where there is no displacement), with regions of high displacement acting as sources of longitudinal waves. Laser scanning measurements, currently used to understand the resonance mode displacement profiles, use a costly measurement system and can take up to 8 hours to produce one image for a single resonance.

PDLC films were produced using LC E7 and UV curable Norland adhesive NOA74 at LC concentrations of approximately 76%, with NOA74 chosen due to its low viscosity and good
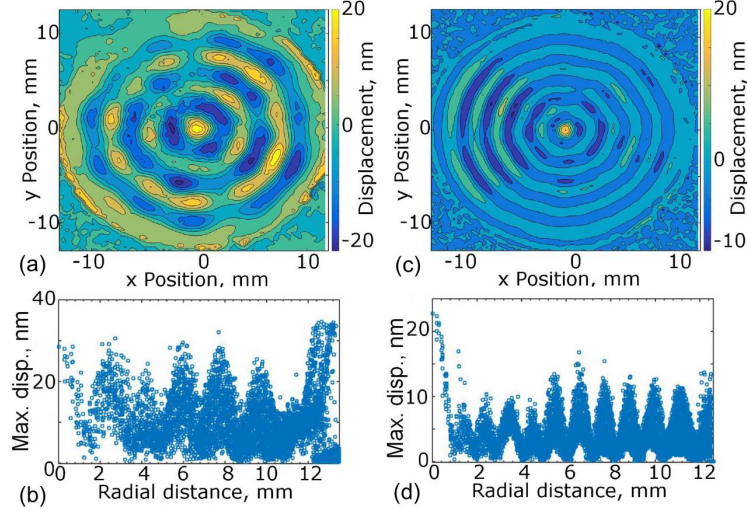
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FIG. 1. Laser vibrometry results on flexural transducer with varnish layer at (a) & (b) mode 6:0 at 300 kHz. (c) & (d) 11:0 mode at 730 kHz. The bottom images show the amplitudes of vibration at the scanned points in a radial direction. Displacements are in nm.
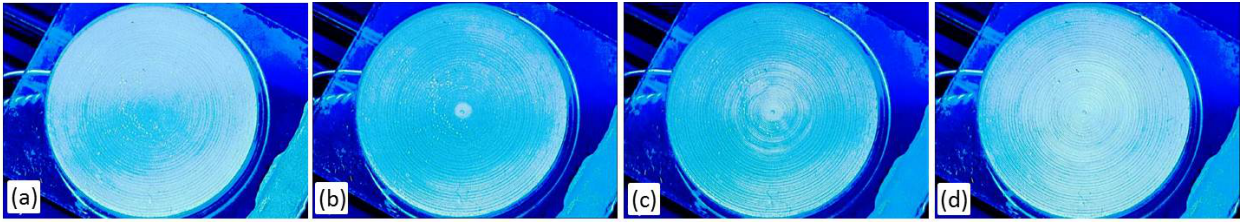

FIG. 2. PDLC film on top of a flexural transducer, 11:0 mode at 730 kHz, (a)-(d) cap clearing on increasing power/time. The machining marks on the cap are visible. The circular cap (light circle) is 25 mm in diameter.

mixing with E7. The resulting PDLC droplet size was less than 3 μm, confirmed by optical microscopy. The PDLC film thickness was set to 100 μm using spacers to obtain optimal optical contrast. The films were placed on the front faces of a set of flexural transducers (25 mm diameter aluminium caps[21]). Two resonant modes were chosen, one a 6:0 axi-symmetric mode, with frequency close to 300 kHz ($\lambda = 41$ μm) depending on the transducer, and one corresponding to the 11:0 axi-symmetric mode, with a frequency around 730 kHz ($\lambda = 26$ μm). As the viscous wavelength is much larger than the droplet size of PDLC, operation was in the intermediate to long wavelength regime. The optical contrast between scattering and transparent states was optimised for some caps by placing a thin layer of UV-

curable varnish (used in the cosmetics industry) underneath the PDLC film. The excitation of the transducers was done using a continuous sine wave generated by a function generator and a 25W RF power amplifier. The PDLC films were covered by glass slides to confine the PDLC and improve the coupling of ultrasound into the PDLC film.

The central frequency for each mode was determined separately for each transducer before and after placing the PDLC film and cover slide (with and without the contrast enhancing layer) using impedance spectroscopy. The PDLC films and contrast enhancing layers did not alter the cap vibration significantly. The mode number and structure were confirmed by laser vibrometry on the transducer surface (using a Polytec vibrometer and a 2D scanning stage, measured without the PDLC film), with the full scans, of 8 hour duration, shown in figure 1. The colour scale shows the surface displacement, and (c) and (d) show the amplitudes across the centre scan line. For the 6:0 mode, the area of the central (strongest) displacement of the cap is 3 ± 0.2 mm in diameter, and the concentric nodal lines are spaced at $\approx 2.4 \pm 0.1$ mm apart. For the 11:0 mode, the area of the central (strongest) displacement of the cap is 1.8 ± 0.2 mm in diameter, and the concentric nodal lines are spaced at $\approx 1.1 \pm 0.1$ mm apart. The rings have uneven amplitude and are modulated, due to tiny variations in the shape and thickness profile of the cap.

When the power supplied to the transducer exceeded 2 W, a characteristic clearing pattern for each mode appeared, with images of the clearing as time progressed shown in figure 2. The clearing pattern coincided with the areas of maximum displacement as measured using laser vibrometry, with the clearing starting to appear at the central region with the largest displacement (figure 2(b)). As the power to the vibrating cap was increased and the amplitude of vibration became larger, the PDLC films cleared in a series of concentric rings (figure 2(c)). The relaxation time associated with these patterns was 1-2 s. As ultrasonic generation is accompanied by heating, prolonged operating times and high powers led to the PDLC film melting and becoming fully transparent. The relaxation time then became of the order of 30-60 s, confirming clearing due to heating.

The PDLC film reproduces the modulation of the displacement intensity in the rings relatively accurately (figure 2(c)). Figure 3 shows the comparison when a contrasting background is used, removing the appearance of the cap machining marks. Mode 6:0 is shown in (a) and (b), with the larger central clearing area much clearer in the contrast image. Here the clearing in the central area is 3mm in diameter, closely correlating with the laser
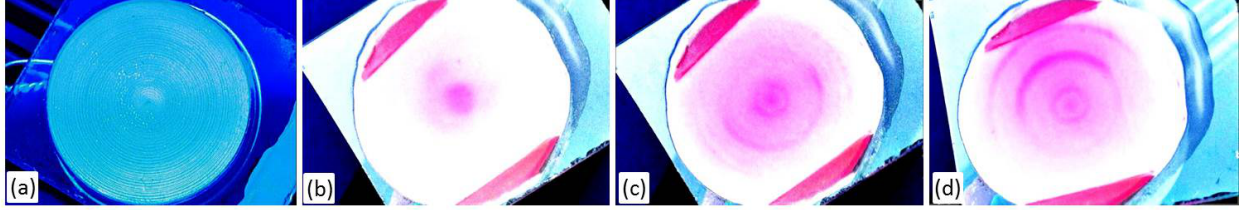
FIG. 3. PDLC films on top of vibrating caps placed directly and with enhanced contrast using varnish layer; (a) mode 6:0 at 320 kHz, (b) mode 6:0 at 296 kHz, (c)11:0 mode at 730 kHz, (d) same mode 11:0, off resonance, 690 kHz - with different amplitude distribution within the peaks.

vibrometry result. Figure 3(c) and (d) show the 11:0 mode, at resonance and at a side resonance, giving different amplitude distribution between the peaks. The clearing in the central area is ≈1.8 mm in diameter, within very good agreement with laser vibrometry. In addition, concentric rings ∼ 0.7 mm thick are visible. This correlates very well with the ring thickness measured by laser vibrometry. These results suggest that the resolution of PDLC films in relation to ultrasound waves is excellent.

Piezoelectric generation of ultrasound is inevitably accompanied by heating of transducers and this demands careful consideration. Heating effects were closely monitored using a "Titanium" thermal imaging camera from Cedip/Flir, with 25 mK sensitivity, with images during operation shown in figure 4. Measurements without cover glass, to facilitate measurement of the actual film temperature, showed that the PDLC films have a clearing temperature of 52°C. This is lower than that of pure E7, due to the residual dissolution of monomer and LC in each other[17]. In the acousto-optic experiments described in this paper cover glass is necessary for efficient transfer of ultrasound into the PDLC. However, the glass acts as an additional convection-cooled heat sink, and the temperature of the PDLC film is slightly higher than measured at the surface of the cover glass.

Figure 4 shows thermal images during operation in the 11:0 mode. For operation at 2-3 W, the PDLC film clears in the pattern shown in figure 3(c), while the temperature distribution is clearly radial (figure 4(a)). When the power was increased further, or the cap left to operate for a long time, the PDLC started to melt, manifested by radial clearing matching the heating profile in figure 4(b) and (c). This clearing takes significantly longer to relax back into the opaque state, of the order of 30-60 s.

This heating effect does have some advantages. The initial switch on time for the acousto-
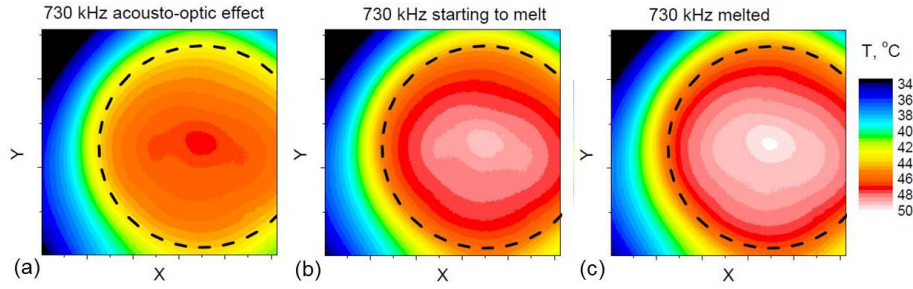
FIG. 4. Thermal maps of the PDLC film with cover glass, placed on top of a cap, vibrating at 730 MHz. The dashed lines indicate cap edges.

optic effect was 30-60 s, depending on the power used, during which the temperature of the cap and the PDLC film increased. After initial warming the switching and relaxation took 1-2 s. The need to raise the temperature of the sample to observe the acousto-optic effect is due to the fact that, as the PDLC temperature is brought close to the temperature of the transition into the isotropic phase, the LC can change optical properties significantly in response to small disturbances, and sensitivity is dramatically increased.

The long wavelength regime acousto-optic effect in PDLC films has been used to visualise vibration of plates (flexural transducers) for two modes; the 6:0 and 11:0 axi-symmetric modes at 300 kHz and 730 kHz respectively, at power levels of 2-3 W. The PDLC films produced greyscale images of cap displacement amplitude, with lateral resolution better than 0.7 mm, with switching times as short as 1 s after the initial period of pre-heating. Heating can improve switching times due to the increased LC sensitivity near the temperature of transition into the isotropic phase. The effect shows promise for ultrasound sensing applications for transducer characterisation, NDT, and medical applications.

ACKNOWLEDGEMENTS

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