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MAPPING OF ACOUSTICAL FIELDS WITH LIQUID CRYSTALS

J. LEBRUN and S. CANDAU

Laboratoire d’Acoustique Moléculaire (E.R.A. au C.N.R.S.)
Université Louis-Pasteur, 4, rue Blaise-Pascal, Strasbourg, France

S. V. LETCHER

University of Rhode Island, Department of Physics, Kingston, R.I. 02881, U.S.A.

Résumé. — La forme de champs acoustiques a été déterminée au moyen de détecteurs formés par des matrices de cristaux liquides nématiques. L’intensité lumineuse transmise par les détecteurs placés entre nicols croisés a été étudiée en fonction de l’intensité acoustique et de la température.

Abstract. — Nematic liquid crystal detectors divided into matrices of arrays have been used for mapping of acoustical fields. The intensity of the light transmitted by such detectors placed between crossed polarizers has been investigated as a function of the acoustical intensity and the temperature.

Introduction. — Acousto-optical effects of homeotropically aligned nematic liquid crystal cells have been studied both experimentally [1-8] and theoretically [6-10].

The acoustically induced birefringence is generally attributed to the tilt of the molecules caused by the acoustic streaming parallel [6] or perpendicular [7-8] to the initial molecular orientation. Because of the hydrodynamic nature of the orientational effect, it is not possible to obtain clear ultrasonic images by using simple nematic layers sandwiched between two substrates. It has been suggested earlier [6] that the spatial resolution could be improved by dividing the nematic cell into a matrix of liquid crystal arrays separated by thin strip spacers which would prevent acoustic streaming between arrays. Such a display has been recently investigated by Nagaï and Iizuka [11-12] who used a cell divided into a square mesh pattern by strips of photo resist film. This subdivision of the detector improved considerably the image definition.

In this paper we present an investigation on the mapping of acoustical fields by a liquid crystal detector divided into a matrix of arrays. We have also investigated the properties of such detectors paying special attention to the temperature and acoustical power dependence of the optical signal.

1. Experiment. — The experimental arrangement used is similar to that described in an earlier paper [13]. The p-n-pentyl p’-cyanobiphenyl (PCB) sample was purchased from BDH Co and used without further purification. The liquid crystal cell consisted of a thin layer of PCB sandwiched between two transparent glass plates (9 cm sq, 100 μm thick).

The subdivision of the cell was achieved by means of a thin grating (50 μm) of copper made by a photo-etching process.

The shape and the mesh sizes of the gratings used in our experiments are shown in figure 1. Homeotropic texture was obtained by applying a thin layer of cetyl trimethyl ammonium bromide (CTAB) to the glass surfaces.

![Photos of gratings](image)

FIG. 1. — Photos of gratings. Magnification 1 : a) Mesh size 1 mm ; b) Mesh size 1.5 mm.

The cell is placed in a water bath which serves as a thermal control and as the medium for propagating the ultrasound. A He-Ne laser was used as a monochromatic light source, except for the mapping experiments when a white light source was used. The cell was placed between crossed polarizers. The light transmitted through a selected area of the cell was focused on a photodiode or projected on a screen.

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The ceramic transducer driven at a frequency 2.64 MHz was mounted vertically at a variable distance from the detector. The acoustical incidence angle could be varied from 5° to 50°. The voltage applied to the transducer is read directly on an oscilloscope and this is calibrated using a torsion pendulum as described earlier [6] to give the acoustic intensity in the water at the position of the detector. The temperature can be held constant to within ± 0.05 °C.

2. Results and discussion. — 2.1 Mapping of an acoustical field. — Figure 2 shows the variation in the optical transmission as a function of the acoustical incidence angle. The transmission coefficient $T_\perp$ is defined as the ratio $(J_\perp - J_{\perp o})/J_{\perp o}$ where $J_\perp$ stands for the transmitted optical intensity under acoustic irradiation and $J_{\perp o}$ is the intensity transmitted in the absence of ultrasound. The angular dependence of $T_\perp$ is complex and exhibits a rather broad maximum between 20° and 30°. This behaviour is quite different from that observed when the substrates of the cell have a thickness much larger than the acoustical wavelength, in which case, only narrow ranges of angle of incidence of the ultrasonic beam provide a strong optical signal [13]. All the following experiments have been performed at an incidence angle of 25°.

Figure 3a shows the optical signal obtained for a distance of the detector corresponding to the beginning of the Fraunhofer region (far field). The observed pattern consists of a central spot and an outer ring. This pattern clearly reproduces the mapping of the

![Figure 3a](image-url)

**FIG. 3.** Optical signals acoustically induced: a) Cell with grating of mesh size 1 mm. White light. Acoustical intensity : 4 mW/cm². $S = 1$. b) Uniform cell of thickness 100 μm. $\lambda = 6328$ Å. Acoustical intensity : 9 mW/cm². $S = 1$. c) Cell containing a suspension of aluminium particles in benzene. Thickness of the cell : 265 μm. White light. Acoustical intensity : 25 mW/cm². $S = 1$. 

![Figure 2](image-url)

**FIG. 2.** Transmission coefficient versus acoustical incidence angle. Mesh size of the grating : 1 mm. Acoustical intensity : 2.4 mW/cm². The coefficient $T_\perp$ has been integrated over the whole area irradiated by the acoustic beam.
acoustic field since the deflection of the molecules of liquid crystal is proportional to the acoustic intensity. The central spot can be attributed to the main acoustic beam and the outer ring to the first secondary maximum. The dark ring is related to the first minimum of the diffraction pattern. Similar patterns are obtained with uniformly filled nematic cells. However, the comparison between photographs reproduced in figure 3a and 3b, respectively, illustrates the improvement in spatial resolution due to the use of gratings. In particular, the dark ring observed in figure 3b is blurred and the transmitted optical signal is modulated by vertical striations. This last feature, which is observed only for cells where the substrates are much thicker than the acoustic wavelength, has been attributed to a conversion of the longitudinal acoustic energy into surfacelike and guided modes that propagate away from the sound source [13].

According to the model of Miyano and Shen [8] interaction of these modes causes periodic rotational motion which in turn produces striations normal to the propagation direction. We have been able to observe this local streaming by investigating thin cells containing suspensions of aluminium particles in benzene. One obtains indeed patterns with periodic striations as shown in figure 3c.

From figure 3a is is possible to make a mapping of the acoustic field by measuring the optical signal transmitted by each individual cell. We have reported in figure 4 the spatial distribution of the transmission coefficient across a diameter of the cross-section of the acoustic beam for different acoustical intensities. When increasing the acoustical intensity the heights of the observed peaks of transmitted intensity increase but their positions do not change. For even higher intensities one observes a decrease of the intensity of the central spot. This effect can be attributed to the variation of the interference conditions in the birefringent layer as the molecular axes rotate increasingly, leading to a series of maxima and minima in the transmitted intensity.

![Figure 4](image_url)

**Fig. 4.** — Spatial distribution of the transmission coefficient. Mesh size : 1.5 mm. Acoustical intensity : ○ 0.5 mW/cm², ● 1.6 mW/cm², ▲ 3.4 mW/cm².

![Figure 5](image_url)

**Fig. 5.** — Radius of the ring of the optical signal as a function of distance. The line is the radius of the first minimum of the Fraunhofer diffraction pattern.

Figure 5 shows the variation of the radius of the dark ring observed either in figure 3a or in figure 3b as a function of the dimensionless parameter $S = z/(\alpha^2/\lambda)$ ($z$, distance between the transducer and the detector, $\alpha$ radius of the transducer, $\lambda$ acoustical wavelength). Shown for comparison is the radius of the first minimum of the Fraunhofer diffraction pattern [14]. One observes a good agreement between the measured ring radii and the Fraunhofer values even, surprisingly, for data obtained at the end of the Fresnel region.
2.2 Influence of the Acoustic Intensity and the Temperature on the Transmission Coefficient.

The intensity transmitted through a nematic layer of thickness $2h$ is given by:

$$J_\perp \propto \sin^2 \left[ \frac{1}{2} \int_{-h}^{h} (2 II/\lambda_\parallel) (n_\parallel - n_\perp) \sin^2 \theta \, dz \right]$$

where $\lambda_\parallel$ is the wavelength of light, $n_\parallel$ and $n_\perp$ are indices of refraction of light polarized parallel and perpendicular to the director, respectively, and $\theta$ is the tilt angle of the director from its initial orientation. Different theories have been developed to describe the acousto-optical effects in nematic liquid crystals [6-10]. In all the mechanisms proposed, the tilt angle $\theta$ is found to be proportional to the acoustic intensity $I$. As a consequence the transmitted optical intensity $J_\perp$ must exhibit an $I^4$ dependence. However a complication arises from the fact that the cells exhibit a stray birefringence in the absence of ultrasound irradiation. Nagai et al. [6] have accounted for this birefringence by assuming an initial average tilt angle which is superimposed on the acoustically induced deflection. This leads to an $I^2$ dependence of the transmission coefficient $T_\perp$. In the case of cells with gratings the stray birefringence arises mainly from misalignment at the near boundaries between the strips and the liquid crystal. Then one would expect a superposition of the transmitted intensities $J_\perp$ and $J_\perp^0$. As a consequence $T_\perp \propto I^4$. In figure 6, we have given a Log-Log plot of $T_\perp$ versus $U^2$ which is proportional to $I$ ($U$ voltage across the transducer). In the range of small acoustical intensities, one obtains a straight line with a slope of about 3.8, that is quite close to the expected value.

The temperature dependence of $T_\perp$ is also of interest in order to understand the mechanism responsible for the acousto-optical effect. For instance, a uniform streaming inside each individual cell of the detector, parallel to the initial orientation of the director, would lead to a variation of $T_\perp$ like the fourth power of the acoustic attenuation $\alpha$ [6] which itself is very sensitive to temperature [15]. However it is well known that acoustic streaming arises also at fluid-solid interface boundaries [16]. Such a streaming which is independent of the acoustical attenuation is presumably significant for cells with gratings. This effect would tend to reduce the dependence of $T_\perp$ with the acoustic attenuation. This is as observed experimentally since the transmission coefficient varies approximately as $\alpha^2$, as shown in figure 7.

Fig. 6. — Log-Log plot of $T_\perp$ versus $U^2$ for a cell of mesh size 1 mm. The different sets of data correspond to measurements over different areas of the detector: + 1 individual cell on the central spot; • 1 individual cell on the outer ring; ⊕ area of the outer ring.

Fig. 7. — Log-Log plot of $T_\perp$ versus the acoustical attenuation per wavelength $\alpha_\lambda$. The value of $\alpha_\lambda$ are taken from ref. [15]. Acoustical intensity : 0.1 mW/cm², Mesh size : 1 mm.
34 °C. The results obtained are of practical importance since they show that it is possible to improve significantly the sensitivity of the set-up by a moderate increase of the temperature.

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