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Mechanical vibration of freely suspended ferroelectric liquid-crystal film excited by sound and electric field

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A study of the mechanical vibrations of a freely suspended (FS) ferroelectric liquid-crystal film has been carried out. Upon excitations by sound irradiation and also by electric-field application, the mechanical vibration of the FS film of the ferroelectric liquid crystal is effectively excited. In the frequency dependence, resonance vibrations are observed for both excitations and the resonance frequencies, and light reflection patterns are found to be different for both excitations, suggesting the different oscillating modes of the FS film for both excitations. In electric-field excitation, the vibration mode, which is consistent with the molecular model of the origin of the vibration due to the reorientation of P_s by $\mathbf{P_s} \cdot \mathbf{E}$ torque is found. In addition, the application of the FS film of the ferroelectric liquid crystal as sensitive acoustic sensors is proposed. © *1997 American Institute of Physics.* [S0021-8979(97)04018-8]

I. INTRODUCTION

Freely suspended (FS) film of ferroelectric liquid crystal has recently attracted much attention as a thin two-dimensional liquid-crystal system,[1–5] because it has a layered structure and its thickness can be varied from only two layers to several hundred layers. Almost all of the articles on FS film of ferroelectric liquid crystal are concerned with peculiar molecular alignments and phase transitions caused by a surface interaction or a size effect.

The FS film is extremely thin, so that it is easily deformed by the change of the pressure of air.[6] It should also be mentioned that this ultrathin FS film is stable for more than months. Therefore, the FS film is interesting as an acoustic membrane. In addition, excitation of mechanical vibration by a piezoelectric effect upon voltage application is expected in the FS ferroelectric liquid-crystal film.

In this paper, the unique mechanical vibration excited by sound and alternating electric field was investigated.

II. EXPERIMENT

Ferroelectric liquid crystal (Chisso, CS-1029) is used in this study. This sample has chiral smectic C phase between -18 and 72.9 °C, and its spontaneous polarization P_s is 41.3 nC/cm^2 at 25 °C.

The FS film was prepared across two metal blades. Two polyethyleneterephthalate (PET) sheets were set between the blades. The sample was loaded in the square-free area surrounded by the blades and PET sheets at the temperature of the SmA phase. One of the PET sheets can slide along the blade to expand the FS film. These blades were also used as electrodes to apply an electric field to the FS film. The distance between the electrodes was 3 mm and the expanded square area was 9 mm^2.

The freely suspended film was settled at a height of 80 mm above an optical bench as shown in Fig. 1. An electrodynamic cone speaker was used as a sound source of the sine wave. The sound source was settled at 270 mm above the FS film. A change of direction of the reflected linearly polarized He–Ne laser light, whose electric vector is oriented in the horizontal, was used to detect the vibration of the film. The beam impinged on the FS film with an incident angle of 45° and its reflection was detected by a photodiode located behind a pinhole of 0.5 mm in diameter. The pinhole was settled at about 500 mm from the FS film.

An unidirectional moving coil dynamic microphone (Audio-Technica Corp.) was used to detect the applied sound wave, and the applied sound pressure was measured by a precision sound level meter (Japan Electronic Instruments Co., Ltd.).

III. RESULTS AND DISCUSSION

The mechanical vibration of the FS film is easily excited by sound. This mechanical vibration induces a bend of the FS film, which results in the oscillating change of the direction of the reflection light. That is, the reflection light is varied oscillatingly in its propagating direction and intensity, depending on the sound frequency and sound pressure. As shown in the inset of Fig. 2, upon sound irradiation, the reflection light intensity observed by a photodiode changes corresponding to the wave form of sound. Figure 2 shows a

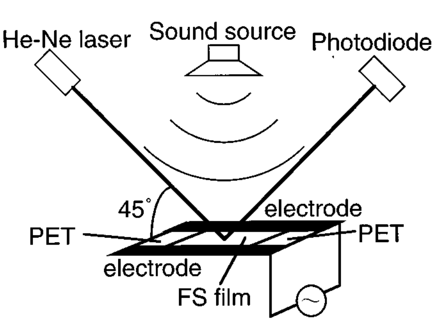

FIG. 1. Schema of experimental setup.

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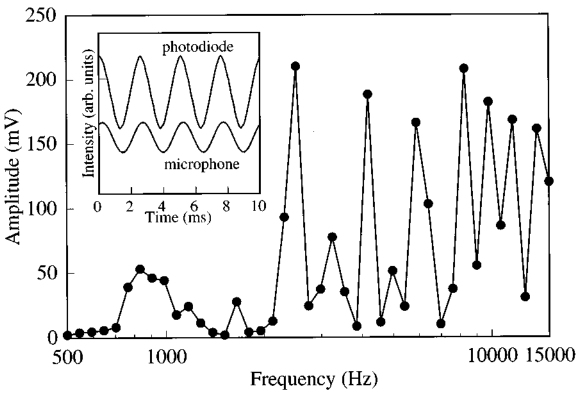

FIG. 2. Sound-frequency dependencies of the amplitude of the signal detected by the photodiode. The sound pressure is 65 dB. The inset shows the signals detected by the photodiode and the microphone.

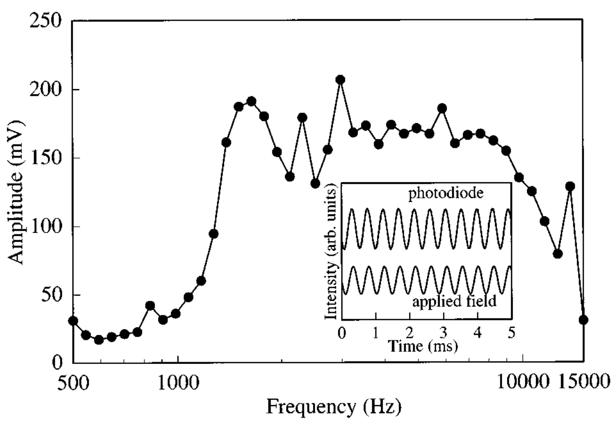

FIG. 3. Applied-field-frequency dependencies of the amplitude of the signal detected by the photodiode. The applied field is ± 500 V/cm. The inset shows the signal detected by the photodiode and the applied field.

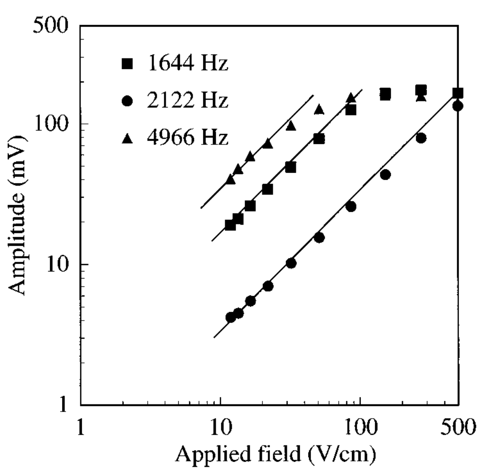

FIG. 4. Applied-field dependencies of the amplitude of the signal detected by the photodiode.

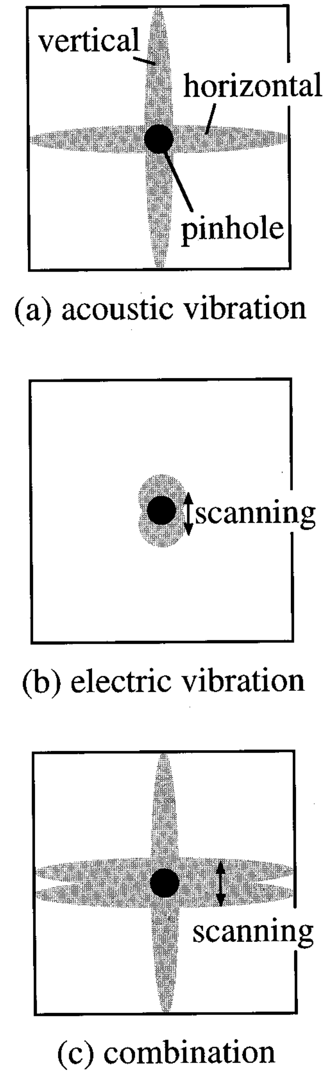

FIG. 5. Illuminated pattern observed on the pinhole plate: (a) during the acoustic excitation, (b) during the electric excitation, and (c) both combined excitation.

sound frequency dependence of the amplitude of the signal detected by the photodiode. It should be noted in Fig. 2 that there are several resonant frequencies at which the amplitude is enhanced.

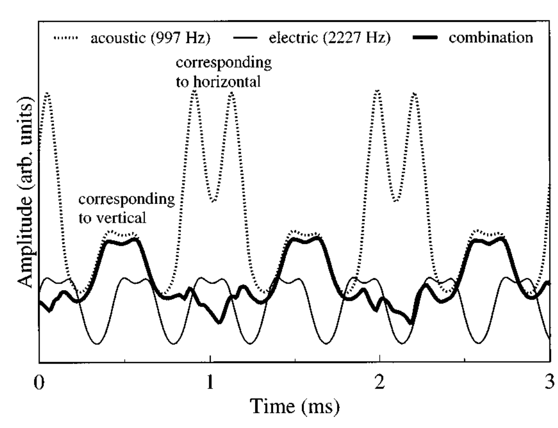

FIG. 6. The response signals detected by the photodiode during the acoustic, electric, and both combined excitation, respectively.

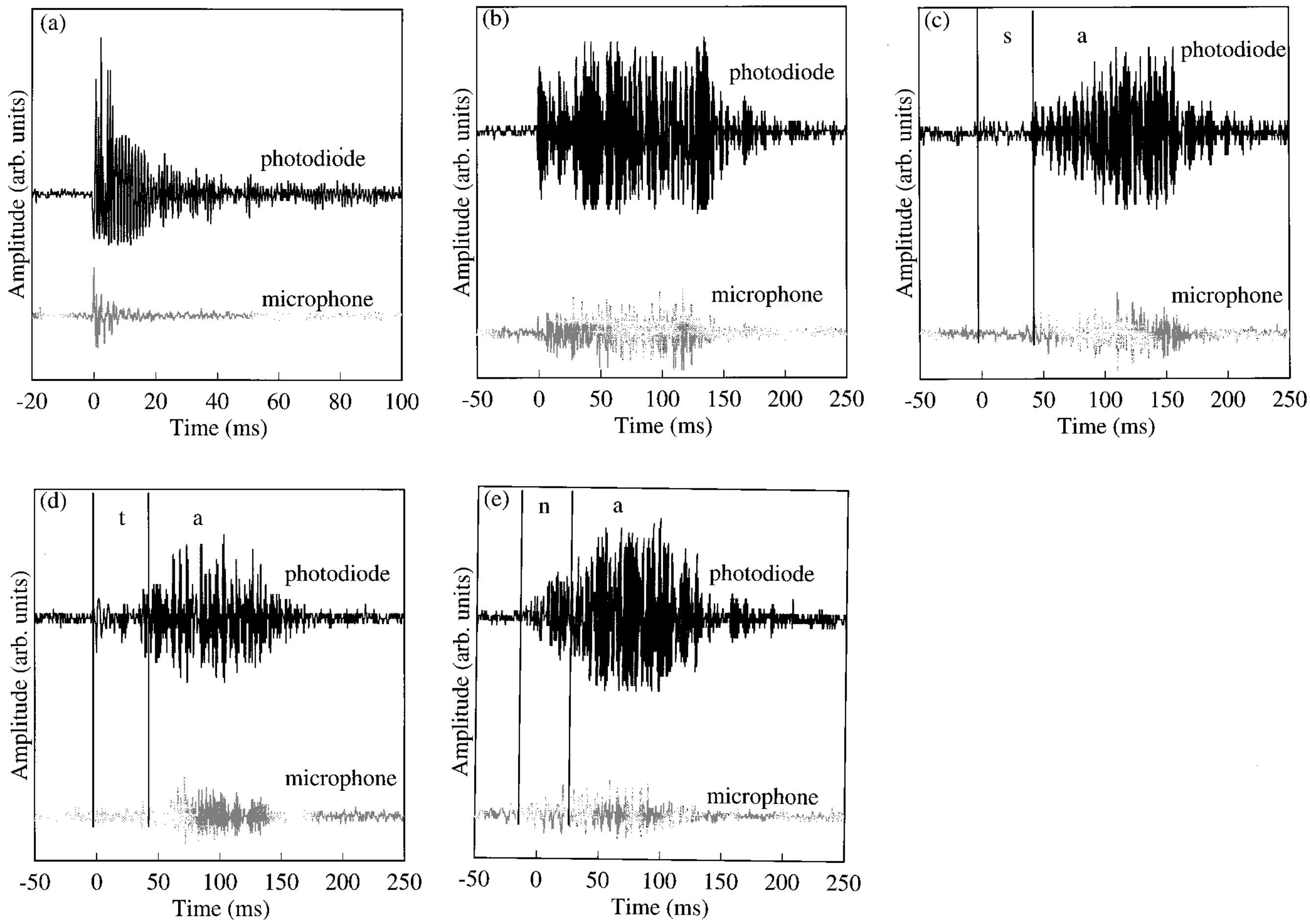

FIG. 7. The response signals excited by several sounds: (a) to a hand clap and (b) to a man's voice /a/, (c) /sa/, (d) /ta/, and (e) /na/, respectively.

An alternating electric field, which is applied parallel to the FS film of the ferroelectric liquid crystal, can also induce the mechanical vibration of the FS film, as shown in the inset of Fig. 3. Figure 3 shows field frequency dependencies of the amplitude of the signal detected by the photodiode. As evident in Fig. 3, the resonance of the mechanical vibration was also observed. However, it should be noted that there is a difference in the resonant frequencies of the sound induced vibrations shown in Fig. 2 and the field induced vibrations shown in Fig. 3. That is, resonant vibration modes are different between the acoustically excited and the electrically excited vibrations.

Figure 4 shows field dependencies of the amplitude of the signal detected by the photodiode at three different frequencies. The amplitude is proportional to the applied field except for saturation. The molecules are vibrated in the direction of the molecular tilt by the alternating field applied perpendicular to the molecular tilt. The microscopic molecular vibration due to the reorientation of spontaneous polarization P_S by the $\mathbf{P_S} \cdot \mathbf{E}$ torque upon application of field $\mathbf{E}$ may induce the macroscopic mechanical vibration of the FS film of the ferroelectric liquid crystal. The saturation means that the reflection light was effectively detected by the photodiode without loss.

The illuminated patterns of the He–Ne laser on the pinhole plate located at the position of the detector were observed under the excitations by the sound and electric field. The reflection laser beam from the vibrating FS film excited by sound irradiation draws a cross on the pinhole plate, as shown in Fig. 5(a). That is, the reflection pattern is composed of two parts, horizontal and vertical components. Here, horizontal means that it is parallel to the PET sheets at the edges of the FS film. On the other hand, the vibration due to the alternating electric field induce a vertical scanning of the beam as shown in Fig. 5(b). This suggests that the wave vector of the vibration of the FS film is perpendicular to the PET and, therefore, parallel to the electrodes. That is, the wave vector should be perpendicular to the direction of electric field. This is consistent with the interpretation of the microscopic model of the origin of the vibration. The direction of the molecular tilt is perpendicular to the dipole moment of the molecule contributing to P_S. Therefore, the reversal of P_S should accompany the reorientation of the molecular tilt perpendicular to the field, resulting in the drive of collective oscillating molecular reorientation in the direction perpendicular to the field, in accordance with the light reflection pattern.

It should also be mentioned that the simultaneous excitation by both sound irradiation and electric-field application induces a unique reflection pattern on the pinhole plate as shown in Fig. 5(c). Corresponding to this pattern, the interference of the acoustic and field excitations indicate the reflection intensity modulation as shown in Fig. 6.

The fact that the FS film can be easily excited by sound indicates that it can be utilized as a microphone and an artificial eardrum. Figure 7 shows the response of several sounds. The vibration of the FS film is detected by the same method already mentioned and the signal from the photodiode is compared with a signal from a usual moving coil dynamic microphone. Figures 7(a), 7(b), 7(c), 7(d), and 7(e) show the detected response signals by the FS film of the ferroelectric liquid crystal to a hand clap and to four Japanese syllables spoken by a man /a/, /sa/, /ta/, and /na/, respectively. Every sound is detected satisfactorily. It should also be mentioned that three consonants /s/, /t/, and /n/ can be also distinguished in the signals satisfactorily.[7]

The lifetime of the FS film placed in the laboratory room was found to be more than months at room temperature. The frequency property shown in Figs. 2 and 3 can be adjusted more suitably by changing the size and shape of the FS film or by attaching a proper cavity, which has a suitable resonant frequency to the film suspender. Hence, the FS film of the ferroelectric liquid crystal can be more improved as the sensitive acoustic sensor in the future.

IV. SUMMARY

The present experimental study on the FS film of the ferroelectric liquid crystal can be summarized as follows:

(1) Upon excitations by the sound irradiation and also by the electric-field application, the mechanical vibration of the FS film of the ferroelectric liquid crystal was effectively excited.

(2) In the frequency dependence, resonance vibrations were observed for both excitations.

(3) Resonance frequencies and light reflection patterns were found to be different for both excitations, suggesting the different oscillating modes of the FS film for both excitations.

(4) In electric-field excitation, the vibration mode in which the wave vectors is in the direction perpendicular to the electric field was confirmed, which is consistent with the molecular model of the origin of the vibration due to the reorientation of P_S by $\mathbf{P_S} \cdot \mathbf{E}$ torque.

(5) The application of the FS film of the ferroelectric liquid crystal as sensitive acoustic sensors was proposed.

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