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# Measurement of the Flexoelectric Coefficients $e_1$ and $e_3$ in Nematic Liquid Crystals

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*The flexoelectric coefficients $e_1$ and $e_3$ for splay and bend are measured using two experiments. The first experiment measures the sum $(e_1+e_3)$ using a $\pi$-cell and applying an ac voltage across the device. The second experiment measures the difference $(e_1-e_3)$ using a TN-cell and applying an in-plane quasi-dc voltage.*

**Keywords:** difference; flexoelectric coefficient; flexoelectricity; sum; TN-cell; $\pi$-cell



## 1. INTRODUCTION

Flexoelectricity in nematic liquid crystal materials is thought to occur due to the co-existence of molecular dipoles with molecular shape anisotropy. These properties lead to a direct coupling between electric field, induced polarisation and elastic distortion. This can be seen in the free energy expression for nematic materials, which can be written as:

$$\begin{aligned} F &= F_{elastic} + F_{flexoelectric} + F_{dielectric} \\ &= \frac{1}{2}\{K_1(\nabla\cdot\mathbf{n})^2 + K_2(\mathbf{n}\cdot\nabla\times\mathbf{n})^2 + K_3(\mathbf{n}\times\nabla\times\mathbf{n})^2\} \\ &\quad - [e_1\mathbf{n}(\nabla\cdot\mathbf{n}) + e_3(\nabla\times\mathbf{n})\times\mathbf{n}]\cdot\mathbf{E} - \frac{1}{2}\varepsilon_0\Delta\varepsilon(\mathbf{n}\cdot\mathbf{E})^2, \end{aligned}$$

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where the first term is the Frank elastic energy, the middle term is the flexoelectric polarisation using the original Meyer convention [1] and the last term is the dielectric energy.

The flexoelectric coefficients $e_1$ and $e_3$ for splay and bend, respectively, are key parameters in technologies such as the 'Zenithally Bistable Device' [2] and the 'flexoelectric-optic effect' [3]. It is difficult to measure $e_1$ and $e_3$. Therefore it is more common to measure the sum $(e_1+e_3)$ and the difference $(e_1-e_3)$ and than calculate $e_1$ and $e_3$.



## 2. MEASURING THE SUM ($e_1 + e_3$)

A structure which has received considerable attention for the measurement of the sum $(e_1+e_3)$ is a hybrid aligned nematic (HAN) cell [4–11]. However, in its ground state the flexoelectric polarisation in the HAN device leads to an offset displacement field [12], which acts like an offset voltage and can lead to ionic migration. A $\pi$-cell [13], in either the H-state or the V-state, avoids this problem (due to the symmetry in the structure) and is used in our work to measure the sum $(e_1+e_3)$ of the flexoelectric coefficients.

### 2.1. Experiment

The experiment uses a HeNe-Laser with a wavelength of $\lambda = 632.8\,\text{nm}$. The laser beam is passed through the device (which is oriented with the average alignment direction at 45° to the polariser axis) and through a beamsplitter, in order to allow detection of p- and s-polarised light, as shown in Figure 1. The detectors are connected to an oscilloscope to measure the transmission and to a lock-in amplifier. To avoid ionic migration during signal application, a sinusoidal ac voltage with a frequency of $f = 100\,\text{Hz}$ is applied. This has the further advantage that the first and second harmonics can be extracted from

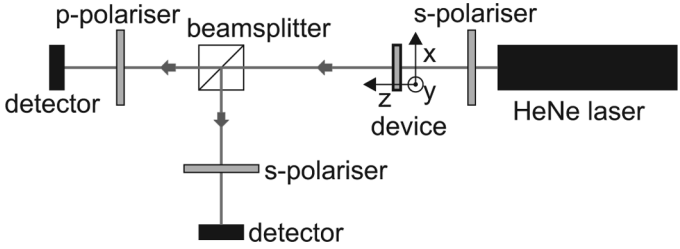


**FIGURE 1** $\pi$-cell experiment to measure the sum $(e_1+e_3)$.

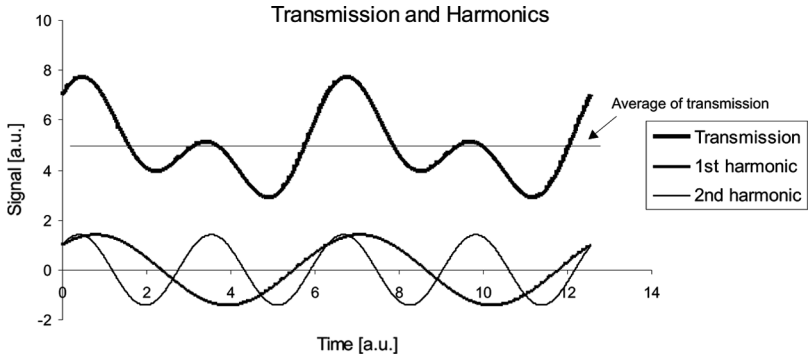


**FIGURE 2** Transmission versus time; extracted first and second harmonic from transmission signal.

the transmission signal by the lock-in amplifier, as illustrated in Figure 2. The first harmonic depends on the electric field $E$, and is strongly dependent on the flexoelectric coefficients of the liquid crystal material, whereas the second harmonic depends on the square of the electric field $E$, and is strongly dependent on the dielectric properties. The amplitude of the sinusoidal waveform is initially set to 20 V, switching the $\pi$-cell into the V-State, and is then decreased in amplitude from 20 V to 0 V in small steps. Through most of this voltage range the device remains in the V-state, although a twisted state forms below around 1 V.

The alignment of the device was created by evaporating SiO at an angle of 85° to the normal of the glass substrate, which leads to a high surface pre-tilt of around 35° [14]. The high surface pre-tilt has the advantage of enhancing the first harmonic signal and the SiO alignment material has a weak surface anchoring which also increases the first harmonic.

## 2.2. Results and Discussion

Due to flexoelectric coupling to the applied field, the director profile within the device differs for positive and negative fields, and hence in principle this can be observed in the harmonic measurement at the fundamental frequency. However, due to the symmetry of the cell, although the director profiles for $\pm$V are different, they lead to the same transmission at normal incidence, and as a result there is no first harmonic observed in the transmission at normal incidence (Fig. 3a2). However, if the cell is tilted about the $y$-axis (Fig. 1), the detectors

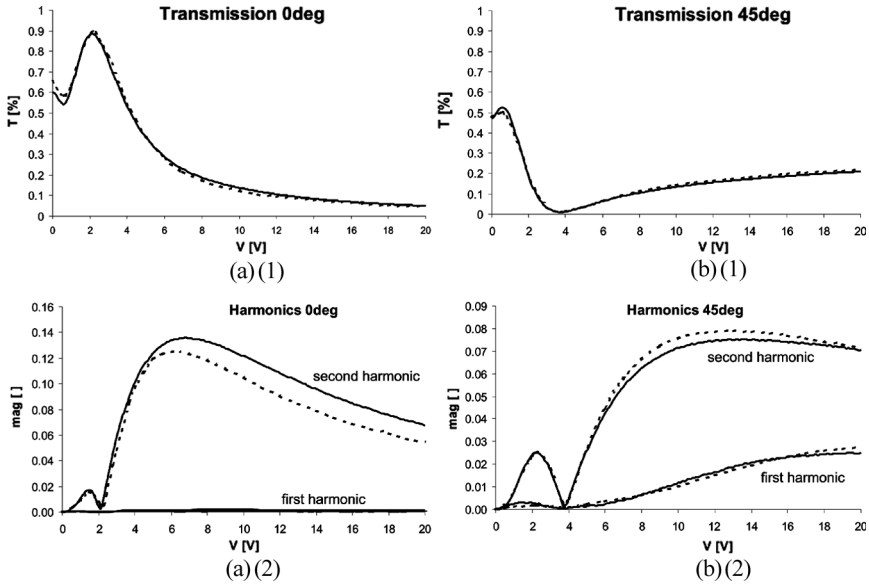


**FIGURE 3** Results of $\pi$-cell experiment for normal and oblique incidence whereby data is shown as solid lines and fitting as dashed lines: (a) normal incidence; (b) oblique incidence; (1) time averaged transmission; (2) harmonics of transmission. The resulting value of the sum of flexoelectric coefficients was measured for E7 as $(e_1 + e_3) = (35.0 \pm 5.0) \times 10^{-12}\,\mathrm{C/m}$.

record the transmission at oblique incidence, and the broken symmetry allows a first harmonic to be seen (Fig. 3b2).

In order to fit the data a simple one-dimensional model was used based on the minimisation of the energy expression presented in the introduction. This used a numerical relaxation approach to determine the director profile. The optical response was then calculated using the well established Berreman method [15]. The fitting of the data was performed in two key steps, whereby parameters determined in the first were kept fixed during the second step of the fitting process:

- First the transmission data at normal and oblique incidence (Fig. 3a1, Fig. 3b1) and the second harmonic data at normal and oblique incidence (Fig. 3a2, Fig. 3b2) were used to determine the cell thickness, surface pre-tilt and surface anchoring energy.
- Then the sum $(e_1 + e_3)$ of the flexoelectric coefficients was varied until the magnitude of the first harmonic at oblique incidence (Fig. 3b2) was correctly fitted.

During this fitting process the elastic, dielectric and optical parameters for the liquid crystal were fixed at values we established using standard methods (Freedericksz transition and Abbe refractometer). The sum $(e_1 + e_3)$ of the flexoelectric coefficients for E7 was thus determined as $(35.0 \pm 5.0) \times 10^{-12}\,\mathrm{C/m}$ at room temperature 22°C, where the error is estimated from the fitting quality.

## 3. MEASURING THE DIFFERENCE $(e_1 - e_3)$

A structure often used to measure the difference $(e_1 - e_3)$ is a uniform lying helix (ULH) structure [3]. However, this has the disadvantage that it is difficult to generate a well-aligned and permanent ULH structure. However, using a TN cell and applying an in-plane field gives a similar effect to a ULH but with a well-defined alignment. This TN structure is used in our work to measure the difference $(e_1 - e_3)$ of the flexoelectric coefficients [16].

### 3.1. Experiment

A HeNe-Laser beam with a wavelength of $\lambda = 543.5\,\mathrm{nm}$ is passed through a beam-splitter. As shown in Figure 4, both parts are reflected with mirrors and focused with lenses into the same measurement area in the device in the middle of an electrode gap. The electrode gap is 500 μm wide and by applying a voltage across the gap, an in-plane electric field can be produced, which forces the molecules to twist and align with the electric field (for a positive dielectric anisotropy $\Delta\varepsilon$). Due to flexoelectricity the molecules also tilt

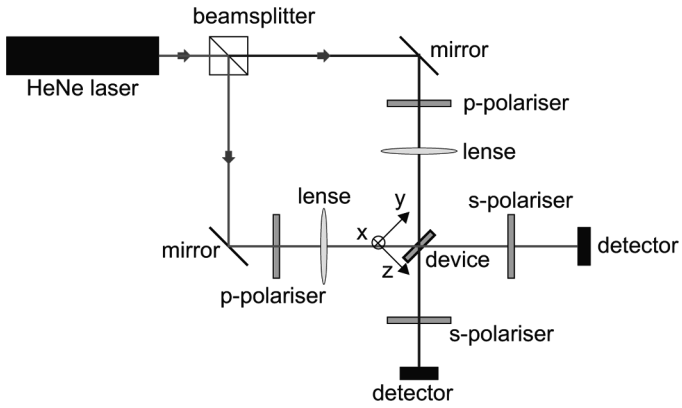


**FIGURE 4** TN-cell experiment with in-plane electric field.

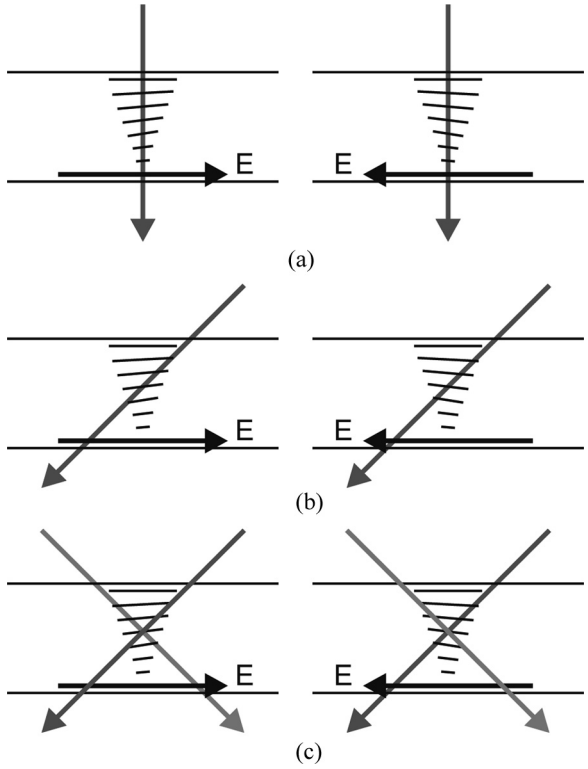


**FIGURE 5** (a) Transmission at normal incidence for $\pm E$-this results in a small response. (b) Transmission at oblique incidence (e.g. 45°) for $\pm E$-this result in a larger response. (c) Further improvement by using two laser beams at oblique incidence.

out of the plane of the cell. This can in principle be measured at normal incidence (Fig. 5a), but shows only a small response for positive and negative electric fields because the tilt angle is in the range of just a few degrees. However, the response is somewhat bigger for oblique incidence e.g. 45° (Fig. 5b). This is because the effective changes in optical anisotropy are greater for tilted structures. The measurement can be further improved by using the two laser beams at opposite incident angles (Fig. 4, Fig. 5c). (This can be understood by analogy with a conventional twisted nematic device whereby the off-axis viewing properties are highly asymmetric due to tilt in the structure.) Further details relating to the experimental arrangement are discussed in [16].

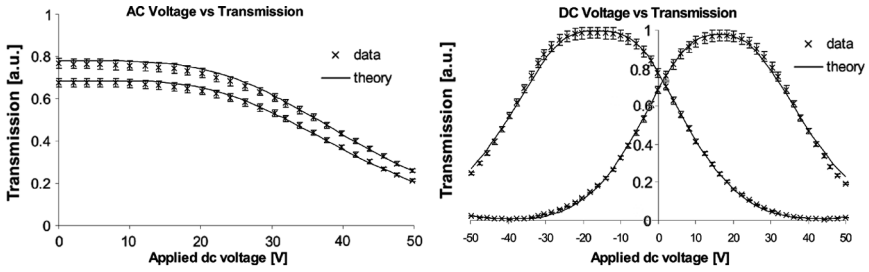


**FIGURE 6** Results and fitting of TN-cell experiment for (a) ac and (b) quasi-dc voltage. In each case the two lines are those for the two laser beams and detectors shown in Figure 4. The resulting value of the difference in flexoelectric coefficients was measured for E7 as $(e_1 - e_3) = (12.2 \pm 1.0) \times 10^{-12}\,\mathrm{C/m}$.



## 3.2. Results and Discussion

Our previously published results for E7 showed a flexoelectric measurement of $(e_1 - e_3) = (9.3 \pm 0.3) \times 10^{-12}\,\mathrm{C/m}$ [16]. Here we have improved the experiment whereby the transmission is measured for an ac (Fig. 6a) and quasi-dc (Fig. 6b) applied voltage. The ac voltage with a frequency of $f = 1\,\mathrm{kHz}$ was varied in amplitude between 0 V and 50 V (Fig. 6a). Due to the high ac frequency, flexoelectricity can be neglected in the fitting of the ac data and these data were used to determine the thickness and surface pre-tilt of the device. (For example, the surface pre-tilt controls the difference in the two signals at zero volts.) These two key parameters were then kept fixed during the fitting process of the quasi-dc data (actually a long period square wave at a frequency of $f = 0.2\,\mathrm{Hz}$) to determine the difference $(e_1 - e_3)$ for the flexoelectric coefficients. Using the ac data to determine the thickness and surface pre-tilt helps to avoid any problems with thickness/pre-tilt degeneracity, which may have influenced the previous result for E7 [16]. During the fitting procedure for determination of the thickness and surface pre-tilt, and the subsequent fitting for the flexoelectric properties, the method discussed in our previous paper is used. Using our new data this leads to a revised result for E7 for the difference $(e_1 - e_3)$ of the flexoelectric coefficients of $(12.2 \pm 1.0) \times 10^{-12}\,\mathrm{C/m}$ at room temperature 22°.

## 4. CONCLUSION

The results for E7 are $(e_1 + e_3) = (35.0 \pm 5.0) \times 10^{-12}\,\mathrm{C/m}$ and $(e_1 - e_3) = (12.2 \pm 1.0) \times 10^{-12}\,\mathrm{C/m}$. Our result for the sum $(e_1 + e_3)$ is higher than

that obtained by others for E7 ($(e_1+e_3) = 15.0 \times 10^{-12}$ C/m [12]) and 5CB ($(e_1+e_3) = 18.0 \times 10^{-12}$ C/m [11]), although it is clearly of the same magnitude. The difference $(e_1 - e_3)$ is very similar to that obtained by others for the related material 5CB ($(e_1+e_3) = 15.0 \times 10^{-12}$ C/m [11]).

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