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CONDENSED MATTER

# Dielectric Behavior of Antiferroelectric Liquid Crystals in Presence of Flexoelectric Effect

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**Abstract** We studied theoretically the effect of flexoelectricity on the behavior of dielectric fluctuations of antiferroelectric liquid crystals (AFLCs) influenced by the mechanical distortion associated with flexoelectric effect. By using the appropriate free energy and the Landau-Ginzburg equation, we found an approximate expression of dielectric permittivity, which was strongly influenced by the existence of flexoelectric polarization for both in-phase and anti-phase motions. Consequently, the corresponding dielectric strength for both in-phase and anti-phase motions were varied due to the existence of flexoelectric polarization.

**Keywords** Antiferroelectric liquid crystals · Flexoelectric effect · Dielectric function · Relaxation · In-phase and anti-phase motions

## 1 Introduction

Antiferroelectric liquid crystals (AFLC) belong to a smectic liquid crystals class ($SmC_A^*$) [1–5], with the variation on the tilt azimuthal direction of the structure, from layer to layer, and give rise to an anticlinic structure. The projection of the average layer molecular director, c- is important to explain the tilt characteristics of the molecules. If the applied electric field is high enough to overcome the antiferroelectric pairing energy, then a field-induced transition may happen from antiferroelectric state to ferroelectric state, via intermediate ferrielectric (FI) state [6]. But for sufficiently large applied electric field, the layer to layer polarization orients along a preferred direction parallel to the applied electric field. Again, the mechanical stress, i.e., flexoelectric effect, produces a polarization parallel to the spontaneous polarization. Therefore, it does not affect the synclinic ferroelectric pattern [7–9]. The polarization coming from the flexoelectric effect ($P^{\rightharpoonup} = \chi c_f \frac{\partial \varnothing_a}{\partial x}$) may be expected to change the sample dielectric behavior. Some researchers [10–22] investigated different modes of AFLC but, most of them, reported two relaxation modes in the frequency range from 100 Hz to 10 MHz. Among them, two researchers [10, 11] reported on supporting the soft mode and molecular relaxation mode. Other groups [12–17] reported two modes—one is the low frequency mode due to phase fluctuation, and another is the high frequency mode due to amplitude fluctuation. The interaction between applied electric field and dielectric anisotropy of the medium can create helicity of the molecular director. Anti-parallel directional pairs of successive layers are formed [16] by the azimuthal angle fluctuation. The lower frequency relaxation mode or in-phase mode is also supported by Parry-Jones et al. [23–25]. In our earlier proposal [26, 27], we explained the interaction between applied electric field and interlayer interaction potential, and in a recent publication, we discussed the influence of ions in its dielectric characteristics. Now, our present proposal is that the mechanical contribution coming from the flexoelectric effect can satisfactorily dominate the dielectric behavior and its different component.

## 2 Theoretical Results

### 2.1 In-phase Motion

The mechanical deformation of the director of antiferroelectric liquid crystals namely ferroelectricity is the generation of a spontaneous polarization. Part of the total free energy comes from the coupling between the applied electric field and this

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polarization. Therefore, the total free energy of the system can be written as [23–28] by considering the mechanical deformation including all terms reported till now relevant to this works:

$$F = -E\left(P - \chi c_f \frac{\partial \varnothing_a}{\partial x}\right)\cos\varnothing_a \cos\varnothing_b + \gamma\cos^2\varnothing_b + 2EV_0\cos(2\varnothing_a) + \frac{1}{2}K\left(\frac{\partial \varnothing_a}{\partial x} - \frac{2\pi}{p}\right)^2, \quad (1)$$

where $\varnothing_a$ and $\varnothing_b$ are two azimuthal angles defined as $\varnothing_a = \frac{\varnothing_e + \varnothing_o}{2}$ and $\varnothing_e$. and $\varnothing_o$ are associated with the c - director in even and odd layers of the AFLC, respectively. The first term in Eq. (1) is the coupling term between applied electric field ($E$) and the modified polarization $\left(P - \chi c_f \frac{\partial \varnothing_a}{\partial x}\right)$ $\chi$ is the dielectric susceptibility, $c_f$ the flexoelectric coefficient and $\frac{\partial \varnothing_a}{\partial x}$ the deformation factor. The modified polarization has been considered by introducing the flexoelectric effect associated with the mechanical deformation. $\frac{\partial \varnothing_a}{\partial x}$ is defined as the deformation factor due to the variation of azimuthal fluctuation with strain. The second term, named as the dipolar term, carries antiferroelectric ordering where the dipolar ordering coefficient $\gamma$ is positive in nature, as mentioned in earlier publications [26–28]. The third one is the interaction term between applied electric field and the interlayer interaction strength ($V_0$) as mentioned in earlier publications [26–28]. The last term accounts for the elastic behavior of the helical structure of the phase [23–28].

As the in-phase fluctuation is almost independent of antiferroelectric ordering, by minimizing the free energy with respect to $\varnothing_a$ to get the stabilized condition of the system in in-phase motion [23–28], we obtain

$$\cos\varnothing_b = \frac{E\left(P - \chi c_f \frac{\partial \varnothing_a}{\partial x}\right)}{2\gamma}\cos\varnothing_a. \quad (2)$$

So the simplified expression of free energy can be written as

$$F = -\frac{E^2P^2}{4\gamma}\left(1 - \frac{2P^*}{P}\right)\cos^2\varnothing_a + 2EV_0\cos(2\varnothing_a) + \frac{1}{2}K\left(\frac{\partial \varnothing_a}{\partial x} - \frac{2\pi}{p}\right)^2, \quad (3)$$

where, $d = \frac{\partial \varnothing_a}{\partial x}$ and $P^* = \chi c_f d$ is the maximum value of the polarization coming from the flexoelectric effect.

The Landau-Ginzburg equation of the azimuthal angle $\varnothing_a$ for this system [23–28]

$$-\frac{\eta_a p^2}{K}\frac{\partial \varnothing_a}{\partial t} = \frac{p^2}{K}\left[\frac{E^2P^2}{4\gamma}\left(1 - \frac{2P^*}{P}\right) - 4EV_0\right]\sin(2\varnothing_a) - \frac{\partial^2 \varnothing_a}{\partial T^2}, \quad (4)$$

where $T = x/p$, a dimensionless parameter and $p$ is the pitch of helix. Applied electric field $E = E_b + E_0\exp(i\omega t)$ has two parts, with $E_b$ as the bias field and $E_0\exp(i\omega t)$ as the oscillating part. Let us take the trial solution [23–28] as

$$\varnothing_a = 2\pi T + (a_1 + a_2\exp i\omega t + a_3\exp 2i\omega t)\sin(4\pi T). \quad (5)$$

The first term in Eq. (5) accounts for ground state of unperturbed helical structure and the second one is the perturbation of the ground state with Fourier component $\sin(4\pi T)$.

Putting this trial solution into the Eq. (4), we get the solution of $\varnothing_a$ as [23–28],

$$\varnothing_a = 2\pi T - \delta(\omega)\sin(4\pi T). \quad (6)$$

Here, the form of $\delta(\omega)$ is [23–28]

$$\delta(\omega) = \left[\left(E_b^2 + \frac{E_0^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right) + \left(2E_bE_0 - \frac{16\gamma V_0}{P^2}E_0 - \frac{32\gamma V_0 P^*}{P^3}E_0\right)\frac{\exp i\omega t}{1 + i\omega\tau_a} + \frac{E_0^2}{2}\frac{\exp 2i\omega t}{1 + 2i\omega\tau_a}\right]\frac{P^2p^2\left(1 - \frac{2P^*}{P}\right)}{64\pi^2 K\gamma}, \quad (7)$$

where $\tau_a = \frac{h_a p^2}{16\pi^2 K}$ is the relaxation time for in-phase motion and $\left(E_b{}^2 + \frac{E_0{}^2}{2}\right)$ is the mean squared electric field.

At very low frequency region $\left(\omega \ll \frac{1}{\tau_a}\right)$ [23–28]

$$\varnothing_a = 2\pi T - \left[\left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right) + \left(2E_bE_0 - \frac{16\gamma V_0}{P^2}E_0 - \frac{32\gamma V_0 P^*}{P^3}E_0\right)\exp i\omega t + \frac{E_0{}^2}{2}\exp 2i\omega t\right] \frac{P^2p^2\left(1-\frac{2P^*}{P}\right)}{64\pi^2 K\gamma}\sin(4\pi T). \quad (8)$$

At very high frequency region $\left(\omega \gg \frac{1}{\tau_a}\right)$ [23–28]

$$\varnothing_a = 2\pi T - \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2p^2\left(1-\frac{2P^*}{P}\right)}{64\pi^2 K\gamma}\sin(4\pi T). \quad (9)$$

The net polarization of two layers AFLC system [23–28] is

$$P_z = P\cos\varnothing_a\cos\varnothing_b. \quad (10)$$

Using eq. (2)

$$P_z = \frac{EP^2\left(1-\frac{P^*}{P}\right)}{2\gamma}\cos^2\varnothing_a. \quad (11)$$

For sufficiently small applied field $\delta(\omega) \ll 1$ [23–28], we have

$$\cos^2\varnothing_a \approx \frac{1}{2}[1+\cos(4\pi T)] + \frac{\delta(\omega)}{2}[1-\cos(8\pi T)].$$

Then, the average value of $P_z$ can be written as [23–28]

$$P_z = \frac{EP^2\left(1-\frac{P^*}{P}\right)}{4\gamma}[1+\delta(\omega)]. \quad (12)$$

Therefore,

$$P_z = \frac{EP^2}{4\gamma}\left[\left(1-\frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right) + \left(2E_bE_0 - \frac{16\gamma V_0}{P^2}E_0 - \frac{32\gamma V_0 P^*}{P^3}E_0\right)\frac{\exp i\omega t}{1+i\omega\tau_a} + \frac{E_0{}^2}{2}\frac{\exp 2i\omega t}{1+2i\omega\tau_a}\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right]. \quad (13)$$

Now extracting the oscillatory component, we get

$$P_z = \frac{P^2}{4\gamma}\left[\left(1-\frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right) + \left(2E_b{}^2 - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{1}{1+i\omega\tau_a}\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right] \times E_0 exp(i\omega t). \quad (14)$$

So, the relative dielectric permittivity of the medium is

$$\varepsilon=\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1-\frac{P^*}{P}\right)+\left\{\left(E_b{}^2+\frac{E_0{}^2}{2}-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)+\left(2E_b{}^2-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)\frac{1}{1+i\omega\tau_a}\right\}\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2K\gamma}\right]. \quad (15)$$

From the above expression of relative dielectric permittivity, we can separate the real $\varepsilon$' and imaginary $\varepsilon$' component. The real component is

$$\varepsilon^{'}=\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1-\frac{P^*}{P}\right)+\left(E_b{}^2+\frac{E_0{}^2}{2}-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)+\left(2E_b{}^2-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)\frac{1}{1+\omega^2\tau_a{}^2}\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2K\gamma}\right], \quad (16)$$

and the imaginary component is

$$\varepsilon^{''}=\frac{P^2}{4\varepsilon_0\gamma}\left[\left(2E_b{}^2-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)\frac{\omega\tau_a}{1+\omega^2\tau_a{}^2}\right]\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2K\gamma}. \quad (17)$$

Now for the limiting condition of $\omega\tau_a\rightarrow 0$ from Eq. (16)

$$\varepsilon^{'}=\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1-\frac{P^*}{P}\right)+\left\{\left(E_b{}^2+\frac{E_0{}^2}{2}-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)+\left(2E_b{}^2-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)\right\}\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2K\gamma}\right]. \quad (18)$$

Using the limiting condition of $\omega\tau_a\rightarrow\infty$ from Eq. (16)

$$\varepsilon^{'}=\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1-\frac{P^*}{P}\right)+\left(E_b{}^2+\frac{E_0{}^2}{2}-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0P^*}{P^3}E_b\right)\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2K\gamma}\right]. \quad (19)$$

So, the dielectric strength of the system of in-phase motion can be obtained by using the difference between Eqs. (18) and (19)

$$\Delta\varepsilon=\left[\left(1-\frac{3P^*}{P}\right)E_b{}^2-\left(1-\frac{3P^*}{P}\right)\frac{8\gamma V_0}{P^2}E_b\right]\frac{P^4p^2}{128\pi^2\varepsilon_0K\gamma^2}. \quad (20)$$

It represents only the strength of in-phase motion. In absence of bias field, $\Delta\varepsilon$=0. The low frequency in-phase mode does not produce any fluctuation in the system in absence of the application of any bias field, as already reported by researchers [23–28] and that was experimentally verified by others [18, 19]. So it is clear that the bias field is essential to produce any change of dielectric strength in in-phase motion of AFLC.

## 2.2 Anti-phase Motion

The high frequency relaxation mode [23–28] is named as anti-phase mode, considering the changes in $\varnothing_b$. So, minimization with respect to $\varnothing_b$ is not valid for higher range of frequencies.

Therefore, the Landau-Ginzburg equation for the system with respect to $\varnothing_b$ is written as [23–28]

$$-\eta_b \frac{\partial \varnothing_b}{\partial t} = EP\left(1 - \frac{P^*}{P}\right)\cos\varnothing_a \sin\varnothing_b - \gamma \sin 2\varnothing_b, \tag{21}$$

with $\cos\varnothing_a = \cos(2\pi T) + \frac{\delta(\infty)}{2}[\cos(2\pi T) - \cos(6\pi T)]$ (22).

Now, substituting the trial solution [23–28]

$\varnothing_b = \frac{\pi}{2} + (a + b\exp i\omega t)\cos(2\pi T) + (c + d\exp i\omega t)\cos(6\pi T)$ in to the L-G equation, we get

$$\varnothing_b = \frac{\pi}{2} - \left(E_b + \frac{E_0 \exp i\omega t}{1 + i\omega\tau_b}\right)\frac{P}{2\gamma}\left\{\cos(2\pi T) + \frac{\delta(\infty)}{2}[\cos(2\pi T) - \cos(6\pi T)]\right\}, \tag{23}$$

where $\tau_b = \frac{\eta_b}{2\gamma}$ is the relaxation time for high frequency anti-phase motion.

The net polarization is

$$P_z = P\cos\varnothing_a \cos\varnothing_b = \left(E_b + \frac{E_0 \exp i\omega t}{1 + i\omega\tau_b}\right)\frac{P^2\left(1 - \frac{P^*}{P}\right)}{2\gamma}\cos^2\varnothing_a. \tag{24}$$

So the average polarization at frequency $\omega$ is

$$P_z = \frac{E_0 \exp i\omega t}{1 + i\omega\tau_b}\frac{P^2\left(1 - \frac{P^*}{P}\right)}{4\gamma}[1 + \delta(\infty)] = \frac{E_0 \exp i\omega t}{1 + i\omega\tau_b}\frac{P^2}{4\gamma}\left[\left(1 - \frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2 p^2\left(1 - \frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right]. \tag{25}$$

Therefore, the relative dielectric permittivity

$$\varepsilon = \frac{1}{1 + i\omega\tau_b}\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1 - \frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2 p^2\left(1 - \frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right]. \tag{26}$$

So, the real component of dielectric permittivity is

$$\varepsilon' = \frac{1}{1 + \omega^2\tau_b{}^2}\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1 - \frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2 p^2\left(1 - \frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right], \tag{27}$$

and the imaginary component is

$$\varepsilon'' = \frac{\omega\tau_b}{1 + \omega^2\tau_b{}^2}\frac{P^2}{4\varepsilon_0\gamma}\left[\left(1 - \frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2 p^2\left(1 - \frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right], \tag{28}$$

when $\omega\tau_b \rightarrow 0$

$$\varepsilon' = \frac{P^2}{4\varepsilon_0\gamma}\left[\left(1 - \frac{P^*}{P}\right) + \left(E_b{}^2 + \frac{E_0{}^2}{2} - \frac{16\gamma V_0}{P^2}E_b - \frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2 p^2\left(1 - \frac{3P^*}{P}\right)}{64\pi^2 K\gamma}\right]. \tag{29}$$

When $\omega\tau_b \rightarrow \infty$

$$\varepsilon' = 0. \quad (30)$$

So, the dielectric strength of anti-phase mode, which is obtained by using the difference between Eqs. (28) and (29), is

$$\Delta\varepsilon = \frac{P^2}{4\varepsilon_0\gamma}\left[\left(1-\frac{P^*}{P}\right)+\left(E_b{}^2+\frac{E_0{}^2}{2}-\frac{16\gamma V_0}{P^2}E_b-\frac{32\gamma V_0 P^*}{P^3}E_b\right)\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2K\gamma}\right]. \quad (31)$$

It represents only the strength of anti-phase mode. In the absence of bias field, when $E_b=0$

$$\Delta\varepsilon = \frac{P^2}{4\varepsilon_0\gamma}\left[\left(1-\frac{P^*}{P}\right)+\frac{E_0{}^2}{2}\frac{P^2p^2\left(1-\frac{3P^*}{P}\right)}{64\pi^2\mathrm{K}\gamma}\right]. \quad (32)$$

### 2.3 Critical Unwinding Field

de Gennes evaluated the critical unwinding field considering the free energy [29] for a helix of cholesteric liquid crystals. He considered the cholesteric system and find out the critical magnetic field from the free energy as given below

$$F_{\text{deGennes}} = -\frac{\chi_a H^2}{2}\sin^2\varnothing_a + \frac{K}{2}\left(\frac{\partial\varnothing_a}{\partial z}-\frac{2\pi}{p}\right)^2, \quad (33)$$

and the reported critical magnetic field for helix unwinding is

$$H_{\text{critical}} = \frac{\pi^2}{p}\left(\frac{K}{\chi_a}\right)^{1/2}. \quad (34)$$

Based on the chirality behavior between the antiferroelectric and cholesteric system, we can obtain the critical unwinding field comparing free energies (3) and (31) of these two systems as given below

$$E_{\text{critical}} = \frac{\pi^2}{p}\left(\frac{K}{\frac{P^2}{2\gamma}\left(1-\frac{2P^*}{P}\right)-\frac{8V_0}{E_{\text{critical}}}}\right)^{1/2}. \quad (35)$$

The pitch of the helix ($p$) is much smaller than the dipolar term ($\gamma$) [24]; considering such condition, we get the critical field as

$$E_{\text{critical}} = \frac{16\gamma V_0}{P^2\left(1-\frac{2P^*}{P}\right)}. \quad (36)$$

## 3 Discussion

The relative dielectric permittivity decreases with the increase of flexoelectric polarization for both phases but this decrease rate is almost the same for both motions illustrated in Fig. 1. It is clearly indicated from Fig. 1 and eq. (16) that real component of dielectric permittivity does not show any monotonous behavior. It increases initially with the increase of $P^*/P$ till 0.36, then it decreases with the increase of $P^*/P$. Such behavior is quite different from the behavior of anti-phase motion. Since the in-phase motion is associated with the azimuthal fluctuation of two adjacent layers in the same direction, the real component of dielectric permittivity is strongly influenced by the flexoelectric polarization for small value pure polarization of the system. It is because the flexoelectric polarization dominates over pure polarization for its low value, which is associated with the differential variation of azimuthal angle. Hence, it decelerates the behavior of electro-optic devices based on AFLC for low fields. Fig. 2 shows the variation of the imaginary component of

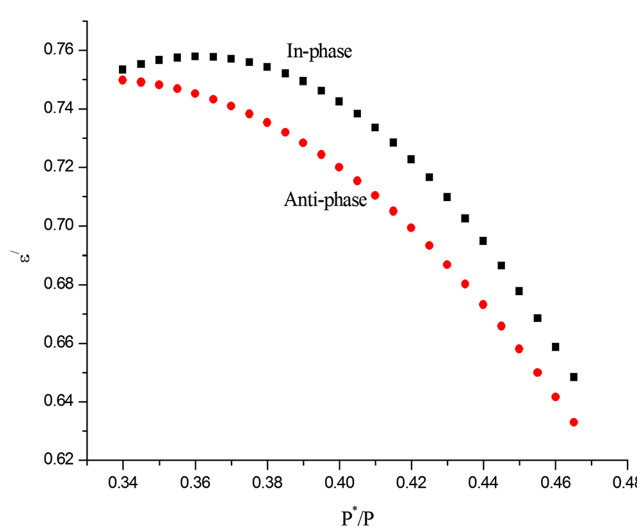


**Fig. 1** Variation of real component of dielectric permittivity ($\varepsilon'$) with the ratio $P^*/P$. The value of different terms have been considered for drawing the figure are $P=8\times10^{-4}\mathrm{C/m^2}$, $\gamma=1.6\times10^4 J/\mathrm{m}^3$, $\varepsilon_0=8.854\times10^{-12}C^2N^{-1}m^{-2}$, $K=2.5\times10^{-11}N$, $E_b=4$ volt, $E_0=1$ volt, $p\approx10^{-6}m$.

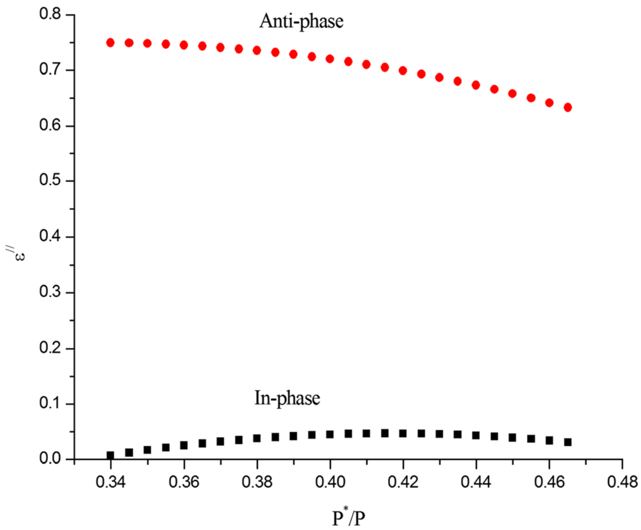


**Fig. 2** Variation of imaginary component of dielectric permittivity ($\varepsilon^{//}$) with the ratio $P^*/P$. The value of different terms have been considered for drawing the figure are $P=8\times10^{-4}$C/m$^2$, $\gamma=1.6\times10^4$J/m$^3$, $\varepsilon_0=8.854\times10^{-12}C^2N^{-1}m^{-2}$, $K=2.5\times10^{-11}N$, $E_b=4$ volt, $E_0=1$ volt, $p\approx10^{-6}m$.

dielectric permittivity ($\varepsilon^{//}$) with flexoelectric polarization for both phases. It also shows the non-monotonic behavior for in-phase motion and higher loss occurs for anti-phase motion.

It can be demonstrated from Fig. 3 that the dielectric strength tends to lower values when the system has higher values of mechanical stress in anti-phase motion and the dielectric strength of in-phase motion also shows lower values. Due to the decrease of the ratio of flexoelectric to spontaneous polarization (Fig. 1), it shows a stability of $\varepsilon^{/}$ and that provides a stability to intermediate phases supported by the experimental findings of Jaradat et al. [30]. Ray et al. [31] and Nayek et al. [32] observed

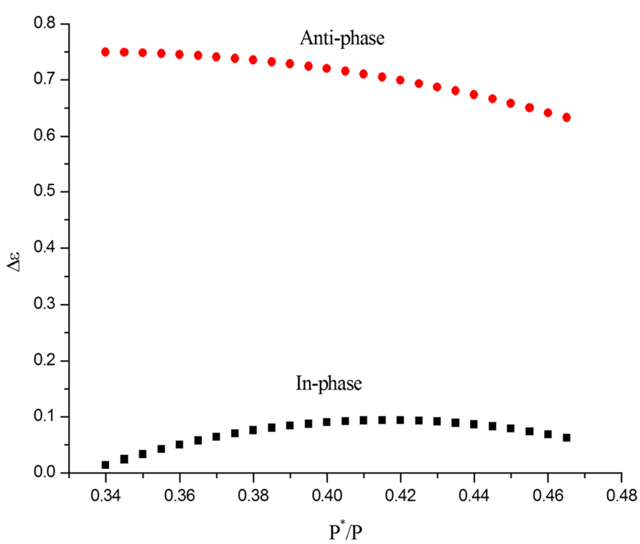


**Fig. 3** Variation of the dielectric strength ($\Delta\varepsilon$) with the ratio $P^*/P$. The value of different terms have been considered for drawing the figure are $P=8\times10^{-4}$C/m$^2$, $\gamma=1.6\times10^4$J/m$^3$, $\varepsilon_0=8.854\times10^{-12}C^2N^{-1}m^{-2}$, $K=2.5\times10^{-11}N$, $E_b=4$ volt, $E_0=1$ volt, $p\approx10^{-6}m$.

experimentally an instability of antiferrielectric phases of normal AFLC and orthoconic AFLC. Although they mentioned it due to the influence of ionic conductivity but such strong instability of intermediate phases may be occurred due to the presence of an excess mechanical stress except the influence of ionic conductivity which we clearly mentioned in Figs. 1–3 for the range from 0.34 to 0.47 of flexoelectric to spontaneous polarization ratio. Fig. 3 shows a strong relaxation phenomena for anti-phase motion which is associated with the azimuthal fluctuation of two adjacent layers in the opposite direction strongly supported by experimental findings [30–32]. But for in-phase motion, the strength of relaxation is very low as well as a non-monotonic behavior noticed. It initially increases with the increase of $P^*/P$ till 0.42, then it decreases with the increase of $P^*/P$. It is clearly indicative that in-phase motion is strongly influenced by the flexoelectric polarization which is mostly responsible for the creation of instability of intermediate phases as experimentally shown [30–32]. Critical unwinding field is strongly depending on the flexoelectric polarization as demonstrated from Eq. (36). With the increase of flexoelectric polarization, the critical unwinding field is increased significantly, which is very much important for the fabrication of devices based on limiting value of applied external field.

## 4 Conclusions

The dielectric permittivity and dielectric strength are remarkably modified due to the mechanical stress of the system for both in-phase and anti-phase motions. But such variation is only significant in the presence of bias field for in-phase motion. In absence of bias field, both components of dielectric permittivity and dielectric strength shows a linear sharp decrease. Such variation is strongly influenced by the existence of an extra mechanical stress of the system, which is associated with the flexoelectric polarization. Therefore, we conclude that the flexoelectric effect produces a mechanical deformation of the system reducing the value of dielectric functions. The dependence of the critical field for the unwinding of the helix on mechanical stress is also predicted in our last two equations. From eq. (36), it is clear that critical field increases with the increase in flexoelectric contribution.

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