



# Influence of ionic conductivity in polymer-dispersed antiferroelectric liquid crystals

TAPAS PAL MAJUMDER

Department of Physics, Kalyani University, Kalyani 741235, India  
 (tpmajumder1966@gmail.com)

MS received 6 April 2021; accepted 22 July 2021

**Abstract.** Dielectric properties of both in-phase and anti-phase motions of polymer-dispersed antiferroelectric liquid crystals (PDAFLC) were changed because of the influence of charge density accumulated on smectic layers and its gradient variation. The elastic constant as well as dielectric parameters were changed because of the coupling between charge density variation and the physical properties of polymer constituents such as free volumes, cross-link chains. The theoretical model provides a clear influence of charge density in PDAFLC which modified the dielectric parameters, such as dielectric constant, dielectric loss, dielectric strength, etc. depending on the variation of charge density as well as polymeric parameters for both in-phase and anti-phase motions. The obtained theoretical basis is discussed by considering the results with the experimental findings and the theoretical deduced equations.

**Keywords.** Antiferroelectric liquid crystal; Landau–Ginzburg equation; polymer cross-link; dielectric spectrum; ionic conductivity.

## 1. Introduction

Polymer-dispersed antiferroelectric liquid crystals (PDAFLCs) in polymer matrix have been studied extensively in experimental work [1–20], but till now, a limited number of works has been done in their theoretical understandings [21–32]. When the molecules or constituents of AFLC dispersed in polymer matrix, the accumulated charge density on each layer of AFLC interacts with the polymer chains as well as the free volumes of polymer matrix, and also encounters with the mobility of charges of AFLC [25,26]. Since the reported information from literature informs about the existence of in-phase and anti-phase motions connected with the movement of chirality, a detailed study of PDAFLC influenced by ionic conductivity or the accumulation of charges on the layer of AFLC needs to be done [25,26]. Since the dielectric functions are associated with the orientation of dipole moments for a particular mode of fluctuation, so a detailed information of dielectric functions, such as dielectric constant, dielectric loss and dielectric strength for both in-phase and anti-phase motions are reported in this work by considering an appropriate Landau free energy. Two collective modes associated with the phase fluctuations of tilt angle in-phase and anti-phase have been studied, till now both experimentally and theoretically, earlier [12–14,19–32]. Although a few experimental findings exists I have tried to incorporate a theoretical model to incorporate with the existing experimental findings as well for establishing a

future experimental motivation. I have also tried to find a theoretical model about the influence of ionic conductivity of AFLC that interact the with polymer matrix in PDAFLCs.

## 2. Theoretical approach

### 2.1 In-phase mode

The expected free energy by considering the influence of ionic conductivity in the PDAFLC by inclusion of polymeric cross-link chains inter-linked throughout the system as a whole, can be written as [25,26,32]:

$$\begin{aligned}
 F = & -EP \cos\varphi_a \cos\varphi_b + \gamma \cos^2\varphi_b + 2EV_0 \cos(2\varphi_a) \\
 & + \frac{1}{2}K \left( \frac{\partial\varphi_a}{\partial x} - \frac{2\pi}{p} \right)^2 + W_p(\theta) \sin^2\varphi_a \\
 & + \frac{1}{2} \left( 1 - \frac{r(\theta)}{R} \cos\varphi_a \right) - \lambda P^2 \left| \left( \frac{\partial\nabla\psi}{\partial P} \right) \right| \cos^2\varphi_b \\
 & + \frac{1}{2} |\nabla\rho|^2 + \frac{1}{4} |\nabla\rho|^4 - \chi\hat{z} \cdot \left\{ \frac{\partial\varphi_a}{\partial x} \hat{x} \times (Q_x\hat{x} + Q_y\hat{y}) \right\} \\
 & + \frac{1}{2} \left( 1 - \frac{r(\theta)}{R} \cos\theta \right) \left\{ \hat{z} \cdot (Q_x\hat{x} + Q_y\hat{y}) \right\} - \eta P \left| \left( \frac{\partial\nabla\psi}{\partial P} \right) \right| \\
 & \left[ \chi\hat{z} \cdot \left\{ \frac{\partial\varphi_a}{\partial x} \hat{x} \times (Q_x\hat{x} + Q_y\hat{y}) \right\} \right] - \xi_1 P \cdot (Q_x\hat{x} + Q_y\hat{y}), \quad (1)
 \end{aligned}$$

In equation (1),  $\phi_a = \frac{\phi_e + \phi_o}{2}$  and  $\phi_b = \frac{\phi_e - \phi_o}{2}$  are two average azimuthal angles connected with the phase fluctuations of the c-director in even and odd layers of the AFLC, respectively, which are associated with both in-phase and anti-phase of such PDAFLC system keeping the amplitude of tilt ( $\theta$ ) as a constant.

By minimizing equation (1) with respect to  $\phi_b$  and the gradient of charges [25,26,32], we get,

$$F = \frac{-E^2 P^2}{4\gamma} \left[ 1 + \lambda \frac{P^2}{\gamma} \left| \frac{\partial \nabla \psi}{\partial P} \right| \right] \cos^2 \phi_a + 2EV_0 \cos(2\phi_a) + \frac{1}{2} K^* \left( \frac{\partial \phi_a}{\partial x} - \frac{2\pi}{p} \right)^2 + W_p(\theta) \sin^2 \phi_a + \frac{1}{2} \left( 1 - \frac{r(\theta)}{R} \cos \phi_a \right) - \frac{\Omega^2}{4\lambda},$$

where

$$K^* = K - \frac{\chi^2}{\Omega} - \frac{2\eta P}{\Omega} \left| \left( \frac{\partial \nabla \psi}{\partial P} \right) \right|. \tag{3}$$

The connecting equation between the rotational viscosity and the antiferroelectric ordering can be written as [25,26,32]:

$$\frac{-\eta_a p^2 \partial \phi_a}{K^* \partial t} = \frac{p^2}{K^*} \left[ \frac{E^2 P^2}{4\gamma} \left\{ 1 + \lambda \frac{P^2}{\gamma} \left| \frac{\partial \nabla \psi}{\partial P} \right| \right\} - 4EV_0 + W_p(\theta) \right] \sin(2\phi_a) + \frac{p^2 \Gamma r(\theta)}{2K^* R} \sin \phi_a - \frac{\partial^2 \phi_a}{\partial T^2},$$

with

$$\tau_a = \frac{\eta_a p^2}{16\pi^2 K^*}. \tag{5}$$

The real component of dielectric permittivity can be written by considering a suitable trial solution [25,26,32] as follows:

$$\begin{aligned} \epsilon_r = & \frac{P^2}{4\epsilon_0 \gamma} \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) \\ & \left[ 1 + \left\{ \left( E_b^2 + \frac{E_0^2}{2} \right) \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) \right. \right. \\ & \left. \left. - \frac{16\gamma V_0}{P^2} E_b + \frac{4\gamma W_p(\theta)}{P^2} + \frac{\gamma \Gamma r(\theta)}{P^2 R} \right\} \right. \\ & \left. + \left\{ 2E_b^2 \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) \right. \right. \\ & \left. \left. - \frac{16\gamma V_0}{P^2} E_b \right\} \frac{1}{1 + \omega^2 \tau_a^2} \right] \frac{P^2 p^2}{64\pi^2 K^* \gamma}. \tag{6} \end{aligned}$$

The imaginary component of dielectric permittivity can be written by considering a suitable trial solution [25,26,32] as given as:

$$\begin{aligned} \epsilon_i = & \frac{P^2}{4\epsilon_0 \gamma} \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) \left[ \left\{ 2E_b^2 \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) \right. \right. \\ & \left. \left. - \frac{16\gamma V_0}{P^2} E_b \right\} \frac{\omega \tau_a}{1 + \omega^2 \tau_a^2} \right] \frac{P^2 p^2}{64\pi^2 K^* \gamma}. \tag{7} \end{aligned}$$

Therefore, the dielectric strength is written as [25,26,32]:

$$\begin{aligned} \Delta \epsilon = & \frac{P^4 p^2}{128\pi^2 \epsilon_0 K^* \gamma^2} \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) \\ & \left[ E_b^2 \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \Psi}{\partial P} \right) - \frac{8\gamma V_0}{P^2} E_b \right]. \tag{8} \end{aligned}$$

For the neat AFLC, in absence of polymer, i.e., the gradient  $\frac{\partial \nabla \Psi}{\partial P} = 0$ , then

$$\Delta \epsilon = \frac{P^4 p^2}{128\pi^2 \epsilon_0 \gamma^2 K^*} \left( E_b^2 - \frac{8\gamma V_0}{P^2} E_b \right). \tag{9}$$

The dielectric strength increases with the increase of bias, but it reaches a minimum value at  $(E_b)_{\text{critical}} = \frac{8\gamma V_0}{P^2}$ .

Dielectric strength becomes zero in the absence of any bias field, i.e.,

$$\Delta \epsilon = 0. \tag{10}$$

### 2.2 Anti-phase mode

Using equation (1) and considering the condition of anti-phase mode [25,26,32], the connecting equation between the rotational viscosity and the fluctuation phase angle for anti-phase mode can be written as:

$$\begin{aligned} -\eta_b \left( \frac{\partial \phi_b}{\partial t} \right) = & EP \cos \phi_a \cos \phi_b \\ & - \left( 1 - \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \psi}{\partial t} \right) \sin 2\phi_b. \tag{11} \end{aligned}$$

The real component of dielectric permittivity for anti-phase mode can be written as [25,26,32]:

$$\begin{aligned} \epsilon_r = & \frac{1}{1 + \omega^2 \tau_b^2} \frac{P^2}{4\epsilon_0 \gamma} \\ & \left[ \left( 1 + \left( E_b^2 + \frac{E_0^2}{2} - 16\gamma V_0 \frac{E_b}{P^2} + \frac{4\gamma W_p(\theta)}{P^2} + \frac{\gamma \Gamma r(\theta)}{P^2 R} \right) \right. \right. \\ & \left. \left. \frac{P^2}{64\pi^2 K^* \gamma} \right) \right] + \frac{1}{1 + \omega^2 \tau_b^2} \frac{P^2}{4\epsilon_0 \gamma} \left[ \left( 1 + (2E_b^2 + E_0^2 \right. \right. \\ & \left. \left. - 16\gamma V_0 \frac{E_b}{P^2} + \frac{4\gamma W_p(\theta)}{P^2} + \frac{\gamma \Gamma r(\theta)}{P^2 R} \right) P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \\ & \left. \lambda \frac{P^2}{\gamma} \frac{\partial \nabla \psi}{\partial P} \right]. \tag{12} \end{aligned}$$

The imaginary component of dielectric permittivity for anti-phase mode can be written as [25,26,32]:

$$\begin{aligned} \varepsilon_i = & \frac{\omega\tau_b}{1 + \omega^2\tau_b^2} \frac{P^2}{4\varepsilon_0\gamma} \left[ \left( 1 + \left( E_b^2 + \frac{E_0^2}{2} - 16\gamma V_0 \frac{E_b}{P^2} \right. \right. \right. \\ & \left. \left. \left. + \frac{4\gamma W_p(\theta)}{P^2} + \frac{\gamma\Gamma r(\theta)}{P^2 R} \right) P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \right] \\ & + \frac{\omega\tau_b}{1 + \omega^2\tau_b^2} \frac{P^2}{4\varepsilon_0\gamma} \left[ \left( 1 + \left( 2E_b^2 + E_0^2 - 16\gamma V_0 \frac{E_b}{P^2} \right. \right. \right. \\ & \left. \left. \left. + \frac{4\gamma W_p(\theta)}{P^2} + \frac{\gamma\Gamma r(\theta)}{P^2 R} \right) P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \lambda \frac{P^2}{\gamma} \frac{\partial \nabla \psi}{\partial P} \right]. \end{aligned} \quad (13)$$

The rotational viscosity for anti-phase mode can be written as [25,26,32]:

$$\tau_b = \frac{\eta_b}{\gamma} \left( 1 + \frac{\lambda P^2}{\gamma} \frac{\partial \nabla \psi}{\partial t} \right). \quad (14)$$

The dielectric strength for anti-phase mode can be written as [25,26,32]:

$$\begin{aligned} \Delta\varepsilon = & \frac{P^2}{4\varepsilon_0\gamma} \left[ \left( 1 + \left( E_b^2 + \frac{E_0^2}{2} - 16\gamma V_0 \frac{E_b}{P^2} + \frac{4\gamma W_p(\theta)}{P^2} \right. \right. \right. \\ & \left. \left. \left. + \frac{\gamma\Gamma r(\theta)}{P^2 R} \right) P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \right] + \frac{P^2}{4\varepsilon_0\gamma} \left[ \left( 1 + (2E_b^2 + E_0^2 \right. \right. \right. \\ & \left. \left. \left. - 16\gamma V_0 \frac{E_b}{P^2} + \frac{4\gamma W_p(\theta)}{P^2} \right. \right. \right. \\ & \left. \left. \left. + \frac{\gamma\Gamma r(\theta)}{P^2 R} \right) P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \lambda \frac{P^2}{\gamma} \frac{\partial \nabla \psi}{\partial P} \right]. \end{aligned} \quad (15)$$

In the absence of bias field,

$$\begin{aligned} \Delta\varepsilon = & \frac{P^2}{4\varepsilon_0\gamma} \left[ \left( 1 + \left( \frac{E_0^2}{2} + \frac{4\gamma W_p(\theta)}{P^2} + \frac{\gamma\Gamma r(\theta)}{P^2 R} \right) \right. \right. \\ & \left. \left. \left. P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \right] + \frac{P^2}{4\varepsilon_0\gamma} \left[ \left( 1 + \left( E_0^2 + \frac{4\gamma W_p(\theta)}{P^2} \right. \right. \right. \\ & \left. \left. \left. + \frac{\gamma\Gamma r(\theta)}{P^2 R} \right) P^2 \frac{P^2}{64\pi^2 K^* \gamma} \right) \lambda \frac{P^2}{\gamma} \frac{\partial \nabla \psi}{\partial P} \right]. \end{aligned} \quad (16)$$

The anti-phase dielectric strength contains two parts. One is strongly depending on the free volumes of polymer systems and another is strongly depending on the both free volumes of the polymeric systems as well as polymer cross link-chains. So, the anti-phase dielectric strength is strongly depending on the polymer cross link-chains.

### 3. Discussion

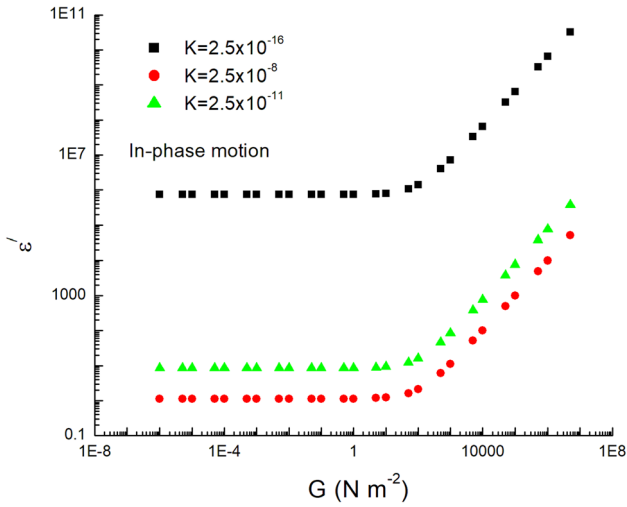
Figures 1, 2 and 3 describe about the variations in dielectric constant ( $\varepsilon'$ ), dielectric loss ( $\varepsilon''$ ) and dielectric strength ( $\Delta\varepsilon$ ) with the variation in polymer chain strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) with three different values of elastic constant for in-phase motion. The dielectric parameters of PDAFLC increases with the increase in  $G$  for all three dielectric parameters. It clearly

indicates that the values of dielectric parameters are almost constant till 100 of  $G$  and then, it increases sharply with the increase in  $G$  for all the elastic constant values. It means that all dielectric constant, dielectric loss and dielectric strength increase remarkably after 100 of  $G$  with the polymer inter-chains. By considering three different values of elastic constant, all the dielectric parameters are decreased remarkably with the increase in elastic constant. So, the elastic constant plays an important role for the values of dielectric parameters in PDAFLC which is directly influenced by the interaction between the ionic conductivity of the system and polymeric cross-linked chain strength of polymer matrix. It clearly indicates from figures 1, 2 and 3 that the polymer cross-linked chains strongly influence the dielectric parameters of PDAFLC for in-phase motion. The interaction between ionic conductivity and polymer cross-linked chain strength influences a little bit to the dielectric parameters.

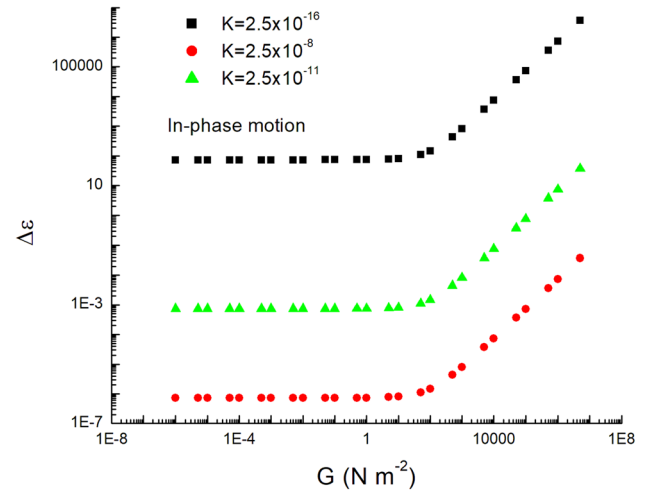
These also depicted a clear variation in dielectric constant, dielectric loss and dielectric strength with the variation in polymer cross-linked chain strength ( $G$ ) for three different values of elastic constant. It clearly indicates from such figures that the polymer cross-linked chain strength strongly influences the dielectric parameters of PDAFLC. It also clearly indicates from such figures that the ionic conductivity and its interaction with polymer cross-linked chain strength ( $G$ ) strongly influence the dielectric parameters of PDAFLC for in-phase motion.

Figures 4, 5 and 6 describe about the variation in dielectric constant ( $\varepsilon'$ ), dielectric loss ( $\varepsilon''$ ) and dielectric strength ( $\Delta\varepsilon$ ) with the variation in  $G$ , respectively, keeping the elastic constant  $K$  and the inter-layer strength ( $V_0$ ) as constants for anti-phase motion. It clearly indicates from figure 4 that the dielectric constant is highly influenced by both polymeric inter-linked chains and ionic conductivity as well as their interaction. The modified elasticity because of the interaction has influenced the dielectric behaviour. For higher values of elastic constant, dielectric constant suppresses more than that of lower values. Higher elasticity makes the system in more restricted geometry which discourages the orientation of dipole moments. The same scenario occurs for both dielectric loss and dielectric strength variation phenomena as depicted in figures 5 and 6 because of the same reasons as mentioned earlier.

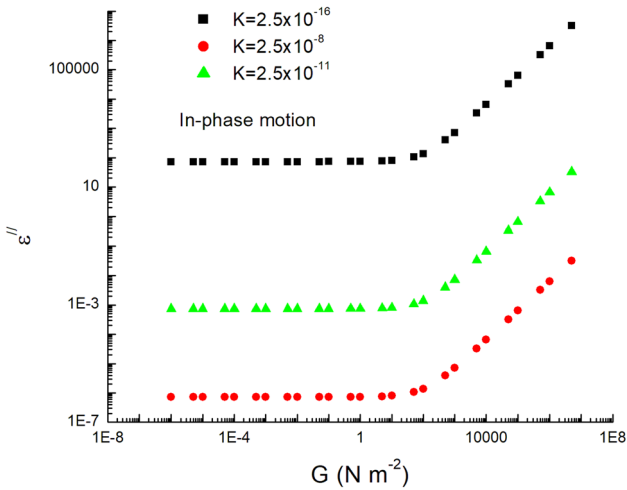
Klosowicz *et al* [33] reported about the variation in modulation of light of an antiferroelectric phase to be shown as a linear increase in the amplitude of such, at 30°C for PDAFLC of W-104 AFLC with NOA-65 photocurable resin with the increase in applied field. Klosowicz *et al* [34] also reported an experimental observation of optical contrast of PDAFLC contained W182 orthoconic AFLC with NOA-65 photocurable resin correlated with the increase in the optical modulation which gives information about the variation and properties of optical as well as its degradation interconnected with the influence of inter-layer charges as well its interaction with the polymer inter-linked chain strengths.



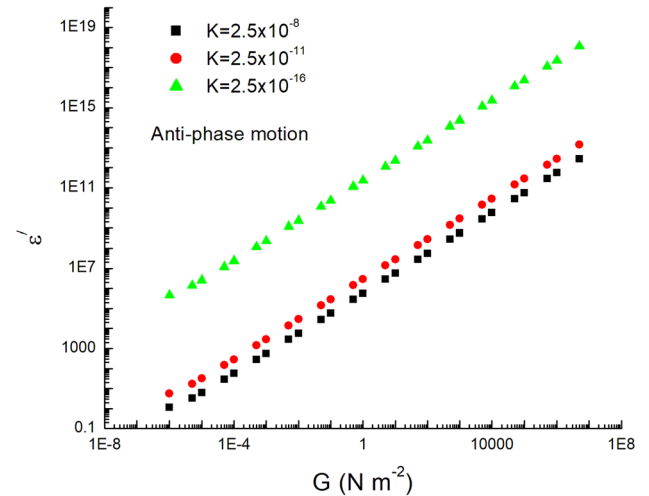
**Figure 1.** Variation in real component ( $\epsilon'$ ) with the variation in polymer cross-link strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) for in-phase motion of PDAFLC at different  $K$  values. The values of parameters taken for calculations are given as:  $P = 8 \times 10^{-4} \text{ C m}^{-2}$ ;  $\gamma = W_p(\theta) = 1.6 \times 10^4 \text{ J m}^{-3}$ ;  $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ ;  $E_b = 4 \text{ volt}$ ;  $E_0 = 1 \text{ volt}$ ;  $p \approx 10^{-6} \text{ m}$ ;  $\lambda = 2.5 \times 10^8$ ;  $V_0 = -1 \text{ a.u.}$ ;  $\frac{r(\theta)}{R} = 1 = \omega\tau_a = \omega\tau_b$ .



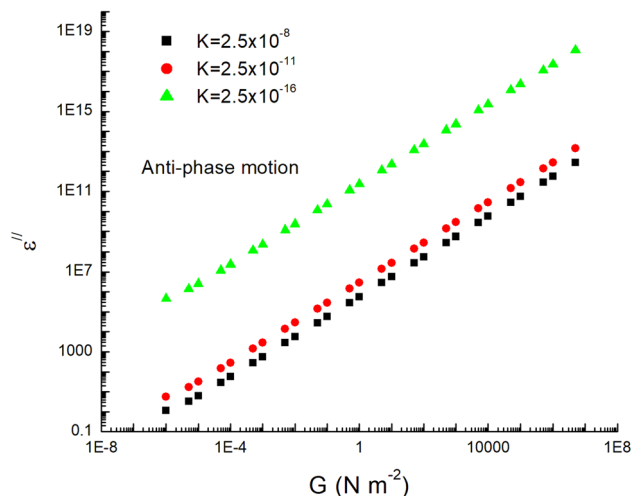
**Figure 3.** Variation in dielectric strength ( $\Delta\epsilon$ ) with the variation in polymer cross-link strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) for in-phase motion of PDAFLC at different  $K$  values. The values of parameters taken for calculations are given as:  $P = 8 \times 10^{-4} \text{ C m}^{-2}$ ;  $\gamma = W_p(\theta) = 1.6 \times 10^4 \text{ J m}^{-3}$ ;  $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ ;  $E_b = 4 \text{ volt}$ ;  $E_0 = 1 \text{ volt}$ ;  $p \approx 10^{-6} \text{ m}$ ;  $\lambda = 2.5 \times 10^8$ ;  $V_0 = -1 \text{ a.u.}$ ;  $\frac{r(\theta)}{R} = 1 = \omega\tau_a = \omega\tau_b$ .



**Figure 2.** Variation in imaginary component ( $\epsilon''$ ) with the variation in polymer cross-link strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) for in-phase motion of PDAFLC at different  $K$  values. The values of parameters taken for calculations are given as:  $P = 8 \times 10^{-4} \text{ C m}^{-2}$ ;  $\gamma = W_p(\theta) = 1.6 \times 10^4 \text{ J m}^{-3}$ ;  $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ ;  $E_b = 4 \text{ volt}$ ;  $E_0 = 1 \text{ volt}$ ;  $p \approx 10^{-6} \text{ m}$ ;  $\lambda = 2.5 \times 10^8$ ;  $V_0 = -1 \text{ a.u.}$ ;  $\frac{r(\theta)}{R} = 1 = \omega\tau_a = \omega\tau_b$ .



**Figure 4.** Variation in real component ( $\epsilon'$ ) with the variation of polymer cross-link strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) for anti-phase motion of PDAFLC at different  $K$  values. The values of parameters taken for calculations are given as:  $P = 8 \times 10^{-4} \text{ C m}^{-2}$ ;  $\gamma = W_p(\theta) = 1.6 \times 10^4 \text{ J m}^{-3}$ ;  $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ ;  $E_b = 4 \text{ volt}$ ;  $E_0 = 1 \text{ volt}$ ;  $p \approx 10^{-6} \text{ m}$ ;  $\lambda = 2.5 \times 10^8$ ;  $V_0 = -1 \text{ a.u.}$ ;  $\frac{r(\theta)}{R} = 1 = \omega\tau_a = \omega\tau_b$ .



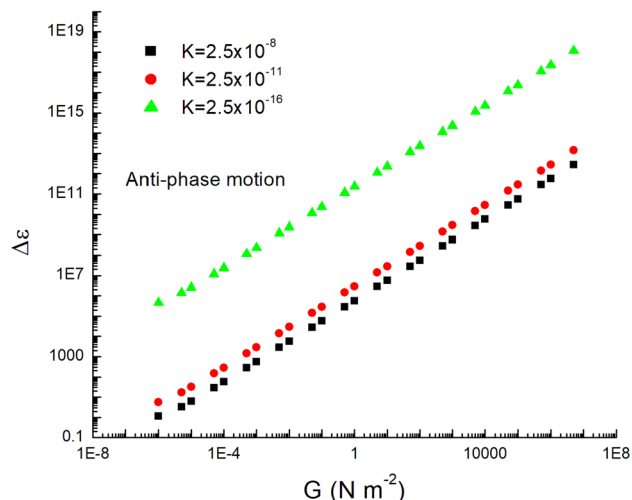
**Figure 5.** Variation in imaginary component ( $\epsilon''$ ) with the variation in polymer cross-link strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) for anti-phase motion of PDAFLC at different  $K$  values. The values of parameters taken for calculations are given as:  $P = 8 \times 10^{-4} \text{ C/m}^2$ ;  $\gamma = W_p(\theta) = 1.6 \times 10^4 \text{ J m}^{-3}$ ;  $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ ;  $E_b = 4 \text{ volts}$ ;  $E_0 = 1 \text{ volt}$ ;  $p \approx 10^{-6} \text{ m}$ ;  $\lambda = 2.5 \times 10^8$ ;  $V_0 = -1 \text{ a.u.}$ ;  $\frac{r(\theta)}{R} = 1 = \omega\tau_a = \omega\tau_b$ .

#### 4. Conclusions

In the presence of polymer cross-link chains, the influence of ionic conductivity has been significantly changing the characteristics of antiferroelectric liquid crystals system both in in-phase and anti-phase motions. The dielectric parameters strongly depend on the strength of the interaction between the charge density and strength of polymer inter-linked chains. Such influence clearly gives us a clear indication about the influence of charge density in PDAFLC related to optical contrast of the system as well as its stability. So, a model is established to account the importance of inter-layers accumulated charges in PDAFLC for fabricating and stabilizing optical devices in future.

#### References

- [1] Takezoe H, Gorecka E and Cepic M 2010 *Rev. Mod. Phys.* **82** 897
- [2] Chandani A D L, Ouchi Y, Takezoe H, Fukuda A, Terashima K, Furukawa K *et al* 1989 *Jpn. J. Appl. Phys.* **28** L1261
- [3] Roy A and Madhusudana N V 1998 *Eur. Phys. Lett.* **41** 501
- [4] Furue H, Kuramochi H and Kakinuma D 2008 *Jpn. J. Appl. Phys.* **47** 7638
- [5] Chandani A D L, Gorecka E, Ouchi Y, Takezoe H and Fukuda A 1989 *Jpn. J. Appl. Phys.* **28** L1265
- [6] Lagerwall S T 1999 *Ferroelectric and antiferroelectric liquid crystals* (Weinheim: Wiley-VCH)



**Figure 6.** Variation in dielectric strength ( $\Delta\epsilon$ ) with the variation in polymer cross-link strength ( $G = \frac{\partial \nabla \psi}{\partial P}$ ) for anti-phase motion of PDAFLC at different  $K$  values. The values of parameters taken for calculations are given as:  $P = 8 \times 10^{-4} \text{ C m}^2$ ;  $\gamma = W_p(\theta) = 1.6 \times 10^4 \text{ J m}^{-3}$ ;  $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ ;  $E_b = 4 \text{ volt}$ ;  $E_0 = 1 \text{ volt}$ ;  $p \approx 10^{-6} \text{ m}$ ;  $\lambda = 2.5 \times 10^8$ ;  $V_0 = -1 \text{ a.u.}$ ;  $\frac{r(\theta)}{R} = 1 = \omega\tau_a = \omega\tau_b$ .

- [7] Hiraoka K, Chandani A D L, Gorecka E, Ouchi Y, Takezoe H and Fukuda A 1990 *Jpn. J. Appl. Phys.* **29** L1473
- [8] Kuczynski W, Dardas D and Nowicka K 2009 *Phase Transit.* **82** 444
- [9] Uchiyama Y, Moritake H, Ozaki M, Yoshino K, Taniguchi H, Satoh K *et al* 1993 *Jpn. J. Appl. Phys.* **32** 4335
- [10] Bibonne F, Parneix J P, Isaert N, Joly G, Nguyen H T, Bouchta A *et al* 1995 *Mol. Cryst. Liq. Cryst.* **263** 27
- [11] Hiraoka K, Takezoe H and Fukuda A 1993 *Ferroelectrics* **147** 13
- [12] Hiller S, Pikin S A, Haase W, Goodby J W and Nishiyama I 1994 *Jpn. J. Appl. Phys.* **33** L1170
- [13] Buivydas M, Gouda F, Lagerwall S T and Stebler B 1995 *Liq. Cryst.* **18** 879
- [14] Buivydas M, Gouda F, Andersson G, Lagerwall S T, Stebler B, Bomelburg J *et al* 1997 *Liq. Cryst.* **23** 723
- [15] Hou J, Schacht J, Giesselmann F and Zugenmaier P 1997 *Liq. Cryst.* **22** 409
- [16] Panarin Yu P, Kalinovskaya O and Vij J K 1998 *Liq. Cryst.* **25** 241
- [17] Kimura Y and Isono H 2004 *Ferroelectrics* **310** 87
- [18] Kimura Y, Hayakawa R, Okabe N and Suzuki Y 1996 *Phys. Rev. E* **53** 6080
- [19] Nayek P, Ghosh S, Kundu S, Roy S, Pal Majumder T, Bennis N *et al* 2009 *J. Phys. D: Appl. Phys.* **42** 225504
- [20] Srivastava A K, Agrawal V K, Dabrowski R, Oton J M and Dhar R 2005 *J. Appl. Phys.* **98** 013543
- [21] Parry-Jones L A and Elston S J 2002 *J. Appl. Phys.* **92** 449
- [22] Parry-Jones L A and Elston S J 2001 *Phys. Rev. E* **63** R050701
- [23] Brown C V and Jones J C 1999 *J. Appl. Phys.* **86** 3333

- [24] Das D, Lahiri T and Pal Majumder T 2011 *Physica B* **406** 1577; Corrigendum: Das D, Lahiri T and Pal Majumder T 2013 *Physica B* **414** 120
- [25] Das D, Pal Majumder T and Ghosh N K 2014 *Physica B* **436** 41
- [26] Das D and Pal Majumder T 2015 *Sci. Lett. J.* **4** 99
- [27] Das D, Mandal P and Pal Majumder T 2015 *Sci. Lett. J.* **4** 194
- [28] Das D, Mandal P and Pal Majumder T 2015 *Braz. J. Phys.* **45** 280
- [29] Mandal P, Das D and Pal Majumder T 2016 *J. Mol. Liq.* **215** 170
- [30] Das D, Mandal P and Pal Majumder T 2017 *J. Pure Appl. Indus. Phys.* **7** 175
- [31] Pal Majumder T, Mandal P and Das D 2017 *J. Pure Appl. Indus. Phys.* **7** 436
- [32] Mandal P, Das D and Pal Majumder T 2018 *Int. J. Curr. Adv. Res.* **7** 9402
- [33] Klosowicz S J, Czuprynski K L and Piecek W 2000 *Mol. Cryst. Liq. Cryst.* **351** 343
- [34] Klosowicz S J, Piecek W, Dabrowski R and Perkowski P 2004 *Mol. Cryst. Liq. Cryst.* **422** 21