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The Effect of Spin-Spin Interaction in the Region of Freedricksz Transition in Antiferroelectric Liquid Crystals

Tapas Pal Majumder, Pravash Mandal and Deblal Das

Department of Physics,
University of Kalyani, Kalyani, Nadia 741235, West Bengal, INDIA.
email:tpm@klyuniv.ac.in or tpmajumder1966@gmail.com

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ABSTRACT

We have studied the Freedericksz transition of antiferroelectric liquid crystals (PDAFLCs) utilizing Landau-Ginzburg (LG) equation. Low frequency in-phase mode and high frequency anti-phase mode in the region of Freedericksz transition influenced by the interactions between spin angular momentum and spin angular momentum of the accumulated charges on smectic layers have been discussed. Dielectric characteristics have been investigated in detail both in in-phase and anti-phase motions in the region of the Freedericksz transition in AFLCs influenced due to spin-spin interactions. We theoretically noticed the dielectric strength become negligibly small for in-phase motion and the dielectric strength become independent with spin because of strong spin-spin interactions of the accumulated charges on smectic layers in AFLCs.

Keywords: Antiferroelectric liquid crystal; Freedericksz transition; Dielectric function; Landau-Ginzburg equation; In-phase and anti-phase motions.

1. INTRODUCTION

Antiferroelectric liquid crystals (AFLCs) have been studied since long times for finding its capability to be applied (SmC_A^*)[1-5] in getting advanced display devices in future for having its spontaneous polarization at different layers oppositely because of its helical structure. The **c**-director of the adjacent layers of antiferroelectric liquid crystals which is roughly antiparallel each other associated with the spontaneous polarization perpendicular to the **c**-director to be considered because about the chiral nature of the elongated molecules in smectic layers. Since the AFLCs to ferroelectric liquid crystals (FLCs) transition is associated with the variation of dipole moment so the application of an external electric can induce the variation of the effective dipole moment for doing such transition[6]. The application of a certain amount of electric field produces the loses of the stability of antiferroelectric configuration loses called critical field. Except that the finite dimensional liquid crystal materials associated with another type of transition below than that region with the application of a very low amount of applied field called threshold field. The Freedericksz transition which is associated with the creation of anisotropy of the medium[7-8] and the surface effect[9] has been extensively studied for finding the variation of the dielectric functions influenced by the effect of spin angular momentum arose because of the accumulated charges on the smectic layers[9-21]. We already studied in detail about the variation of dielectric functions for both in-phase and anti-phase motions in the region of Freedricksz transition by taking into the consideration of flexoelectric polarization effect[22] of AFLCs. In this paper, we have considered the effect of spin angular momentum for finding any expected variation of dielectric functions in the region of Freedericksz transition.

2. THEORY AND DISCUSSION

2.1. In-phase motion

The Landau free energy has been considered by taking into the consideration of dielectric anisotropy, surface anchoring and spin-spin interactions among adjacent layers for the study of Freedericksz transition in a finite dimension AFLCs. The expected free energy including spin-spin interactions between adjacent layers of antiferroelectric liquid crystals within the limit of Freedricksz transition can be written as[23-26]:

$$F = -EP\cos\emptyset_a\cos\emptyset_b + \gamma\cos^2\emptyset_b + 2EV_0\cos(2\emptyset_\mathrm{a}) + \frac{1}{2}\mathrm{K}\left(\frac{\partial\emptyset_a}{\partial\mathrm{x}} - \frac{2\pi}{\mathrm{p}}\right)^2 - \frac{\varepsilon_0\Delta\varepsilon sin^2\theta_0}{2}\mathrm{E}^2 sin^2\emptyset_a + W(z)sin^2\emptyset_a + B_0\vec{E}\cdot\hat{n}_{ij}\times\left(\vec{S}_i\times\vec{S}_j\right) - \chi\hat{Z}\cdot\left(\vec{\nabla}\phi_a\times\vec{\nabla}\rho\right) + \frac{1}{2}\beta\left|\vec{\nabla}\rho\right|^2 + \frac{1}{4}\lambda\left|\vec{\nabla}\rho\right|^4 \tag{1}$$

Where $\emptyset_a$ and $\emptyset_b$ are two azimuthal angles associated with the azimuthal angles $\emptyset_e$ and $\emptyset_\mathrm{o}$ for even and odd layers, as defined by $\emptyset_a = \frac{\emptyset_e+\emptyset_\mathrm{o}}{2}$ and $\emptyset_b = \frac{\emptyset_e-\emptyset_\mathrm{o}}{2}$. The second first term in Eq. (1) is the dipolar term associated with the antiferroelectric ordering with γ as positive in nature. The first is the coupling term between applied electric field (E) and polarization (P). The third one is the coupling term between the applied electric field and the inter-layer interaction strength (V_0). The fourth one is only because of the elasticity with the helical structure of AFLCs. The fifth term is the contribution coming because of the dielectric anisotropy of AFLCs for its finite dimensions. The sixth term is the term containing W(z) as a surface anchoring energy. The seventh term is associated with the spin-spin interactions of the accumulated charges on layers. The last three terms are associated with the charge density of such accumulated charges on layers.

The expected simplified free energy can be written as for in-phase motion at the stabilized condition[23-26]:

$$F = -\frac{E^2P^2}{4\gamma}\cos^2\emptyset_a + 2EV_0\cos(2\emptyset_a) + \frac{1}{2}K^*\left(\frac{\partial\emptyset_a}{\partial x} - \frac{2\pi}{p}\right)^2 - \frac{\varepsilon_0\Delta\varepsilon sin^2\theta_0}{2}E^2 sin^2\emptyset_a + W(z)sin^2\emptyset_a + B_0\, E\, S^2 \sin\theta\cos\emptyset_a - \frac{\beta^2}{4\lambda} \qquad (2)$$

Where, $K^* = K - \frac{\lambda^2}{\beta}$,

The Landau-Ginzburg equation for the azimuthal angle $\emptyset_a$ connecting the viscosity with the in-phase motion is given as[23-26]:

$$-\frac{\eta_a p^2}{K^*}\frac{\partial\emptyset_a}{\partial t} = \frac{p^2}{K^*}\left[\frac{E^2P^2}{4\gamma} - 4EV_0 - \frac{\varepsilon_0\Delta\varepsilon sin^2\theta_0}{2}E^2 + W(z)\right]\sin(2\emptyset_a) - \frac{B_0 E\, S^2 p^2\sin\theta}{K^*}\sin\emptyset_a - \frac{\partial^2\emptyset_a}{\partial T^2} \qquad (3)$$

Where, $T = x/p$, a dimensionless parameter and p is the pitch of helix. By considering the trial solution, $\emptyset_a = 2\pi T + (a + bexpi\omega t + cexp2i\omega t)\sin(4\pi T)$ into the Eq. (3) we get the solution of $\emptyset_a$ as

$$\emptyset_a = 2\pi T - \delta(\omega)\sin(4\pi T) \qquad (4)$$

The first term of the trial solution describes the ground state part of the helical structure and the second part is its perturbation with the Fourier component, $\sin(4\pi T)$. So, $\delta(\omega)$ can be written as the form given below[23-26]:

$$\delta(\omega) = \frac{p^2}{16\pi^2 K}\left[\left(\frac{P^2}{\gamma}\left(E_b^2 + \frac{E_0^2}{2}\right) - 16\, E_b V_0 - 2\,\varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E^2 + 4\, W(Z) - 2B_0E_bS^2\sin\theta\right) + \left(\frac{2\, E_bE_0P^2}{\gamma} - 16\, E_0V_0 - 4\,\varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E_bE_0 - 2B_0E_bS^2\sin\theta\right)\frac{expi\omega t}{1+i\omega\tau_a} + \left(\frac{P^2}{\gamma} - 2\varepsilon_0\Delta\varepsilon\sin^2\theta_0\right)\frac{{E_0}^2}{2}\frac{exp2i\omega t}{1+2i\omega\tau_a}\right] \qquad (5)$$

The average value of P_z can be written as[23-26]:

$$\langle P_z\rangle = \frac{EP^2}{4\gamma}[1 + \delta(\omega)] \qquad (6)$$

Therefore, the average value of polarization at frequency ω is given below[23-26]:

$$\langle P_z at\omega\rangle = \frac{EP^2}{4\gamma}\left[1 + \left\{\left(\frac{P^2}{\gamma}\left(E_b^2 + \frac{E_0^2}{2}\right) - 16\, E_bV_0 - 2\,\varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E^2 + 4\, W(Z) - 2B_0E_bS^2\sin\theta\right) + \left(\frac{2\, E_bE_0P^2}{\gamma} - 16\, E_0V_0 - 4\,\varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E_bE_0 - 2B_0E_bS^2\sin\theta\right)\frac{expi\omega t}{1+i\omega\tau_a} + \left(\frac{E_0^2P^2}{2\gamma} - \varepsilon_0\Delta\varepsilon\sin^2\theta_0\right)\frac{exp2i\omega t}{1+2i\omega\tau_a}\right\}\frac{p^2}{64\,\pi^2K^*}\right] \qquad (7)$$

After the separation of the coefficients of exponential terms, the polarization can be written as[23-26]:

$$\langle P_z at\omega\rangle = \frac{P^2}{4\gamma}\left[1 + \left\{\left(\frac{E_b^2P^2}{\gamma} + \frac{E_0^2P^2}{2\gamma} - 16\, E_bV_0 - 2\,\varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E_b^2 - \varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E_0^2 + 4\, W(Z) - 2B_0E_bS^2\sin\theta\right) + \left(\frac{2\, E_b^2P^2}{\gamma} - 16\, E_bV_0 - 4\,\varepsilon_0\Delta\varepsilon\sin^2\theta_0\, E_b^2 - 2B_0E_bS^2\sin\theta\right)\frac{1}{1+i\omega\tau_a}\right\}\frac{p^2}{64\pi^2K^*}\right] \times E_0 exp(i\omega t) \qquad (8)$$

$$\langle P_z at\omega\rangle = \frac{P^2}{4\gamma}\left[1 + \left\{4A\left(E_b^2 + \frac{E_0^2}{2}\right) - 16\, E_bV_0 - 2B_0E_bS^2\sin\theta + 4W(Z)\right\} + \left\{(8A\, E_b^2 - 16\, E_bV_0 - 2B_0E_bS^2\sin\theta)\frac{1}{1+i\omega\tau_a}\right\}\frac{p^2}{64\pi^2K^*}\right] \times E_0 exp(i\omega t) \qquad (9)$$

The relative complex dielectric permittivity of the liquid crystal medium is[23-26]:

$$\varepsilon = \frac{P^2}{4\varepsilon_0\gamma}\left[1 + \left\{4A\left({E_b}^2 + \frac{{E_0}^2}{2}\right) - 16E_bV_0 + 4\mathrm{W(z)} - 2B_0E_bS^2\sin\theta + \left(8A{E_b}^2 - 16E_bV_0\right)\frac{1}{1+i\omega\tau_a}\right\}\frac{p^2}{16\pi^2\mathrm{K}^*}\right] \quad (10)$$

Where, $A = \frac{P^2}{4\gamma} - \frac{\varepsilon_0\Delta\varepsilon\sin^2\theta_0}{2}$ (11)

After the separation of the real and imaginary components of the dielectric permittivity, the real component can be written as [23-26]:

$$\varepsilon_r = \frac{P^2}{4\varepsilon_0\gamma}\left[1 + \left\{4A\left({E_b}^2 + \frac{{E_0}^2}{2}\right) - 16E_bV_0 - 2B_0E_bS^2\sin\theta + 4\mathrm{W(z)} + \left(8{E_b}^2A - 16E_bV_0 - 2B_0E_bS^2\sin\theta\right)\frac{1}{1+\omega^2{\tau_a}^2}\right\}\frac{p^2}{16\pi^2\mathrm{K}^*}\right] \quad (12)$$

And the imaginary component as[23-26]:

$$\varepsilon_i = \frac{\omega\tau_a}{1+\omega^2{\tau_a}^2}\left[8{E_b}^2A - 16E_bV_0 - 2B_0E_bS^2\sin\theta\right]\frac{P^2p^2}{256\pi^2\varepsilon_0\mathrm{K}^*\gamma} \quad (13)$$

When, $\omega << \frac{1}{\tau_a}$, where $\tau_a = \frac{\eta_a}{16\,\pi^2K^*}$

$$\varepsilon_r = \frac{P^2}{4\varepsilon_0\gamma}\left[1 + \left\{4A\left({E_b}^2 + \frac{{E_0}^2}{2}\right) - 16E_bV_0 - 2B_0E_bS^2\sin\theta + 4\mathrm{W(z)} + \left(8{E_b}^2A - 16E_bV_0 - 2\,B_0E_bS^2\sin\theta\right)\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] \quad (14)$$

When, $\omega >> \frac{1}{\tau_a}$

$$\varepsilon_r = \frac{P^2}{4\varepsilon_0\gamma}\left[1 + \left\{4A\left({E_b}^2 + \frac{{E_0}^2}{2}\right) - 16E_bV_0 - 2B_0E_bS^2\sin\theta + 4\mathrm{W(z)} + \left(8{E_b}^2A - 16E_bV_0 - 2B_0E_bS^2\sin\theta\right)\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] \quad (15)$$

Therefore, the dielectric strength for in-phase motion of the medium is[23-26]:

$$\Delta\varepsilon = \left(8A{E_b}^2 - 16E_bV_0 - 2B_0E_bS^2\sin\theta\right)\frac{P^2p^2}{256\pi^2\varepsilon_0\mathrm{K}^*\gamma} = \left[8\left(\frac{P^2}{4\gamma} - \frac{\varepsilon_0\Delta\varepsilon\sin^2\theta_0}{2}\right){E_b}^2 - 16E_bV_0 - 2B_0E_bS^2\sin\theta\right]\frac{P^2p^2}{256\pi^2\varepsilon_0\mathrm{K}^*\gamma} = \frac{\alpha}{4}\left(2P^2E_b^2 - 16E_bV_0\right) - \alpha\varepsilon_0\,\Delta\varepsilon\,\sin^2\theta_0E_b^2 - \frac{\alpha}{2}B_0E_bS^2\sin\theta = \frac{\alpha}{2}\left(P^2E_b^2 - 8E_bV_0\right) - \beta\,\Delta\varepsilon\sin^2\theta_0E_b^2 - \frac{\alpha}{2}B_0E_bS^2\sin\theta \quad (16)$$

2.2. Anti-phase motion

The Landau-Ginzburg equation for the system with respect to $\emptyset_b$ for high frequency relaxation mode can be written as[23-26]:

$$-\eta_b\frac{\partial\emptyset_b}{\partial t} = EP\cos\emptyset_a\sin\emptyset_b - \gamma\sin 2\emptyset_b \quad (17)$$

The net polarization is[23-26]:

$$\langle P_z\ at\ \omega\rangle = \frac{\mathrm{E_0 expi\omega t}}{1+\mathrm{i}\omega\tau_\mathrm{b}}\frac{P^2}{4\gamma}\left[1 + \delta(\infty)\right] \quad (18)$$

$$\langle P_z\ at\ \omega\rangle = \frac{\mathrm{E_0 expi\omega t}}{1+\mathrm{i}\omega\tau_\mathrm{b}}\frac{P^2}{4\gamma}\left[1 + \left\{4A\left({E_b}^2 + \frac{{E_0}^2}{2}\right) - 16E_bV_0 + 4\mathrm{W(z)} - 2B_0E_bS^2\sin\theta\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] \quad (19)$$

So the dielectric permittivity of the liquid crystal medium for anti-phase motion is[23-26]:

$$\varepsilon = \frac{1}{1+\mathrm{i}\omega\tau_b}\frac{P^2}{4\gamma}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}-2B_0E_bS^2\sin\theta\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] \quad (20)$$

After the separation of the real (ε_r) and imaginary (ε_i) components of relative dielectric permittivity, the real component of relative dielectric permittivity can be written as[23-26]:

$$\varepsilon_r = \frac{P^2}{4\varepsilon_0\gamma}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}-2B_0E_bS^2\sin\theta\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right]\frac{1}{1+\omega^2{\tau_b}^2} \quad (21)$$

And the imaginary component of relative dielectric permittivity can be written as[23-26]:

$$\varepsilon_i = \frac{P^2}{4\varepsilon_0\gamma}\left[1+\left\{A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}-2B_0E_bS^2\sin\theta\right\}\frac{p^2}{16\pi^2\mathrm{K}^*}\right]\frac{\omega\tau_b}{1+\omega^2{\tau_b}^2} \quad (22)$$

When, $\omega << \frac{1}{\tau_b}$

$$\varepsilon_r = \frac{P^2}{4\varepsilon_0\gamma}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}-2B_0E_bS^2\sin\theta\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] \quad (23)$$

When, $\omega >> \frac{1}{\tau_b}$

$$\varepsilon_r = 0 \quad (24)$$

Therefore, the dielectric strength for anti-phase motion is[23-26]:

$$\Delta\varepsilon = \frac{P^2}{4\varepsilon_0\gamma}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}-2B_0E_bS^2\sin\theta\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] = \frac{\alpha}{4}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}\right\}\right]-\frac{\alpha}{2}B_0E_bS^2\sin\theta \quad (25)$$

Except the very close to the surface region, W(z) is insignificant to provide any contribution. Therefore, the dielectric strength can be written as[23-26]:

$$\Delta\varepsilon = \frac{P^2}{4\varepsilon_0\gamma}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0+4\mathrm{W(z)}-2B_0E_bS^2\sin\theta\right\}\frac{p^2}{64\pi^2\mathrm{K}^*}\right] = \frac{\alpha}{4}\left[1+\left\{4A\left({E_b}^2+\frac{{E_0}^2}{2}\right)-16E_bV_0\right\}\right]-\frac{\alpha}{2}B_0E_bS^2\sin\theta \quad (26)$$

In the absence of spin-spin interactions and bias field, neglecting surface anchoring strength, the dielectric strength is given by[23-26]:

$$\Delta\varepsilon = \frac{P^2}{4\varepsilon_0\gamma}\left[1+2AE_0^2\right]\frac{p^2}{64\pi^2\mathrm{K}^*} \quad (27)$$

2.3. Discussion

Figure 1 represents the variation of dielectric strength with spin associated with the accumulated charges on smectic layers for both in-phase and anti-phase motions. The figures have been drawn on the basis of the data obtained from literatures to assume all constant parameters[24]. The in-phase motion has been frozen and the strength of it is negligibly small as depicted in figure 1. The anti-phase has a significant value of dielectric strength but it is roughly constant with the variation of spin. Figure 2 represents the variation of dielectric strength with spin associated with the accumulated charges on smectic layers for both in-phase and anti-phase motions at the bias field of 10 volts. It also shows the same behavior like figure 1. Figure 3 represents the variation of dielectric strength with spin associated with the accumulated charges on smectic layers for both in-phase and anti-phase motions at the bias field of 20 volts. It also shows the same behavior like figures 1 and 2. The critical field does not have any effect because of Freedericksz transition.

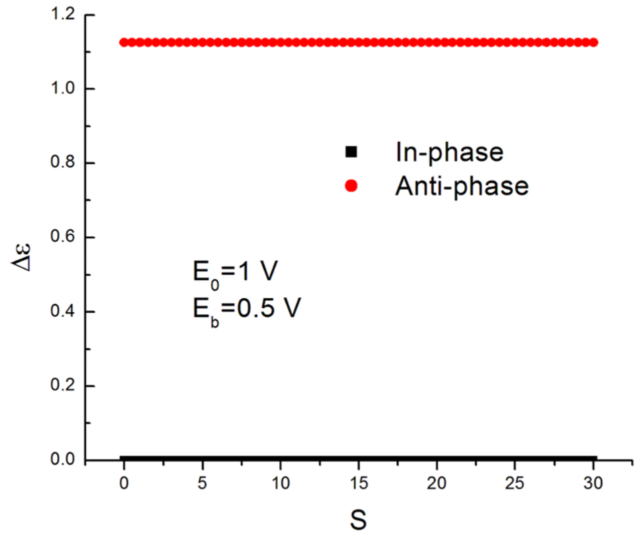

Fig. 1. Variation of dielectric strength [Δε] with the variation of spin angular momentum for both in-phase and anti-phase motions of an antiferroelectric liquid crystals at 0.5 bias voltage. The calculation is only performed for spin S=n+1/2, with n as an integer. The values are taken for the graphs are $A=0.9xP^2/4\gamma$, E_0=1V, E_b=0.5V, $\omega\tau_a$=1, $\omega\tau_b$=1, $\frac{P^2}{4\varepsilon_0\gamma} \approx 1.125$, P≈80 nC/cm^2, $\gamma \approx 1.6x10^4$ J/m^2, $K \approx 2.5x10^{-11}$ N, $\frac{P^2p^2}{64\pi^2K\gamma} \approx 2.53 \times 10^{-13}$, $\lambda \approx 2.5x10^8$, B_0=10 pGauss.

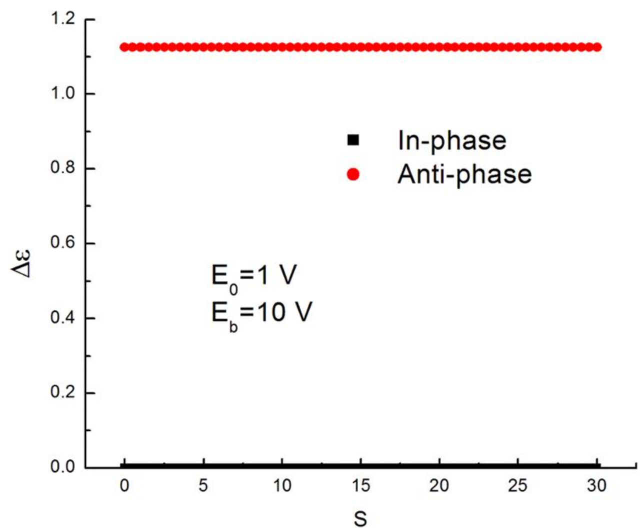

Fig. 2. Variation of dielectric strength [Δε] with the variation of spin angular momentum for both in-phase and anti-phase motions of an antiferroelectric liquid crystals at 10 bias voltage. The calculation is only performed for spin S=n+1/2, with n as an integer. The values are taken for the graphs are $A=0.9xP^2/4\gamma$, E_0=1V, E_b=10V, $\omega\tau_a$=1, $\omega\tau_b$=1, $\frac{P^2}{4\varepsilon_0\gamma} \approx 1.125$, P≈80 nC/cm^2, $\gamma \approx 1.6x10^4$ J/m^2, $K \approx 2.5x10^{-11}$ N, $\frac{P^2p^2}{64\pi^2K\gamma} \approx 2.53 \times 10^{-13}$, $\lambda \approx 2.5x10^8$, B_0=10 pGauss.

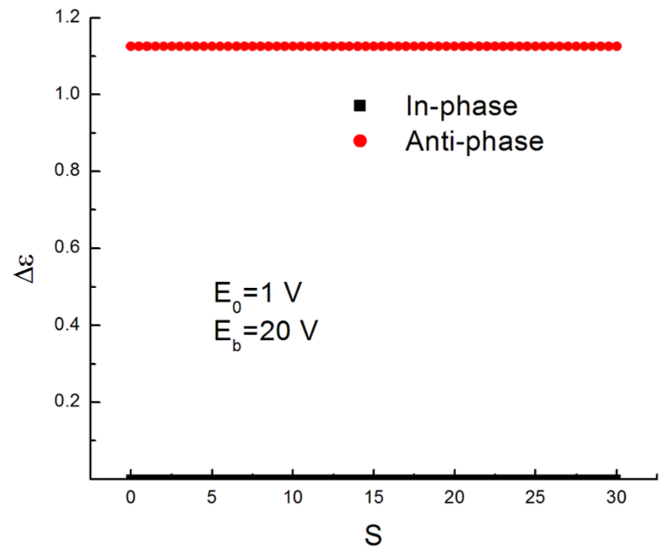

Fig. 3. Variation of dielectric strength [Δε] with the variation of spin angular momentum for both in-phase and anti-phase motions of an antiferroelectric liquid crystals at 20 bias voltage. The calculation is only performed for spin S=n+1/2, with n as an integer. The values are taken for the graphs are A=0.9xP^2/4γ, E_0=1V, E_b=20V, $\omega\tau_a$=1, $\omega\tau_b$=1, $\frac{P^2}{4\varepsilon_0\gamma} \approx 1.125$, P≈80 nC/cm^2, γ≈1.6x10^4 J/m^2, K≈2.5x10^{-11} N, $\frac{P^2p^2}{64\pi^2K\gamma} \approx 2.53 \times 10^{-13}$, λ≈2.5x10^8, B_0=10 pGauss.

3. CONCLUSION

Both in-phase and anti-phase motions have been unaffected due to the variation of bias field within the region of freedericksz transition in presence of spin-spin interactions. If we ignore the spin-spin interactions of the accumulated charges then the dielectric strength may vary with the variation of bias field. In the absence of bias field and spin-spin interactions the dielectric strength of anti-phase motion become strongly dependent on the bias field within the region of Freedericksz transition.

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