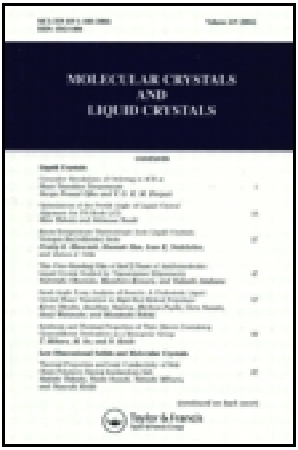

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UNWINDING OF THE HELIX IN THIN PLANAR CHOLESTERIC LAYERS

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Unwinding of a helix in thin planar cholesteric layers induced by the varying external parameters (temperature, electric or magnetic field) and its dependence on the surface anchoring are theoretically investigated for the defectless mechanism of the cholesteric pitch changing connected with a slipping of the director on the surface through the anchoring potential barrier. It is shown that the critical field of the helix unwinding E_c in a thin layer may be as essentially lower than the critical field in a bulk cholesteric so larger than this field and the unwinding process in a layer is a jump-like one contrary to the case of bulk cholesteric. The changes of E_c in a layer relative to the bulk critical field (growth or lowering) are dependent, in particular, on the initial (i.e. at zero field) director distribution in the layer. The expressions connecting E_c (the field of the pitch jump) with the cholesteric layer parameters, anchoring potential and the initial director distribution in the layer are found. The hysteresis of E_c and the corresponding bistability of the cholesteric layer for the opposite directions of the field changes are investigated. In particular, it is shown that for some range of the relevant to the problem parameter values the helix unwound by the field remains to be unwound after removing of the field. The analytically revealed qualitative features of the unwinding are illustrated by computations for the specific values of the cholesteric layer parameters.

Keywords: bistability in electric field; chiral smectics; cholesterics; hysteresis

INTRODUCTION

It is known that in an external electric (or magnetic) field applied perpendicularly to the helical axis of a chiral liquid crystal (CLC) a deformation of the spiral and its unwinding occur and the spiral becomes completely unwound (its pitch becomes infinite) at some critical value of the field [1,2]. The phenomena of deformation and unwinding of the spiral are

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studied quite well for the bulk CLC. The cholesterics were studied in [1,2] and the ferroelectric smectics in [3]. For the cholesterics as well for the smectics in bulk samples the pitch increase proceeds continuously with increasing of the applied field and the pitch reaches an infinite value for the critical value of the field. A similar picture of the spiral unwinding is observed for the temperature changes of the CLC pitch [4,5].

The temperature and field unwinding of the spiral in CLC layers of finite thickness is investigated considerably poorer. However just the CLC layers of finite thickness down to monomolecular layers [6] are investigated most intensively and reveal some interesting phenomena connected, in particular, with the molecular anchoring at the layer surfaces. The effects observed in the CLC layers and their influence on the optical properties of the layer are of a great applied value because just the electrooptics of the LC layers forms a basis of numerous efficient applications of LC in the displays and the information processing devises.

As it was known quite long ago the changes of CLC structure in the applied changing field [7,8] or at the temperature changes [4,5] at the presence of the surface anchoring may be along with continuous ones also jumpwise and the corresponding structure changes may reveal hysteresis for the opposite directions of the applied action changes [5,9,10]. The changes of the CLC structure and its hysteresis for the fields far away from the critical value were investigate in the theoretical paper [11], and the corresponding problem for the temperature changes was investigated in [12].

In the present paper the changes of the CLC layers structure and its hysteresis are investigated for the values of external actions close to the critical ones and the dependences of the critical actions (temperature or unwinding field) on the anchoring potential, layer thickness and parameters of CLC are analyzed.

IMPOSITION OF THE PROBLEM

The configuration of director distribution in a planar CLC layer is characterized, in particular, by a number N of the half-turns of the director spiral at the layer thickness d. It is assumed below, to be specific, that the alignment directions at the both surfaces of the layer are coinciding. Just before unwinding of the spiral under the imposed external action the director configuration in a layer is characterized by $N = 1$ while the configuration characterized by $N = 0$ corresponds to the final stage of unwinding. For finite forces of the surface anchoring the numbers N may be slightly different from the integer numbers due to the possibility of the director deviation from the alignment direction.

The forces of surface anchoring [11,12] are very essential in the process of spiral unwinding. Their influence results in jumps and hysteresis in the director configuration changes along with its smooth changes alone present in absence of the anchoring. Determine as a point of temperature or field unwinding of the spiral in a layer of finite thickness the jump transition of director configuration from N = 1 to N = 0. As it will be seen further an unwinding of the spiral in a layer of finite thickness may occur as in the field less than the critical field for a bulk sample so in the field larger than that field depending on the strength of the anchoring.

We shall not consider below the spiral unwinding connected with creation of defects in the field of director. It will be assumed that the spiral unwinding mechanism and associated with it jump from the configuration with N = 1 to the configuration with N = 0 proceeds by a slipping of the director on the surface of the layer through the potential barrier of surface anchoring.

It should be mentioned here that the actual value of the jump field (unwinding field) is dependent essentially on the director configuration in the layer at zero field. Really, the needed for the spiral unwinding field is dependent on the value of φ, the angle of director deviation at the surface from the alignment direction, at zero field. If this angle is close to the critical angle φ_c [12], which determines the value of φ corresponding to the jump to the configuration with N = 0, then the jump occurs at weak applied field or small temperature variations. If φ is far from φ_c then the needed for the jump value of the external action may be quite significant.

TEMPERATURE UNWINDING OF THE HELIX

Before discuss in details the field unwinding of the spiral examine the spiral unwinding at the temperature changes. This case occurs to be more simple because in the case there are only changes of the CLC pitch and of the number of half-turns N at the sample thickness due to the temperature variations while the spiral remains to be harmonic (undistorted). In the case of applied field along with the changes of the pitch there are also distortions of the spiral, i.e. it does not remain harmonic [1–3].

Examine a perfect planar layer of CLC assuming for definiteness the liquid crystal being a cholesteric. Assume also that the surface anchoring are identical at the both surfaces, the initial state of the cholesteric layer corresponds just one half-turn of the spiral, i.e. N = 1, and the alignment directions are the same at both surfaces. Under the made assumptions the pitch in the layer coincides with the pitch for a bulk sample, and the variations of the pitch due to the changes of the temperature are determined by a minimum of the free energy which according to [4] may be presented in the form:

$$F(T) = 2W_s(\varphi) + (K_{22}d/2)(2\pi/p_d(T) - 2\pi/p(T))^2, \qquad (1)$$

where K_{22} is the Frank twist modulus, $W_s(\varphi)$ is the surface anchoring potential, d is the sample thickness, p(T) is the equilibrium for the temperature T pitch value for a bulk cholesteric sample, $p_d(T)$ is the pitch value for the same temperature in the layer, φ is the angle of director deviation from the alignment direction at the surface. Because the pitch in layer $p_d(T)$ is connected uniquely with the angle φ and the equilibrium pitch p(T) is uniquely connected with the angle $\varphi_0(T)$ which corresponds to the free deviation (in the absence of anchoring) of the director from the alignment direction at the surface the expression (1) may be presented as a function of these angles and the variations of the angle φ due to the pitch (temperature) changes may be described by the following equation [11]:

$$\partial W_s(\varphi)/\partial\varphi + (2K_{22}/d)[\varphi - \varphi_0(T)] = 0. \qquad (2)$$

The pitch jumps occurs when the angle φ reaches some critical value φ_c wich is determined by the shape of the anchoring potential $W_s(\varphi)$. The value of the free rotation angle $\varphi_0(T)$ at the jump point (by the other words the corresponding value of pitch for a bulk CLC) is connected by the following relation with the surface anchoring potential

$$\varphi_0(T_j) = \varphi_c + (\partial W_s(\varphi)/\partial\varphi)_{\varphi=\varphi_c}/(2WS_d), \qquad (3)$$

where T_j is the jump temperature and $S_d = K_{22}/dW$ is the dimensionless parameter (where W is the depth of surface potential). Because the maximal possible change of φ_0 corresponding to a complete unwinding of the spiral for the initial director configuration in layer with $N = 1$ is equal to $\pi/2$ it follows from this condition and the Eq. (3) that a complete unwinding of the spiral in a layer (jump to the configuration with $N = 0$) can take place not for any value of the parameter S_d but only if its value sutisfy the inequality

$$S_d \geq [(\partial W_s(\varphi)/(\partial\varphi)_{\varphi=\varphi_c}/(2W)]/(\pi/2 - \varphi_c) \qquad (4)$$

For the model Rapini potential [4,12,13] determined by the formula $W_s(\varphi) = -(W/2)\cos^2\varphi$, $\varphi_c = \pi/4$ and the inequality (4) results in $S_d \geq 1/\pi$, i.e. the critical value of the parameter $S_{dc} = 1/\pi$. The calculations of the temperature variations of the director deviation angle at the surface from the alignment direction for several values of the parameter S_d are presented at Figure 1 for the Rapini anchoring potential. Usually a temperature increase of the pitch corresponds to decrease of the pitch. For the mentioned pitch dependence the temperature increase corresponds to variation of φ at the right bunch of curves at Figure 1 from zero to negative

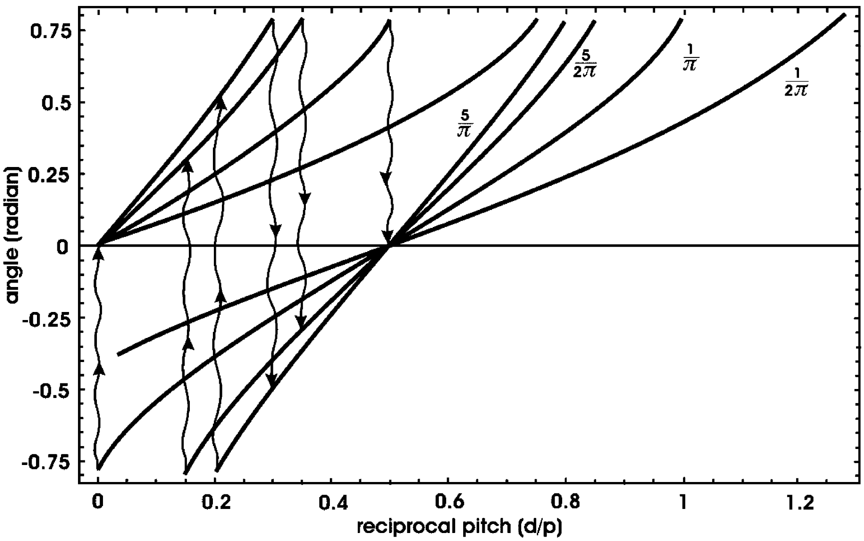

FIGURE 1 Calculated temperature dependence of the angle of director deviation from the alignment direction in the range of the spiral unwinding (N = 0,1) for several values of the parameter S_d, specified at the figure.

values. Upon reaching by φ of the critical value $-\varphi_c$ a jumpwise unwinding of the spiral occurs (marked at the figure by wavy arrows and corresponding to a jump from the lower curves of the right bunch (N = 1) to the curves of left bunch (N = 0)) and the value of φ starts to be determined by the left bunch of curves related to the spiral configuration with N = 0. As may be seen from the figure the transition of the layer from the state with one half-turn to the state with zero half-turn according to (4) is possible not for all values of S_d. At the opposite direction of the pitch change, i.e. at its decrease (φ increase at the left bunch of curves), a temperature hysteresis takes place i.e. a jumpwise return of the spiral configuration to the state with one half-turn occurs at a different value of the pitch. Note that the less is the S_d, the larger is the value of temperature hysteresis which according to (2), (3) is determined by the following expressions

$$d(1/p(T_+) - 1/p(T_-)) = (\partial W_s(\varphi)/\partial\varphi)_{\varphi=\varphi_c}/(\pi W S_d) + (4\varphi_c/\pi - 1)/2,$$
$$d(1/p(T_+) - 1/p(T_-)) = 1/2\pi S_d, \tag{5}$$

where the second expression corresponds to the Rapini anchoring potential and T_+, T_- are the jump temperatures for the increasing and decreasing temperature, respectively.

Note that after the jump to the state with c N = 0 which was called an unwinding of the spiral the orientation of director in the layer is actually nonuniform but is slightly changing from one surface to another. To get a homogeneous director orientation in the layer after the jump one has to use layers with changed orientations of the alignment directions, namely, the alignment directions at the both surfaces should be rotated at the angle φ_j (where φ_j is the value of φ after the jump in the problem with the same alignment directions at the both surfaces) in the direction opposite to the spiral rotation direction.

UNWINDING IN THE FIELD

Beginning the investigation of the field (electric or magnetic) unwinding of the spiral emphasize that this problem is more complicated for description because now a new direction of anisotropy arise which is determined by the applied to the layer field and the spiral becomes distorted by the applied field [1–3]. In the general case additional deformations of CLC occur which make director to be nonperpendicular to the spiral axes and change the angle between the director and the spiral axes [15].

To simplify the problem examine a perfect planar CLC layer in the electric (or magnetic) field applied perpendicularly to the spiral axes assuming also that the only permissible deformation in the field is a twist deformation which does not change the angle between the director and the spiral axes. Then the expression for the volume density of the free energy is of the form [3,14]:

$$F_v(E) = (K_{22}/2)(d\varphi/dz - 2\pi/p_0)^2 + EP_s \cos\varphi + (\varepsilon_a E^2/16\pi)\cos 2\varphi, \quad (6)$$

where p_0 is the equilibrium value of the pitch in bulk CLC at zero field, $\varphi + \pi/2$ is the angle between the director and applied field, ε_a is the dielectric anisotropy of CLC and P_s is the spontaneous polarization. The free energy of the layer in the applied field may be presented in the form (1) if the second term in the right hand side is substituted by $\int F_v(E)dv$ where integration is carried out over the layer volume.

It is reasonable also to investigate the problem for some specific directions of the field in the plane perpendicular to the helix axis. These directions, being investigated below, correspond to the fields applied along and perpendicular to the alignment direction. However, before to discuss these two cases separately reveal some features common for the both cases. Let us neglect for the beginning the dependence of the unwinding process on the field orientation relative to the alignment direction. It may be done if one neglects the spiral deformation in the field and takes into account only the pitch growth in an increasing field. In the mentioned approximation the spiral unwinding in the field is described by the equation similar to the equation for the temperature unwinding (2) if the pitch for a bulk sample, i.e. φ_0, will be considered to be a function of the applied field.

Let us calculate the CLC spiral behavior in a layer as a function of the applied field (up to the value corresponding to the unwinding field for a bulk sample) assuming to be specific as an anchoring potential the Rapini model anchoring potential. The Figure 2 presents the calculations of the twist angle in the layer, i.e. the whole angle of the director rotation at the layer thickness as a function of the applied field for several values of the parameter S_d. The half of the director twist angle at the layer thickness versus the applied field E normalized by the unwinding field for a bulk sample E_c is depicted at the figure. In the calculations, as a simple example of the pitch dependence on the applied field for a bulk sample, was assumed the pitch to be given by the analytical formula (5) of the paper [3]. The upper curves describe the twist angle variations in the field for the initial configuration with $N = 1$, the lower curves describe the same variations after the jump to the final configuration with $N = 0$. In the assumed approximation the applied field equal to the unwinding field for a bulk sample does not result in an unwinding of the spiral in a layer and the unwinding happens for the field exceeding the unwinding field for a bulk sample if the parameter S_d value is lower than $1/\pi$. For S_d exceeding $1/\pi$ the unwinding (pitch jump) occurs at the fields lower than the unwinding field for a bulk sample.

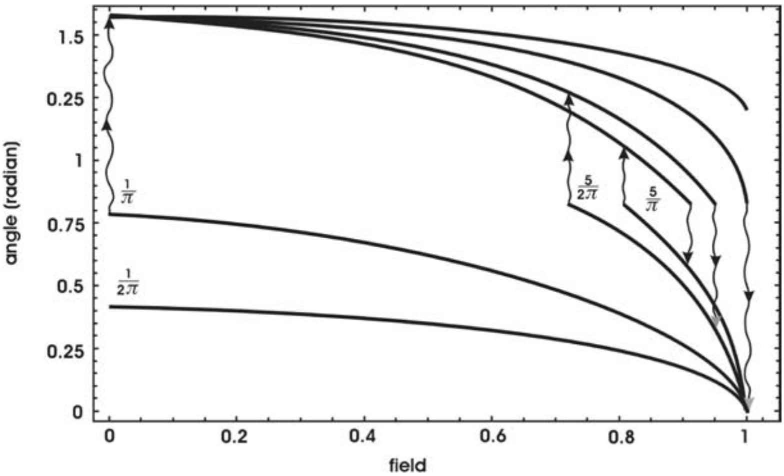

FIGURE 2 Calculated field dependence of the spiral twist angle in the range of pitch jump ($N = 0,1$) for several values of the parameter S_d, specified at the figure.

The hysteresis of the jump field at the opposite directions of the field variations decreases with increasing of S_d similarly to the case of the temperature unwinding. For the S_d values less than $1/\pi$, after the jump in an increasing field (which occurs at $E > E_c$) a removing of the field does not results in returning of the layer to the initial configuration with $N = 1$ (the curves with $S_d = 1/2\pi$ at the figure just correspond to this case), i.e. after the removing of the field the spiral remains to be unwound revealing a bistability of the CLC layer in the applied field. If a jump at the increasing field happens at its value lower than the unwinding field for a bulk sample then a completely homogeneous orientation of the director in a layer at further field increase will be reached only for the field value coinciding with the unwinding field for a bulk sample. However, similarly to the case of the temperature unwinding a homogeneous director orientation in the layer may be reached by a slight changing of the alignment direction orientations at the surfaces.

Let us discuss qualitatively in what changes of the described above unwinding process does the taking into account of the dependence of the spiral deformation on the direction of the applied field result. Assume for the simplicity that CLC is a cholesteric, i.e. a liquid crystal with zero spontaneous polarization. From the physics of the phenomenon it is clear that for a positive dielectric anisotropy of the cholesteric for the external field direction coinciding with the alignment direction the field action will effectively strengthen the anchoring forces and the unwinding field value (jump points) will be shifted towards the larger values compared to the values at the Figure 2. For the external field direction perpendicular to the alignment direction the field action will effectively weaken the anchoring forces and the unwinding field value (jump points) will be shifted towards the smaller values compared to the values at the Figure 2.

After the jump the external field direction coinciding with the alignment direction will help to create a homogeneous director orientation in the CLC layer. So, from the said above it is clear that the external field direction coinciding with the alignment direction is favorable for creation of a homogeneous director orientation in the CLC layer.

CONCLUSION

The performed above investigation of the CLC spiral unwinding in layers of a finite thickness, being by a model one, describes nevertheless correctly the qualitative features of the phenomenon. First of all these are a jump-like unwinding process in a layer and an unwinding hysteresis both of which are due to the surface anchoring forces and depending on the value of parameter S_d. The other model independent result relates to the value of the unwinding field in the layer that occurs to be different from the corresponding value for a bulk CLC sample and may be, in particular, less than the unwinding field for an infinite CLC. From the application point of view the result on the layer bistability in the applied field and the quantitative criteria of this bistability (limitations on the parameter S_d value) along with the result on the possibility of a complete spiral unwinding in the field less than the unwinding field for a bulk sample look as promising ones. What is concerned of the quantitative side of the problem which is important for specific experiments it looks as reasonable if the problem will be considered by means of numerical solutions of the corresponding equations, for example, in the framework of the approach of the papers [3,12], with the values of parameters and the anchoring forces corresponding to the LC materials being under the investigation and with taking into account their dependences on the external actions. Note also that some quantitative changes of the results, mainly slight shifts of the found jump points and reducing of the hysteresis, have to be connected with the temperature fluctuations of the director orientation which were not taken into the account above. The role of fluctuations in the problem is worthy to be investigated separately. However, as the results of preliminary investigation [11,12] and the measurements [5] show the role of fluctuations for the studied phenomena is decreased for the thin layers compared to the thick ones. It is why the results obtained here for the thin layers are not subjected to essential quantitative changes due to the fluctuations.

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