

Chapter 5

Thermo-nonlinear optics in cholesteric liquid crystals

5.1 Introduction

In the previous chapters, we considered situations where the laser beam acted as a probe. In these situations, we used low intensity laser beams and the samples were non absorbing. However, if a laser beam is intense enough and the system is absorbing, it could lead to nonlinear effects in liquid crystals. Some of these effects will be discussed in this chapter. Nonlinear optics of liquid crystals has attracted a great deal of attention in recent times. The electric field of a laser beam can exert a dielectric torque on the director of liquid crystals and reorient it. This director reorientation leads to very high optical nonlinearities and has been studied in detail [1,2]. In one case [3] the nonlinear optical (NLO) coefficient for a dye doped nematic liquid crystal was found to be as high as $6 \text{ cm}^2/W$. In these materials, the dye molecules result in a space charge, which in turn leads to an enormous torque on the director. Very recently a colossal NLO coefficient of the order of $10^3 \text{ cm}^2/W$ has been found in dye doped nematic liquid crystals due to surface induced nonlinear effects [4,5]. Such high optical nonlinearities in nematic liquid crystals find applications in optical image processing [6]. Optical nonlinearities can also arise from the heating of the absorbing material due to laser beam. Here the nonlinearity is because of the change in refractive index of the medium due to light absorption. This is often referred to as thermal indexing. Thermal nonlinearities in absorbing nematics have been studied [7–9] extensively. The nonlinear optical coefficient

due to thermal indexing is very large near nematic to isotropic transition point.

Cholesteric liquid crystals have many interesting optical properties like selective reflection of circularly polarized light, high optical rotation and circular dichroism. Applications based on these properties include polarizers, band pass and band rejection optical filters [10]. Nonlinear optics of such media is of technological importance. Winful [11] has predicted bistability in the reflection band of a cholesteric liquid crystal. This is caused by the torque of electric field of the laser beam on the local director. Lee *et al.* [12] have observed self-focusing in the Bragg reflection mode in a cholesteric liquid crystal. This self-focusing arises from the distortion of the cholesteric structure induced by the laser beam through the process of director reorientation. However, thermal nonlinearities in cholesteric liquid crystals have not been studied in great detail.

This chapter deals with the study of such nonlinear processes in cholesteric liquid crystals. The absorption of a laser beam can lead to large optical nonlinearities in cholesteric liquid crystals. The mechanism involved here is very different from the director reorientation process found in other liquid crystals [1, 2, 11, 12]. This thermal nonlinear effect is neither due to laser light induced director reorientation nor due to changes in principal refractive indices of the material. It is induced by the change in pitch of the helical structure resulting from absorption of the laser beam. In a right (left) handed cholesteric, for a right (left) circularly polarized light wave, the NLO coefficient can be more than a billion times than that found in usual nonlinear media like CS_2 . On the other hand, for a left (right) circularly polarized light wave, NLO coefficient can be more than a million times than that found in usual nonlinear media. The sign of NLO coefficient is positive or negative depending on whether the pitch increases or decreases with laser intensity. In the case where principal refractive indices change with intensity due to light absorption, the NLO coefficient of the right (left) circularly polarized wave changes sign near the Bragg reflection band [13].

An incident laser beam with a radial intensity distribution can induce a pitch profile in cholesteric, across the beam. When the pitch is not very large compared to the wavelength of light, the base states are right and left circular waves [14] whose refractive indices depend on

the pitch. Therefore, inside the medium, a refractive index profile for left and right circularly polarized waves can exist. Thus, for an incident right or left circularly polarized plane wavefront the output is not a plane wavefront. As a result, the emerging rays will not be parallel. Thus, phase modulation leads to self-focusing or self-divergence of the circularly polarized beam. Lee *et al.* [12] have experimentally found self-focusing in the retro reflection mode of a cholesteric but this effect is due to a torque on the director by the electric field of laser beam and not due to the pitch change resulting from the absorption.

Interestingly, when the pitch is very large compared to the wavelength of light, the base states are linear vibrations polarized along and perpendicular to the local director. For the linear vibration along the local director the radial intensity distribution of laser beam results in a radial variation in refractive index again leading to self phase modulation. Here, there is no torque on the director. This effect in cholesterics, is an analogue of an effect detected in nematics by Ono [15].

A compensated cholesteric is a mixture of two cholesteric liquid crystals having opposite handedness. Such mixtures often show the structural transition from left handed cholesteric to right handed cholesteric or *vice-versa* leading to a compensation point where the helix unwinds completely [16]. In compensated cholesterics pitch varies rapidly near the compensation or nematic point with intensity and can lead to a new defect lattice.

5.2 Theory

In this section we present the theory of absorbing cholesteric liquid crystals. A dye doped cholesteric liquid crystal can absorb the laser beam, which increases the temperature of the cholesteric. This in turn changes the pitch of the cholesteric, which is related to the refractive indices of the base states. A cholesteric liquid crystal can be looked upon as a helically twisted birefringent medium. It has a periodically varying dielectric constant along its helical axis (z axis). If the light is propagating along z axis then, the Maxwell's equations for such a

system can be written as [14]

$$\frac{d^2}{dz^2} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = -\left(\frac{\omega}{c}\right)^2 \hat{\epsilon}(z) \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

The dielectric tensor $\hat{\epsilon}(z)$ is given by,

$$\hat{\epsilon}(z) = \frac{\epsilon_{\parallel} + \epsilon_{\perp}}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\epsilon_{\parallel} - \epsilon_{\perp}}{2} \begin{pmatrix} \cos(2q_0z) & \sin(2q_0z) \\ \sin(2q_0z) & -\cos(2q_0z) \end{pmatrix}$$

where, ω is the frequency of light, ϵ_{\parallel} and ϵ_{\perp} are the components of the dielectric tensor along and perpendicular to the local director and q_0 is the wave vector corresponding to the pitch.

The dispersion relation is given by:

$$(-k_0^2 + l^2 + q_0^2)^2 - 4q_0^2 l^2 - k_1^4 = 0$$

where $q_0 = 2\pi/P$, $k_1 = \frac{2\pi}{\lambda}(\bar{n}\delta n)^{1/2}$, $k_0 = \frac{2\pi}{\lambda}\bar{n}$, $\bar{n} = (n_e + n_o)/2$, and $\delta n = (n_e - n_o)$.

Here P is the pitch of the cholesteric, n_e and n_o are the refractive indices parallel and perpendicular to the local director, λ is the wavelength of light and $(l + q_0)$ and $(l - q_0)$ are the wave vectors of right *i.e.* $(E_x + iE_y)$ and left *i.e.* $(E_x - iE_y)$ circularly polarized waves, respectively. In the two regimes, $P < \left(\frac{\lambda}{\bar{n}}\right)$ and $\left(\frac{\lambda}{\bar{n}}\right) < P < \left(\frac{\lambda}{\delta n}\right)$, where pitch of the cholesteric is not very large compared to the wavelength of light (de Vries regime), the base states are right and left circularly polarized waves. We find that the refractive indices n_R and n_L for these two base states are given by:

$$n_R = \mp \frac{\lambda}{2\pi} \sqrt{k_0^2 + q_0^2 - 2k_0q_0 \left(1 + \frac{k_1^4}{4k_0^2q_0^2}\right)^{1/2}} + \frac{\lambda}{2\pi}q_0 \quad (5.1)$$

$$n_L = \frac{\lambda}{2\pi} \sqrt{k_0^2 + q_0^2 + 2k_0q_0 \left(1 + \frac{k_1^4}{4k_0^2q_0^2}\right)^{1/2}} - \frac{\lambda}{2\pi}q_0 \quad (5.2)$$

In Eqn. (5.1) the negative sign is taken for $P < \left(\frac{\lambda}{\bar{n}}\right)$ and the positive sign is taken for $\left(\frac{\lambda}{\bar{n}}\right) < P < \left(\frac{\lambda}{\delta n}\right)$. It can be seen that for $q_0 > 0$ *i.e.* for a right handed cholesteric structure, n_R becomes complex within a range of pitches $\left(\frac{\lambda}{n_o}\right) > P > \left(\frac{\lambda}{n_e}\right)$. In this region the right circular wave does not propagate through the medium but gets reflected back. However, outside this range of pitches it propagates through the medium. On the other hand, left circular wave propagates

unaltered through the medium in the two regimes. We emphasize here that when a right or left circularly polarized light is going through the medium, there is no optical torque acting on the director.

On the other hand, when the pitch is very large compared to the wavelength of incident light, $P \gg \left(\frac{\lambda}{\delta n}\right)$ (commonly termed as Mauguin regime), the base states are found to be linear vibrations parallel and perpendicular to the local director [14]. Thus, for the linear vibration parallel to the local director not only the absorption and hence thermal effects will be a maximum but also there will be no torque on the director due to the electric field of light. Thus, in all the cases considered here, there will be only thermal nonlinear effects. We next discuss the effect of light induced heating on the cholesteric sample.

5.2.1 Effect of heating due to light absorption

Here, we establish a relation between the light absorption and the rise in temperature. Temperature rise depends on many experimental and material parameters like cell thickness, beam size and thermal conductivity. It is possible to obtain to a first approximation, the temperature increase from the well known heat conduction equation [17]

$$\kappa \nabla^2 T - \rho c_v \frac{\partial T}{\partial t} = -\beta I \quad (5.3)$$

where β is the optical absorption coefficient, κ is the thermal conductivity, ρ is the mass density and c_v is the specific heat at constant volume. Optical absorption coefficient specify the absorbing power of the medium. For a laser beam with initial intensity I_0 , propagating along z -axis, the intensity at any point in the medium is given as:

$$I = I_0 \exp(-\beta z)$$

It is to be noted that β is related to the imaginary part of the refractive index of the medium.

For a beam width larger than the sample thickness, under steady state conditions ($\frac{\partial T}{\partial t} = 0$), we can estimate the increase in temperature δT from Eqn. (5.3). It is given by:

$$\delta T \approx \left(\frac{d^2 \beta}{\pi^2 \kappa}\right) I \quad (5.4)$$

Here d is the sample thickness. Thus, the temperature rise is a linear function of the laser intensity and has a square dependence on sample thickness. Typically, $\kappa \approx 10^{-3} \text{ W}/^\circ\text{C cm}$. For $\beta \approx 1.0 \text{ cm}^{-1}$ and in a $100 \mu\text{m}$ thick sample

$$\delta T = I/A \quad (5.5)$$

where, $A \approx 100 \text{ W}/\text{cm}^2 \text{ }^\circ\text{C}$. Further, over a sample thickness of $100 \mu\text{m}$ the attenuation of the wave inside the medium is about 1.0%, which can be ignored. In principle we should also take into account the anisotropy in thermal conductivity and optical absorption in liquid crystals. Therefore, a proper analysis of heat conduction equation needs elaborate calculations. As an example we may refer to the work of Janossy [18], who has studied the case of a homeotropically aligned nematic.

The absorption of the laser beam by the medium, results in the heating of the medium and in turn the pitch of the cholesteric changes. We next discuss the variation of cholesteric pitch with laser intensity.

5.2.2 Pitch variation with light intensity

It is known that the pitch of a cholesteric is usually a function of temperature [19] and hence laser intensity for absorbing cholesterics. Generally, the pitch of a cholesteric is inversely proportional to the temperature. For a single cholesteric, pitch decreases with increase in temperature. But, as stated earlier, one can have a mixture of cholesterics with opposite handedness whose pitch can increase with increasing temperature. We have shown in Fig. 5.1 the variation of inverse pitch for a 1.75 : 1 weight percent mixture of right handed cholesteryl chloride and left handed cholesteryl myristate. We have taken the data from literature [19]. The pitch was determined by the diffraction of light. The change in the sign of pitch at 42.0°C represents the change in the handedness of cholesteric liquid crystal. Fig. 5.1 shows the pitch inverse is linearly related to temperature. If the compensated cholesteric system is absorbing, then from Eqn. (5.5), we get that pitch inverse is linearly related to the light intensity. Thus, we can say that the change in wave vector (corresponding to pitch of the

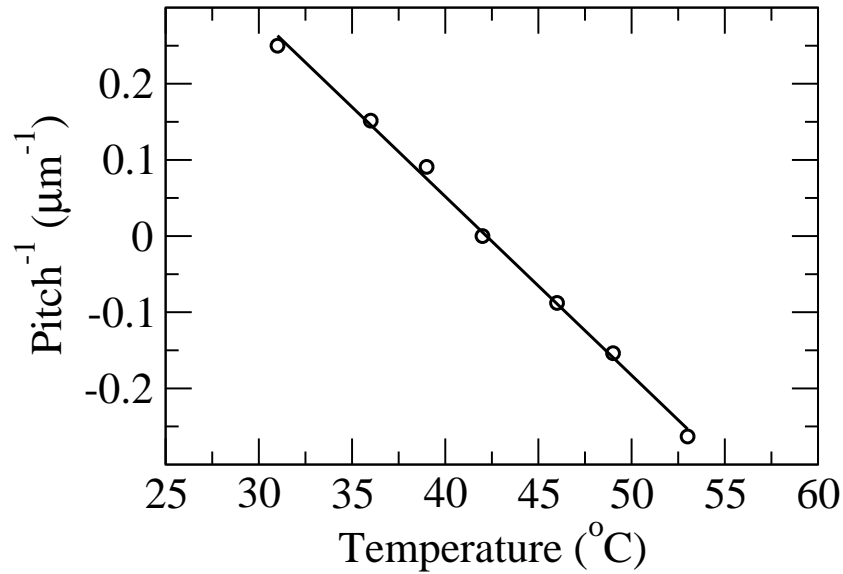


Figure 5.1: The variation of pitch inverse as a function of temperature. Pitch was measured by laser diffraction [19] in a 1.75 : 1 weight percent mixture of cholesteryl chloride (right handed) and cholesteryl myristate (left handed). The mixture is nematic at 42.0°C.

cholesteric) with respect to the light intensity is a constant.

$$\frac{\partial q_0}{\partial I} = \gamma \quad (a \text{ constant}) \quad (5.6)$$

γ can be a positive or negative number. It is negative when pitch increases with increase in intensity and positive when pitch decreases with increase in intensity. From Eqn. (5.1) to (5.6) the NLO coefficient $\partial n / \partial I$ can be calculated as a function of laser intensity.

5.3 Results and Discussion

The thermal indexing in a cholesteric depends on the way the pitch and other parameters vary due to laser light absorption with corresponding raise of temperature. It is important to emphasize here that the optical absorption also affects the optical properties of cholesteric liquid crystals. Calculations indicate, that the dispersion curves for right and left circular waves remain same due to absorption, in the limit small absorption coefficient. Therefore, the absorption coefficient (β) results only in a change in the pitch of the structure through absorption and does not alter the inherent optical properties of the cholesteric. Further, in practice, the right and left circular waves are absorbed to slightly different extents. Our

calculations are based on the assumption that the heating effect is nearly the same for both states of polarization and is largely due to the average absorption. In all our calculations a right handed cholesteric was considered and similar results are valid *mutatis mutandis* for a left handed cholesteric. Here, we present some special cases of thermal indexing in cholesterics.

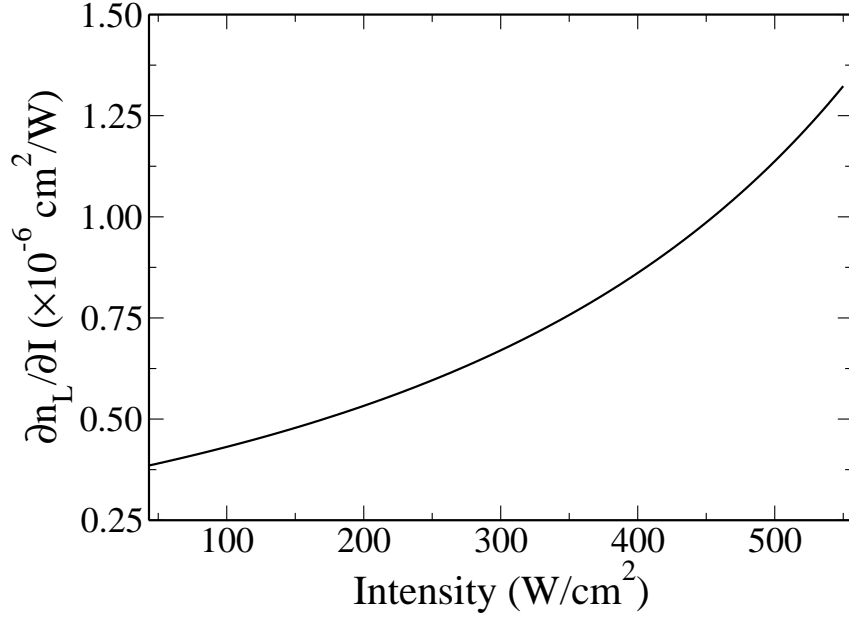
5.3.1 Large optical nonlinearities in cholesterics

5.3.1.1 Rapid variation of pitch with intensity

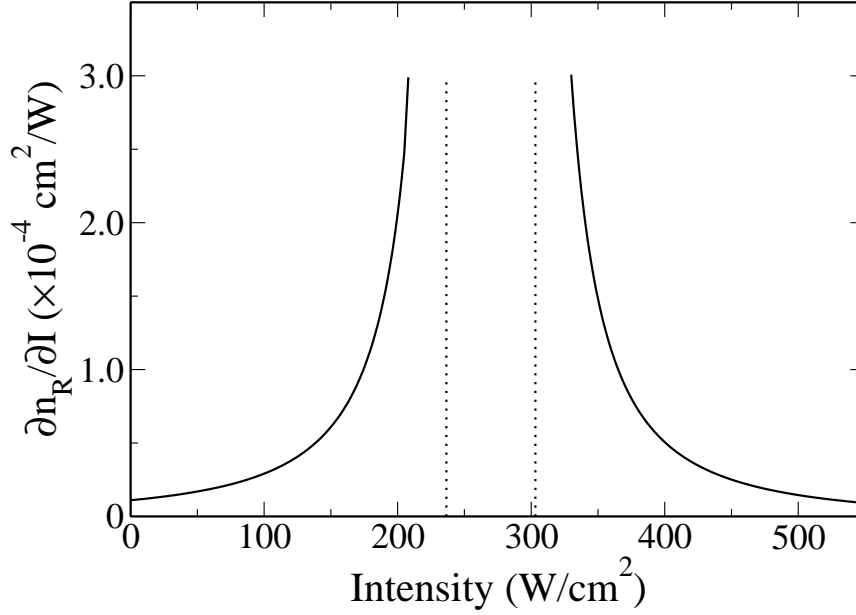
For large values of γ , the cholesteric pitch varies rapidly with the laser intensity. A small change in the intensity of the laser beam changes the pitch by considerable amount. In such cases, the accompanying change in temperature is not high. Then it can be assumed that the average refractive index (\bar{n}) and the local linear birefringence (δn) of the cholesteric medium remain unaltered in the small range of intensities considered. To a first approximation these can be taken as constants and only the pitch of the structure varies with intensity. It is possible to have a cholesteric with the pitch either increasing or decreasing with an increase of laser intensity. We show the theoretical dependence of NLO coefficients ($\partial n_L/\partial I$ and $\partial n_R/\partial I$) on laser intensity in Figs. (5.2) and (5.3). Even away from the reflection band, the NLO coefficient can be as high as $10^{-4} \text{ cm}^2/W$ for the right circular wave. On the other hand, for the left circular wave it is about $10^{-6} \text{ cm}^2/W$. Both the NLO coefficients are positive if pitch increases with increasing intensity (Fig. (5.2)) and negative if pitch decreases with increasing intensity (Fig. (5.3)). The NLO coefficient of the left circular wave monotonically increases with intensity when the pitch increases with intensity (see Fig. 5.2(a)). It exhibits a monotonic approach to a saturation when the pitch decreases with increasing intensity (see Fig. 5.3(a)). The magnitude of the NLO coefficient for right circularly polarized wave increases as we approach the reflection band.

5.3.1.2 Slow variation of pitch with intensity

For small values of γ the variation of pitch with laser intensity is slow. Then to get a considerable change in pitch, intensity (equivalently temperature) has to be changed by a relatively

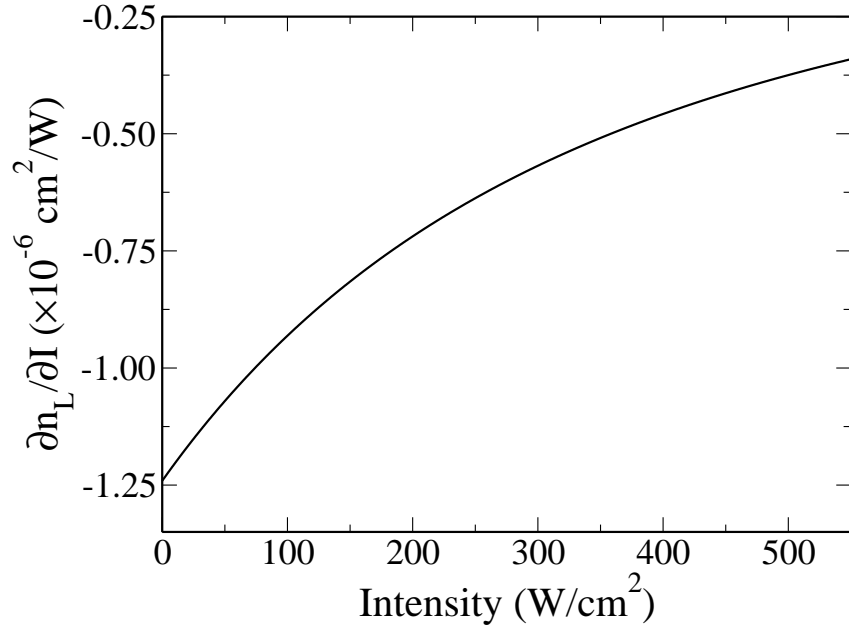


(a)

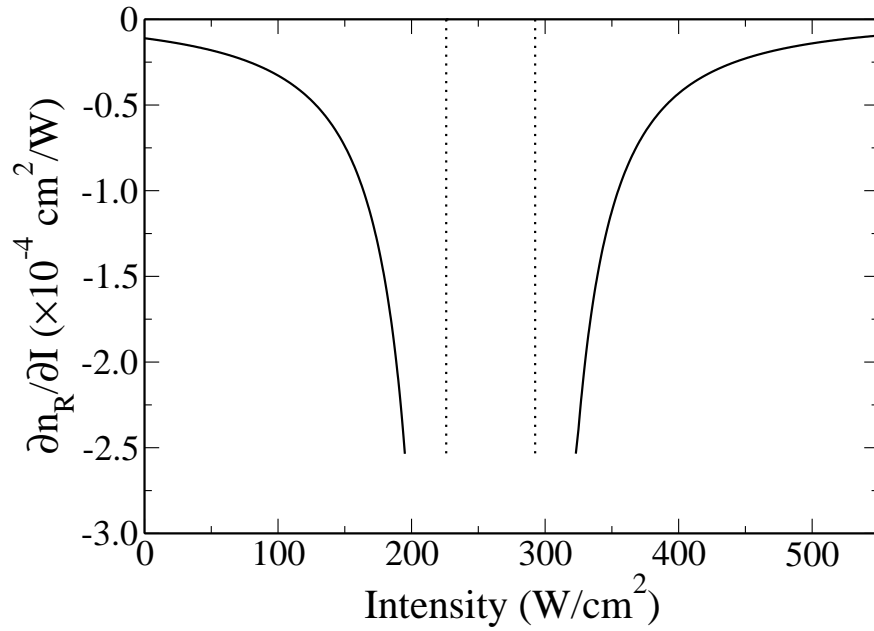


(b)

Figure 5.2: The variation of the NLO coefficient with intensity. (a) for left circularly polarized wave and (b) for right circularly polarized wave, for γ being a large negative number. The value of γ is -157.1 cm/W . In the intensity range considered here the pitch varies from $0.3 \mu\text{m}$ to $0.54 \mu\text{m}$. Here, $\lambda = 0.6 \mu\text{m}$, $\bar{n} = 1.5$ and $\delta n = 0.1$. The region between dotted lines represents the reflection band.



(a)



(b)

Figure 5.3: The variation of the NLO coefficient with intensity. (a) For left circularly polarized wave and (b) for right circularly polarized wave, for γ being a large positive number. The value of γ is $+157.1 \text{ cm/W}$. Other parameters are same as Fig. (5.2).

larger amount. Then, over this intensity range, the average refractive index (\bar{n}) of the medium varies with intensity. Exact calculations of the temperature variation of the average refractive index is difficult for cholesterics [20]. For other liquid crystals, the average refractive index decreases almost linearly with temperature. We have used the experimental data of Demus and Wartenberg [21] to estimate the temperature variation of \bar{n} in nematics. In a similar fashion, absorption coefficient (β) is also temperature dependent. It can be assumed to vary like average refractive index *i.e.* linear decrease with an increase of temperature. However, over the intensity range considered here, we find that the correction due to absorption coefficient is small. Thus, the temperature and pitch of the structure are determined by an invariable absorption coefficient to a good approximation. The variation of birefringence with intensity is negligible since the system is assumed to be far from the cholesteric to isotropic transition. The results for intensity dependence of NLO coefficients are shown in Figs. (5.4) and (5.5). The NLO coefficient is of the order of $10^{-5} \text{ cm}^2/W$ for both left and right circularly polarized wave. In the case of right circular wave (Fig. 5.4(b)), the NLO coefficient not only increases considerably, near the reflection band, but also changes sign. This occurs only when the pitch increases with intensity of the laser beam.

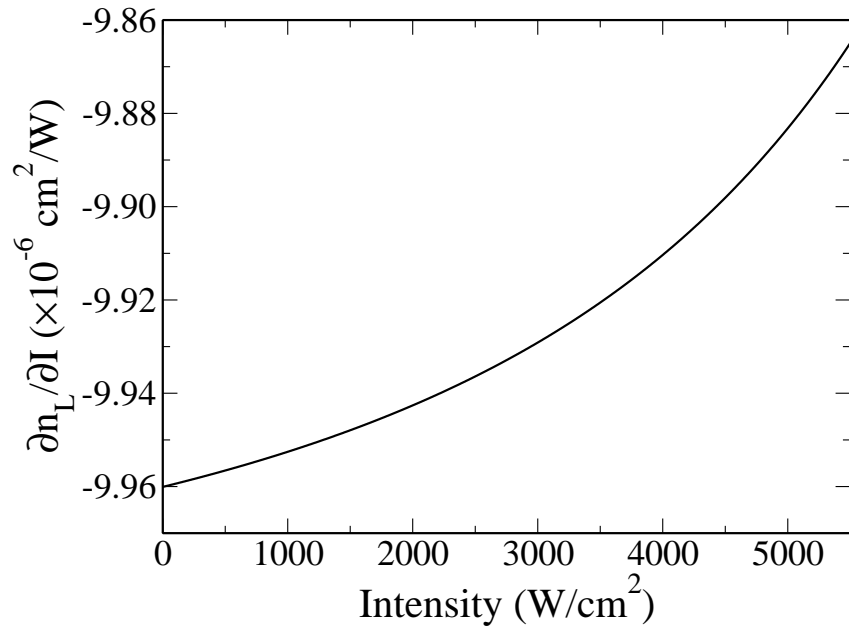
It should be emphasized here that we have excluded the region of the reflection band in these calculations. The calculations were limited to a point at which the transmission coefficient for the right circular wave reaches 0.95. In the regimes considered here, the base states are right and left circular polarized states to a very good approximation (ellipticity is greater than 0.9).

5.3.1.3 Nonlinear optical rotation

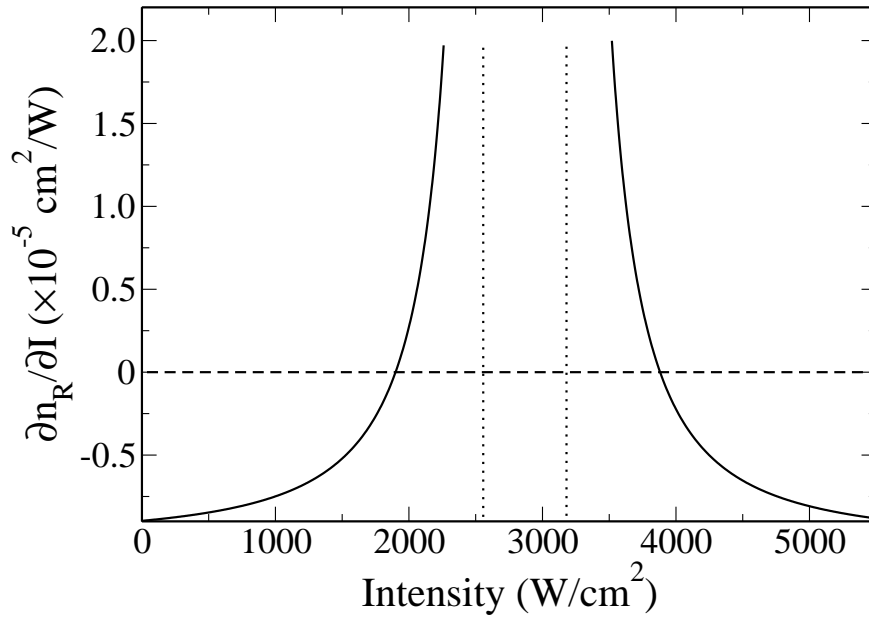
The optical rotatory power of a cholesteric liquid crystal is defined as:

$$\rho_{opt} = \frac{\pi}{\lambda}(n_R - n_L) \quad (5.7)$$

We have considered the case where, the intensity of the laser beam is enough to change the pitch but does not distort the structure through the optical torque. Then, we get an intensity dependent optical rotation which also changes sign with the handedness of the

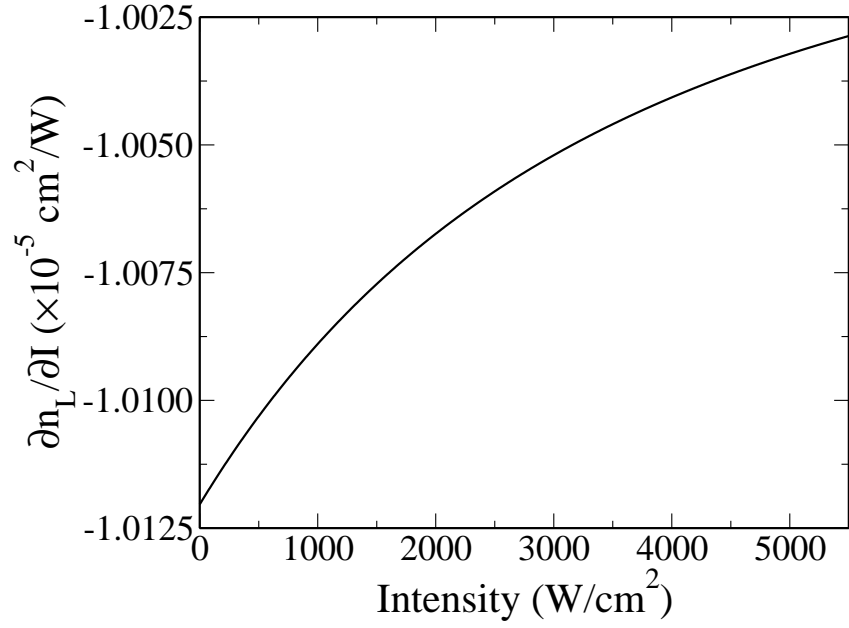


(a)

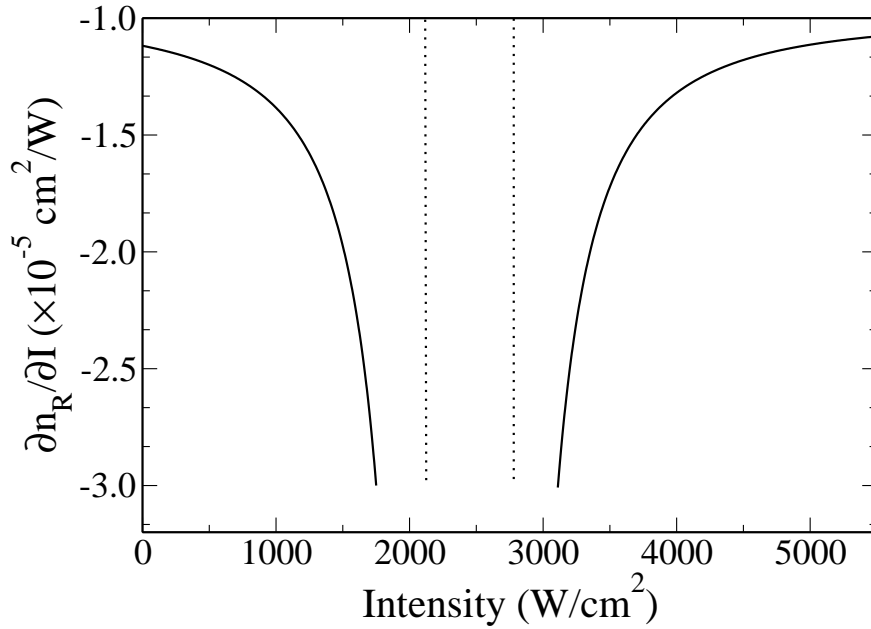


(b)

Figure 5.4: The variation of the nonlinear optical (NLO) coefficient with intensity. (a) For left circularly polarized wave and (b) for right circularly polarized wave for γ being a small negative number. The value of γ is -15.71 cm/W . Here, to bring out the same change in pitch high intensities (about 10 times) are needed. Also, average refractive index (\bar{n}) can not be taken to be a constant with intensity. Other parameters are same as Fig. (5.2). The value of $\partial \bar{n} / \partial I$ is $= 10^{-5} \text{ cm}^2 / \text{W}$.



(a)



(b)

Figure 5.5: The variation of the NLO coefficient with intensity. (a) For left circularly polarized wave and (b) for right circularly polarized wave for γ being a small positive number. The value of γ is 15.71 cm/W . Other parameters are same as Fig. (5.2). The value of $\partial \bar{n} / \partial I$ is $= 10^{-5} \text{ cm}^2/\text{W}$.

cholesteric structure. This is peculiar to thermo-nonlinear optics in cholesterics and is quite different from the one predicted by Tabiryian *et al.* [1]. In their case, the intensity dependent optical rotation exists only for an elliptically polarized light and is independent of the sign of chirality of the cholesteric.

5.3.2 Finite laser beams

The above theory and discussion is applicable for a very wide beam. A beam is called wide if the beam width is much larger than the wavelength of light. The effects in the presence of a finite beam are discussed briefly in this section.

5.3.2.1 Self phase modulation

Consider a plane wavefront of the laser beam having a radial intensity profile, incident on a cholesteric medium parallel to its twist axis. Then, there will be pitch variation within the beam. If the pitch variation is small compared to the intrinsic pitch of the cholesteric then, in the de Vries limit both right and left circular waves have a refractive index profile across the wavefront. This leads to the self phase modulation. In the case of a Gaussian intensity profile of incident laser beam, there will be self-divergence when NLO coefficient is negative and self convergence when NLO coefficient is positive. Compensated cholesterics [16] are the right systems to observe these effects since they exhibit a tunable pitch variation with temperature. A Gaussian laser beam will undergo self divergence when the pitch decreases with increasing temperature. By changing the concentration of the components in compensated cholesteric one can have a situation where pitch increases with increase in temperature. In that case a Gaussian beam will undergo self focusing.

5.3.2.2 Spatial solitons

It is well known that a finite beam undergoes self diffraction. As a result, the beam spreads out as it propagates through the medium. However, in the presence of optical nonlinearity, there will be self phase modulation of the incident plane wave front. Thus, the nonlinear effect can compensate for diffraction process, resulting in a beam which can travel inside the

medium without any change in its spatial intensity profile. Such beams are referred to as spatial solitons. Spatial solitons due to various NLO processes in liquid crystals have been discussed in literature [22]. The exact compensation between the two processes takes place at a critical laser power. If the NLO coefficient is positive, then a bright soliton with a central peak intensity will be generated and if the NLO coefficient is negative, then a dark soliton with a central dip in intensity will be generated.

In the cases of cholesterics having pitch comparable to the wavelength of light, the base states are nearly right and left circularly polarized waves with accompanying positive or negative NLO coefficients. Hence, the above soliton structure can be expected in cholesterics as well, which exist only at a certain critical laser intensity.

5.3.2.3 New beam structures

In section 5.3.1, we have considered the cases when both the base states, namely, right and left circular waves propagate through the structure. However, inside the reflection band, (centered at $P = \left(\frac{\lambda}{\bar{n}}\right)$) the right (left) circularly polarized light gets reflected from a right (left) handed cholesteric. We consider a right (left) circularly polarized beam with an intensity profile such that its intensity at the center drives the cholesteric into the reflection band. But, its periphery is not intense enough to alter the pitch. Then the central part of the wavefront, will get reflected and what emerges will be a ring like beam. One can get such beam structures just by increasing the laser intensity. On the other hand, if the pitch matches with the wavelength then the cholesteric is already in the reflection band. Then by increasing the intensity pitch can be driven out of the reflection band. In that case, only the center of the beam will pass through and periphery will get reflected. Thus, new beam structures can be generated in such thermo-nonlinear cholesterics.

5.3.2.4 Defect lattice in compensated cholesterics

In a compensated cholesteric liquid crystal [16], the pitch can be changed by changing the concentration of individual components of the mixture. In these systems, the pitch is extremely sensitive to the temperature. If the system is absorbing the pitch becomes sensitive

to laser intensity. The pitch variation is very large in the vicinity of compensation or the nematic point. If the wavelength of light is very small compared to the pitch of the structure near the nematic point then, the base states will be linear vibrations parallel and perpendicular to the local director. If a linear state parallel to the local director is considered then there will not be any torque on the director but laser heating will be present. Hence, we can expect the region with large pitch differences in a cholesteric, when a finite laser beam with intensity profile is incident on the medium. Such regions can be matched only by a periodic array of twist disclination loops and not the usual χ or λ lines [14]. In the case of usual χ and λ lines the pitch of cholesteric does not alter. A typical representation of such a defect lattice with disclination loops is shown in Fig. (5.6). It may be pointed out that near a cholesteric to smectic transition the cholesteric pitch diverges. In such systems large variation in the pitch can be found within the beam and therefore, again a similar defect structure can be expected. For a thick enough sample, in the wide beam limit where the intensity of light is almost constant within the wavefront, the pitch may so vary that the handedness of the helix can change inside the medium. The intensity of light decreases progressively inside medium. Hence, the heating effect also progressively decreases. Thus, successive layers of a right (left) handed cholesteric, a nematic and a left (right) handed cholesteric can be expected along the sample thickness inside the medium.

5.3.3 Chiral smectic C

For light incident along the twist axis, the chiral smectic C liquid crystals are optically similar to cholesterics. We considered their nonlinear optical properties. If we consider the same pitch variation with the intensity as in cholesterics, then in normal chiral smectic C and compensated chiral smectic C also we get essentially the similar results. However, one important difference is that near a transition to the smectic A phase, the extraordinary refractive index seen by laser beam changes as the tilt angle goes from a finite value to zero continuously. This does not affect the ordinary refractive index which remains nearly the same.

In this chapter, we have considered a simple model which leads to large thermal nonlin-

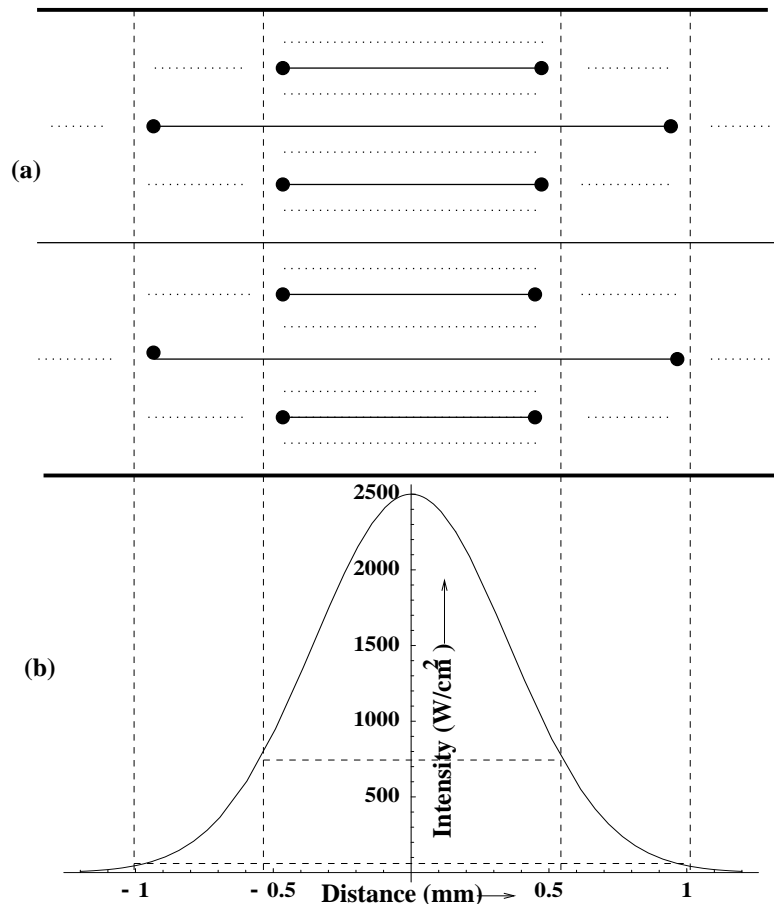


Figure 5.6: A typical calculation showing (in cross section) disclination loops in a cholesteric induced by a laser beam of Gaussian intensity profile. (a) cholesteric defect structure, (b) beam profile. Here, the pitch of cholesteric decreases with increasing intensity. At zero intensity pitch is $4 \mu m$ and as the intensity reaches $2500 W/cm^2$ at the peak of Gaussian beam, the pitch becomes $1 \mu m$. The cholesteric is assumed to be strongly anchored at the boundaries.

earities in absorbing cholesteric liquid crystals. In the next chapter we discuss the situations where the laser field is high enough to change the order parameter that leads to many interesting phase transitions in liquid crystals.

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