Theoretical and Experimental Investigation of Polarization and Spectral Properties of Light in Multilayer Cholesteric Liquid-crystalline Systems

H. Grigoryan, H. Gharagulyan, M. Rafayelyan, A. H. Gevorgyan and R. B. Alaverdyan
Yerevan State University, 1A.Manoogian, Yerevan, Republic of Armenia

Keywords: Cholesteric Liquid Crystals, Photonic Crystals, Selective Reflection, Photonic Band Gap.

Abstract: At the present work we have studied the polarization and spectral properties of light in different cholesteric liquid-crystalline systems, particularly in the systems prepared from mixture of right and left-handed cholesterics and nematic liquid crystal. The following systems were also examined: a) system consisting of right and left handed cholesterics (with the same pitch), which have selective reflection in the same range of the visible spectrum, b) system consisting of right and left handed cholesterics, which have selective reflection in red and green ranges of the visible spectrum and c) 4-layer system consisting of cholesterics with different pitches. As a result of our investigations, we have verified the possibility of controlling of polarization plane rotation of light. We propose a new device for expansion of Bragg's reflection range.

1 INTRODUCTION

Materials with a sufficiently strong periodic modulation of the refractive index exhibit a photonic band gap, which means that in certain frequency ranges light propagation is forbidden. Such optical media are called photonic crystals (PCs). Cholesterics liquid crystals (CLCs) are one of the most attractive one-dimensional PCs due to their unique optical properties. As a result of their helical structure a circularly polarized light with the same handedness as the CLC helix propagating along a helical axis is selectively reflected, while the rest of the light is transmitted, therefore a stop band appears (De Gennes and Prost, 1993). CLCs have attracted scientists and engineers for the past decade also because their properties offer ways to control light polarization. The investigation of polarization characteristics, namely polarization plane rotation and light polarization controlling is important from the point of view of application in modern photonics and optoelectronics. The essence of this phenomenon lies in the fact that linear polarized light passing through the cholesteric film remains linear polarized but direction of its polarization (electric vector) is rotated by angle α in respect to the incident light ($\theta=\alpha-2\pi k$, where k=0;1;2;3...). The angle α depends on the properties of the medium and on the d thickness of the cell: $\alpha=\rho\cdot d$, where ρ is the specific rotation. In cholesterics ρ has a very big value (Belyakov et al., 1982); (Khoo, 2007). If the thickness of the system is increased, the rotation of the polarization plane is decreased. The investigations of CLCs have shown that they are very sensitive towards external factors such as electric, magnetic or strong light fields, UV radiation or thermal gradient. From this point of view it is interesting to examine the use of liquid-crystalline mediums, if we take into account the wide possibility to control them by an external field, including optical (Simoni, 1997). Therefore varying the parameters of the CLCs it becomes possible to control its photonic band gap and other properties. The polarization plane rotation property is widely used in different optical devices, such as light modulators, valves, etc. From an application point of view, PC devices for polarization control should be important because they do not rely on the intrinsic properties of the constituent materials of PC. In particular, the properties of photonic crystals are dependent on the boundary conditions, which can be engineered to suit a wide variety of diverse applications. Additionally the polarization control of light is important for optical information processing, display and storage devices (Mochizuki et al., 2000); (Furumi and Sakka, 2006); (O'Neill and Kelly,

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Theoretical and Experimental Investigation of Polarization and Spectral Properties of Light in Multilayer Cholesteric Liquid-crystalline Systems.
DOI: 10.5220/0004339801110114
In *Proceedings of the International Conference on Photonics, Optics and Laser Technology* (PHOTOPTICS-2013), pages 111-114
ISBN: 978-989-8565-44-0

2003); (Yeh and Gu, 1999); (Wu and Yang, 2001). The aim of this work is to experimentally and theoretically investigate the characteristics of the behavior of light polarization in the liquid crystalline medium.

2 EXPERIMENT

2.1 Sample Preparation

In order to investigate polarization plane rotation of light we have prepared cholesteric liquid-crystalline cell through the contact of two cholesteric liquid crystals. For that purpose a mixture of right-handed pelargonium, left-handed oleate and E-7 nematic liquid crystals was prepared. These two mixtures were one reflecting in the green range named SG, the other reflecting in the red range, named SR. One of the substrates was coated with Cholesteric liquid crystal (1), which was green in colour, and other substrate was coated with Cholesteric liquid crystal (2), which was red in colour. Clearly between two adjacent surfaces the diffusion process has occurred. The inner surfaces of glass substrates were first coated with thin polymide layer and were then rubbed with a special material. As a result, the orientation of CLCs director was parallel to the surfaces, which means that the helix axis was perpendicular to the surfaces of the cell. The mixture was drop filled into the empty cell. The thickness of our sample was 15μm.

2.2 Experimental Set-up

In order to investigate the polarization plane rotation of light we have assembled the experimental set-up, depicted in Figure 1. The CLC cells were illuminated He-Ne laser with λ=0.63μm and with λ=0.53μm wavelength diode pumping semiconductor laser radiations.

Before the investigation of the polarization plane rotation the selective reflection bands for green and red CLCs were observed.

In order to investigate polarization plane rotation the primary direction was defined. The angle of polarization plane rotation was measured every hour in the temperature range 14-21°C, which includes selective reflection band gaps of both green and red CLCs. Measurements were done on the daily basis. As a source of laser radiation both He-Ne laser and diode pumping semiconductor laser were used. In figure 2 dependences of polarization plane rotation angle on temperature for different cases are represented. Figure 2 a) corresponds to the case, when light from semiconductor laser first falls on a cell substrate coated with green CLC, and figure 2 b) corresponds to the case, when substrate of the cell, coated with red CLC, is illuminated with light from He-Ne laser. In Figure 2 c) and d) are shown the following cases: c) substrate of the cell, coated with green CLC, is illuminated with light from He-Ne laser, d) substrate of the cell, coated with red CLC, is illuminated with light from semiconductor laser.

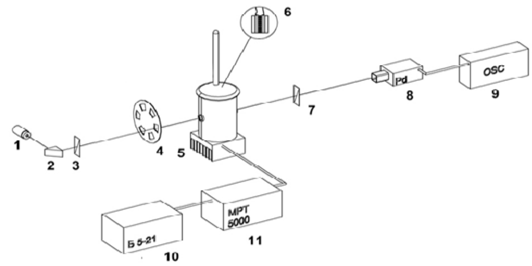


Figure 1: Scheme of experimental set-up for investigation of polarization plane rotation of light: 1.Source of laser radiation,2.Prism,3.Polarizer,4.Modulator,5.Microrefrigirator,6.CLCcell,7.Polarizer,8.Photodiode,9.Oscillograph,10. DC source,11.Controller of temperature.

As it is seen from the graphs, the polarization plane rotation has maximum value in the cases a) and b) and approximately equals to 35°, but the polarization plane rotates only by a few degrees in the cases c) and d).

So the main purpose was to obtain large polarization plane rotation with small loss.

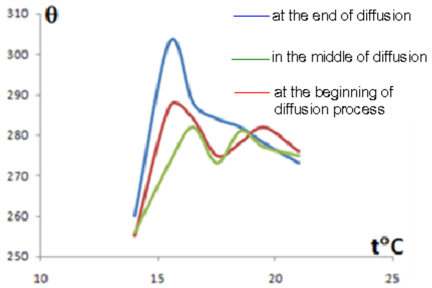
We have also obtained the reflection spectra of green and red CLCs for the mutual temperature t=17°C .

In order to investigate the transmission and reflection spectra for unpolarized and linear polarized lights (at normal incidence) we have assembled the experimental set-up, depicted in Figure 3. In our experiment StellarNet spectrometer with optical resolution of 0,75 nm was used. The reflection spectra for linear polarized light is depicted in figure 4.

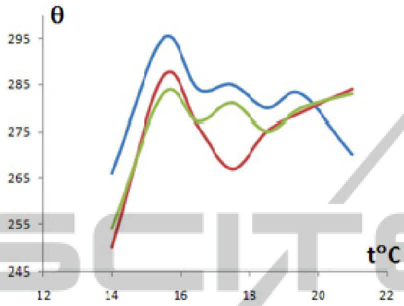
3 THEORY

3.1 Method of Analysis

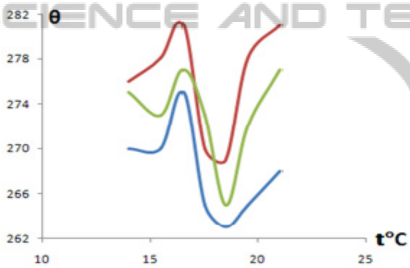
The problem is solved by Ambartsumian's layer addition modified method. This method was earlier developed for the solution of astrophysical problems of multiple scattering in turbid media. It has been



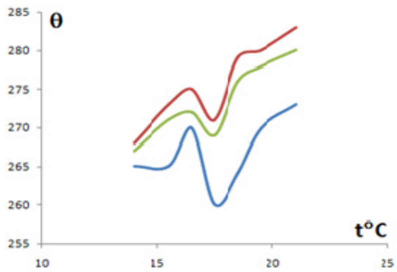
a)



b)



c)



d)

Figure 2: Dependences of polarization plane rotation angle on temperature for different cases: a) substrate of the cell, coated with green CLC, is illuminated with light from semiconductor laser, b) substrate of the cell, coated with red CLC, is illuminated with light from He-Ne laser, c) substrate of the cell, coated with green CLC, is illuminated with light from He-Ne laser, d) substrate of the cell, coated with red CLC, is illuminated with light from semiconductor laser. The different colours correspond to the measurements of different days.

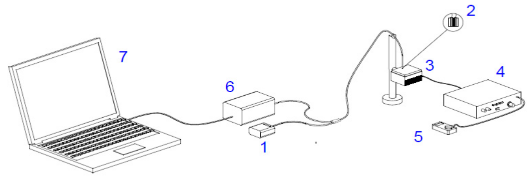


Figure 3: Scheme of experimental set-up for investigation of discussed system's reflection and transmission spectra: 1.Tungsten-krypton lamp.2. CLC cell, 3. Microrefrigerator, 4. Controller of temperature, 5.Tester, 6.Spectrometer, 7. PC.

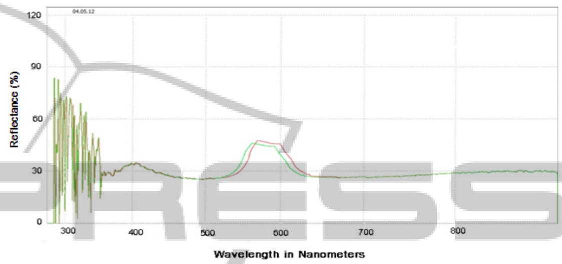


Figure 4: Reflection spectra for linear polarized light.

developed for optical wave propagation through inhomogeneous media. The employed method rigorously takes into account the boundary conditions and interface reflections of the CLC medium. A CLC film can be treated as a bilayer system: CLC(1)- CLC(2). Let us present the solution of the boundary problem of light transmission through the multi-layer system in the form:

$$\vec{E}_r = \hat{R}\vec{E}_i, \quad \vec{E}_t = \hat{T}\vec{E}_i \tag{1}$$

where the indices *I*, *r* and *t* denote the incident, reflected and transmitted waves' fields, $\hat{R}$ and $\hat{T}$ are the reflection and transmission matrices.

$$\vec{E}_{i,r,t} = E^p_{i,r,t}\vec{n}_p + E^s_{i,r,t}\vec{n}_s = \begin{bmatrix} E^p_{i,r,t} \\ E^s_{i,r,t} \end{bmatrix}, \tag{2}$$

where $\vec{n}_p$ and $\vec{n}_s$ are the unit vectors of orthogonal linear polarizations, $E^p_{i,r,t}$ and $E^s_{i,r,t}$ are corresponding amplitudes of the incident, reflected and transmitted waves. According to Ambartsumian's layer addition modified method, if there is a system consisting of two adjacent (from left to right) layers, *A* and *B,* then the reflection transmission matrices of the system, *A*+*B* , viz. $\hat{R}_{A+B}$ and $\hat{T}_{A+B}$, are determined in terms of similar matrices of its component layers by the matrix equations:

$$\widehat{R}_{A+B} = \widehat{R}_A + \tilde{\widehat{T}}_A \widehat{R}_B \left[\widehat{I} - \tilde{\widehat{R}}_A \widehat{R}_B \right]^{-1} \widehat{T}_A,$$
$$\widehat{T}_{A+B} = \widehat{T}_B \left[\widehat{I} - \tilde{\widehat{R}}_A \widehat{R}_B \right]^{-1} \widehat{T}_A, \quad (3)$$

where the tilde denotes the corresponding reflection and transmission matrices for the reverse direction of light propagation, and $\hat{I}$ is the unit matrix(Wohler et al. 1991). The exact reflection and transmission matrices for a finite *CLC layer* (at normal incidence) are well known.

The ellipticity e and the azimuth ψ of the transmitted light are expressed by $\chi = E_t^s / E_t^p$ through the following formulas:

$$\psi = \frac{1}{2}\text{arctg}\left(\frac{2\,\text{Re}(\chi)}{1-|\chi|^2}\right) \quad e = tg\left(\frac{1}{2}\arcsin\left(\frac{2\,\text{Im}(\chi)}{1+|\chi|^2}\right)\right) \quad (4)$$

Due to Ambartsumian's layer addition modified method in our experiment the azimuth of the transmitted light was calculated. In figure 5 the azimuth dependence on wavelength for three different moments of diffusion process is presented.

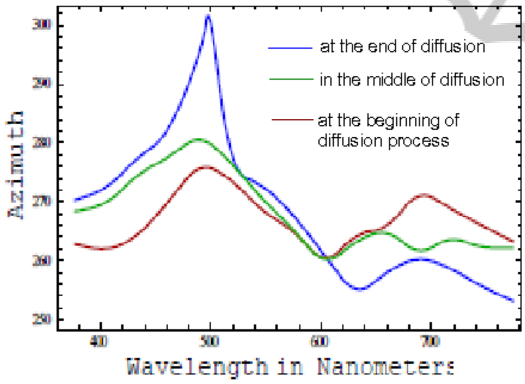


Figure 5: Azimuth dependence on wavelength for different moments of diffusion process.

Let us note, that there are many methods of solving the light propagating problem through a system containing liquid-crystalline layer. Here it is convenient and novel to apply Ambartsumyan's layer addition modified method, because the exact reflection and transmission matrices of the finite CLC layer are known.

4 CONCLUSIONS

We have studied polarization features of light in CLC systems consisting of right and left-handed cholesterics and nematic liquid crystal. These investigations provide much information on possible new applications of photonic crystals in optics. Our results can be used in the systems as a band optical diode for circularly polarized incident light as well as in sources of elliptically polarized light with tunable ellipticity. We also showed that the bandwidth of cholesteric reflection was broadened. So, the most important peculiarity of cholesteric liquid crystals is related to control of their optical characteristics. The investigations of the polarization and spectral properties of light in other systems such as: systems consisting of right and left handed cholesterics with the same pitch and 4-layer CLC systems with pitch gradient, are still in progress.

ACKNOWLEDGEMENTS

This work was supported by Grant 11-1c194 of State Committee of Science of Republic of Armenia.

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