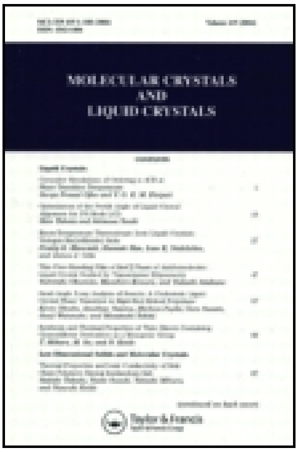

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OPTICAL PROPERTIES OF SINGLE LAYER NON-ABSORPTIVE BROAD-BAND CLC POLARIZERS

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Abstract We report for the first time the results of theoretical study on the optical properties of single layer non-absorptive broadband cholesteric liquid crystals (BBCLC) polarizers. The objective of this study is to understand the effect of material parameters and sample configuration on the performance of BBCLC films and therefore provide guidance for the fabrication of high quality single layer broadband polarizers. The study is based on Berreman's 4x4 matrix formalism. Nonlinear pitch distribution across the cell thickness is used in the simulation. Pitch gradient smaller than 20 nm/μm is found necessary for high extinction ratio for chosen material system. The extinction ratio decreases significantly when the incident angle (internal angle) is greater than 20^0 and an extinction revere region is found in the case of large angle of incidence. The theoretical results are compared with the experimental results of Reveo's broadband polarizers and show reasonably good agreement.

INTRODUCTION

Polarizers are widely used in optical systems. Conventional polarizers use the dichroic property of certain materials. By using this type of polarizers, at least 50% of light is adsorbed and transformed into heat which causes sever problems for many applications. Recently, intensive research is being conducted to develop polarizers based on the optical properties of cholesteric liquid crystals (CLCs)[1,2,9]. CLCs are formed by elongated molecules. The molecules undergo twisting along a direction so called helical axis. Light incident onto a film of CLCs is reflected when the twisting sense of incident circularly polarized light matches that of CLC materials and wavelength of the light meets Bragg reflection condition $\lambda = nP\cos\beta$, where n and P are average refractive index and pitch of CLC materials, respectively, and β is the incident angle. The reflected light is circularly polarized and hence CLC films are naturally circular polarizers. Linear polarizers can be achieved by using the combination of a CLC film with a $\frac{1}{4}\lambda$ wave plate. However, the band width of this type polarizer is limited if the conventional CLC film is used. The band width is determined by the pitch and optical birefringence of CLC materials: $\Delta\lambda = \Delta n \bullet P$, where Δn is the optical birefringence of the material. For most commercially available liquid crystal materials, Δn is below 0.25. That means the band width for thus made polarizers is less than 110 nm in the visible range. Reveo and Philips research groups have invented so called broadband CLC polarizers by introducing the pitch gradient into the cholesteric liquid crystal film [1,2]. The wide range of pitch in the sample results in broad band reflection spectra. In this paper, we report for the first time the results of theoretical study of optical properties of broadband polarizers. The purpose of this study is to understand the effect of material parameters and sample configuration on the performance of BBCLC polarizers and therefore provides guidance for the fabrication of high quality BBCLC films. Our theoretical study is based on Berreman's 4x4 formalism. Exponential pitch distribution is used for the model calculation. The results are compared with Reveo's BBCLC polarizers and show reasonably good agreements.

BERREMAN'S 4X4 MATRIX FORMALISM

Berreman's 4x4 matrix method has been used by several authors to study the reflection and transmission properties of CLC films with uniform pitch. The configurations which have been studied so far include: (1) the CLC materials in *perfect* planar texture, where the helical axes are uniformly orientated and perpendicular to the substrate surfaces[3,4], and (2) CLC materials in *imperfect* planar texture, where CLCs are in domain structure and uniform pitch inside a domain is assumed[5,6]. A distribution of helical axis orientation among domains is also assumed. The difference of the BBCLC system studied in this paper from above cases is that the pitch gradually and continuously changes along helical axes, although helical axes are uniformly oriented and perpendicular to the substrate surfaces, as shown in Figure 1. This system is of great interest currently because it results in broad band reflection and can be used to enhance the light efficiency of backlight system of notebook computers and other optical systems[7].

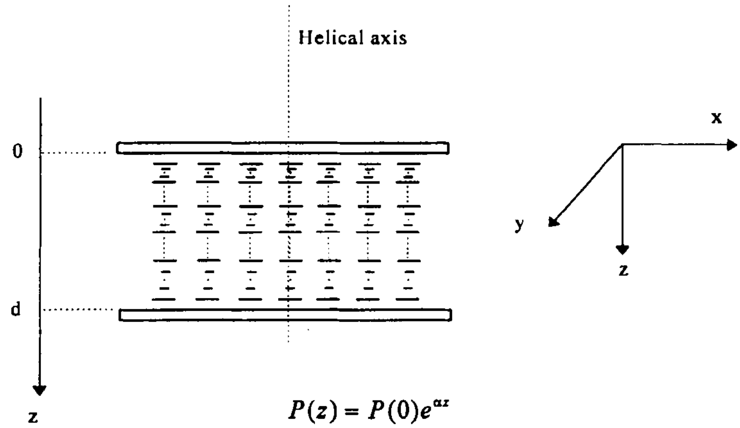

FIGURE 1. Helical structure of single layer BBCLC polarizer.

In the model calculation, we divide the BBCLC film into numerous very thin slices. Each slice is assumed to have uniform pitch. The actual pitch variation in a slice is set to be less than 0.4 nm to guarantee the accuracy of the calculation. The dielectric tensor for each slice is then expressed as:

$$\vec{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & 0 \\ \varepsilon_{21} & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} = \begin{bmatrix} \bar{\varepsilon} + \bar{\varepsilon}\delta \cos\frac{4\pi}{P(z)}z & \gamma\bar{\varepsilon}\delta \sin\frac{4\pi}{P(z)}z & 0 \\ \gamma\bar{\varepsilon}\delta \sin\frac{4\pi}{P(z)}z & \bar{\varepsilon} - \bar{\varepsilon}\delta \cos\frac{4\pi}{P(z)}z & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{bmatrix} \quad (1)$$

Where $\bar{\varepsilon} = \frac{\varepsilon_{\perp} + \varepsilon_{//}}{2}, \delta = \frac{\varepsilon_{//} - \varepsilon_{\perp}}{\varepsilon_{//} + \varepsilon_{\perp}}, \gamma = \pm 1$ (γ=1 if CLC is right hand and γ=-1 if CLC is left hand), and P(z) is the pitch distribution function.

The pitch distribution function is chosen as exponential type and expressed as:

$$P(z) = P(0)e^{\alpha z} \quad (2)$$

Where P(0) is the pitch at top surface and α is a constant which determines pitch gradient in the sample. We have actually tried both exponential and linear pitch distribution functions in the simulation of the spectra. The results show that exponential pitch distribution agrees much better with Reveo's BBCLC system as far as the spectrum characteristics are concerned. The exponential pitch distribution in Reveo's BBCLC system has also been confirmed by earlier AFM study[1].

In the calculation, we also assume that a BBCLC film is surrounded by medium the refractive index of which is same as that of the average refractive index of CLC material. This assumption matches reasonably well with experimental configuration where the BBCLC film is covered by glass plates and is placed in a cylindrical container filled with glycerol.

THICKNESS EFFECT

By using the exponential pitch distribution function (2), we have calculated the spectra for samples with thickness: 5μm (Sample1), 10μm (Sample2), and 20μm (Sample3). The angle of incidence is set at 0° and both unpolarized light and circularly polarized light have been used. Using unpolarized light eliminates the experimental restriction of the bandwidth of circular polarizers and much broader wavelength range can be studied, while using both right hand circularly (RHC) and left hand circularly (LHC) polarized light clearly explains the efficiency of BBCLC polarizers. Material constants: $\Delta n = 0.16$, $n = 1.62$ are used in all model calculation. The values of P(0) and α for each sample are obtained by comparing the simulated spectra of unpolarized light with those of experimental results and are listed in the table of Figure 2. Figure 2 also shows the sketch of pitch distribution along the thickness for all the three samples. In the study of this paper, samples are right hand. The material composition and UV irradiation process are experimentally controlled to be identical for all the samples.

The simulation results for unpolarized light are shown in Figure 3. For comparison, the experimental results are also plotted in a separate column in Figure 3. The experimental spectra are measured by using spectrophotometer from Perkin Elmer. Both theoretical and experimental spectra show the following features:

(1) The reflectance within the bandwidth increases with the increase of sample thickness.

(2) For all the three samples, reflectance is higher for shorter wavelength and lower for long wavelength.

Samples	1	2	3
Thickness(μm)	5	10	20
P(0) (nm)	235	235	235
α (1/μm)	0.148	0.092	0.051

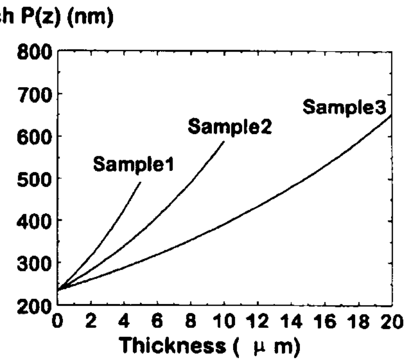

FIGURE 2. Table of values of P(0) and α for Sample1, Sample2 and Sample3 and pitch distribution curves for all the three samples.

These results can be explained by the difference in pitch gradient. As we know, the selective reflection from CLC film with uniform pitch is caused by interference of reflected light from the periodic structure[8]. To some extent, for a chosen material system, the thicker the film, the higher the reflectance in the selective reflection band[5, 6]. Similarly for a BBCLC film, smaller pitch gradient results in higher reflectance in the corresponding wavelength. In a BBCLC film with exponential pitch distribution, pitch changes slower (smaller gradient) at short wavelength side and faster (larger gradient) at long wavelength side, as shown in Figure 2. The reflectance increases with the decrease of pitch gradient until a critical pitch gradient $(\frac{dP}{dz})_c$. Gradient lower than this value results in saturated reflectance (50% for unpolarized light).

Table I shows the mid-layer pitch gradient and corresponding reflectance in the spectra. The wavelength is calculated in terms of pitch and average refractive index (λ=nP). The smoothed reflectance is obtained by averaging out the oscillation in the spectrum and measured at the corresponding wavelength. For Sample1($(\frac{dP}{dz})_{z=d/2}$ = 50.4 nm/μm), only 28% of incident light is reflected at mid-layer wavelength, which is very low comparing with the maximum value of 50%, while Sample3($(\frac{dP}{dz})_{z=d/2}$ = 20.0 nm/μm) results in 44% reflected light at mid-layer wavelength.

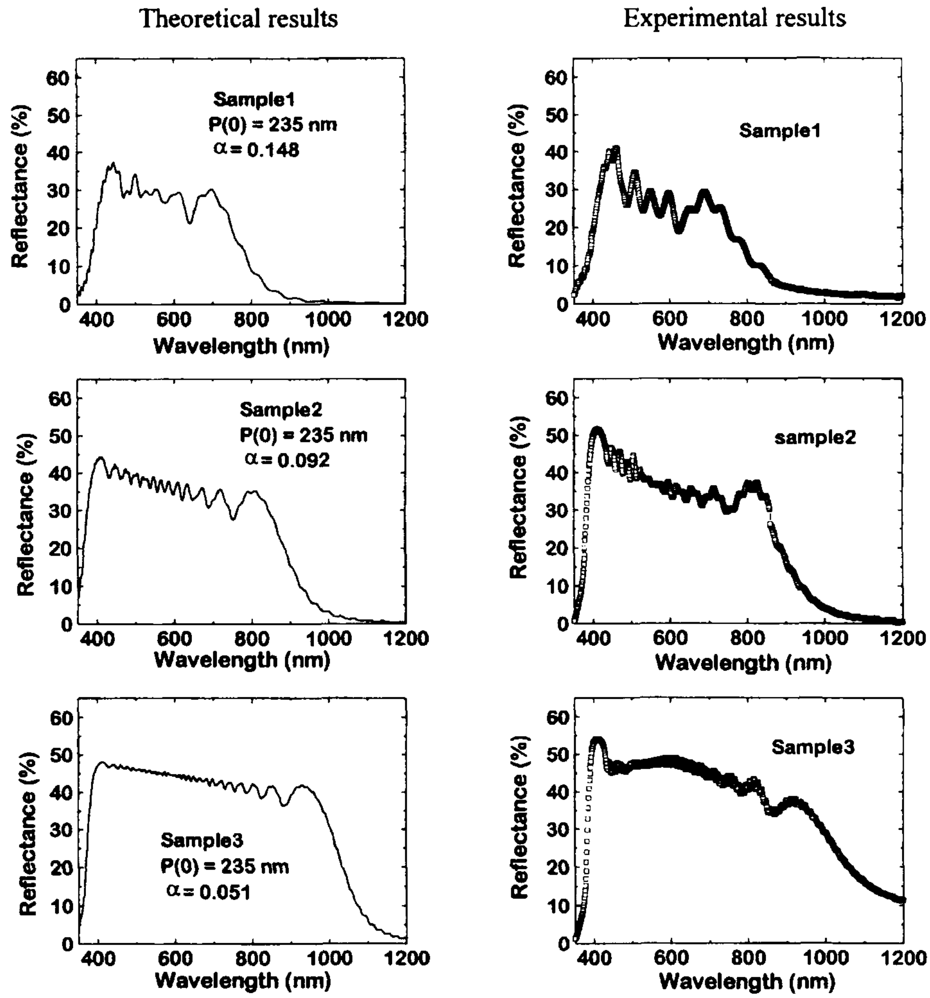

FIGURE 3. Theoretical results of reflection spectra for samples with different thickness. The incident light is unpolarized. Experimental results are plotted for comparison.

As mentioned earlier, samples used in experimental measurement have exactly same material composition and UV polymerization condition. However, the measurement shows that the bandwidth exhibits difference. In Reveo's BBCLC system, materials are composed of non-polymerizable low molecule nematic liquid crystal and polymerizable polysiloxane oligomer[1]. The pitch gradient is generated by the relative

Table I Mid-layer pitch gradient and the reflectance for corresponding wavelength

Sample thickness (μm)	Mid-layer pitch gradient $(\frac{dP}{dz})_{z=d/2}$ (nm/μm)	Mid-layer pitch/wavelength (nm/nm)	Smoothed reflectance* (%)
5 (Sample1)	50.4	340.2/544.3	28
10 (Sample2)	34.2	372.2/595.6	36
20 (Sample3)	20.0	391.3/626.1	44

* Data are taken from the theoretical curves in Figure 3.

concentration change across the sample thickness during the UV polymerization process. We believe it is reasonable for the thicker sample to have wider pitch range. It is also worth mentioning that for sample3 (20 μm), the pitch distribution is different from that reported in an earlier paper[9]. This difference is caused by the difference in material composition.

Figure 4 shows the polarization effect of BBCLC films with different thickness. Experimental results, obtained by using the setup shown in Figure 5, are also plotted for comparison. The wavelength range is truncated at 450 nm and 750 nm due to the limit from the response of PMT and light intensity of the light source. The incident angle is fixed at 0°. For the convenience of experiments, transmission spectra are measured. The reflection spectra can be easily obtained in terms of transmission spectra. Both theoretical and experimental results show that for RHC components (samples are made with right hand CLC materials), the transmitted light decreases significantly with the increase of thickness, which is consistent with the observation of reflection spectra in the case of unpolarized light incidence. However, the change of thickness does not affect the transmittance of LHC component. The contrast ratio, defined as T_{LHC}/T_{RHC}, where T_{LHC} and T_{RHC} are the transmittance of LHC and RHC components, respectively, increases significantly with the increase of thickness. The contrast ratio of 20 is achieved at short wavelength side for Sample3.

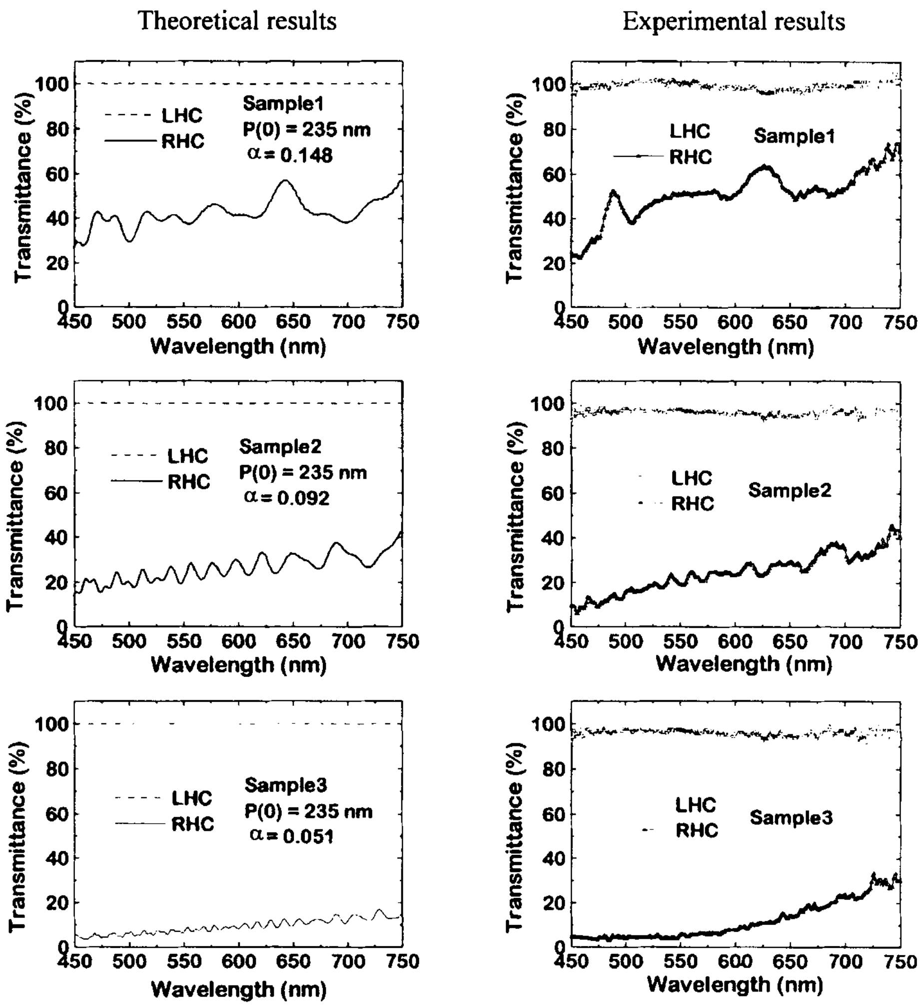

FIGURE 4. Theoretical results of transmission spectra for both RHC and LHC light. The samples are right hand. Experimental results are plotted for comparison.

ANGULAR DEPENDENCE

The angular dependence of BBCLC films is of particular interest when applications with oblique incidence are desired. Berreman's 4x4 matrix formalism is used by simply taking into account non-zero incident angle. Experimental measurement is performed with the setup shown in Figure 5. The combination of a linear polarizer and a Fresnel Rhomb is used as a broadband circular polarizer. The circularly polarized light is produced by setting the optical axis of the linear polarizer 45° with respect to the baseline of Fresnel Rhomb. By rotating the optical axis of the linear polarizer 90°, the handness of the circularly polarized light is reversed. The BBCLC sample is placed in a cylindrical glass container filled with glycerol for refractive index matching. The angle is changed by a rotating stage and light is incident from long pitch side of the sample. The transmitted light is detected by a photomultiplier tube (PMT). A digital oscilloscope is used for data acquisition and is synchronized with monochromator. A PC is used for all the controlling of the setup.

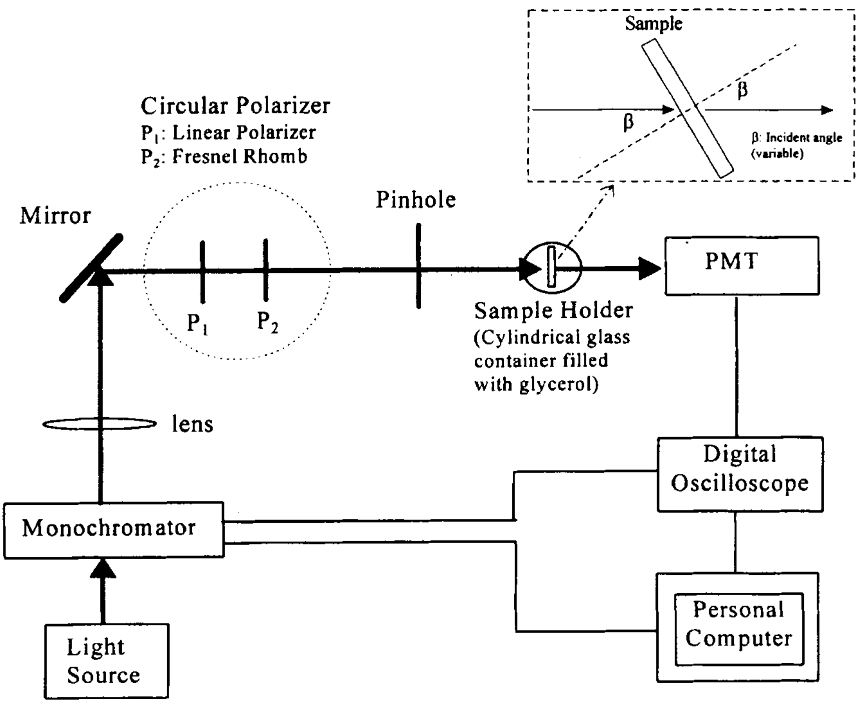

FIGURE 5. Experimental setup used for angular dependence measurement.

In the angular dependence study, the angle of incidence is changed from 0° to 50° at an increment of 10°. The angles indicated here are internal angles due to the existence of refractive index matching solution (glycerol).

Sample3 (20 μm) is chosen for the angular dependence study. Simulation results are shown in Figure 6, along with experimental spectra as comparison. The transmission spectra for 0° and 10° incidence look very similar. No cross talk of RHC and LHC takes place for small angle of incidence. At these angles, all LHC light is transmitted and almost all RHC light is reflected. When the angle of incidence is increased to 20°, the transmittance of LHC becomes smaller, which indicates that certain amount of LHC light is reflected, while the transmittance of RHC light becomes higher, indicating that certain amount of RHC light leaks through the film. This type of cross talk effect is more significant at short wavelength end for the current configuration (light is incident from long pitch side of BBCLC film). When the angle of incidence is continually increased, the transmission spectrum shows a minimum for LHC light and a local maximum for RHC light at wavelength ~ 525 nm. The values of local minimum (for LHC) and maximum (for RHC) show significant decrease (for LHC) or increase (for RHC) when the angle of incidence is changed to 40° and 50°. Extinction reverse at these angles is observed in the vicinity of 525 nm. Preliminary study shows that the polarization reverse also takes place and the wavelength region shifts if the light is incident from short pitch side.

The studies have shown that in current material and cell configuration, internal angle of 20° or external angle of 30° (assuming the refractive index of substrates is ~ 1.5) is the limit for most applications. The thorough investigation of optical properties of BBCLC films at large angle of incidence is out the scope of this paper.

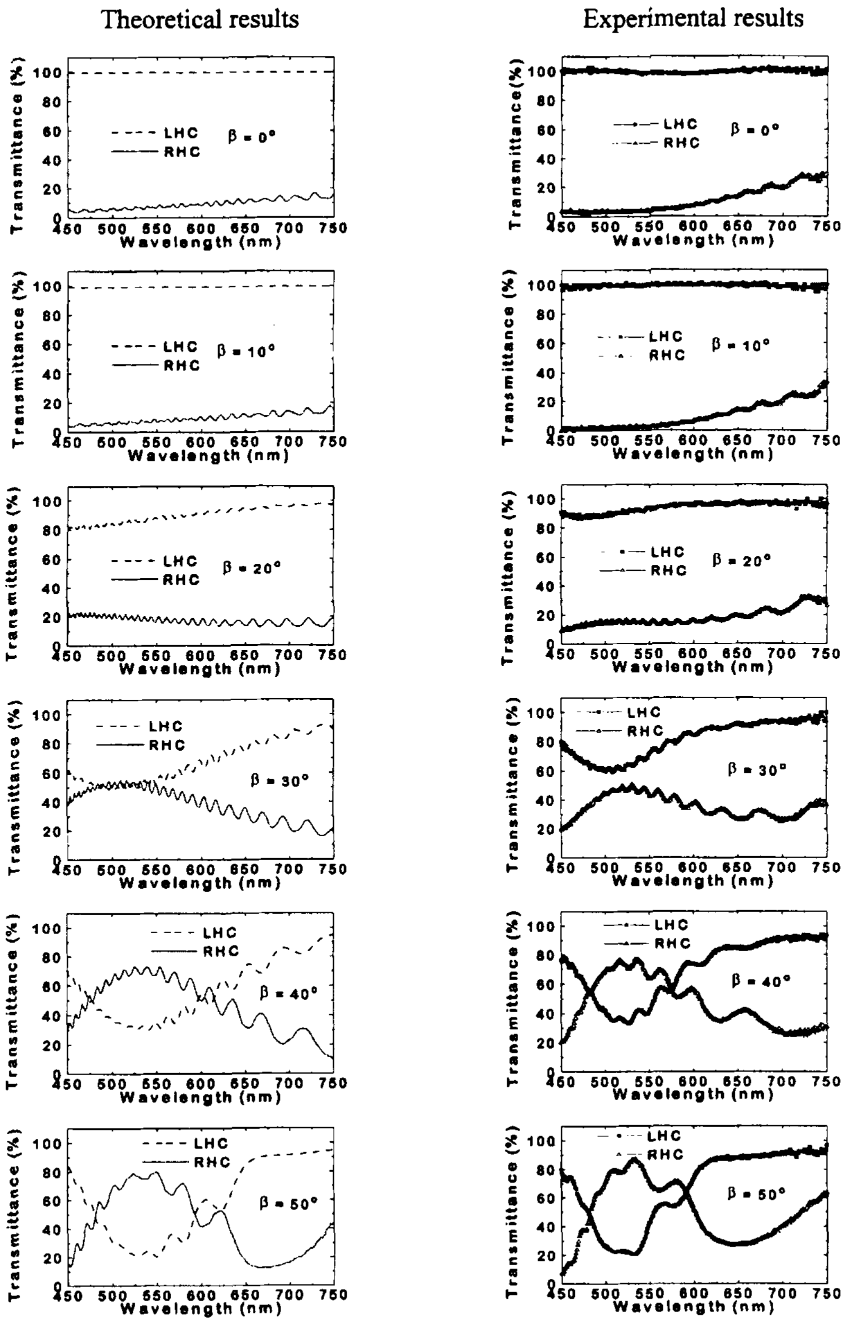

FIGURE 6. Theoretical results of transmission spectra at oblique incident angles. Experimental results are plotted for comparison.

CONCLUSION

We have for the first time theoretically investigated the optical properties of single layer non-absorptive broadband CLC polarizers. The theoretical study shows reasonably good agreement with experimental results based on Reveo's BBCLC polarizers. For the chosen material system, the value of pitch gradient has been shown to be a critical parameter for high extinction ratio. Both theoretical and experimental results show that the extinction ratio ~ 20 is achieved for Reveo's BBCLC polarizer and the ratio does not show significant decrease up to an incident angle of 20° (internal angle, or 30° external angle).

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