

# Broadband circular polarizer using stacked chiral polymer films

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**Abstract:** A scattering-free broadband (~120 nm bandwidth) circular polarizer is demonstrated by stacking three chiral polymer films with different pitch lengths. Using 4×4 matrix method, we have theoretically simulated the transmission spectra of each chiral polymer film and the three stacked films. Simulation results agree well with experiment. A broadband circular polarizer with bandwidth ranging from 400 to 736 nm can be achieved by stacking 8 such chiral polymer films together. Simulation results indicate that if a high birefringence ( $\Delta n \sim 0.35$ ) polymer film is employed the number of films can be reduced to three. Potential applications of these circular polarizers for liquid crystal displays, optical communications, and optical remote sensors are discussed.

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**OCIS codes:** (230.3720) Liquid-crystal devices; (160, 3710) Materials; (140, 3300) Lasers and laser optics

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## 1. Introduction

Circular polarizers are useful for optical communications, optical remote sensors, and liquid crystal displays (LCDs) [1-3]. For reflective and transmissive LCDs, circular polarizer is a crucial component for achieving high contrast ratio. While for transmissive LCDs, circular polarizer in conjunction with a quarter-wave plate can be used for converting a randomly polarized backlight light to a linearly polarized light [4]. Two methods have been commonly employed for making a circular polarizer: 1) to laminate a linear polarizer with a quarter wave film [5, 6] and 2) to utilize the Bragg reflection of a cholesteric liquid crystal (CLC) film [7-11]. In the first approach, if an absorption-type linear polarizer is employed, then more than 50% of the incident light is absorbed. Therefore, a non-absorbing type polarizer, such as polarizing beam splitter (PBS) should be considered. Let us assume the PBS transmits p-wave and reflects s-wave. If we let the reflected s-wave pass through a half wave plate and recombine with the p-wave, then the unpolarized light can be converted to a linearly polarized light. As a result, the LCD optical efficiency would be doubled. As a matter of fact, this approach has been commonly used in projection displays [12].

For large screen direct-view LCDs, the film-based polarization converter is more practical than PBS. A polarization converter using CLC film with a reflector and a quarter-wave film has been proposed [13]. However, the bandwidth of a CLC film is determined by the LC birefringence ( $\Delta n$ ) and the pitch length. To cover the entire visible spectral range (400-750 nm), a CLC film with  $\Delta n > 0.7$  is required if the uniform pitch length approach is employed [9]. Although some super high birefringence liquid crystals do exist [14], their viscosity is high and chemical and photo stabilities are inadequate. A more practical approach is to use a modest birefringence ( $\Delta n \sim 0.2$ ) CLC which has a gradient pitch distribution along the helical axis [15-17]. Such a broadband circular polarizer has been experimentally demonstrated. However, in order to establish Bragg reflection for a broadband light, the required CLC layer is relatively thick. In a thick CLC layer, defects can be easily formed which cause light scattering and therefore dramatically decrease the film's reflectivity.

In this paper, we demonstrate a scattering-free broadband circular polarizer by stacking multiple chiral polymer films with different pitch lengths. To prove concept, we stacked three CLC films to achieve a circular polarizer with  $\sim 120$  nm bandwidth. Because each film we used is only  $5 \mu\text{m}$  thick, the stacked films are free from defects and scattering. We also performed computer simulations and found that the simulated results agree with experiment well. Based on the simulation model, we designed a broadband circular polarizer whose bandwidth spans from 400 nm to 736 nm using three high birefringence chiral polymer films.

## 2. Experiment and results

To fabricate chiral polymer films, the chiral monomer mixture was prepared by mixing the reactive mesogen monomer RMM154, reactive monomer RM82, and chiral CB15 (all from Merck) together. We prepared three chiral monomer mixtures with different chiral agent/monomer ratio to get three films with different pitch lengths. The mixtures were thoroughly mixed before they were capillary-filled into the empty LC cells ( $5 \mu\text{m}$  cell gap) in an isotropic state. The inner surfaces of the glass substrates were first coated with a thin transparent conductive indium-tin-oxide (ITO) electrode and then overcoated with a thin polyimide layer. The substrates were subsequently rubbed in antiparallel directions to produce  $\sim 2\text{-}3^\circ$  pretilt angle. The samples were slowly cooled down to  $55^\circ\text{C}$  to reduce the defect

formation. Then a UV light was used to illuminate each sample for ~1 hr while keeping the temperature at 55°C to turn the chiral monomer into chiral polymer film. Figure 1 shows the transmission spectra of the three chiral polymer films we fabricated. Each chiral polymer film has ~54 nm bandwidth. The films were confined in glass substrates. The ~20% transmission loss observed in Fig. 1 is due to the reflections of the employed ITO glass substrates. These substrates do not have any antireflection coating. Thus, the chiral polymer films we fabricated are basically scattering free.

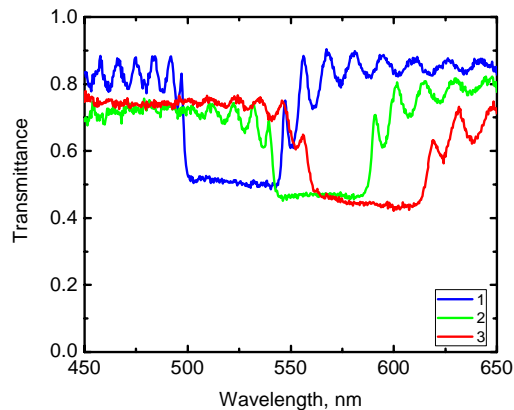


Fig. 1. Transmittance spectra of chiral polymer films: red, green and blue lines represent the transmittance spectrum of film1, 2, and 3, respectively.

Afterwards, we peeled off the chiral polymer films from the glass substrates and stacked the three films together carefully in order to avoid the formation of surface corrugation. Figure 2 is the plot of the transmission spectrum of the stacked films. The bandwidth of the film is broadened from 54 nm to 120 nm. From Fig. 2, we can see that the transmittance of the three stacked film within and beyond the band gap is almost the same as that from a single film, which indicates that the three stacked films do not cause any additional optical loss.

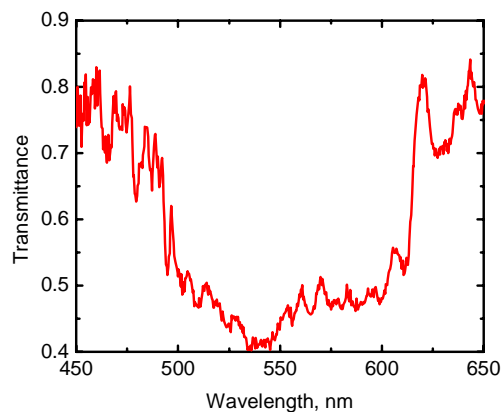


Fig. 2. Transmittance spectrum of a circular polarizer with three stacked chiral polymer films.

Next, we used an experimental setup as Fig. 3 shows to test the extinction ratio of the circular polarizer consisting of three stacked chiral polymer films. In this experiment, a circular analyzer consisting of a broadband quarter wave plate and a linear polarizer was used

to analyze the polarization purity of the chiral polymer films. The relative angle between the optic axis of the polarizer and the quarter wave plate is  $45^\circ$ . By rotating the optic axis of the polarizer by  $90^\circ$ , a circular polarizer with opposite handedness is obtained. Therefore, bright and dark states can be obtained by rotating the linear polarizer by  $90^\circ$  when the reflected light from the chiral polymer films passes through the circular polarizer.

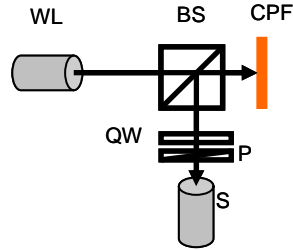


Fig. 3. Schematic of the experimental setup for measuring the extinction ratio of the circular polarizer composed of three chiral polymer films. WL: white light source; BS: beam splitter; CPF: chiral polymer film; P: polarizer; QW: quarter wave plate; S: spectrometer

Figure 4 shows the measured reflection spectra of the stacked polymer films after the circular analyzer. Lines 1 and 2 represent the reflection spectra of the polymer films when the circular analyzer exhibits the same or opposite handedness to that of the chiral polymer films, respectively. The measured extinction ratio of the circular polarizer made of three stacked chiral polymer films ranges from 8:1 to 30:1, depending on the wavelength. Two factors contributing to the variation of the extinction ratio. Firstly, the circular polarizer employed is not broadband. A good dark state can only be obtained in a narrow spectral range. Secondly, there is an air gap between films which causes interference. As a result, higher extinction ratio appears at the dark interference fringes and lower extinction ratio at the bright interference fringes. If a broadband circular polarizer is employed in the measurement and the air gap between the films is eliminated by improving the fabrication process, then the extinction ratio should remain above 15:1. Although not perfect, it is still acceptable to use the circular polarizer together with a broadband quarter-wave film to convert an unpolarized white light into a linearly polarized light for LCD applications [15]. In an LCD, two crossed linear polarizers are always needed in order to obtain a contrast ratio higher than 1000:1. Thus, through polarization conversion the optical efficiency of a LCD can almost be doubled if the circular polarizer made of stacked chiral polymer films can cover the whole visible range.

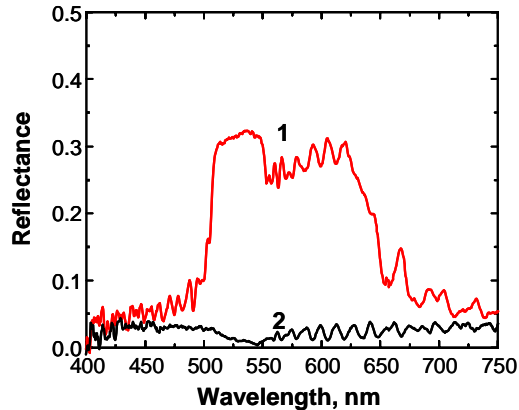


Fig. 4. Reflection spectra of the circular polarizer at normal angle incidence. Red and black lines represent the bright and dark states, respectively.

### 3. Simulation results

By stacking more chiral polymer films with different pitch lengths together, it is possible to obtain a broadband circular polarizer to cover the whole visible range. In this section, we use 4×4 matrix method to simulate our experimental results and then design a broadband circular polarizer to cover the entire visible spectral range.

According to our experimental results, the effective birefringence, average refractive index, and pitch length (in nm) of films 1-3 are calculated to be (0.146, 1.58, 371.66), (0.128, 1.575, 358.66), (0.138, 1.565, 333.50), respectively. With these parameters, we simulated the transmittance spectra of films 1-3 using our improved 4×4 transfer matrix and scattering matrix [18, 19]. In this method, the 4×4 matrix for each slice is diagonalized and thus the equations become very concise. The employed method rigorously takes into account the boundary conditions and multiple interface reflections of the LC medium. The simulation results are plotted in Fig. 5. The red, green, and blue lines in Fig. 5 represent the transmission spectra of films 1, 2, and 3, respectively.

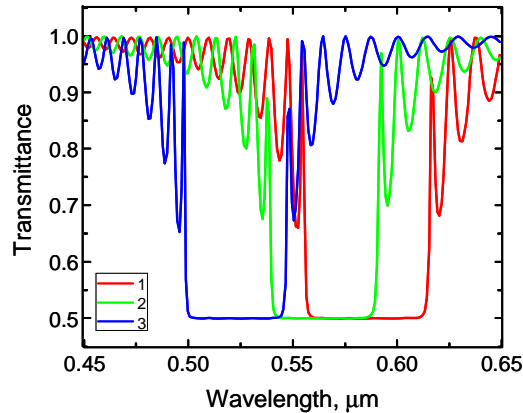


Fig. 5. Simulation results of the transmission spectra through each chiral polymer film.

Next, we simulated the transmission spectrum of the circular polarizer made of three stacked chiral polymer films using the same parameters. Results are shown in Fig. 6(a). In comparison with the experimental data shown in Fig. 6(b), we find that the simulation results agree well with the experiment.

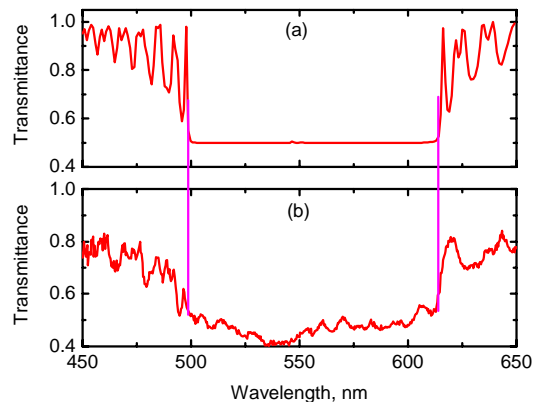


Fig. 6. Simulation (a) and experimental (b) results of the circular polarizer composed of 3 chiral polymer films.

To enhance the optical efficiency of a LCD, a broadband circular polarizer covering the entire visible range is needed in order to avoid color shift at oblique angles. Therefore, we designed a broadband circular polarizer by stacking 8 CLC films with different pitch lengths. In our simulation, the birefringence of the monomers is assumed to be  $\Delta n \sim 0.15$ . The pitch lengths (in nm) for the 8 films are  $P_1 = 286$ ,  $P_2 = 308$ ,  $P_3 = 331$ ,  $P_4 = 358$ ,  $P_5 = 381$ ,  $P_6 = 413$ ,  $P_7 = 266$ , and  $P_8 = 445$ , respectively. Figure 7 is the plot of the transmission spectrum of the simulated circular polarizer. The reflection bandwidth covers from 400 to 736 nm. If a high birefringence chiral polymer ( $\Delta n \sim 0.35$ ) is employed, then we only need three films with pitch lengths  $P_1 = 266$  nm,  $P_2 = 325$  nm,  $P_3 = 400$  nm to achieve the same bandwidth. To reduce fabrication complexity, fewer films are highly desirable.

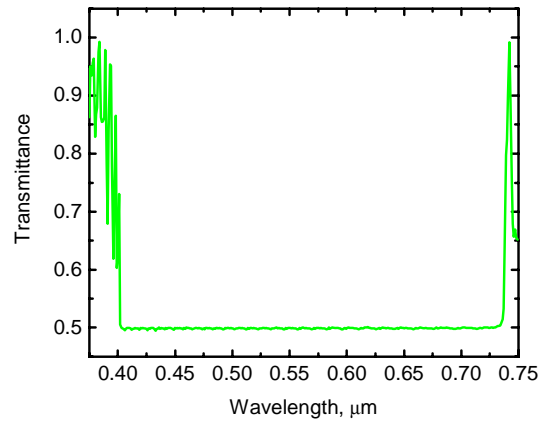


Fig. 7. Simulation result of a broadband circular polarizer by stacking 8 chiral polymer films together.

#### 4. Conclusion

We have demonstrated a scattering-free circular polarizer with  $\sim 120$  nm bandwidth by stacking 3 chiral polymer films with different pitch lengths. Using  $4 \times 4$  matrix method, we simulated the transmission spectra of each chiral polymer film and the circular polarizer made of three stacked films. The simulation results agree well with experiment. Using the same method, we find that we can achieve bandwidth ranging from 400 to 736 nm by stacking 8 films if the chiral monomer has  $\Delta n \sim 0.15$ . But if a high birefringence ( $\Delta n \sim 0.35$ ) chiral polymer is employed only three layers are needed. In addition to optical communication and optical remote sensor, the proposed broadband circular polarizers are particularly useful for liquid crystal displays to double the optical efficiency.