

Polymer-Stabilized Cholesteric Liquid Crystal for Polarization-Independent Variable Optical Attenuator

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A reflective-type polymer-stabilized cholesteric liquid crystal (PSCLC) cell was demonstrated at $\lambda = 1550$ nm laser wavelength. It showed a high attenuation range (~ 30 dB), a low operating voltage ($\sim 12 V_{\text{rms}}$), a highly efficient polarization-independent behavior and flat wavelength dependence in the range of 1525–1575 nm. The combined effects of curing temperature, chiral dopant, and monomer concentration were investigated and optimized to maximally improve the PSCLC properties. The potential application of PSCLC as a polarization-independent variable optical attenuator is emphasized. [DOI: 10.1143/JJAP.43.7083]

KEYWORDS: liquid crystal, polymer, variable optical attenuator

1. Introduction

Polymer-stabilized cholesteric liquid crystals (PSCLCs), also called polymer-stabilized cholesteric textures (PSCTs), have been developed for light shutters,^{1,2)} reflective polarizers³⁾ and many other applications. In a PSCLC, a few percent ($< 10\%$) of monomer is dissolved in a cholesteric liquid crystal (LC) host. The cholesteric LC material consists of nematic LC molecules with a chiral dopant. The cholesteric LC/monomer mixture is injected into an empty cell with homogeneous alignment and then exposed to UV light to induce photo-polymerization. A PSCLC cell is highly transparent in the voltage-off state and stabilized in the planar structure where helical axes are perpendicular to the cell substrate. If a sufficiently high voltage is applied, the LC system switches into the so-called “focal conic” state where helical axes are more or less randomly aligned. In this configuration, the cell strongly scatters light. In addition, for a sufficiently short cholesteric pitch, the scattering from the focal conic domains is independent of incident light polarization.⁴⁾ This polarization insensitivity is particularly attractive for optical communications where polarization-dependent loss is an important issue.

Variable optical attenuators (VOAs) have been extensively used in telecommunications for power control, equalization, and protection of the photodiode detector. LC-based VOAs^{5,6)} are attracting increasing attention because of their low cost, compact size, no moving parts and reliable performance. However, due to the birefringence effect most LC devices are polarization-dependent. To achieve polarization independence, polarizers or other polarization control systems are required which, in turn, increase material and assembly cost. For example, a polymer network LC (PNLC) developed for VOA application⁷⁾ is polarization-dependent in which a linearly polarized input beam is required. The VOA using polymer-dispersed LC (PDLC)⁸⁾ is independent of light polarization; however, its operating voltage is relatively high (~ 50 – $60 V_{\text{rms}}$ for a $15 \mu\text{m}$ cell gap). The inadequate attenuation, relatively high operating voltage and polarization dependence limit LC-based VOA applications. It is highly desirable to develop a VOA with a high attenuation, a low operating voltage and a small polarization-dependent loss.

In this paper, we report a polarization-independent reflective-type PSCLC with a ~ 30 dB dynamic range and a $\sim 12 V_{\text{rms}}$ operating voltage that resulted from a detailed optimization of the combined effects of curing temperature, chiral dopant and monomer concentration. The effects of these parameters on PSCLC performance are discussed. The potential application of PSCLC as a polarization-independent variable optical attenuator at $\lambda = 1550$ nm is emphasized.

2. Sample Preparation

To fabricate a PSCLC cell, we mixed 0.66 wt% chiral dopant S1011 in a Merck E44 LC mixture ($\Delta n = 0.26$ at $\lambda = 589$ nm). The pitch length of a PSCLC cell was controlled by the chiral concentration in the mixture and helical power of the chiral dopant. For the 0.66 wt% S1011, the corresponding pitch length was $\sim 3 \mu\text{m}$. According to the given pitch length, the reflection band was in the far-infrared region and the cell was transparent at $\lambda = 1550$ nm wavelength. In the next fabrication step, the mixture was mixed with 3 wt% bisphenol A dimethacrylate monomer, injected into an empty homogeneous cell and exposed to a weak UV light ($100 \mu\text{W}/\text{cm}^2$) to induce polymerization. During the polymerization, the cell was first kept at an elevated temperature for 0.5 h for UV exposure then continued for another 2.5 h at room temperature to further stabilize polymer networks. Curing temperature has a major effect on the performance of a PNLC⁹⁾ and the network morphology of PSCT.¹⁰⁾ The cell used in the experiments was $\sim 15 \mu\text{m}$ thick with anti-parallel rubbed polyimide layers on the inner surfaces of the substrates. Due to the surface rubbing effect and the planar structure of the cholesteric LC, the polymer networks formed are parallel to the cell surface and follow the local helical order of the LC directors.

3. Experimental Results

We used the experimental setup shown in Fig. 1 to characterize the PSCLC cells. A tunable laser source (ANDO AQ4321D) output a polarized beam at $\lambda = 1550$ nm. To test the PSCLC cell performance in different polarization states, a polarization controller was introduced. The port 1 of a fiber optic circulator was connected to the light source. Port 2 was connected to a collimating lens with a 3 cm working distance. For an actual reflective-type VOA, the reflector should be deposited on the inner side of the rear

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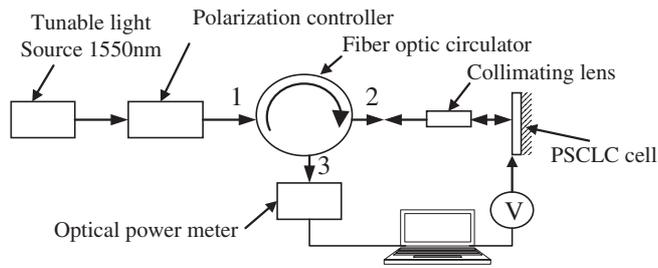


Fig. 1. Experimental setup for measuring properties of reflective E44 PSCLC cells.

LC substrate. To prove this principle, we simply placed a mirror immediately behind the PSCLC cell. The reflected light was captured by the collimating lens and coupled back to the fiber. The circulator redirected the reflected beam from the PSCLC cell to an optical power meter, connected to circulator port 3. A computer-controlled system was used to supply voltage to the PSCT cell and to record the voltage-dependent reflectance as well. Due to the thin LC cell gap ($15\ \mu\text{m}$) and the small absorption coefficient of the LC mixture at $\lambda = 1550\ \text{nm}$,¹¹⁾ the light absorption loss of our sample was negligible. In the voltage-off state, the cell was transparent. As the applied voltage increased, the laser beam was scattered by the micron-sized domains resulting in the decrease of the reflected light from the PSCLC cell.

Several factors affect the performance of a PSCLC cell, such as cell gap, polymer concentration, pitch length, and curing conditions. We studied these experimental conditions to optimize the PSCLC performances. The polymer concentration requires to be optimized as it affects the domain size which, consequently, affects the light scattering and operating voltage. If the domain size is comparable to the laser wavelength, the scattering efficiency is high. On the other hand, if the domain size is too large or too small, then the scattering efficiency will decrease. For display applications in the visible spectral region, the optimum domain is small due to the short wavelength involved. However, for telecommunication application at $\lambda = 1550\ \text{nm}$, domain size should be increased, i.e., polymer concentration should be decreased. Decreasing polymer concentration also leads to a low operating voltage. However, if the monomer concentration is 2 wt%, we find that the PSCLC structure is unstable and the electro-optic properties of these low-polymer-concentration PSCLC ($\leq 2\ \text{wt}\%$) cells are not repeatable after being switched on and off consecutively several times. Therefore these low-polymer-concentration cells are undesirable and the monomer concentration should be maintained at more than 2 wt%. Conversely, if the polymer concentration is too high, the domain would be too small so that attenuation range decreases and operating voltage increases. In our experiments, we found that a $15\ \mu\text{m}$ cell gap, 0.66 wt% chiral concentration, and 3 wt% polymer concentration provided a reasonably good overall performance for the E44 PSCLC cells. Unless specifically mentioned, this is the recipe used in our PSCLC cells.

To investigate the curing temperature effects on the properties of the PSCLC cells, we prepared cells at various curing temperatures (from 23 to 70°C) and measured their voltage-dependent attenuation at $\lambda = 1550\ \text{nm}$. In the

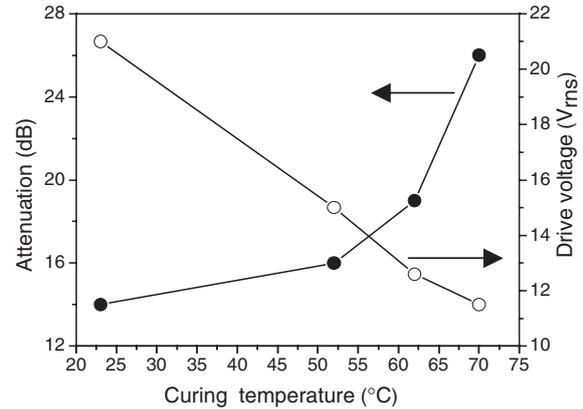


Fig. 2. Performance of reflective 3 wt% E44 PSCLC cell at various temperatures. Cell gap $d = 15\ \mu\text{m}$. The measurements were taken at $\lambda = 1550\ \text{nm}$ and $T = 23^\circ\text{C}$.

voltage-off state, the cells were stabilized in a planar configuration and highly transparent. With applied voltage, the polymer networks resisted LC directors from being reoriented by the electric field. When the voltage was slightly more than the threshold, LC molecules first reoriented in the regions where polymer density was low, while the polymer-rich regions remained unchanged. As the voltage was increased further, more LC molecules were rotated. As a result, the cell was gradually switched into focal conic state where multiple microdomains were formed and incident light was strongly scattered. Figure 2 shows the optical attenuation range and scattering-state voltage of the PSCLC cells at various curing temperatures. For the cell cured at room temperature, the attenuation range is only $\sim 14\ \text{dB}$ at $V = 21\ V_{\text{rms}}$. As curing temperature increases from 23 to 70°C , attenuation increases to 26 dB and drive voltage decreases almost linearly from 21 to $11.5\ V_{\text{rms}}$.

The curing temperature affects the average size of the voids (micro-domains) within the polymer network. A high curing temperature generates large size voids.¹⁰⁾ If the microdomain size is comparable to the laser wavelength, the maximum light scattering efficiency is achieved.¹²⁾ For the PSCLC sample cured at room temperature, microdomains within the polymer network are too small compared with those in the case of the 1550 nm laser wavelength. As a result, these domains do not scatter light efficiently. In addition, a small domain at a low curing temperature implies a strong interaction between the polymer network and LC molecules, which indicates that a high drive voltage is required to unwind the helical order. Conversely, by increasing the curing temperature, large LC voids form within the polymer network resulting in an increased light scattering efficiency and decreased operating voltage.

It is highly desirable that the VOA has a sufficiently broad bandwidth to cover a whole wavelength band defined by the international telecommunication union (ITU). To investigate the wavelength dependence of the properties of the PSCLC cell, an ANDO ASE light source (covering the ITU C-band wavelength range 1525–1575 nm) and an optical spectrum analyzer with a 0.2 nm resolution were employed. The wavelength-dependent attenuations of the E44 PSCLC cell which is cured at 70°C are shown in Fig. 3. In Fig. 3, the attenuation of the PSCLC is relatively insensitive to the

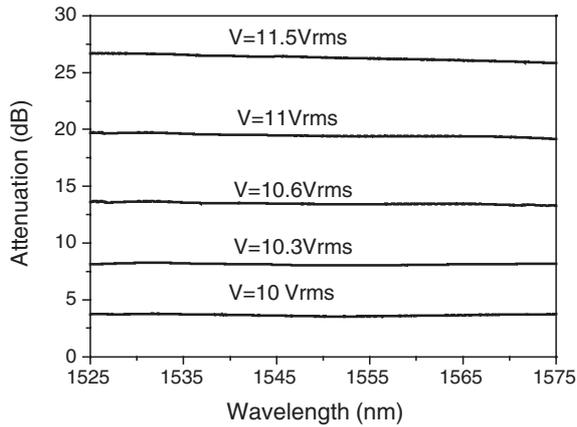


Fig. 3. Reflection spectrum of reflective 15 μm E44 PSCLC cell containing 3 wt% monomer. Curing temperature $T = 70^\circ\text{C}$, operating temperature $T = 23^\circ\text{C}$.

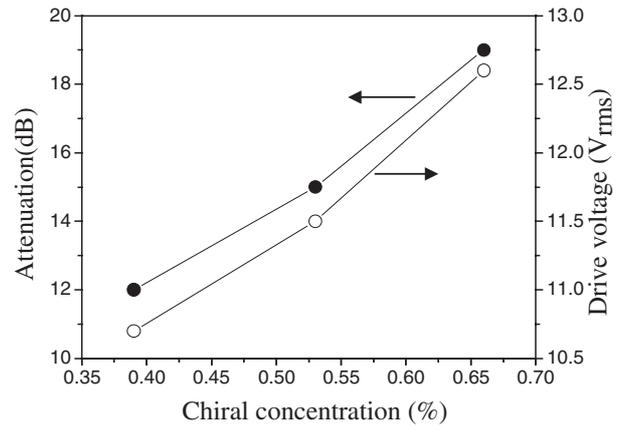


Fig. 5. Properties of reflective 15 μm E44 PSCLC cell containing various chiral dopant concentrations. Curing temperature $T = 62^\circ\text{C}$, operating temperature $T = 23^\circ\text{C}$, and $\lambda = 1550\text{ nm}$.

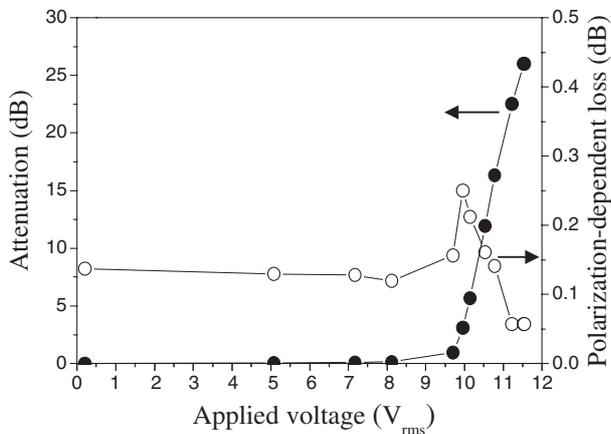


Fig. 4. Voltage-dependent attenuation and polarization-dependent loss of reflective E44 PSCLC cell containing 3 wt% monomer. Cell gap $d = 15\ \mu\text{m}$, curing temperature $T = 70^\circ\text{C}$, operating temperature $T = 23^\circ\text{C}$, and $\lambda = 1550\text{ nm}$.

wavelength in the 1525–1575 nm range. From bottom to top, the attenuation variations are 0.2 dB, 0.25 dB, 0.5 dB, 0.6 dB and 0.8 dB. The experimental data has been calibrated to remove the power variation of the ASE light source.

Figure 4 shows a plot of the voltage-dependent attenuation and polarization-dependent loss (PDL) of the E44 PSCLC cell at 70°C curing temperature. The PDL is less than 0.25 dB within the 0–11.5 V_{rms} range, which corresponds to a 0–26 dB attenuation level. Typically, the acceptable PDL for VOA devices should be less than 0.5 dB within the 0–10 dB range. Our present result indicates that the PSCT device has overcome the polarization-dependent issue of VOA based on polymer-stabilized LC.⁶⁾

Pitch length is another important factor in determining focal conic domain size. We have studied the chiral-concentration-dependent optical attenuation and operating voltage of the PSCLC cells at 62°C curing temperature. The chiral concentration was varied from 0.39%, 0.53% to 0.66%. Figure 5 shows a plot of the measured results. A low chiral concentration indicates a long pitch. As indicated in Fig. 5, if the chiral pitch is too long, the domains are too large to scatter light effectively. For a 0.66% chiral

concentration, the microdomain size is more favorable to scatter a 1550 nm laser beam.

Polymer networks have two important effects on the PSCLC. The first is to influence the focal conic domain structure and consequently light scattering efficiency. The second effect is to assist LC molecules to relax back once the voltage is removed. A high polymer concentration leads to a fast response time, except for the increased voltage. However, in our experiment, for maximizing optical attenuation, the employed monomer concentration was only 3 wt%. Therefore, the response times of our PSCLC cell using E44 were $\sim 50\text{ ms}$ and $\sim 20\text{ ms}$ for the rise and decay, respectively. To improve the response time, a higher monomer concentration is helpful. However, its tradeoff is the degraded optical attenuation. To maintain a high attenuation while retaining a low operating voltage, the use of a high birefringence LC material is a preferred approach.

The birefringence of an E44 mixture can be enhanced by adding alkyl isothiocyanato (NCS) tolanes.¹³⁾ In the experiment, we mixed 25% NCS tolane with E44. The new mixture was designated as E44-2. Its birefringence increased to $\Delta n \sim 0.25$ at $\lambda = 1.55\ \mu\text{m}$, as compared to 0.22 for E44. The LC birefringence decreases as wavelength increases and saturates in the near infrared region.¹⁴⁾ The PSCLC-2 cell is composed of an E44-2 LC mixture and 4 wt% bisphenol A dimethacrylate monomer was prepared and cured at $T = 62^\circ\text{C}$. Table I summarizes the performance of the PSCLC-2 cell. The optical attenuation of the cell increased to 30 dB while the response time decreased to 28 ms (rise) and 11 ms

Table I. Performance of PSCLC-2 cell composed of E44-2 LC mixture, 4 wt% monomer and 0.66 wt% S1011. Cell gap $d = 15\ \mu\text{m}$, curing temperature $T = 62^\circ\text{C}$, $\lambda = 1550\text{ nm}$, and operating temperature $T = 23^\circ\text{C}$.

Attenuation mechanism	Scattering
Cell gap	15 μm
Attenuation range (dB)	30
Control voltage (V_{rms})	0–12
Rise time/fall time (ms)	28/11
Polarization dependent loss (dB)	<0.2
Wavelength dependence (1525–1575 nm)	<1 dB

(decay), respectively. The longer rise time resulted from that the applied voltage ($V = 12 V_{\text{rms}}$) is not too different from the threshold ($V \sim 10 V_{\text{rms}}$).

4. Conclusions

The combined effects of the curing temperature, chiral and monomer concentrations on the properties of PSCLCs were investigated. By simultaneously optimizing the curing conditions and LC/monomer compositions, we demonstrated a reflective-type PSCLC cell with a high attenuation range (~ 30 dB) and a low operating voltage ($\sim 12 V_{\text{rms}}$) operating at $\lambda = 1550$ nm telecommunication wavelength. In addition, the PSCLC cell is insensitive to incident light polarization and wavelength in the 1525–1575 nm range. Such high-performance PSCLC will be useful for applications as polarization-independent variable optical attenuator or a light shutter.

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