Variable optical attenuator with a polymer-stabilized dual-frequency liquid crystal

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A transmission-type variable optical attenuator (VOA) based on a polymer-stabilized dual-frequency liquid crystal (PSDFLC) is demonstrated at $\lambda = 1.55\ \mu m$. The VOA is highly transparent in the voltage-off state but scatters light in the voltage-on state. By using a birefringent beam displacer incorporated with half-wave plates, we can obtain a VOA that is polarization independent and that exhibits a 31 dB dynamic range. The polymer networks and dual-frequency effect together reduce the response time (rise + decay) of a 16 μm PSDFLC cell to 30 ms at room temperature and at a voltage of 24 V_{rms}. © 2005 Optical Society of America

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1. Introduction

A polymer-stabilized liquid crystal[1–3] (PSLC) is a fundamentally interesting and practically useful material system. Both anisotropic scattering[4] and scattering-free[5] PSLC systems have been developed, depending on the polymer concentration and operating wavelength. The anisotropic light-scattering PSLC is useful for amplitude modulation because it has, e.g., a reflective display, switchable polarizer, and variable optical attenuator (VOA).[6–10] On the other hand, the scattering-free PSLC is particularly attractive for phase modulation in the near-infrared region.[5] In spite of the need for amplitude or phase modulation, a fast response time is a standard requirement. This is particularly problematic for VOAs operating in the near-infrared region ($\lambda = 1.55\ \mu m$), where a larger cell gap is required, which results in a longer response time. To keep the response time short, a PSLC-based *reflective* VOA has been considered. For a 16 μm reflective PSLC cell using a Merck E44-LC mixture, the measured response time is ~30 ms and the dynamic range is ~30 dB at room temperature. If we use the cell parameters in the transmissive mode, the dynamic range would be reduced to ~15 dB. If we want to keep the same dynamic range, then we need to double the cell gap, but the response time would be 4× slower.

In this paper we demonstrate a polarization-independent transmissive VOA by using the polymer-stabilized dual-frequency liquid crystal (PSDFLC) to obtain a large dynamic range (31 dB) while keeping a 30 ms frame time. The unique feature of a DFLC is that it exhibits a crossover frequency (f_c).[11,12] The dielectric anisotropy of the DFLC remains positive ($\Delta\varepsilon > 0$) when $f < f_c$ but changes to negative when $f > f_c$. For practical applications, the crossover frequency is usually in the 5–10 kHz range. For the DFLC-based homogeneous cell, we use a low-frequency (~1 kHz) electric field to drive the VOA and a high-frequency (~30 kHz) electric field to accelerate the relaxation process. Owing to the presence of electric field in both turn-on and turn-off processes, fast rise and decay times can be obtained simultaneously.

2. Light Modulation Mechanism

Figure 1 illustrates the light modulation mechanism of the PSDFLC cell. If a low-frequency ($f < f_c$) voltage is applied to the cell, as shown in Fig. 1(a), the polymer networks tend to resist LC molecules from being reoriented by the electric field. As a result, microdomains are formed, which scatter the extraordinary ray because of the refractive-index mismatch between the DFLC and the polymer networks. The ordinary ray is not affected because of good index match with the polymer matrix. If we keep the ac voltage unchanged but switch the frequency to a high frequency ($f > f_c$), the electric field exerts a torque to bring the LC directors back to their original homo-

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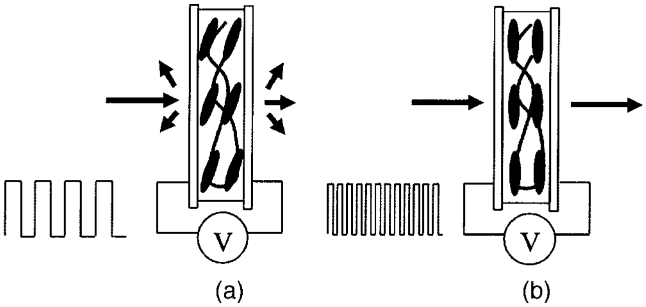

Fig. 1. Light modulation mechanism of a PSDFLC cell. (a) At low-frequency (1 kHz), light scattering occurs for the extraordinary ray. (b) At high frequency (30 kHz), the device is highly transparent.

geneous positions, as shown in Fig. 1(b). Thus the PSDFLC cell is highly transparent. The anisotropic light-scattering behavior of the PSDFLC cell is polarization dependent. For fiber-optic communication, it is highly desirable to have a VOA whose performance is independent of light polarization.

Because the PSDFLC cell attenuates only the extraordinary ray, we need to convert the incident unpolarized light into linearly polarized light. Figure 2 shows such a device configuration. The polarization beam displacer (BD) used in Fig. 2 is a 45°-cut birefringence crystal, e.g., YVO_4 or calcite. Inside the beam displacer, the incident unpolarized light is separated into two components: ordinary ray (upper trace) and extraordinary ray (lower trace). The half-wave plate on the top part of the beam displacer transforms the ordinary ray into an extraordinary ray. The rubbing axis of the PSDFLC cell is positioned parallel to the polarization axis. The outgoing light intensity is modulated by the voltage applied to the LC cell. To recombine the two separated outgoing beams, we used a second but erected beam displacer, as depicted in Fig. 2. Continuous optical attenuation can be achieved by varying the frequency or amplitude of the applied voltage. The preferred approach is to keep the same voltage while switching the frequency. Relatively fast rise and decay times can be obtained because an electric field is present in both switching states. Increasing the bias voltage is favorable for shortening the rise and decay times. However, a high voltage driver is costly. Thus it is in our

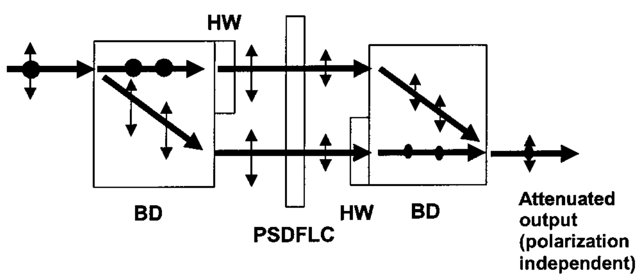

Fig. 2. Polarization-independent PSDFLC-based VOA; HW, half-wave plate; BD, beam displacer; $\lambda = 1.55$ μm.

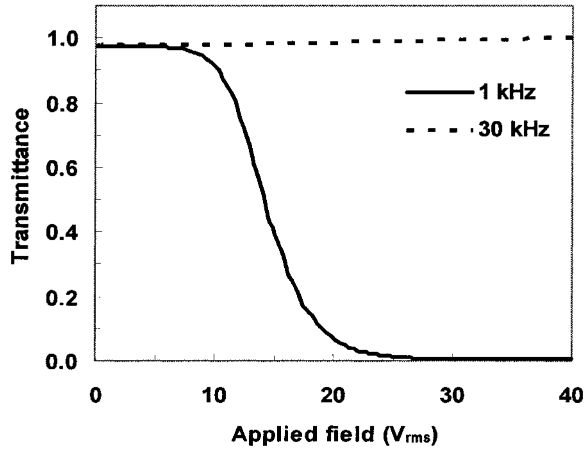

Fig. 3. Voltage-dependent transmittance of a PSDFLC-based VOA with $\lambda = 1.55$ μm.

interest to keep the operating voltage as low as possible.

3. Experiment

To fabricate the PSDFLC cell, we mixed 4 wt. % of a rodlike monomer (M1) to a homemade dual-frequency mixture, designated as DFLC-25. The physical properties of DFLC-25 mixture are summarized as follows: birefringence $\Delta n = 0.24$ at $\lambda = 1.55$ μm, dielectric anisotropy $\Delta\varepsilon = +5$ at $f = 1$ kHz, $\Delta\varepsilon = -4$ at $f = 30$ kHz, and the crossover frequency is $f_c = 6$ kHz at T = 25 °C. The LC–monomer mixture was injected into an empty homogeneous cell with gap $d = 16$ μm and was then exposed to UV light $\lambda \sim 365$ nm at intensity $I \sim 6$ mW/cm^2 for ~ 30 min at an elevated temperature, followed by 4 h at room temperature (25 °C). After the mixture was cured, the crossover frequency of the PSDFLC cell was found to increase from 6 to 8 kHz.

To characterize the PSDFLC's performance, a tunable laser (Ando AQ4321D) at $\lambda = 1.55$ μm was used as the light source. Figure 3 depicts the voltage-dependent transmittance measured by a computer-controlled LabVIEW system. At $f = 1$ kHz, the optical threshold voltage of the PSDFLC ($V_{th} \sim 8.5$ V_{rms}) is much higher than that of the pure DFLC because of the polymer network effect.[5] As the applied voltage increases, light scattering gradually increases so that the transmittance decreases. The photodetector was set at 7 cm behind the second beam displacer, which corresponds to 1.2° acceptance angle. At a voltage of 24 V_{rms}, a good dark state is achieved and the measured dynamic range reaches 31 dB. In an actual fiber-to-fiber system, the dynamic range should be higher than 31 dB because of the smaller acceptance angle. The large dynamic range originates from two mechanisms: the enhanced light scattering from micrometer-sized domains and the large index mismatch between the DFLC-25 mixture and the polymer networks. To obtain gray levels, we simply vary the frequency of the bias voltage. For example, in Fig. 2, if we bias the VOA at 24 V_{rms} and increase the

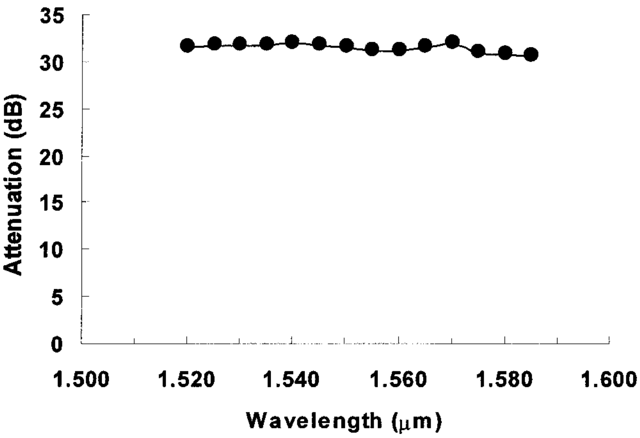

Fig. 4. Wavelength-dependent attenuation ratio of the PSDFLC VOA.

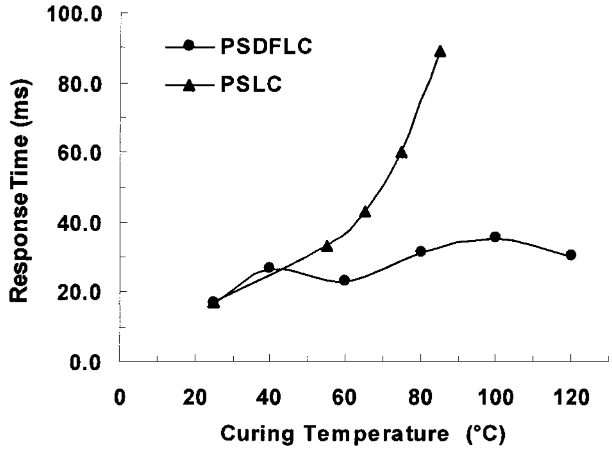

Fig. 6. Curing-temperature-dependent response time of PSDFLC (circles) and PSLC (triangles) cells.

frequency from 1 to 8 kHz, various gray levels can be obtained.

The dashed line in Fig. 3 represents the measured transmittance by using a high-frequency electric field. For a homogeneous cell at $f = 30$ kHz, the effective dipole of the LC directors is parallel to the electric field. Such an electric field cannot reorient the LC molecules so that the transmittance is independent of the voltage.

For fiber-optic applications, a VOA is desired to have a broad bandwidth over the whole spectral range defined by the International Telecommunication Union. To investigate the wavelength dependency, we used an Ando amplified spontaneous emission light source ($\lambda = 1525$ to 1575 nm) and an optical spectrum analyzer. Figure 4 shows the wavelength-dependent optical attenuation of the PSDFLC VOA. The attenuation ratio remains relatively flat in the entire C-band. This is because the microdomain sizes are comparable with the wavelength.

Polarization-dependent loss (PDL) is another important parameter for fiber-optic application. Figure 5 plots the wavelength-dependent PDL of the VOA measured at the normal-on state. The variation is

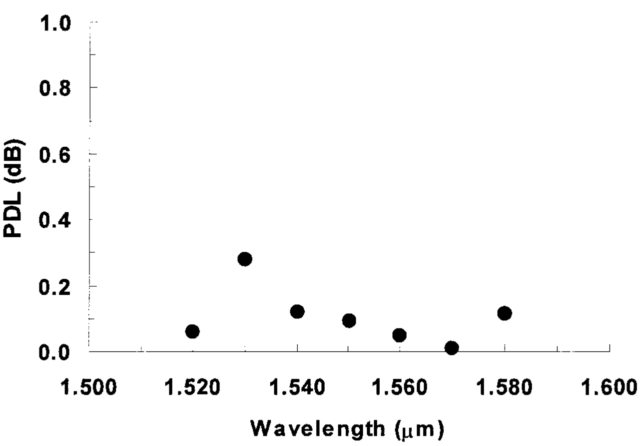

Fig. 5. Measured polarization-dependent loss (PDL) of the PSDFLC VOA with $d = 16$ μm.

approximately 0.1–0.2 dB. The PDL increases as the attenuation increases. The PDL at 15 dB attenuation is approximately 0.5–0.6 dB. On the basis of the data shown in Figs. 4 and 5, the PSDFLC exhibits promising properties for VOA applications.

4. Discussion

To obtain a wider dynamic range of a PSDFLC device, we could increase the cell gap, LC birefringence, and UV curing temperature. Light scattering increases as the cell gap increases. However, a thicker cell gap leads to a slower response time and a higher operating voltage. High-birefringence liquid crystals help to increase the dynamic range owing to their larger refractive-index mismatch, but their viscosity is increased because of their elongated molecular structures. Furthermore, higher viscosity increases the response time.

Curing temperature affects the domain size, dynamic range, and response time of a PSLC.[13] Figure 6 shows the relation between the curing temperature and the measured total response (rise-and-fall) time. As the curing temperature increases, the response time of a regular PSLC cell increases dramatically. This is because the domain sizes increase with increasing curing temperature. In contrast, the PSDFLC cell is inert to the curing temperature; its response time is kept at ~30 ms (rise time, ~17 ms; decay time, ~13 ms) when the curing temperature increases from 25 °C to 120 °C. This is because the rise and decay times of the PSDFLC cell are driven by the applied low- and high-frequency electric fields. Therefore fast rise and decay times can always be achieved, regardless of the curing temperature. A high curing temperature plays a key role in enhancing the dynamic range. Thus we can use a high curing temperature to achieve a large dynamic range without sacrificing the response time.

In Fig. 6, the PSLC data represent a reflective scattering-type VOA by using a non-DFLC material.[14] If the same LC layer thickness were used for a transmissive PSLC device, the dynamic range would be lower than 15 dB at $\lambda = 1.55$ μm at each curing temperature. In our transmissive PSDFLC VOA, the dynamic range remains at ~30 dB in the 60–120 °C curing-temperature range. Moreover, the transmissive mode has a much simpler optical setup than the reflective mode and still preserves a high dynamic range and fast response time.

To further improve the PSDFLC VOA's response time, one could use the overdrive voltage method[15,16] or use a high-birefringence, low-viscosity DFLC mixture. The overdrive method is used to shorten the rise time by applying a short but high voltage to kick the LC molecules to the desired tilt angle, whereas the undershoot method is particularly useful for reducing the gray-scale response time. Although the overdrive and undershoot methods could lead to submillisecond response times, the required voltage is ~100 V_{rms}.

The insertion loss of the PSDFLC cell is approximately −3 dB owing to the quadruple passes of the uncoated glass substrates and the initial scattering effect in the transparent state. To reduce the insertion loss, we recommend that the LC cell be antireflection coated. In addition, by choosing a proper polymer material to match the refractive index of the LC material, one can further reduce the insertion loss. The hysteresis of the PSDFLC cells is relatively small at a high curing temperature. For example, the PSDFLC sample cured at 120 °C has a hysteresis of less than 0.1 V_{rms}.

5. Conclusion

We demonstrate a transmissive VOA by using a polymer-stabilized dual-frequency liquid crystal (PSDFLC). By using the high-birefringence, dual-frequency material and polymer networks, we obtain a high-dynamic-range and fast-response-time device. In addition, the response time does not increase with increasing curing temperature. Therefore we could choose a higher curing temperature to achieve a larger dynamic range without sacrificing the response time. The PSDFLC approach can be extended to other scattering-type devices used in photonic applications.

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