Submillisecond-Response Polymer Network Liquid Crystal for Next-Generation Spatial Light Modulators

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Abstract

We report a scattering-free polymer network liquid crystal (PNLC) for spatial light modulator (SLM) applications. In reflective mode, the PNLC exhibits $V_{2\pi}$~23V at λ=514 nm and 250 μs response time at room temperature. This enables PNLC to be integrated in a high resolution liquid-crystal-on-silicon device for next-generation SLM applications.

Keywords

Polymer network liquid crystals, LCoS, spatial light modulator

1. Introduction

High resolution spatial light modulators (SLMs) based on Liquid-Crystal-on-Silicon (LCoS) have widespread applications [1-4]. For phase modulation, 2π phase modulo is commonly required. For a typical nematic, say E7, to obtain 2π phase change at λ=633 nm would require a cell gap of ~2 μm (reflective mode), which results in ~8-ms response time. Polymer network liquid crystals (PNLCs) scatter light at visible region because of the micron sized LC domains [5]. Although near infrared scattering-free PNLCs have already been studied [6-9], visible scattering free PNLCs remain a challenge. Until recently, PNLCs with nano-scale LC domain sizes (~100 nm) were reported [10-12]. These PNLCs are free from scattering in the visible region. However, the required voltage is $V_{2\pi}$~50V, which is twice higher than the maximum allowable voltage (24V) of a high resolution LCoS. There is an urgent need to develop low voltage PNLCs to be integrated in an LCoS.

The objective of this paper is to develop a low-voltage and highly transparent PNLC for LCoS SLM applications. To reduce operation voltage, we employed a high dielectric anisotropy (Δε~302) nematic LC, JC-BP07N, developed by JNC. We demonstrated a PNLC with $V_{2\pi}$~23V in reflective mode at λ=514 nm. The measured scattering loss is <1% for wavelengths greater than 514 nm (single optical path). Both rise and decay times are in submillisecond range, and hysteresis is around 1.7%. We also develop a model to further optimize the PNLC performance. Our simulation results show that a PNLC with $V_{2\pi}$ ~9.6V is achievable in reflective mode. This opens a new door for widespread applications of high resolution LCoS SLMs.

2. Sample Preparation

To reduce operation voltage, we employed a large Δε nematic LC mixture JC-BP07N. Its clearing point is 87 °C, birefringence Δn=0.17 at λ=514 nm, visco-elastic coefficient γ_1/K_{11}=224 ms/μm^2 at 22°C. As depicted in Fig. 1, JC-BP07N shows a low frequency Δε~302 (at 100Hz, 22°C). The measured frequency dependent Δε (dots) agrees well with the Debye equation. Figure 2 shows the wavelength dependent Δn of JC-BP07N in the visible region.

To fabricate the PNLC sample, we prepared a precursor by mixing JC-BP07N with 7.2% RM257 and 0.5% BAPO photo-initiator. The precursor was then filled into a homogeneous LC cell with 5-μm cell gap. After one hour of UV curing, the PNLC sample (PNLC-1) was ready for characterization.

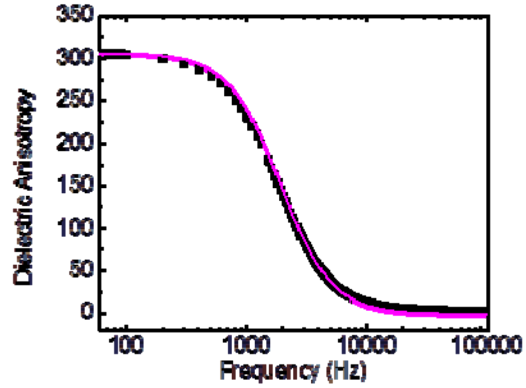

Figure 1. Frequency dependent Δε of JC-BP07N.

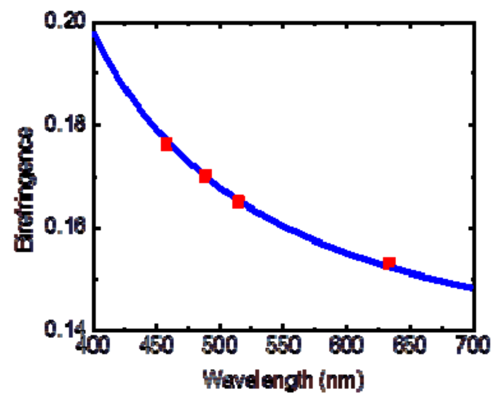

Figure. 2. Wavelength dependent Δn of JC-BP07N.

3. Characterization and Results Discussion

We determined the voltage-on state scattering of PNLC-1 by measuring the transmission of the sample. The red curve in Fig. 3(a) corresponds to the transmission spectrum of PNLC-1 at a voltage-on state, where maximum scattering occurs. Figure 3(b) shows the measured normalized transmission spectrum of the on-state PNLC-1. Results indicate that the scattering loss of this PNLC is negligible for wavelengths above 500 nm (<1% at λ=514 nm).

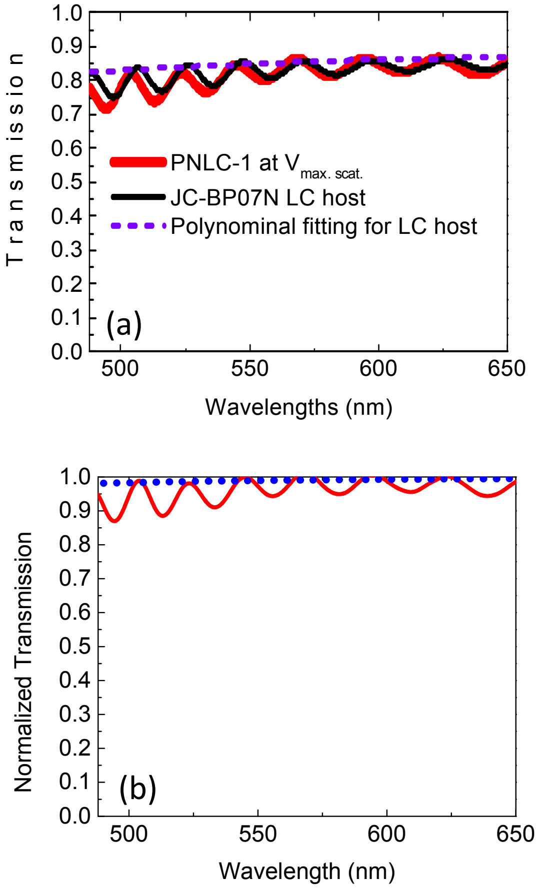

Figure 3. (a) Transmission spectra of PNLC-1 based on JC-BP07N with a voltage applied leading to maximum scattering (red line). The spectrum of the LC host (black line) is included for comparison. Purple dashed lines represent a numerical fitting of LC host spectrum. (b) Transmission spectra of on-state PNLC-1normalized to LC host.

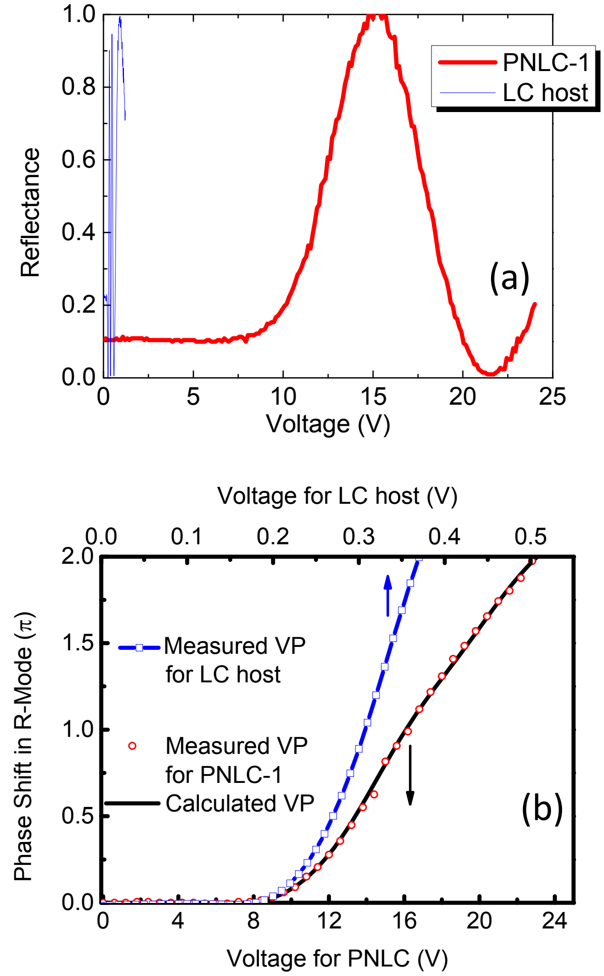

Figure 4. (a) Measured VR curves of PNLC-1 with driving frequency ~100Hz, and (b) VP curves.

Figure 4(a) shows the voltage-dependent reflectance (VR) curve of PNLC-1 at λ=514 nm. We use a mirror to fold the optical path. The rubbing direction of the LC cell was at 45^o with respect to the optical axis of the linear polarizer. The 2π operation voltage of PNLC-1 is 23V. Figure 4(b) shows the voltage-dependent phase shift (VP) curves (e-wave) for LC host and PNLC-1.

The hysteresis of PNLC-1 was measured to be 1.7%. Relaxation time defined from 100% to 10% phase change is 250 μs. Under the same definition, the measured rise time is 680 μs at the room temperature. Since relaxation time can be approximated as $\tau \sim\gamma_1 d_{12}/K_{11}\pi^2$, where d_1 is the LC domain size, we can estimate the average LC domain size, which is ~105 nm.

To better understand the device operation mechanisms, we developed a model to correlate PNLC performance with its LC host. If PNLC domain size is d_1, then we can roughly divide the LC cell into $N=d_0/d_1$ layers, where d_0 is the total cell gap. In this way, the threshold voltage of PNLC is N times larger than that of the LC host. If we assume the operation voltage is proportional to threshold voltage under the same birefringence and cell configuration, we can write the operation voltage as: [12]

$$V_{on} = \frac{d_0}{d_1} V_{on,0} \propto \pi \frac{d_0}{d_1} \sqrt{\frac{K_{11}}{\varepsilon_0 \Delta\varepsilon}} \quad (1)$$

where $V_{on,0}$ is the operation voltage of the LC host cell. Through the fitting of threshold voltage alone we are able to extract the domain size of PNLC-1 to be d_1~103 nm. Note that this value is almost the same as the one we estimated from the measured response time. However, due to the strong anchoring effect of the 7% polymer and the greatly increased LC/polymer surface area, the electric field induced refractive index change for PNLC δn_1 is smaller than that of the LC host δn_0. Assuming $\delta n_1(V)$ is linearly proportional to δn_0, i.e., $\delta n_1 = A \cdot \delta n_0$, the voltage-dependent phase shift of PNLC can be written as:[12]

$$\phi(\lambda, V_{on}) = \frac{2\pi}{\lambda} A \cdot \delta n_0(\lambda, V_{on,0}) d_0 \qquad (2)$$

Combining Eq. (1) and Eq. (2), we are able to simulate the VP curve of PNLC-1 (shown in Fig. 4(b)). The only fitting parameter A is extracted to be 0.51.

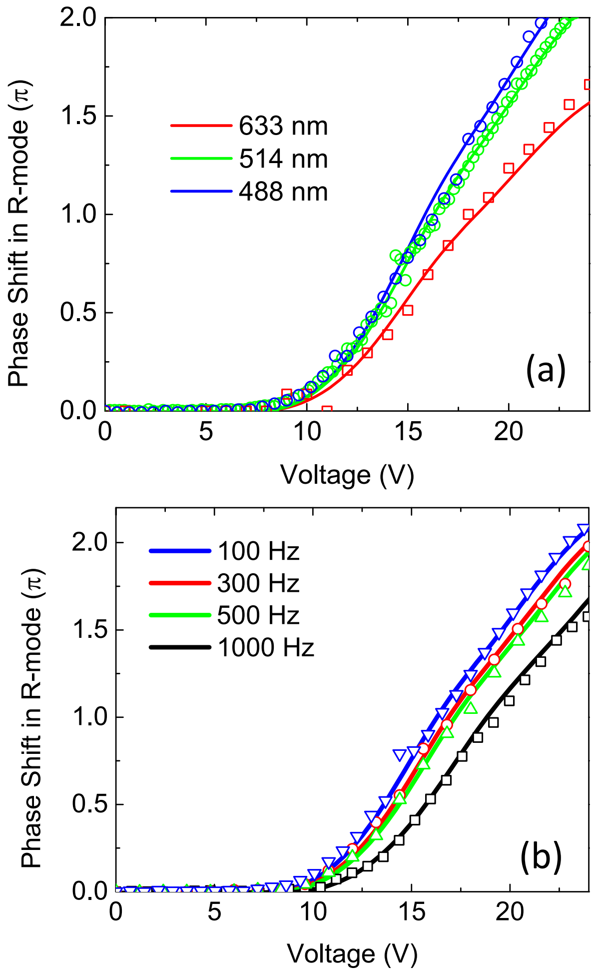

Figure. 5 (a) Wavelength effect and (b) driving frequency effect on the phase shift curves of PNLC-1. Symbols are measured results and lines are simulation results.

To validate the effectiveness of this model, we compare the measured wavelength dependent VP curves and the simulated curves in Fig. 5(a). As the wavelength increases, phase dynamic range within 24V decreases due to the smaller LC birefringence. This model can also predict the frequency effect on VP curves as Fig. 5(b) shows. As driving frequency increases from 100 Hz to 1000 Hz, the dynamic range (at 24V) gradually decreases because the LC dielectric anisotropy decreases as frequency increases according to Fig. 1.

To further reduce $V_{2\pi}$, increasing LC domain size d_1 is the most effective way for a given LC host. The tradeoff is that both scattering and relaxation time will increase accordingly. Therefore, we simulated the performance of PNLCs with different domain sizes based on JC-BP07N LC host. The relationships between operation voltage, scattering loss and relaxation time are plotted in Fig. 6 for λ=514 nm. If the LC domain size is ~250 nm, we find $V_{2\pi}$<10V while scattering loss is ~5% at λ=514 nm and relaxation time increases to ~1.4 ms. But if we operated at a slightly elevated temperature, say 30°C, the response time will be <1 ms.

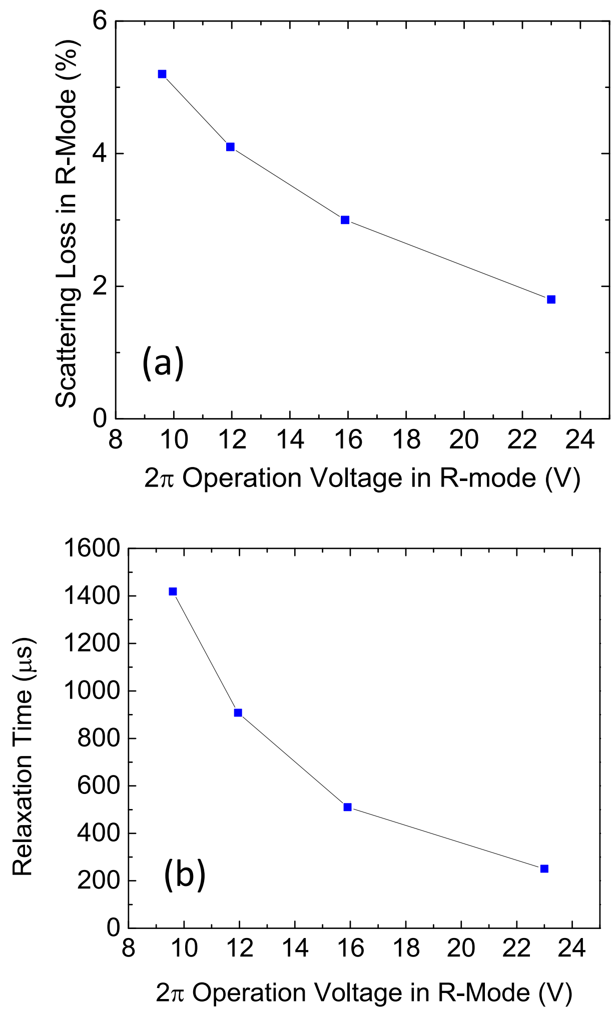

Figure. 6 (a) Tradeoff between operation voltage and scattering loss. Here, double optical path has been considered in scattering loss simulation. (b) Tradeoff between operation voltage and relaxation time.

4. Impact

We report a low voltage and scattering-free PNLC with submillisecond response time. By using a large Δε LC host JC-BP07N, we are able to lower the $V_{2\pi}$ to ~23V at λ=514 nm in a reflective device. This is important because it enables PNLC to be implemented in a high resolution LCoS for widespread applications. We also developed a model to simulate the performance of PNLC devices. By controlling the domain size delicately, a PNLC with $V_{2\pi}$ <10V can be achieved. The tradeoff is in slightly increased scattering and response time.

Acknowledgements

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