Submillisecond-Response Sheared Polymer Network Liquid Crystals for Display Applications

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***Abstract*—A 4π phase modulator with an average gray-to-gray response time of $\sim$ 400 μs is demonstrated based on sheared polymer network liquid crystal (SPNLC). This device exhibits a low scattering at 532 nm due to our new material set and shearing technique. We also discuss the application of SPNLCs for 3D display, such as lenticular lens.**

***Index Terms*—Fast response, lenticular lens, liquid crystals (LCs), sheared polymer network liquid crystal (SPNLC), 3D display.**

I. INTRODUCTION

FAST response liquid crystal (LC) phase modulators with a large modulation depth are of great interest because of its important applications in LC lens and 3D displays, especially in time-multiplexing autostereoscopic displays [1], [2]. The focal length of a LC lens can be written as [3], [4]:

$$f = \frac{r^2}{2d\delta n} \qquad (1)$$

where r is the radius of the lens aperture, d is the LC layer thickness, and δn is the refractive index difference between the lens center and edge. Therefore, for a LC lens with a certain aperture size, large $d\delta n$ is required in order to obtain a short focal length. However, since the response time of LC is proportional to d^2, nematic LCs usually exhibit slow response time (>100 ms) for a phase shift greater than 2π. Dual frequency LCs can achieve fast response without sacrificing cell thickness, but require a sophisticated driving scheme [5]–[7]. Polymer network liquid crystal (PNLC) is an efficient way to get both fast response and large phase modulation depth, but these cells exhibit strong scattering in the visible region [8], [9]. Sheared PNLC (SPNLC) reduces light scattering by employing a mechanical shearing process to obtain uniform alignment of LCs [10]–[12]. But until recently, suppression of scattering in SPNLC devices remains a challenging task for visible region. New developments in materials and fabrication techniques in SPNLC are in high demand.

In this paper, a relatively low scattering submillisecond SPNLC with 4π phase shift is demonstrated at $\lambda = 532$ nm. We studied the temperature effect on the electro-optical properties of SPNLCs. The application of SPNLCs for 3D displays, such as lenticular lens, is presented.

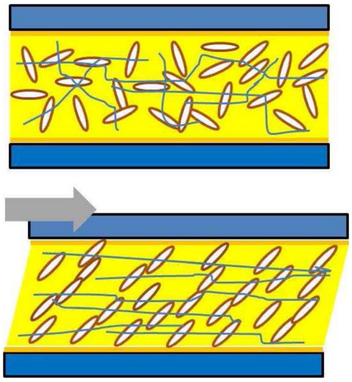

Fig. 1. LC directors configuration before (top) and after (bottom) shearing. The ellipses denote the LC molecules, solid lines the polymer network, and arrow the direction of shearing force.

II. EXPERIMENT

We prepared a photopolymerizable SPNLC precursor with step-growth monomer, chain-growth monomer and E7 nematic LC host (80%). Then, the precursor was drop-filled between two fused silica substrates with a cell gap of 14 μm. The inner surfaces of both substrates were coated with indium-tin-oxide. No alignment layer was required. UV-light with a wavelength of 365 nm was employed to illuminate the cell in a two-step process. Right after the curing process, the cell was translucent because of the refractive index mismatch between the randomly oriented LC and the polymer. Then, a precision shearing force was applied to the upper substrate. The shearing distance was 350 μm. The cell became transparent because the LC molecules were uniformly aligned. Fig. 1 schematically describes the shearing process.

We used a *Cary* 500 scan spectrophotometer to measure the optical transmittance of the device in the wavelength range of 450–800 nm. The electro-optical (EO) properties were measured with a LabVIEW system. The SPNLC cell was sandwiched between two crossed polarizers. We used a green diode laser ($\lambda = 532$ nm to measure the phase retardation of the SPNLC cell [13]:

$$\delta = \frac{2\pi}{\lambda} d\Delta n \qquad (2)$$

where d is the cell gap, Δn is the birefringence, and λ is the wavelength. From (2), birefringence can be calculated. Meanwhile, thru measuring the decay time of the SPNLC cell we obtained the visco-elastic coefficient (γ_1/K_{11}) [14].

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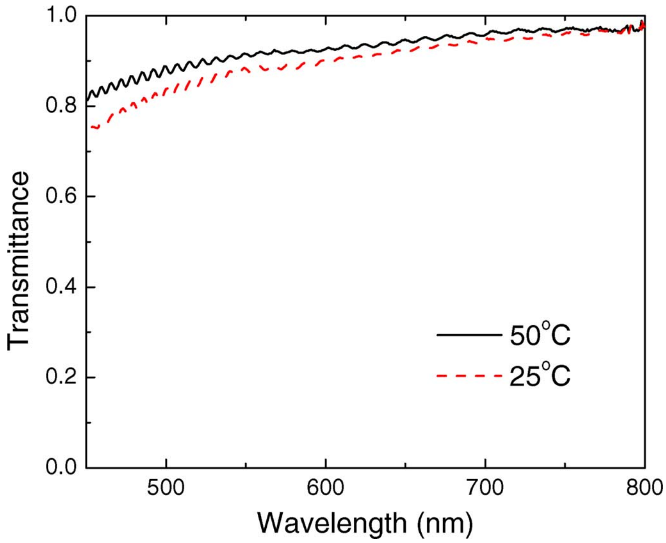

Fig. 2. Measured transmission spectra of an E7-based SPNLC cell, normalized to the transmittance of the cell above clearing temperature (~ 60 °C). Cell gap $d = 14\ \mu$m.

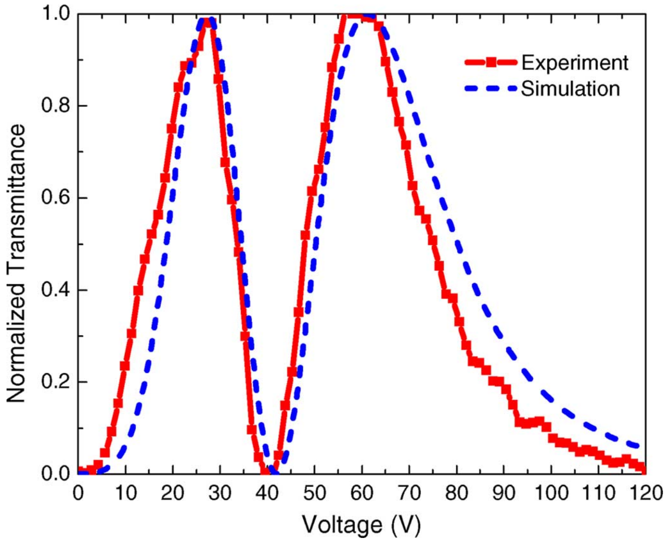

Fig. 3. Measured and simulated VT curves of the SPNLC sample. $T = 21\ ^\circ$C and $\lambda = 532$ nm. Solid line denotes experimental data and dashed lines the fitting results.

III. Results and Discussion

A. Transmittance Spectra

Fig. 2 depicts the measured transmittance spectra of the SPNLC cell. Here, the transmittance is normalized to that measured in an isotropic phase. The transmittance of the sample decreases gradually as the wavelength gets shorter because of the increased scattering, but still keeps over 75% at $\lambda = 450$ nm. If no sheering process was taken, the transmittance of the sample would be below 40%. When the temperature increases from 25 °C (dashed lines) to 50 °C (solid line), transmittance is increased by ~6% for a better refractive index match. Since the refractive indices of liquid crystal and polymer are wavelength dependent [15], [16], it is possible to further reduce scattering for blue light by choosing index-matched polymer and LC [17].

B. EO Properties

Fig. 3 shows the measured (solid line) voltage-dependent transmittance (VT) of the SPNLC cell at room temperature. This sample achieves a total phase retardation of $\delta = 4\pi$ at 120 V and $\lambda = 532$ nm. The dashed lines represent the simulation results. We assume Δn and $\Delta\varepsilon$ of E7 do not change, since LC molecules are completely separated from the polymer. From fittings, we obtain elastic constant $\mathrm{K}_{11} = 18\,000$ pN and $K_{33} = 20\,000$ pN. These values are more than 1000X larger than that of E7. This is because polymer networks exert a strong anchoring force on the LC molecules, so they become difficult to be reoriented. Also from simulation, we find that the pretilt angle of the SPNLC cell is as high as $\sim 45^\circ$, which results from the shearing process and the employed monomers. For this reason, there is almost no threshold voltage observed in the VT curve, as Fig. 3 shows. This feature helps to lower the operating voltage, but the tradeoff is the decreased phase change. The operating voltage, light scattering and response time are all dependent on the polymer concentration. A smaller polymer ratio will reduce operating voltage, increase response time and scattering because of the larger domain sizes [18].

TABLE I
Gray-to-Gray Response Time for SPNLC

Response Time (μs)		Final Phase (π)				
		0	1	2	3	4
Initial Phase (π)	0		751	406	334	204
	1	259		651	338	214
	2	338	383		464	216
	3	340	369	431		517
	4	401	362	468	228	

Table I shows the measured gray-to-gray switching time. The total phase retardation is divided into five gray levels. The response time is defined as a 100%–10% phase change. The average response time is calculated to be 392 μs. The slowest process is the rising from an initial phase ($\delta = 0$) to a final phase of $\delta = \pi$, which takes 751 μs. This is because the rise time is related to the voltage switching ratio [19]. A small phase change usually corresponds to a small voltage switching ratio.

C. Temperature Effect

For different applications of LC devices, the operating temperature can vary over a wide range. However, many EO properties of LC material are largely dependent on the temperature. This, it is necessary to study the temperature effect of the SPNLC cell.

Fig. 4 depicts the temperature dependent birefringence of the SPNLC cell. The triangles are experimental data and the solid line represents fitting results based on the following equation [20], [21]:

$$\Delta n = \Delta n_0 (1 - T/T_c)^\beta \tag{3}$$

where Δn_0 and β are material constants. The fitting parameters are $\Delta n_0 = 0.123$ and $\beta = 0.22$. As the operating tempera-

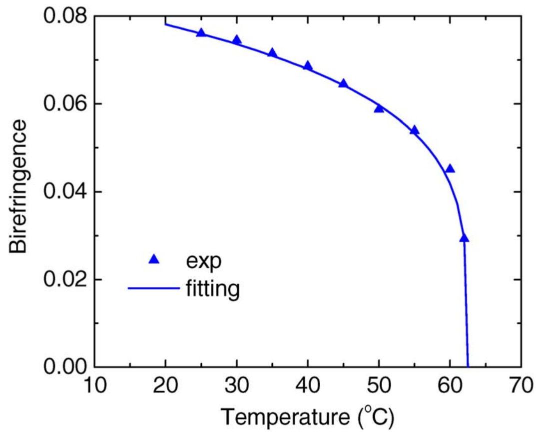

Fig. 4. Temperature dependent birefringence of the E7-based SPNLC. Triangles are experimental data and line is fitting result. $\lambda = 532$ nm.

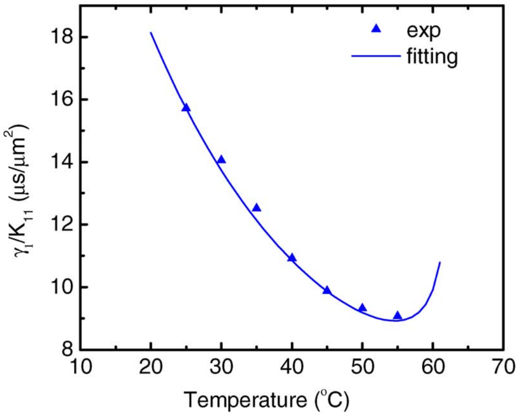

Fig. 5. Temperature dependent visco-elastic constant of the E7-based SPNLC cell. Triangles are experimental data and solid line is fitting result using (4) with $A = 4.2 \times 10^{-4}$ μs/μm^2 and $E = 258$ meV.

ture increases from 25 °C to 40 °C, the birefringence decreases from 0.076 to 0.069. SPNLC shows a lower birefringence than the E7 host because of the high pretilt angle mentioned above. From (3), high $\Delta \mathrm{n}_o$ and high T_c are favorable for enhancing the birefringence of SPNLC. For example, E44 has higher birefringence and higher clearing point than E7. Therefore, under the same polymer concentration, the E44 SPNLC should have a higher birefringence than E7.

Next, we measured the temperature dependent visco-elastic coefficient (γ_1/K_{11}) of the SPNLC cell. From [22], γ_1/K_{11} decreases exponentially as the temperature increases:

$$\frac{\gamma_1}{K_{11}} = A\frac{\exp(E/k_B T)}{(1 - T/T_c)^{\beta}} \tag{4}$$

where γ_1 is the rotational viscosity, K_{11} is the splay elastic constant, E is the activation energy, and k_B is the Boltzmann constant. Results are shown in Fig. 5. Here, triangles and solid line represent experimental and fitting data, respectively. As the temperature increases from 25 °C to 40 °C, γ_1/K_{11} decreases by $\sim 40\%$. In comparison with the E7 host, the γ_1/K_{11} of SPNLC is $\sim 1000\times$ smaller due to the dramatically increased K_{11}.

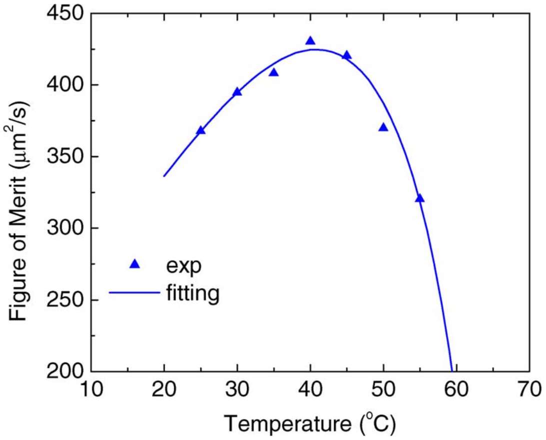

Fig. 6. Temperature dependent FoM of the E7-based SPNLC cell. Triangles are experimental data and solid line is fitting result. $\lambda = 532$ nm.

Under the small angle approximation and strong anchoring condition, the response time of a nematic LC cell can be expressed as follows:

$$t_{\text{rise}} \sim \frac{\tau_o}{(V/V_{\text{th}})^2 - 1} \tag{5}$$

$$t_{\text{relax}} \sim \tau_0 = \frac{\gamma_1 d^2}{K_{ii}\pi^2} \tag{6}$$

where V is the operating voltage, V_{th} is the threshold voltage, γ_1 is the rotational viscosity, and K_{ii} is the effective elastic constant. To compare the performance of a LC phase modulator, we define a figure-of-merit (FoM) as following [19]:

$$\text{FoM} = \frac{K_{11}}{\gamma_1}(\Delta n)^2 \propto \frac{1}{\tau_0}. \tag{7}$$

Thus, we use FoM to characterize the temperature dependent performance of SPNLC. A larger FoM corresponds to a faster response time. Fig. 6 shows the measured FoM of the SPNLC cell at different temperatures. Triangles are experimental results while solid line is the fitting curve with (7) using $A = 4.2 \times 10^{-4}$ μs/μm^2 and $E = 258$ meV, as we obtain from Fig. 5. From Fig. 6, E7-based SPNLC exhibits the highest FoM at ~40 °C, known as the optimal operating temperature [22]. The FoM of SPNLC is $\sim 200\times$ larger than that of E7, corresponding to a $\sim 200\times$ faster response time.

IV. LENTICULAR SPNLC LENS

Tunable-focus cylindrical lens using nematic LC and slit structure has been demonstrated previously [23]. Fig. 7 shows the structure of SPNLC lenticular lens; here only one cylindrical lens, instead of lens array, is depicted. The slit aperture of the cylindrical lens is 150 μm. The shearing direction of the SPNLC is parallel to the cylindrical lens. Using the following parameters of our SPNLC: maximum $\delta n = 0.076$, cell gap $d = 14$ μm, and $\lambda = 532$ nm, we find the phase change of 4π can be achieved as the operating voltage swings from 0 to 120 V. Based on (1), the minimum focal length of this lens is estimated to be ~ 2.6 mm.

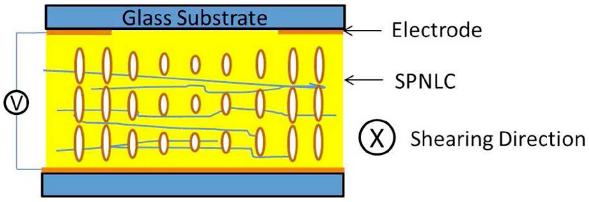

Fig. 7. Lenticular lens based on SPNLC.

V. CONCLUSION

We demonstrate a fast-response SPNLC phase modulator with a 4π phase change at $\lambda = 532$ nm. The average gray-to-gray response time at room temperature is $\sim$400 μs. Due to the new material set and fabrication procedures, this device shows a fairly low scattering in the visible spectral range while allowing for large phase modulation. To further suppress scattering, we could operate the SPNLC device at an elevated temperature. The optimal operating temperature of the E7-based SPNLC is found to be $\sim$40 °C. Our sheared PNLC has potential applications in time-multiplexing 3D displays because of its ultra-fast switching speed.

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