American Journal of
Physical Science
(AJPS)

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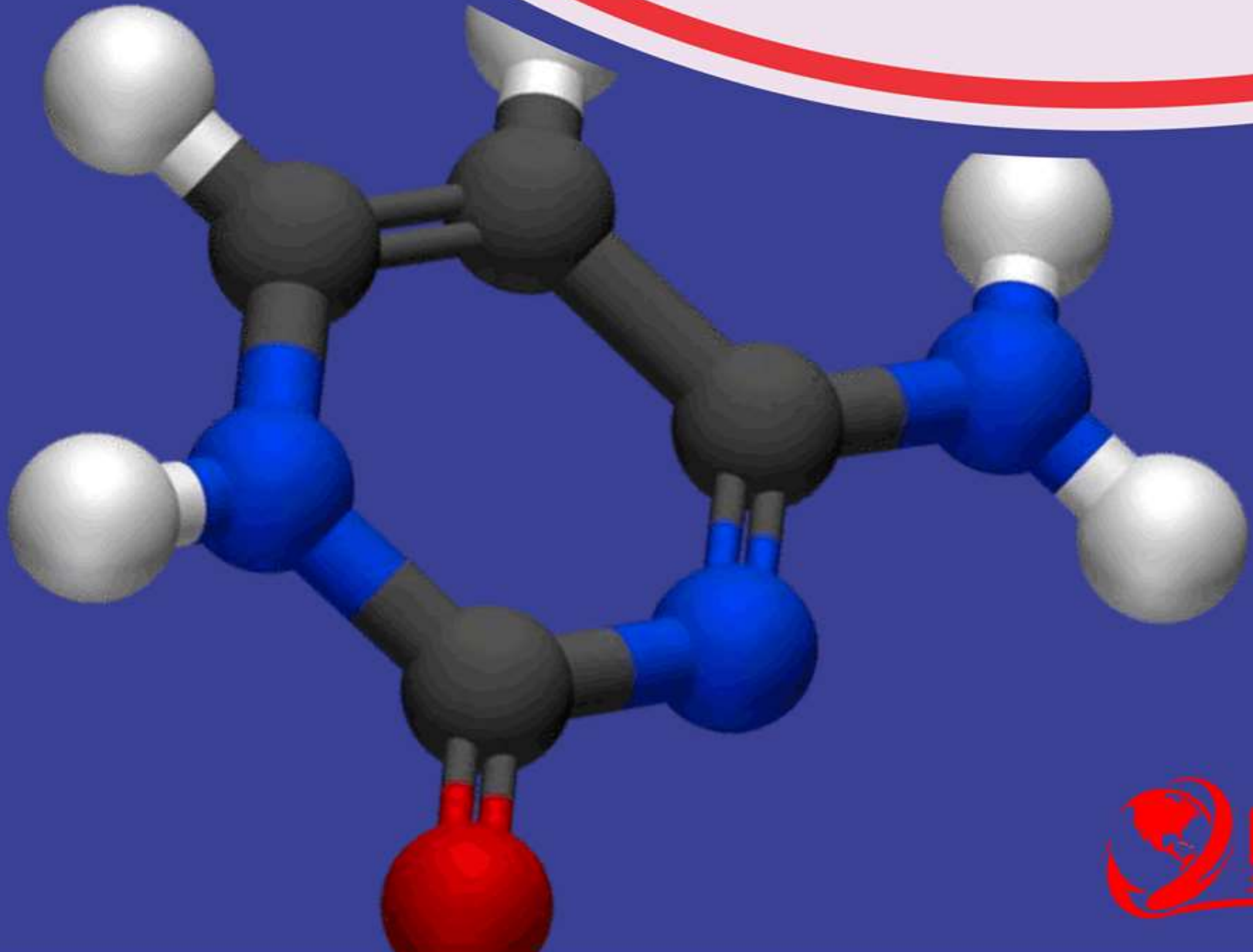

American Journal of Physical Sciences
ISSN: 2958-969X (Online)
Vol. 2, Issue 1, No. 2, pp 26 - 39, 2024

www.iprjb.org

Binary Nematic Liquid Crystals Mixture with Enhanced Electro-Optics Properties for Photonic Applications

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Article History

Received 10th March 2024

Received in Revised Form 19th April 2024

Accepted 20th May 2024

Abstract

Purpose: In this work, we mix two simple nematic liquid crystals (NLCs) and investigated the binaryNLCs mixtures of 7CB/PCH5 of different mixing ratios.

Methodology: The pure liquid crystals 7CB and PCH5 and binary mixtures of them of high temperature stability were thermally analyzed by differential scanning calorimetry. The mixture 7CB/PCH5:30/70 wt% has the highest thermal stability with a nematic-isotropic (N-I) transition temperature at 50°C. The electrooptic properties of 7CB, PCH5, and the mixture 7CB/PCH5:30/70 wt% at room temperature were also investigated using an amplitude modulated electric signal (1 kHz - 100 Hz) by increasing diving peak voltage from 0 V to 10 V. The threshold volage is relatively reduced for the binary mixture in comparison to that value for PCH5. In comparison to the pure LCs, the mixture 7CB/PCH5:30/70 wt% has the fastest response times of values 2.36 ms total time response, 0.41 ms rise time, and 1.95 ms fall time. It has also the highest contrast ratio. Moreover, it has a maximum measured transmission that is higher than those for PCH5 and 7CB by about 17 % and 8%, respectively, at a field strength of 2V/μm.

Findings: The obtained results indicate that the electrooptic properties of PCH5 was improved when mixed with a proper ratio of 7CB, of lower cost, more stablity , and higher potential for photonic applications.

Unique Contriburibution to Theory, Practice and Policy: This expermental study shows that simply by mixing two relatively low cost NLCs materials, one of high thermal stability and low electro-optic properties with other one of low thermal stability and better electro-optic properties; this would improve the stability, response, and transmition of the binary mixture. If the a suitable driving method is applied, without doping with other orgnic or inorganic matrial.

Keywords: *Liquid Crystal Mixtures, Nematic, PCH5, 7CB, Amplitude Modulated Electric Signal*

INTRODUCTION

Nematic liquid crystals (NLCs) are thermotropic materials widely utilized nowadays in photonic and electrooptic applications such as smart watches, TVs, computer displays, light switches, thermometers, temperature sensing applications, and smart windows when mixed with proper polymer material [1-5]. Liquid crystals have mesophases that combine the physical properties of isotropic liquid and a crystalline solid. It possesses some of the mechanical properties of liquids and the anisotropy of optical, electrical, and magnetic properties like crystals. One of the main classes of LCs is the NLCs. The molecules of thermotropic NLC are oriented almost linearly along a longitudinal axis, or director, that indicates their local orientation and can be easily distorted or aligned under the effect of electric field, or linear alingment surfaces that is in direct contact with the LC molecules to modify their orientation and physical properties. The pure NLC materials compared to other LC materials are of relatively lower cost. Thus, by mixing different NLCs, best switching properties with affordable cost can be attained [6-12]. Nowadays it is of great interest to design new NLCs or to find new miscible binary mixtures of NLCs of low cost, low viscosity, modest dielectric anisotropy, proper elastic constants, high thermal stability for long-term operation, positive birefringence, and high Nematic to Isotropic transition temperatures (T_{NI}) much higher than room temperature [13]. The physical properties of any organic material are controlled by their molecular structure. Therefore, it is great interest to investigate the binary mixing of proper NLCs plays a crucial role in getting a mixture with modified and improved properties suitable for the LCs-based devices applications with improved properties than those of pure LC [14-19].

A fast response of LCs is the main requirement for photonic applications. The selected thickness of the LC is an important paramter when considering the balance between response time and manufacturing yield. A narrower cell gap leads to a faster response time, but the manufacturing yield could be sacrificed and subsequently a higher birefringence LC is needed to satisfy the minimum requirements for applications. However, a LC of high birefringence tends to have less thermal stability. Also, for a proper transmission, the required LC birefringence should be around 0.10–0.15 that is higher than the values of the PCH5 which is proposed for our investigation as it is comparably of low cost, small molecular weight, and is valuable for for applications of fast response time around room temperature rage and slightly higher [20] with optimum electropotic properties. This would be done if PCH5 is mixed with another LC that is also of low cost and a small molecule such as 7CB. Since both also have the other desirable parameters for applications including low viscosity, modest dielectric anisotropy, proper elastic constants, and good material stability for long-term operation. When proper combination of the applied field strength and modulating frequency of an amplitude modulating (AM) driving applied electic signal is applied on NLC sample; electrooptic properties are improved applying a relatively low applied voltages [21,22].

Also proper mixing of two NLCs with certain mixing ratios can improve effectively the electrooptic properties of a proper binary mixture of both 7CB and PCH5 under the effect of an AM electrical signal.

In this work, we first analyzed thermally pure and binary mixtures of two NLCs of relativly low cost and molecular weight, 7CB/PCH5 of different mixing ratios. This is followed by studying the electro-optic response of the pure 7CB, PCH5, and the mixtures of most thermally stable (higher nematic to isotropic transition temperature (T_{NI})) mixing ratio, applying an amplitude modulating driving electric field as well as the pure samples.

MATERIALS

In this study, we used two commercial NLCs:7CB (4-*n*-heptyl cyanobiphenyl) and PCH5 (trans-4-(4-Pentylcyclohexyl) benzonitrile). The nematic phase for 7CB ranges from 14.5 to 42.8 °C [23,24], while the nematic phase of PCH5 that possesse a nematic phase ranges from 30 to 54.9 °C [25]. One of the key parameters of the LCs is its refractive indices. The extraordinary (n_e) and ordinary refractive indices (n_o) are 1. 6001 and 1. 4854 for PCH5 at wavelength 633 nm and room temperature [26], while the values for 7CB are 1.713 and 1.517, respectively [27].

We investigated the two liquid crystals 7CB and PCH5, purchased from Sigma-Aldrich Company, as well astwoof their mixtures of higher PCH5 content (in order to shift the nemati to isotropic transition temperature to higher value), thus to increase the mixtures themal stability. Thus we got two mixtures of different mixing ratios; 7CB/PCH5:50/50 wt% and 30/70 wt%.

Samples Preparation for Electro-Optic Measurements

Individual ITO glass cells were filled with 7CB and PCH5 nematic liquid crystal materials and mixture 7CB/PCH5: 50/50 wt% and 30/70 wt% subsequently by capillary action effect on a hotplate above the isotropic transition temperature. In our case a temperature of 70^{o}C was enough for all samples. Mini hotplate with magnetic stirrer is used for mixing LC materialsthen ITO glass cells that have a linear alignment layer of cell gap spacingof 5 □m is filled with pure LCs as well as with their mixtures.

RESULTS AND DISCUSSION

DSC Measuments

Differential scanning calorimetry (DSC) was measured to all LC samples in order to thermally analyze the samples and to detect their Nematic-to -Isotropic phase (*N*-*I*) transition temperatures. DSC measurements are important to identify also the range of thermal stability of LC binary mixture. Material stability is crucial for utilizing the LC binary mixture in electro-optic device applications. The nematic phase should be stable within a wide temperature range below and above room temperature.

We used a DSC-Q2000 (TA instruments) and a pure indium standard was applied to calibrate the temperature and energy scale. The weight of the samples ranges between 6.0 and 8.0 mg.

The obtained results from the DSC measurements of phases transition temperatue for pure and mixtures samples are listed in table (1). Showing change of phase from crystalline-to-nematic (Cr-N) and and from nematic-to-isotropic (N-I) for 7CB, PCH5 and their binary mixtures.

DSC resultfor LC samples and for mixture with higher PCH5 content, denotes that the mixture with mixing ratio 30/70 wt% has the longest thermal stability of nematic phase until a temperature of 50 ^{o}C. Thus, it has higher thermal stabilty above room temperature and could be applied in LC-basd photonic applications in hot weather countries.

Table 1: Sample

Sample	**T_{Cr-N} (°C)**	**T_{N-I} (°C)**
7CB	29.9	42.4
PCH5	29.05	54.06
7CB/PCH5 : 50/50 wt%	-	44.245
7CB/PCH5 : 30/70 wt%	-	50

Electro-Optical Measurements

In our previous study [21, 22], an amplitude modulated (AM) electric signal was applied to enhance the electro-optic response of liquid crystals by increasing the modulating signal frequency. High modulating frequency, 100 Hz, was applied in this study with all samples that are homogeneously aligned in cells of thickness 5 μm. In order to enhance the electro-optic properties of NLC. We applied a short pulsed electric field or amplitdue modulated (AM) driving electric field signal totus to get faster response time, [28, 29].

For measuring the samples electro-optic response, a linearly collimated beam of He-Ne laser of power 5 mW and wavelength 633 nm passes normally across each sample. A square electric field signal of frequency 1 kHz modulated by another square signal of frequency 100 Hz is applied to the LC cells and their EO response and transimition were investigated. The applied voltage across the cell was increased gradually from 0V to 10V and the light transmission intensity was detected by a photodiode EOT's Silicon Photodetector (ET-2030). The output from the photodiode is recorded via a storage oscilloscope (4 channels Oscilloscope DSOX2024A, 4 channels,200 MHz, KEYSIGHT TECHNOLOGIES). An AC amplitude modulated (AM) electric pulses of enough voltage was applied to switch the LC directors between on- and off-states. The applied driving AM signal voltage ranges from 0 to 10 V. The electrical signals were generated from B-Series Waveform generator, 33500B Waveform generator 33500, 30 MHz, 2 channels, Keysight Technologies.

The applied-voltage signal was displayed on the storage oscilloscope together with the out-put trasmitted signal from each sample. The rise, fall, and total response times (τ_r, τ_f, τ_t) were determined from the transmitted optical signals. The threshold and the saturation voltages, and the contrast ratio were detected from the transmission-voltage curves. Images for the samples was captured from LABOMED Polarizing Microscope LB-594 with a digital camera - (digital USB storage camera – LC-20 USB 3.0 colorful- LABOMED INC-USA). A schematic diagram of experimental setup is shown in Figure (1).

Polarizing Optical Microscopy (POM) Images

POM is a common technique used for testing optically the LC samples texture, orientation, and alignment, morphology and phase transitions of liquid crystals.

Figure (2) shows images for the three samples, 7CB, PCH5, and mixture 7CB/PCH5: 30/70 wt% as seen under the polarizing microscope. The LC molecules in all samples appear to be homogeneouly aligned along the aligmenent layer coated above the ITO glass in LC cells as detected between the two crossed polarizers of the polarizing microscope.

Response Time and Transmission Measurements

Applying an AM square waveform of sufficient amplitude of 100% modulation depth with a carrier electric signal of frequency 1 kHz modulated by a lower modulating frequency allows

LC molecular director to switch periodically between on- and off- states. This can afford enough time for LC switching dynamics and relaxation processes to enhance the LC switching properties and achieve fast and stable response with low driving voltage [28-30]. When high voltage is applied the LC molecular director align along the applied electric field direction, on-state. As high voltage is removed, LC molecules relax back to their initial orientation quickly, off-state. Thus, switching from high voltage to low voltage enhances NLC fall time (relaxation time) significantly.

The applied driving voltage was varied from 0–20 volts (V_{pp}; peak-to-peak voltage). When the electric field is applied, the homogeneously aligned LC molecules along the rubbing direction of the alignment layer inside ITO glass cell; start to be aligned along the applied electric field direction. The driving square electric carrier signal of frequency 1 kHz was modulated by a signal of a frequency of 100 Hz. Typically, 1 kHz frequency is used as carrier signal for driving LC-based devices to ensure stable EO performance and to avoid conductivity effects [27-30]. All the output transmission from the samples is measured between two crossed polarizers.

From the transmission – voltage curve shown in Figure 3, the maximum calculated transmission is 87.5%, 80%, 70.8% for 7CB, mixture 7CB/PCH5: 30/70 wt%, and PCH5, respectively at peak voltage 10 Volts (2V/μm field strength). Thus, the highest transmission is that of 7CB, then mixture 7CB/PCH5:30/70 wt%, then the lowest transmission is obtained for the sample PCH5. This reflects the strength of molecular dipole moment for each sample. 7CB molecule has the highest dipole and PCH5 molecule has the lowest dipole moment. Thus, 7CB molecule of the highest dipole moment is affected rapidly and strongly by the applied electric field and orients long its direction.

The threshold voltage, is the voltage at which the LC molecule starts to respond and align along the applied driving voltage. The saturation voltage at which the maximum transimition I reached for all samples is reached at ~ 9 Volts.

The contrast ratio is the ratio between the maximum transmission to the minimum transmission. The calculated contrast ratio and the threshold voltages for the investigated samples, 7CB, PCH5, mixture 7CB/ PCH5: 30/70 wt% are presented in Tables 2 and 3, respectively.

As given in Table 2, the mixture 7CB/PCH5: 30/70 wt% has the highest contrast ratio in comparison to the pure LCs samples. The lowest contrast ratio is for PCH5 due to the low dipole moment of its molecule that weakens the molecules strength to be oriented along the applied electric field. However,7CB molecules have the highest dipole moment. That’s why, the 7CB sample shows higher contrast ratio than PCH5.

Table 2: Calculated Contrast Ratio

LC	PCH5	7CB	7CB/ PCH5: 30/70 wt%
Contrast ratio	3.73	4.77	5.74

As presented in Table 3, the mixture 7CB/ PCH5: 30/70 wt% has a threshold voltage that is relatively lower than that for PCH5. Because on mixing PCH5 with 7CB this leads to strengthens the overall dipole moment of the mixture. Thus, mixing two liquid crystals; one of low dipole moment with another of higher dipole moment, will enhance the dipole moment strength and so the response to the applied electric field.

Table 3: Threshold Voltages

LC	PCH5	7CB	7CB/ PCH5: 30/70 wt%
Threshold voltage (V)	1.6	1	1.56

The response times of all the samples; the rise (τ_r) and fall (τ_f) times are measured from the output transimeted signal displayed on the oscilloscope screen and plotted as a function of the applied peak voltages as shown in Figure 4.

At 10 V driving voltage the rise times are 0.54 ms, 1.28 ms, and 0.411 ms successively for PCH5, 7CB, and mixture 7CB/PCH5:30/70 wt%. The fall times are 2.67 ms, 2.8 ms, and 1.95 ms for PCH5, 7CB, and mixture 7CB/PCH5:30/70 wt%, respectively. Then, the total response time (T_t) is calculated by adding the rise time (τ_r) and fall time (τ_f), i.e. ($\tau_r + \tau_f$), Figure 5. It is 3.21 ms, 4.08 ms, and 2.36 ms successively for PCH5, 7CB, and mixture 7CB/PCH5:30/70 wt%. The mixture 7CB/PCH5:30/70 wt% has a rise time of about 0.8 and 0.3 of those value for PCH5 and 7CB. However, its fall time is about 0.7 of those for PCH5 and 7CB. The fastest total response time is that for the mixture 7CB/PCH5:30/70 wt% in comparison to the total response time values for pure PCH5 and pure 7CB: about 0.7 and 0.6 of those for PCH5 and 7CB.

At applied voltages higher than 5 Volts (electric field 1 V/μm), the total response time is faster for the mixture 7CB/PCH5; 30/70 wt%. As the voltage is increased more reaching 10 Volts (2 V/μm field strength), the total response time for 7CB, PCH5, and mixture 7CB/PCH5; 30/70 wt% reaches the values 4.08 ms, 3.21 ms, and 2.36 ms, respectively as shown in (Fig. 5). Thus it is clear that response time of the 7CB/PCH5: 30/70 wt% mixture is perfectly enhanced and reduced with respect to that of the pure LCs samples.

CONCLUSION AND RECOMMENDATIONS

Conclusion

By mixing two simple low-cost nematic liquid crystals, we could shift the nematic to isotropic phase transition temperature of the mixture in order to get a mixture of optimum optical and electrical properties. In this work, binary NLC mixture of 7CB/PCH5 of mixing ratios with higher PCH5 content is studied thermally then electro-optically. The mixture 7CB/PCH5:30/70 wt% shows higher thermal stability of nematic-to-isotropic (N-I) transition temperature, till 50^{o}C. Then, the optoelectronic properties for pure 7CB and PCH5 and the mixture 7CB/PCH5:30/70 wt% is investigated. The mixing of two liquid crystals; one of low molecular dipole moment with another of higher dipole moment. this enhances the dipole moment strength of the mixture and its response to the applied electric field.

On applying an AM electric signal (1 kHz-100Hz) at a driving peak voltage of 10V (2V/μm field strength). The fastest total response time is obtained from the mixture 7CB/PCH5:30/70 wt% of value 2.36 ms; 0.411 ms rise time and 1.95ms fall time. Therefore, the fastest total response time is for mixture 7CB/PCH5:30/70 wt% in comparison to that for PCH5 and 7CB is about 0.7 and 0.6 of those for PCH5 and 7CB. The maximum measured transmission is 70.8%, 80%, and 87.5% successively for PCH5, mixture 7CB/PCH5: 30/70 wt%, and 7CB at 10 Volts (2V/μm field strength). Thus, the thermal and electrooptic properties of 7CB was enhanced by mixing it with a proper higher content of PCH5 and as well as driving the sample with an AM electrical signal of high enough modulating signal frequency.

Recomendations

By mixing two relatively low cost NLCs materials, one of high thermal stability and low electro-optic properties with other one of low thermal stability and better electro-optic properties; we can obtain economic NLCs binary mixture with improved thermal stability, response, and transmition. And thus by applying a suitable electric driving method, we can get a low cost binary NLC mixture of enhanced EO properties. Thus that is economically better than using expensive NLCs materials or high cost Ferroectric Liqid Crystals (FLC) material in photonic applications.

Acknowledgment

The authors would like to thank Deanery of academic research and Physics department for providing support to Research project 60329 at Physics department, Taibah University.

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Table Captions

Table 1: The measured transion temperatures from crystaline phase to nematic phase (Cr-N) and from nematic phase to the isotropic phase (N-I).

Table 2: The contrast ratio of the prepared pure and mixed LC samples.

Table 3: The threshold voltage of the prepared pure and mixed LC samples.

Figure Captions

Figure 1: Schematic diagram of experimental setup: S is the sample, PD is the photodiode, AM is the amplitude-modulating signal generator, and SO is the storage oscilloscope.

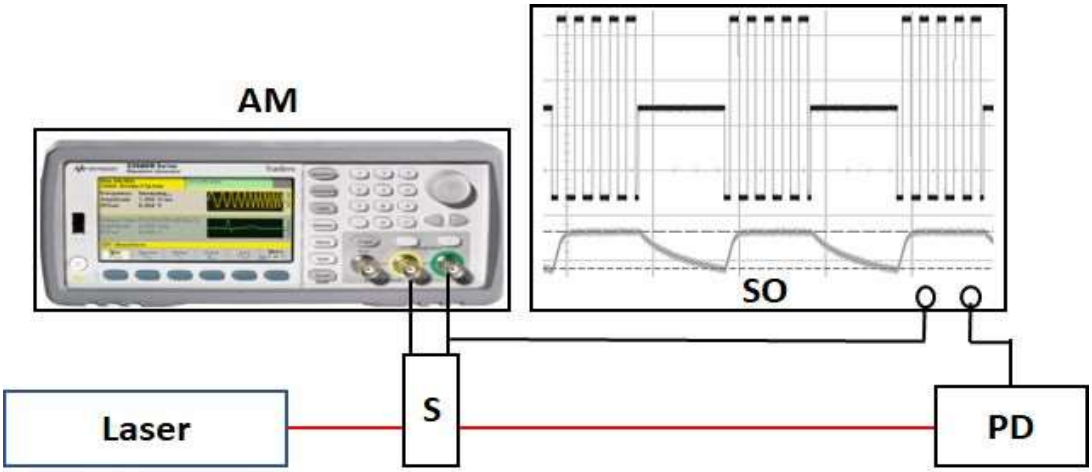
Figure 2: Images as seen under a polarizing microscope for samples (a) 7CB, (b) PCH5, and (c) mixture 7CB/PCH5: 30/70 wt%.

Figure 3: Transmission-voltage curve for nematic liquid crystals 7CB, PCH5, and mixture of 7CB/PCH5: 30/70 wt%.

Figure 4: The rise (τ_r) and fall (τ_f) times for 7CB, PCH5, and the mixture 7CB/PCH5: 30/70 wt% at different applied peak voltage applying AM electric driving signal 1KHz /100Hz.

Figure 5: The total response time for 7CB, PCH5, and the mixture 7CB/PCH5: 30/70 wt% at different applied voltages.

Figures



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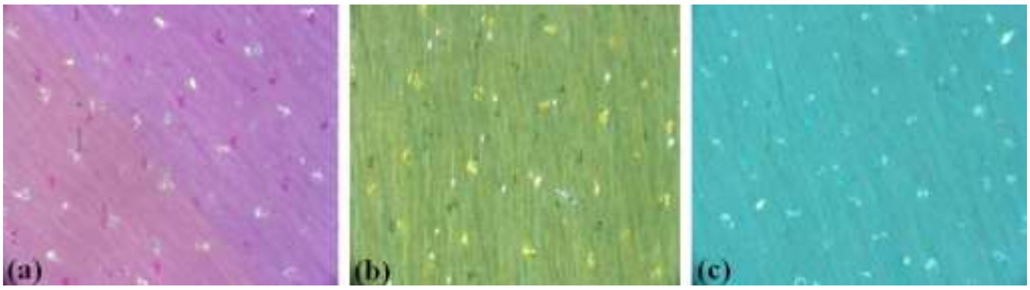

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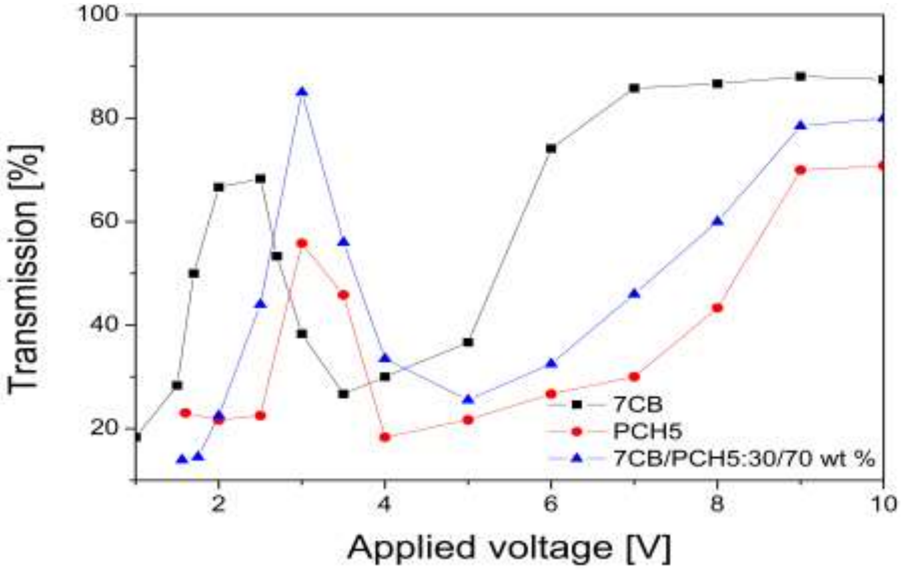


Figure 3: Transmission-Voltage Curve for Nematic Liquid Crystals 7CB, PCH5, and Mixture of 7CB/PCH5: 30/70 wt%.

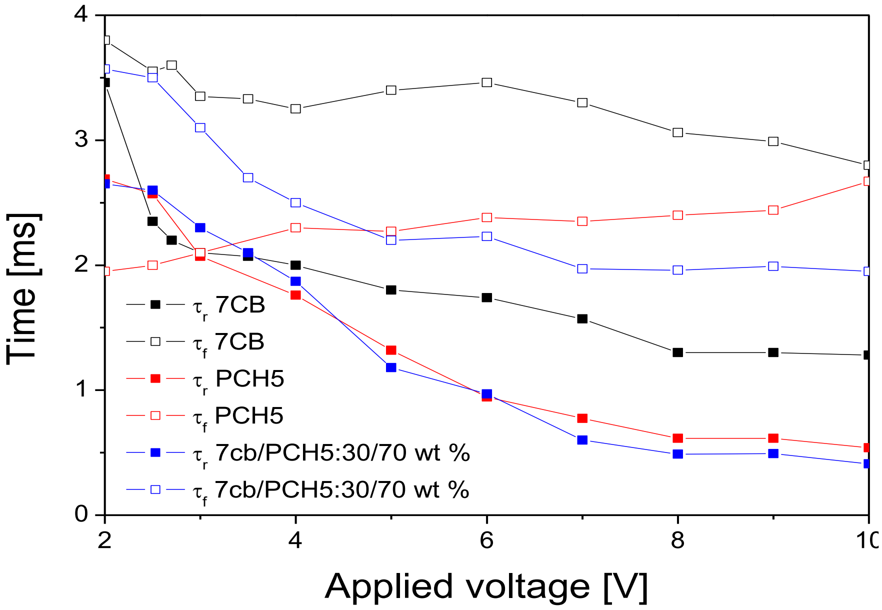
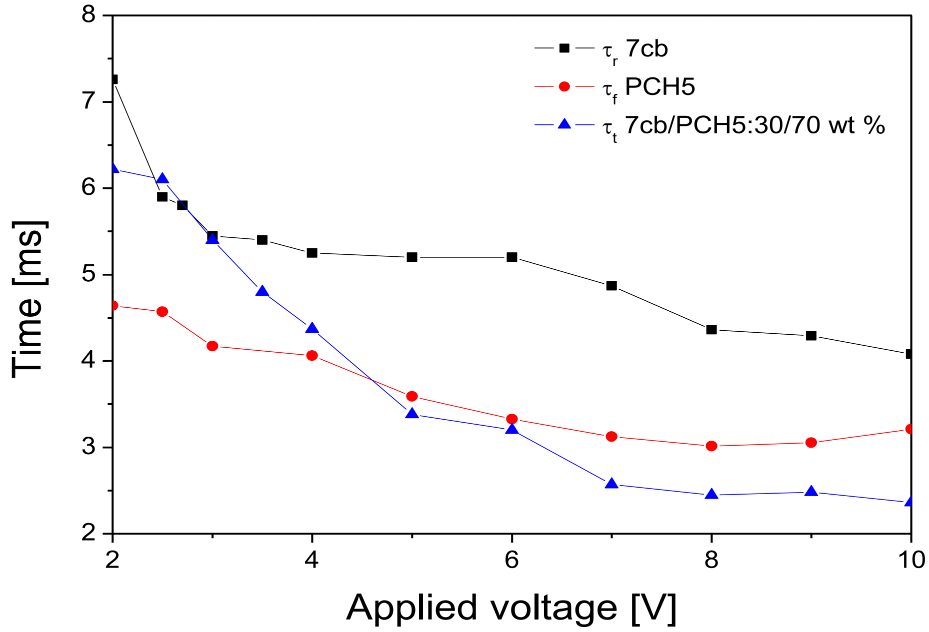


Figure 4: The rise (τ_r) and fall (τ_f) Times for 7CB, PCH5, and the Mixture 7CB/PCH5: 30/70 wt% at Different Applied Peak Voltage Applying AM Electric Driving Signal 1KHz /100Hz.



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