Enhancement in Electro- Optical Kerr Constant of Nematic Liquid Crystal by Doping SiO_2 Nanoparticles

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Regular Paper-Received: Jan. 05, 2026, Revised: Feb. 21, 2026, Accepted: Feb. 28, 2026, Available Online: Feb. 30, 2026
DOI: Due to the current conditions, there is no possibility to buy DOI for papers. We hope to buy them as soon as possible.

ABSTRACT— **In this research the electro-optical Kerr effect of pure and doped nematic liquid crystal (NLC), E7, with different concentrations of SiO_2 nanoparticles were investigated at different temperatures. And the Kerr constant and pre-transitional behavior of the pure and doped samples experimentally were measured. The measurements indicate that Kerr constant varies inversely with temperature for all mixtures, which is in good agreement with Landau-De Gennes model. Also, induced birefringence versus the square value of applied voltage in three temperatures near the isotropic-nematic phase transition temperature were measured. The results imply that, the electro-optical response of liquid crystal increases by optimizing nanoparticle- liquid crystal composites. In the other words, the Kerr constant and induced birefringence of doped Liquid crystal increase by adding nanoparticles up to 0.07% wt.**

KEYWORDS: Electro-Optics, Kerr effect, Liquid Crystal, SiO_2 nanoparticles.

I. INTRODUCTION

In recent decades, photonic and optoelectronic devices utilizing materials with high nonlinear properties have been studied and designed. Liquid crystals with unique optical and electro-optical properties are proper choice for this aim [1]. They have become indispensable materials in everyday life, with their applications ranging from high-resolution television displays to being a part of sophisticated and modern equipment for telecommunications and sensing purposes [2]. Due to anisotropic nature of molecules, nematic liquid crystals (NLCs) are highly nonlinear materials with large and broadband birefringence, And, their molecular orientation is highly sensitive to applied external electric, magnetic and optical fields [3].

Nowadays heterogeneous LC systems because of their potential for additional useful properties over the conventional LCs have attracted much scientific attention [4]. By combining different constituents, it is possible to design novel smart materials with unique properties that the initial substances don’t have. So liquid crystals have been doped with various types of additives, azo dyes [5],[6], nanoparticles [7]-[9] and polymers [10]-[14]. Dispersion of nanoparticles in a controlled amount doesn’t induce much distortion in the symmetry of LCs, but by controlling the orientation of host, modifies and improves the electro-optical responses which may be beneficial for display devices characteristics [15]. The improvement in LC properties depends on the type, shape, size, concentration, physical form and chemical stability, mutual interactions, anchoring energy, stability of nanoparticles and the preparation method [2]. Liquid crystals doped with nanoparticles can exhibit large nonlinear optical effects due to their fast response, high levels of controllable birefringence and high value of nonlinear optical parameters such as nonlinear refractive index [1].

LC devices based on the Kerr effect have generated considerable excitement over the past few years, because of their outstanding potential for novel display device mode [16]. Materials with a large Kerr constant offer a straightforward approach to reducing the driving voltage, which is one of the major requirements from the applications point of view [17], therefore immense work was done on dispersed liquid crystal materials doped with high Kerr Constant nanoparticles [18],[19].

Silica nanoparticles is one of the best choices of nanomaterials to use in various fields and it is attributed to their superior features such as nanoscale size, high surface area, high stability, the most valuable property of SiO_2 is its ability to be merged with different materials (modifier) efficiently for potential applications [20]. silica nanoparticles are dispersed in LCs and then investigated by various research groups [21]-[23]. silica nanoparticles are widely used as fillers and possess self-assembly of LC molecules in silica – polymer nanocomposites [22]. Researchers have found that dispersion of Silica nanoparticles into FLC causes an increase in spontaneous polarization, conductivity, and a decrease in switching time and permittivity [24], also it is found that high mutual interaction between FLC molecules and Silica nanoparticles leading to an increase in spontaneous polarization and anchoring energy coefficient [25]. Experiments using dispersion of silica nanoparticles in 5CB nematic liquid crystal revealed enhancement in memory effect in nematic liquid crystals [26].

The enhancement of the Kerr constant specifically affects the response times and driving voltages in electro-optical devices. An increased Kerr constant implies that a stronger birefringence can be achieved at lower electric field strengths, which can lead to faster response times due to more efficient modulation of the optical properties. Furthermore, the enhancement in the Kerr constant allows for the reduction of driving voltages, making the devices more energy-efficient and potentially extending their operational lifetimes [27].

In this experimental work the effect of temperature and dopant concentration of silica nanoparticles on the electro-optical properties of nematic liquid crystal E7 is investigated. At the first, using the nulled intensity method, the Kerr constant is calculated for pure and doped samples with different concentrations of silica nanoparticles in the isotropic phase. Then, using the temperature dependence of the Kerr constant, the pre-transition temperature is determined for all samples, and the effect of the concentration of silica nanoparticles on the changes in the pre-transition temperature of pure E7 is studied. Also, to investigate the Landau-De Gennes theory, the dependence of the Kerr constant with temperature in the isotropic phase is studied for all samples. Considering the importance of birefringence in nonlinearity, the induced birefringence caused by the electric field applied to the samples at temperatures close to the isotropic-nematic phase transition is calculated for all samples.

II. THEORY

The electro-optic Kerr effect, which was first observed by John Kerr in 1875, is a quadratic electro-optic effect induced by an electric field (E). An electric field applied to a transparent and optically isotropic medium induces an optical birefringence Δn, the magnitude of which is proportional to the square of the field, E, according to Kerr’s law [16]:

$$\Delta n(\lambda, E) = \lambda B E^2 \tag{1}$$

where, λ is the wavelength of the probe light and B denotes the temperature-dependent Kerr constant. The phase difference $(\Delta\varphi)$ resulted from the induced birefringence as below:

$$\Delta\varphi = 2\pi l B E^2 = \frac{2\pi l \Delta n}{\lambda} \tag{2}$$

where l is the medium length. In the case of using an external electric field across the Kerr cell, the angular difference between the principal planes of the polarizer and the analyzer (α) is:

$$\alpha=\frac{\Delta\varphi}{\lambda} \quad (3)$$

by using equations (1), (2), (3) we can obtain [28]:

$$\alpha=\frac{\pi l B E^2}{2} \quad (4)$$

According to Landau-De Gennes theory the relationship between the Kerr constant and liquid crystal temperature in isotropic phase of nematic liquid crystal is given by [29]:

$$B=\frac{\varepsilon_0\Delta n_0\Delta\varepsilon_0}{4a\lambda\sqrt{\varepsilon}(T-T^*)} \quad (5)$$

where a, λ, and Δn_0 are the temperature independent coefficient, the laser beam wavelength and the high frequency optical birefringence corresponding to complete alignment, respectively. T^* is the second-order pre-transitional temperature, $\Delta\varepsilon_0$ is the low frequency dielectric anisotropy in the completely ordered phase. So, from the Eq. 5, there is a reciprocal relationship between the Kerr constant B and the temperature i.e. Δn is proportional to $(T-T^*)^{-1}$ [28]-[30].

III. EXPERIMENTAL: MATERIALS AND KERR EFFECT SETUP

The experiments were carried out with a nematic liquid crystal E7, which is composed of four liquid crystals, 5CB- 7CB- 80CB- 5CT, was supplied from Merck, doped with SiO_2 nanoparticles at different concentrations.

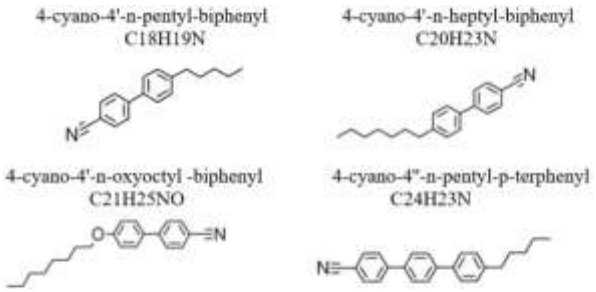


Fig. 1: Molecular structure of nematic E7 LC.

Silica nanoparticles with spherical shape and diameter about 20 nm were supplied from Aldrich.

The experimental set-up used to measure the Kerr constant through the nulled intensity method is shown in Fig. (2) [30].

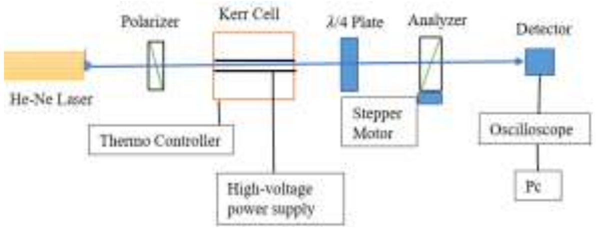
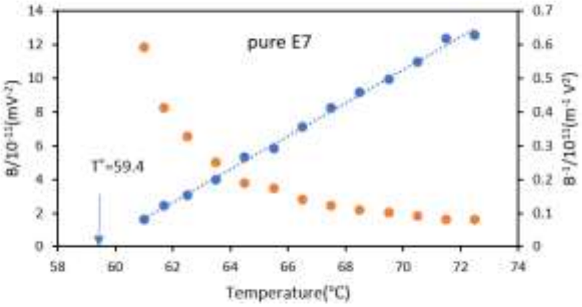


Fig. 2. Schematic view of the experimental setup.

A He-Ne laser emitting at a wavelength of 632.8 nm with a power of 5mw was used as a prob light. A quartz spectrophotometer cell, with a path length of 10 mm, was used as the Kerr cell. The stainless-steel electrodes were inserted into the Kerr cell, leaving an active column of liquid measuring 2×1.8×10 mm. A Teflon spacer was used to provide insulation between the electrodes and to maintain an electrode gap of 1.8 mm. The lower part of the Kerr cell was fitted into a thermo-stated metal jacket, which was cut away to allow passage of the light beam. Temperatures were determined with a PT100 sensor and could be maintained to an accuracy of ±0.1°C. The detection of the light was obtained by a photodiode, optical signal from the photodiode was displayed using a digital storage oscilloscope and a PC. The electric field is generated by means of a high-voltage power supply that was applied as a short duration rectangular shaped pulse from a pulse generator, to the electrodes of the Kerr cell. The polarizer and analyzer were Glan-Thompson double refraction type prisms were adjusted in a crossed position, making an angle of 45° with respect to the applied AC field (1 kHz). The quarter waveplate used in these experiments was mica cut specifically for use at 632.8 nm and mounted between glass discs. The quarter waveplate can convert linear polarized light to elliptically polarized light and vice versa. The elliptically polarized light emerging from the Kerr cell, converted to linearly polarized light by quarter waveplate. After passing through a quarter wave retarder oriented with its principal optical axis 45° to the direction of the applied electric field, the resultant plane-polarized light will be nulled by rotating the analyzer, measuring the rotation of the polarization angle

(α) and using Eq. 4, Kerr constant in certain voltage can be obtained.



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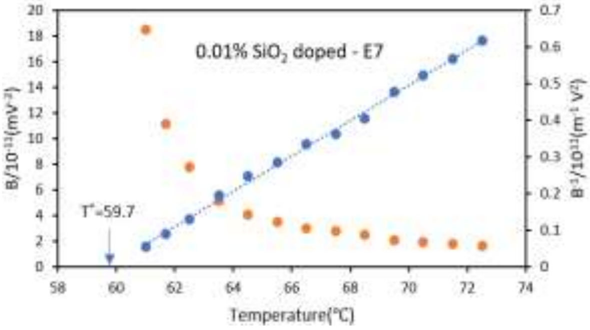

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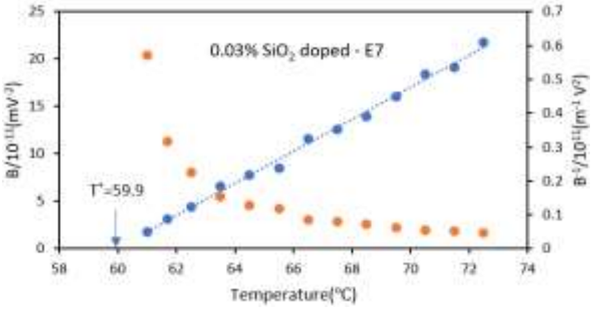

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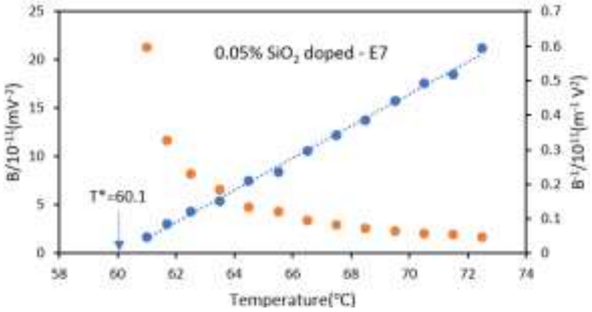

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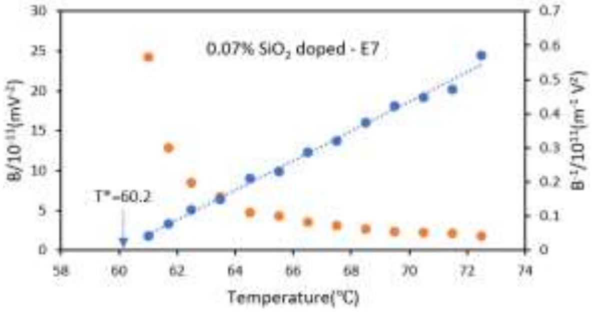

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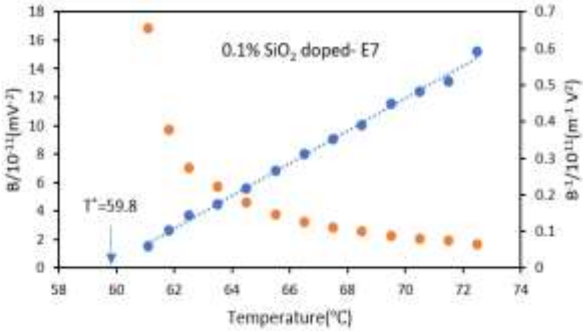

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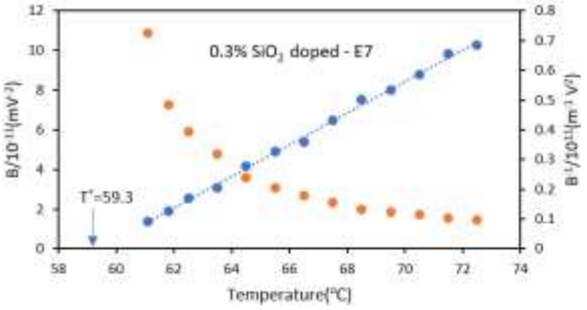


(g)

Fig. 3. Temperature dependence of B (Kerr constant, (orange points)) and B^{-1} (reciprocal of Kerr constant (blue points)) for (a) pure E7 and doped with SiO_2 nanoparticles at six different concentrations (b) 0.01% wt., (c) 0.03% wt., (d) 0.05% wt. (e) 0.07% wt., (f) 0.1% wt., (g) 0.3% wt.

The elliptically polarized light emerging from the Kerr cell, converted to linearly polarized light by quarter waveplate. After passing through a quarter wave retarder oriented with its principal optical axis 45□ to the direction of the applied electric field, the resultant plane-polarized light will be nulled by rotating the analyzer, measuring the rotation of the polarization angle (□) and using Eq. 4, Kerr constant in certain voltage can be obtained.

IV. RESULTS AND DISCUSSION

The temperature dependence of the Kerr constant and the inverse of the Kerr constant for pure E7 and SiO_2 NPs doped E7, in the isotropic phase is shown in Fig. 3. As expected, the Kerr constant (orange points) increases with decreasing temperature for pure and doped samples as the isotropic to nematic phase transition is approached.

It is clear from Fig. 3 the Kerr constant of pure liquid crystal greatly improves by increasing the amount of doping concentration to 0.07% wt. and in the case of 0.07%wt. SiO_2 doping, the Kerr constant was 24×10^{-11} mV^{-2} at temperature 61℃, which is roughly 2 times larger than that of pure case, So, it should be noted that the Kerr constant of SiO_2 doped LC has its maximum value, when doping percentage is 0.07.

As can be deduced from diagrams of Fig. (3) the Kerr constant comes down by adding nanoparticles to 0.1% wt. (however it is greater that pure LC).

As a result, at 0.3% wt. NPs doping concentration, the Kerr constant of doped LC becomes lower than the pure LC.

This might be explained by that doping nanoparticles into LC can affect the molecular orientation and alignment properties of the host liquid crystal, this alignment behaviour is majorly affected by changes in the concentration of doped NPs, so as it is clear at low concentrations of silica nanoparticles doping, when an external electric field is applied, NP-induced alignment and molecular orientation leads to improving the order parameter of the liquid crystal, and consequently the electro-optical response of the LC enhances. But increasing dopant concentration to 0.3%wt. leads to the formation of aggregation of nanoparticles and therefore the order parameter of liquid crystal reduces. By decreasing order parameter of LC, the Kerr constant and induced birefringence will reduce.

According to Landau-De Gennes theory birefringence (Δn) in the isotropic phase is given by

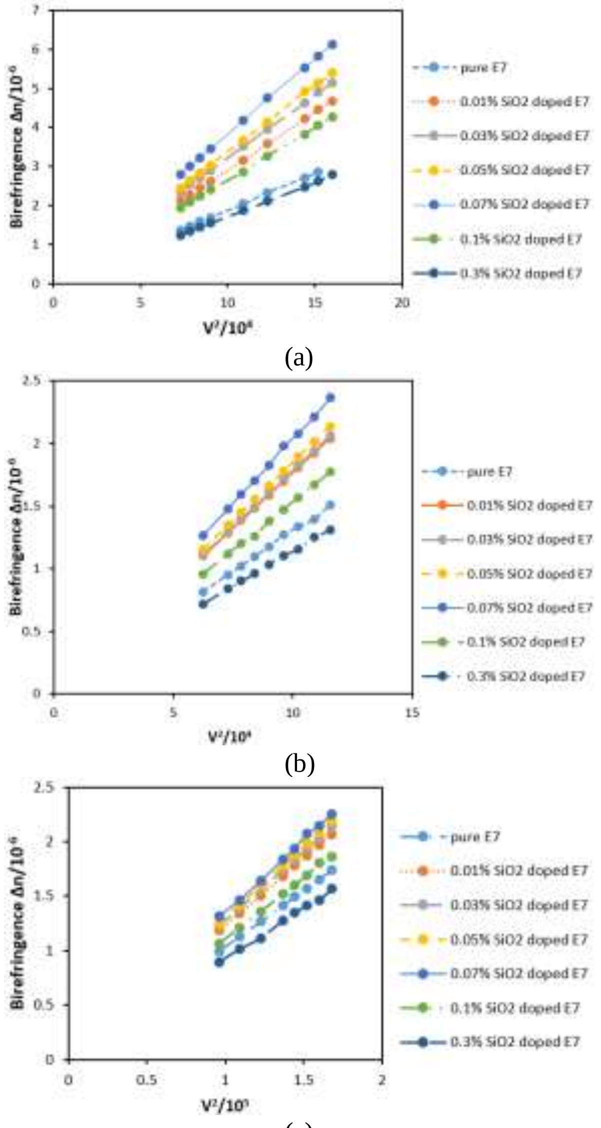
$$\Delta n \propto (T-T^*)^{-\gamma} \tag{6}$$

where T^* is the second order pre-transition temperature, and can be obtained by a linear extrapolation of the reciprocal of Kerr constant (B^{-1}) versus temperature, γ is a numerical factor which equals unity in Maier-Saupe theory [31].

As it is clear from Fig. 3, the inverse of Kerr constant (blue points) varies linearly with temperature, so the temperature dependence of $(T-T^*)^{-1}$ on the Kerr effect in the isotropic phase of samples was in good agreement with Landau- De Gennes theory.

Figure (4) displays plots of the electric-field-induced birefringence of pure and SiO_2 NPs doped LC as a function of square of the applied voltage at temperatures 61^{oc}, 61.7^{oc}, 62.5^{oc}, measured by the experimental setup shown in Fig. (2).

It is clear that the electric field induced birefringence is approximately proportional to the square of the electric field, which means that Kerr effect is applicable in the entire temperature range measured.



(a)

(b)

(c)

Fig. 4. The voltage- birefringence curves for the pure and doped E7 liquid crystal at the Temperatures (a) T= 61˚C (b) T= 61.7˚C, (c) T= 62.5˚C.

In order to demonstrate the importance and novelty of the results obtained from this study, it would be very useful to compare the results of this work with previous researches. Table 1 reports the results of the investigation of changes in the optical and electro-optical properties of liquid crystals doped with different nanoparticles in the last few years, according to the reported findings, the type and concentration of nanoparticles affect the molecular order parameter, birefringence, dielectric anisotropy, response time, and threshold voltage of the host liquid crystal.

Table 1. A comparison between present work, and previous works.

Key observations	**Nanoparticle type+ LC system**
Influence of SiO_2 surroundings on the threshold voltage and memory effect [26]	SiO_2+5CB
NPs increase the dielectric permittivity and the spontaneous polarization [25]	SiO_2+FLC
NPs enhanced intensity of photoluminescence with a small red shift in peak. conductivity, birefringence and UV absorption increased, energy band gap decreased [32]	SiO_2+BBEA
MWCNTs shift T^* of pure LC and enhance birefringence and order parameter [33]	MWCNT+E7
NPs increased the electrical conductivity and molecular ordering and dielectric anisotropy, and lowered relaxation time and threshold voltage [34]	MgO+E7
NDs improve Dielectric anisotropy and molecular ordering, and decrease pretilt angle and rise time and fall time [35]	carboxyl-functionalized nanodiamonds (NDs)+E7
Kerr constant and induced birefringence optimized at low concentration; changes in T^* at different doping concentrations	SiO_2 nanoparticles+E7 Present work

In this experimental work, we have investigated the effect of silica nanoparticles on the pre-transition temperature and the Kerr constant of E7 nematic liquid crystal and obtained the optimum concentration required to increase the Kerr constant in the isotropic phase. The Kerr constant is an important parameter in nonlinear and electro-optical phenomena because a high Kerr constant will lead to high birefringence, fast response, and reduced driving voltage in electro-optical devices, which is important in optoelectronics. [25]-[26] and [32]-[35]. Therefore, the results obtained from this work could have the potential for designing optical and photonic devices.

V. CONCLUSION

In this research, first electro-optical responses of E7 nematic liquid crystal doped with SiO_2 nanoparticles with different concentrations were investigated. As illustrated, adding SiO_2 NPs to E7 up to 0.07%wt. enhances its nonlinear properties, including birefringence and Kerr constant. Increasing doping percentage from 0.07 to 0.1 leads to decrease in the electro optical responses of doped nematic liquid crystal (NLC), therefore at 0.3%wt doping concentration, the electro-optical parameters of doped NLC become fewer than pure NLC.

In the second step, the pre-transitional temperature (T^*) of liquid crystal samples was determined. Finally, the linear relationship between reciprocal of Kerr constant $(B^{-1})$and temperature for pure and doped samples, proved that our experimental measurements are in accordance with landau- De Gennes model.

Our results show that silica nanoparticles in proper concentration, is not only responsible for improving the electro-optical response of NLC but also provide a better understanding to develop the novel materials of improved physical properties for display applications.

The results obtained from this work could have the potential for designing optical and photonic devices.

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