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MgO nanoparticle effect on nonlinear refractive index of nematic liquid crystal doped with Sudan black B dye using of Z-scan method

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MgO nanoparticle effect on nonlinear refractive index of nematic liquid crystal doped with Sudan black B dye using of Z-scan method

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Abstract

The effect of added MgO nanoparticles on nonlinear optical properties of 6CHBT liquid crystal doped with Sudan black B dye were studied by z-scan technique using of cw He-Ne laser at 632.8 nm. The cell used had homogeneous alignment. The MgO nanoparticles were added to 6CHBT liquid crystal doped with 0.3 wt% Sudan black B dye, at three concentrations of 0.1, 0.3 and 0.6 wt%. It was found that the added MgO nanoparticles did not significantly change the nonlinear refractive index of the compound at concentrations of 0.1 and 0.6 wt% while increasing it at 0.3 wt%.

Keywords: Liquid crystals; Nanoparticles; Nonlinear refractive indices

1. Introduction

A large number of photonic applications have been developed based on the nonlinear optical properties of materials. Different kinds of media have been studied and engineered aiming their use in photonics devices. Among the myriad of studied compounds, organic materials particularly liquid crystals are of great importance due to their large optical nonlinearities and fast responses [1-4]. The liquid crystals show a large light-induced nonlinearity. This is due to the large dielectric anisotropy in them, which is related to the collective reorientation of the molecules. In the case of a reorientating optical field, the easy susceptibility and collective response of liquid crystals (LCs) leads to a very strong cubic nonlinearity of the medium the so called optical orientational nonlinearity of nematic. The research on LC nonlinear optical property (NLO) has experienced tremendous development in the past thirty years. Starting from isotropic state study to later nematic phase investigation, accompanied with the discovery of dye enhanced effect, trans-cis isomerization, orientational photorefractive effect, and surface mediated reorientation, stronger and stronger nonlinear response of Nematic liquid crystal (NLC) has been reported. In addition, their optical properties can be easily controlled using a weak electric or magnetic field. The physical properties of crystals such as phase transition temperatures, viscosity, etc. can be easily changed by mixing them together. These specifications make them suitable for various applications such as the production of displays, optical storage devices, optical computers. In this regard, improvement and increment of nonlinear optical properties of NLCs via doping with different materials like dyes, nanoparticles. have attracted much attention in recent years [5, 6, 7, 8, 9]. Although the liquid crystals are inherently highly nonlinear materials, their molecular reorientation response is greatly enhanced by the addition of a small amount of a dichromatic, light-absorbing dye. The enhancement of the liquid crystals nonlinearity by adding dye is the result of the fact that in this case, in addition to the optical torque effect, the director orientation process is performed with the participation of another torque induced by the dye. This dye-induced torque is often much larger than the optical torque. The addition of dye to liquid crystal significantly affects their nonlinear effects, including nonlinear refractive index and nonlinear absorption coefficient, which depends on the concentration of dopants [10].

Magnesium oxide has a regular structure of the same type as NaCl, in which the bonds are strongly ionic. The electrostatic nature of the binding forces and the spherical symmetry of the distribution of charge mean that single ions in the crystalline network are surrounded by as great as possible a number of ions with opposite charge. In this form, MgO is viewed as an inert oxide. The atoms on the surface, edges and corners have lower coordination. However, in the case of nano-MgO, atoms in analogous locations offer a high density of catalytically active sites. This phenomenon means that magnesium oxide in the form of nanoparticles is useful as a heterogeneous catalyst [11].

Apart from its catalytic properties, synthetic magnesium oxide with small particle sizes and large surface areas also demonstrates excellent adsorption properties. The reactivity of MgO is determined not so much by its relatively high surface area, as by the number of defect sites per unit area, which supports the process of adsorption [12, 13, 14]. Magnesium oxide also has high dielectric constant and electrical resistance [15, 16, 17, 18].

To observe the effect of nanoparticles on the nonlinear refractive index of liquid crystal, due to its small and insignificant amounts, we decided to add a very small amount of about 0.3 %wt. of Sudan black B dye to the liquid crystal and then the effect of adding nanoparticles with different concentrations on the nonlinear refractive index of the desired composition was studied. In this experimental work, we investigated the effect of adding magnesium oxide nanoparticles on the nonlinear properties of dye-stained liquid crystals in a homogeneous alignment of its molecules with CW laser. Dyeing the liquid crystal with dye makes it possible to observe nonlinearity in samples with homogeneous alignment with low powers.

2. Z-Scan technique

One of the primary tools used to determine the nonlinear properties of materials is the Z-scan technique that was invented and reported for the first time in 1989 by Sheik-Bahae et al. According to this technique, the changing of the normalized transmittance of a tightly focused Gaussian beam through a finite aperture in the far field as function of the sample position, z, when the sample is displaced along beam propagation (z-direction) [19, 20] (Fig. 1). The change in the normalized transmittance is due to the self-focusing effect in the sample environment.

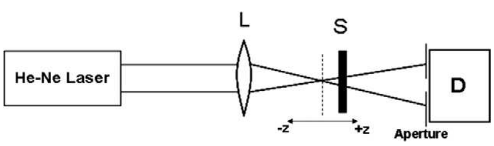

Fig. 1. Schematic diagram of the experimental arrangement for the closed Z-scan set up. D, detector; L, convex lens; S, sample.

A typical graph of the normalized transmittance through a finite aperture (closed aperture) is shown in figure 2. A valley followed by a peak is appeared in foregoing graph when the sample with a positive nonlinear refraction index is moved away from the lens. The difference between the peak and valley of the normalized transmittance is given by following equation

$$\Delta T_{p-v} = 0.406(1-s)^{0.25}|\Delta\varphi_\circ| \qquad |\Delta\varphi_\circ| \le \pi \tag{1}$$

Were $s = 1 - e^{-2\frac{r_a^2}{\omega_a^2}}$, r_a and ω_a are the radius of the aperture and the beam radius in the aperture plane in the linear regime ($\Delta\varphi_\circ = 0$), respectively. The induced on-axis phase shift at the beam waist defined a

$$\Delta\varphi_\circ = \frac{2\pi}{\lambda} I L_{eff} n_2 \quad \& \quad L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \qquad \Rightarrow \quad n_2 = \frac{\lambda}{2\pi}\frac{\Delta\varphi_\circ}{I L_{eff}} \tag{2}$$

Where λ, α, L and I are the laser wavelength, the linear absorption coefficient, the thickness of sample and the on-axis intensity at focus in the sample, respectively. With determining the $|\Delta\varphi_\circ|$ from equation (1), n_2 can be obtained from equation (2).

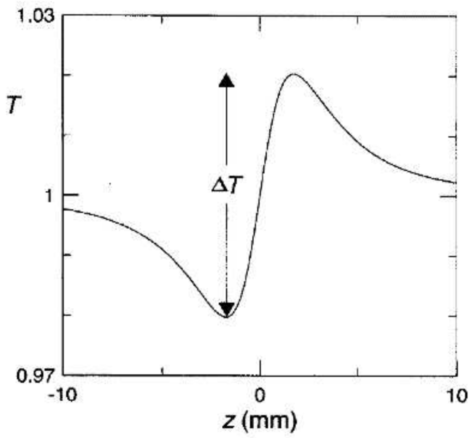

Fig.2 A typical graph of the normalized transmittance through closed aperture.

3. Experimental

The 6CHBT nematic liquid crystalline materials were purchased from the institute of chemistry of the military technical academy, Warsaw, Poland. The clearing points of this material was determined from the DSC curves drawn up by the DSC822e model of the DSC system, the

Swiss Mettler Toledo company (Fig. 3). According to these curves, the clearing temperature during heating and cooling are approximately 43.23 and 42.47˚C respectively. The Sudan black B dye was used as an additive to increase mixture nonlinearity, so that the nonlinear refraction index of the final mixture can be measured. The absorption spectra of Sudan black B dye and The chemical structure of these compounds are shown in Fig. 4.

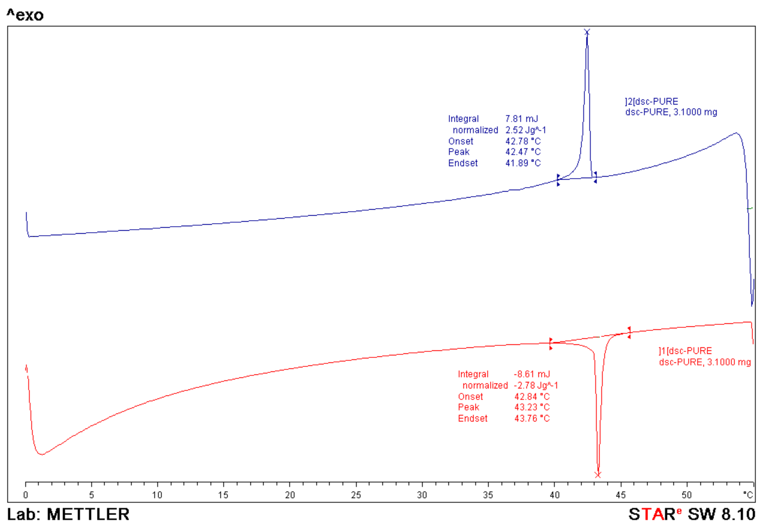

Fig. 3 DSC thermograms of the pure 6CHBT showing nematic to isotropic transitions in the heating and cooling cycles at the scan rate of 1 °C/min measured by METTLER (DSC822).

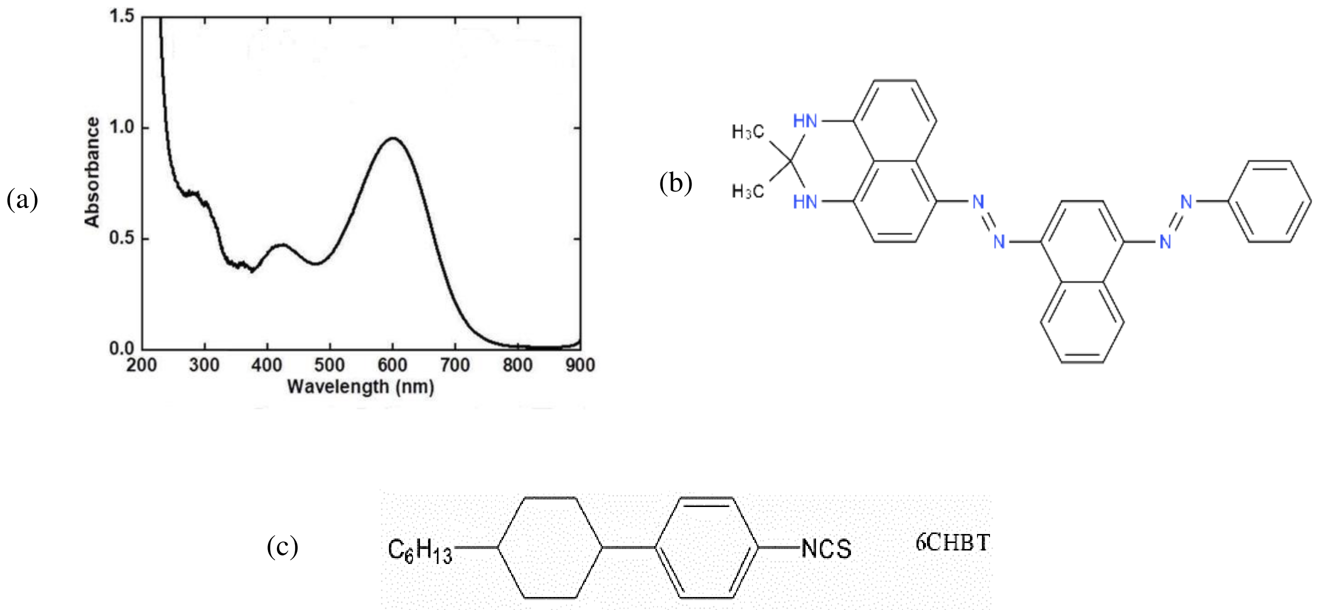

Fig. 4 (a) Absorption spectra of Sudan black B dye (b) Chemical Structure of Sudan black B dye (c) Chemical structure of nematic liquid crystal 6CHBT.

The MgO nanopowders smaller than 50 nm in diameter were supplied from US research nano-materials institute. Transmission electron microscopy (TEM) image and particle size distribution of MgO nanoparticles are shown in Fig. 5 [21].

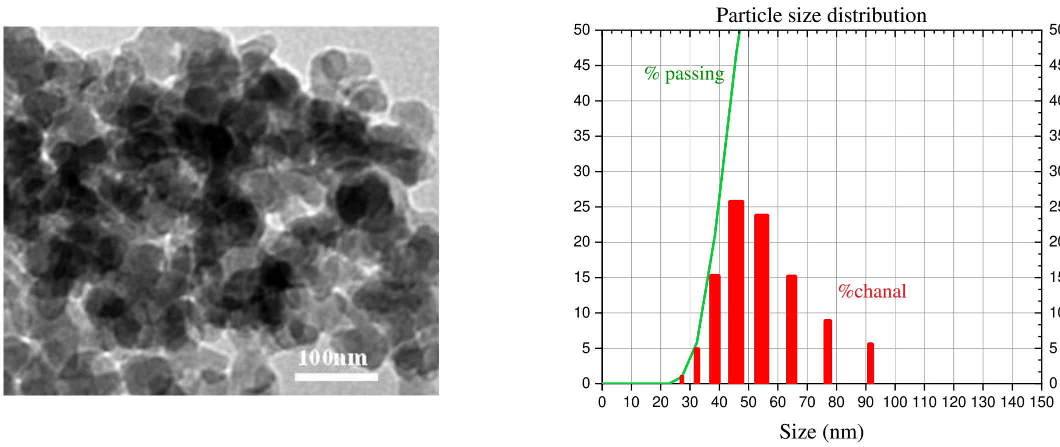

Fig. 5. Transmission electron microscopy (TEM) image and particle size distribution of used MgO nanoparticles (refer to Ref. [21]).

The cells used in the experiments were made from two glass plate. The glass substrates were coated by dipping in PVA solution for homogeneous alignment. The nematic liquid crystal and the SBB (Sudan black B) dye were combined at a concentration of 0.3 wt.%, then The resulting combination was doped with MgO nanoparticles at three different concentrations 0.1, 0.3 and 0.6 wt.%. The obtained mixture is agitated with an ultrasonic stirrer to uniformly disperse the nanoparticles for 45 minute. The empty cells were filled with final mixture by capillary action. A He –Ne laser at λ=632.8 nm with a power of 2.2 mw was used as a light source for recording z-scan data Whose power decreased by 0.5-0.6 mw using a polarizer for the determining of the polarization of incident light on the cell. The focal length of the lens used in the experiment setup was 50 mm. A precision stepper motor drove the sample with 0.5 mm steps along the beam. Aperture diameter was 2mm in closed mode. By reducing the laser beam's intensity through a polaroid pair, the linear absorption coefficient was calculated from the well-known relation $I = I_{\circ} e^{-\alpha L}$. An edge scan method was used to measure the radius of the laser Gaussian beam.

4. Results and discussion

The z-scan data of prepared samples was obtained using the setup above at the room temperature. The curves of normalized transmittance changes versus the sample position (z) was drawn for all samples by Originpro 2018 software. Fig.6 shows these curves:

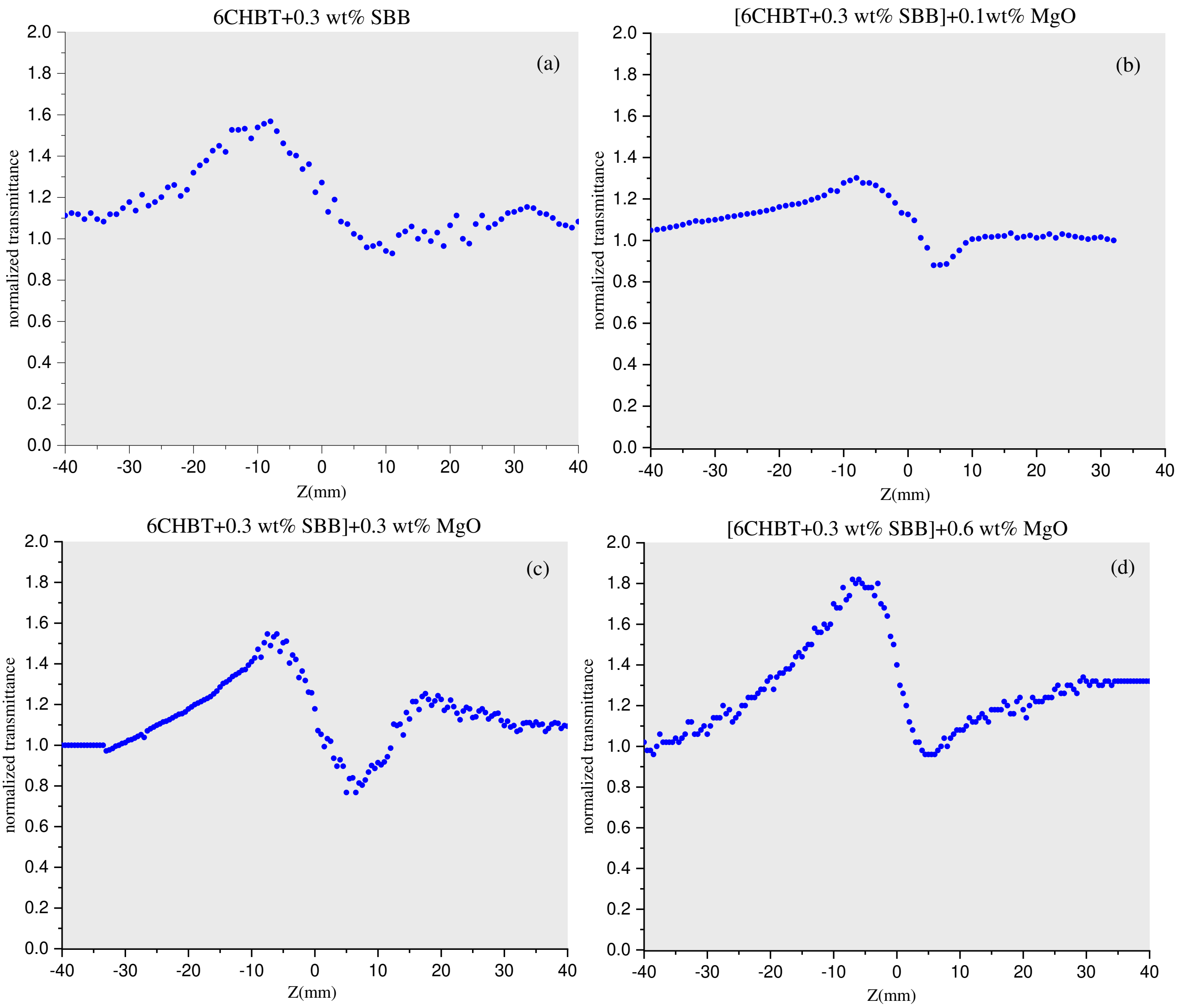

Fig.6 Closed-aperture normalized transmittance curves for different percent composition of MgO by combining [6CHBT +0.3 wt% SBB] a) 0 wt% b) 0.1 wt% c) 0.3 wt% d) 0.6 wt%.

The linear refractive index values of pure liquid crystal 6CHBT for homeotropic and homogenous alignment configuration were obtained by A. Jafari and M. H. Majles Ara, $+10 \times 10^{-5}$ and $-0 \cdot 71 \times 10^{-5} \frac{\mathrm{cm}^2}{\mathrm{w}}$, respectively. Also, the nonlinear refractive index of 6CHBT-liquid crystal composition with high concentrations of Sudan black B dye has been studied [10, 22]. The change in the nonlinear refractive index of the liquid crystal due to the addition of dye to it can be explained by the Janossy effect [23].

The effect of nanoparticles on the nonlinear refractive index of the samples is clearly evident from the shape differences of the above curves. This difference manifests itself in the difference between the peak and valley of the normalized transmittance. The nonlinear refractive index (n_2) can be calculated from the related relationships referred to in Section 2. The nonlinear refractive indices of different percent composition are given in table 1. According to the values in this table, adding nanoparticles to the compound at a concentration of 0.3 wt% significantly increases its refractive index, while at other concentrations this is not the case. This behaviour may be interpreted by dilution theory [24].

Nanoparticles decrease the ordering in the nanocomposite systems by lessening the interaction between the liquid crystal molecules. The strong dipole–dipole interaction between NPs and nematic molecule forces the NPs to align themselves in the direction of nematic director leading to a strong elastic coupling. But a higher concentration, that is, 0.6 wt% of MgO doped in Composition of liquid crystal and dye, shows an abnormal behaviour. As the nanoparticles begin to accumulate, in 0.6 wt% of MgO, the number of single free nanoparticles per unit volume of the liquid crystal decreases. So, the regulatory domains of liquid crystal matrix reduce, as compared 0.3 wt% of MgO, and the liquid crystal molecular order increase.

Table 1 The linear absorption coefficient (α), the difference between the peak and valley of the normalized transmittance (ΔT_{p-v}) and the nonlinear refractive indices of different percent composition

Compositions	α (cm^{-1})	ΔT_{p-v}	$10^5 \times n_2$ (cm^2/w)
[6CHBT + 0.3 wt% SBB]	150	0.60	-30
[6CHBT + 0.3 wt% SBB] + 0.1 wt% MgO	126	0.55	-29
[6CHBT + 0.3 wt% SBB] + 0.3 wt% MgO	105	0.75	-69
[6CHBT + 0.3 wt% SBB] + 0.6 wt% MgO	110	0.85	-35

5. Conclusion

Examining the results shows that added MgO nanoparticles don’t change nonlinear refractive index of combination at 0.1 wt% and at 0.6 concentrations significantly while at 0.3 wt% concentration increase it. The reason for this different behavior and the increase in the nonlinear refractive index of the compound with a concentration of 0.3 wt% can be attributed to the accumulation of nanoparticles at high concentrations. This behaviour may be interpreted by dilution theory. As mentioned in Vafaee's work, MgO nanoparticles accumulate at concentrations higher than 0.5 wt% [25]. The accumulation of nanoparticles within the composition reduces the number of single free nanoparticles and this may reduce their effect on nonlinear properties such as nonlinear refractive index. To add MgO nanoparticles to 6CHBT liquid crystal doped with Sudan black B dye also changed the sign of its nonlinear refractive index.

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Author contribution:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dvoud Pourmostafa, Habib Tajalli, Ali vahedi, Karim Milanchian. The first draft of the manuscript was written by Davoud Pourmostafa and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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