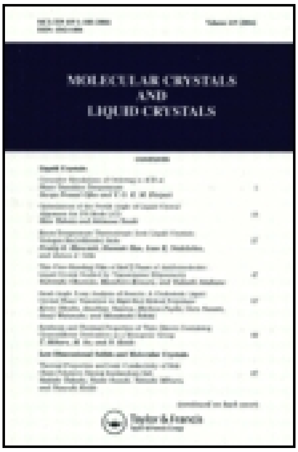

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Recent Studies of Optical Limiting, Image Processing and Near-Infrared Nonlinear Optics with Nematic Liquid Crystals

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ABSTRACT

The mechanisms for recently observed optically induced refractive index changes in nematic liquid crystals, and their use in novel optical limiting and image processing are reviewed, along with an assessment of their potentials for applications. We have also studied the optical nonlinearities of nematic liquid crystals in the near IR communication spectral region [1.55 μm]. Phase modulation of several π's can be generated with mW laser power in micron thick films.

Keywords: Optical limiting, image processing, communication channe wavelength, liquid crystals, near-infrared, refractive index change, lase induced, 1.55 μm.

INTRODUCTION

Nematic liquid crystals (NLCs), with their unique physical and optical characteristics such as the easy susceptibility of the birefringent director axis orientation to externally applied fields, broadband birefringence and transparency, have found widespread use in various optoelectronics information display and processing devices. In the last decade, studies of NLC's optical responses have revealed optical nonlinearities of NLCs that are among the largest of all known materials [2-9]. These nonlinearities have enabled recent demonstration of novel phenomena with low power lasers, including image conversion[10], soliton formation[11], Fourier plane image processing[12], all-optical polarization switching[13], and optical limiting action[14]. In this paper, we provide a critical review of some of these interesting observations, the underlying fundamental mechanisms, new results and their application potentials. We also present results from preliminary studies of NLC's nonlinearities in the near IR communication wavelength channel.

MECHANISMS FOR REFRACTIVE INDEX CHANGE

Upon optical irradiation, several processes can be simultaneously at work to cause director axis reorientation, as schematically depicted in **Fig. 1**. In general, the reorientation angle θ is described by a torque balance equation of the form:

$$\mu \frac{d^2\theta}{dt^2} + \gamma_1 \frac{d\theta}{dt} + M_{el} + M_f = \Gamma_{appl} \tag{1}$$

where μ is the moment of inertia, γ_1 the viscosity coefficient, M_{el} the elastic restoring torque, M_f the shear torque caused by flow, and Γ_{appl} is the torque caused by the applied field.

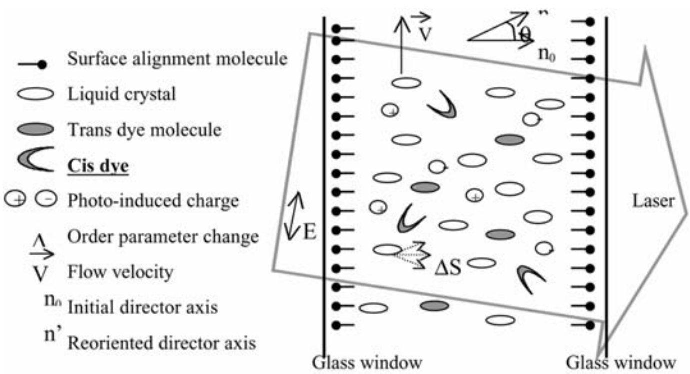


Fig. 1. Schematic depiction of various laser-induced photochemical and photo-physical processes in a nematic liquid crystal film.

In pure non-absorbing nematic liquid crystals, the impinging optical field imparts a torque through the dielectric interaction given by

$$\mathbf{\Gamma}_{opt} = (\Delta\varepsilon/8\pi)\,(\hat{n}.\mathbf{E}^*)\,(\hat{n}\,\mathrm{x}\mathbf{E}) \tag{2}$$

where $\Delta\varepsilon$ is the (optical) dielectric anisotropy. In some anthraquinone or dye-doped NLC, studies[15] have shown that the excited dye molecules could exert an intermolecular torque $\mathbf{\Gamma}_{mole}$ that is proportional to $\mathbf{\Gamma}_{op}$, i.e.,

$$\mathbf{\Gamma}_{mole} = \zeta\,\mathbf{\Gamma}_{op} \tag{3}$$

where the proportionality factor ζ can be as high as over 100. In recent studies of methyl-red doped nematic films [4,5,7], there are evidence that suggest that the intermolecular torque, coupled with adsorption of the excited dyes on the cell walls, could be orders of magnitude larger. This process gives rise to the so-called supra-nonlinearities characterized by refractive index coefficient as large as 10 cm^2/Watt.

Besides these optical and molecular torques, nematic liquid crystals doped with photocharge-producing agents such as Fullerene C60 have also been found to exhibit orientational photorefractivity[3,4]. The incident optical field excites the doped liquid crystals to form charge transfer complexes (CTC). The CTCs subsequently dissociate and create dc space charge fields E_{sc} $_{through}$ ionic diffusion, migration and other electrodynamics processes. These space charge fields exert a torque of the form:

$$\mathbf{\Gamma}_{dc} = (\Delta\varepsilon_{dc}/8\pi)\,(\hat{n}\,.\mathbf{E}_{int}{}^*)\,(\hat{n}\,\mathrm{x}\mathbf{E}_{int}) \qquad (3)$$

where E_{int} is the total internal field consisting of contains the applied dc field E_{dc} and the generated dc space charge field E_{sc}

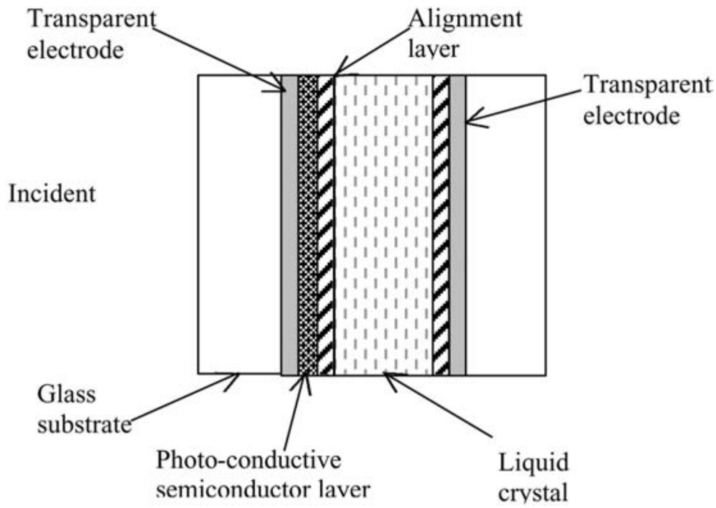
Besides these field induced effects, studies of azo-dye doped NLC have also identified a very effective index changing mechanism, namely, order parameter changes associated with trans-cis isomerization of the excited dye. These mechanisms in heavily doped NLC could yield refractive index coefficient as high as 2 cm^2/W [6].

COMPARISON WITH OPTOELECTRONIC LC DEVICES

In terms of light induced refractive index changing mechanism, it is important to note here that there are existing optoelectronic devices that could yield equally impressive refractive index under low optical One example of such an optoelectronics device is Optically Addressed Liquid Crystal Spatial Light Modulator [OA-LCSLM]. Fig. 2 depicts the typical construction[1]. An aligned nematic film is sandwiched between two transparent electrodes. A photoconducting semiconductor layer on one of the windows serves as a photosensitive [PS] layer. An incident light distribution creates a corresponding conductivity distribution on the PS layer. This in turn gives rise to a voltage drop across the NLC layer, thereby causing a director axis reorientation and refractive index change.

In typical OA-LCSLM's, the sensitivity in terms of index change per unit optical intensity is rather impressive. A phase shift $\Delta\phi$ of π can be induced with an incident optical intensity on the order of 0.5 mW/cm^2

in an OA-LCSLM in which the LC film is on the order of a few microns. The equivalent nonlinear index coefficient n_2 corresponding to this level of sensitivity can be estimated from the relationship $\Delta\phi = n_2 I\, 2\pi d/\lambda$. If $I = 0.5$ mW/cm^2 , $\Delta\phi = \pi$, and λ is 500 nm, we have $n_2 \sim 10$ cm^2/W. This is in the rank of supra-optical nonlinearity, similar to methyl-red dye doped NLC film. Nevertheless OA-LCSLM is rather costly, and functions basically as a 2-dimensional image-processing device. On the other hand, dye-doped NLC films are versatile as they do not need bias field and electrodes, and they are low cost [no need for processing the photo-conducting semiconductor layer]. More importantly, the doped NLC film can respond as a bulk film. They therefore offer an inexpensive alternative for real time processing or nonlinear optical element. In some studies, they have been shown to be desirable high-resolution recording media [9]. In the following section, we review some of the studies undertaken in our laboratory.



OPTICAL LIMITING

Various materials and device operational principles have been investigated for passive optical limiting applications [17]. The mechanisms involved in these devices include self-defocusing, nonlinear absorption, nonlinear scattering, laser-induced plasma formation...etc. In particular, various groups have investigated the use of RSA [Reverse Saturable absorption] and/or two-photon absorbing materials [18-20]. These nonlinear photonic absorption processes are highly dependent on the optical intensity. Since for a given energy the laser intensity decreases with increasing laser pulse length, nonlinear absorption processes become rather inefficient for limiting action against long-pulse lasers.

We have previously demonstrated that dye-doped NLC films, in conjunction with polarizers, could be configured to provide a large dynamic range optical limiter against long-pulse or cw laser [14]. Fig. 3 shows the device structure. A planar twisted nematic film is oriented between two crossed polarizers so that the polarization vector of the incident [low power] optical field will follow the director axis orientation adiabatically from the incident plane to the output plane, i.e., a low power input beam will be maximally transmitted. On the other hand, as the power of the incident laser is increased, the optical field induces the director axis to rotate away from the optical electric field, thereby diminishing the output through the crossed-polarized analyser at the output end.

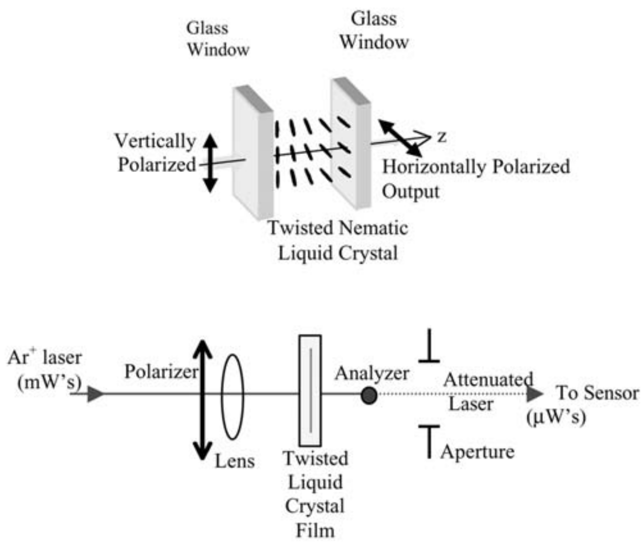


Fig. 3. (Upper) Schematic depiction of a planar twisted nematic film. Methyl-red doped 5CB. Dopant concentration is 0.5 % Film thickness is 25 μm.(lower) Experimental set up for demonstrating optical limiting action of the film.Focused laser spot size on NLC film is100 μm.

Fig. 4 shows a series of recently obtained photographs of the transmitted output beam as the films is moved through different region of the focused laser beam, starting at a distance away from the focus to the focal plane, i.e. increasing laser intensity. Clearly, the transmitted laser beam power is severely 'limited' as the input optical intensity is increased. We noticed that at the onset of the limiting action, self-lensing of the Gaussian input beam beam and the increased divergence also contribute significantly to the optical limiting action. By placing the film at or near the focal plane, and measuring the transmitted laser power as a function of the input power, we obtain a typical limiting curve, c.f. Fig. 5. The oscillatory behavior in the output is attributed to the self-phase modulation induced ring formation in the output beam intensity distribution, c.f. Fig. 4.

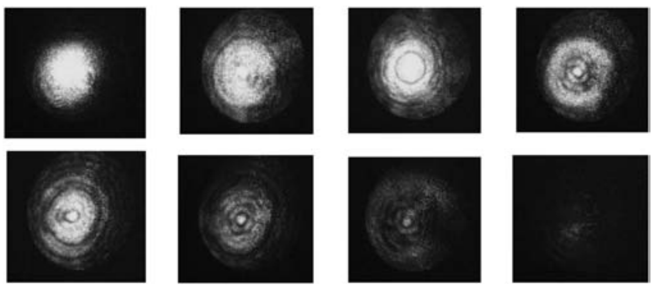


Fig. 4 Top left to lower right – observed variation of the output laser beam pattern and power showing power limiting effect.

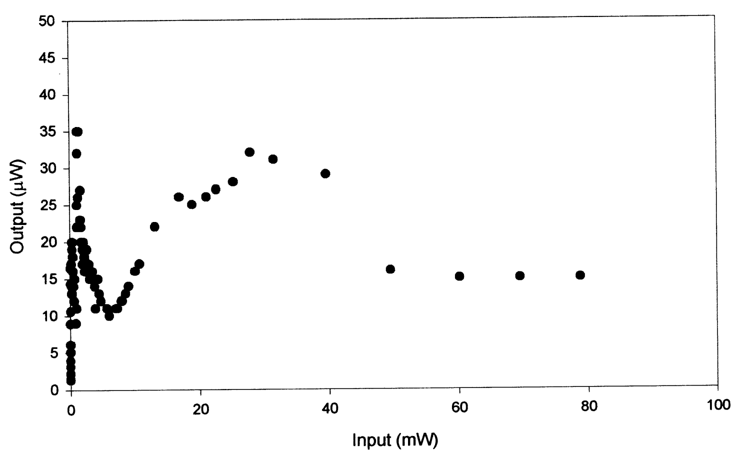
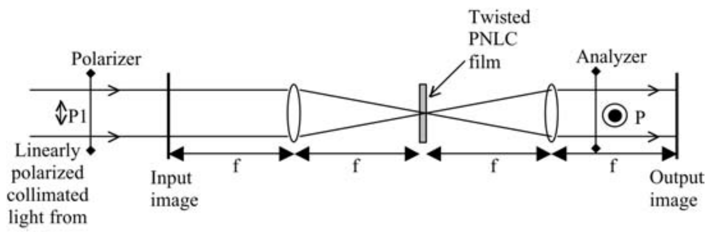


Fig.5. Plot of output versus input power for the NLC limiter.

Because of the finite absorption of the dye-doped cell, the cell is heated towards the isotropic transition point T_c [T_c is 35° C for 5CB and 62° C for E7]. When the sample turns isotropic [at an input power of about 40 mW], the exit laser's polarization is orthogonal to the analyzer, and the transmission of the limiting device is decided by the extinction coefficient of the polarizer/analyser combination. With good quality polarizers, the extinction coefficient, and thus the dynamic range of the limiting 'device' can be $>10^4$.

IMAGE EDGE ENHANCEMENT

Using the nonlinear 'limited' transmission properties of the twisted cell, we have recently demonstrated an all-optical image edge enhancement technique. In analogy to other Fourier Transform techniques[1-3], the methyl-red doped nematic film is set at the focal plane of a 4-f optical system, c.f. Fig. 6. We utilize the fact that, in



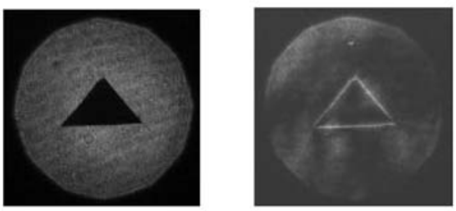


Fig. 6. (Upper) Schematic of experimental set up for image edge enahncement demonstration. (lower left) input triangle object (lower right) output image with edge enhancement.

general, the intensities of lower-order spatial-frequency components at the Fourier plane of an input image are higher than the intensities of higher-order components. The low power higher-order components that carry information about the edges of the image experience a high transmission through the NLC film. On the other hand, the higher intensities of the lower-order components will have lower transmission due to the optical limiting effect discussed in the preceding section. As a result, the ‘device’ consisting of the set of polarizer, twisted PNLC film, and analyzer selectively attenuates the low-order components. The output image therefore exhibits an edge-enhancement effect, as illustrated in the photo-insert in Fig 6. Using the same dye-doped film, we have also demonstrated image addition and subtraction capability [12].

OPTICAL NONLINEARITY AT 1.55 μM

As remarked earlier, the birefringence of NLC spans a very broad spectrum, from near UV to far IR. As a result, their nonlinearities in this spectral regime are expected to be as large as in the visible regime. We have recently conducted some measurements of the refractive index changing mechanisms of NLC with a 1.55-μm laser using a simple self-phase modulation technique. Fig. 7 illustrates the experimental set up used. The nonlinear phase shift induced by a 7-mW 1.55.micron laser is read by a visible He-Ne probe laser.

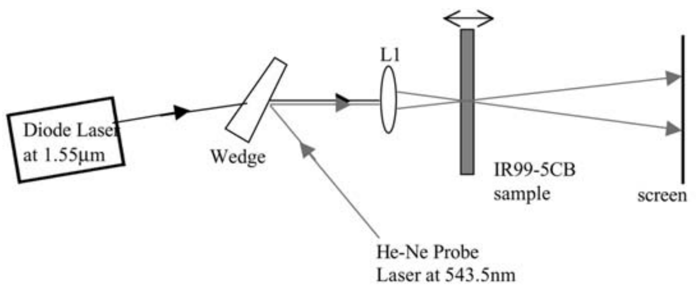


Fig. 7. Experimental Set-up for studying phase modulation effect induced by a near-infrared [1.55-μm] laser.

Fig. 8. He-Ne probe beam profile (a) when 1.55 μm pump beam is off (b) pump beam on. A118 dye-doped 5CB film.

The 1.55 μm pump beam is focused to a spot diameter of about 150 μm on the liquid crystal cell. Figure 8a shows the He-Ne beam profile when the infrared beam is off. When the infrared beam is turned on, the He-Ne beam profile exhibits a typical ring pattern with increased divergence, c.f. Fig. 8.

Table 1 lists the various samples we have studied and some measured results. All the samples are planar aligned. The infrared absorbing dye-doped samples exhibit typical thermal indexing effect, whereas the pure 5Cb sample, with very small absorption at 1.55 mm, exhibits mostly orientational effects. Samples made with ITO coated glass windows all exhibit laser heating effect, regardless of the liquid crystal

Table 1.

Sample	**Thickness [μm]**	**Dye concentration**	**Liquid crystal**	**Absorption coefficient at 1.55 μm [cm^{-1}]**	**Number of SPM rings observed**
1	25	18% azobenzene (ALC)	E7	9.5	4
2a**	20	*20% IR99 dye*	5CB	4	11
2b**	20	*pure*	5CB	4	11
3	50	0.5% A118 dye	5CB	14.3	6
4	50	0.5% A156 dye	5CB	4.7	6
5	60	0.4% Epolite 125 dye	5CB	11	7
6	200	no dye (pure)	5CB	1	3

**** Sample made with ITO coated windows**.

used, i.e., independent of the LC's absorption coefficient. Therefore, the thermal index effect is attributed to the laser heating of the ITO coating. In both thermal and orientational responses, the phase modulation effects are manifested in the form of ring formation and increased divergence at the far-field observation plane. The main difference is in the response times. Usually, thermal effect is characterized by a time constant on the order of a few milliseconds for the 20-60 μm thick sample, whereas the orientational response time for the 200-μm thick sample is on the order of a few seconds. Table 1 provides the details of all the samples we used and their absorption coefficients at 1.55 μm.

The magnitude of the refractive index coefficient n_2 can be simply estimated from such ring structure according to the equation:

$$\phi=2\pi/\lambda *\Delta n *L$$

where L is the thickness of the film and the phase change ϕ can be estimated as ϕ = N (the number or fringes) * π. Consider the sample made of 5CB doped with 0.4% [by weight] of Epolite 125 dye. We observed 7 rings in a 60-μm thick cell. This gives $\Delta n \sim 0.032$. Since the intensity used is about $30 W/cm^2$, this gives an index coefficient $n_2 = 1.04 \times 10^{-3}\ cm^2/W$. For the pure sample, the orientational index coefficient is found to be on the order of $10^{-4}\ cm^2/W$, which is close to the value at the visible region.

CONCLUSION

In conclusion, dye-doped nematic films possess very broadband nonlinearities. Their nonlinear index changing coefficients are now reaching the level competitive to existing optoelectronic devices. These dye-doped films can be employed for optical limitng, image processing and other nonlinear optical applications in the visible as well as near IR regime. Practical low cost versatile optical elements and devices are anticipated.

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