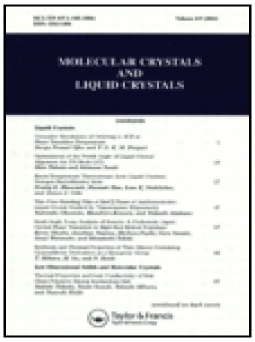

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Wavelength Independent "Babinet Compensator Optical Limiter" (BCOL)

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We present a new, wavelength-independent optical limiter based on the Babinet compensator principle. The initial polarization change of an incident optical wave passing through a nematic liquid crystal placed between two parallel polarizers is compensated with a second identical sample, with its director vector perpendicular to that of the first cell. If there is some small absorption in just one of the cells, there is a thermally induced index change that produces an irradiance-dependent retardance. The resulting polarization change causes a decrease in the transmittance by more than one order of magnitude as the input energy is increased. Experiments were performed using a frequency-doubled 7 ns pulsed Nd-YAG laser, at a 10 Hz repetition rate as a pump, and a cw He-Ne as a probe to monitor the pump laser generated limiting effect.

Keywords: Optical limiters; Liquid crystals; Polarization changes

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INTRODUCTION

The variety of available laser wavelengths and of frequency-agile lasers means that optical limiters must operate over very broad wavelength bands.[1] Nonlinear optical limiting processes such as nonlinear scattering [2,3], multi-photon absorption [4,6], and reverse saturable absorption [7,8], have been studied in different materials including particle suspensions, organics, inorganics, organometallics, and liquid crystals.[6,8-13] Recently, optical induced birefringence in bacteriorhodopsin has been studied for optical limiting.[14] However, with the exception of nonlinear scattering, all of these processes in these materials are wavelength dependent, at best operating over tens of nanometers.

Here we propose a new wavelength-independent optical limiter based on a nonlinear Babinet compensator placed between parallel polarizers.[15] Using nematic liquid crystals as a nonlinear medium in a Babinet compensator, we have studied the transmission change vs. the input fluence of a polarized light. The change in transmittance due to the beam polarization change is the result of an thermally induced change in the birefringence within the sample by the input laser pulse.

It is well known that the Babinet compensator consists of two wedge-shaped prisms made from the same birefringent material but with perpendicular optics axes.[15]. A linearly polarized beam passing through these wedges, with polarization vector at a finite angle to the optical axes, will experience a retardance after the first wedge because the refraction index parallel to the optical axis ($n_{//}$) is different to the perpendicular one ($n_{\perp}$). If the optical path through the first and second wedges is identical, the retardance, $\Delta\phi$, defined as the phase shift between perpendicular polarizations, becomes equal to zero for any wavelength [15]. If the refractive indices are changed in only one of the wedge, the wave experiences a net retardance, as the phase shift compensation is no longer exact. When the net retardance becomes equal to π, the output polarization is linear but rotated through 90^{O}[15]. As the compensator is placed between parallel polarizers, the transmittance of the system will be very low at this point. Hence, the device can be used as an optical limiter. As nematic liquid crystals combine high birefringence with a strong dependence of refractive index on temperature, they are ideal materials for such a device.

Liquid crystals are materials that possess interesting optical and physical properties [16]. The optical properties of nematic liquid crystals (NLC) can be modified in different manners: applying magnetic, electric, and optical fields, changing the boundary conditions, or changing the pressure and/or temperature [12]. Optically induced perturbations to the optical properties can occur via reorientational or thermal effects that may change the birefringence of the material

The total phase shift of an optical wave passing through a birefringent material which is subject to thermal perturbations, can be described as:

$$\Delta\Phi = \Delta\Phi_0 + \Delta\Phi_T , \tag{1}$$

where $\Delta\Phi_0$ and $\Delta\Phi_T$ are the initial and the thermally retardances respectively, equal to;

$$\Delta\Phi_0 = \frac{2\cdot\pi}{\lambda}\cdot(n_{//} - n_{\perp})\cdot l$$

$$\Delta\Phi_T = \frac{2\cdot\pi}{\lambda}\cdot(\frac{dn_{//}}{dT} - \frac{dn_{\perp}}{dT})\cdot\Delta T\cdot l \tag{2}$$

Where, λ is the wavelength, l is the cell thickness, $n_{//}$ and $n_{\perp}$ are the extraordinary and ordinary refraction index of the material, and $\frac{dn_{//}}{dT}$

and $\frac{dn_\perp}{dT}$ are the thermal gradients of it. ΔT is the temperature change that depends on the absorption coefficient, pump beam shape and temporal width, radiation energy, spot size, cell thickness and material constants [17,18]. In nematic liquid crystals there are few terms responsible of the $\frac{dn_i}{dT}$ which are directly proportional to $\frac{d\varepsilon_i}{dT}$.[19]

$$\frac{d\varepsilon_{//}}{dT} = (C_1 - \frac{2}{3}\cdot C_2 \cdot S)\cdot\frac{d\rho}{dT} + \frac{2}{3}\cdot C_2 \cdot \rho \cdot \frac{dS}{dT}$$

$$\frac{d\varepsilon_{\perp}}{dT} = (C_1 - \frac{1}{3}\cdot C_2 \cdot S)\cdot\frac{d\rho}{dT} + \frac{1}{3}\cdot C_2 \cdot \rho \cdot \frac{dS}{dT} \qquad (3)$$

Here $\frac{d\rho}{dT}$ is the density thermal gradient, $\frac{dS}{dT}$ is the order parameter thermal gradient, S is the order parameter, ρ is the material density and C_i are constants that are proportional to the molecular polarizabilities and the second order tensor elements [19]. Equation (3) shows the density and order parameter dependence with the temperature as responsible of the induced refraction indexes changes [19]. The contribution of the order parameter gradient is much more bigger than the density gradient contribution. Elsewhere, the temporal response of the density change is faster ($t_R \leq 10^{-9}$ s) than the order one ($t_R \geq 10^{-6}$ s) [12].

EXPERIMENTAL SETUP

The experimental set-up is shown in figure 1. We used a Q-switched linearly polarized, frequency-doubled (λ = 532 nm) 7 ns (full width at half-maximum) Nd-YAG laser, working at 10 Hz repetition rate as the pump. An attenuated, 10 mW cw He-Ne (632.8 nm) laser with linear polarization parallel to the pump, and propagating colinear with the pump was used to monitor the thermal Nd-YAG induced changes. The pump and probe beams were focused by the same lens to spot sizes of 6 μm and 7 μm, respectively. Due to chromatic aberration in the lens, the distance between foci was 1.14 mm, but the experiment was arranged so that the probe beam was completely within the 532 nm pump beam inside the nonlinear part of the sample. Although this means that the nonlinear sample was not exactly at the pump focus, the pump energy was sufficiently high that this was not a problem. A convergent lens (L3) after the second polarizer was used to collect all the light into a photo-diode.

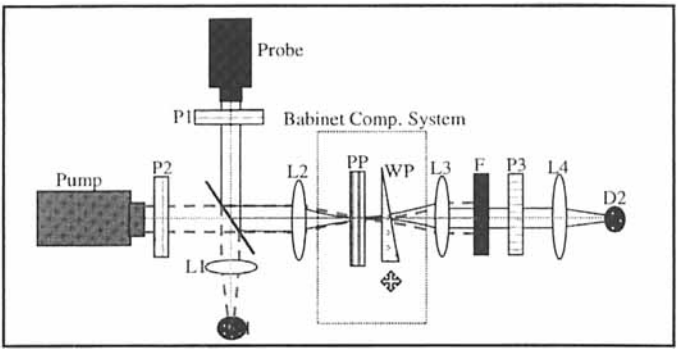

FIGURE 1. Experimental setup.

Experiments were performed with nematic liquid crystals (NLC) at room temperature. We prepared a parallel plate (PP) sample with a LC mixture of E201 + 1% C15 doped with iodine (I_2) at saturation concentration (NLC-I_2), and a wedge of nematic liquid crystal (WP) with the same liquid crystal mixture but without I_2. The purpose of the I_2 is to provide linear absorption to initiate the thermal effect. We used 110 ± 2.5 μm spacers for the parallel plate cell. The wedge thickness was 90 ± 2.5 μm and 120 ± 2.5 μm at each side, making an angle of 0.859^{O}. The sample was placed between two polarizers ((P1//P2)⊥P3), perpendicular for the single sample experiment (NLC-I_2), and parallel for the Babinet compensator experiment using both cells (NLC-I_2 + LCW).

Both experiments were performed at the probe beam focus. During the measurements the NLC's director axes was 45^{O} respect to the incident beam polarization vector. For the two samples experiment we put both of them with optics axes perpendicular one to each other. Then, moving just the wedge (WP) we found the maximum compensation position.

RESULTS AND DISCUSSION

(i) Results using a single I_2 doped NLC cell.

For the first set of experiments, the wedged compensation cell was removed, leaving the I_2-NLC as the only birefringent element. Using only the 7 ns second harmonic of the Nd-YAG laser and observing its transmission as a function of incident pulse energy, we did not see any large change in transmittance. Therefore, we performed the pump-probe experiment using the same sample (NLC-I_2). Figure 2 shows the light normalized transmittance (output transmittance/input transmittance) of the probe as function of the pump fluence. It is clear that as the pump fluence is increased the probe transmittance decreases.

In order to confirm the thermal origin of the polarization change we measured the response and decay time using a Si detector and oscilloscope. We find a 1/e rise time of 25 ± 2.5 ms and a decay time 355 ± 25 μs. According to Khoo,[12] this is consistent with polarization changes due to thermally induced changes in the order parameter of the NLC. We also observed a change of the signal sign at very early times 350 μs after the pump pulse) for high energy. This situation corresponds to a higher temperature change, which induce a total phase shift greater than $2\pi - \Delta\Phi_0$. In this case, more light can pass through the second polarizer for early times.

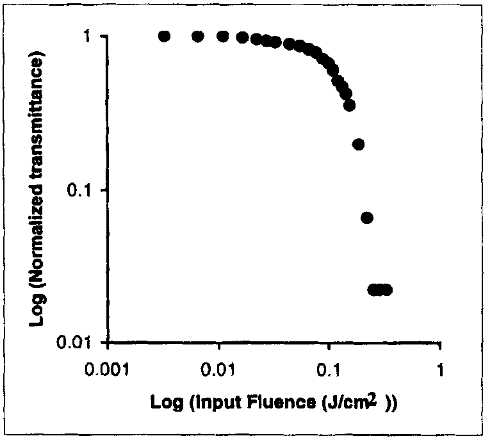

FIGURE 2. Normalized probe beam transmittance as a function of the incident pump fluence (J/cm^2), for a single I_2 doped nematic liquid crystal at the saturation concentration.

For later times the signal becomes zero and then negative. This means that the temperature is decreasing due to thermal diffusion making the phase shift smaller. This behavior corroborates the thermal origin of the perturbation. It is possible that, at these high intensities, there is also a small contribution of reorientational effects but they seem to be negligible.

(ii) Results using I_2 doped NLC and undoped wedged NLC cell.

It is known that NLC samples work under this experimental configuration as a wave plate. This feature makes this kind of optical device to be strongly wavelength dependent. To avoid the dependence on input wavelength we introduced a second NLC sample between the two polarizers under the Babinet compensator configuration (figure 1) [15]. To verify the initial phase shift compensation we measured the ratio of transmittance with and without second polarizer for NLC-I_2

and for NLC-I_2 + LCW. For the NLC-I_2 the transmission ratio was 53.13 % while for the NLC-I_2 + LCW was 87.50 %.

In Fig. 3 we show the normalized transmittance of the probe through the nematic liquid crystals (NLC-I_2 + LCW) as a function of the pump fluence. One can see the probe-beam transmission decreases in more than one order of magnitude when the pump fluence is increased.

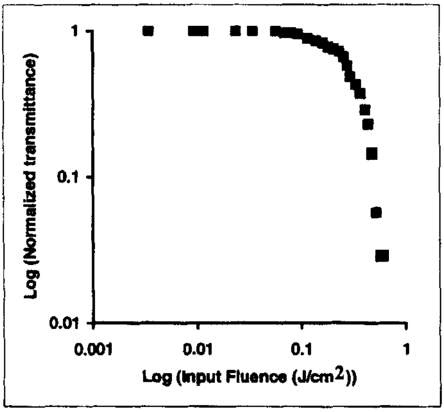

FIGURE 3. Normalized probe beam transmittance as a function of the incident pump fluence (J/cm^2), for an I_2 doped nematic liquid crystal at the saturation concentration under the Babinet compensator principle, using a wedge as second cell

Comparing Figs. 2 and 3, we can see a difference between the point where they reach the minimum transmittance. For the Babinet compensator system the minimum is reached at higher fluence. When we use only the NLC-I_2, the beam polarization is changing from approximately circular polarization (T = 53.13 %) to linear polarization, which is perpendicular to the second polarizer axis. In the other case using the compensator, the polarization is changing from sharp elliptic polarization (T % = 87.50) with major axis near parallel to the second polarizer axis, to a linear polarization perpendicular to the second polarizer axis. Thus, in the second case system must induce a larger change in retardance.

This means that the system requires more energy to reach the same final state of polarization. The sign of Δn is not important, as the polarization change may be in any direction (right or left) and the second polarizer will block the light passing through the sample since the experiment starts from a condition of maximum transmittance. Even although the total phase shift depends weakly on the wavelength (Eq.2), the initial phase shift and the overall behavior of this new optical limiter is wavelength independent. In this specific work the linear transmittance for both experiments was 11 %. The damage threshold was over 0.6 J/cm^2. To improve the response time, linear transmittance, the optical limiting threshold and the material damage threshold, one may change the dye concentration, the cell thickness and/or the liquid crystal. To get the best initial phase shift compensation we must prepare two samples with identical thickness. For a practical device, it would be desirable to have 100% compensation for any λ and at any place over the cells.

CONCLUSIONS

This new principle for optical limiting opens new possibilities for the design if useful optical limiting devices. Here the thermal effect modifies the order parameter. A goal is to find liquid crystals with stronger and faster nonlinearities (e.g. thermal density change) that can change refractive index within the nematic configuration

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