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L. Petti; P. Mormile; P. Musto; G. Ragosta; P. Villano; F. Simoni

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3D mapping of the output laser beam from a PDLC sample

L. PETTI, P. MORMILE*
Istituto di Cibernetica del CNR, via Toiano 6, I-80072 Arco Felice, Italy

P. MUSTO, G. RAGOSTA, P. VILLANO
Institute of Research and Technology of Plastic Materials-CNR, via Toiano 6, I-80072 Arco Felice, Italy

and F. SIMONI
Dipartimento di Scienze dei Materiali e Istituto Nazionale per la Fisica della Materia, Università di Ancona, via Brecce Bianche, I-60131 Ancona, Italy

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Self-transparency due to thermal non-linearities is presented as a basic switching effect in a thick polymer dispersed liquid crystal sample. For the first time a detailed 3D mapping of the output laser beam as a function of the *x-y* coordinates is presented: changes of the transmitted beam profile are recorded vs. both incident power and time. It is discussed how light intensity and temperature can be used as control parameters for the non-linear part of the refractive index. The experimental results confirm the existence of a threshold value of the incident light intensity at which the device switches from the scattering state to the transmissive state.

1. Introduction

Polymer dispersed liquid crystal (PDLC) composites have been the subject of extensive research in recent years due to their peculiar optical properties which can find applications in many types of optical device [1–4]. PDLCs are formed by phase separation of the LC component from a homogeneous solution in a prepolymer or polymer [5]. The liquid crystal forms droplets whose size, shape and distribution depend on the preparative technique used.

These materials produce strong light scattering, so that the samples appear opaque, but by applying an external voltage it is possible to reorient the liquid crystal molecules to obtain optical switching to a high transmission state. This effect has been explained as being due to a matching of the ordinary refractive indices of the droplets with that of the polymeric matrix [6]. A similar phenomenon can be observed by heating the sample to a temperature above the phase transition to the isotropic state, it being well known that a nematic liquid crystal at its transition temperature changes from the nematic state to the isotropic state. As a consequence, the ordinary refractive index n_0 of the nematic state increases to a value very close to the refractive index of the polymeric matrix. The matching of the two refractive indices yields an increase of transmittivity. This last phenomenon has been the basis for the first observation of the non-linear optical behaviour of a PDLC sample obtained by light-induced thermal effects [7, 8]. The observed non-linear quenching of light scattering is what we call *self-transparency*.

In the present work we studied a PDLC system, 0.68 mm thick, obtained by a PIPS method based on a photochemically initiated polymerization process. The LC component is commercially available under the trade name E7, while the polymer matrix is an unsaturated polyester resin. A molecular, morphological and thermo-optical characterization of this system has been presented in previous publications [9, 10], where we provided evidence of a self-transparency effect in a PDLC at a low incident intensity when the temperature rose above a threshold value of 58°C. Under this condition, we have demonstrated a transmission switching from a very low level (scattering state) to a high level (transmission state).

In this paper we report a detailed investigation of the self-transparency effect through a thick PDLC sample, studying the switching behaviour for increasing intensity at a fixed sample temperature and for increasing temperature at a fixed impinging light intensity. Our data confirm the observations previously made on dye-doped samples [7, 8] claiming that the thermal non-linearities

*Author for correspondence; e-mail: mormile@inter.cib.na.cnr.it

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are responsible for the effect and represent the first three-dimensional mapping of the transmitted beam. This analysis clearly shows the effect of 'beam shaping' occurring during the self-transparency phenomenon.

2. Experimental

The unsaturated polyester prepolymer was obtained by a condensation reaction between propylene glycol, maleic anhydride and isophthalic anhydride in the molar ratio 0.50/0.45/0.05. The polyester prepolymer had a number average molecular weight, $\bar{M}_n$, of 2.4×10^3, a weight average molecular weight, $\bar{M}_w$, of 8.0×10^3 and an average number of double bonds per chain of 9.5. The formulation used in the present contribution contained 35 wt % of styrene as coreactive monomer; therefore the initial molar ratio between styrene and polyester unsaturation was 1.1. The LC component was a eutectic mixture of four liquid crystals, commercially available as E7 (Merck). The PDLC samples were prepared by mixing the appropriate amounts of E7 with the uncured resin at 70°C, obtaining a visually transparent, homogeneous solution. 1.0 wt % of the UV curing agent 1,2 diphenyl-2,2-dimethoxyethan-1-one, (IRGACURE 651 from Ciba-Geigy) was added at room temperature and the formulation was poured between two glass plates separated by a 0.68 mm teflon spacer. The assembly was placed under a UV lamp and irradiated for 5 min. In order to analyse the light propagation through this material, and study the beam profile changes induced by thermal non-linearities, we used the experimental set-up shown in figure 1.

The sample with a thickness of 0.68 mm is placed in a programmable thermostatic cell which allows temperature control to ± 0.1°C and heating rates as low as 0.1°C min^{-1}.

The light beam from an Argon ion laser (λ = 514 nm) is normally incident on the sample; the transmitted optical power P_t is focused on a screen where the projected

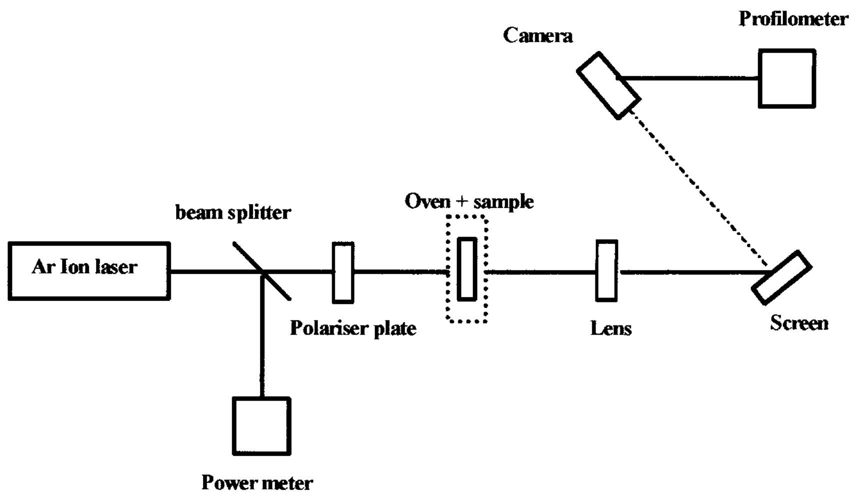

Figure 1. Experimental set-up for the analysis of the beam profile propagating in a PDLC.

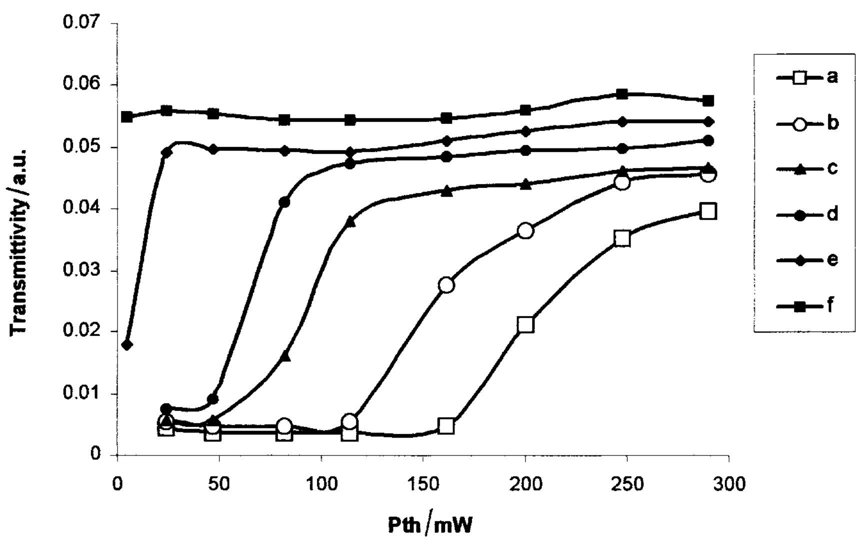

Figure 2. Experimental results on the light transmittivity as a function of the incident light intensity for different temperatures: (*a*) T = 25°C, (*b*) T = 35°C, (*c*) T = 45°C, (*d*) T = 50°C, (*e*) T = 55°C and (*f*) T = 60°C.

image of the sample is collected by a profilometer to give a complete 3D map of the output beam as a function of the *x-y* coordinates. A beam splitter just before the sample allows monitoring of the incident power P_i. The self-transparency effect has been studied in various situations: (a) for increasing values of the incident power with constant temperature of the sample; (b) at different temperatures in the oven with fixed light power that corresponds to a threshold value (P_{th}) at which the transmittivity passes from the OFF to the ON state, considering also the temporal evolution of the phenomenon being analysed.

In figure 2 we report the transmittivity as a function of the incident power of light at $T = 25°C$ (*a*), $T = 35°C$ (*b*), $T = 45°C$ (*c*), $T = 50°C$ (*d*), $T = 55°C$ (*e*) and $T = 60°C$ (*f*). A clear switching effect is observed with different threshold values of the incident power P_{th} on increasing the temperature from (*a*) to (*e*). For the highest temperature considered there is no threshold, as expected: we are above the transition temperature ($T = 58°C$) of the nematic liquid crystal to the isotropic state, and transmission is always ON whatever the incident power.

In figure 3, two-dimensional profiles of the output laser beam at an incident power $P_i = 100$ mW are presented for $T < 35°C$, (*a*) and (*b*), when a weak scattering of light is observed, and for $T > 35°C$, (*c–f*), when the laser beam is transmitted. A similar phenomenon is observed on analysing the time evolution of the beam profile at $T = 25°C$ and $P_i = P_{th}$ (see figure 4). The response time of the optical switching is 12 s; this is the time necessary for the light to pass from the scattering state to the transmissive state, at constant T and P.

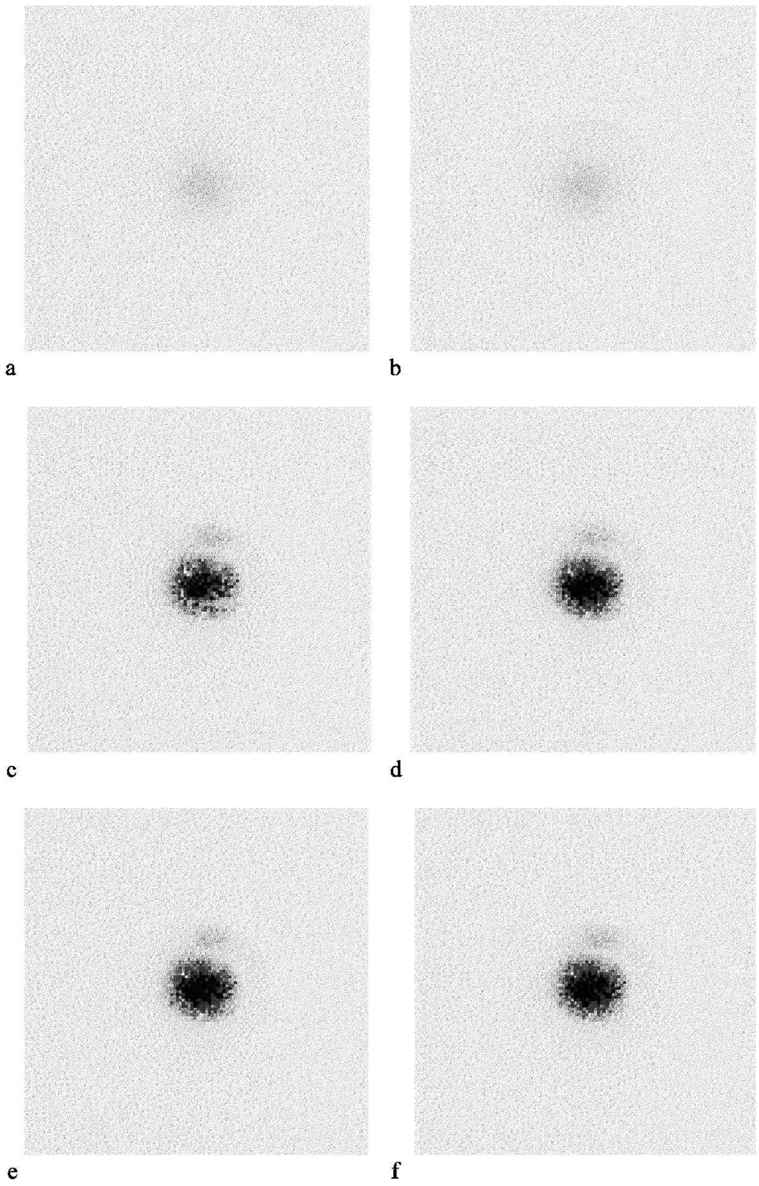

Figure 3. Two-dimensional profile of the transmitted light intensity as a function of temperature at $P_{in} = 100$ mW: (*a*) $T = 25°C$, (*b*) $T = 35°C$, (*c*) $T = 45°C$, (*d*) $T = 50°C$, (*e*) $T = 55°C$, (*f*) $T = 60°C$.

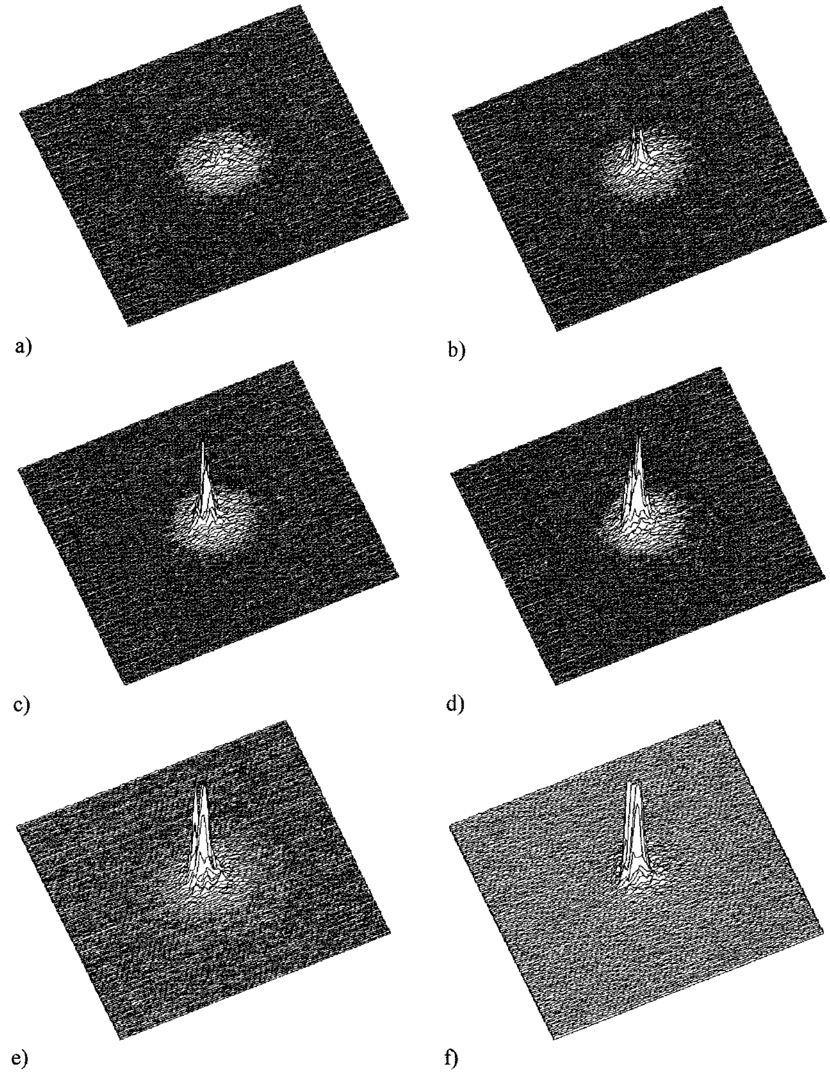

Figure 4. Pictures showing the beam self-transparency effect after travelling through the PDLC sample vs. time at input power of 188 mW at 25°C: (*a*) $t = 0$ s, (*b*) $t = 12$ s, (*c*) $t = 13$ s, (*d*) $t = 14$ s, (*e*) $t = 15$ s, (*f*) $t = 18$ s.

In figure 5, three-dimensional profiles of the laser beam travelling through the PDLC at $T = 45$°C for different values of the incident power P_i are presented. At this temperature the threshold value of the incident power P_{th} is about 60 mW. Again a clear switching effect is shown: below P_{th}, (*a*), we have an OFF state with no transmission, while above P_{th}, (*b–d*), the ON state is reached.

3. Discussion

A three-dimensional map of the beam profile coming out from a thick PDLC sample, at increasing values of the incident intensity, allows us to study the self-transparency effect in a PDLC. Let us consider the refractive index of the LC droplets written in the following form:

$$n_D = n_D^O + \delta n_D(I) + \delta n_D(T)$$

where n_D^O is the refractive index at room temperature and without any applied field; $\delta n_D(I)$ is its variation depending on the light intensity and $\delta n_D(T)$ its variation depending on the temperature.

At the same time we can write the refractive index of the polymeric matrix:

$$n_M = n_M^O + \delta n_M(I) + \delta n_M(T)$$

where the terms n_M^O, $\delta n_M(I)$ and $\delta n_M(T)$ have similar definitions to those given above in the case of the LC droplets.

The experimental data show that increasing the temperature has the same effect as increasing the intensity, since the actual intensity effect is a local rise of temperature. For this reason the two terms $\delta n(I)$ and $\delta n(T)$ represent two different contributions to the same effect which is a thermal variation of the refractive index. We have written them as separate terms to point out that we actually have two ways of controlling the transmission

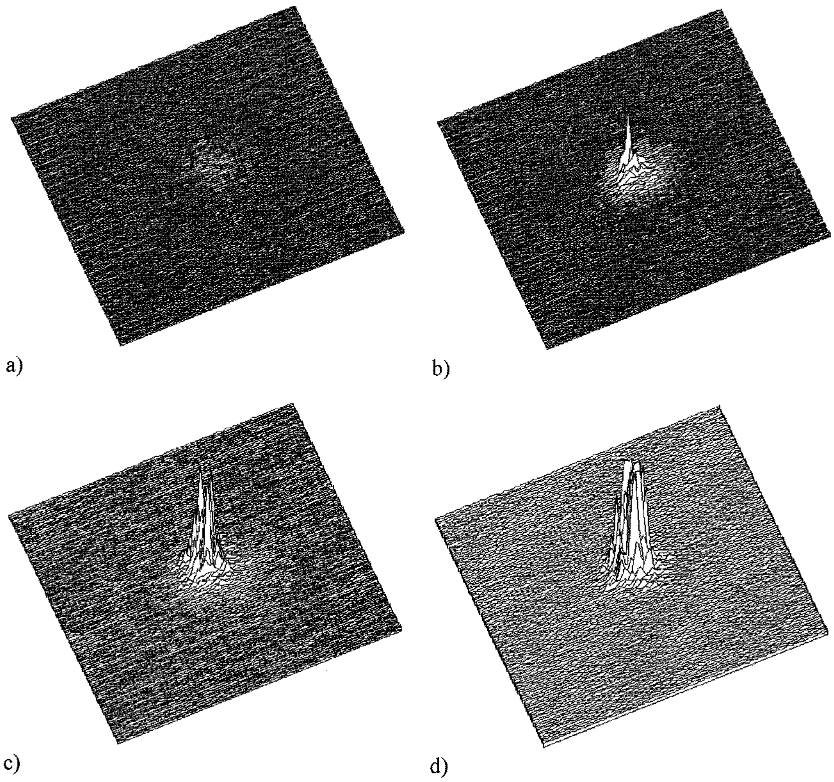

Figure 5. Three-dimensional profiles of a laser beam travelling through the PDLC at $T = 45°C$ for increasing values of the incident power: (*a*) $P = 35$ mW, (*b*) $P_{th} = 60$ mW, (*c*) $P = 80$ mW and (*d*) $P = 109$ mW.

state of the sample. In this way the mismatching condition which strongly affects light scattering (proportional to Δn^2) can be written as:

$$\Delta n = n_D - n_M = \Delta n^0 + \Delta n(I) + \Delta n(T).$$

Both $\Delta n(I)$ and $\Delta n(T)$ being negative for increasing values of I and T, respectively, self-transparency can be achieved when Δn approaches zero.

This equality shows that one can adjust both I and T to get the transmission state. In fact, by increasing T we change the temperature of the whole sample, while by increasing I only the local temperature of the spot hit by the pumped light is changed. As a consequence, as reported in figure 2, the incident power required for switching is strongly dependent on temperature.

The index matching condition, $\Delta n(I) + \Delta n(T) = -\Delta n^0$, demonstrates that a large variation of the temperature of the whole sample requires a small light-induced effect to obtain transparency and *vice versa*. This fact is well demonstrated by the data in the table below:

Temperature/°C	Threshold power/mW	Response time/s
25	188	12
35	134	14
45	60	28
50	35	40
55	19	54

An increasing temperature of the sample corresponds to a decrease in the threshold power values: the sample is already heated by the oven and needs to absorb a lower amount of light from the incident beam to switch to the transparent state. In this table there is also shown the response time necessary to switch to the transmission state for various threshold values. It is obvious that the switching becomes faster for higher intensities due to a faster heating of the sample induced by the light.

Another important feature that stands out from the 3D map is the 'beam shaping' effect. This means that due to the intensity-dependent switching, the spatial light distribution is modified in the transmitted beam producing a self-steepening of the beam. This is clear from figure 6, where we compare a 2D profile of the beam with a theoretical gaussian curve, which properly fits the incident beam. The evident squeezing effect may be qualitatively explained in the following way. The tails of the gaussian beam are below the threshold for transparency and are strongly attenuated due to scattering, while the central part of the beam is far above threshold and is transmitted with low losses. In fact, however, a quantitative analysis is made difficult due to a self-phase modulation effect which arises on the transmitted beam as a consequence of the non-linear propagation.

4. Conclusion

In this article we have analysed the self-transparency effect which can occur in a highly scattering medium,

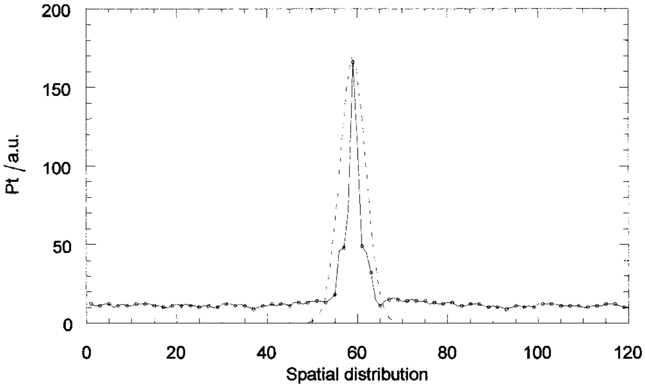

Figure 6. Two-dimensional profile of the output beam above the theshold power $P = 60$ mW at $T = 45$°C (full line) compared with the gaussian profile of the incident power (dotted line).

with thermal non-linear properties, when increase of the incident light intensity determines a local temperature variation of the material necessary to switch from the opaque state to the transmissive state. This mechanism is due to the competition between the components of the refractive indices of both the LC and the polymeric matrix. An explanation of the way in which these components depend on both the temperature and the incident power has been given.

The experimental observations presented here confirm the existence of such a type of effect in PDLCs and show the self-confinement of the propagating laser beam inside the medium by the changes in the beam profiles. We have devoted particular attention to the way in which the beam profile changes while propagating through the sample as a function of both incident power and time. The 3D profiles, experimentally monitored by a profilometer, show a rather sharp shape when the incident light power, with an initial gaussian form, increases. At the same time, we have followed the temporal evolution of the beam propagation while maintaining unchanged the initial conditions (same incident light power at constant temperature): the process starts with no transmission and high scattering, and after a few tens of seconds the output beam shows its typical configuration.

In conclusion, we have studied the propagation of a light beam inside a PDLC and reported experimental evidence of light transmission from an OFF to an ON state. Such a thermally/optically-induced self-bleaching, due to the index matching, of our PDLC indicates the possibility of employing this material to design thermal sensors or a device working as an optical switch.

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