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Incoherent-to-coherent optical conversion by means of azobenzene liquid-crystalline films

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Abstract. A new approach to incoherent-to-coherent optical conversion based on the erasing locally of the photo-induced birefringence is reported. The employed sample is an azobenzene liquid-crystalline film, which possesses photoinduced birefringence of large magnitude and the characteristic of long-term optical storage. A steady birefringence is induced in the sample by linearly polarized light and then erased locally by an incident incoherent image. The coherent image is read from the film placed between two crossed polarizers with a He-Ne laser beam. The obtained coherent image is a negative replica of the incident scene.

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Azo polymers have attracted much attention as materials for their potential applications in optoelectronics and optical storage [1–9]. Stable birefringence can be optically induced and erased in these materials. Erasable optical storage in liquid-crystalline azobezene side-chain polymers has been an area of intensive research since the pioneering work of Eich and Wendorff [10–17]. An incoherent-to-coherent optical conversion is a useful operation for optical storage. The common method to accomplish this conversion is with a conventional spatial light modulator based on a detector–modulator sandwich [18, 19]. The holographic technique is also an attractive alternative [20], in which the photorefractive materials were used usually for this application. Recently, Huang and Wagner [21] employed a methyl orange/polyvinyl alcohol (MO/PVA) film as the real-time holographic medium for the incoherent-to-coherent optical conversion. They practised the incoherent-to-coherent optical conversion by recording the interference between two plane waves from an Ar^+ laser and then erasing locally this grating structure with an incoherent image focused upon the sample. In this paper, we introduce a new way to accomplish the incoherent-to-coherent optical conversion by means of azobenzene side-chain liquid-crystalline films. The optical conversion process is based on an incoherent erasure of a polarization anisotropy. A coherent negative replica of the incident incoherent image is achieved with the help of crossed polarizers.

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1 Investigation of photoanisotropy

1.1 Sample

The medium that we used for the incoherent-to-coherent optical conversion is an azobenzene liquid-crystalline polymer. Its molecular structure is shown in Fig. 1. We chose the polymer P_1 as the achiral composition due to its low glass transition temperature and broad mesophase, and the polymer P_2 as the chiral composition due to its containing azo group. The DSC data (G48.7 °C Sc*83.2 °C S_A96.9 °C I) show the glass transition temperature of the sample is 48.7 °C (T_g). The polymer films were prepared by heating a little copolymer powder between two clean quartz glass slides to its melting point under an appropriate pressure, followed by a rapid cooling to the temperature below the glass transition temperature, leading to the formation of a thin homogeneous film. The typical thickness of the film in this sandwich structure is about 10 μm. The absorption spectrum of the sample containing 90% azo groups (feed content) is shown in Fig. 2.

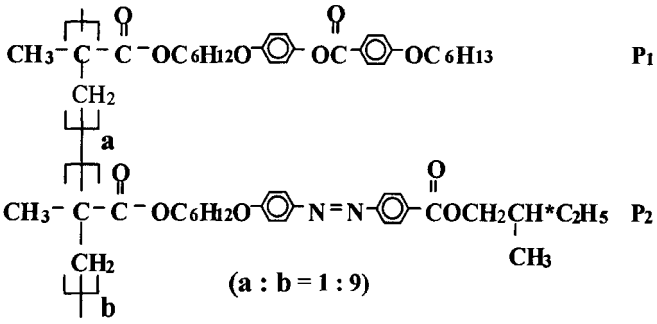

Fig. 1. The structure of the copolymer

1.2 Photoinduced birefringence

It is well known that azo-dye molecules can exist in two forms, *trans* and *cis*, of which only the former is stable in darkness. On illuminating the dye, a process of *trans-cis* isomerization followed by a *cis-trans* thermal or optical isomerization takes place, and a photo-stationary equilibrium is reached in which some of the molecules are in *cis* form. A simple model may be constructed by assuming that *trans* molecules are one-dimensional, i.e., that their polarizability tensor has only one component α_z parallel to the molecular axis. The source of the photoanisotropy is the selective optical pumping proportional to $\alpha_z \cos^2 \theta_p$ [3], where θ_p is the angle between the pumping light electric field and the molecular axis. If the light is linearly polarized, the azo molecules tend to order themselves in the direction perpendicular to the polarization direction of pumping light, and the anisotropy is optically induced in the film. Along with the photoanisotropy, light birefringence exists in the sample. We investigated the photoinduced birefringence at 633 nm, which is outside the absorption band of the photochromic groups. The pumping light is a cw 532-nm laser with the intensity of 300 $\mathrm{mW/cm^2}$. The sample film was placed between two crossed polarizers in the path of the He-Ne laser beam. The film was irradiated with the pumping light, linearly polarized at 45° with respect to the polarizers. The temporal behaviors of the photoinduced birefringence in the investigated sample are shown in Fig. 3. At $\lambda = 633$ nm, the transmission is due solely to the photoinduced birefringence which is given by $I = I_0 \sin^2(\pi \Delta n d/\lambda)$, where I is the transmitted light intensity, I_0 is the intensity of the light passing through the pair of parallel polarizers before the sample is irradiated, d is the thickness of the film, and Δn is the birefringence. The value of Δn depends on the intensity of the pumping light, dye concentration, and the performance of the investigated material. From the results in Fig. 3, we calculated the value of Δn to be 2.1×10^{-2}. This large value of photoinduced birefringence illustrates that the investigated medium is a polarization-sensitive material. Another noteworthy phenomenon is that the photoinduced birefringence did not show any decay when the writing light was turned off, as shown in Fig. 3 (from point b to point c). Actually, the photoinduced birefringence did not show any decay in several months. The stable birefringence can be erased either by heating the sample to near its clear-point temperature or by irradiating the film with circularly polarized light as shown in Fig. 3 (after point c). Using incoherent unpolarized light (for example, Hg light) can also erase the birefringence. The photoanisotropy can be rewritten with no fatigue after erasure. These results imply that the copolymer has a potential application in long-term optical storage.

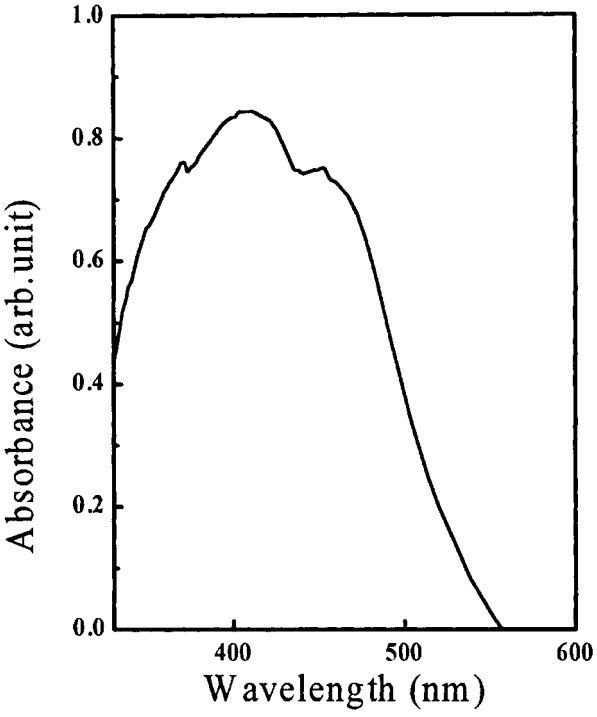

Fig. 2. The absorption spectrum of the copolymer film

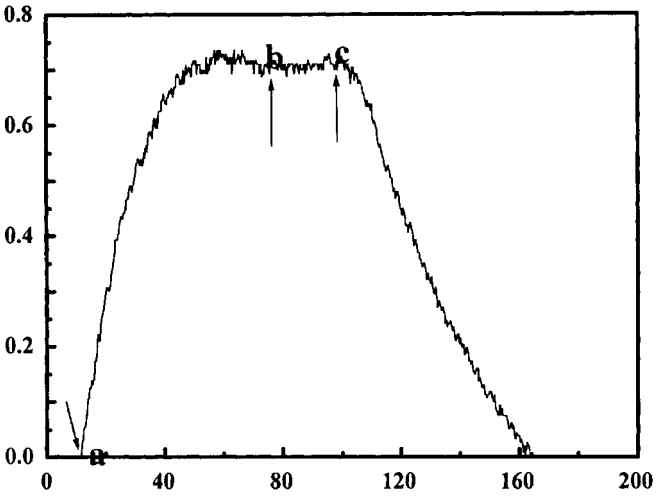

Fig. 3. Photoinduced birefringence in the copolymer film at room temperature. The pumping light is turned on at point a, is turned off at point b, the circularly polarized erasing light is turned on at point c

2 Experimental results

As stated above, the investigated sample has two advantages. First, it shows large photoinduced birefringence. Second, it possesses a long-term optical storage characteristic. Therefore, this azobenzene liquid-crystalline polymer is an ideal polarization-sensitive medium for optical information storage. The incoherent-to-coherent optical conversion process presented here is based on an incoherent erasure of a photoinduced birefringence. This process may be seen as a combination of recording the polarization anisotropy with linearly polarized coherent laser and of erasing part of the anisotropy with incoherent unpolarized light. The optical arrangement for incoherent-to-coherent optical conversion is schematically shown in Fig. 4. The sample is placed between two crossed polarizers in the path of He-Ne collimation beam. The cw 532-nm laser, linearly polarized at 45° with respect to the polarizers, aligns the liquid-crystalline azobenzene polymer, and so the polarization anisotropy or the birefringence is optically induced in the polymer film. The incoherent beam, which comes from a 400-W high-pressure Hg lamp, images a transmissive object upon the film.

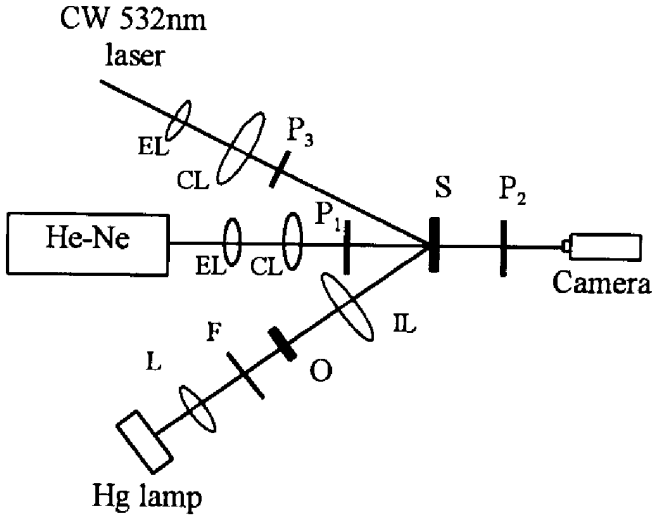

Fig. 4. Experimental setup for incoherent-to-coherent optical conversion: EL, expanding lens; CL, collimating lens; P_1 and P_2, two crossed polarizers; P_3, polarizer at $\pm 45°$ with respect to P_1 or P_2; S, sample; F, UV filter; L, condensing quartz lens; O, object to be converted; IL, imaging quartz lens

The incoherent unpolarized light can randomize the alignment of azobenzene groups. The 633-nm beam is used to read the coherent signal through the pair of crossed polarizers. The incoherent-to-coherent optical conversion experiment worked in two steps. First, we exposed the polymer film to the cw 532-nm laser for about 1 min, so that the photoinduced birefringence reached saturation value, and the intensity of the transmitted He-Ne light through the two crossed polarizers remained unchanged (as shown in Fig. 3 after point b). Then, the Hg light was turned on, and the erasure of the photoinduced birefringence took place. In the region where the incoherent image was bright, the birefringence was erased. After about 1 min, which was dependent upon the intensity of Hg light and the temperature of the film, a dark image resembling a negative replica of the incident image could be seen in the bright background of the transmitted He-Ne beam. We recorded this coherent image with a camera, as shown in Fig. 5. Figure 5a shows the word "OK" and Fig. 5b show Chinese words that mean "photons". The bright regions in Fig. 5 corresponded to the steady photoinduced birefringence (as shown in Fig. 3 from point b to point c), and the dark images corresponded to the erasure region where the incoherent image was bright. The spatial resolution was determined with a photomask to be about 31 lines/mm. The horizontal resolution of the readout coherent image is equal to the vertical resolution in this method, but the resolution performance shows anisotropy in the photoanisotopic incoherent-to-coherent optical conversion with the holographic technique [21].

This image conversion can also work in the simultaneous erasure/writing mode. In this mode of operation we expose the film to the coherent 532-nm writing beam and the incoherent erasure image simultaneously, so that the formation and erasure of the polarization anisotropy are performed at the same time. It needs about 1 min to get a stable image. The result in this simultaneous operation is the same as in the above two-step operation. Many Fourier-optics-based image-processing operations can function adequately with

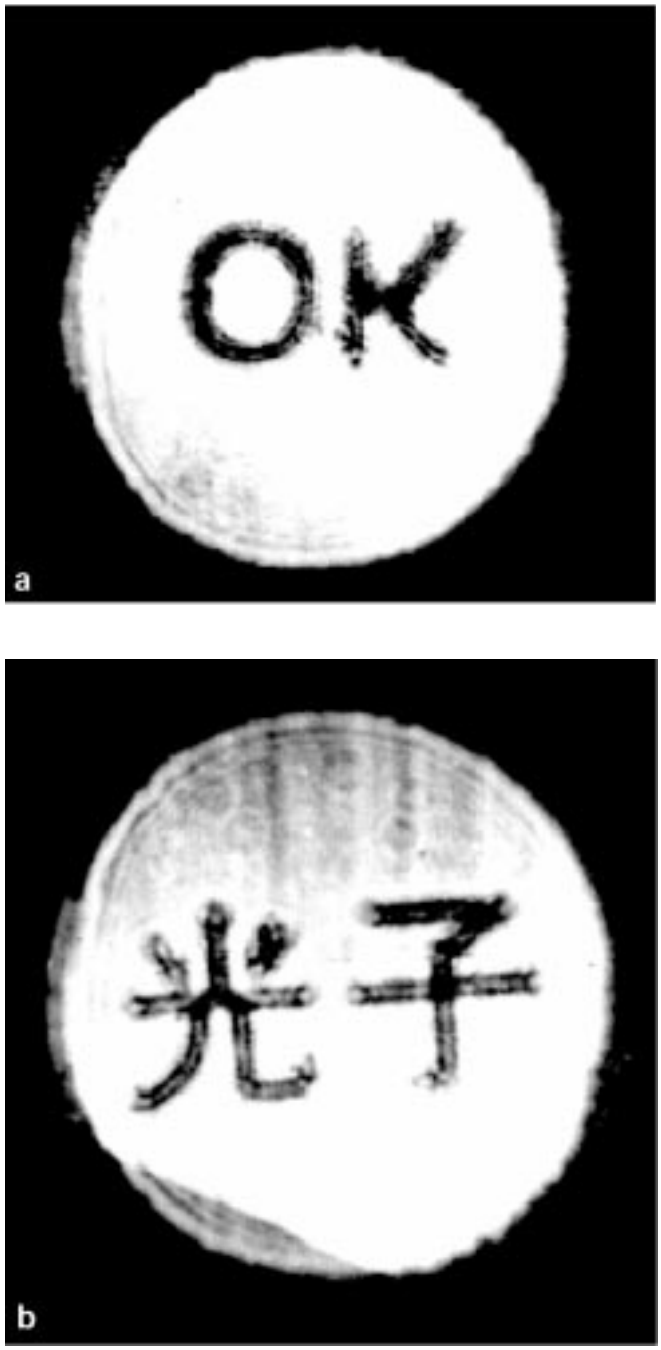

Fig. 5a,b. The converted negative coherent images: **a** word "OK", **b** Chinese words meaning "photons"

a contrast-reversed version of the image, and for many other applications this image negation is an extremely useful operation, such as in logic [22] and bipolar neurons [23].

3 Conclusion

A new approach to incoherent-to-coherent conversion was presented. This method is based on the erasing partially of the photoinduced birefringence. An azobenzene liquid-crystalline film was employed as the optical storage medium for the image conversion. The sample possesses large photo-

induced birefringence and long-term optical storage characteristics. The use of linearly polarized light aligned the azobenzene liquid-crystalline molecules, which yielded a photoinduced birefringence. Through illuminating the oriented sample with an incoherent image, the photoinduced birefringence was erased in the region where the incoherent image was bright. A coherent negative replica of the incident incoherent image was achieved with the help of crossed polarizers. The incoherent-to-coherent image conversion by means of azobenzene liquid-crystalline films was realized. The spatial resolution of the readout coherent image is 31 lines/mm. We come to the conclusion that the method as stated above is simple and useful.

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