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Improvement of all-optical switching effect based on azobenzene-containing polymer films

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ABSTRACT A method for improving the quality of all-optical switching is presented. Pumping poly(methyl methacrylate) (PMMA) films doped with azobenzene chromophore Disperse Red 1 (DR1) with two beams (a linearly and a circularly polarized), all-optical switching effects with very low background and high stability are demonstrated. High frequency switching, which is hard to be realized under pump of a single beam, is obtained. The circularly polarized pump beam can erase the photoinduced birefringence and quicken the relaxation process, thus lowering the background and improving the stability and the extinction ratio of the switching signal.

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1 Instruction

It is well known that azo polymer under irradiation of a linearly polarized pump beam causes photoinduced birefringence owing to photochemical reactions. Azo polymer has generated wide interest in recent years because it offers possibilities for the application in optical storage and switching [1–3]. However, many problems in the optical switching experiments [4–13] based on polymers still need to be tackled, such as the slow response (millisecond order of magnitude), the large background, the low stability and extinction ratio of the switching signal etc. The response speed depends mainly on the characters of the material, such as the size, structure and the photochemical characters of the chromophore, light absorption and the thickness of the sample etc. Polymers with high response speed are still under development. Yet, to our knowledge, for a given material, the improvement of the switching signals has not been attracted much attention so far. In this paper, based on the traditional pump-probe technique, we add a circularly polarized beam to pump the polymer films and present the significant improvement of all-optical switching effects in lowering the background, increasing the stability and extinction ratio. High frequency switching effect, which is often hard to be realized in the case of a single pump beam, is obtained.

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2 Experiment

2.1 *Samples*

Samples used in our experiments are PMMA films doped with DR1. The concentrations of DR1 are 3% and 5 wt. % and the samples are marked as DR1 (3%) and DR1 (5%), respectively, in brevity. The thickness of the sample is about 100 micrometers. The preparation methods are given in our previous work [13] in detail.

2.2 *Experimental setup*

Figure 1 is the schematic illustration of our experiments. The sample S is placed between two crossed polarizers P_1 and P_2. A He-Ne laser (633 nm, in weak absorbing band of the sample) and a semiconductor laser (532 nm, in strong absorbing band of the sample) are used as the probe and the pump beam respectively. In our experiment, the pump beam is divided into two beams by a beam-splitter BS_1. One is modulated with a chopper, reflected by a mirror M_1, passes through the polarizer P_3 and is reflected by a beam-splitter BS_2 and then shoots at the sample as a linearly polarized beam (I_1). The other is reflected by a mirror M_2, passes through a polarizer P_4 and a quarter wave plate and then shoots at the sample as a circularly polarized beam (I_2). The probe beam and the two pump beams are adjusted to shoot at the same spot on the surface of the sample. The polarization direction of I_1 (controlled by P_3) is adjusted to be 45° with respect to the probe beam (controlled by P_1). The filter F is used to stop the pump beam

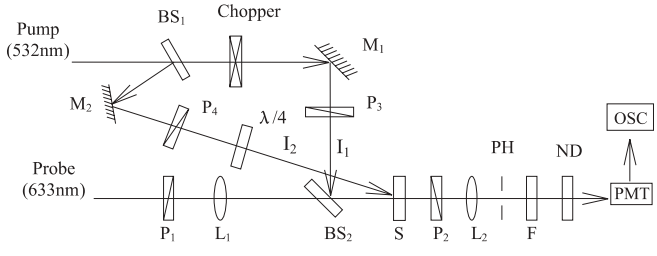

FIGURE 1 Experimental setup. P's: polarizer; L's: lens; M's: mirror; S: sample; PH: pinhole; F: filter (stop 532 nm, pass 633 nm); ND: neutral density filter; PMT: photo-multiplier tube; OSC: oscilloscope

and pass the probe beam. The output probe beam is received with a photomultiplier tube PMT and the signal is displayed and stored with a high-speed digital phosphorous oscilloscope OSC (modeled TDS-3032).

2.3 *Principle of the optical switching*

Before irradiation of the pump beam, the sample is optically isotropic, so the probe beam cannot pass through the two crossed polarizers. After irradiation, the sample shows photoinduced anisotropy because the azo chromophores of the sample undergo cycles of trans-cis-trans isomerizations and finally tend to align in the direction perpendicular to that of the linearly polarized pump beam [14]. The probe beam can then pass through the polarizer P_2 and the signal with increasing intensity (related to the formation of the induced birefringence) can be received by the photomultiplier. When the pump beam is turned off, the induced birefringence relaxes, owing to the thermal isomerization and reorientation of the aligned chromophores, and thus the output signal of the probe beam decreases. If the turning-on and off of the pump beam is controlled by a chopper at a frequency, the intensity of the probe beam received by the photomultiplier is modulated with the same frequency. In this way, the optical switching effect is obtained.

3 Results and discussions

3.1 *Switching effects with a single pump beam (linearly polarized)*

In the traditional experiments, where only a single pump beam is used, we find that it usually needs several minutes for the optical switching signals to be stable, as shown in Fig. 2a. Furthermore, the background of the stable optical switching signal is often very high. The sample shows a macroscopic optical anisotropy because it usually needs a long time for those aligned chromophores to relax back to the original disordered state. While the chopping time is often fast and the aligned chromophores cannot relax back to the original isotropy in such a short time. So, the higher the chopping frequency, the shorter the time for the chromophores to relax and consequently the higher the background and the smaller the amplitude of the switching signals. As an example, the effect of frequency on the switching for sample DR1 (5%) is shown in Fig. 3.

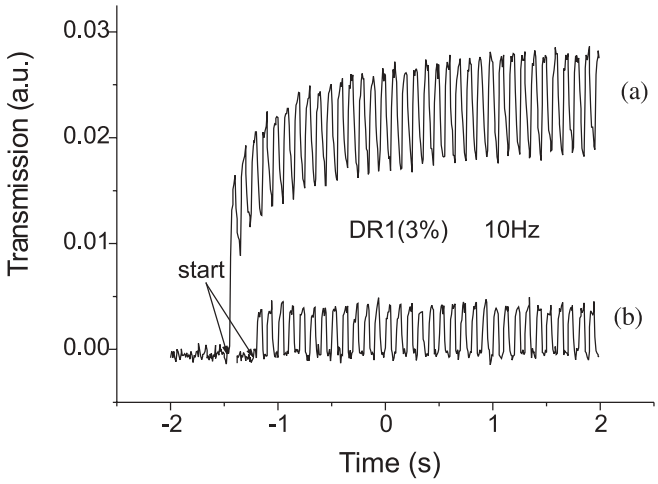

FIGURE 2 Switching of DR1 (3%) at 10 Hz under pump of (a) a single linearly polarized beam (3.35 mW) and (b) a linearly polarized beam and a continuous circularly polarized beam (28 mW and 10 mW respectively)

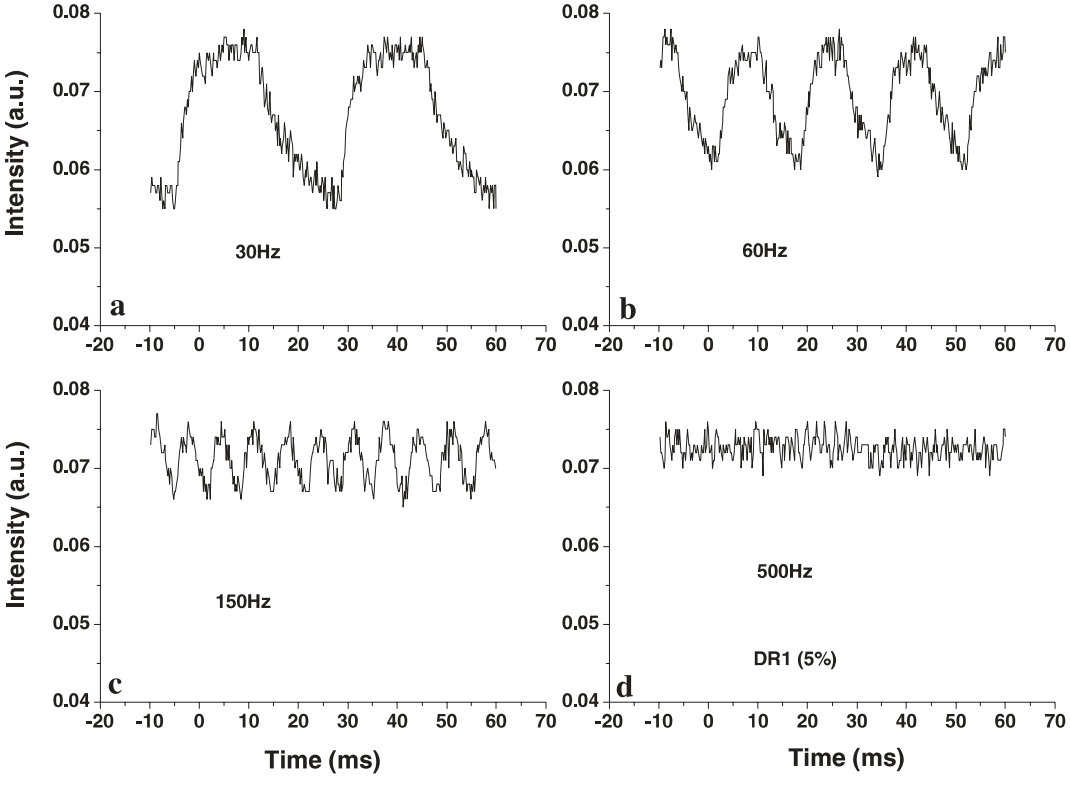

FIGURE 3 Effects of frequency on the switching for DR1 (5%) under pump of a single beam (10 mW)

4 Method for lowering the background

Figure 4 shows the dark relaxation and the erasure of the photoinduced birefringence for DR1 (5%). We see that the circularly polarized beam can be used to erase the photoinduced birefringence and quicken the relaxation process significantly, as reported in [15, 16]. By means of this property, we used a linearly polarized beam and a continuous circularly polarized beam to pump the sample simultaneously, and got switching signals with very low background and high stability, shown as Fig. 2b and Fig. 5.

As Fig. 5 shows, when a circularly polarized beam is added, significant decrease of the background and increase of the extinction ratio of the switching signal are obtained. Furthermore, the lower the intensity of the linearly polarized beam, the lower the background when the intensity of the circularly polarized beam is given. We think that the circularly polarized beam can randomize the orientation; moreover, the thermal effect in the case of two pump beams (when a circularly polarized beam is added) is more significant than that in the case of a single beam. And heat can accelerate the irregular thermal motion of the molecules, speed up the thermal relaxation of the chromophores [17, 18] and quicken the process back to the disordered state. So, due to the randomization of the circularly polarized beam and the more significant thermal effect of the two beams, the background of the switching signal decreases significantly.

4.1 *Realization of high frequency all-optical switching effects*

As the circularly polarized beam can significantly decrease the background and increase the extinction ratio, we pump the sample with two beams simultaneously and obtain a high frequency switching effect shown as Fig. 6, which is often hard to be realized under pump with a single beam, as shown in Fig. 3d.

4.2 *Further improvement of the optical switching with two pump beams*

We noticed that along with the great improvement in the stability and the background, the amplitude of the switching signal is weakened significantly when a continuous circularly polarized beam is added. In Fig. 2, the amplitude of the switching signal in the case of two pump beams ($I_1 = 28$ mW, $I_2 = 10$ mW) is smaller than that in the case of a single pump beam ($I_1 = 3.35$ mW) even if the power of I_1 is much bigger. Given the sample, the power of the linearly polarized pump beam and the chopping frequency, the amplitude of Fig. 5(a), 0.003, is much smaller than that of Fig. 3b, 0.015. We think that, the circularly polarized pump beam, on the one hand, can result in the decrease of the background owing to the randomization and the thermal effect, as mentioned above. Yet, on the other hand, the process for chromophores to align orderly (related to the formation of induced birefringence) would be restrained by this randomization and thermal effect. So, with the addition of a continuous circularly polarized beam, the induced birefringence is weakened and the amplitude of the signal is decreased.

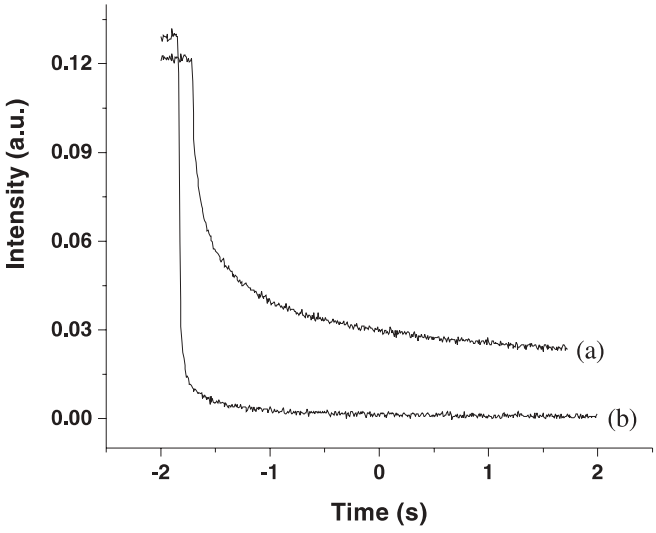

FIGURE 4 Dark relaxation (a) and erasure (b) of the photoinduced birefringence of DR1 (5%); (erase with a circularly polarized beam of 10 mW)

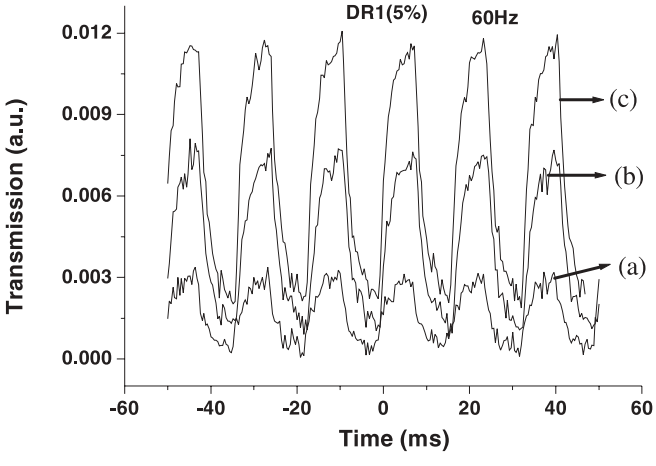

FIGURE 5 Switching of DR1 (5%) at 60 Hz pumped by a continuous circularly polarized beam (10 mW) and a chopped linearly polarized beam with powers of (a) 10 mW, (b) 14 mW and (c) 20 mW

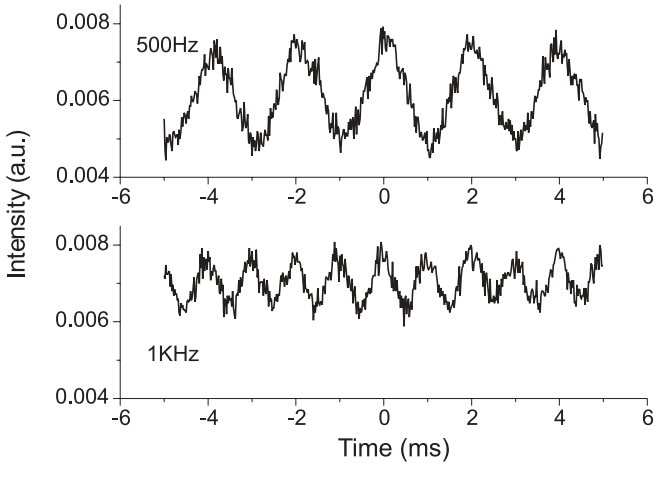

FIGURE 6 Switching effects of DR1 (3%) at 500 Hz and 1 KHz under pump of a linearly polarized beam (40 mW) and a continuous circularly polarized beam (26 mW)

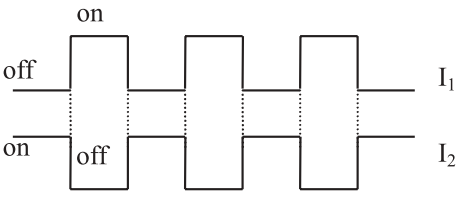

FIGURE 7 Wave forms of the two pump beams when modulated at the same frequency yet with a phase difference of π (I_1: linearly polarized and I_2: circularly polarized beam)

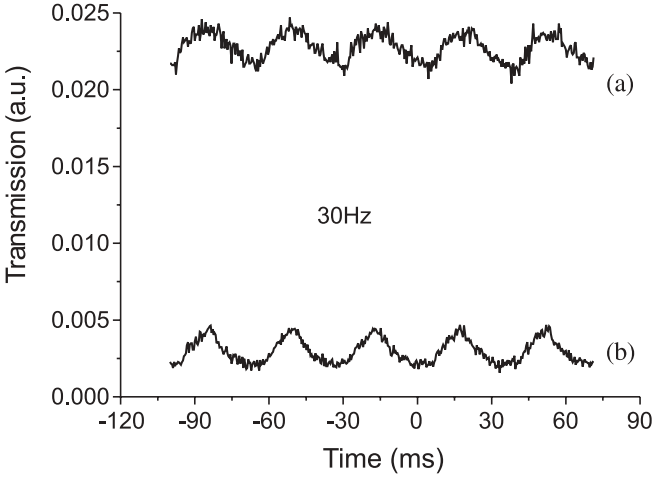

FIGURE 8 Switching of DR1 (3%) at 30 Hz under pump of (a) a single beam ($I_1 = 13$ mW) and (b) two modulated beams ($I_1 = 13$ mW and $I_2 = 17.2$ mW respectively)

Based on Fig. 1, placing the chopper (modeled SR540, Stanford Research Systems, Inc.) in a proper position (ensuring that both the two pump beams can pass the chopper), we modulated the two beams at the same frequency yet with a phase difference of π (as shown in Fig. 7). We find that the background is lowered and the amplitude is not decreased, shown as Fig. 8(b). This is because in the formation stage of birefringence (when I_1 is on), the circularly polarized beam I_2 is off, thus the restraint of the induced birefringence mentioned above does not exist. And in the relaxation stage (when I_1 is off), I_2 is on. The circularly polarized beam disorders the aligned chromophores and erases the induced birefringence in this stage. So, the background is lowered but the amplitude is not decreased.

Similar results can also be seen in the switching of high frequency, as shown in Fig. 9. Comparing the switching signals of three different pump conditions, we can see clearly that the background is decreased significantly by two pump beams, shown as Fig. 9(b) and (c). Yet the amplitude of the signal is not decreased under pump of two beams that are modulated with a phase difference of π, as shown in Fig. 9(c).

5 Conclusions

In conclusion, based on the pump-probe technique, switching effects with low background and high stability are obtained in DR1 doped PMMA films by two pump beams. High frequency switching, which is often hard to be realized under pump with a single beam, is demonstrated.

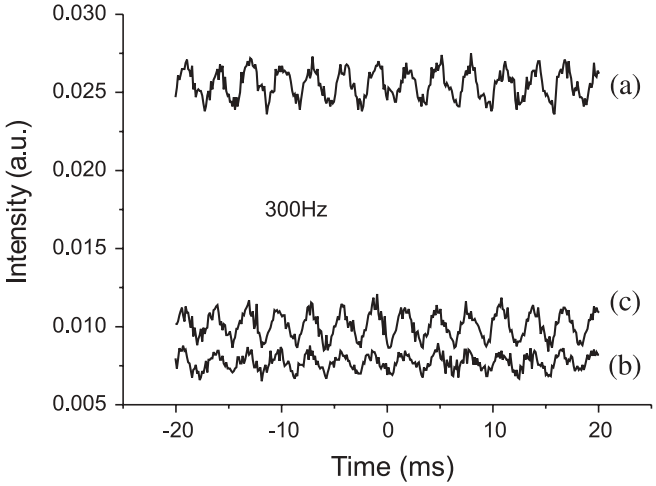

FIGURE 9 Switching of DR1 (5%) at 200 Hz under pump of (a) a single beam ($I_1 = 13$ mW), (b) two beams ($I_1 = 13$ mW, $I_2 = 29$ mW) and (c) two modulated beams ($I_1 = 13$ mW, $I_2 = 29$ mW)

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