Photoinduced Birefringence and Broadband All-Optical Photonic Switch in a Bacteriorhodopsin/Polymer Composite Film *

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Photoinduced birefringence with large optical nonlinearity in a bacteriorhodopsin/polymer composite film is observed. A high refractive index change of 8.5×10^{-5} *photoinduced by 476 nm pumping beam is reached at the low intensity of 6.5 mW/cm*^{2}*. Based on it, a broadband all-optical photonic switch is realized with an optical controlling switch system. Because of controlling beam's selectivity in switching, the transporting beams of different wavelengths with different intensities and shapes can be modulated by adjusting the wavelength and intensity of the controlling beam.*

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Bacteriorhodopsin (bR), found in the purple membrane of halophilic organism halobacterium salinarium,[1] is an active photochromic protein, which has attracted much attention in recent years. A great deal of development in bR's application has been made in the field of photoelectricity and biology. Especially in optical area, based on bR's unique optical properties, such as broadband absorption in the visible range, strong nonlinear optical responses and astonishing stability against chemical and thermal degradation,[2,3] a series of optical applications have been explored.[4−9] Among them, application in the optical switch is a promising one.[10−11]

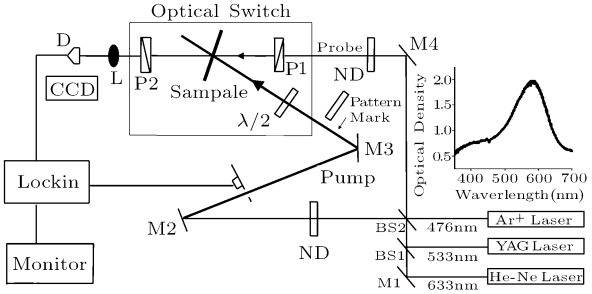


Fig. 1. Experimental setup for investigation of photoinduced birefringence in the bR/PC film and of later photonic switch. P1, P2, polarizers; $\lambda/2$ plate, for rotating linearly polarized state of laser beam; ND, neutral density plate. A lock-in amplifier and a monitor are employed for measuring the birefringence signal. Inset: absorption spectrum of the bR/PC film.

In this Letter, we investigate the photoinduced birefringence property of a homemade bacteriorhodopsin/polymer composite (bR/PC) film in broadband wavelength (nearly covering the whole visible range) and research the feasibility of all-optical photonic switch. When the linearly polarized pumping beam presents, the photoinduced birefringence is generated, by which the probing beam is modulated, thus the transmittance of probing beam is changed accordingly. In our experiment, we choose the wavelength 633 nm (He-Ne laser), 533nm (YAG laser) and 476 nm (Ar^+ laser) as the probing and pumping beam wavelengths. We find that the bR/PC film can reach comparatively larger optical nonlinear effect under low pumping beam intensity, based on which we realize multi-wavelength transportation by photonic switch in a visible range. Because of controlling beam's selectivity in switching, we can manage to transport beams of different wavelengths in different intensities and waveforms by adjusting the wavelength and intensity of the controlling beam.

The sample we prepared is the polymeric film made of poly(vinyl alcohol) (PVA) and active bR molecules. PVA possesses the features of hydrophilicity, biocompatibility, high transparency, and good mechanical property, which make it an ideal polymer material for fabrication of composite films with active proteins included. The thickness of the film is about 80 μm and the optical density at absorption peak is 2.0 at the wavelength of 570 nm as shown in the inset of Fig. 1. The experimental apparatus is shown in Fig. 1. Three linearly polarized lasers of different wavelengths of 476, 533, 633 nm are used as probing and pumping beams. The polarized direction of pumping beam is converted by a half wave plate and then the pumping beam overlaps with the probing beam on the sample film, which is placed between two crossed Glan–Thompson polarizers, P1 and P2. The polarized di-

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rection of pumping beam is oriented at 45° with respect to the probing beam. Without pumping beam, the bR/PC film is isotropic and no transmitted signal can be detected. When the pumping beam is present, the bR molecules with the electric dipole moments aligning along the linearly polarized direction are excited and go into the photocycle, while those perpendicular to the polarized direction remain on their initial state.[1] Roughly, there are six states in one photocycle, bR (initial state with largest absorption at 570 nm), K(610 nm), L(550 nm), M(410 nm), N(560 nm), O states(640 nm), and different states correspond to different bR molecule structures. Thus in the pumping beam's polarized direction, a macroscopic optical axis is generated. As a result, the refractive index of the film is different between the axis direction and its perpendicular one, which rotates the polarized direction of probing beam through the bR film, causing a portion of probing beam detected.

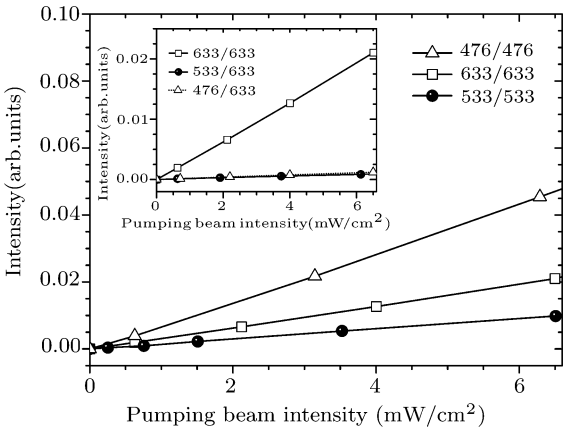


Fig. 2. Transmitted intensity of the probing beam as a function of the intensity of the pumping beam. The numbers such as 476/476 refer to the wavelength of pumping beam and that of probing beam in units of nm. Inset: the probing beam with different wavelengths to the pumping beam.

We firstly choose one laser beam as probing and pumping beams with the same wavelength investigating the photoinduced birefringence. Figure 2 shows the transmittance of probing beams depending on the intensity of pumping beams in three groups of 476, 533 and 633 nm. It is seen that the effect of photoinduced birefringence is the strongest at the wavelength of 476 nm, the next stronger one is at 633 nm and the weakest one at 533 nm. According to photoinduced anisotropy, the further the wavelength located away from the absorption peak, the greater the photoinduced birefringence effect is. The transmitted probing beam intensity by photoinduced birefringence can be written as[9]

$$I_{\rm out} = I_{\rm in} \sin^2(2\beta) \sin^2(\pi \Delta n d/\lambda_{\rm probe}), \qquad (1)$$

where $I_{\rm out}$ is transmitted beam intensity, $I_{\rm in}$ is probing beam intensity, β is an angle between the directions of polarization of probing and pumping beams (45° in our experiment), Δn is the change of photoinduced refractive index and d is the film thickness (80 μm). At the wavelength of 476 nm, the transmittance of the probing beam ($I_{\rm out}/I_{\rm in}$) could reach 0.006 and the refractive index change Δn could reach 8.5×10^{-5} at 6.5 mW/cm^2 of 476 nm pumping beam intensity. Compared with other organic and inorganic material, the bR/PC film could obtain much larger optical nonlinearity at such lower pumping beam intensity.

Then based on the experimental apparatus as shown in Fig. 1, we mix the three probing beams of wavelength 476, 533 and 633 nm with the same polarized direction into one beam overlapping with the pumping beam onto the bR/PC film. The pumping beam is chosen from one of the three beams. Compared with the birefringence signal induced from the group of probing-pumping beams with the same wavelength, the signal is very small under the condition with different wavelengths of probing-pumping beam groups. The reason could be such that the probing beam easily identifies the molecules which have been photoinduced anisotropy by the selfsame wavelength of the pumping beam. As shown in the inset of Fig. 2, the pumping beam at the wavelength of 633 nm and the three probing beams with the same intensity, the birefringence effect is strongest at the probing beam of 633 nm and is very small at the probing beams of 476 and 533 nm. We can see that the probing beam only with the same wavelength as the pumping beam can be responded or detected, which means the pumping beam possessing the selectivity in detecting the probing beams.

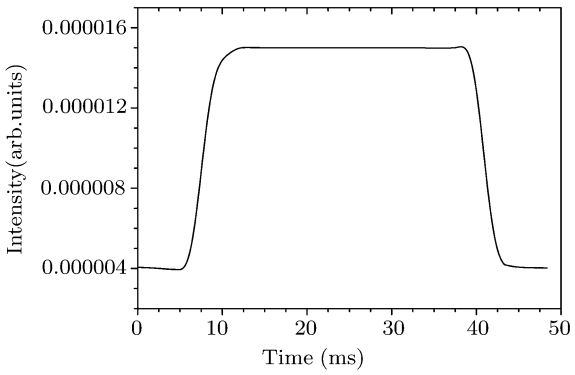


Fig. 3. Transmitted intensity of the probing beam with pumping beam on and off as a function of time.

Next we investigate the bR/PC film's application of photoinduced birefringence to photonic switch. As shown in Fig. 3, when the pumping beam illuminates the bR/PC film, the photoinduced birefringence signal firstly increases quickly and goes to a stable value. After the pumping beam is off, the birefringence signal decreases quickly and later disappears. Thus the

pumping beam acts like the controlling beam, which can control the transmitted probing beam considered as transporting beam, and the whole equipment involving the bR film, two polarizers and half-wave plate, acts as the photonic switcher. The response time of the switch is about 5 ms and the time depends on the lifetime of M state (about 4.0 ms), which has the longest lifetime among states in bR's photocycle. Then we use a modulated controlling beam with the chopped frequency of 1000 Hz illuminating the bR/PC film and at the meantime observe the output signal of transporting beam. As shown in Fig. 4, the output signal shown in Fig. 4(b) could generally respond to the controlling beam but the time of going up and down becomes longer as shown in Figs. 4(a) and 4(b). The reason is that the longer the lifetime of the M state, the longer the response time is. One could acquire the ideal lifetime of the M state by controlling the humidity and pH value in the production of the bR film in order to shorten the response time to improve the performance of the photonic switch.[10]

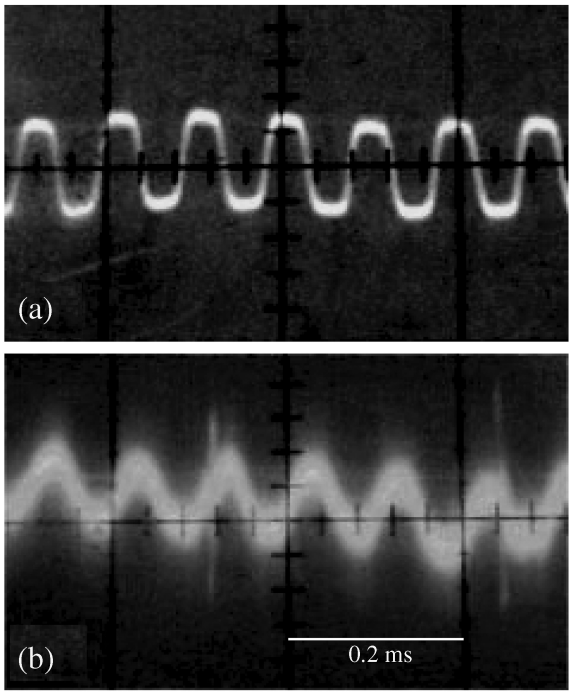


Fig. 4. (a) Controlling beam signal with the chopped frequency of 1000Hz. (b) Output signal of the transporting beam.

Furthermore, based on the selectivity discussed above, we can use one controlling beam to switch multiple transporting beams and a specific beam. This selectivity can be used in optical information process. We can selectively switch the beam with specific colour and shape by choosing the light parameters of the controlling beam. Firstly, the three transporting beams illuminate the film in different directions overlapping with the controlling beam. Then we put the patterns of square, triangle and circle before the three transporting beams reaching the bR/PC film and use the CCD camera to capture the output of the transporting beams. Without the controlling beam, the transporting beams cannot be obtained by the switch system. When the controlling beam is present, the transporting beam with the same wavelength to the controlling beam can be switched and the corresponding shapes and colour of the transporting beam are displayed in the CCD. Meantime, the beams with the different wavelength to controlling beam can not be switched and captured by the CCD. As shown in Fig. 5(a), using a controlling beam at wavelength 633 nm, we can obtain a clear red triangle of 633 nm beam transporting while the blue square, green circle of 476, 533 nm beams can not be switched to transport. Similarly we can obtain a blue square and a green triangle by controlling the beam with wavelengths 476 and 533 nm, as shown in Figs. 5(b) and 5(c), respectively. We can also change the intensity of the switched beam by controlling the intensity of the controlling beam.

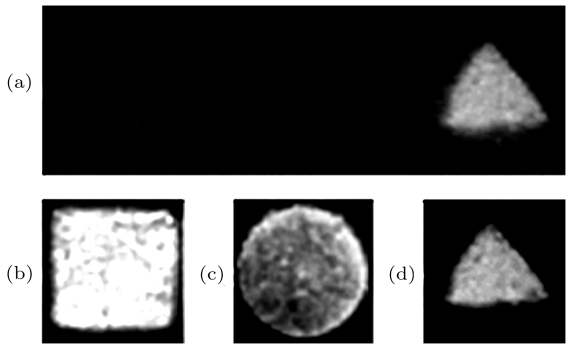


Fig. 5. Photographs of the transporting beam switched with different shapes and wavelengths: (a) red triangle, 633 nm, (b) blue square, 476 nm, (c) green circle, 533 nm, (d) red triangle, 633 nm.

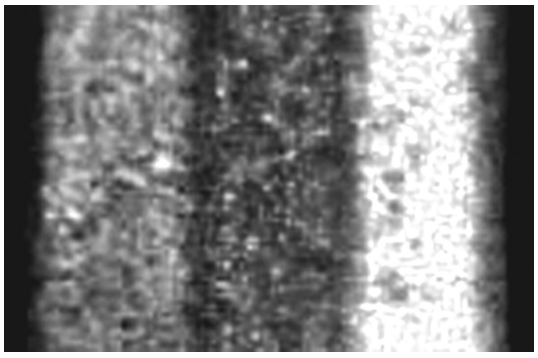


Fig. 6. Photograph of the transporting beam switched with a rectangle at different wavelengths: 633 nm (left), 533 nm (middle) and 476 nm (right).

We also adopt more laser beams as one controlling beam to realize the switching multiple transporting beams. We mix 476, 533 and 633 nm laser beam

into one beam as the controlling and the transporting beam, and put a rectangle before the transporting beam reaches the bR/PC film. The transporting beam is switched by the bR/PC film and a prism is placed between P2 and the CCD to disperse the mixed transporting beam into different wavelengths. The result is shown in Fig. 6.

In conclusion, we have investigated the photoinduced birefringence of a bR/PC film and obtained very large optical nonlinearity. Also, we have demonstrated the application of photoinduced birefringence for photonic switch making and realized selectively switching specific transporting beam and multiple transporting beams. By changing the light parameters of the controlling beam, the transporting beams with different shapes and wavelengths can also be switched selectively.

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