

Enhancement of photoinduced anisotropy and all-optical switching in Bacteriorhodopsin films

Pengfei Wu^{a)} and D. V. G. L. N. Rao^{b)}

Department of Physics, University of Massachusetts, Boston, Massachusetts 02125

B. R. Kimball, M. Nakashima, and B. S. DeCristofano

Material Science Team, U.S. Army Soldier Systems Center, Natick, Massachusetts 01760

(Received 20 May 2002; accepted 20 September 2002)

Large enhancement of photoanisotropic effects is demonstrated in thin films of the biomaterial Bacteriorhodopsin by using two exciting beams of orthogonal polarization. The mechanism of the enhancement originates from optimization of direction-selected photoisomerization of the biomaterial controlled by the polarized exciting beams. The technique is applied for achieving an all-optical switch with the additional feature of output sign control. © 2002 American Institute of Physics. [DOI: 10.1063/1.1521581]

Photocontrols of molecules and resulting optical anisotropic effects are useful for many photonic applications such as optical storage,^{1,2} optical switch,^{3,4} optical waveguide,^{5,6} optical display,⁷ and optical power limiter.⁸ High spatial resolution can be obtained due to the small molecular size. Microscopic photonic devices or optical chips with molecular-level photonic elements may also be achieved. The optical anisotropic effect is one of the important parameters for controlling photons to achieve various opto-optic and electro-optic devices which are potential alternatives for replacing the electronic devices for many applications. Polymer films embedded with functional molecules have been receiving much attention in recent years due to their large optical effects and low cost.^{9–11} However, several factors such as molecular movement and electrostatic interactions reduce the photoanisotropy.¹² The biological material of Bacteriorhodopsin (BR) and its derivatives are among the most promising candidates for potential applications in photonics in view of their large optical nonlinearity, ease of optimization, and tailoring optical properties.^{13–17} Nonlinear photoinduced anisotropy in films of BR and its derivatives was studied in detail by Song *et al.*¹⁸ and Korchemskaya *et al.*¹⁹ All the previous work (including ours) on photoinduced anisotropy in BR films and its applications was based on a single exciting beam. Here, we report a scheme for significant enhancement of photoanisotropic effects using two exciting beams with orthogonal polarization resulting in optimization of molecular anisotropic distribution. We also demonstrate an all-optical switch with the additional feature of output sign control.

The biological BR doped in polymer film of poly(vinyl alcohol) is used for our studies. The sample films were purchased from Munich Innovative Biomaterials GmbH. Optical density of the films is about 5 at 570 nm. We studied photoinduced anisotropy in thin films of BR by use of two polarized exciting beams with different wavelengths. Figure 1 shows the experimental arrangement to investigate the fea-

tures of enhancement of photoanisotropy. The sample is placed between two crossed polarizers (vertical polarizer P_1 and horizontal analyzer P_2) and a weak He-Ne 633 nm beam of intensity 5 mW/cm² is used to probe the effects of photoanisotropy of the sample. A 568 nm exciting beam from Ar-Kr ion laser irradiates the sample with linear polarization at 45° clockwise from the vertical. Another exciting beam of 442 nm from a He-Cd laser irradiates the sample with polarization perpendicular and propagation counter to the 568 nm beam. The two exciting beams have the same size of about 3 mm diameter on the sample surface and overlap the probe beam (about 2 mm diameter). When the 568 nm and the 442 nm beams are blocked, no light reaches the detector due to random distribution of the BR molecules in the film. When we first turn on the 568 nm beam only, the analyzer transmits some 633 nm probe light. Upon excitation of the initial *B* state, the BR molecule goes through several intermediate states with short lifetimes to the relatively long-lived *M* state and relaxes back to the initial state spontaneously. We may consider only the *B* and *M* states as the other intermediate states in the photocycle are short lived. The

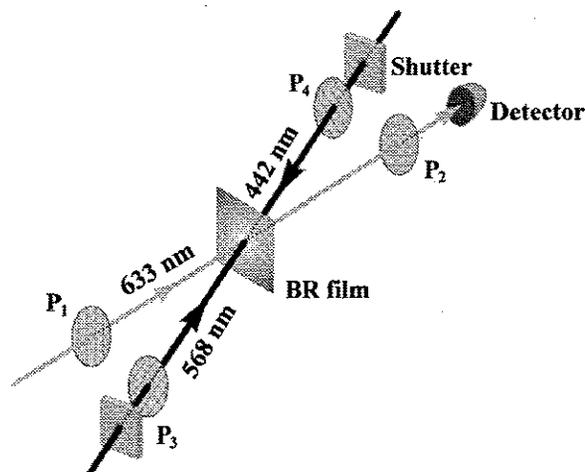


FIG. 1. Experimental arrangement for investigations of enhancing photoanisotropy and optical switching by use of polarized exciting beams of two colors.

initial *B* state has an absorption peak at 570 nm while the long-lived *M* state has an absorption peak at 412 nm. Under linear-polarized light with a wavelength close to the absorption peak, the anisotropic distribution of BR molecules results in photoanisotropic properties of photoinduced dichroism and photoinduced birefringence due to the polarized saturable absorption effects, that is, only those BR molecules oriented with their transition dipole moments in or near the electric field direction of the light absorb the light and are saturated. It is found that the probe beam transmitted through the film is near-linearly polarized. With an intensity of 300 mW/cm² for the 568 nm beam, the ratio of the minimum to the maximum intensity of the probe polarization is about 1:80. The result indicates that the photoinduced birefringence is very weak. The direction of major axis of the polarization state is clockwise rotated by about 3° (due to small photoinduced dichroism) from the initial polarization direction of probe beam looking in the input direction of the probe beam. The results are similar when we turn on only the 442 nm exciting beam with the wavelength close to the absorption peak of the *M* state. With an intensity of 180 mW/cm² and polarization orthogonal to the 568 nm beam, the minimum-to-maximum intensity ratio of the probe polarization is about 1:13, and the major axis of the polarization is clockwise rotated about 8° (same direction as for the 568 nm beam). This photoanisotropy is due to the polarized saturable absorption effects of the *M* state of BR molecules in the direction of polarization of the 442 nm beam. The initial distribution of the *M* state in BR film originates from the excitation of red probe beam. Since the BR molecules can undergo photoisomerization with weak irradiation, the *M* state molecules can be formed by the 633 nm probe beam. On the other hand, when the polarization of the 442 nm beam is parallel to that for 568 nm, the direction of the probe polarization is rotated by almost the same magnitude in the direction opposite to that by the 568 nm beam because the photoisomerized direction induced by the yellow light is reverse to that by the blue. Therefore, the sign of photoinduced dichroism induced by the 442 nm exciting beam is reverse to that by the 568 nm beam.

We found that the single exciting beam of either 568 or 442 nm results in relatively small photoanisotropic effects. However, the photoanisotropy of BR film can be significantly changed by simultaneous excitation with two polarized beams. In the case that the 568 nm beam is polarized perpendicularly to the 442 nm beam, the photoinduced an-

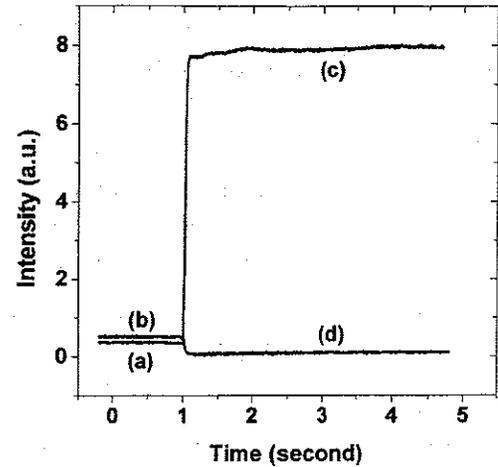


FIG. 2. Experimental results of photoanisotropy by use of different exciting beams with different polarized combinations. Before the time of 1 s the photoanisotropy is induced by only one exciting beam (a) 568 and (b) 442 nm. At the time of 1 s, turn on another exciting beam (c) 442 nm polarized perpendicularly to the 568 nm and (d) 568 nm polarized parallel to the 442 nm.

isotropy is considerably enhanced. Figure 2 shows the results of photoanisotropy by use of different exciting beams of 568, 442 nm, and polarization combinations of 568 and 442 nm. Compared with the case of single exciting beam, near 20 times increase of emergent probe intensity is observed when we use a perpendicular polarization combination of 568 and 442 nm beams. It is also found that the polarization state of the probe beam passing through the film becomes elliptic (the minimum-to-maximum intensity ratio is 1:4) as compared with the case of single-beam excitation in which the emergent probe beam is near linear polarized. Moreover, the major axis of the probe polarization is rotated by about 20° (clockwise from the vertical) as compared to 3° with single 568 nm excitation and 8° with single 442 nm excitation. The results indicate both photoinduced dichroism and photoinduced birefringence are significantly enhanced. The enhancement of photoanisotropy can be understood by the optimization mechanism of direction-selected photoisomerization of BR molecules controlled by the polarized beams. With perpendicularly polarized combination of the exciting beams, the BR molecules in the direction of 568 nm polarization are isomerized to the *M* state by both the 568 nm beam and a projection of 633 nm probe beam, but the molecules in the direction of blue beam polarization are dominated with the *B* state because the initial *M* state induced by weak 633 nm

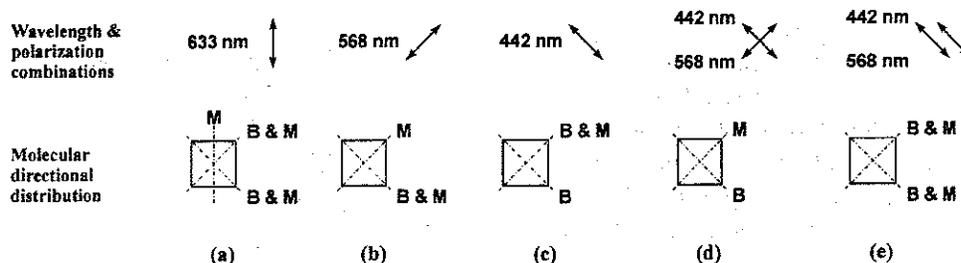


FIG. 3. Schematic illustration of molecular direction-selected distribution of biomaterial controlled by linearly polarized beams of different wavelengths as well as by their polarization combinations. (a) Probe beam 633 nm only; (b) 633 nm probe with 568 nm exciting beam; (c) probe with 442 nm exciting beam; (d) probe with both exciting beams (orthogonal polarization); (e) probe with both exciting beams (parallel polarization). It is clear that the photoinduced anisotropy is maximum for (d) and zero for (e) due to direction-selected photoisomerization.

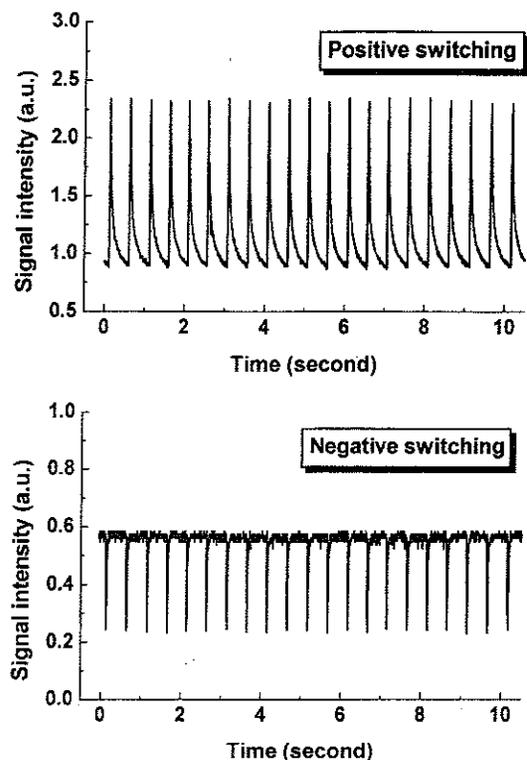


FIG. 4. Optical switching results with the additional facility of controlling output sign. The 442 nm exciting beam with 250 mW/cm^2 is modulated to a pulsed train with 5 ms exposure and 0.5 s delay. Positive switching is achieved by shining another perpendicularly polarized 568 nm beam and negative switching is achieved by shining a parallel-polarized 568 nm beam. The intensity of 568 nm beam is 280 mW/cm^2 .

probe beams are isomerized back to the B state by 442 nm exciting beam. As a result, the strong anisotropic distribution of the B and M state molecules is formed in the film, which results in strong photoanisotropic effect due to significant difference of molecular structure and absorption index between B and M states. With parallel-polarized combination of the exciting beams, the distribution of BR molecules is not changed because the yellow beam induces $B \rightarrow M$ photoisomerization and the blue light beam induces the reverse $M \rightarrow B$ photoisomerization in the same direction of polarization of the exciting beams. As a result, minimal photoanisotropic effect is induced in this case. Figure 3 shows schematic illustration of molecular directional distributions of the two states, B and M , controlled by linearly polarized beams of different wavelengths as well as by their polarization combinations.

We also study all-optical switching properties of the film by using this technique of enhanced photoanisotropy. The 442 nm exciting beam is modulated to a pulsed train with 5 ms exposure and 0.5 s delay. It is found that the probe beam will be switched by turning-on/off the blue exciting pulse. It is interesting that we are able to control the sign of the output from positive to negative by applying the polarized yellow beam in addition to the blue beam. When the applied yellow beam is polarized perpendicularly to the blue beam, positive switching results are obtained, i.e., the signal is turned on as soon as the blue light is turned on and turned off when the

blue light is turned off. If we change the yellow beam to be polarized parallel to the blue beam, negative results are observed, that is, the probe beam is turned off as soon as the blue light is turned on and turned on when the blue light is turned off. Figure 4 displays transient switching results of the 633 nm probe beam by the exciting beams. The polarization-dependent switching behavior can be understood by the mechanism of photoanisotropy induced by different polarization combinations. The perpendicularly polarized combination of yellow and blue beams causes positive enhancement of photoanisotropy while the parallel-polarized combination causes disappearance of photoanisotropy which blocks the probe beam, i.e., the negative switching.

In conclusion, we presented a scheme to significantly enhance the photoanisotropic effects by using two laser beams of different wavelengths with orthogonal polarization. Near 20 times intensity enhancement of the photoanisotropy has been observed as compared with the case of one-color exciting beam. We also demonstrated an all-optical switching device with the output sign controlled by just changing the polarization of one exciting beam. It is possible to achieve ultrafast optical switching since the photoisomerization of the M to B state may be as fast as nanoseconds. The enhancement technique demonstrated here can be applied with other optical materials with properties of photoisomerization or photoinduced molecular reorientation for use in many photonic applications. It may also be useful for enhancement of second- and third-order optical nonlinearities.

- ¹H. Ono and N. Kawatsuki, Appl. Phys. Lett. **74**, 935 (1999).
- ²J. Peretti, J. Biteau, J. P. Boilot, and F. Chaput, Appl. Phys. Lett. **74**, 1657 (1999).
- ³H. Inoue, H. Sakaguchi, and T. Nagamura, Appl. Phys. Lett. **73**, 10 (1998).
- ⁴H. Imam, L. R. Lindvold, and P. S. Ramanujam, Opt. Lett. **20**, 225 (1995).
- ⁵H. Knobloch, H. Orendi, M. Buchel, T. Seki, S. Ito, and W. Knoll, J. Appl. Phys. **77**, 481 (1995).
- ⁶H. Knobloch, H. Orendi, M. Buchel, T. Seki, S. Ito, and W. Knoll, J. Appl. Phys. **76**, 8212 (1994).
- ⁷T. Ikeda and O. Tsutsumi, Science **268**, 1873 (1995).
- ⁸G. E. Dvgalenko, M. Klotz, G. J. Salamo, and G. L. Wood, Appl. Phys. Lett. **68**, 287 (1996).
- ⁹M. Kidowaki, T. Fujiwara, S. Morino, and K. Ichimura, Appl. Phys. Lett. **76**, 1377 (2000).
- ¹⁰E. V. Keuren, T. Wakebe, R. Andraus, H. Möhwald, W. Schrof, V. Belov, H. Matsuda, and R. Rangel-Rojo, Appl. Phys. Lett. **75**, 3312 (1999).
- ¹¹M-C. Oh, H. Zhang, A. Szep, V. Chuyanov, W. H. Steier, C. Zhang, L. R. Dalton, H. Erlig, B. Tsap, and H. R. Fetterman, Appl. Phys. Lett. **76**, 3525 (2000).
- ¹²S. Bauer, J. Appl. Phys. **80**, 5531 (1996).
- ¹³K. Clays, S. V. Elshocht, and A. Persoons, Appl. Phys. Lett. **25**, 1391 (2000).
- ¹⁴D. V. G. L. N. Rao, F. J. Aranda, D. Narayana Rao, J. Joseph, J. A. Akkara, and M. Nakashima, in *Photonic Polymer Systems*, edited by D. L. Wise, G. E. Wnek, D. J. Trantolo, T. M. Cooper, and J. D. Gresser (Marcel Dekker, New York, 1998), Chap. 16, pp. 633–691.
- ¹⁵M. Sanio, U. Settele, K. Anderle, and N. Hampp, Opt. Lett. **24**, 379 (1999).
- ¹⁶Y. Okada-shudo, Proc. SPIE **4461**, 138 (2001).
- ¹⁷P. Bhattacharya, J. Xu, G. Váró, D. L. Marcy, and R. R. Birge, Opt. Lett. **27**, 839 (2002).
- ¹⁸Q. W. Song, Y.-H. Zhang, R. R. Birge, and J. D. Downie, Proc. SPIE **3470**, 226 (1998).
- ¹⁹E. Y. Korchemskaya, D. A. Stepanchikov, A. B. Druzhko, and T. V. Dyukova, J. Biol. Phys. **24**, 201 (1999), and references therein.