All-optical display using photoinduced anisotropy in a bacteriorhodopsin film

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Photoinduced anisotropy in a bacteriorhodopsin film using the pump–probe method was investigated. A diode-pumped second-harmonic YAG laser was used as the pump beam, and three wavelengths, at $\lambda = 442, 532, 655$ nm, from different lasers were used as probe beams. Without the pump beam, the probe light cannot transmit the analyzer to the detector. However, because of photoinduced anisotropy, a portion of the probe light is detected when the pump beam is present. Based on this property, we demonstrate a full-color all-optical display.

Bacteriorhodopsin (bR) is a photchromic protein contained in the purple membrane fragments from the halophile bacterium Halobacterium halobium. Without illumination, the bR film has broadband absorption in the visible spectral region, with an absorption peak at $\lambda \sim 570$ nm. On illumination at $\lambda \sim 570$ nm, the molecules undergo several structural transformations that correspond to intermediate states K, L, M, N, and O in a well-defined photocycle.1 Because bR exhibits a large optical absorption cross section and nonlinearity, and good stability to photodegradation and temperature, it has been regarded as the most promising biological molecule for photonic applications. Various applications have been proposed.2–9 Among them, all-optical display is particularly interesting.7–9 An optically addressed direct-view display that uses the photoinduced absorption change in bR has been demonstrated.7 However, the display based on the bR's absorption change can switch between purple and yellow spectral regions only, as bR transmits purple wavelengths in its metastable excited (M) state. For all-optical displays, the device should operate in the whole visible region while exhibiting a high contrast ratio.

In this Letter we demonstrate a high-contrast and broadband all-optical display that uses the photoinduced anisotropy in bR film. Photoinduced anisotropy is due to photoanisotropic selective bleaching of randomly distributed anisotropic molecules under linearly polarized light.10 Photoinduced dichroism and photoinduced birefringence are two possible causes of the observed photoinduced anisotropy. Photoinduced dichroism predominates when the probe wavelength is near the absorption peak, whereas photoinduced birefringence predominates when the probe wavelength is far from the absorption peak. Because bR absorbs visible light, the photoinduced anisotropy should cover the entire visible range. Therefore an all-optical display based on photoinduced anisotropy can be achieved in the whole visible region.

We used the photoinduced anisotropy of bR at blue (B; $\lambda = 442$ nm), green (G; $\lambda = 532$ nm), and red (R; $\lambda = 655$ nm) wavelengths as examples to demonstrate that the photoinduced anisotropy of bR is indeed broadband.

First we investigated the intensity-dependent photoinduced anisotropy at three laser wavelengths: $\lambda = 442, 532, 655$ nm. Figure 1 depicts the experimental apparatus. A linearly polarized diode-pumped Nd:YAG laser ($\lambda = 532$ nm) was converted to circularly polarized light by a quarter-wave plate (Newport 10RP44-1) and then split into two beams by a beam splitter. One of the green beams was used as a pump beam. We used linear polarizer P1 to select the desired polarization state. The other green diode laser beam ($\lambda = 455$ nm) was used as a probe beam. The sample was placed between two crossed Glan–Thompson polarizers, P2 and P3. Polarizer P2 was oriented at 45° with respect to polarizer P1 to produce maximum phase retardation.11 As illustrated in Fig. 1, the pump beam overlapped the probe beam on the bR film. The bR samples were purchased from Munich Innovative Biomaterials GmbH (order number WT1N3). The thickness of a bR sample was $\approx 80 \mu m$, and the optical density was 3 at $\lambda = 570 \mu m$.

Figure 2 shows the pump-beam-induced probe-beam transmission through the bR film. In the beginning, the anisotropic photosensitive molecules are randomly distributed in the bR film, so the film appears

![Diagram](image)

Fig. 1. Experimental apparatus for investigating photoinduced anisotropy in a bR film: P1, P3, crossed polarizers; P2 is at 45° with respect to P1. NDs, neutral-density filters.
isotropic. In this case the polarization direction of the probe beam is not rotated by the bR film. Therefore the probe beam does not transmit the analyzer, which is perpendicular to the polarizer. When the pump beam is present, a portion of the probe beam is transmitted by the analyzer, as shown in Fig. 2. On excitation of linearly polarized light, those bR molecules with the dipole moment aligned along or close to the direction of light polarization are bleached and then go through several intermediate states (K, L, M, N, and O) and relax to the initial state spontaneously.1 Those molecules with perpendicular orientation are spared. As a result, the bR film exhibits macroscopic optical anisotropy in the illumination area. This photoinduced birefringence causes phase retardation of the probe beam. Therefore a portion of probe beam transmits the analyzer to the detector.

From Fig. 2, the contrast ratio (CR) can be calculated from the following equation:

$$CR = I_{\text{max}} / I_{\text{min}},$$

(1)

Our measured CR was greater than 300:1 for all three wavelengths employed. The rise time was ~0.6 s, and the decay time was ~1.5 s. The slow response time is due to the long lifetime (~5 s) of the M state. One can easily improve the M-state lifetime by changing the pH value and the humidity of the sample during fabrication. Therefore the demonstrated all-optical display will have a fast response time if the new bR film is employed.

Then we investigated the intensity-dependent transmittance of the probe beam. We observed that the transmittance of the probe beam depends strongly on the intensity of the incident pump beam. Figure 3 plots the pump beam’s intensity-dependent transmittance of the RGB probe beams (λ = 655, 532, 442 nm) at $I \sim 39,28,45$ mW/cm², respectively. When the pump beam’s intensity was low, the probe beam’s transmittance was almost linearly proportional to the pump beam’s intensity. As the pump beam’s intensity got higher than ~500 mW/cm², the transmittance of the probe beam gradually saturated. This result is easy to explain: When the pump beam is weak, the number of excited molecules is proportional to the intensity of the pump beam. As a result, the photoinduced anisotropy is proportional to the pump beam’s intensity. Accordingly, the transmittance of the probe beam is proportional to the pump beam’s intensity. However, in the high-intensity regime almost all the molecules in the ground state have been bleached to the excited state, so no more molecules are spared for the increased pump beam intensity. As a result, the photoinduced anisotropy is saturated. Consequently, the transmittance also saturates. Because bR has a larger absorption cross section at 532 nm than at 442 and 655 nm, the transmittance of the probe beam at 532 nm is less than that at 442 and 655 nm, as illustrated in Fig. 3.

Here we use the photoinduced anisotropy at the three wavelengths of λ = 442, 532, 655 nm as examples to demonstrate its potential applications for all-optical display. The experimental setup is similar to that shown in Fig. 1, except that both the pump and the probe beams are expanded to ~20 mm in diameter and the detector is replaced by a CCD camera. A test pattern is projected by the pump laser at λ = 532 nm onto the rear side of the bR film. We use the CCD camera to capture the pattern of the expanded probe beam at λ = 532, 442, 655 nm.

When the pump beam is blocked, we cannot capture the test pattern on the probe beam. But, when the pump beam is turned on, we can capture the test pattern on the probe beam no matter whether the probe beam is 655, 532, or 442 nm. Figure 4 shows the results when the intensity of the pump beam was 24 mW/cm² and the intensity of the probe beam (λ = 655, 532, 442 nm) was 0.3, 0.6, and 0.25 mW/cm², respectively. We found that the pattern attained by λ = 532 nm is darker than that by λ = 442, 655 nm. As described above, this result is due mainly to the larger absorption of bR at 532 nm than at 442 and

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**Fig. 2.** Experimental results before and after the pump beam is turned on: (a) $\lambda = 442$ nm, (b) $\lambda = 532$ nm, (c) $\lambda = 655$ nm. The intensity of the green pump beam is 1400 mW/cm², and the intensities of the 442-, 532-, and 655-nm probe beams are $I = 110,70,90$ mW/cm², respectively.

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**Fig. 3.** Transmittance of the probe beam as a function of pump-beam intensity.

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**Fig. 4.** Transmittance of the probe beam at different wavelengths as a function of pumping beam intensity.
Fig. 4. Images measured with a CCD camera: (a) original image, (b) $\lambda = 442$ nm, (c) $\lambda = 532$ nm, (d) $\lambda = 655$ nm. Pump beam, $\lambda = 532$ nm with $I = 24$ mW/cm$^2$. Probe-beam intensities, $I = 0.3, 0.6, 0.25$ mW/cm$^2$ for $\lambda = 655, 532, 442$ nm, respectively.

655 nm. One can enhance the brightness by increasing the incident intensity of the pump or the probe beam.

A critical requirement for such an all-optical display is to obtain balanced white and gray scales. The spectral content of each color depends on the laser wavelengths that are employed and on their transmittance. In our case, the three primary colors are R = 655 nm, G = 532 nm, and B = 442 nm. From the CIELAB chromaticity diagram we calculated that the ratio of the RGB spectral content for achieving the standard D65 white color should be 26:32:42. However, as shown in Fig. 3, the bR film has a different transmittance for the RGB laser wavelengths. Taking this intensity-dependent transmittance of the probe beams into account, we found that the incident RGB laser intensity ratio should be approximately 5:18:2. If we want to obtain 10-mW/cm$^2$ white-light output, the incident probe RGB beam intensities should be 565, 2000, and 221 mW/cm$^2$, respectively. One can obtain gray scales by controlling the pump beam’s intensity and different colors by monitoring the incident probe beam’s intensity. To maintain a linear gray scale, one should keep the pump beam’s intensity within the linear regime, that is, $I_{\text{pump}} < 500$ mW/cm$^2$, as observed from Fig. 3. In addition, the display brightness can easily be controlled in the acceptable range of the human eye by choice of a suitable intensity of the pump and probe beams. Therefore the bR film can be used for direct-view all-optical display or wavelength conversion. Its major advantages are broad bandwidth, coherent (incoherent) to coherent (incoherent) image conversion, low cost, and high resolution.$^{12}$

In conclusion, we have investigated photoinduced anisotropy in bR film at RGB wavelengths and demonstrated its application for all-optical display. Because bR exhibits broadband photoinduced anisotropy in the whole visible region, the all-optical display based on the photoinduced anisotropy can be used in the whole visible range. The measured contrast is higher than 300:1. Although the response time of the present bR film is slow, one can easily improve it by changing the humidity and the pH values of the sample during fabrication.

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