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The behaviours of optical novelty filter based on bacteriorhodopsin film*

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The quality of the novelty filter image is investigated at different intensities of the incident blue and yellow beams irradiating a bacteriorhodopsin (bR) film. The relationship between the transmitted blue beams and the incident yellow beams is established. The results show that the contrast of the novelty filter image depends on the lifetime of longest lived photochemical state (M state). These results enable one to identify the direction of a moving object and to improve the quality of the novel filter image by prolonging the lifetime of M state.

Keywords: optical novelty filter, bacteriorhodopsin film
PACC: 4240F, 4270J, 4280C

1. Introduction

An optical novelty filter in an incoherent light system has been designed based on a special property of dynamic complementary suppression modulated transmission (DCSMT) in the bR film.[1−3] Compared with other kinds of optical novelty filters,[4−10] it has many advantages[1,11] and great potential applications in image processing systems. The relationship of the contrast of the novelty filter image with the parameters of the bR film has been investigated,[12] which shows that the quality of the novelty filter image depends on the parameters of the bR film and the rates of input image. In this paper, it is indicated that the quality of the novelty filter image is dependent on not only the intensities of incident yellow and blue beams but also the lifetime of the longest lived photochemical state (M state).

Firstly, the intensities of incident yellow beams that can suppress about 95 percent of the incident blue beam are discussed; Secondly, the contrast of the novelty filter image as a function of incident intensity is presented; Finally, with the intensity of incident blue beam fixed and that of the incident yellow beam changed, the contrast of the novelty filter image varying with the lifetime (τ) of M state is studied, from which it is found that the quality of novelty filter image can be improved by prolonging the lifetime of M state in the bR film.

2. Principle

Bacteriorhodopsin is a type of light-transducing protein in the purple membrane of Halobacterium salinarium,[12,13] and extremely sensitive to the light in a broad visible region. Upon absorbing light energy, the bR undergoes a complex photocycle characterized by several spectroscopically distinct thermal intermediates, among which two important photochemical states are referred to as B state and M state. The B state represents the ground state, which is characterized by a strong absorption peak located at 568 nm, while the M state denotes the longest lived (ms–s) state, which exhibits a strong blue-shifted absorption around 412 nm. With the bR film irradiated by the yellow light, its transmission increases at 568 nm while it decreases at 412 nm. Based on the simplified energy level diagram,[13,14] the transmitted intensity through the sample is described by the Lambert–Beer Law of absorption. For a thick layer of absorbing sam-

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ple, the effective transmitted intensities are given by the following differential equations:

$$\mathrm{d}I_1/\mathrm{d}z = -2.3026\varepsilon_1 N_B I_1\,, \tag{1}$$

$$\mathrm{d}I_2/\mathrm{d}z = -2.3026\varepsilon_2 N_M I_2\,, \tag{2}$$

where N_B and $N_M = (Nk_1/k)(1-\mathrm{e}^{-kt})$ are the molecular concentrations of B and M states, respectively, N the total molecular concentration in the bR film, and $k = k_1 + k_2 + k_3$, among which $k_3 = 1/\tau$, and k_1 and k_2 are the different photochemical rate constants, which can be determined by the optical properties of the film and the intensities of incident beams via the following relationships:

$$k_1 = 2.3026\phi\varepsilon_1\lambda_1 I_1/N_a hc, \tag{3}$$

$$k_2 = 2.3026\phi\varepsilon_2\lambda_2 I_2/N_a hc, \tag{4}$$

where $\varepsilon_1 = 63000$ and $\varepsilon_2 = 45000$ are the molecular extinction coefficients for the considered photo-reaction at wavelengths $\lambda_1 = 568$ nm and $\lambda_2 = 418$ nm, respectively, ϕ the quantum yield of the photo-transformation, N_a Avogadro number, h Plank's constant, c the speed of light (in m/s) in vacuum, and I_1 and I_2 (in mW/cm^2) are the incident intensities corresponding to wavelengths λ_1 and λ_2 respectively.

3. Modulation of incident blue and yellow beams

Figure 1 shows the variation in transmitted blue intensity with the intensity of incident yellow beam in a stable state. Curves 1, 2, 3 and 4 in Fig.1 are for the incident blue beams at intensities of 1, 2, 3 and 4 mW/cm^2, respectively, while the intensity of transmitted blue beam decreases with the increase of intensity of incident yellow beams. Figure 1 clearly shows that the lowest intensities for yellow beams that can suppress about 95 percent of blue beams are 3, 4, 5 and 6 mW/cm^2 as shown in curves 1, 2, 3 and 4 respectively. The intensities of transmitted blue beams varying with time are shown in Fig.2, where the intensities of incident blue beams corresponding to curves 1, 2 and 3 are 1, 2, 3 mW/cm^2, and those of yellow beams are 3, 4, 5 mW/cm^2 respectively. At $t = 10$ s, curves 1, 2 and 3 overlap together and all approach zero. While for $t < 10$ s, the higher the intensity of incident blue beam is, the higher the intensity of transmitted blue beam becomes and the faster the intensity of transmitted blue beam decreases.

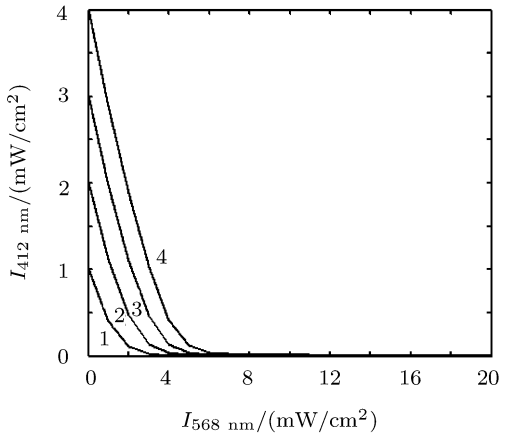


Fig.1. The intensities of transmitted blue beams versus intensities of incident yellow beam where the thickness (d) of the film is 0.02 cm, the lifetime (τ) of M state is 5 s, and the molecular concentration (N) of the bR film is 0.003 mol$\cdot$L^{-1}.

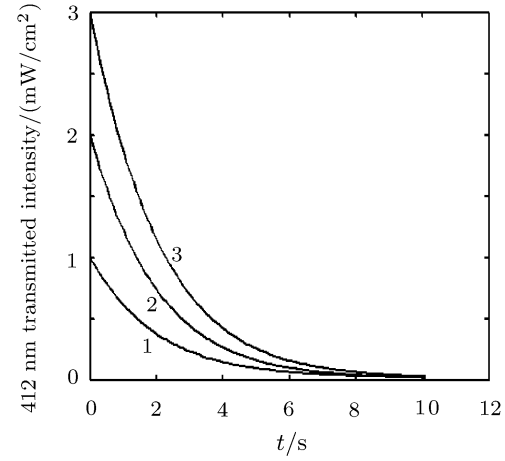
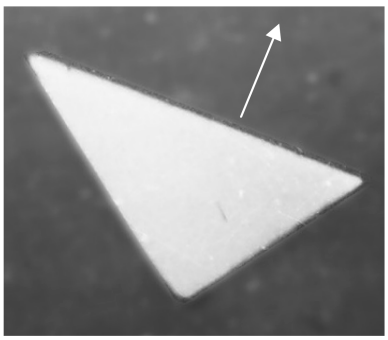


Fig.2. The intensities of transmitted blue beams versus time where $d = 0.02$ cm, $\tau = 5$ s, and $N = 0.003$ mol$\cdot$L^{-1}.

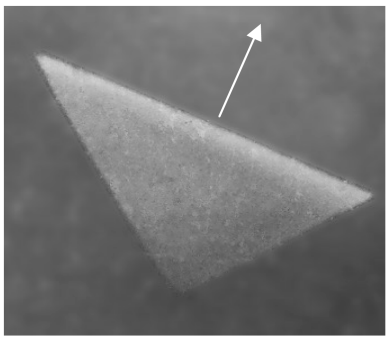
4. Proof of principle

The experimental setup is shown in Ref.[1]. The bR film has the lifetime of M state $\tau = 5$ s, the thickness $d = 0.02$ cm and the molecular concentration $N = 0.009$ mol$\cdot$L^{-1}. A yellow beam with an intensity of 2.0 mW/cm^2 from a tungsten lamp is filtered by a 568 nm filter, and a blue beam with an intensity of 1.0 mW/cm^2 from a xenon lamp is filtered by a 412 nm filter. The two beams simultaneously irradiate the pattern through a half-reflecting mirror (HR).

The pattern is inserted into the path through which the yellow and the blue beams pass, and then the bR film is irradiated at the same position. The output image on the bR film can be monitored on the screen or recorded by a CCD camera. When the object is immovable, which means the molecular concentrations in B state and M state are balanced, there is no output image of the immovable object on the screen with a background intensity of about 0.1 mW/cm^2, because the blue beam is suppressed by the yellow beam. Once the pattern starts to move from its immovable state, the balance of molecular concentrations in B state and M state is broken, and we catch an output image at $t = 6$ s as shown in Fig.3(b) while the input image (triangle pattern) on bR film moves at a speed of 0.15 cm/s.



(a)



(b)

Fig.3. Experimental demonstration of the novelty filter by the bR film, (a) and (b) are the input pattern and the output image respectively.

The leading edge of the output image becomes brighter than the other parts and stays the brightest, because the irradiation time t of this part is the shortest ($t \sim 0$), and the intensity of the transmitted blue beam is maximum (see Fig.2). In the middle part of the input image on the bR film, which is exposed to the blue beam for a longer time than the leading edge, the intensity of the transmitted blue beam is lower than that of the leading edge (see Fig.2), so the middle part becomes darker. The back part of the input image is irradiated for a longest time, thus the corresponding output image is darkest. Therefore, the leading edge of the output image is brightest and the back part is darkest, though the pattern moves at the same speed.

5. The contrast dependence on incident intensities

The quality of the image is often measured by the contrast dependence on the intensities of the image and background. In the novelty filter image, the leading side of the image corresponds to the brightest image side with the highest transmitted intensity, while the other side corresponds to the darkest side with the lowest transmitted intensity. The contrast of the image can be defined as

$$I_{\mathrm{c}} = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}), \qquad (5)$$

where $I_{\min}$ and $I_{\max}$ are the image intensities of the darkest side and the brightest side respectively. Based on the contrast, the intensity distribution in the novelty filter image can be evaluated, which has the guidance information of showing the direction of the moving object and the observed area of the novelty filter image under a fixed background. When the contrast is equal to 1, the full area of the novelty image can be observed only under the background intensity being zero since the lowest intensity on the back side of novelty image is zero. Once the intensity of the background is more than zero, only a part of image can be observed. In this case, the quality of novelty filter is poor.

Figure 4 shows the contrast of the novelty filter varying with the thickness at different intensities of incident blue and yellow beams on condition that the movement speed (v) of the input image on the bR film equals 1 cm/s, $\tau = 5$ s, and $N = 0.003$ mol$\cdot$L^{-1}. The intensities of incident blue beams are 1, 2 and 3 mW/cm^2 corresponding to curves 1, 2 and 3, and those of incident yellow beams are 3, 4, 5 mW/cm^2, respectively. The lowest contrasts corresponding to curves 1, 2 and 3 are 0.47, 0.57 and 0.65 respectively where the product of the molecular concentration and the thickness is 3×10^{-5}mol$\cdot$L$^{-1}\cdot$cm

(where $d = 0.01$ cm). As the product increases to $1.4 \times 10^{-3}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$, all contrasts are equal to 1, which means that the lowest zero intensity of the novelty filter image depends only on the product, and it is independent of the incident intensity. When the product lies between $3\times10^{-5}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$ and $1.4\times10^{-3}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$, the full area of the novelty image can be observed under a background of zero. Obviously, curve 3 has the highest contrast, which means that a biggest difference between $I_{\max}$ and $I_{\min}$ exists and increases with the increase of intensities of incident blue and yellow beams.

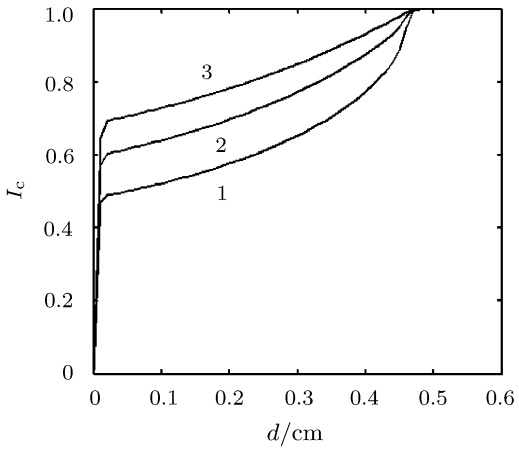


Fig.4. The contrast of the novelty filter versus the thickness at different intensities of incident blue and yellow beams.

6. The contrast dependence on the lifetime of M state

The relationship between the contrast and the molecular concentration at different lifetimes of M state is shown in Fig.5, where the lifetimes of M state corresponding to curves 1, 2 and 3 are 5 s, 10 s and 25 s, respectively. The intensity of incident blue beam is 1.0 mW/cm^2 and the intensities of incident yellow beams corresponding to curves 1, 2 and 3 are 3, 2 and 1.3 mW/cm^2 respectively, namely the lowest intensities that can suppress 95 percent of blue beams. For a fixed intensity (1.0 mW/cm^2) of incident blue beam, it is clear that the longer the lifetime of M state, the lower the contrast and the higher the lowest intensity of the novelty filter image.

The lowest contrasts corresponding to curves 1, 2 and 3 are 0.46, 0.32, and 0.2, respectively, where the product of the molecular concentration and the thickness is $3\times10^{-5}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$. When the product equals $1.4\times10^{-3}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$, the contrasts are all equal to 1. While the product lies between $3 \times 10^{-5}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$ and $1.4 \times 10^{-3}\text{mol}\cdot\text{L}^{-1}\cdot\text{cm}$, the full area of the novelty filter image can be observed under a background of zero. With the lifetime of M state prolonged, the image becomes brighter.

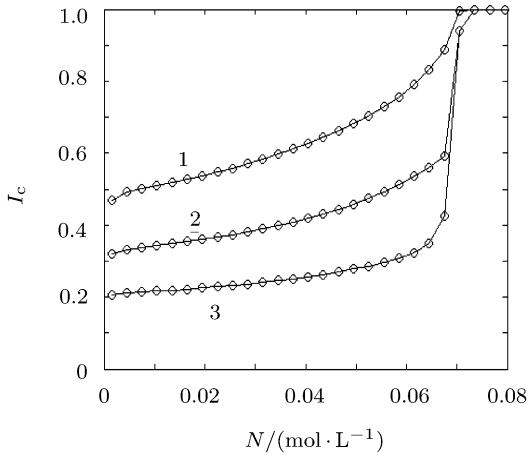


Fig.5. The contrast versus the molecular concentration at different lifetimes of M state where $v = 1$ cm/s, and $d = 0.02$ cm.

7. Conclusions

We have discussed the characteristics of modulation of the different intensities of incident blue and yellow beams in a stable state and obtained the lowest intensity of incident yellow beam that can suppress 95 percent of blue beam. The transmitted intensity versus time at different intensities of incident blue and yellow beams is investigated, and the relationships of the contrast with the lifetime of M state and the incident intensities are established, from which two conclusions can be drawn. One is that the difference in intensity between $I_{\min}$ and $I_{\max}$ becomes larger with the increase of incident intensity, from which one can identify the direction of moving object easily by using a single image; the other is that if the lifetime of M state is prolonged, the intensity of the lowest side image in the novelty filter image will increase, which makes the image easy to be observed in the real-time monitoring screen.

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