Vol 17 No 11, November 2008
1674-1056/2008/17(11)/4218-08

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

An all-optical time-delay relay based on a bacteriorhodopsin film*

Chen Gui-Ying(陈桂英)[a)†], Xu Xu-Xu(许旭旭)[a)], Zhang Chun-Ping(张春平)[b)], Qi Shen-Wen(祁胜文)[c)], and Song Qi-Wang(宋奇望)[d)]

[a)] *Key Laboratory of Tropical Marine Environmental Dynamics, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou* 510301, *China*

[b)] *The Key Laboratory of Weak Light Nonlinear Photonics (Nankai University, Tianjin* 300457*), Ministry of Education, China*

[c)] *Department of Physics, Dezhou University, Shandong* 253023, *China*

[d)] *Department of Electrical Engineering and Computer Science, Syracuse University, Syracuse, NY* 13224-1240, *USA*

(Received 1 November 2007; revised manuscript received 30 May 2008)

Using a special property of dynamic complementary-suppression-modulated transmission (DCSMT) in the bacteriorhodopsin (bR) film, we have demonstrated an all-optical time-delay relay. To extend our work, the relationship between the delay time of the all-optical time-delay relay and parameters of a bR film is numerically studied. We show how the delay time changes with the product of concentration and thickness (PCT) of a bR film. Furthermore, the shortest and longest delay times are given for the relay of 'switch off'. The saturable delay time and maximum delay-time of 'switch on' are also given. How the wavelengths (632.8, 568, 533 and 412 nm) and intensities of the illuminating light influence the delay time is also discussed. The simulation results are useful for optimizing the design of all-optical time-delay relays.

Keywords: bR film, all-optical time-delay relay, dynamic complementary-suppression-modulated transmission

PACC: 4280V, 4225B

1. Introduction

A time-delay relay is a relay that stays on for a certain amount of time once activated. It plays an important role in an automatic control system. An all-optical time delay is a significant unit and has potential applications in an optical control system. Since the photochromic protein bacteriorhodopsin has its unique properties, such as large optical nonlinearity and high stability towards photodegradation and temperature, it is one of the most promising candidates for potential applications in photonic devices.[1−12] Using the dynamic properties of a bacteriorhodopsin (bR) film, some all-optical devices were recently reported, among them were novel filters and time-dependent all-optical logic gates.[10,11] In addition, an all–optical time-delay relay[1] has been designed and demonstrated based on the property of complementary-suppression-modulated transmission (DCSMT) in a bR film. We should emphasize that the former requires 'fast' dynamic properties of the bR film, while the latter uses the 'slow' dynamic properties of the bR film. In this paper, we study the relationship among all-optical delay time of time-delay relays, parameters of the bR film, wavelengths and intensities of the illuminating light. Our results are useful for designing all-optical time-delay relays, and can provide a guideline in optimizing all-optical time-delay relays.

2. Principle

Bacteriorhodopsin is a light-transducing protein in a purple membrane of Halobacterium salinarium[13,14] and is extremely sensitive to light in a broad visible region. On the absorption of light energy, bR undergoes a complex photocycle characterized by several spectroscopically distinct thermal intermediates, among which are two important photochemical states, referred to as the B state and the M state. The B state is the ground state, which is characterized by a strong absorption band B with an absorption peak located at 568 nm; the M state is

*Project supported by the National Natural Science Foundation of China (Grant Nos 10774152, and 60578020), the Natural Science Foundation of Shangdong Province, China (Grant No Y2006A01), and the Key Laboratory of Weak Light Nonlinear Photonics.

†E-mail: Julie_chen6323@yahoo.com.cn

the longest-lived state, which exhibits a strong blue shifted absorption band M near 412 nm. The bR absorption spectra in the B state and the M state are shown in Fig.1. With yellow light illumination (or the light beams at wavelengths of 533 and 632.8 nm) near the absorption peak in the B state, the transmission of the bR film at 568 nm (or 533 and 632.8 nm) increases but the transmission at 412 nm decreases. Based on a simplified energy-level diagram,[15−17] the transmitted

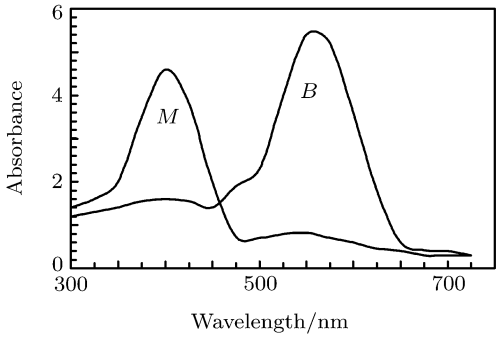


Fig.1. Absorption spectrum.

intensity passing through the sample is described by the Lambert–Beer law of absorption: for a thick layer of absorbing sample, it is divided into 100 layers; and for each layer, the effective transmitted intensity is given by the differential equations (1) and (2) as follows:

$$\frac{\mathrm{d}I_1}{\mathrm{d}z} = 2.3026(\varepsilon_B^{\lambda_1} N_B + \varepsilon_M^{\lambda_1} N_M) I_1, \tag{1}$$

and

$$\frac{\mathrm{d}I_2}{\mathrm{d}z} = 2.3026(\varepsilon_B^{412} N_B + \varepsilon_M^{412} N_M) I_2, \tag{2}$$

where

$$N_M = (Nk_1/k)[1 - \exp(-kt)], \tag{3}$$

with N being the total molecular concentration of the bR film, N_B and N_M being the molecular concentrations of the B state and the M state, respectively, parameter $k = k_1 + k_2 + k_3, k_3 = 1/\tau$, where τ is the lifetime of the M state, and k_1 and k_2 are the different photochemical rate constants that can be written as a function of the film optical properties and the intensities of the illumination beams as follows:

$$k_1 = 2.3026\phi\varepsilon_B^{\lambda_1}\lambda_1 I_1/(N_a hc), \tag{4}$$

and

$$k_2 = 2.3026\phi\varepsilon_M^{412}\lambda_2 I_2/(N_a hc), \tag{5}$$

where ϕ=0.64 is the quantum yield of the photo transformation; λ_1=568, 533 or 632.8 nm, λ_2=412 nm; The molecular extinction coefficients ε_B^{568}=63000, ε_B^{533}=54000, $\varepsilon_B^{632.8}$=15000 and ε_B^{412}=5000 are for $B \rightarrow M$, while ε_M^{412}=45000, ε_M^{568}=10000, ε_M^{533}=3000 and $\varepsilon_M^{632.8}$=0 are for $M \rightarrow B$; parameters I_1 and I_2 (mW/cm^2) are the intensities at wavelengths λ_1 and λ_2, respectively; N_a is Avogadro's number; h is Planck's constant; c is the speed of light (m/s). From Eqs.(1) and (2) and expressions (3)–(5), the transmitted intensity of the last layer can be obtained as an output.

For a given value of the incident light, based on Eqs.(1) and (2) the transmitted intensity depends on both molecular concentration and integral variable z (an integral of the thickness of the bR film), or the product of concentration and thickness (PCT). In other words, the transmitted intensity depends on how much incident light is absorbed. The absorption relies on the molecular number at the position where incident light illuminates, which is related to PCT. In order to describe universally the characteristics of the bR film, in our study we choose the PCT as a parameter to discuss the delay time of all-optical time-delay relay.

3. Delay time of a time-delay relay

3.1. Delay-time of switch off dependent on parameters

The experiment setup is given in Ref.[1]. The bR film with radix of polyvinyl alcohol (PVA) has good optical properties and flexibility in fabrication. It has a lifetime of the M state τ=5 s, a thickness d=0.02 cm, a molecular concentration N=0.003 mol·L^{-1}, and the optical density at 570 nm being about 3. Using a yellow beam and a blue beam we can demonstrate a switch that has a delay time after 'switch off' or 'switch on' is activated.

In the following discussion, for the switch off, the delay time is corresponding to the time when the output intensity (blue beam) decreases down to 60% of the value at t=0. For the switch on, the delay time is corresponding to the time when the output intensity (yellow, green or red beam) increases up to 60% of the normalized value.

The lifetime of M state for the bR film can be prolonged by chemical methods,[18] for example, by adding $LaCl_3$, $LuCl_3$ or ethylenediamine. There are two types of bacteriorhodopsins, i.e. wild type and

enhanced type. The lifetime of M state can be controlled in 5–25 s or longer for the enhanced bacteriorhodopsin (eg.N96); namely, the lifetime of M state can be controlled in a range for the same type of bR film. Thereby, for a particular type of bR film we use a model to discuss cases for different lifetimes of M state to indicate appropriate lifetimes of M state according to the requirement.

Figure 2 shows the simulation results. The delay time varies with the product of concentration and thickness for different lifetimes of the M state. Curves with open circles, triangles, crosses and without mark are for τ=5, 10, 15 and 20 s, respectively. Figure 2(a) shows that the wavelengths of the input beam are 568 and 412 nm, and the corresponding intensities are the same, each with a value of 2 mW/cm^2. Curves with open circles indicate that the delay time of 7.72 s is given theoretically for τ=5 s, which is corresponding to the lowest value of PCT of 0.24×10^{-4} mol·L^{-1}·cm we have calculated. When the PCT is less than this lowest value, the output blue beam cannot be depressed to 60% of the initial value without the input yellow beam (IYB). It is easy to understand that a low PCT is corresponding to a low concentration of bR molecules in the bR film, thereby the function of DCSMT is weak, that is, the output blue beam is depressed weakly by the yellow beam. It is obvious that in order for the output blue beam to be depressed to 60% of IYB, the lowest value of PCT is required to be 0.24×10^{-4} mol·L^{-1}·cm for τ=5 s. When the value of PCT increases, the property of DCSMT becomes more prominent, and the blue beam is quickly de-

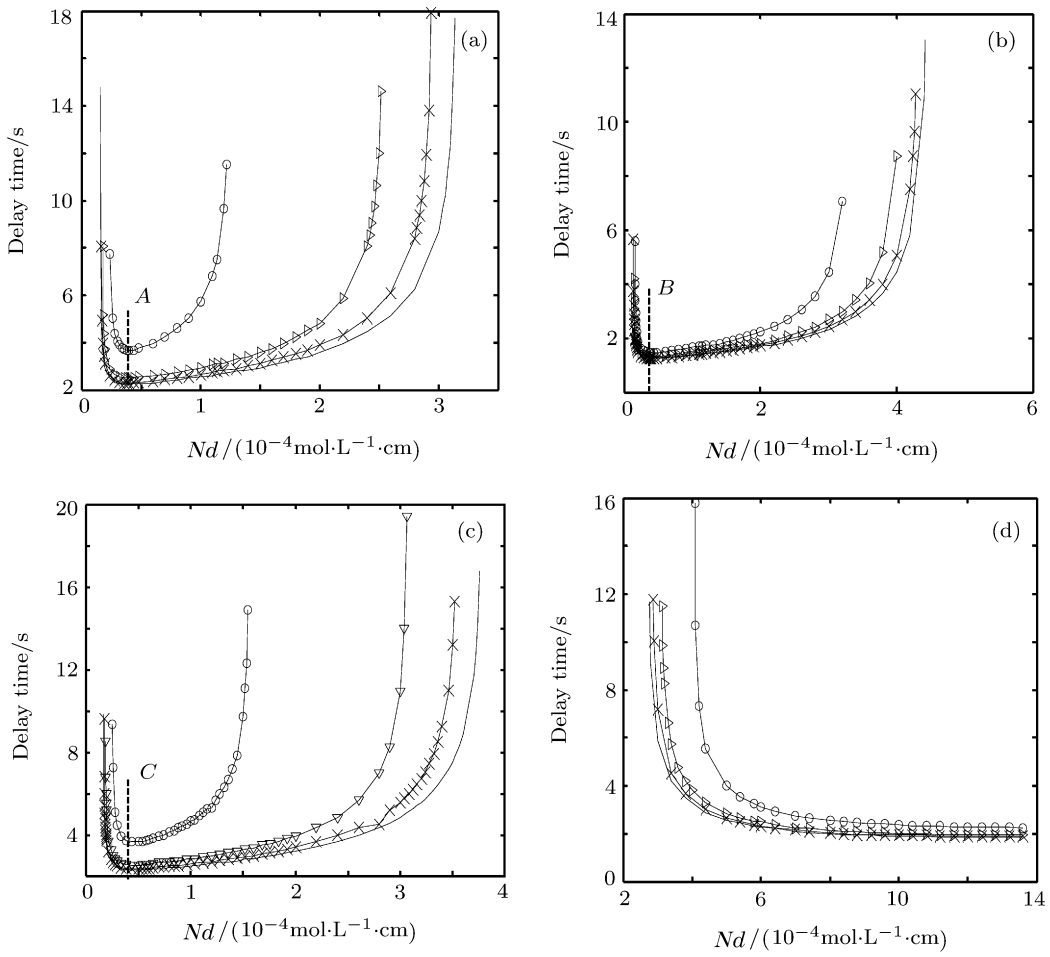


Fig.2. The variation in delay time of "switch off" with PCT, where curves with circles, triangles, crosses and without mark are for τ=5, 10, 15 and 20 s, respectively; panel (a) is for the input wavelengths of 568 and 412 nm each with an input intensity of 2 mW/cm^2; panel (b) is for input intensities of 3 mW/cm^2 for 568nm, and 2 mW/cm^2 for 412nm; panel (c) is for wavelengths of input beams of 533 and 412 nm each with an input intensity of 2 mW/cm^2; panel (d) is for input wavelengths of 632.8 and 412 nm each with an input intensity of 2 mW/cm^2.

pressed by the yellow beam; as a result, the delay time decreases as the PCT increases. When the PCT is between 0.36×10^{-4} and 0.44×10^{-4} mol·L^{-1}·cm, the delay time has a minimum value of 3.68 s. However, when the PCT increases further, the delay time increases too. This is because when the concentration of bR molecules is high enough, according to Fig.1, most of yellow beam is absorbed; in the meantime, the blue beam is less absorbed by bR molecules than the yellow beam, that is, less yellow beam depresses the blue beam. Thus, the property of DCSMT becomes weaker again, and the blue beam is slowly depressed by a yellow beam, which is the reason for delay-time increase with PCT increasing. When the PCT increases from 0.44×10^{-4} to 0.8×10^{-4} mol·L^{-1}·cm, the delay time increases slowly, and when the PCT is over 0.8×10^{-4} mol·L^{-1}·cm, the delay time increases quickly. The longest delay time is 11.5 s when the PCT increases to 1.22×10^{-4} mol·L^{-1}·cm. When the PCT increases further, the output blue beam cannot be depressed to 60% of IYB. It means that there is not enough matched yellow beam to depress 60% of the blue beam from the input yellow beam.

In the same way, curves with triangles, crosses and without mark are, respectively, for τ=10, 15 and 20 s, and their smallest values of PCT are 0.178×10^{-4}, 0.166×10^{-4} and 0.16×10^{-4} mol·L^{-1}·cm, which are corresponding to delay times of 8.08, 8.08 and 14.8 s. When the PCT is between 0.36×10^{-4} and 0.44×10^{-4} mol·L^{-1}·cm, the delay times have minimum values, which are 2.48, 2.28 and 2.2 s for τ=10, 15 and 20 s, respectively. As the PCT continuously increases, the delay time continuously increases, too. For τ=10 s, the delay time increases slowly between 0.44×10^{-4} and 0.22×10^{-4} mol·L^{-1}·cm, and if the PCT is more than 0.22×10^{-4} mol·L^{-1}·cm, the delay time increases quickly. The longest delay time is 14.6 s, corresponding to the largest PCT of 2.52×10^{-4} mol·L^{-1}·cm. For τ=15 s, the delay time increases slowly between 0.44×10^{-4} and 2.24×10^{-4} mol·L^{-1}·cm, and if the PCT is more than 2.24×10^{-4} mol·L^{-1}·cm, the delay time increases quickly. The longest delay time is 17.92 s, and its corresponding largest PCT is 2.94×10^{-4} mol·L^{-1}·cm. For τ=20 s, the delay time increases slowly between 0.44×10^{-4} and 2.5×10^{-4} mol·L^{-1}·cm, and if the PCT is more than 2.5×10^{-4} mol·L^{-1}·cm, the delay time increases quickly. The longest delay time is 17.68 s, and its corresponding largest PCT is 3.14×10^{-4} mol·L^{-1}·cm.

In Fig.2(a), when the PCT is between 0.44×10^{-4} and 0.22×10^{-4} mol·L^{-1}·cm for different lifetimes of the M state, an extremum is reached (marked by line A). A long τ is corresponding to a short extremum of the delay time. On the right side of line A, the values of sensitive PCT which cause the delay time to change sharply are around 1.2, 2.46, 2.9 and 3.0×10^{-4} mol·L^{-1}·cm for τ=5, 10, 15 and 20 s, respectively. On the left side of line A, the values of sensitive PCT are 0.24, 0.178, 0.166 and 0.16×10^{-4} mol·L^{-1}·cm, respectively. In other words, a long τ is corresponding to either a large sensitive PCT or a small sensitive PCT.

Figure 2(b) shows that the wavelengths of input beam are 568 and 412 nm, and the corresponding intensities are 3 and 2 mW/cm^2, respectively. Line B there indicates the PCT where a small extremum of delay time exists. Between 0.36×10^{-4} and 0.48×10^{-4} mol·L^{-1}·cm, the delay time of extremum is 1.44 s for τ=5 s. For τ=10, 15 and 20 s, the extrema of delay times of are 1.28, 1.24 and 1.24 s, respectively, and the corresponding PCT ranges are 0.32×10^{-4}–0.48×10^{-4}, 0.32×10^{-4}–0.6×10^{-4} and 0.28×10^{-4}–0.7×10^{-4} mol·L^{-1}·cm, respectively. It is obvious that a long lifetime of the M state is corresponding not only to a short extremum of the delay time but also to a wide range of the PCT. On the left side of line B, the delay time decreases with PCT increasing, and the values of sensitive PCT are very close, with the values of τ being in a range of 5–20 s. The lowest values of PCT are 0.158×10^{-4}, 0.142×10^{-4}, 0.136×10^{-4} and 0.134×10^{-4} mol·L^{-1}·cm, respectively, and their delay times are 5.6, 4.2, 5.68 and 4.96 s for τ=5, 10, 15 and 20 s, respectively. On the right side of line B, between 0.6×10^{-4} and 2×10^{-4} mol·L^{-1}·cm, there appears a small difference in delay time for τ=5, 10, 15 and 20 s, and it increases with PCT increasing. When the PCT is over 2×10^{-4} mol·L^{-1}·cm, there appears a noticeable difference in delay time for different values of τ. The values of sensitive PCT are around 3×10^{-4}, 3.8×10^{-4}, 4.26×10^{-4} and 4.4×10^{-4} mol·L^{-1}·cm for τ=5, 10, 15 and 20 s, respectively. The longest delay times are 7.08, 8.76, 11.04 and 13.04 s, and their corresponding values of PCT are 3.2×10^{-4}, 4×10^{-4}, 4.28×10^{-4}, 4.42×10^{-4} mol·L^{-1}·cm for τ=5, 10, 15 and 20 s, respectively.

By comparing Figs.2(a) and 2(b), we know that when the yellow beam is increased, firstly the extremum of the delay time becomes smaller; secondly, the sensitive PCT located to the left of the extremum

becomes lower, however, the sensitive PCT located to the right of the extremum becomes higher; thirdly, each longest delay time is shorten; finally, the difference around the extremum of the delay time becomes smaller for different lifetimes of the M sate.

Figure 2(c) shows that the wavelengths of the input beam are 533 and 412 nm, and their intensities each are 2 mW/cm^2. Line C marks the extremum of the delay time. For τ=5 and 10 s, when the PCT is between 0.44×10^{-4} and 0.5×10^{-4} mol·L^{-1}·cm, the shortest delay times are 3.64 and 2.52 s, respectively. For τ=15 and 20 s, the short extrema of the delay times are 2.36 and 2.28 s, which are corresponding to a wide range of the PCT from 0.38×10^{-4} to 0.6×10^{-4} mol·L^{-1}·cm. For τ=5, 10, 15 and 20 s, the lowest values of PCT are 0.256×10^{-4}, 0.19×10^{-4}, 0.176×10^{-4} and 0.17×10^{-4} mol·L^{-1}·cm, and their delay times are 9.32, 8.48, 9.6 and 9.84 s, respectively. From the lowest value of PCT to the value marked by the line C, the delay times decrease sharply till their minima. When the PCT is larger than the value marked by the line C, the delay times increase slowly first, then sharply. For τ=5 s, when 0.5×10^{-4} < PCT < 1.28×10^{-4} mol·L^{-1}·cm, the delay times increase slowly, and when the PCT is over 1.28×10^{-4} mol·L^{-1}·cm, they increase sharply. The maximum delay time is 14.88s, which is corresponding to the highest value of PCT, i.e. 1.54×10^{-4} mol·L^{-1}·cm. In the same way, for τ=10 s, when 0.5×10^{-4} < PCT < 2.5×10^{-4} mol·L^{-1}·cm, the delay times increase slowly. When the PCT is larger than 2.5×10^{-4} mol·L^{-1}·cm, the delay times increase sharply. The maximum delay time is 19.4 s, which is corresponding to the highest value of PCT, i.e. 3.06×10^{-4} mol·L^{-1}·cm. For τ=15 s, when 0.5×10^{-4} < PCT < 2.8×10^{-4} mol·L^{-1}·cm, the delay times increase slowly, and when the PCT is larger than 2.8×10^{-4} mol·L^{-1}·cm, the delay times increase sharply. The maximum delay time of 15.28 s is shorter than that for τ=10 s, which is corresponding to the highest value of PCT, i.e. 3.52×10^{-4} mol·L^{-1}·cm. For τ=20 s, when 0.5×10^{-4} < PCT < 3.24×10^{-4} mol·L^{-1}·cm, the delay times increase slowly, and when the PCT is larger than 3.24×10^{-4} mol·L^{-1}·cm, the delay times increase sharply. The maximum delay time (16.76 s) is a little longer than that for τ=15 s, which is corresponding to the largest value of PCT, i.e. 3.76×10^{-4} mol·L^{-1}·cm. It is evident that for τ=5, 10, 15 and 20 s, the values of sensitive PCT are 0.256×10^{-4}, 0.19×10^{-4}, 0.176×10^{-4} and 0.17×10^{-4} mol·L^{-1}·cm on the left side of the line C. In addition, on the right side of the line C, for τ=5, 10, 15 and 20 s, the values of sensitive PCT are close to 1.54×10^{-4}, 3.06×10^{-4}, 3.52×10^{-4} and 3.76×10^{-4} mol·L^{-1}·cm, which are higher than those for the case in Fig.2(a).

Figure 2(d) shows that the wavelengths of the input beams are 632.8 and 412 nm, and their intensities each are 2 mW/cm^2. When the PCT is equal to 0.408×10^{-4} mol·L^{-1}·cm, the longest delay time is 15.8 s for τ=5 s. For τ=10, 15 and 20 s, when the values of PCT are 0.314×10^{-5}, 0.288×10^{-5} and 0.276×10^{-5} mol·L^{-1}·cm, the longest delay times are 11.48, 11.76 and 11.68 s, respectively. When the PCT is less than 0.5×10^{-4} mol·L^{-1}·cm, the delay time sharply decreases with the value of PCT. When the PCT is between 0.5×10^{-4} and 0.8×10^{-4} mol·L^{-1}·cm, the delay time decreases slowly. When the PCT is 1.2×10^{-4} mol·L^{-1}·cm, the delay time is the shortest and does not change with the value of PCT. The shortest delay times are 2.24, 1.96, 1.88, 1.84 s for τ=5, 10, 15 and 20 s, respectively. By comparing Figs.2(a), 2(c) and 2(d), we know that the longest delay time (17.02 s) can be obtained by using the input light beams with wavelengths of 632.8 nm and 412 nm when the value of PCT is low.

In summary, for the delay relay of "switch off," the longest delay time (19.4 s) can be obtained in the sensitive PCT, and the shortest delay time (1.24 s) can be achieved at an appropriate value of PCT. There are two possible ways to shorten the delay time: one is to increase the intensity of the light located near the absorption peak of the B state, and the other is to use the bR molecules with a longer lifetime of the M state.

3.2. Delay time of switch-on dependent on parameters

Figure 3 shows that the delay time of 'switch on' increases with PCT for different input wavelengths and intensities. The calculated minimum output intensity is about 1–5 μW/cm^2. Curves with open circles, triangles, crosses and without mark are for τ=5, 10, 15 and 20 s, respectively. Figure 3(a) shows that the delay-time increases with PCT for input wavelengths of 568 and 412 nm. The input light intensities of 568 and 412 nm are 5 and 2 mW/cm^2, respectively. For τ=5 s, when PCT =0.6×10^{-5} mol·L^{-1}·cm, the delay time is 0.08 s. As the PCT increases, the delay time increases, too. When the PCT is be-

tween 0.06×10^{-4} and 0.38×10^{-4} mol L^{-1}·cm, the delay times almost have no difference among different lifetimes of the M state but the delay time linearly increases as the PCT increases. For τ=5 s, when PCT increases from 0.64×10^{-4} to 0.8×10^{-4} mol·L^{-1}·cm, the delay time increases to 3.88 s and does not change with PCT, which is saturable. For τ=10 s (15 s), when the PCT is larger than 0.4×10^{-4} mol·L^{-1}·cm, the delay time increases quickly; when the PCT increases to 0.88×10^{-4} mol·L^{-1}·cm (0.96×10^{-4} mol·L^{-1}·cm), the delay time 8.64s (13.48s) is saturable. For τ=20 s, when 0.4×10^{-4} < PCT < 0.96×10^{-4} mol·L^{-1}·cm, the delay time increases quickly, and when the PCT reaches 0.96×10^{-4} mol·L^{-1}·cm, the delay time has a maximum value of 18.32 s. When the PCT further increases to 1.0×10^{-4} mol·L^{-1}·cm, the delay time is 18.28 s, which decreases a little from the maximum. It is obvious that the longer the lifetime of the M state is, the longer the saturable delay time will be. The longest delay time is 18.32 s.

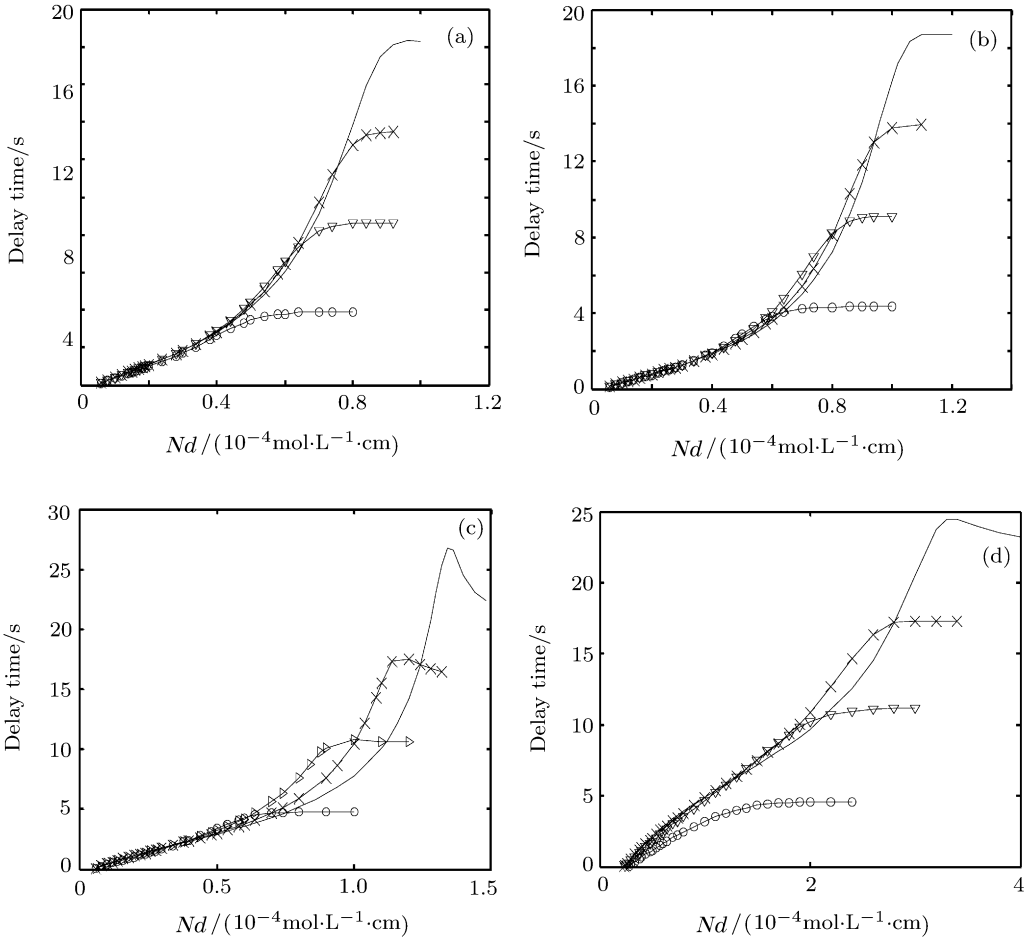


Fig.3. The variation in delay time of "switch on" changes with PCT for different input wavelengths and intensities; where curves with open circles, triangles, crosses and without mark are for τ=5, 10, 15 and 20 s, respectively; panel (a) is for wavelengths of input beams being 568 and 412 nm and the corresponding intensities being 5 and 2 mW/cm^2, respectively; panel (b) is for wavelengths of input beams being 632.8 and 412 nm and the corresponding intensities being 7 mW/cm^2 for 632.8 nm and 2 mW/cm^2 for 412nm; panel (c) is for wavelengths of input beams being 533 and 412 nm and corresponding intensities being 5 and 2 mW/cm^2, respectively; panel (d) is for wavelengths of input beams being 632.8 and 412 nm and corresponding intensities being 5 mW/cm^2 for 632.8nm, and 2 mW/cm^2 for 412 nm.

Figure 3(b) shows that the delay time increases with PCT for input light wavelengths of 568 and 412 nm. The input light intensities are 7 and 2 mW/cm^2 for 568 and 412 nm, respectively. When the PCT is 0.06×10^{-4} mol·L^{-1}·cm, the delay time is 0.08 s for τ=5 s. Similarly, for τ=10, 15 and 20 s, when the lowest value of PCT is 0.6×10^{-5} mol·L^{-1}·cm, the delay time is 0.12 s. The delay time increases

with PCT. When the PCT increases from 0.06×10^{-4} to 0.6×10^{-4} mol·L^{-1}·cm, there appears a very small difference among their delay times for τ=5, 10, 15 and 20 s. When the PCT is between 0.06×10^{-4} and 0.4×10^{-4} mol·L^{-1}·cm, the delay time increases linearly with PCT. For τ=5, 10, 15 and 20 s, the longest delay times are 4.36, 9.12, 13.92 and 18.68 s, corresponding to the values of PCT of 1×10^{-4}, 1×10^{-4}, 1.1×10^{-4} and 1.2×10^{-4} mol·L^{-1}·cm, respectively. Compared with Figs. 3(a) and 3(b), the longest delay time is not enhanced considerably by enhancing the input intensity of 568 nm. The PCT range becomes wider, where the delay times are almost the same for different lifetimes of the M state. The PCT corresponding to the saturable delay time becomes higher. The longest delay time becomes a little longer.

Figure 3(c) shows that the variation in delay time of "switch on" with PCT for input light wavelengths of 533 and 412 nm, and their input intensities are 5 and 2 mW/cm^2 for 533 and 412 nm, respectively. When the PCT is 0.06×10^{-4} mol·L^{-1}·cm, the delay time is 0.08 s for τ=5, 10, 15 and 20 s. When the PCT is between 0.08×10^{-4} and 0.5×10^{-4} mol·L^{-1}·cm, the delay time increases linearly, and there appears a very small difference in delay time for different lifetimes of the M state. When the PCT is larger than 0.5×10^{-4} mol·L^{-1}·cm, the delay time increases sharply and then reaches a maximum value. For τ=5 s, when the PCT is 0.8×10^{-4} mol·L^{-1}·cm, the delay time reaches a maximum of 4.76 s. For τ=10 s, when PCT is 1.0×10^{-4} mol·L^{-1}·cm, the delay time reaches a maximum of 10.76s and then it decreases very slowly with PCT increasing. Similarly, for τ=15 s, when the PCT is 1.2×10^{-4} mol·L^{-1}·cm, the delay time reaches a maximum of 17.52 s and then decreases slowly with PCT increasing. For τ=20 s, when the PCT is 1.34×10^{-4} mol·L^{-1}·cm, the delay time reaches a maximum of 26.76 s and then quickly decreases to 22.4 s with PCT increasing. The longest delay time is 26.76 s. The values of PCT corresponding to the longest delay times are 0.8×10^{-4}, 1.0×10^{-4}, 1.2×10^{-4} and 1.34×10^{-4} mol·L^{-1}·cm. The longest delay time (26.76 s) is longer than that in Fig.3(a) or Fig.3(b).

Figure 3(d) shows that the delay time of 'switch on' increases with the PCT for input light wavelengths of 632.8 and 412 nm. The input intensities are 5 and 2 mW/cm^2 for 632.8 and 412 nm, respectively. The lowest values of PCT we calculated are 0.28×10^{-4} and 0.246×10^{-4} mol·L^{-1}·cm, respectively, for τ=5 and 10 s, where the delay time is 0.04 s for both τ=5 s and τ=10 s. For τ=15 s and τ=20 s, when their corresponding values of PCT are 0.234×10^{-4} and 0.23×10^{-4} mol·L^{-1}·cm, the shortest delay time is 0.04 s. When the PCT increases, the delay time increases sharply first, and then reaches a maximum. For τ=5 s (10 s), when the PCT increases to 2.1×10^{-4} (2.8×10^{-4} mol·L^{-1}·cm), the longest delay time is 4.56 s (11.12 s). When the PCT further increases, the delay time does not change. For τ=15 s (20 s), when the PCT increases to 3.0×10^{-4} mol·L^{-1}·cm (3.4×10^{-4} mol·L^{-1}·cm), the longest delay time is 17.32 s (24.48 s). When the PCT further increases, the delay times decrease to 17.28 and 23.34 s for τ=15 and 20 s, respectively.

Compared with Figs.3(a), 3(c) and 3(d), when the input light intensities are 5 and 2 mW/cm^2, the longest delay times are achieved by the input light wavelengths of 533 and 412 nm. When the input wavelengths are 568 and 412 nm, there is a saturable delay time, which does not change as the PCT increases for each τ. When the input wavelengths are 533 and 412 nm, there is a saturable delay time for τ=5 s. But for τ=10–20 s, the longest delay time exists and the PCT corresponding to the maximum delay time can be represented. When the input wavelengths are 632.8 and 412 nm, the saturable longest delay time exists for τ=5–15 s. But for τ=20 s, the PCT corresponding to the maximum delay time can be obtained.

In our calculation, the time step is 0.04 s. The thermo-effect is not obvious and therefore ignored in this paper; this is because the input intensity is low and has a less influence on the delay time.[12,19,20] If the PCT is larger than the maximum value we used, the output beam will be too weak (less than about 1 μW/cm^2). From Fig.3, we know that the longest delay time can be obtained by the input light with 533 and 412 nm. If the input light beams are 632.8 and 412 nm in wavelength, the required PCT for each maximum delay time is much larger than that for the input light beams with wavelengths of 568 and 412 nm, or 533 and 412 nm.

4. Conclusions

To extend our work on time-delay relay,[1] we numerically study the variation in delay time with PCT for different lifetimes of the M state and input light intensities. It is useful for designing the all-optical time-

delay relay, and choosing appropriate parameters. For the relay of 'switch off', the longest delay time is given for different lifetimes of the M state and input wavelengths. Through the discussion, we find that when the input light beams with wavelengths of 533 and 412 nm, the longest delay time can be achieved. We should point out that a short delay time of 'switch off' can be induced by a long lifetime of the M state, or a strong input intensity with the wavelength nearby the absorption at the B state. When the input light wavelengths are 568 and 412 nm or 533 and 412 nm, there are two ranges of sensitive PCT. When the input light wavelengths are 632.8 and 412 nm, there is only one range of sensitive PCT.

For the relay of 'switch on', the longer the lifetime of the M state is, the longer the maximum delay time of 'switch on' will be. When the PCT is between 0.08×10^{-4} and 0.38×10^{-4} mol·L^{-1}·cm, how the delay time increases linearly with PCT is discussed for different input light wavelengths. In addition, how the saturable longest delay time is dependent on input wavelength is given for different lifetimes of the M state. The maximum delay times and their corresponding PCTs are represented.

References

[1] Chen G Y, Yuan Y Z, Zhang C P, Yang G, Tian J G, Xu T and Song Q W 2006 *Opt. Lett.* **15** 1531

[2] Wu P F and Rao D V G L N 2005 *Phys. Rev. Lett.* **95** 253601

[3] Ormos P, Fábián L, Oroszi L, Wolff E K, Ramsden J J and Dér A 2002 *Appl. Phys. Lett.* **80** 4060

[4] Yang W Z, Hou X, Chen F and Yang Q 2004 *Acta. Phys. Sin.* **53** 296 (in Chinese)

[5] Huang Y H, Wu S T and Zhao Y Y 2004 *Appl. Phys. Lett.* **84** 2028

[6] Chen G Y, Yuan Y Z, Liang X, Xu T, Zhang C P and Song Q W 2006 *Chin. Phys.* **15** 2007

[7] Wang Y L, Yao B L, Menke N, Ren Z W, Lei M and Ren L Y 2006 *Acta Phys. Sin.* **55** 5200 (in Chinese)

[8] Rao D V G L N, Aranda F J, Narayana D and Chenet Z 1996 *Opt. Commun.* **127** 193

[9] Singh C P and Roy S 2003 *Opt. Commun.* **218** 55

[10] Zhang C P, Chen G Y, Wang X Y, Zhang G Y and Song Q W 2005 *Opt. Lett.* **30** 81

[11] Chen G Y, Zhang C P, Shang X D, Guo Z X, Wang X Y, Tian J G and Song Q W 2005 *Opt. Commun.* **249** 563

[12] Chen G Y, Zhang C P, Xu T, Tian J G and Song Q W 2006 *Optical Materials* **29** 416

[13] Birge R R1990 *Biochem. Biophys. Acta* **1016** 293

[14] Oesterheltand D and Stoeckenius W 1971 *Nature* **233** 149

[15] Song Q W, Zhang C P, Blumer R, Gross R B, Chen Z and Birge R R 1993 *Opt. Lett.* **18** 1373

[16] Gu L Q, Zhang C P, Zhang G Y, Niu A. F, Li J, Zhang G Y, Wang Y M, Tong M R, Pan J L, Song Q W, Parsons B and Birge R R 1996 *Opt. Commun.* **131** 25

[17] Werner O, Fischer B, Lewis A and Nebenzahl I 1990 *Opt. Lett.* **15** 1117

[18] Hampp N 2000 *Chem. Rev.* **100** 1755

[19] Guo Z X, Chen G Y, Zhang C P, Tian J G, Song Q W, Shen B and Fu G H 2004 *Chin. Phys. Lett.* **21** 2418

[20] Chen G Y, Xu T, Zhang C P and Song Q W 2006 *Opt. Commun.* **264** 229