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Dynamics of All-Optical Switching in Bacteriorhodopsin and its Application to Optical Computing

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All-optical switching has been demonstrated in bacteriorhodopsin (bR) based on nonlinear intensity induced excited state absorption. The transmission of a cw probe laser beam at 410 nm corresponding to the peak absorption of M state through a bR film is switched by a pulsed pump laser beam at 570 nm that corresponds to the maximum initial B state absorption. The switching characteristics have been analyzed using the rate equation approach considering all the six intermediate states (B, K, L, M, N and O) in the bR photocycle. The switching characteristics are shown to be sensitive to life time of the M state, absorption cross-section of the B state at probe wavelength (σ_{Bp}) and peak pump intensity. It has been shown that the probe laser beam can be completely switched off (100 % modulation) by the pump laser beam at relatively low pump powers, for $\sigma_{Bp} = 0$. The switching characteristics have been used to design all-optical NOT, OR, AND and the universal NOR and NAND logic gates for optical computing with two pulsed pump laser beams.

Key words: all-optical switching, logic gates, optical computing, bacteriorhodopsin, bio-molecular photonics

INTRODUCTION

Recent years have witnessed dramatic progress in designing all-optical devices for ultrahigh bandwidth communication and computing [1]. Current interest has focused on molecular devices that offer advantages of small size and weight, high intrinsic speed, extremely low propagation delay and power dissipation and the ability to tailor properties to suit specific applications [2-4]. The photochromic retinal protein bacteriorhodopsin (bR) contained in the purple membrane fragments of *Halobacterium halobium*, has emerged as an excellent material for bio-molecular photonic applications due to its unique properties and advantages [3-7]. By absorbing green-yellow light, the wild type bR molecule undergoes several structural transformations in a complex photocycle (B→K→L→M→N→O→B). In this paper we analyze all-optical switching in bR based on nonlinear intensity induced excited-state absorption and its application to design all-optical logic gates for optical computing.

THEORETICAL MODEL

We consider bR molecules exposed to a light beam of intensity I_m, which modulates the population densities (N) of different states through the excitation and de-excitation processes and can be described by the rate equations in the following form,

$$\frac{dN}{dt} = \hat{O}N \tag{1}$$

where $\hat{O}$ operator is defined in terms of the photo-induced and thermal transitions of B, K, L, M, N and O states as shown by Roy et al. [7].

The propagation of the probe beam is governed by

$$\frac{dI_p}{dx} = -\alpha_p(I_m)I_p \tag{2}$$

where α_p is the nonlinear intensity-dependent absorption coefficient of the probe beam written here as

$$\alpha_p(I_m) = N_B(I_m)\sigma_{Bp} + N_M(I_m)\sigma_{Mp} \tag{3}$$

where σ is the absorption cross-section of the state denoted by the subscript and p denotes the value at probe wavelength. The modulating pump laser pulse is given by

$$I_m = I_{m0}\exp\left(-c\left(\frac{t-t_m}{\Delta t}\right)^2\right) \tag{4}$$

where I_{m0} is the peak pumping intensity, c is the pulse profile parameter and Δt is the pulse width.

RESULTS AND DISCUSSION

The optical switching characteristics, namely the variation of the normalized transmitted intensity of the probe laser beam with time have been computed by solving the rate equations

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for the intermediate states through computer simulations, for typical values of the rate constants and absorption cross-sections of various states [7], with pump pulse width Δt= 5 ms.

The life time of the M state (τ_M) can be changed over a wide range, by both chemical and genetic variations [3,7]. The variation in the normalized transmitted intensity of the probe beam with time for different τ_M values is shown in Fig. 1 for I_{m0} = 1 W/cm^2. This can be achieved with a 50 nW laser focused to a 5 μm^2 spot size. The transmitted intensity of the probe beam at t = 0 gets modulated due to absorption by B state only as all molecules are in this initial state. When a pulsed laser beam at 570 nm pumps the sample, the B state gets depleted and the transmitted probe beam intensity varies with time for different values of τ_M i.e. it increases for smaller τ_M values and decreases for larger τ_M values, finally attaining its initial value in both cases. These variations are due to the variation in the population of the M intermediate state in comparison to the N and O states depending on its life time.

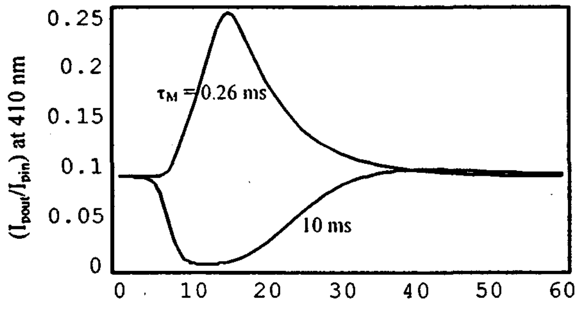

Figure 1. Variation of normalized transmitted intensity of the probe laser beam at 410 nm with time for different values of τ_M, with I_{m0} = 1 W/cm^2 and film thickness L = 30 μm.

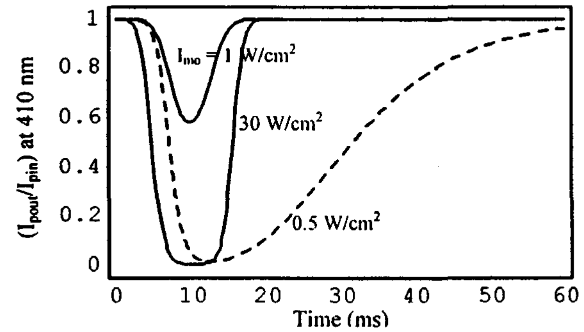

Figure 2. Variation of normalized transmitted intensity of the probe laser beam at 410 nm with time, with σ_{Bp}= 0 and film thickness L = 30 μm for τ_M = 0.26 ms (solid lines), τ_M = 10 ms (dashed line).

Increasing τ_M results in increase in the M state population. For τ_M = 10 ms, as the modulating pulse now appears, the transmitted probe intensity decreases due to increased absorption by the M state and finally saturates to the initial value. Considering the on and off states corresponding to high and low transmission of the probe beam, for τ_M = 0.26 ms, the switch on and off time is 8 ms and 22 ms respectively with 16 % modulation of the probe laser beam, while for τ_M = 10 ms, the switch off and on time is 8 ms and 23 ms respectively with 8 % modulation of the probe laser beam.

Figure 2 shows the variation of the normalized transmitted intensity of the probe beam with time for σ_{Bp}= 0. For this case, the probe beam is switched due to absorption by only the M state and gets modulated by 41 %. Complete switching i.e. 100 % modulation can be achieved by increasing the peak pumping intensity to 30 W/cm^2. While for τ_M = 10 ms, 100 % switching can be achieved for I_{m0} = 0.5 W/cm^2. Hence, complete switching for larger values of τ_M can be achieved at lower peak pumping intensity. Increasing the pulse width results in increase in switch off time for τ_M = 10 ms.

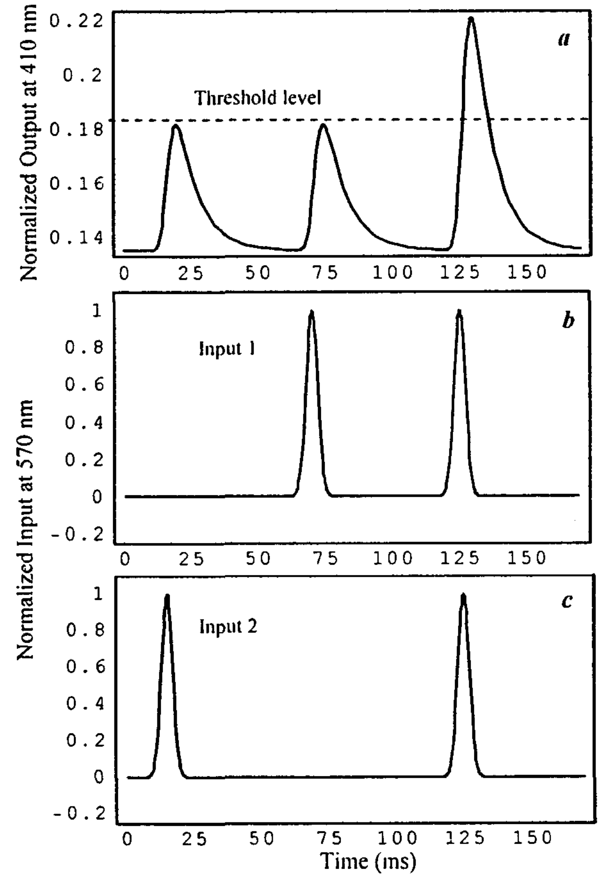

Figure 3. All-optical logic operations: (a) optical OR gate function (without threshold) and optical AND gate function (with threshold), with variation of normalized transmitted intensity of the probe laser beam at 410 nm as output with time; (b) and (c) are normalized pulse profiles of the two inputs 1 and 2 at 570 nm with I_{m0} = 100 mW/cm^2 and film thickness L = 25 μm.

The switching characteristics have been used to design all-optical NOT, OR, AND and the universal NOR and NAND logic gates with multiple pulsed pump laser beams. Amplitude modulation of the cw probe laser beam at 410 nm considered as output and the two pulsed pump laser beams at 570 nm, as the two inputs 1 and 2, for $\tau_M = 0.26$ ms, are shown in Figs. 3(a)–3(c). The switching characteristics exhibit an increase in the normalized probe beam transmission as each pulse pumps the sample and when both pump simultaneously, the transmission increases further as the total pump intensity increases. These characteristics correspond to the all-optical OR logic gate, as the output is high when either one or both the input pulses are present and is low only when none of the pulses is present as is shown in Figs. 3(a), (b) and (c).

The same configuration can also result in an all-optical AND logic gate, if a threshold level is considered as shown by the dashed line in Fig. 3(a). In this case, the output can be considered to be low when either one or none of the pulses are present and high only when both the input pulses are present simultaneously.

Considering the life time of the M state to be 10 ms, as shown in Fig. 1, the output is low when the input is high and vice versa, and hence the switching characteristics conform to an all-optical inverter (NOT) logic gate.

The switching characteristics can also be used to design the universal NOR and NAND logic gates as shown in Fig. 4 for the same input and output conditions as in Fig. 3. For the all-optical NOR logic gate, the output is low when either one or both the input pulses are present i.e. the input is high, and is high when none of the two pulses is present.

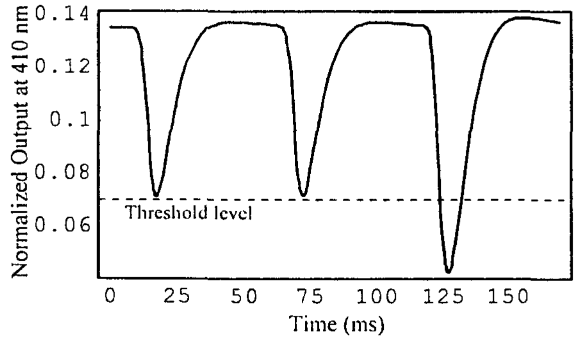

Figure 4. All-optical logic NOR gate function (without threshold) and NAND gate function (with threshold), with variation of normalized transmitted intensity of the probe laser beam at 410 nm as output with time, with $I_{m0} = 100$ mW/cm^2 and film thickness = 25 μm.

The same configuration can also result in an all-optical NAND logic gate by considering a threshold level shown by the dashed line in Fig. 4. In this case the output can be considered to be high when either one or none of the input pulses is present and low only when both the input pulses are present simultaneously.

It is evident from these results that the switching characteristics are sensitive to peak pumping intensity and film thickness. For a fixed value of τ_M, the OR and AND logic gates and the NOR and NAND logic gates respectively, can be realized with the same experimental setup, only by suitably defining the threshold level for the transmission of the probe laser beam. Both the input and output are in digital form.

All-optical switching in bR is at low pump powers compared to other molecular configurations such as C_{60} and phthalocyanine. Since bR can also be processed as a film or in a crystalline form for 2D/3D applications, bR based NOT gates (all-optical switches) would be potentially useful in optical signal processing in optical networks. They can provide an alternative to the widely required thermo-optic, MEMS and liquid crystal switches that also operate in the ms range. As large, high-density arrays of these proposed logic gates can also be fabricated that can operate at very low switching energies with high thermal stability, they would be useful in parallel optical computing.

CONCLUSION

We have demonstrated all-optical switching of a cw probe laser beam by a pulsed pump laser beam using the M state dynamics of bR. The effect of various parameters such as variation in life time of the M state, absorption cross-section of the initial B state at probe wavelength, thickness of the film, pump pulse width and the peak pumping intensity, on the switching characteristics have been analyzed. It has been shown that the probe laser beam can be completely switched off (100 % modulation) by the pump laser beam at relatively low pump powers, for $\sigma_{Bp} = 0$. The switching characteristics have been used to design all-optical NOT, OR, AND and the universal NOR and NAND logic gates. The proposed all-optical logic gates would be useful due to advantages of small size, simple and low power digital operation, small linear absorption coefficient, mirror-less structure, and flexibility in design.

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