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Low power spatial light modulator with *pharaonis* phoborhodopsin

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Abstract

Spatial light modulation (SLM) has been theoretically analysed in *pharaonis* phoborhodopsin (*p*pR) and its mutants based on nonlinear intensity induced excited-state absorption, to achieve large percentage modulation at low power. Amplitude modulation of probe laser read beam (I'_p) transmissions at 560, 512 and 390 nm, corresponding to the peak absorption of $p\mathrm{pR}_O$, $p\mathrm{pR}_{KL}$ and $p\mathrm{pR}_M$ intermediate states, respectively, of *p*pR photocycle, by write beam intensity (I'_m) at 498 nm, corresponding to the peak absorption of the initial *p*pR state, have been analysed using the rate equation approach, considering all six intermediate states in its photocycle. The SLM characteristics are shown to be sensitive to the normalized small signal absorption coefficient (β) and the rate constants of intermediates. For a given I'_m range, there is an optimum value of β (β_{opt}) for maximum percentage modulation. We can achieve 100% modulation of the read beam if the initial *p*pR state does not absorb the respective probe beams. The SLM characteristics of F86D *p*pR have also been used to design an all-optical XOR logic gate. High dynamic range and sensitivity can be achieved at low write beam intensities in *p*pR compared to wild-type bacteriorhodopsin (WT-bR).

Keywords: Bacteriorhodopsin; Nonlinear optics; Excited-state absorption; Optical computing

1. Introduction

Optically addressed real-time reusable spatial light modulators (SLMs) or input output transducers are essential components for high speed high bandwidth optical communication and computing systems [1]. SLMs find wide applications as input and output transducers for image amplification, time/space transformation, scratch pad memory, programmable detector masking and page composition for holographic and three-dimensional memories. The basic element in the development of optically addressed SLMs is the fast response photosensitive material that is free from photo degradation effects usually encountered in organic dye molecules. Hence, tremendous research effort is directed currently to develop suitable nonlinear optical materials to design all-optical molecular devices. These devices would 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 [2–5].

The photochromic retinal protein bacteriorhodopsin (bR) contained in the purple membrane fragments of *Halobacterium halobium*, has emerged as an excellent material for biomolecular photonic applications due to its unique advantages [6–8]. More recently, the photoreceptor sensory rhodopsin II (sRII) or phoborhodopsin (pR) protein, synthesized from *Natronobacterium pharaonis*, a halophilic alkaliphilic bacterium termed *pharaonis* phoborhodopsin (*p*pR), has received much attention due to its stability and its recent structure elucidation [9,10]. *p*pR works as a photoreceptor of the negative phototactic response of this bacterium [11]. It exhibits unique properties that are distinct from other retinal proteins. It exhibits a photocycle similar to bR. The intermediate states in its photocycle are with shorter absorption maximum wavelength (blue shifted), with vibration fine structure [10–13]. Its unique absorption spectrum exhibits spectral shoulders at wavelengths shorter than their absorption maxima, in contrast to other retinal proteins that

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have broad bell-shaped spectra [10–13]. It also exhibits absence of ppR$_L$ intermediate and high thermal stability of the ppR$_K$ intermediate at low temperatures. The ppR photocycle shows more extended structural changes, considerably longer lifetime of the intermediate states and no light–dark adaptation of all-*trans* and 6S-*trans* retinal ground state [10–14]. The ppR molecule undergoes several structural transformations in a photocycle by absorbing green light: ppR-($h\nu$)→ppR$_K$-(50 ns)→ppR$_{KL}$-(990 ns)→ppR$_L$-(32 μs)→ppR$_M$-(1.7 s)→ppR$_O$-(770 ms)→ppR [10,12].

We have recently studied the SLM characteristics of WT-ppR based on ppR$_M$ and ppR$_L$ state dynamics [15]. In this paper, we theoretically analyze SLM characteristics of ppR and its mutants considering ppR$_O$, ppR$_{KL}$ and ppR$_M$ state dynamics based on nonlinear intensity-induced absorption to achieve large percentage modulation at low powers. Amplitude modulation of probe laser read beam transmissions at 560, 512 and 390 nm corresponding to the peak absorption of ppR$_O$, ppR$_{KL}$ and ppR$_M$ intermediate states of ppR by the modulating laser write beam intensity-induced population changes at 498 nm, corresponding to the peak absorption of initial ppR state, have been analyzed using the rate equation approach, considering all six intermediate states in the ppR photocycle [15–18]. SLM characteristics considering ppR$_O$ state dynamics of the mutant F86D/L40T ppR have been compared with that of wild type ppR (WT-ppR) at typical values. Optimized designs of ppR based SLMs have been presented considering the respective dynamics of three states, i.e. ppR$_O$ state in F86D/L40T ppR mutant and ppR$_{KL}$ and ppR$_M$ in WT-ppR. These characteristics have also been used to design an all-optical XOR logic gate.

2. Theoretical model

The photocycle of ppR molecules can be represented by the simple rate equation approach in terms of the population densities in the various intermediate states. We consider the ppR molecules exposed to a light beam of intensity I'_m, which modulates the population densities of different states through the excitation and de-excitation processes, and can be described by the rate equations in the following form [15–18].

$$\frac{d}{dt}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \\ N_6 \end{pmatrix} = \begin{pmatrix} -I_m\sigma_1\psi_{12} & I_m\sigma_2\psi_{21} & I_m\sigma_3 & I_m\sigma_4 & I_m\sigma_5 & k_6+I_m\sigma_6 \\ I_m\sigma_i\psi_{12} & -(k_2+I_m\sigma_2\psi_{21}) & 0 & 0 & 0 & 0 \\ 0 & k_2 & -(k_3+I_m\sigma_3) & 0 & 0 & 0 \\ 0 & 0 & k_3 & -(k_4+I_m\sigma_4) & 0 & 0 \\ 0 & 0 & 0 & k_4 & -(k_5+I_m\sigma_5) & 0 \\ 0 & 0 & 0 & 0 & k_5 & -(k_6+I_m\sigma_6) \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \\ N_6 \end{pmatrix}, \quad (1)$$

where N_i, i=1–6, are the population densities of ppR, ppR$_K$, ppR$_{KL}$, ppR$_L$, ppR$_M$ and ppR$_O$ states, respectively; σ_i and k_i are the absorption cross-sections and rate constants, respectively, of different states denoted by respective subscripts; ψ_{12}=0.51 is the quantum efficiency for the ppR→ppR$_K$ transition and is considered equal to ψ_{21} corresponding to ppR$_K$→ppR and I_m is the photon density flux of the modulation laser beam, i.e. ratio of the intensity I'_m to the photon energy $h\nu$. The typical numerical values of rate constants and absorption cross-sections for different intermediates at different wavelength are given in Table 1 [10–14]. The intensity induced population densities for various states at steady-state can be obtained from Eq. (1). The total number of active ppR molecules $N = \sum_{i=1}^{6} N_i$.

The absorption coefficient at the modulation pump wavelength $\alpha(I_m) = \sum_{i=1}^{6} N_i(I_m)\sigma_i$. Assuming optically thin ppR samples, the propagation effects on the modulating light beam can be neglected in the following analysis. We consider a laser probe beam of intensity I'_p at a wavelength corresponding to the absorption maximum of the ppR$_O$, ppR$_{KL}$ and ppR$_M$ states, respectively, modulated by a pump beam of intensity I'_m such that $I'_p \ll I'_m$. The propagation of the probe beam is governed by $(dI'_p/dx) = -\alpha_p(I_m)I'_p$, where x is the distance in the medium and α_p is the nonlinear intensity-dependent absorption coefficient

Table 1
Absorption cross-sections and rate constants of different intermediates of ppR [10–14]

Rate constant	WT-ppR value (s^{-1})	F86D/L40T ppR value (s^{-1})	Absorption cross-section	Value (cm^2)			
				498 nm	560 nm	512 nm	390 nm
			σ_1	1.6×10^{-16}	1.6×10^{-17}	1.36×10^{-16}	3.2×10^{-17}
k_2	2.0×10^{7}	2.0×10^{7}	σ_2	6.4×10^{-17}	–	–	–
k_3	1.0×10^{6}	1.0×10^{6}	σ_3	1.3×10^{-16}	4.3×10^{-17}	1.36×10^{-16}	3.2×10^{-17}
k_4	3.1×10^{4}	3.1×10^{4}	σ_4	1.0×10^{-16}	1.6×10^{-17}	8.0×10^{-17}	3.2×10^{-17}
k_5	0.59	1.9×10^{2}	σ_5	0	–	–	1.5×10^{-16}
k_6	1.3	0.66	σ_6	4.4×10^{-17}	1.76×10^{-16}	6.4×10^{-17}	–