Slow light in bacteriorhodopsin solution using coherent population oscillations

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Slow light is demonstrated in liquid phase in an aqueous bacteriorhodopsin (bR) solution at room temperature. Group velocity as low as 3 m/s (all the way to c) is achieved by exploiting the photoisomerization property of bR for coherent population oscillations. Slow light in the liquid phase offers several advantages over solids or vapors for a variety of applications: (i) shorter lifetimes of the M state facilitate slow light at higher modulation frequencies, (ii) convection makes it possible to obtain large signal delays even at high input powers, and (iii) solution concentration is another convenient parameter to vary the signal delay over a wide range. © 2007 Optical Society of America

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The control of group velocity of light is attracting considerable attention recently in view of its interesting basic physics and potential applications. The group velocity of light in materials with highly dispersive regions can exhibit either very large, small, or even negative values [1]. Slow light was first demonstrated in gases at low temperatures using the quantum interference technique. It was reduced to $c/165$ in a dense 10 cm long Pb vapor cell using the electromagnetically induced transparency (EIT) configuration [2]. Low temperatures and high vacuum, however, are required for such experiments due to the delicate interference process. In view of practical applications, the focus of observation of slow light has been shifted to solid-state materials and room temperatures. A variety of mechanisms was exploited to demonstrate slow and fast light in solids by transmitting light through metamaterials [3], dispersive amplifying or absorbing media [4], inorganic crystals [5], fibers [6], photorefractive materials [7], and semiconductor materials [8], to name a few. These studies hold promising applications such as controllable optical delay lines, optical data storage, optical memories, and devices for quantum information processing.

Recently our group demonstrated ultraslow light in a bacteriorhodopsin (bR) doped polymer film at room temperature [9]. By exploiting the photoisomerization property of bR for coherent population oscillation, the group velocity was all-optically controlled from 0.09 mm/s all the way to the speed of light. Unique features of this technique are (i) flexibility of photoisomerization, (ii) all-optical control of speed of light over an enormous span, (iii) high energy efficiency due to large quantum yield for the photoreaction—ultraslow light is observed at low light levels of the order of microwatts, (iv) high transparency of the medium due to low saturation intensity, and (v) low cost of commercial films. As bR was embedded in a polymer matrix, however, the isomerization rates were slow, and hence the effect was limited to modulation frequencies of the order of 1 Hz. But for practical importance, slow light at higher modulation frequencies needs to be achieved. Toward that end, and also in view of possible potential applications that are briefly discussed below, we present here the observation of slow light in liquid phase. We used aqueous solutions of the biological photomembrane bR for the study. This has all the benefits of slow light achieved in the biomaterial film, with the added advantages offered by the liquid phase.

Slow light in liquid phase offers several distinct advantages over that in solids or gases. For example, it may be possible to use any two-dimensional porous structure, as a host, for slow light propagation, by incorporating the solution into it. Similarly, by injecting the solution into a photonic crystal (PC) structure, one can tune the PC based sensor for applications at different wavelengths. PC structures have been used for optofluidic devices and are promising candidates for lab-on-a-chip. Such platforms offer attractive features for sensing applications. Optical sensors that exploit surface plasmon resonance have already been demonstrated, and PC sensors using slow light can boost the device sensitivity. Even though PC structures are generally designed for a particular wavelength region, when the liquid analyte that has the capability of slowing light is injected into these nanoscopic holes, it is possible to use them at other wavelengths. Similarly slow light pulse propagation enhances the energy density of the electromagnetic field within a waveguide structure. Such an effect can lower the threshold for exploiting nonlinear optical effects. Thus even though slow light for

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telecommunication applications is not expected in the immediate future, nontelecommunications applications may be realized soon.

In the photocycle of bR, the initial B state is in its all-trans molecular configuration and has a broad absorption band with the peak at 570 nm. Upon shining yellow light, the chromophore undergoes light-induced isomerization. This initiates a series of short lived structural conformations leading to the relatively stable M state. The M state can revert to the initial B state either via a slow thermal process or by a fast photochemical process upon excitation with blue light. It is possible to switch between B⇆M reversibly with relatively low power (microwatts). The M state lifetime depends on the reprotonation process, and it can be substantially varied by several orders of magnitude [10]. It can also be made as fast as nanoseconds by all-optical means [11]. Due to its unique advantages, bR is an ideal material for low power nonlinear optics [12,13]. For our purpose, we treat it as a two level system considering only the B and M states, neglecting the remaining short lived intermediate states.

As in the case of bR film [9], in the solution also, a narrow spectral hole is created by a periodic modulation of the B and M states. The 568 nm output of an Ar–Kr laser is modulated at a frequency f using an electro-optics modulator (Conoptics Inc, Danbury, Connecticut). The resulting pulse train contains the beating of pump $Ee^{-i\omega t}$ and probe $E_1e^{-i(\omega+\delta)t}$, where $\delta=2\pi f$ is the detuning of the probe frequency from the pump frequency ω. Beating between the pump and probe causes the molecular population to coherently oscillate between the B and M states. This leads to a rapid variation of the refractive index over a very narrow wavelength range reducing the group velocity. In the experiment, a beam splitter is used to sample the output of the electro-optic modulator. While the reflected beam serves as the reference arm, the transmitted beam (signal arm) goes through a 1 cm sample cell containing the bR solution. Outputs of the signal and reference arms of equal length are measured using identical photodiodes and are fed to a multichannel digital oscilloscope (LeCroy). The relative delay is measured by comparing the waveforms.

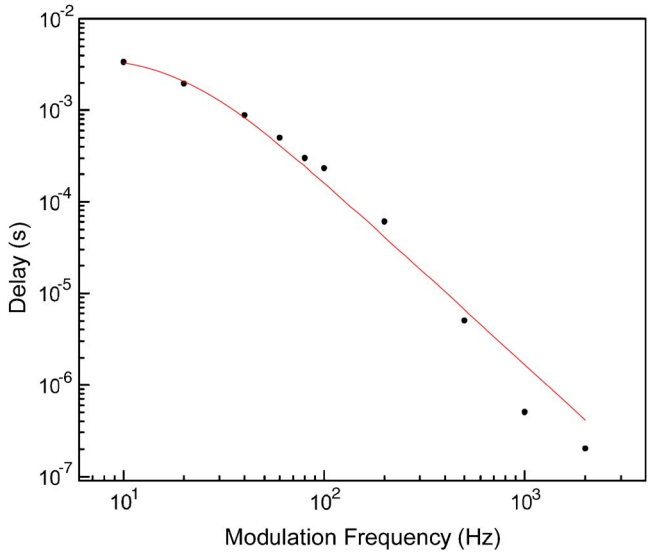


Fig. 1. (Color online) Experimental results of slow light pulse delay in bR solution with the increase of modulation frequency. The input is a sinusoidally modulated laser beam at 568 nm with an average power of 25 mW. The sample thickness is 1 cm, and it has a transmission of 20%. The solid curve is the theoretical fit to the experimental data.

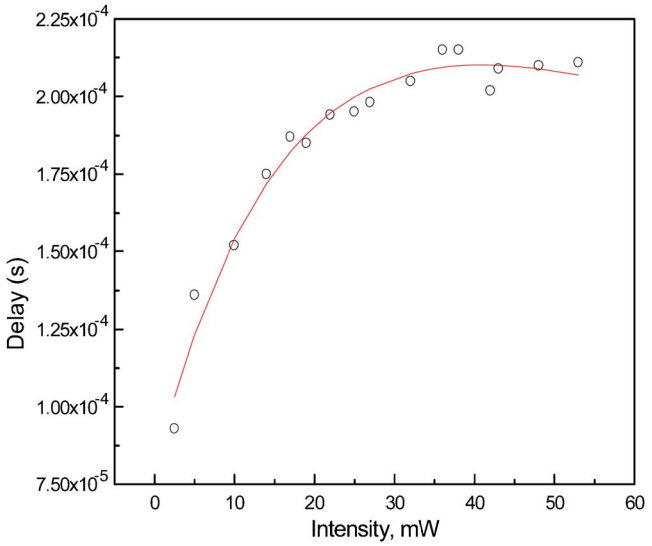


Fig. 2. (Color online) Dependence of slow light pulse delay on the input power. As the input is increased, the delay increases before approaching a constant value at ~30 mW. The modulation frequency is 50 Hz, and the sample transmission is 20%. The solid curve is the theoretical fit to the experimental data.

Figure 1 displays the pulse delay (Δt) versus the modulation frequency for a bR solution of 20% transmission [optical density (OD)=0.7]. At 10 Hz modulation frequency and an average input power of 25 mW, a maximum pulse delay of 3.33 ms is observed. This corresponds to a group velocity of 3 m/s. The maximum fractional advancement, i.e., ratio of the pulse delay to the full width at half maximum of the pulse, is 0.3. As the modulation frequency is increased, the delay decreases and vanishes at 2 kHz. Such relatively high modulation frequencies were not possible in bR films due to the long M state lifetimes (τ). The theoretical curve (solid curve) in Fig. 1 is obtained using the equation [9]

$$\Delta T = \Delta n(\delta) L/c, \tag{1}$$

where $\Delta n(\delta)$ is derived from the group index due to the coherent population oscillation as

$$n_g = n(\omega) + \frac{\alpha_0 c \tau I_B}{2[(1+I_B)^2 + (\delta^2\tau^2)]} = n(\omega) + \Delta n(\delta), \tag{2}$$

where α_0 is the linear absorption coefficient and $I_B = I_b/I_s$ is the normalized intensity for 568 nm light with the saturation intensity (I_s). The best fit is found for I_s=21 mW and τ=77 ms. For bR solution, the M state lifetime is relatively short due to the faster reprotonation process: it is ~3 orders of mag-

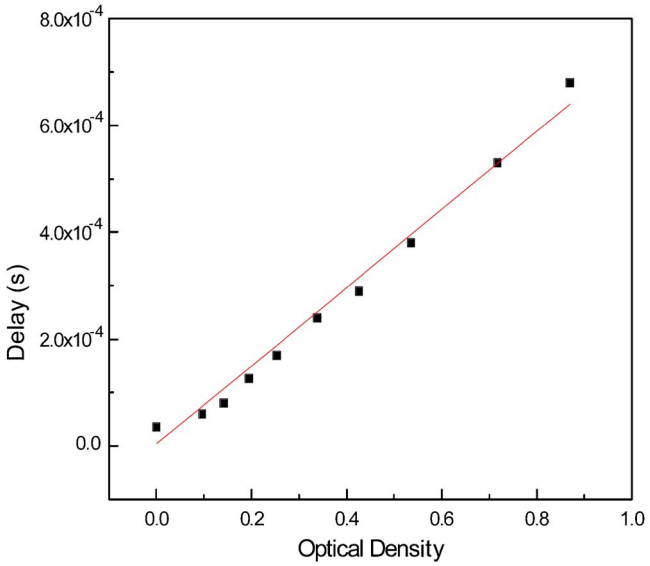


Fig. 3. (Color online) Control of the slow light delay with optical density of the bR solution. The solid line is the theoretical fit to the experimental data.

nitude shorter than the value for film (~1.5 s) [13]. This correlates well with the observed behavior: whereas for the film, slow light is observed for modulation frequencies of the order of a few hertz or less, in the case of the solution it is observed up to the kilohertz range.

Figure 2 demonstrates the slow light pulse delay as a function of input power with 50 Hz modulation frequency. Initially the delay increases with input power, as in the case of the film. But whereas in the film the delay decreases with further increase in the input power, in solution the pulse delay saturates at ~30 mW. The solid curve in Fig. 2 is the theoretical fit using Eq. (1) to the experimental data. This difference in behavior compared with the film may be attributed to convection in the liquid phase. In the film, bR molecules are locked in the polymer chain. Hence as the input power is increased, the M state lifetime decreases due to the local heating, leading to the decrease in slow light delay. However in the solution, the molecules are free, and hence, heat dissipation is more efficient. This sustained delay, which is found in the solution phase even at high powers may be favorable for some applications.

An added advantage of the liquid phase is the ability to conveniently alter the concentration and hence the optical density, thus enabling variable delay. Figure 3 shows the light pulse delay as a function of the OD of the bR solution obtained at 50 Hz modulation frequency. The theoretical fit to the experimental data is obtained using Eq. (1). By diluting the bR solution, the transmitted power is varied from 1.5 to 11.4 mW for an input of 11.5 mW; the corresponding OD varied from 0.87 to 0.0008, resulting in variation in pulse delay over a wide range.

In conclusion, we have demonstrated slow light in liquid phase using an aqueous solution of the biomaterial bR. Compared with the film, where the modulation frequency was limited to less than 1 Hz, in the bR solution, the frequency range can be extended up to the kilohertz regime. Furthermore, the higher thermal diffusion and molecular mobility in the solution phase renders the possibility of slow light even at high laser powers. It is an added advantage that the optical density, and hence, the delay can be varied conveniently. As in the case of films, all-optical control of delay with a second (blue) beam also is possible. If the pump wavelength is detuned from the absorption peak of the medium, this will result in a decrease of pulse delay. In addition, if the temperature of the solution is varied, M state lifetime τ will change causing variations in pulse delay. Slow light may be possible in porous media such as solgels by incorporating appropriate solute molecules for applications.

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