

Future switching technology: bacterial protein-based programmable all-optical switch for integrated optics applications?

Gopalkrishna M. Hegde* and K. P. J. Reddy

We report on the bacterial protein-based all-optical switches which operate at low laser power, high speed and fulfil most of the requirements to be an ideal all-optical switch without any moving parts involved. This consists of conventional optical waveguides coated with bacteriorhodopsin films at switching locations. The principle of operation of the switch is based on the light-induced refractive index change of bacteriorhodopsin. This approach opens the possibility of realizing protein-based all-optical switches for communication network, integrated optics and optical computers.

Keywords: All-optical switching, bacteriorhodopsin, biophotonics, integrated optics.

AN important component of high-speed optical communication networks is an all-optical switch that allows one optical signal to control another optical signal, i.e. control of light by light¹⁻⁴. For quantum information networks, it is important to develop optical switches that are actuated by a single photon. The attractions of using all-optical switches are significant. All-optical switches steer the light pulses among different fibre spans without converting them into electrical signals at any point. They promise to have potential capacity to increase speed, make it compact, slash costs and make it easier for telecom operators to deploy future developments in transmission technology. Other prominent applications of such switches are in integrated optics (IO) and in emerging optical computers. IO is aiming at integrating miniature active and passive optical components on the surface of a single substrate (usually silicon or glass) similar to conventional integrated electronics. The active elements in IO are all-optical switches and modulators which play the role of transistors in IO circuits and the passive elements are the waveguide structures. Researchers are working on a variety of optical switching technologies. These include arrays of tiny tilting mirrors (MEMS), liquid crystals, bubbles, holograms, silicon photonic crystal, rubidium vapour and thermo-acousto-optics⁴⁻¹⁰. However, none of these switches is fulfilling all the requirements of information networks due to their limitations either with structure, mechanical movements, speed, large power consumption, programmability or compatibility. Also, at present, none of them is ready in full scale for widespread deployment in carrier

networks. Much work needs to be done before a reliable, high speed and commercially viable all-optical switch will be available.

Progress in the development of all-optical switches, IO devices and hence the much awaited full-scale optical computers is severely hindered due to the lack of appropriate materials to mass produce the fast responding photonic switches, which can be operated with the help of light pulses. The conventional approach has been to exploit the nonlinear property of the established photonic materials to control the propagation of optical signals with intense laser pulses. In parallel with these developments, several biomaterials have been explored for photonic applications¹¹. In particular, the photochromic protein called bacteriorhodopsin (BR) has emerged as a prominent candidate for the fabrication of future biomolecular photonic devices. BR is a light-sensitive bacterial protein found in the purple membrane of *Halobacterium halobium*, having all the necessary characteristics to be a good photonic material¹²⁻¹⁵. The advantages of BR molecules include high quantum efficiency of converting light into a state change, large absorption cross-section and optical nonlinearities, robustness to degeneration by environmental perturbations, capability to form thin films in polymers and gels, repeatability and existence of genetic variants with enhanced spectral properties for specific device applications. Due to these modifiable properties, BR can be regarded as a programmable protein. These photochromic properties of BR molecules have resulted in applications like three-dimensional memories¹²⁻¹⁵, pattern recognition systems¹⁶, holography¹⁷⁻¹⁹, second harmonic generation²⁰, mode locking²¹, spatial light modulation²²⁻²⁴, logic gates^{25,26}, optical computing²⁷, optical displays and image processing^{28,29}. Several reviews have been published on the potential of protein based optical devices¹²⁻¹⁵.

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Another interesting property of BR is its reversible refractive index (RI) change when switched photochemically from one state to the other; such transformations also change the absorption spectrum of the material^{30–33} following Kramers–Kronig relations. This property of BR has drawn a lot of attention in recent years for its technical applications.

In this article we shall explore the technological potential of BR, which has some unique properties suitable for all-optical switching. We describe a new type of BR-based 2D programmable photonic switch embedded in an optical waveguide. This bio-photonic switch is integrated with matured technology of optical waveguides and has the potential to replace the other forms of optical waveguides such as photonic crystals, which are fast emerging as new light-guiding channels. The present system utilizes light-induced reversible RI change in the biological material for its switching action. The switch being all-optical has an added feature of programmability, where the required switching speed could be selected through appropriate software.

Materials and methods

When exposed to light the BR molecule undergoes a complex photocycle having many intermediate states, with absorption maxima spanning the entire visible region of the spectrum (Figure 1). In the initial *B* state, also called the light adapted state, the retinal chromophore is in its all-trans molecular configuration. After excitation with yellow light at 570 nm, the molecule in the initial *B* state gets transformed into the *J* state with an absorption maximum at ~650 nm within about 450 fs. The species in the *J* state thermally transforms in 3 ps into the intermediate *K* state, which in turn transforms in 2 μ s into the *L* state. The relatively long-lived intermediate *M* state is generated by thermal relaxation of species from the *L* state in 50 ms. The molecule returns to the *B* state via a couple of intermediate states *N* and *O* through thermal relaxation in about 10 ms.

From the all-trans configuration of *O*, the *P* state is formed in a photochemical transition induced with red light (640 nm). In the dark, a thermal decomposition of the *P* state into the *Q* product has also been observed. There is no thermal decay from the *P* or *Q* state to the initial *B* state, and the initial *B* state can be regenerated only through photochemical excitation of the *P* and *Q* states. An important feature of all the intermediates is their ability to photochemically switch back to the initial *B* state on shining light of wavelength that corresponds to the absorption peak of the intermediate state in question.

The well-known volumetric memories using BR utilize just two states of the molecule: the initial green-absorbing state *B* and the long-lived blue absorbing *M* state^{12–15}. Also, BR has high quantum efficiency (65%) of

converting light into a state change. The light-activated forward reaction (*B*→*M*) takes only about 50 μ s whereas the reverse reaction (*M*→*B*) can be driven by light or heat and takes a few nanoseconds. For data storage purposes, the *B* state represents a '0' and *M* state represents a '1'. The other approach for long-term data storage using BR involves the so-called branched photocycle of *P* and *Q* states by exposing to the corresponding wavelengths. The cache memory process utilizes only the state change of BR upon exposing to the light within its photocycle, whereas many nonlinear optical applications are possible using light-induced RI change of BR. Among them optical switching has generated a lot of interest in recent years. Various all-optical switching schemes based on the induced anisotropy³⁴, absorption shift³⁵ and changes in the RI³⁶ have been demonstrated using BR. Switching based on RI change is attractive because of speed.

Switch design and experimental protocol

The light-induced RI change of BR, followed by changes in its absorption spectra were measured by several groups^{30–33}. It has also been reported that the RI change in BR is intensity-dependent and the size of the RI change of the film is of the order 5×10^{-3} . The optical power range required for such a change in RI of BR is 5–20 mW/cm², with 90% intensity modulation. Using this property of BR, possible IO switching has been demonstrated in which BR was used as an adlayer^{36–38}. In this configuration the changes in the incoupling angle to the waveguide due to changes in RI of BR film were about 6.5°. Making use of the intensity-dependent reversible RI change of BR film upon exposing to light of wavelengths falling within its photocycle described above, we have designed new type of all-optical switches³⁹. The basic principle of operation of the device is presented schematically in Figure 2. It consists of a conventional optical waveguide (compatible to the BR film), usually a thin film of photoactive material

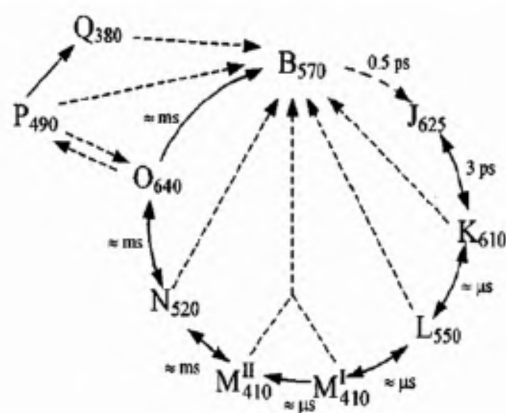


Figure 1. Schematic representation of the photochemical cycle of bacteriorhodopsin (BR) molecule when exposed to 570 nm laser light, indicating various intermediate states.

coated on a glass or silicon substrate which allows light beams to travel in the specified directions. BR films of desired thickness are deposited at the channel junctions within the waveguide structure as shown. BR-coated microcavities have already been demonstrated for optical switching³⁵. The novelty of the present protein-based all-optical switch is in its ability to steer the optical signal in the desired direction by applying an index modulation light beam on the BR film.

As long as the BR film is not illuminated with the modulating light beam, the signal beam follows the straight channel. When the BR film is illuminated with 570 nm light (beam 1), the induced RI change in the BR film will change the direction of the signal beam (beam 2) travelling along the waveguide, thereby realizing switching. The mechanism of RI change in the BR is well explained using *M*-state dynamics of its photocycle^{12–16,31,32}. Thus, if a pulsed laser beam is used as the index modulating light source, it is possible to control the switching speed of the proposed device depending on the pulsewidth and the repetition rate of the modulating laser beam. The speed of light modulation in this case is about 50 μ s, limited by the kinetics of *M*-state formation in the photocycle of wild-type BR. A faster switch can be realized making use of the photoreaction of the *M* state: driving the *M* form back to ground state using blue light pulse. This photochromic process occurs in submicrosecond time. Thus the speed of optical switching is characterized by submicrosecond timescale, while the observed refractive change is almost the same as the forward reaction, but with opposite sign. The RI change is clearly reversible. This allows us to achieve an optical switching device capable of operating at a high speed with low power consumption. Recent studies³⁸ on light-induced RI changes of BR have shown that the *K* intermediate has remarkable nonlinear optical properties that seem even more favourable than those of *M* due to the picosecond kinetics of the RI change, and may readily be utilized in IO applications. So far the various switching schemes demonstrated using

BR are in the visible band. Recently, it has been extended into the telecom band (1310/1550 nm) where BR is virtually transparent³⁵. Since BR has no absorption at the signal wavelengths of communication interest (850, 1330 and 1550 nm), there is only RI change without affecting the BR photocycle. Hence an all-optical switch most suitable for communication networks can be fabricated.

The amount of RI change in the BR film required for steering the input signal beam into the desired channel can be estimated from the following analysis: let n_1 be the RI of the waveguide medium and n_2 that of the BR film after exposure to the modulation beam. Using the condition of total internal reflection, the angle at which the BR film is to be deposited to direct the guided light into the desired locations of the integrated device can be estimated. It is given by the relation $\sin \theta = n_2/n_1$, where θ is the turning angle. Assuming that $n_1 \approx 1.5$, in order to create an interface at 45° to the input beam (beam 1), the required change in RI (Δn_2) in the BR material is estimated to be 0.43933. Such a large change in RI is unlikely to be achieved. In such a situation a suitable combination of the light-induced RI change and the corresponding angle of incidence can be used to realize the proposed switching (based on Brewster angle). However, chemically enhanced BR has exhibited^{31–33} a light-induced RI change of the order of 5×10^{-3} . Taking a light-induced RI change of about 5×10^{-2} , the estimated angle of the BR film interface for the incoming beam is about 72° . Still this is a large angle of incidence to realize perfect 45° switching. A suitably modified BR structure so as to achieve an RI change of the order of 10^{-1} would help realize this all-optical switching device for communication networks and IO.

An alternative approach is to use a suitable combination of the channel angle and the light controlled beam deflection angle by BR films, so that a fast, all-optical switch can be realized in waveguide structures. The switching fabric for this combination is shown in Figure 3. Waveguides have to be formed with re-routing channels fabricated at desired angles so as to match the beam deflection angle caused by the light-induced RI change of the BR. The BR films of desired thickness and width are formed at the channel junctions as shown. Modulating light beams are switched on wherever the signal beam is to be coupled to the desired channel; otherwise it follows the normal path (Figure 3a). Another switching module with multiple channels is shown in Figure 3b. In this configuration waveguides with multi-channels are fabricated with slightly varying angles. Using the property of intensity-dependent reversible RI change in BR, the incoming light can be coupled to the desired channel of the communication network in sequence, as shown in Figure 3b. However, this needs precise control of the laser power, RI change and channel angle on the waveguide fabric. Since the theory and measuring techniques for IO are well established, it is possible to provide a low-loss

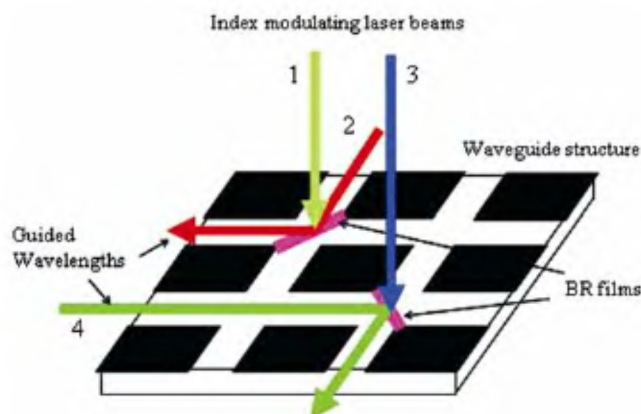


Figure 2. All-optical switching using BR embedded in waveguide structure.

and high-contrast all-optical switching device using BR, which can respond at a very high speed and may fulfil most of the requirements of communication networks.

All the BR-based switches described above can be made to operate at the required switching rate using ultrashort light pulses from a mode-locked or gain-switched semiconductor laser. A schematic diagram of the computer controlled BR based photonic switch with programmable switching rate is shown in Figure 4. In this scheme the index modulation beam is a continuous train of light pulses of required pulsewidth (\sim ps) and repetition rate. These pulses are generated by regenerative gain switching the diode laser⁴⁰. The advantage of this method is that the pulse repetition rate can be varied using a computer-controlled bandpass filter. Thus we can vary the switching rate of the proposed photonic switch

through a computer program, without any hardware changes. The data to be transmitted are launched into the waveguide by the conventional technique of using a diode laser. Incorporation of protein switch-based routing described here has several distinct advantages, including compactness, optically controlled switching speed, improvement in switch isolation, wavelength selection, programmability and no moving parts involved.

The BR-based, programmable, high-speed photonic switch has many applications. Predominantly, it can be used for the rerouting of optical channels in fibre optic communications. This family of devices provides an optical switching and routing system that is useful for inter-connecting any of the optical channels of an input array to any of the optical channels of an output array utilizing an optically controlled switching speed. Also, they can be used in optical interconnects to store and retrieve data in a computer.

Concluding remarks

In conclusion we note that, although the best material for all-optical switches remains a subject of debate, there is a general agreement among the researchers that all-optical switches and hence all-optical computers are a realistic goal. Also the switch architectures shown in this article have not been made, though the concept has been proved³⁹ and may be few years away from reality. However, the architecture in Figure 3b has been partially demonstrated using BR as waveguides in an integrated optics Mach-Zehnder interferometer configuration with two channels³⁸. It remains to be seen whether the all-optical BR switch described here will have any commercial value. Also, all-optical 3D switches using BR may be still far from reality. Nevertheless, we hope that the proposed BR switching fabric fosters new 2D all-optical switching architectures for the potential use of protein-based switches in communication networks, IO devices as well as in optical computer architectures. We also hope that this article will help stimulate renewed interest not only in BR-based photonic devices, but also in exploring other similar proteins for molecular electronics.

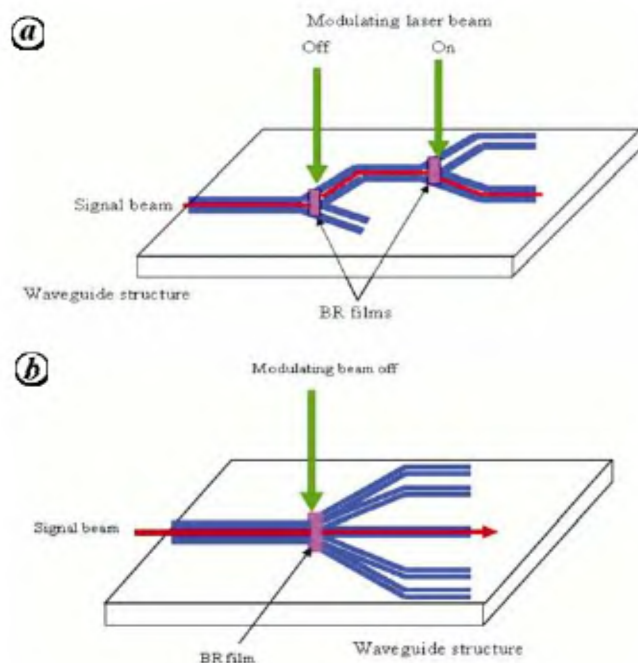


Figure 3. BR-based all-optical switching fabrics. *a*, Single-channel multi-switching type. *b*, Multichannel, intensity-dependent type.

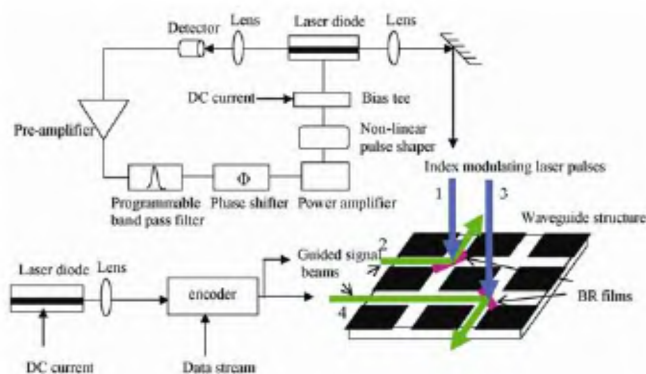


Figure 4. Schematic of programmable BR-based all-optical switch.

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