Smart Signal Interconnection by the Use of a Photosensitive Polymer

Mitsunori Saito, Takamasa Hamazaki, and Kohei Sakiyama
Department of Electronics and Informatics
Ryukoku University
Seta, Otsu 520-2194, Japan
msaito@rins.ryukoku.ac.jp

***Abstract*—Photosensitivity of a dye-dispersed polymer was utilized for creating a self-controlled photonic interconnection. Polydimethylsiloxane that contained photochromic diarylethene changed its color depending on wavelengths of irradiated laser beams. Transmission characteristics of this polymer were examined by using laser pulses of 405 (violet), 450 (blue), or 532 nm (green) wavelength as photonic signals. When violet or green signal pulses (1 kHz or 1 kbps) were launched into this polymer, an optical path was formed in self-organized manner, and consequently, the output signal intensity increased as time passed. By contrast, the intensity of blue pulses decreased gradually, since they erased their optical path by themselves.**

Keywords—optical interconnection; optical signal processing; self-control; photochromism; polymer

I. INTRODUCTION

Advanced communication systems or signal processors require smart materials that act not only as a sensor but also as a controller for selective transmission. Living bodies adapt themselves to environmental changes by use of self-formed synapse connections between a great number of neurons. In electrical or optical systems as well, self-organized or self-controlled interconnections are required to create artificial neural networks that are modeled on living bodies [1−6].

Photochromic dyes are promising materials for constructing smart optical systems, since their optical properties change when they are exposed to incoming signal pulses; i.e., the refractive index and absorbance change due to photochemical reactions [7−10]. Diarylethene, for example, has two photosensitive isomers that are shown in Fig. 1(a) [11]. As the black line in Fig. 1(b) shows, the closed-ring isomer has an absorption band at around 500 nm wavelength (green), and accordingly, exhibits a red color. When exposed to green light, the ring opens and the dye molecule takes the other structure. Consequently, the absorption band at 500 nm disappears, whereas the absorbance increases at around 400 nm (violet), as shown by the gray line in Fig. 1(b). This open-ring isomer is nearly transparent or slightly yellowish. Violet light irradiation causes the dye molecule to turn to the closed-ring structure, and accordingly, it gets colored again.

These reversible photochromic reactions were used to create an optical fiber that exhibited nonlinear input-output characteristics [12]; i.e., the fiber transmittance changed notably depending on the input signal intensity. Although this experiment was conducted with a liquid-core fiber consisting of a glass pipe (cladding) and a dye solution (core), solids are generally preferred to liquids from the viewpoint of handling capability and chemical stability [13]. In a solid matrix, however, the photochromic reactions become less efficient and slower than those in liquid, since a small free-volume restricts the molecular deformation (isomerization) [14−16]. In previous studies, the authors created photochromic polymers that contained a dye solution in either nano-sized pores of a membrane (porous film) or flexible intermolecular space of a polymer [17−19]. In these polymers dye molecules can behave as they do in liquids, whereas the material can be handled like solids.

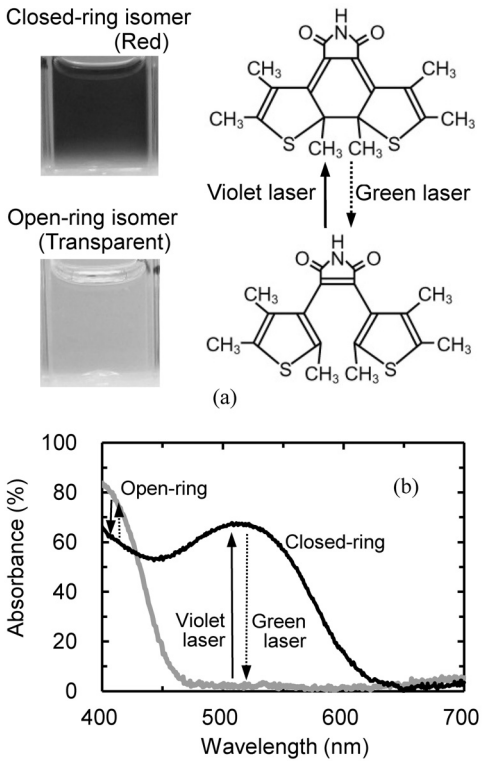

Fig. 1. (a) Molecular structures of diarylethene isomers. The photographs show a toluene solution of the corresponding diarylethene isomers. (b) Absorption spectra of the closed- or open-ring isomers that are dispersed in a polydimethylsiloxane polymer. The sample was exposed to a violet or green laser beam before the spectral measurement.

ISBN 978-0-9928626-7-1 © EURASIP 2017

In this study we prepared a photosensitive polymer in which photonic signals create or erase their path in self-organized manner. Experiments on a selective signal transmission were conducted with this polymer by launching photonic signals at different pulse frequencies.

II. EXPERIMENTS

Polymers were prepared by mixing polydimethylsiloxane (PDMS) oil and a curing agent (Shin-Etsu Chemical, KE-103). Diarylethene (Tokyo Kasei Kogyo, B1535) was dissolved in toluene, and the solution was mixed with the PDMS oil so that the toluene ratio was 60 vol% and the dye concentration was 0.6 mM. As Fig. 2(a) shows, the mixed solution was enclosed in a sample cell that consisted of glass plates and an O-ring (inner diameter: 44 mm) [20]. The glass plates were pressed with aluminum plates and screws so that the sample thickness became 3 mm. Fig. 2(b) shows a photograph of two samples that were prepared in this manner. The left sample had been exposed to green light, and hence, it was transparent (the open-ring state). On the other hand, the right sample exhibited a red color (the closed-ring state), since it had been exposed to violet light. Although both the open- and closed-ring isomers were stable, the absorbance changed slightly after a few hours, since the two isomers replaced one another due to molecular diffusion in the PDMS matrix [19, 20].

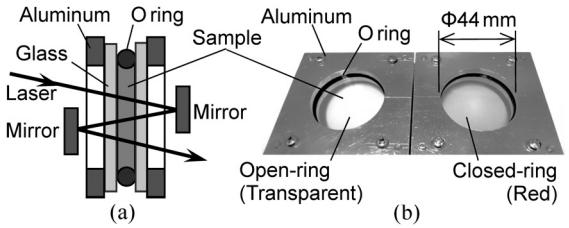

Fig. 2. (a) Cross-section of the sample cell. (b) Photographs of the samples in the open- or closed-ring states.

The thickness of the current sample was insufficient to induce strong absorption. As Fig. 2(a) shows, therefore, the laser beam was reflected by two mirrors so that it made a round trip in the sample. Signal sources were laser diodes of 405 (violet) or 450 nm (blue) and a frequency-doubled Nd:YAG laser (532 nm, green). Signal pulses were generated by chopping a laser beam at 1 kHz. The input signal intensity and the beam diameter were adjusted to ~5 mW and 1.5 mm, respectively. The signal beam that passed through the sample was detected by a photodiode. The output signal in Fig. 3(a) was measured for the sample that had been bleached to the open-ring state by exposure to green light. When the violet pulses were put into this sample, no output signal was detected in the first few seconds, since, as the gray line in Fig. 1(b) shows, the open-ring isomer absorbed violet light. As time passed, however, the output signal emerged and its intensity increased gradually. This process indicated that the violet signal self-formed its optical path by inducing molecular deformation to the closed-ring isomer. As Fig. 3(b) shows, the

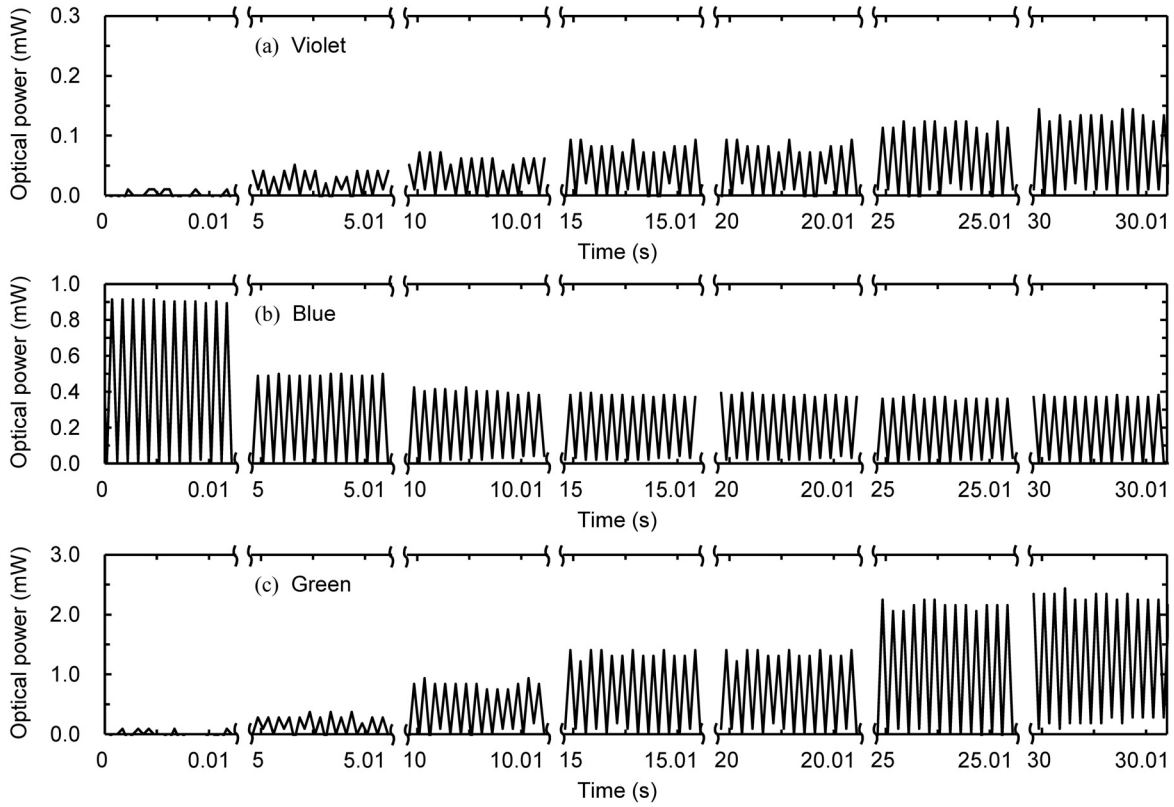

Fig. 3. Transmitted light intensities that were measured for (a) violet, (b) blue, or (c) green signal pulses. The input laser beams were modulated at 1 kHz, and the irradiation started at 0 s. The sample was initially in the (a, b) open- or (c) closed-ring state.

ISBN 978-0-9928626-7-1 © EURASIP 2017

opposite phenomenon took place when the blue pulses were put into the sample. A strong output signal was detected immediately after start of the signal input, since the absorbance of the open-ring isomer was low at 450 nm. The output signal, however, decreased notably in 10 s. This result indicated that the blue pulses erased the optical path by themselves. When the green pulses were used as an input signal, the entire sample had been exposed to violet light before measurement, since otherwise the open-ring isomers absorbed no green light and no reaction took place. As Fig. 3(c) shows, the green signal exhibited the self-formation characteristic.

III. Discussion

In regard to the violet and green signals, we predicted occurrence of the self-formation process on the basis of the spectral change in Fig. 1(b). However, the behavior of the blue signal was unpredictable before the experiment, since it was unknown whether blue light would open or close the molecular ring. The result in Fig. 3(b) indicates that blue photons induce isomerization to the closed-ring state as violet photons do. Probably the violet absorption band, which promotes creation of the closed-ring isomers, is stronger than the green absorption band at the blue wavelength.

Although all signals had the same input power, the output signal intensity changed notably depending on the signal wavelength; i.e., ~0.1, ~1, and ~2 mW, respectively, for the violet, blue, and green signals. This difference was caused by spectral dependence of the sample absorbance that was shown in Fig. 1(b). The output signal intensity or the contrast between the on- and off-states depends on both the optical path length and dye concentration. Decreasing the absorbance enhances the output intensity but reduces the photochromic efficiency. The intensity and wavelength of the input signal also affect the efficiency and response time of the self-formation and erasure processes. Various design parameters have to be adjusted suitably for constructing an efficient photonic interconnection.

IV. Application

A learning function plays an important role when synapses construct a network between neurons. Simulating those neural networks, the authors are trying to create an optical device that exhibits a learning function. The current photosensitive polymer is useful for creating such a smart interconnection that transmits frequent signals but blocks noisy occasional signals (Hebbian learning) [21, 22]. Fig. 4 illustrates the scheme of this device. Nodes that emit signal pulses are embedded in an opaque medium, and the signals self-form an optical path depending on the pulse frequency or the bit rate. The node 2, for example, emits signal pulses frequently toward the node 0, and hence, a signal path is formed between these nodes. By contrast, the node 4 cannot create a connection to the node 0, since it rarely emits signal pulses.

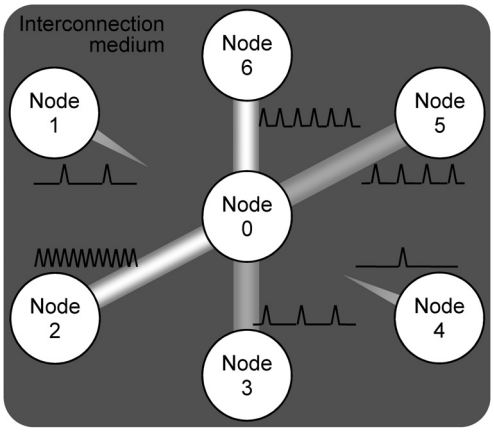

Fig. 4. Schematic illustration of the self-organized network. The nodes 1–6 transmit signal pulses toward the node 0 at different frequencies. The signal, however, does not reach the node 0 unless the pulse occasion frequency is high enough to create the optical path in a self-organized manner.

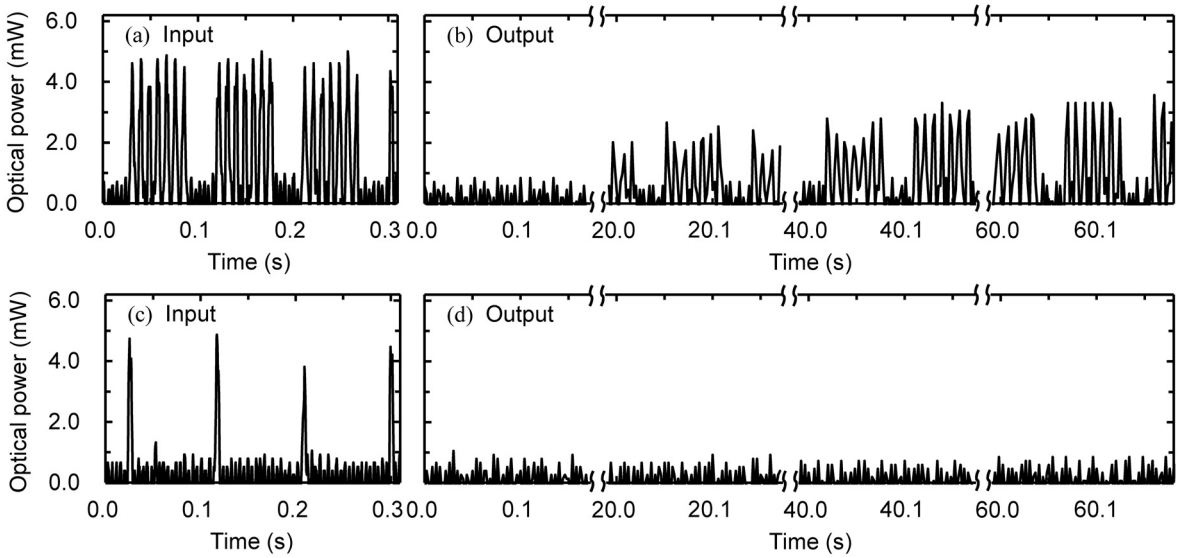

Fig. 5. Dependence of signal transmission on the frequency of pulse occurrence, i.e., (a, b) 84 or (c, d) 12 pulse/s. The input signals in (a) and (c) were generated by modulating a green laser beam. The output signals in (b) and (d) correspond to the input signals in (a) and (c), respectively.

ISBN 978-0-9928626-7-1 © EURASIP 2017

Experiments were conducted by using the green signal, which exhibited the most efficient self-formation function (Fig. 3). Here we describe the experimental result briefly, since details were reported in [23]. As Fig. 5(a) shows, the pulse width of the input signal (532 nm) was 5 ms, and the peak power was ~5 mW. These pulses were put into the photochromic polymer that had been exposed to violet light for creating the closed-ring isomers. When the pulse frequency was 84 pulse/s (84 bit/s), the output signal exhibited a gradual increase, as shown in Figs. 5(a) and 5(b). By contrast no output signal was detected when the pulse frequency decreased to 12 pulse/s, as shown in Figs. 5(c) and 5(d). Although even occasional pulses induce isomerization to the open-ring state, those open-ring isomers were replaced by closed-ring isomers in the surrounding region [19, 20]. Consequently, no signal transmission was observed when the pulse frequency was low.

V. Conclusion

A photosensitive polymer was fabricated by dispersing photochromic diarylethene in PDMS rubber. The optical absorbance changed notably by irradiation of violet, blue, or green lasers. Consequently, pulse signals that were generated from these lasers formed or erased optical paths by themselves. This photosensitive polymer will be useful to construct smart networks in which signal pulses exhibit a self-control function.

Acknowledgment

This research was supported by Japan Society for the Promotion of Science.

References

[1] Y. S. Abu-Mostafa and D. Psaltis, “Optical neural computers,” Sci. Am., vol. 256, pp. 88–95, 1987.

[2] D. Haronian and A. Lewis, “Elements of a unique bacteriorhodopsin neural network architecture,” Appl. Opt., vol. 30, pp. 597–608, 1991.

[3] M. T. Hill, E. E. E. Frietman, H. de Waardt, G. Khoe, and H. J. S. Dorren, “All fiber-optic neural network using coupled SOA based ring lasers,” IEEE Trans. Neural Netw., vol. 13, pp. 1504–1513, 2002.

[4] S. Kawata and A. Hirose, “Coherent optical neural network that learns desirable phase values in the frequency domain by use of multiple optical-path differences,” Opt. Lett., vol. 28, pp. 2524–2526, 2003.

[5] R. J. Vogelstein, U. Mallik, J. T. Vogelstein, and G. Cauwenberghs, “Dynamically reconfigurable silicon array of spiking neurons with conductance-based synapses,” IEEE Trans. Neural Netw., vol. 18, pp. 253–265, 2007.

[6] K. Kravtsov, M. P. Fok, D. Rosenbluth, and P. R. Pruncnal, “Ultrafast all-optical implementation of a leaky integrate-and-fire neuron,” Opt. Express, vol. 19, pp. 2133–2147, 2011.

[7] G. H. Brown, ed., Photochromism, New York: Wiley, 1971.

[8] H. Takei and N. Shimizu, “Optical device with excitatory and inhibitory optical outputs,” Opt. Lett., vol. 21, pp. 537–539, 1996.

[9] D. P. Shelton, “Bacteriorhodopsin optoelectronic synapses,” Opt. Lett., vol. 22, pp. 1728–1730, 1997.

[10] S. A. Kandjani, R. Barille, S. Dabos-Seignon, J.-M. Nunzi, E. Ortyl, and S. Kucharski, “Multistate polarization addressing using a single beam in an azo polymer film,” Opt. Lett., vol. 30, pp. 1986–1988, 2005.

[11] K. Uchida and M. Irie, “Photochromism of diarylethene derivatives,” in Organic Photochemistry and Photobiology, 2nd ed., W. Horspool and F. Lenci, Eds., Boca Raton: CRC Press, 2004, Chapter 35.

[12] M. Saito, A. Honda, and K. Uchida, "Photochromic liquid-core fibers with nonlinear input-output characteristics," J. Lightwave Technol., vol. 21, pp. 2255–2261, 2003.

[13] M. Saito and Y. Takahashi, "Photochromism induced by infrared two-photon absorption," Opt. Lett., vol. 33, pp. 1687–1689, 2008.

[14] J. G. Victor and J. M. Torkelson, "On measuring the distribution of local free volume in glassy polymers by photochromic and fluorescence techniques," Macromolecules, vol. 20, pp. 2241–2250, 1987.

[15] N. Tamai, T. Saika, T. Shimidzu, and M. Irie, "Femtosecond dynamics of a thiophene oligomer with a photoswitch by transient absorption spectroscopy," J. Phys. Chem., vol. 100, pp. 4689–4692, 1996.

[16] K. Uchida, A. Takata, S. Ryo, M. Saito, M. Murakami, Y. Ishibashi, H. Miyasaka, and M. Irie, "Picosecond laser photolysis studies on a photochromic oxidation polymer film consisting of diarylethene molecules," J. Mater. Chem., vol. 15, pp. 2128–2133, 2005.

[17] M. Saito and Y. Tsubokura, "Photochromic isomerization of spirobenzopyran in nanoholes of anodic alumina," Appl. Opt., vol. 45, pp. 8019–8025, 2006.

[18] M. Saito, Y. Tsubokura, N. Ota, and A. Fujiuchi, "Nanostructured solid-liquid compounds with rewritable optical functions," Appl. Phys. Lett., vol. 91, pp. 061114-1–3, 2007.

[19] M. Saito, T. Nishimura, K. Sakiyama, and S. Inagaki, "Self-healing of optical functions by molecular metabolism in a swollen elastomer," AIP Adv., vol. 2, pp. 042118-1–3, 2012.

[20] M. Saito, T. Nishimura, and T. Hamazaki, “Fade-resistant photochromic reactions in a self-healable polymer,” Opt. Express, vol. 23, pp. 25523−25531, 2015.

[21] D. O. Hebb., The Organization of Behaviour: A Neuropsychological Theory, New York: Wiley, 1949.

[22] T. V. Bliss and T. Lomo, “Long-lasting potentiation of synaptic transmission in the dentate area of the anaesthetized rabbit following stimulation of the perforant path,” J. Psyiol., vol. 232, pp. 331–356, 1973.

[23] M. Saito and K. Sakiyama, “Self-healable photochromic elastomer that transmits optical signals depending on the pulse frequency,” J. Opt., vol. 15, pp. 105404-1–6, 2013.

ISBN 978-0-9928626-7-1 © EURASIP 2017