Optically Programmable Microring Resonator Filter

A. Bahari[1], M. Spiegelberg[1], D.R.D. Van Luijk[2], R.P. Sijbesma[2], O. Raz[1]

[1]Eindhoven University of Technology, Dept. of Electrical Engineering, Groene Loper 19, 5612 AP Eindhoven, The Netherlands

[2]Eindhoven University of Technology, Dept. of Chemical Engineering and Chemistry, Het Kranenveld 14, 5612 AZ Eindhoven, The Netherlands

This paper demonstrates a method to program photonic integrated circuits (PICs) by using a tunable cladding. It is based on using photoswitchable molecules called diarylethenes (DAE), which induce a photoisomerization. The use of DAEs is promising as the optical properties change after light stimulation is applied. Optical tuning can be easily realized with light sources in the visible and long ultra-violet (UV-a) range. Rapid programming times and a reversible group index change of approximately $\Delta n_g \approx$ 0.04 have been achieved between the two states of the DAE cladding which has been applied to a microring resonator (MRR).

Introduction

PHOTONIC integrated circuits are used in key applications such as data communication, biomedical, metrology[1], [2], and show great promise in the fast-growing fields of neural networks and quantum information processing[3], [4]. PICs have been bespoke devices and only in recent years the growing maturity of the technology has introduced the idea of *programmable* photonic integrated circuits[4]. Programming can be achieved through numerous mechanisms such as electrical or thermal tuning as well as using more complex means like MEMS technology[5]. Unfortunately, all these solutions can only maintain their state while constant power is applied to the system. Thus, a need has been created for a programming mechanism that is sustainable as well as reversible. This introduces the idea of using a programmable layer to rectify or optimize the output characteristics of a photonic device. These layers change their optical characteristics through physical stimulation. This enables the possibility to compensate for process tolerances. The method in this paper focuses on photoswitchable compounds, in particular diarylethenes (DAEs). The DAE molecules undergo photoisomerization when they are irradiated with light of a certain wavelength. This results in a refractive index change of the DAE molecule and

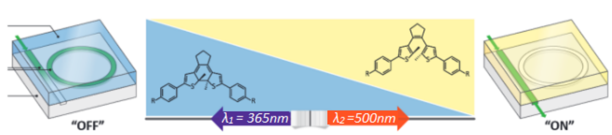

Figure 1. Example of switching due to light stimulation of the optical sensitive cladding

therefore of the cladding. The light-induced isomerizations also exhibit different absorption spectra. When combining this chemical compound with an integrated photonic component, such as a waveguide, the refractive index change of the cladding will influence the optical properties of the component. The strength of the effect depends on the sensitivity of the PIC's surface.

In this paper it is shown that the use of programmable waveguide cladding is promising. Physical and optical properties change when light stimulation is applied.

Optical tunable compound

The compounds that have been investigated belong to the group of diarylethenes (DAEs). DAEs are optically sensitive. Two different isomer configurations of the DAEs can be seen in Figure 2. This paper tests these DAE variations called DAE 1 and DAE 2. The first one is based on a perfluorocyclopentene derivative. The second one is structurally similar but without fluorine atoms.

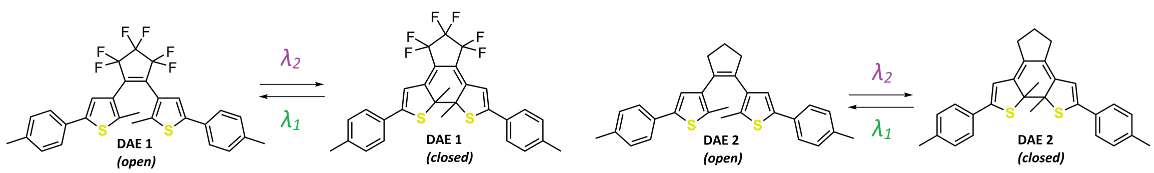

Figure 2. Structural formulas of DAE 1 and DAE in the open and closed forms

The quantum yield is a parameter specifically used in photochemical reactions and is defined as the ratio between the number of molecules undergoing undergoing a transition from state A to state B, and the number of photons that are absorbed for this reaction. This applies to a molecule undergoing a photoisomerization from an isomer A to isomer B. The DAEs in this paper have two isomer configurations, a closed-ring and an open-ring form. The molecule will switch to its closed-ring form when illuminated with UV-light, or to its open-ring form using light in the visible spectrum.

Method and Results

The DAEs have been analyzed by spinning them as a cladding layer on a PIC. This device is based on a silicon on insulator (SOI) platform enabling high interaction of the guided waveguide mode with the surface. The PIC that has been used for testing is an MRR which operates as a wavelength filter. By changing the state of the DAE the refractive index of the cladding changes and therefore a shift of the filtered wavelength can be measured. To characterize the MRR a transmission measurement is performed. Therefore light is coupled in and out of the PIC via single mode fibers using TE optimized grating couplers. As light source, a tunable laser is used and the transmitted signal is measured with an optical power meter. As a reference, a fiber Bragg grating (FBG) is used for any wavelength discrepancies. This FBG filters at a wavelength of 1547.75nm. The wavelength range has been chosen to be 1540 to 1550 nm. The input power is fixed for all wavelengths at 5 dBm. A polarization controller is used to tune the polarization state.

The PIC contains a 24 μm MRR with a 55 nm separation gap between the ring and the

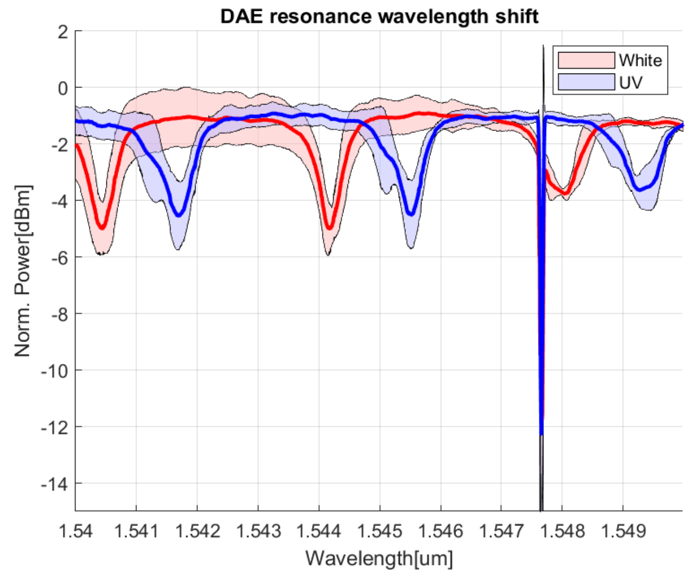

Figure 3. Mean and standard deviation of congregate data

buswaveguide. The photoswitching has been achieved by a common small desk-lamp (2700 K, 220 lumen) as the white light source, and a 390 nm UV lamp with a radiant flux of 6 W. The DAE sample has been been measured through multiple cycles. Each cycle the MRR has been measured between and after each exposure of white light for 5 minutes, and UV for 1 minute. This data has been normalized against the wavelength dependent propagation loss. Some discrepancies still exists between cycles due to external factors such as ambient light and too long/short exposure times. The DAE is highly sensitive, measuring for longer/short timeframes will give different results. In Figure 3 the mean and standard deviation of the transmission measurement are shown. The two colors (red and blue) represent the two programming states. A wavelength shift in a MRR will scale linearly with the refractive index. The refractive index change can be approximated by analyzing the group index:

$$n_g = \frac{\lambda^2}{FSR \cdot L} \tag{1}$$

FSR is *the free spectral range*, L is the optical path length of the MRR. This results in an Δn_g of approximately 0.04. The Q-factor of the ring is $Q \approx 4500$.
To evaluate the usability of the DAE an estimation can be made regarding the quantum yield and maximum programming time. The quantum yields for the two DAEs are calculated using an estimation of the photon flux determined by the LED driver current and quantum efficiency of the laser setup. It can be estimated roughly with the following equation:

$$photonflux = \frac{I_{driver} \cdot QE}{q_e \cdot area} \tag{2}$$

where I_{driver} is the LED driver current, q_e is the elementary charge in Coulombs, and QE is the quantum efficiency. The quantum yield of the solid films of DAE 1 is approximately 50% and for DAE 2 30%.

The maximum programming time rounds to 60 minutes for both DAEs for visible light. The programming time using the UV source is a factor 10 smaller at 5 minutes. However, the largest measured refractive index change occurs within 10 minutes for visible light and within 1 minute for UV light.

Discussion

To enable better modeling of the system consisting of the PIC and the DAE cladding layer it is important to know the effective refractive index change instead of the group index change. It has estimated to be $\Delta n_{eff} \approx 0.03$ at 1550 nm. This is slightly lower than the measured refractive group index of 0.04. This is because the group index is expected to be higher for Si[6], and also due to approximation errors of the fitting software.
With regards to the sustainability of the DAE layers, it needs to be considered that while its optical behaviour seems ideal for photonic programming, it is limited in the amount of cycles it can switch states. Another limitation of the system is the fact that the DAE is easily affected by ambient light, reducing the remaining cycle life of the molecules even further. It is therefore vital that the DAE films are not exposed to external light sources for experimental as well as potential industrial applications.

Conclusion

The DAE shows great potential for photonic programming. For the used PIC a group index change of $\Delta n_g \approx 0.04$ has been measured. The resonance wavelength shift of the tested MRR was controllable, reversible, and maintains its state if not exposed to light sources.

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References

[1] M. A. Mohammed, C. C. Sproncken, B. Gumí-Audenis, E. Lazdanaité, R. Stabile, I. K. Voets, and O. Raz, "Reversibly Programmable Photonics via Responsive Polyelectrolyte Multilayer Cladding," *Advanced Optical Materials*, vol. 8, no. 16, 2020. [Online]. Available: https://doi.org/10.1002/adom.202000325.

[2] "Birth of the programmable optical chip," p. 1, dec 2016. [Online]. Available: https://www.nature.com/articles/nphoton.2015.265

[3] S. Xu and J. Wang, "Performance evaluation of an integrated photonic convolutional neural network based on delay buffering and wavelength division multiplexing."

[4] J. Capmany, I. Gasulla, and D. Pérez, "Microwave photonics: The programmable processor," pp. 6–8, dec 2016. [Online]. Available: https://www.nature.com/articles/nphoton.2015.254

[5] W. Bogaerts, H. Sattari, P. Edinger, A. Y. Takabayashi, I. Zand, X. Wang, A. Ribeiro, M. A. Jezzini de Anda, C. Errando-Herranz, G. Talli, K. Saurav, M. A. Garcia Porcel, P. Verheyen, B. Abasahl, F. Niklaus, N. Quack, K. B. Gylfason, P. O'Brien, and M. U. Khan, "MORPHIC: Programmable photonic circuits enabled by silicon photonic MEMS." SPIE-Intl Soc Optical Eng, feb 2020, p. 1.

[6] E. Dulkeith, F. Xia, L. Schares, W. M. J. Green, and Y. A. Vlasov, "Group index and group velocity dispersion in silicon-on-insulator photonic wires," *Optics Express*, vol. 14, no. 9, p. 3853, may 2006. [Online]. Available: https://opg.optica.org/viewmedia.cfm?uri=oe-14-9-3853&seq=0&html=true https://opg.optica.org/abstract.cfm?uri=oe-14-9-3853 https://opg.optica.org/oe/abstract.cfm?uri=oe-14-9-3853