Improving Effective Mode Index Modulation Using Slot-Waveguides in Programmable Photonics Based on Photochromic Diarylethene Coatings

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Integrated photonics has gained significant interest in recent times, impacting fields such as telecommunications, quantum computing, and medical applications by offering advantages like high-speed, high-bandwidth connections, minimal signal loss, and resistance to electromagnetic interference. However, challenges remain, particularly the limited reusability of photonic integrated circuits (PICs), which are often designed for specific applications, requiring new fabrication processes each time.

This work addresses these challenges by focusing on programmable integrated photonics, which allow for reconfigurable circuits increasing the usability and potentially the production yields. Current programming methods alter the refractive index, but they face issues such as scalability and energy consumption. This research explores novel polymer coatings, specifically Diarylethene (DAEs), which can reversibly and non-volatilely change their refractive index (Δn_{DAE} ≈ 0.03) through a light-induced chemical reaction, potentially overcoming existing limitations.

For this purpose, Finite Difference Eigenmode (FDE) simulations have been performed to maximize mode confinement inside the coating material in silicon slot waveguides. By adjusting the silicon ridge width and size of the slot gap, the effective refractive index change of the fundamental mode improves from Δn_{ridge} ≈ 0.005 up to Δn_{slot} ≈ 0.025, 83.3% of the change in the DAE layer.

Introduction

Photonics has become a key technology for telecommunication, sensing and quantum computation and as demand surges for efficient and cost-effective solutions, photonic integration is increasingly needed to enable compact, high-performance systems [1]. Traditionally, Photonic Integrated Circuits are designed as application specific (ASPICs), tailored to solving particular tasks. However, when requirements change or new functionalities are needed, their fabrication cycle must start anew. This involves redesign, new materials acquisition and processing, which is a time-consuming, costly and non-sustainable approach [2].

To address these limitations, programmable integrated photonics (PIP) has emerged as an alternative strategy. PIP allows to alter the functionality of a PIC post manufacturing, by using a software interface to reconfigure the devices within seconds. PIP uses a meshed network of optical waveguides, called optical cores, which resemble field-programmable gate arrays (FPGAs) [3, 4]. Several approaches have been proposed to achieve programmability in these optical cores, including thermal-optic effect, electro-optic phase shifters, or phase-changing materials [5, 6]. Despite these advancements, significant challenges remain, as drawbacks for these methods include thermal crosstalk, high energy consumption due to volatility of the programmed state, lack of scalability, optical absorption and in the case of some phase-changing materials high programming temperatures (> 200 °C) and expensive apparatuses to do the programming [6].

In our previous works [7], DAE coatings have shown refractive index changes of Δn_{DAE} $\approx$ 0.03 while addressing many of the previously mentioned drawbacks. However, in a silicon waveguide, small light-cladding interactions limited the change in effective index of the fundamental mode (henceforth referred to as effective mode index) to $\Delta n_{eff} \approx 0.005$, corresponding with a relative change of only 16.7 % when comparing to the DAE material. This work presents a fivefold enhancement in the change in effective mode index $\Delta n_{eff,optmized} \approx 0.025$, which drastically improves the relative change to 83.3 %. This approaches the maximum possible index modulation of the DAE material itself and is realized by significantly increasing the light-cladding interaction through the introduction of slot waveguides.

Diarylethene for Programmable Integrated Photonics

First experimental results for thermally stable DAE molecules date back to the late 1980's [8]. It was shown that these polymers undergo a reversible photoisomerization reaction between two states at room temperature upon illumination with light. When using ultraviolet light the DAE transitions from transparent to a colored state, the reverse is achieved by illumination with visible light, as shown in Figure 1.

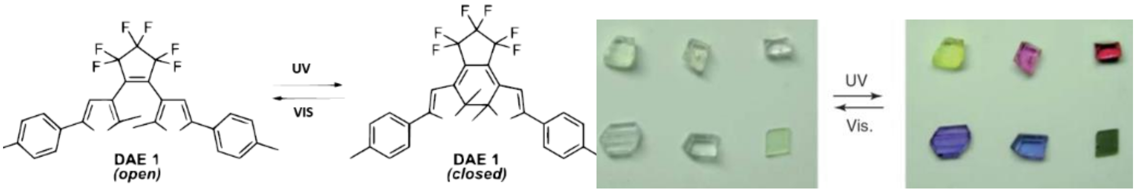

Figure 1: Open and closed state of a DAE molecule. The refractive index grows due to KK relations. Adapted from [9].

The colored state is explained by the bond rearrangement in the hexatriene ring of the DAE molecule, which introduces a new absorption peak in the visible range. This change in absorption subsequently increases the index of the material at all wavelengths following the absorption peak, as they are correlated by the Kramers-Kronig relations for physical materials [10]. This change in index is the sought after property for PIP applications, and using DAE offers advantages such as room temperature operation, non-volatility, simple illumination programming setup and no inherent optical loss in the material at telecommunication wavelengths.
The main drawback of DAEs is increased device sizes, as the refractive index contrast is small $\left(\Delta n_{DAE:\,Open\leftrightarrow Closed} = 0.01\sim 0.05\right)$ at telecommunication wavelengths $(n_{1550\text{ nm}} \approx 1.55)$ [8, 11]. Furthermore, there are limitations in the number of switching cycles due to material fatigue, although through clever chemical design the fatigue resistance can be improved to show no deterioration under $< 10^4$ switching cycles [12].

Modeling Optimal Slot-Waveguide

In our previous work [7], DAE coatings were used to demonstrate a change in resonant wavelength for a ring resonator ($L = 24$ μm) of $\Delta\lambda_c = 1.3$ nm in silicon waveguides. This change is small relative to the free-spectral range (FSR) of the same ring ($FSR = 4$ nm), due to the weak interaction of the modal field with the polymer coating.
To investigate this, new FDE simulations were conducted using 400×220 nm silicon waveguide coated with 150 nm of DAE. These simulations showed that only 9.5 % of

the optical power is confined within the coating, as shown in Figure 2E. Consequently, the change in effective mode index was limited to $\Delta n_{eff} \approx 0.005$, a mere 16.7 % relative to DAE coating ($\Delta n_{O\leftrightarrow C} = 0.03$), which is modeled as a homogeneous layer with $n_{open} = 1.553$ and $n_{closed} = 1.583$. The determined $\Delta n_{eff} \approx 0.005$ can be used in the analytical model of a ring resonator, yielding results in-line with the previous experimental findings [7]. To increase the light-cladding interaction, slot-waveguides were introduced to maximize optical confinement in the DAE coating by varying the slot gap (g) and silicon ridge widths (rw). The confinement in the coating and corresponding effective mode index change Δn_{eff} are shown in Figure 2A and B. To account for first-order dispersion effects [13], the group index n_g and the resonance shift $\Delta\lambda_c$ of the ring resonator (shown in Figure 2C and D) can be related by $\Delta\lambda_c = \frac{\Delta n_{eff} \cdot \lambda_c}{n_g}$ (1).

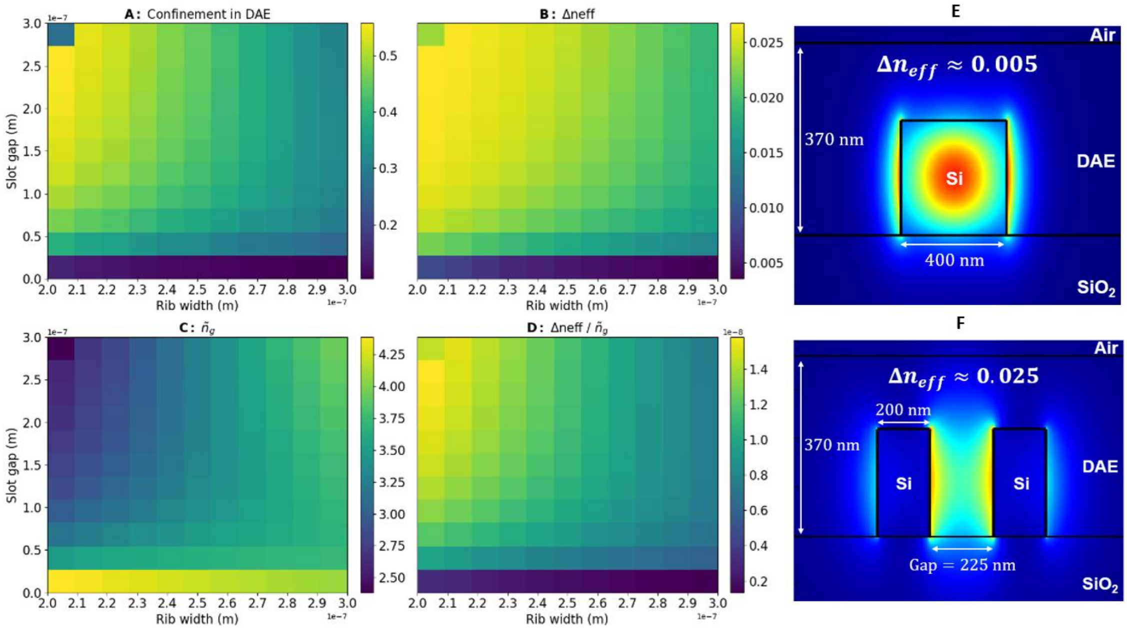

Figure 2: A: Confinement factor (optical power) in the DAE coating. B: Effective mode index change. C: $\tilde{n}_g$ as found by averaging the group index for the modes in the open and closed DAE states. D: $\Delta\lambda_c$ as determined by equation 1. At $rw = 200$ nm and $g = 300$ nm the fundamental mode is guided along the top and bottom (in the silica) of the silicon ridges instead of between them. E: FDE simulation showing the fundamental mode of a 400 nm silicon waveguide topped by 150 nm of DAE coating. F: Fundamental mode of optimized slot-waveguide.

The mode corresponding to the optimal slot gap and the silicon ridges widths, is shown in the Figure 2F. This optimum is determined by maximizing the ratio $\Delta n_{eff}/\tilde{n}_g$ while maintaining a margin from the point where the fundamental mode changes shape (At $rw = 200$ nm and $g = 300$ nm). The optimal configuration, achieved with $rw = 200$ nm and $g = 225$ nm, ensures high effective mode index change ($\Delta n_{eff} \approx 0.025$) while maintaining fabrication feasibility. This change corresponds to 83.3% of the original modeled $\Delta n_{O\leftrightarrow C} = 0.03$ for the fundamental mode, a significant improvement over conventional silicon waveguides. Following this, the change in resonance can be determined analytically for a simple ring resonator, yielding $\Delta\lambda_c = 25.7$ nm [14], or applying equation (1), resulting in slightly lower $\Delta\lambda_c = 16.1$ nm. Both results deliver an order of magnitude improvement over the previously measured and simulated $\Delta\lambda_c = 1.3$ nm, surpassing the FSR of the original ring over four times.

Discussion

Further investigation is needed to determine how to improve the fatigue resistance of the used DAE coating. Currently, it is theorized that the fatigue is influenced by oxidization, thus strategies to cap the chip after applying the DAE coating will be tested.

Conclusion

Simulations were conducted to enhance light-cladding interactions by introducing a slot waveguide, thereby maximizing the effect of small refractive index changes in DAE coating layers. The optimized slot waveguide improved the change of the effective mode index fivefold when compared to the models using conventional silicon waveguide designs. The slot waveguide configuration retained as much as 83.3 % of the change introduced to the DAE layer, resulting in a modeled resonance shift that exceeded four times the free spectral range.

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