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Thermo-optic devices on polymer platform

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ABSTRACT

Optical polymers possess in general relatively high thermo-optic coefficients and at the same time low thermal conductivity, both of which make them attractive material candidates for realizing highly efficient thermally tunable devices. Over the years, various thermo-optic components have been demonstrated on polymer platform, covering (1) tunable reflectors and filters as part of a laser cavity, (2) variable optical attenuators (VOAs) as light amplitude regulators in e.g. a coherent receiver, and (3) thermo-optic switches (TOSs) allowing multi-flow control in the photonic integrated circuits (PICs). This work attempts to review the recent progress on the above mentioned three component branches, including linearly and differentially tunable filters, VOAs based on 1×1 multimode interference structure (MMI) and Mach–Zehnder interferometer (MZI), and 1×2 TOS based on waveguide Y-branch, driven by a pair of sidelong placed heater electrodes. These thermo-optic components can well be integrated into larger PICs: the dual-polarization switchable tunable laser and the colorless optical 90° hybrid are presented in the end as examples.

1. Introduction

The fast developing optical networks demand highly integrated optical modules that not only offer capacity for high speed, polarization-multiplexed and coherent operations, but also provide broadband tunability and allow light amplitude regulation and propagation path control, a powerful functionality that enables the system-level software to manage the dataflow directly on the optical circuit level in real time with the varying traffic conditions [1].

In the last decade, polymer-based photonic devices and polymer integration platform have witnessed significant advancement. Low-loss polymer waveguides have been reported as board-level optical interconnects for data center applications [2–4]. Multilayer polymer waveguide arrays have been fabricated as a bridging device toward spatial-division-multiplexed (SDM) transmission systems [5–7]. Polymer arrayed waveguide gratings (AWGs) coupled with 40-channel laser diodes and photo detectors have been demonstrated as optical line terminals in the wavelength-division-multiplexed passive optical network (WDM-PON) [8,9]. Ultrafast electro-optic polymer modulators, integrated with InP-based driver electronics, have been packaged into transmitter modules, providing serial 100 Gb/s connectivity in data centers and metro-area optical networks [10–14].

Furthermore, the unique thermal properties of polymer materials, i.e., high thermo-optic coefficient (TOC), ranging from $-1 \times 10^{-4}\,K^{-1}$ to $-3 \times 10^{-4}\,K^{-1}$, and low thermal conductivity, ~0.3 W/m/K, have been exploited to make highly power-efficient tunable devices. Wavelength tunable external cavity lasers based on the hybrid integration of an InP gain element and a polymer Bragg grating reflector has been studied and improved to meet industry demands [15–20]. All-polymer VOAs and TOSs have been combined to form various kinds of switching networks [21–30]. These thermo-optic elements have been further monolithically integrated in larger polymer PICs for wavelength tuning, phase shifting, amplitude damping and light-path switching [31–34].

In this work, a review is performed summarizing the latest development of the polymer-based thermally tunable photonic components and their integration into larger circuits. Starting with the polymer waveguide and heater electrode design, three heating schemes are introduced and further implemented to generate either a uniformly heated area or a strong temperature gradient across the waveguide region. Optical filters, VOAs and TOSs with unique features are first demonstrated as individual components and then combined to form more complicated circuits, in which fabrication compromises have to be made considering thermal crosstalk suppression and device footprint confinement.

2. Polymer waveguide and heater electrode design

Optical polymer layers are usually formed on silicon wafer by spin-coating and subsequent UV and temperature curing processes. Polymer waveguides can be fabricated using mainly the following three methods [35]: (1) standard semiconductor

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processing methods with photolithography and reactive ion etching; (2) direct UV lithographic patterning followed by wet-chemical rinsing; and (3) soft molding and imprinting. A typical waveguide cross-section is sketched in Fig. 1. The cladding index is 1.45 and the core is 1.48 at 1550 nm wavelength, taken from the commercially available polymer materials (ZPU-12 series from ChemOptics Inc.). The buried single mode waveguide core has a square shape ($W=H=3.2$ μm) to minimize the waveguide birefringence. The optical mode field diameter is around 4.2 μm.

Heater electrode is usually placed in the vicinity of the waveguide core for effective heating but far enough to avoid disturbing the light field. Since air has a lower thermal conductivity than polymer (~0.025 W/m/K compared to ~0.3 W/m/K at room temperature, the value for silicon is 163 W/m/K for comparison), deep trenches are often etched next to the waveguide to confine the thermal energy, improve the tuning efficiency and reduce the thermal cross-talk.

Depending on the applications, the heater electrodes can be structured on top of the polymer upper cladding (top heater), buried underneath the waveguide (bottom heater) as shown in Fig. 1, or deposited on the sidewall of the air trench (side heater). Thermal simulations have been performed using commercial software (COMSOL) to compare the three heater schemes. The heater consists of 100 nm-thick Au and the width is set to 15 μm. The heater power density is 25 W/m. The ambient temperature is 20 °C. The bottom boundary of the silicon substrate is taken as the heat sink. The steady-state temperature distributions are presented in Fig. 2.

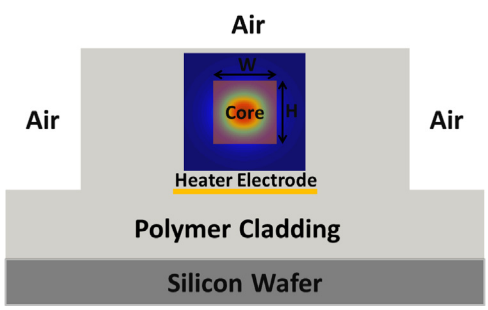

Fig. 1. Cross-section of the polymer waveguide with air trenches and the bottom heater electrode.

As shown in Fig. 2(a), the top heater generates the highest temperature (116 °C) at the heater itself and also at the center of the waveguide (86 °C), but a strong temperature gradient can be seen through the waveguide region in the Y direction. The bottom heater is least efficient as it is placed the closest to the silicon substrate (heat sink). With the same heater power density, the temperature reaches only to 76 °C at the heater and 66 °C at the waveguide center. However, the waveguide region is uniformly heated, as shown in Fig. 2(b). The side electrode, on the other hand, provides a strong temperature gradient through the waveguide in the X (in-plane) direction, as indicated in Fig. 2(c).

To investigate further, the temperature distribution along the central X and Y planes is extracted and plotted in Fig. 3(a) and (b), respectively. The waveguide mode region is marked as shaded bars. For the bottom heater, the temperature variation through the mode region (4.2 μm × 4.2 μm) is calculated to be 0.3 °C in the X direction and 3.5 °C in the Y direction. For the top heater a temperature drop of 14.5 °C is expected through the mode region in the Y direction while the temperature change in the X direction remains below 0.5 °C. The situation for the side electrode is reversed, with 5.1 °C temperature drop in the X direction and 1.9° drop in the negative Y direction.

To summarize, the top heater is efficient, however, the strong temperature drop in the vertical direction can distort the mode profile, introducing extra polarization dependence. In contrast, the buried bottom heater sacrifices some heating efficiency in exchange for a more uniformly heated ambient for the optical field. In addition, the electrically insulating polymer ridge covering the heater can also protect against contamination, electrical shortcuts and discharges. The bottom heater scheme is widely used in tunable laser devices, ensuring also a long-term reliable operation

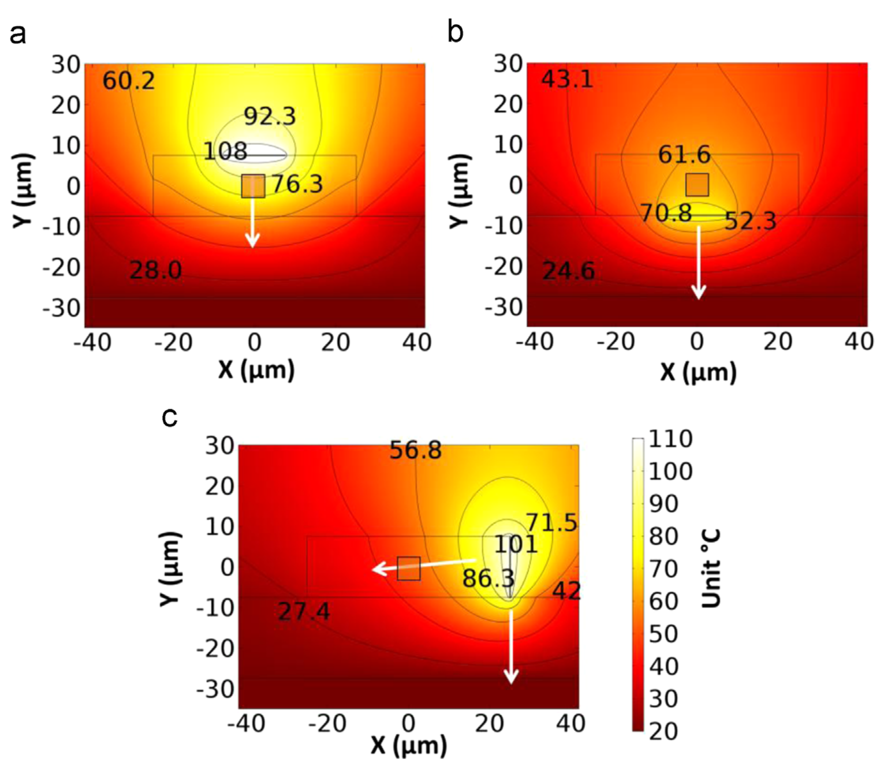

Fig. 2. Thermal simulation showing the temperature distribution in the polymer waveguide by the (a) top, (b) buried, and (c) single side electrode.