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Thermal field analysis of polymer/silica hybrid waveguide thermo-optic switch

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ABSTRACT

The thermal field and the temperature change of the optical waveguide core of thermo-optic (TO) switch generated by heating the Al electrode are simulated using the finite-element method (FEM), and the steady-state temperature distribution and time response of TO switch are presented. Our research covers several conditions, including different electrode heater widths, upper cladding layer thicknesses, under cladding layer materials and different structures. The results turn out that the performance of the TO switch can be improved using the polymer/silica hybrid and the air trench waveguide structures. The TO switch was fabricated and the surface thermal field distribution was measured. A good agreement between the experimental results and theory analysis has been observed.

1. Introduction

With the rapid development of optical communication systems, planar lightwave circuits (PLCs) are of more and more interest. As the basic element, optical switches play an important role in many applications including optical cross connect (OXC), optical add-drop multiplexing (OADM), optical true time delay (TTD) [1–5], and can also be integrated with lot of other components on a chip such as variable optical attenuators, optical delay lines, array waveguide gratings, wavelength division multiplexers and so on [6–9]. So it is important to develop optical switches with lower cost, better performance and that are easy to integrate with other circuits; thermo-optic (TO) switches made of polymer materials are an ideal choice. The TO switch works utilizing the TO effect which accounts for the change in the refractive index of the dielectric material due to its temperature variation. The change is generated by transmitting the electrical current through an electrode that is heated by the Joule effect. Polymer materials are well suited to a TO switch not only because of their low cost and simple production process, but also because they have a larger thermal optical coefficient (TOC), lower heat conductivity and a higher power conversion efficiency [10–12]. For a TO device, better parameter characteristics and reliable performance are very important for its popularity and commercial availability. The thermal field distribution and the temperature change of the TO switch have great influences upon device performance, so it is necessary and significative for us to study its thermal behavior.

In this paper, 1×1 polymer/silica TO switch based on the Mach–Zehnder interferometer (MZI) structure is designed and the thermal field is analyzed. At the same time, the air trench structure was recommended to reduce the power consumption effectively. Computer simulations are performed using the finite-element method (FEM) to show the thermal field distribution and the temperature change in the waveguide core under different conditions. The surface thermal field distribution was measured by Temperature Mapping Microscope and agreed with the results of our simulations.

2. Device design and simulation

As shown in Fig. 1(a), the TO switch based on the Mach–Zehnder interferometer (MZI) structure consists of an input waveguide, a symmetric Y-junction splitter which splits the light into two decoupled waveguides, a phase tuning section with 10 mm length on one of the waveguides, a similar Y-junction as the output combiner, and an output waveguide. The angle of the Y-splitter is designed to be 1° to get a low splitting loss. There is a heating

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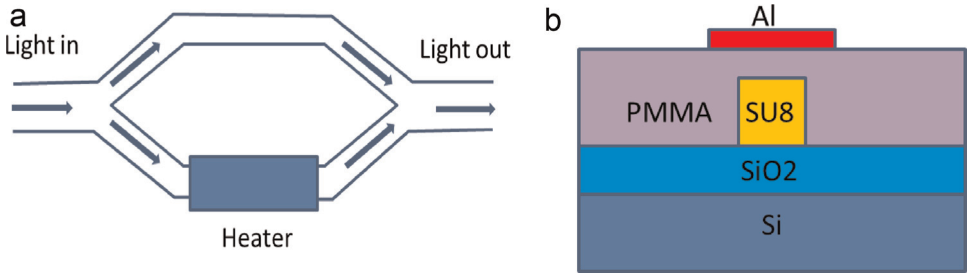

Fig. 1. (a) Schematic of the MZI thermal-optic switch. (b) Cross-section of the polymer/silica hybrid waveguide structure.

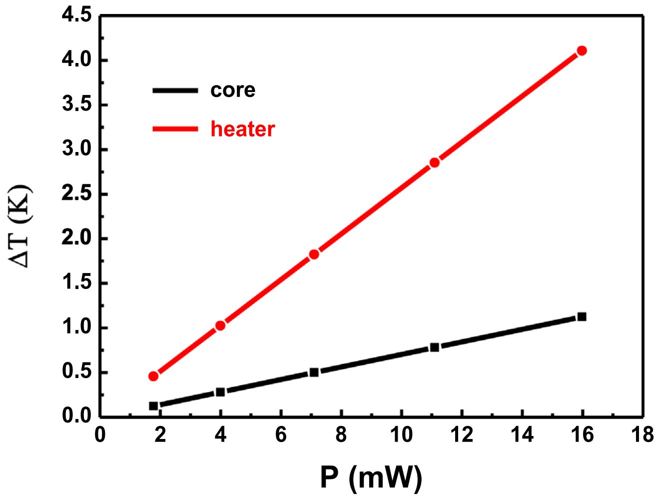

Fig. 2. Temperature change of the waveguide core and the electrode heater versus driving power.

electrode on one of the waveguides by which the temperature rises and induces a refractive index drop of the waveguide because of the negative TO coefficient and the phase difference of two modes that interfere in the output Y-junction can be achieved. The phase difference between the two arms can be determined by:

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n\cdot L \tag{1}$$

Due to the temperature dependence on refractive index, to realize the phase difference π, the temperature difference between the waveguide cores of two arms should be:

$$\Delta T = \frac{\lambda}{2L}\left(\frac{\partial n}{\partial T}\right)^{-1} \tag{2}$$

The temperature difference of two waveguide cores, ΔT can be obtained by heating the electrode. Considering infinitely long compared with the electrode width, the temperature difference $\Delta T'$ of the heating electrode is [13]:

$$\Delta T' = \frac{J^2\rho}{\frac{K}{ht}\left(1+\frac{0.88t}{w}\right) - J^2\rho\beta} \tag{3}$$

Because the temperature coefficient of the resistivity β is very small (about 10^{-3} orders of magnitude), the $J^2\rho\beta$ is far less than K/ht and can be neglected. Ignoring the temperature coefficient of the resistivity β, Eq. (3) can then be written in a simpler form [13,14]:

$$\Delta T' = \frac{\frac{P}{L}}{K\left(\frac{w}{t}+0.88\right)} \tag{4}$$

where P is the electrode heating power, L is the length of the heating electrode, K is the thermal conductivity of the polymer, w is the linewidth of the electrode heater, and t is the thickness of the polymer.

Fig. 1(b) shows the cross-section diagram of the TO switch. The waveguide is fabricated on a silicon substrate which has much higher thermal conductivity and can be treated as a heat sink. Because of its higher TO coefficient (-1.8×10^{-4} K^{-1}) and better thermal stability [15], SU-8 is employed as the waveguide core material. The refractive index of SU-8 is 1.573 under 1550 nm wavelength, which is measured by an M-2000 UI variable angle incidence spectroscopic ellipsometer. And the waveguide core dimension is designed to be 2.5×2.5 μm^2 to achieve a single-mode waveguide switch. The 2 μm-thick polymer PMMA is used as the upper cladding layer and 2 μm-thick silica is used as the under cladding layer. The silica under cladding is beneficial to accelerate the heat transfer from core to substrate and improve the response time of the TO switch because of its higher thermal conductivity [15]. The electrode heater is formed by a 100 nm-thick and 5 μm-wide thin layer of aluminum (Al) film.

The most important characteristics of TO switch are the driving power and the switching time, which are both highly dependent on the distribution and the change of the temperature. So the thermal field is simulated in different conditions using the FEM.

As shown in Fig. 2, the temperature change is almost linear responding to the driving power either the waveguide core or the electrode heater. The temperature change in the waveguide core is $\Delta T=0.43$ K which can exactly realize the phase difference π between the two MZI arms. Under this condition, the driving power is about 6.13 mW and the temperature change at the electrode heater is 1.58 K which is similar to the calculated value 1.54 K derived by Eq. (4).

The width of the Al heating electrode and the thickness of upper cladding are very important parameters which play decisive roles in the switching power and the switching time. Keeping upper cladding layer thickness $b=2$ μm and the same driving power $P=6.13$ mW, the temperature difference was evaluated by changing the width of the electrode heater from 3 μm to 9 μm. As shown in Fig. 3(a), with the increase of the width of the heating electrode, the waveguide core temperature is lower at the same driving power and so it can be achieved by decreasing the metal electrode width to reduce the power consumption. But too small electrode width will lead to the nonuniform thermal field distribution in the core, meanwhile originating some problems of the technology and affecting the reliability. Moreover, the influence of the electrode material and thickness of the electrode on the performance of the device was also studied. Under the same applied driving power, different electrode materials have little impact on the thermal field distribution of the device. And with the increase of the thickness of the electrode heater, the waveguide core temperature will be a little lower at the same driving power, but the impact is not very noticeable and can be neglected. Then keeping at the same electrode heater width $w=5$ μm and the same driving power $P=6.13$ mW, the temperature difference was evaluated by changing the thickness of upper cladding layer from 1.5 μm to