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DESIGN OF POLYMER BASED DIRECTIONAL COUPLER THERMOOPTIC OPTICAL SWITCH

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ABSTRACT

Design considerations that have been made in realizing a 2x2 asymmetrical directional coupler based thermooptic switch using all polymeric material is described. The design is based on the theory of optical waveguide as the key element and the thermal analysis for heater electrodes and heater pads. The coupling length variation as a function of waveguide dimension, waveguide gap and effective refractive index difference has been studied. The position of the heater electrode, which maximizes the effective refractive index difference between branches have been optimized. Crosstalk level of -40 dB and -37 dB for the cross state and the bar state have been achieved, respectively.

1. INTRODUCTION

There is an increasing need for optical switch matrices for routing, switching, protection switching, cross connection and add-drop multiplexing. The recent progress in WDM lightwave communication system will further increase the necessity of optical switch modules. Among the recent developments of optical waveguide technology, silica waveguides on silicon play an important role due to superior performance such as low propagation loss and low waveguide to fiber coupling loss. Various integrated optic devices architectures have been proposed and implemented in silica on silicon or glass substrates, Ti-LiNbO$_3$ and semiconductors [1, 2, 3] for applications in optical communication. However, the thermooptic coefficient (TOC), $\partial n/\partial T$ for silica does not exceed a value of $10^{-5}\ {}^{o}C^{-1}$ for a wavelength, λ = 1.3 μm to 1.6 μm [4] and is difficult to control. On the other hand, polymeric optical devices have attracted large attention recently. Polymer integrated optical devices have great potential for applications in high speed optical interconnects due to their microelectronics processing compatibility, multilevel high density feasibility and ultra high speed operation [5]. Furthermore, the thermal changes in the density is much higher, leading to a large negative temperature coefficients of typical value in order of $-10^{-4}\ {}^{o}C^{-1}$ [6]. Therefore the TOC of polymer is ten times larger than silica. Unique devices having twisted optic axes have been demonstrated by Oh and Shin [7], a possibility of which did not exist before polymers. Furthermore the polymer devices can be fabricated directly on electronic substrates and assembled with integrated circuits (ICs) to create a hybrid optoelectronic package [7]. However, the fabrication of polymer integrated optical devices is still trial and error due to inaccurate design schemes of thermal analysis and insufficient characterization of materials and processing steps.

This paper describes the design of thermally induced 2x2 asymmetric directional coupler thermooptic polymer switch (ADCTOPS), where precise control of refractive index is essential for fabricating a single mode channel optical waveguide. A polymer based waveguide with a buried square core (BSC) structures has been adopted for single mode operation at a wavelength of 1550 nm. The thermooptic effect, which results from the fact that refractive indices are temperature dependent, is achieved by heating one of the heater electrodes placed alongside the directional coupler branches.

2. DESIGN

Fig. 1 shows a vertical cross section of the designed 2x2 ADCTOPS. It consists of two symmetric waveguides separated by a waveguide spacing of g.

The center-to-center distance between the core and the heater electrode is d. The refractive index contrast between the upper cladding and the waveguiding region is 0.03 and the refractive index contrast between the lateral section of the waveguiding region and lower cladding is 0.005.

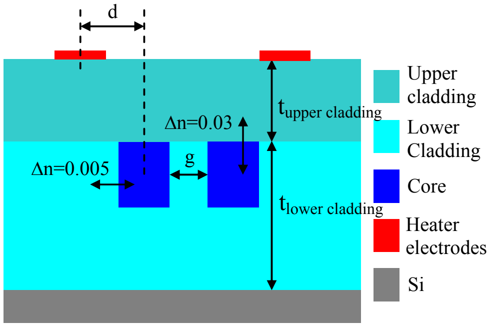

Fig. 1 Vertical cross-section of 2x2 ADCTOPS

The dimensions of the BSC polymer waveguides are 7 μm by 7 μm. The thermal conductivity of the polymer layers is 0.17 W/m/K [6] and for the Si layer, it is 1.5 W/m/K [8]. The TOC is zero, except for the polymer layer where it is assumed to be $-1.7\times10^{-4}\ K^{-1}$. The Si substrate is treated as a perfect heat sink with zero temperature.

3. THERMAL ANALYSIS

Gold (Au) was used as the material for the heater electrodes and Chromium (Cr) was used for adhesion between polymer cladding layer and Au. The thin film heater electrode width is taken to be equal to the width of the waveguides and the length is varied depending on the coupling length. A 400 nm thick, Au thin film heater electrode is put on top of the cladding. The thickness of the upper cladding and the lower cladding are limited by mode attenuations. The thickness of the upper cladding is bound to attenuation, resulting from absorption by the Au thin film heater electrode. The under-cladding is bound to attenuation into the Si substrate. To avoid this attenuation, the cladding has been taken rather thick, 15 μm for the upper cladding and 20 μm for the under cladding and therefore the Si substrate layer does not have to be included in the optical simulation.

In ADCTOPS, the differences in effective refractive index between the two identical and parallel waveguide branches were achieved through TOC of the wave guiding material by heating up one of the branches. This heating is achieved by means of a heater electrode placed alongside the branch. As the temperature is increased the effective refractive index contrast between the waveguides will increase, causing a gradual shift of power from one branch to the other. Therefore the position of the heater electrode d, which maximizes the effective refractive index difference between branches, must be optimized. Fig. 2 presents effective refractive index (n_{eff}) as a function of the distance d. Fig. 3 shows the effective refractive index difference between the branches for various waveguide gap g, which was obtained by using Fig. 2. It is readily seen that for every given waveguide gap g, there is an electrode position that maximizes the index contrast. As a rule of thumb it can be expressed that for the given geometry, this position is on average at d = 5 μm from the heated core.

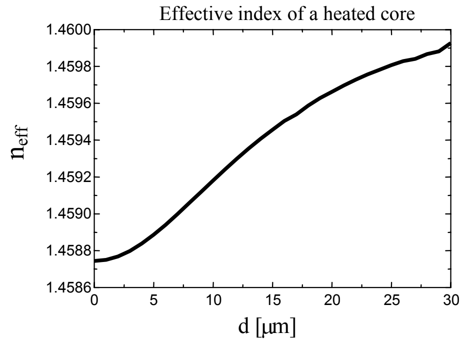

Fig. 2 Effective refractive index as a function of electrode heater position, d

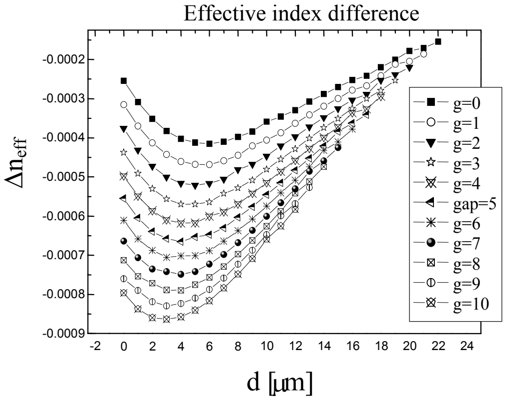

Fig. 3 Difference in effective refractive indices between branches for various waveguide gap, g

4. SIMULATION OF 2x2 ADCTOPS

Fig. 4 shows a schematic diagram of the ADCTOPS. The bend waveguides with curvature of radius, R_c are connected to both the input and output port to form the ADCTOPS.

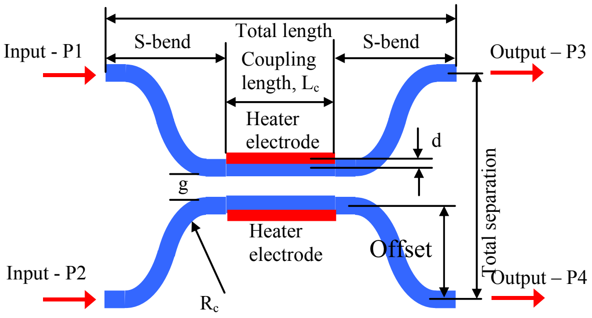

Fig. 4 A schematic view of 2x2 ADCTOPS

Near the end of the two symmetric waveguides, where the switching occurs, the transferred power has to be prevented from coupling back to the other output channel. We therefore investigate the coupling length of two identical parallel waveguide branches in the absence of a thermal field. Under these conditions the two channels have identical propagation constant and 100% of power will transfer from one channel to the other channel and this will occur at a distance equals to an integer times the coupling length [9] and is given by

$$L_c = \frac{\lambda}{2\left(N_{sym} - N_{asym}\right)} \qquad (1)$$

N_{sym} and N_{asym} are the effective refractive indices of the two lowest order system modes referred as symmetric and asymmetric modes respectively and λ is the optical wavelength in free space.

The switch may have so many variations in the device fabrication process. Those variations could be the waveguide dimension (w x t), waveguide spacing g, and effective refractive index of the waveguides and so on. These variations will affect the coupling length and the switching characteristics of the switch. Thus, the following calculations are needed to know how much tolerance the switch has. From the calculation results, we found out that the coupling length vary over a range of 200 μm as waveguide dimension (w x t), waveguide spacing g and the effective refractive index change. Therefore we conclude that for the fabrication process the coupling length tolerance of 200 μm can be adopted. Since the coupling length tolerance is 200 μm, the coupling length of the switch was designed to be 50 μm spacing in a mask layout. Fig. 5, Fig. 6 and Fig. 7 show the simulation results for various design conditions.

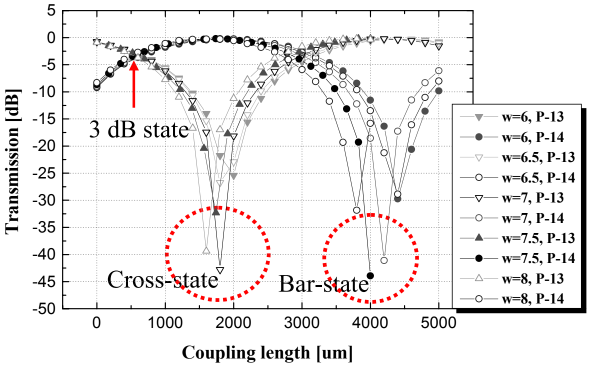

Fig. 5 Coupling length as a function of various waveguide dimension

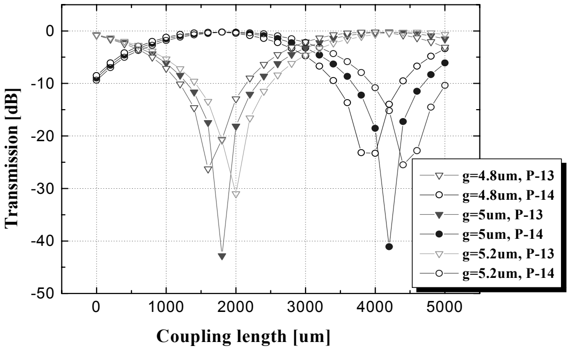

Fig. 6 Coupling length as a function of various waveguide spacing for w = t = 7 μm

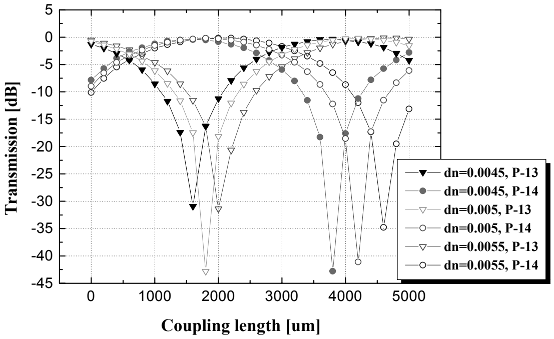

Fig. 7 Coupling length as a function of various effective refractive index contrast between the waveguides for w = t = 7 μm

5. SWITCHING CHARACTERISTICS

The crosstalk of the cross state and the bar state was calculated in dB for the power ratio of undesired output port to the total power of desired output port.

The cross state and the bar state mean the light is coupled from input port P1 to output port P4 and from input port P1 to output port P3 respectively. With the optimization results obtained from the previous section, the switching characteristics have been simulated. The result obtained is shown in Fig. 8.

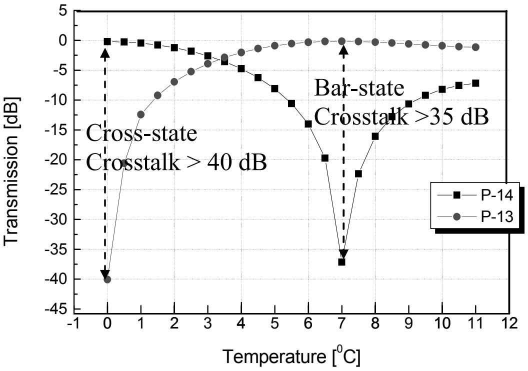

Fig. 8 Switching characteristic for the 2x2 ADCTOPS

6. CONCLUSIONS

The design of the 2x2 ADCTOPS with buried square core waveguides structures had been described. An exceptionally low thermal switching operation, having a coupling length of approximately 1.85 mm, have been achieved. The switching occurs at a temperature change of 7 ^{o}C. The crosstalk level of -40 dB and -37 dB for the cross state and the bar state was been achieved, respectively.

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