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Trench Structure Improvement of Thermo-Optic Waveguides

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Abstract: The heat generated by a thin film heater causes the temperature of a nearby waveguide to increase. The thermal coupling increases with the waveguide depth. Thermal coupling could be reduced by etching a trench between the waveguides. A rib structure under the trench between the waveguides was proposed to further reduce the thermal coupling. The temperature profiles of thermo-optic waveguides are analyzed by the finite element method and show significant improvement on reducing thermal coupling between the waveguides.

Keywords: thermal coupling; finite element analysis; thermo-optic waveguides; trench

1. Introduction

Thermo-optic waveguides are useful device in channel switching of lightwave communication system and fiber optic sensing application [1,2]. The thermo-optic waveguide devices are normally fabricated on a quartz glass substrate. The core ridges are formed through the lithography and reactive-ion etching processes. After that, cladding glass is form by hydrolysis deposition. The heater for individual waveguide is deposited on the top of upper cladding layer using evaporation technique.

In optical signal processing, Mach-Zehnder interferometers (MZI) are utilized for preparing signals of optical routing-switching. Silicon technology is of special interest because of the unique properties of the substrate material and the availability of large-area substrate, good thermal conductivity and low cost. Silicon-oxynitride was also proposed [3] for passive optical components like branching waveguides, couplers, interferometers and filters. It enables the realization of compact integrated optoelectronic circuits at low cost.

The thin-film heater is utilized to change the refractive index and propagation characteristic of the waveguide. Heat generated by the thin-film heater spreads out and causes the temperature of a nearby waveguide to increase. Consider the case in Figure 1 of a Mach-Zehnder Interferometer (MZI). A heated electrode is placed upon one of the two waveguide arms. The branch angle is usually on the order of 1° to 2°, which causes a small gap between the parallel arms. As the temperature of waveguide 1 increased, the refractive index is changed by thermo-optic effect. Due to thermal coupling, the temperature of waveguide 2 becomes higher also [4]. For some sensitive applications, thermal coupling becomes an important issue. For example, in four channel planar lightwave network [5] the amplitude controllers were based on symmetric Mach-Zehnder Interferometer. A

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desired phase shift of the millimeter-wave signal was provided by the heater elements. When multiple MZI's were placed on the same substrate, thermal coupling limited the device's performance [5]. Therefore, it is important to reduce the amount of thermal coupling between the waveguides.

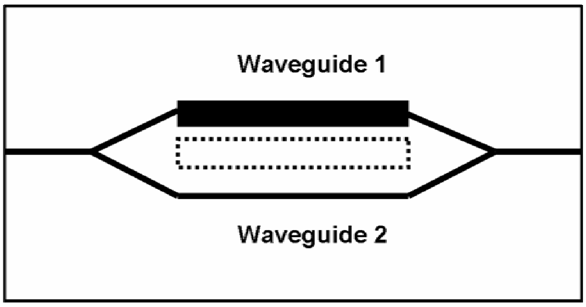


Figure 1. The schematic diagram of a Mach-Zehnder Interferometer (MZI). A heater electrode is placed upon one of the two arms. Laser light is incident from the left endface and then spitted into two arms by the Y junction.

2. Reducing thermal crosstalk

The thermal coupling coefficient, representing the magnitude of the temperature field interference on a nearby waveguide, is defined as

$$K = \triangle T_2 / \triangle T_1 \qquad (1)$$

where $\triangle T_2$ and $\triangle T_1$ are the temperature rises in waveguide 2 and 1, respectively.

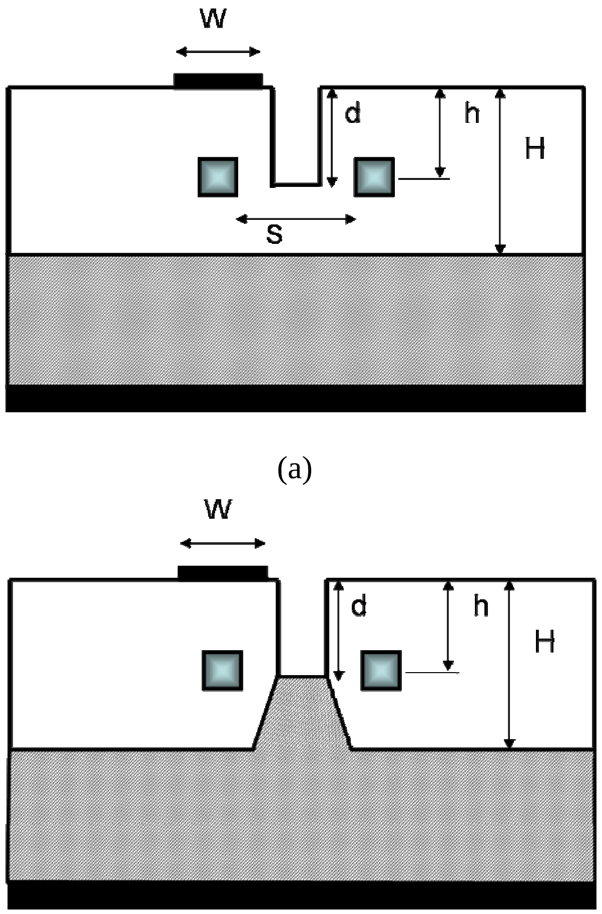
Several approaches have been proposed to reduce the thermal coupling. Phase shifters provided a planar lightguide circuit which exhibits reduced thermal crosstalk by reducing the thermal resistance between the waveguide cores and the substrate. This is accomplished by removing some of the glass from the backside of the chip over a small area under the phase shifters, depositing metal on the backside, and soldering it to a copper block heat sink [6]. The thermo-optic Mach-Zehnder interferometer with a tunable range of 0 to 6 dB and a response time of approximately 1-10 milliseconds [7] was also proposed. To reduce thermal crosstalk, a heat sink is attached to the back of the chip to dissipate the heat from the Mach-Zehnder interferometer.

Trench structure [8] is one of the common approaches to reduce the thermal coupling between the waveguides of Mach-Zehnder Interferometer. Figure 2(a) shows the cross section of the trenched waveguides; a heater is located on the top of waveguide 1. The SiO_2 layer between the parallel waveguides is partially removed to eliminate the conduction of heat from the heater to the adjacent waveguide.

For further reducing thermal crosstalk, the rib structure will be discussed in this present study. In Figure 2(b), a rib structure between the waveguides is formed on the upper surface of silicon substrate, which we show as dark area, on the top of the rib structure part of the SiO_2 cladding layer is trenched. The thermal conductivity of silicon is much higher than that of SiO_2 cladding layer; consequently, the rib structure between two waveguides act like a thermal bypass path to the substrate. The rib structure on silicon substrate can be made by reactive ion etching before the deposition of cladding layer. Due to the crystal structure of the silicon, a 54.74° surface along the side edges of the rib will be formed during the wet etching process. Consequently, the manufacturing process of the proposed rib structure is not complicated.

3. Analysis of temperature profile

The thermal analysis of multilayer structures has been studied by analytical and numerical method [9]. Due to the complicated geometric and physical properties in thermo-optic waveguides, the finite element method [10] is adopted for analyzing the temperature distribution.



(a)

(b)

Figure 2. The cross section of a thermo-optic phase shifter: (a) trench waveguide (b) rib structure.

Since the thermal conductivity of a silicon substrate is high, the silicon substrate is used as a heat sink. It is assumed that the only mechanism of heat transfer is conduction (radiation and convection are disregarded). Since the length of the heater is much longer than the width of the heater, the two dimensional analysis is used. The governing equation for steady-state heat conduction is

$$k(x,y)\bullet\left[\frac{\partial^2 T(x,y)}{\partial x^2}+\frac{\partial^2 T(x,y)}{\partial y^2}\right]=-Q(x,y) \qquad (2)$$

where $T(x,y)$ is the temperature (℃), $Q(x,y)$ is the internal heat generation (Watt/m^3), and $k(x,y)$ is the thermal conductivity (Watt/m℃). It is assumed that the heat does not transfer from the left- and right hand side boundaries. Since the analyzed domain is large enough, this assumptions are suitable.
The boundary conditions are

T = ambient temperature at the bottom of the silicon (3)

$-k\frac{\partial T}{\partial x}=0$ at the left- and right-hand side boundaries (4)

$-k\frac{\partial T}{\partial y}=q_c$ at the heater/ SiO$_2$ interface (5)

$-k\frac{\partial T}{\partial y}=0$ on the top of the SiO$_2$ boundary (6)

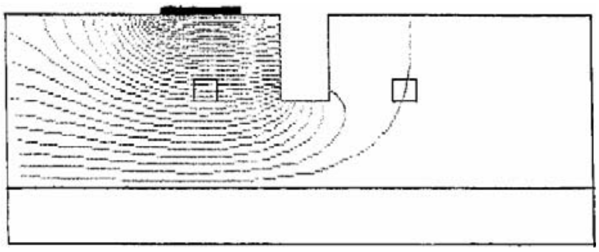
The analyzed domain is first discretized into 430 elements. The geometric and physical parameters are listed in Table 1. The system matrix equation is solved by using Gaussian elimination, and the temperature distribution is obtained. The numerical results have been checked with a simple analytical solution [11]; the results were in good agreement with each other.

The temperature distribution of the trenched waveguides with the thin-film heater is shown in Figure 3(a). It can be seen that the temperature distribution is blocked partially by the trench structure. It had been shown that the thermal coupling decreases with the trench depth [11]. Hence, deep trench can decrease the coupling between waveguides. On the other side, deep trench is not preferred from processing and device reliability point of view.

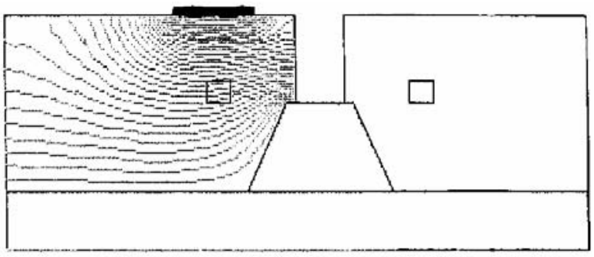
The temperature distribution of the rib structure with the thin-film heater is shown in Figure 3(b). It can be seen that the temperature distribution is blocked significantly by the trench. The rib structure provides a thermal bypass path, part of the heat transfer through the rib to the substrate. The thermal coupling coefficients for the cases in Figure 3(a) and Figure 3(b) are 0.274 and 0.12 respectively. The rib structure shows a good performance on reducing thermal crosstalk. As can be indicated from the analysis data, the temperature of the heated waveguide decreases as the rib structure exists, therefore it needs more power to maintain a required temperature rise. The reducing of thermal coupling coefficients causes the temperature difference between the adjacent waveguide to increase. The refractive index difference by thermo-optic effect of the two waveguides will then be increased.

Table 1. Geometric and physical parameters of the waveguides

Items	Value
Heater width (W)	3μm
Core depth (h) and spacing (S)	7μm, 9μm
Cladding thickness (H)	16μm
Trench width and depth (d)	2μm, 7μm
Cladding thermal conductivity	0.02 Watt/cm ℃
Substrate thermal conductivity	120 Watt/cm ℃



(a)



(b)

Figure 3. The temperature distributions of the waveguides (a) trench waveguide (b) rib structure.

4. Conclusion

Heat generated by the thin-film heater spreads out and causes the temperature of a nearby waveguide to increase. Thermal coupling coefficient can be reduced by placing trench between the adjacent waveguide; however, a deep trench is required for reducing thermal crosstalk for deep waveguides.

Thermal conductivity of silicon is much higher than that of the SiO_2 cladding layer. In silica based waveguide, the rib structure on silicon substrate is useful in minimizing the thermal coupling for deep waveguides. The temperature of the heated waveguide decreases as the rib structure exists, therefore it requires more power to performing its functions.

Owing to the speed of the integrated optic device are increasing, the transit phenomenon of the thermal crosstalk of thermo-optic waveguide needs investigations in future studies. The substrate material, such as the silicon-oxynitride material system, becomes more complicated. The feasibility of the rib-structure in those situation is required too.

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