Temperature Insensitive Silicon Slot Waveguides with Air Slot

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Abstract. *We report numerical simulation about thermal stabilities of silicon slot waveguide. A polymer cladding, which has negative thermo-optic(TO) coefficient, was used to compensate positive TO coefficient of silicon and silicon-dioxide(SiO_2). We found athermal waveguide can be realized with air slot, and even with SiO_2 slot.*

Introduction

High index contrast waveguides are very attractive, with the advantage of small footprint and large nonlinearity due to their high optical density because of their sub-micron sized dimensions. Novel nonlinear devices have been proposed and demonstarated by using sub-micron sized silicon (Si) waveguides. Si has, however, high thermo-optic (TO) coefficient which is one magnitude larger than that of silicon-dioxide (SiO_2) which is utilized for various photonic applications in industry. Very accurate and power consumable temperature controller should be used to stabilize the device performance, especially the devices which have wavelength dependent characteristics, such as arrayed waveguide gratings (AWGs), ring resonators, Bragg gratings, Mach-Zehnder interferometers.

Recently, a novel design of high index contrast waveguide, called slot waveguide, have been proposed[1],[2]. Since it can confine a light in low index region, we can employ various materials as optical nonlinear materials by filling the slots with them. High optical intensity in the slot enhances their optical nonlinearity. One of the advantages of the slot waveguides is the design flexibility. Slot width can be another design degree of freedom additional to the height and width of the waveguides. However, when we use Si as a host material of a waveguide, thermal stability should be suffered from the large TO coefficient of Si. A thermally stable ring resonator based on Si slot waveguide was proposed and experimentally demonstrated using a polymer as over cladding and slot region[3]. In this paper, we investigate on thermal stability of Si slot waveguides focusing on slot materials. We found that filling slot regions with polymer materials is not necessary to achieve temperature insensitive slot waveguides.

Athermal silicon slot waveguides with polymer slot

Fig. 1 shows a schematic cross-sectional structure of a slot waveguide. The slot waveguide has a slot region which is embedded with two high index regions, and the structure is surrounded by under cladding and over cladding which have lower refractive index comparing to that of high index region. A material of slot region can be the same with those of over cladding or under cladding as far as the material has lower refractive index comparing to that of high index regions. In this paper, we assume symmetric waveguides, or two high index regions have the same width.

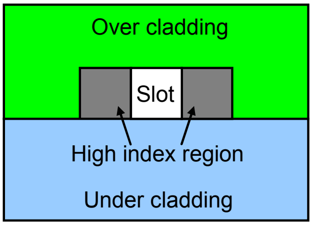

Fig. 1 Cross-sectional schematic structure of a slot waveguide

In this section, we assume slot waveguides which consist of SiO_2 under cladding, Si high index region, and slot region and over cladding polymethyl methacrylate (PMMA). In the simulation, the refractive indecies of Si, SiO_2 and PMMA were 3.48, 1.46 and 1.481[4], and their TO coefficients were 1.84×10^{-4}, 1.0×10^{-5} and -1.0×10^{-4}, respectively. We fixed the waveguide heights as 250 nm, and calculated effective refractive index (n_{eff}) with changing Si and slot width using finite different method based modesolver. Only TE mode was considered in this paper since light confinement in the slot region appears only in TE modes.

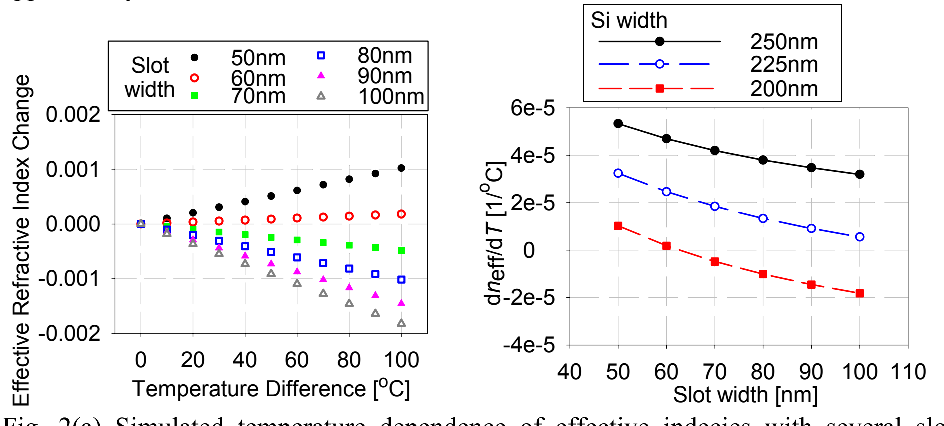

Fig. 2(a) Simulated temperature dependence of effective indecies with several slot width
(b) Simulated effective index change slope as a function of slot width, 250nm height

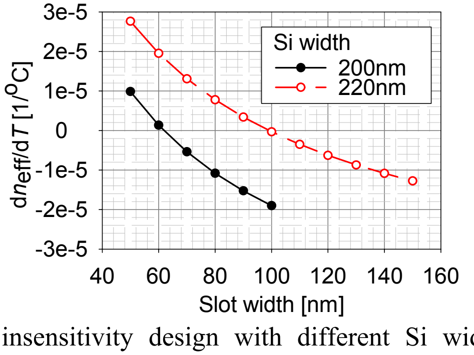

Fig. 3 Temperature insensitivity design with different Si width without changing waveguide heights (250nm)

Fig. 2(a) and (b) show the simulated temperature dependence of effective index of the waveguide with several slot widths and the slot width dependence of effective index slope (dn_{eff}/dT) with three different Si widths, respectively. In the case that a waveguide is temperature independent, effective refractive index change stay zero at any temperature. Widening slot width decreased dn_{eff}/dT from positive to negative slope shown in Fig. 2(a). A zero-crossing point in Fig. 2(b) are the temperature insensitive waveguide structure, and ~62 nm slot width was the optimum for Si width of 200 nm.
Temperature independence can be achieved in various waveguide designs without changing their heights. Fig. 3 shows temperature dependence of the Si slot waveguides with two different Si widths. Waveguide heights were 250 nm. 100 nm slot width was the optimum size for Si slot waveguides whose Si width is 220 nm.

Athermal silicon slot waveguides with air slot

In practical fabrication process, it is difficult to fill the slot region with a material, such as PMMA. However, temperature insensitive slot waveguides can be realized without filling any materials in the slots, or with air slots. Fig. 4 shows the effective index slope of slot waveguides as a function of slot width. The refractive index and TO coefficient of air were assumed as 1.0 and 0, respectively. The waveguide heights were fixed at 250nm. Under cladding were SiO_2. For the case of Si width of 200nm and 220nm, athermal Si slot waveguides could be achieved with the slot width of ~65nm and ~125nm, respectively.
The refractive index of air is much smaller than that of PMMA and the light is much highly confined inside the slot region. Since the TO coefficient of air is zero, temperature insensitivity could be realized with air slot, covering slot structures was sufficient to compensate the TO coefficient of Si and SiO_2.

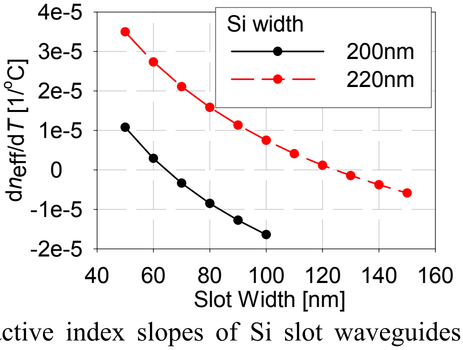

Fig. 4 Effective refractive index slopes of Si slot waveguides with air slots, 250nm heights, TE modes

Athermal silicon slot waveguides with SiO_2 slot

We reported the athermal Si slot waveguide filled with air in previous section. While the waveguides are easier to fabricate than the PMMA slot waveguides, we cannot utilize the advantage of slot waveguides, enhancement of optical nonlinearity due to the high optical concentration inside the slots. To use the advantage, the slots must be filled with a material. In this section, we report simulation results of athermal Si slot waveguides which had SiO_2 slot and PMMA over cladding.

The simulation results of Si slot waveguides with SiO_2 slots are shown in Fig. 5. Their heights were 250nm, same as the waveguides in the previous sections. Under cladding was SiO_2. For the case of Si width of 200nm and 210nm, athermal Si slot waveguides could be achieved with the slot width of ~103 nm and ~145 nm, respectively.

The SiO_2 slot itself cannot compensate the positive TO coefficients of Si and under cladding SiO_2. For this reason, the wider slot and narrower Si width were necessary than those of PMMA and air slot. Narrow Si width and wide slot width decrease the optical component inside the Si region. This permits the compensation of positive TO coefficient mainly comes form Si part, by PMMA over cladding. By using a polymer material which has larger negative TO coefficient than that of PMMA, athermal slot waveguides can be realized by narrower slot and wider Si width.

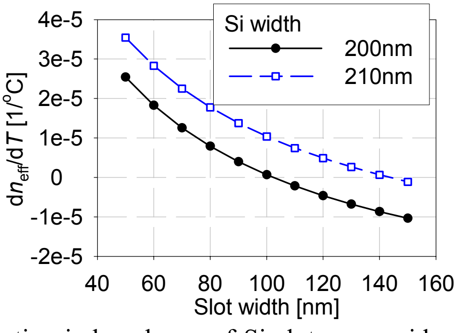

Fig. 5 Effective refractive index slopes of Si slot waveguides with SiO_2 slots, 250nm heights, TE modes

Summary

We reported the numerical simulation of temperature insensitive Si slot waveguide to achieve thermally stable optical devices. The positive TO coefficients of Si and SiO_2 can be compensated using PMMA, whose TO coefficient is negative, as an over cladding material of Si slot waveguides. We showed temperature insensitive design of Si slot waveguides whose slot regions were filled with PMMA. Temperature insensitive waveguides with air slots were proposed for easy fabrication. SiO_2 was employed as an example of slot material to use the advantage of slot waveguides, the enhancement of optical nonlinearity.

References

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