Athermal Si photonic waveguide devices with TiO_2 hybrid polymer over-cladding

Wataru Mashiko, Tomohiro Kita and Hirohito Yamada
Department of Communications Engineering, Graduate School of Engineering, Tohoku University
6-6-05 Aramaki-Aza-Aoba Aoba-ku Sendai 980-8579, Japan
{mashiko, tkita, yamada}@ecei.tohoku.ac.jp

Abstract— **We investigate the athermal characteristics of Si photonic waveguide devices with TiO_2 hybrid polymer over-cladding for 1.5 µm wavelength. Si photonic waveguide device is expected to be utilized in short-haul communication for its ultra-small size and low production cost. But the devices are sensitive to environmental temperature due to large Thermo-Optic(TO) coefficient of Si. The typical method for realizing the temperature independent waveguide device is to make over-cladding of the material with negative TO coefficient to compensate for the positive TO coefficient of Si core. In this study, we use TiO_2 hybrid polymer as cladding material. It is the polymer containing rutile TiO_2 nanoparticles, the TO coefficient can be controlled by changing TiO_2 concentration. To demonstrate the athermal operation of silicon MZIs experimentally, we fabricated silicon Mach-Zehnder interferometer (MZI)s with the hybrid polymer over-cladding whose TiO_2 concentrations adjusted depending on each core geometry, and measured their transmission spectra over 30-60 °C. Measured resonance wavelength shifts are nearly 1/5 in same core geometry with no over-cladding. It indicates the potential Si/hybrid polymer structure is more widely applicable than other structure with pure substance cladding.**

Keywords-component; Si photonic waveguide, athermal, TiO_2, hybrid polymer

I. INTRODUCTION

Silicon photonics, the technique integrating photonic devices with Si core on SOI wafer, enables the drastic downsizing of photonic integrated device owing to well lightwave confinement due to huge refractive index difference between Si core and SiO_2 cladding. Also, we can mass-produce silicon photonic devices at low cost utilizing mature CMOS fabrication techniques. For these advantages, the device is expected to be used in short-haul communication such as the in-vehicle optical network with the strict limitation to cost and size, LAN in the data center where communication modules crowd. However, Si waveguide devices such as resonators and wavelength-filters are very sensitive to environmental temperature due to large Thermo-Optic(TO) coefficient of Si (Fig. 1).

Therefore, the temperature independent Si photonic devices over wide temperature range are strongly demanded. The typical method for realizing the temperature independent waveguide device is to make over-cladding of the material with negative TO coefficient to compensate for the positive TO coefficient of Si core. In previous research, pure polymer or TiO_2 is used as cladding material with negative coefficient. In this way, core geometry is restricted since we must adjust it depending on the fixed TO coefficient of cladding material.

On the other hand, we use TiO_2 hybrid polymer as the cladding material. It is the polymer containing rutile TiO_2 nanoparticles and the TO coefficient can be controlled by changing TiO_2 concentration. In this study, we experimentally demonstrated the athermal operation of Si waveguide devices to control TO coefficients of the polymer depending on each core geometry.

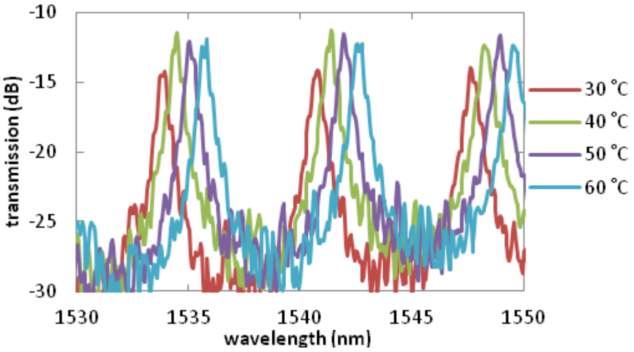

Fig. 1. Transmission spectra of Si wavelength-filter in 30~60 °C.

II. TEMPRATURE DEPENDENCE OF WAVEGUIDE

The temperature dependence of the resonance wavelength of wavelength-filter can be expressed as follows.

$$\frac{d\lambda_0}{dT} = \frac{\lambda_0}{n_g}\frac{dn_{eff}}{dT} \tag{1}$$

Where λ_0 is the resonance wavelength; T is temperature; n_{eff} is effective index of waveguide; n_g is the group index of the waveguide. The athermal condition is archived when Eq. (1), that is, dn_{eff}/dT equals to zero. dn_{eff}/dT can be expressed as follows,

$$\frac{dn_{eff}}{dT} = \Gamma_{core}\frac{dn_{core}}{dT} + \Gamma_{top}\frac{dn_{top}}{dT} + \Gamma_{bottom}\frac{dn_{bottom}}{dT} \tag{2}$$

Where dn_{core} / dT, dn_{top} / dT, dn_{bottom} / dT are TO coefficient of core, over-cladding and bottom cladding, respectively; Γ_{core}, Γ_{top}, Γ_{bottom} are confinement factor, express the strength ratio of guided light existing inside each part. Typical structure of Si wire waveguide is Si core and SiO_2 cladding, TO coefficient of Si is approximately $+1.8 \times 10^{-4}$, 18 times as large as SiO_2. Therefore, dn_{eff} / dT eventually $d\lambda_0 / dT$ become large positive value, and the resonance wavelength of wavelength-filter λ_0 moves in the long-wavelength side with a rise in environmental temperature.

To realize the temperature independent Si waveguide device, we make over-cladding of the material with negative, opposite to Si, TO coefficient. Then, in Eq. (2), second term expressing over-cladding cancels other term. To archive athermal operation, we must coordinate each term so that Eq. (2) equals to zero. However, if pure substance is used as cladding material, we can't change TO coefficient of each part and must adjust it only in confinement factor. So, core geometry is restricted since it is related with confinement factor.

On the other hand, if TiO_2 hybrid polymer is used as cladding material, we can archive athermal operation by adjusting TO coefficient of the polymer.

III. DEVICE DESGIN AND MEASUREMENT

We fabricated Mach-Zehnder interferometers with Si core, TiO_2 hybrid polymer over-cladding and SiO_2 under-cladding. Thickness of the polymer over-cladding is approximately 1 μm. To demonstrate athermal operation experimentally, we prepared two MZIs. One has 550 nm × 80 nm core coated with the polymer whose TiO_2 concentration is 20 vol%, another has 500 nm × 80 nm core with the 11.2 vol% polymer. Transmission spectra of them were measured in 30~60 °C and 1.48-1.58 μm wavelength range.

Then, we show system of measurement in Fig. 2. LED (central wavelength: 1.53 μm) is used as light source, and LED light is polarized in TE-like mode by wavelength plate. Next, the light is incident on the tip by lensed fiber, passes through MZI and then be incident on lensed fiber on the other side. Lensed fibers and waveguides leading to MZI is coupled in high efficiency by the coupler with double cladding on the tip end. Finally, the light is divided into two with fiber coupler and incident on the spectrum analyzer or the power meter. The spectrum analyzer is utilized for measurement of transmission spectrum, and the power meter for fixing positions of lensed fibers. Tips are mounted on variable temperature stage with thermo-electric cooler.

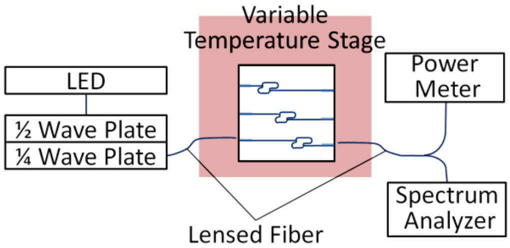

Fig. 2. The block diagram of measurement system.

IV. MEASURMENT RESULT AND DISCUSSION

Measured transmission spectra and thermal dependency of resonance wavelength shift of each peak existing in 1.53-1.55 μm are shown in Fig. 3. Resonance wavelength shift are 0.31 nm, 0.32 nm in maximum over 30-60 °C. And, resonance wavelength shifts in same core geometry with no over-cladding is 1.52 nm, 1.27 nm calculated by finite element method. From Fig. 3.. resonance wavelengths shifts were suppressed to nearly 1/5 with TiO_2 hybrid polymer over-cladding. Figure 4 shows that the slope ($d\lambda_0 / dT$) changes positive to negative with a rise in temperature. It indicates dn_{eff} / dT changes so, From Eq. (1). We consider it is caused by thermal dependency of dn_{top} / dT. In Eq. (2), each Γ and dn_{bottom} / dT almost unchanged since the former is determined by n and core geometry which almost unchanged, and the latter is so small that its thermal dependency can be ignored. In addition, it is reported in [4], dn_{core} / dT, TO coefficient of Si increases in a positive direction. From the above, dn_{top} / dT, TO coefficient of the polymer increases in a negative direction with a temperature rise.

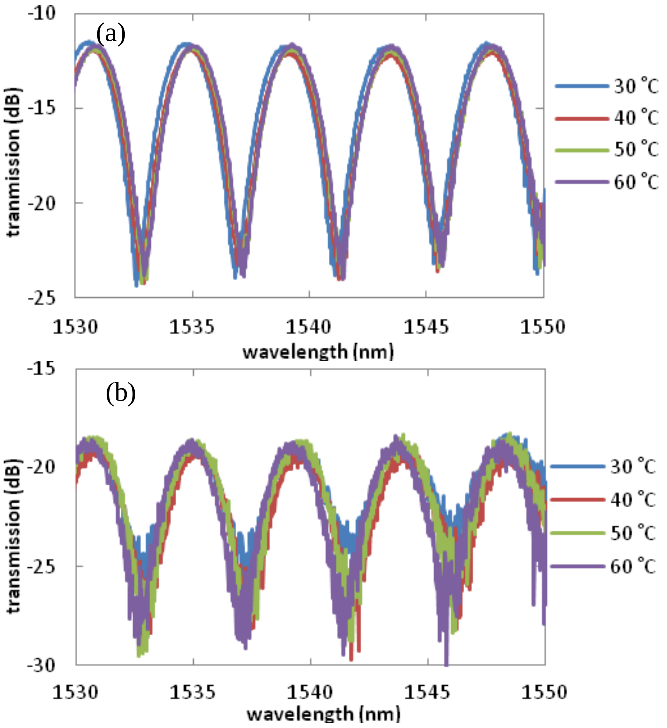

Fig. 3. Thermal dependencies of transmission spectra of MZI with TiO_2 hybrid polymer over-cladding. (a) 550 nm × 80 nm, 20.0 vol%, %(b) 500 nm × 80 nm, 11.2 vol%.

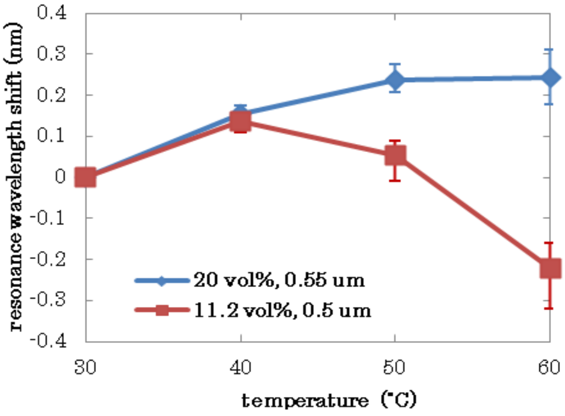

Fig. 4. Thermal dependencies of resonance wavelength shift.

V. CONCLUSION

We experimentally demonstrated the athermal operation of Si waveguide devices to control TO coefficients of the polymer depending on each core geometry. We fabricated Si MZIs clad with TiO_2 hybrid polymer whose TiO_2 concentration were adjusted dependent on each core geometry and measured their transmission spectra near 1.5μm wavelength and in 30-60 °C temperature range. Measured thermal dependencies of resonance wavelengths were suppressed to nearly 1/5 in same core geometries with no over cladding. It indicates the potential Si/hybrid polymer structure is more widely applicable than other structure with pure substance cladding. And, we observed that TO coefficient of the polymer increased in a negative direction, in opposite to coefficient of Si. So, if we coordinate thermal dependency of TO coefficient of Si and the hybrid polymer to cancel each other out, Si/TiO_2 hybrid polymer device become athermal in even wider temperature range.

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