Tunable Grating Coupler Based on Thermo-Optic Effect in Silicon

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Abstract

We demonstrate an efficient tunable grating coupler using thermo-optic heater in silicon. Tuning of the central wavelength from 1537nm to 1573nm is achieved with an increased 1 dB-bandwidth up to 59nm.

I. Introduction

Coupling of light between the silicon waveguide and the optical fiber still remains a problem due to the large mismatch in mode size and shape [1]. Several approaches have been investigated to minimize mode mismatch, such as an edge coupling with taped waveguide or inverted taper waveguide [2]. These structures can be fabricated with complicate processes and requires additional components like lensed or high NA fiber to couple the light [3]. Grating coupler is an attractive solution to provide relatively easy fabrication and packaging, because light can be coupled out of plane without polishing facets by contrast with the inverted taper structures [4]. However, it is still not suitable for wavelength division multiplexing (WDM) optical communication due to serious degradation of coupling efficiency for the wavelengths deviated from a central wavelength of a grating coupler.

To implement broadband grating couplers, several researches have been attempted devising various structures. Subwavelength grating couplers (SWGCs) were proposed to increase operation bandwidth employing the waveguide dispersion engineering [5-6]. Metal grating couplers on silicon waveguides were also proposed and demonstrated a maximum coupling efficiency of 34% with 1 dB-bandwidth of 40nm [7]. While most previous studies have focused on change of physical structure of grating couplers, broadband operation of grating coupler is still limited by waveguide dispersion [8].

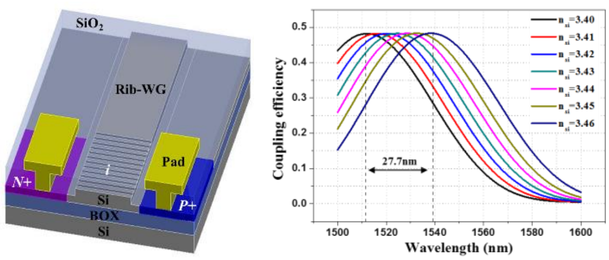
In this paper, we propose to embed thermo-optic heater inside of grating coupler to shift the central wavelength actively. Our structure was fabricated on silicon-on-insulator (SOI) wafer with standard CMOS–compatible processes. In addition, a 1 dB-bandwidth of grating coupler can be extended up to 59nm. Proposed structure can be implemented for any grating structure easily to broaden the operation wavelength and can decrease optical power budget for applications of WDM networks.

II. Principle and Design

The structure we proposed is depicted in Fig. 1. A rib waveguide was formed on an SOI wafer with a silicon thickness of 250nm. Grating coupler is formed on the silicon rib waveguide. The grating structure is designed with the well-known phase matching condition as follows:

$$k_o n_{eff} - k_o n_c \sin\theta = \frac{2\pi}{\Lambda_G} \quad (1)$$

where $k_o = 2\pi/\lambda_o$ is the wavenumber in vacuum, λ_o is the central wavelength, n_{eff} is the effective refractive index (RI) of grating, n_c is the RI of cladding, θ is the incident angle, and Λ_G is the grating period. For a fixed grating structure, the central wavelength λ_o can be tuned by changing the effective RI of the grating. For the tuning of the effective RI, a thermo-optic heater with a *p-i-n* diode was embedded on the grating as Fig. 1(a). The variation of RI by the thermo-optic effect in silicon is given by $\Delta n/\Delta T = 1.86\times10^{-4}K^{-1}$ and its variable range is wider than that by the electro-optic effect based on the free carrier plasma dispersion. As a thermo-optic heater, the *p-i-n* diode is employed for effect heating by current injection into a high resistive intrinsic (*i*) region and also for minimizing the change of RI induced by the *p* and *n* doping. The variable range of the centers wavelength is shown in Fig. 1(b), which is simulated by Lumerical FDTD solutions [9]. We set the grating parameters with a grating period of 620nm, a filling factors of 0.5 and an incident angle of 15°. For this structure, redshift of the central wavelength is predicted with a relation of $\Delta\lambda_o/\Delta T = 0.086 nm\cdot K^{-1}$.

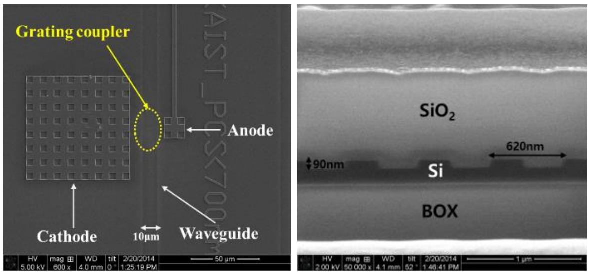


(a) (b)

Fig. 1. (a) Three dimensional schematic of proposed tunable grating coupler embedding p^+-i-n^+ diode, (b) 2D-FDTD simulation results with change of refractive index of grating.

III. Fabrication and Experimental Results

The proposed structure was fabricated on an 8-inch SOI wafer which has a top silicon with a thickness of 250nm and a buried oxide (SiO_2) of 2μm. Grating coupler was defined on a rib multimode waveguide with a width of 10μm to neglect the waveguide loss, using 248nm deep ultra-violet lithography. The etched depth of the grating was 90nm. Ion implantations of boron and phosphorous were performed to form the p^+-i-n^+ region. Heavily doped (p^+, n^+) regions to contact with metal electrodes were located 1μm away from the waveguide region to avoid carrier absorption loss. Finally, oxide cladding layer was deposited on the silicon waveguide as a thickness of 1μm. Fabricated structure is shown in Fig. 2, with an SEM images (a) and a focused-ion-beam image (b) for the longitudinal cross section of the grating.



(a) (b)

Fig. 2. (a) SEM image of fabricated tunable grating couplers, (b) Cross-sectional image of grating coupler using focused ion beam.

The tunable function of the fabricated grating coupler was characterized with the fiber-to-fiber measurement, applying the bias voltage in the *p*-*i*-*n* diode, which can directly generate the joule-heat on silicon waveguide. In this study, only input coupler was controlled with the thermo-optic heater. TE polarized light was coupled into the input grating coupler using single-mode fiber connected with a tunable laser and captured from the output grating coupler with single-mode fiber connected to a photodetector. Both ends of the single-mode fiber were tilted with 15° from vertical axis. The measured coupling efficiency from the grating coupler was up to 38.4% at the central wavelength of 1537nm with a 1 dB-bandwidth of 30nm. Under a bias, the central wavelength was tuned from 1537nm to 1573nm with a thermal tuning efficiency of 0.25nm/mW. The 1 dB-bandwidth of the grating coupler was expanded up to 59nm dynamically, as shown in Fig. 3. Note here that the spectrum of the optical intensity tuned from the input grating coupler with the heater is distorted when it passes through the output grating coupler without the heater. Thus the optical intensity curve for each voltage was normalized assuming that input and output couplers has the same coupling efficiency for the same wavelength.

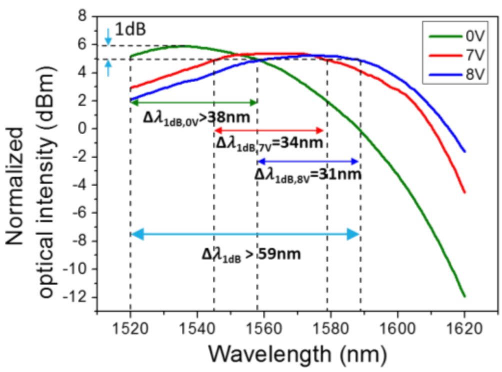


Fig. 3. Spectra of the transmitted optical intensity for tunable grating coupler with the variation of the applied bias voltage.

IV. Conclusions

We have designed and demonstrated an efficient tunable grating coupler using thermo-optic effect in silicon. Embedding a *p*-*i*-*n* diode as a heater in the grating coupler we successfully tune the central wavelength from 1537nm to 1573nm with a thermal tuning efficiency of 0.25nm/mW. This structure can be implemented easily in any grating couplers based on the CMOS compatible process and can be applied for broadband operation of the silicon photonic couplers for WDM applications.

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