The Si-Photonic Modulator Using Three-Waveguides Coupler Structure

Jong-Hun Kim, Muhyun Jin, Seok-Min Seo, Sanggu Yeo, Seong-Hwan Kim,
Dong-Eun Yoo, Dong-Wook Lee & Hyo-Hoon Park
School of Electrical Engineering
Korea Advanced Institute of Science and Technology
Daejeon,Korea
Jhkim09@kaist.ac.kr , yesheis@kaist.ac.kr

***Abstract*—We proposed and demonstrate the Si-modulator using three-waveguides coupler structure for the first time. By using three-waveguide structure can decrease the coupling lengthcontrary to conventional directional coupler structure. For the modulation operation, *pn* diode is employed to have junction at the only one waveguide. The proposed structure was fabricated using CMOS-compatible process and shows the compact device size about ~500 μm^2 which is much smaller than MZI modulator structure. By applying forward bias voltage of 1.2 V, π-phase shift is achieved with V_{sw}·L ~ 0.23 V·mm. Finally, it shows operation speed up to 3 Gbps with extinction ratio of 3 dB which is faster than carrier injection using *p-i-n* diode. Itcan affordable for the operation speed up to 3 Gbps using carrier injection of *pn* diode by applying forward bias. We expect that performance of device can be enhanced using more sophisticated fabrication process and can be used as the new structure of Si-photonic modulator.**

***IndexTerms*—Si-photonics, optical modulator, waveguide coupling, electro-optic effect.**

I. Introduction

Demand of massive data transmission, optical interconnection is required in networks and intra-/inter chip data link. Silicon photonics is promising technology for the application of optical interconnection due to its large bandwidth and low fabrication cost with CMOS process [1]. To obtain high speed optical interconnection, it requires high speed modulator to convert electrical signal to optical signal. Thus, optical modulator is essential component in silicon photonics [2]. Recently, several high speed modulators have been demonstrated with Mach-Zehnder interferometer (MZI)[3], Ring resonator [4], and directional coupler[5] using free carrier plasma dispersion(FCPD) effect in silicon.

There are several directional coupler based modulator have been reported [5,6]. These are typically based on two-waveguides directional coupler, so they have disadvantage in long coupling length. We demonstrate new type of three-waveguides directional coupler in this paper. Using three-waveguides directional coupler, coupling length can be reduced $\frac{1}{\sqrt{2}}$ time compare to typical directional coupler [7].

II. Device Design and Simulation Results

The schematic of the proposed Si-photonic modulator using three-waveguides coupler structure is depicted in Fig. 1. For the silicon waveguide structure, SOI (silicon-on-insulator) wafer is used with top silicon thickness of 250 nm and buried oxide thickness of 2 μm. Rib waveguide structure is mainly used for effective light coupling among waveguides with waveguide width of 500 nm and slab height of 120 nm. Under fabrication condition, gap distance is determined as 500 nm.

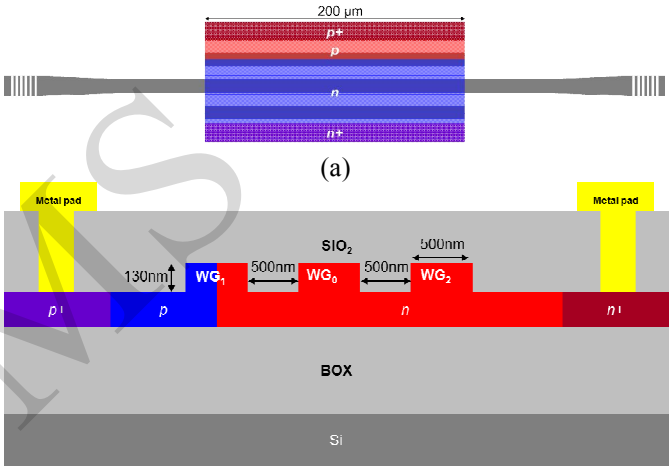


Fig.1: The Schematic Of Proposed Si-Photonic Modulator Using Three-Waveguide Coupler Structure: (A) Top View, And (B) Cross-Sectional View.

Basically, proposed device is operated using waveguide-coupling phenomenon which is demonstrated in several way in Si-photonic devices [7]. The coupling coefficient should be defined based on coupled mode theory [8] and the perturbation theory [8]. The waveguide coupling between two guided modes a` and $b$` can be described by following approximation of wave equation [8] :

$$\mathrm{E(r,t)} = \mathrm{a(z)}\varepsilon_a(x,y)\exp[i(\omega t - \beta_a z)] + b(z)\varepsilon_b(x,y)\exp[i(\omega t - \beta_b z)] \quad (1)$$

where $\varepsilon_a(\mathrm{x,y})$ and $\varepsilon_b(x,y)$ are the transverse spatial electric field distributions of particular unperturbed guided modes of waveguides a` and $b$`, respectively, and their propagation constants are denoted by β_a and β_b accordingly. The amplitudes a(z) and b(z) vary along the coupler length due to the evanescent coupling between the two modes.The governing

IJSMS

set of coupled mode equations derived from perturbation theory [8]:

$$\frac{dR(z)}{dz} = i\delta R(z) - i\kappa S(z) \quad (2)$$

$$\frac{dR(z)}{dz} = -i\delta S(z) - i\kappa R(z) \quad (3)$$

where $a(z) \equiv R(z)\exp(i\delta z)$, $b(z) \equiv S(z)\exp(-i\delta z)$, $2\delta \equiv \beta_a - \beta_b$, and κ is the coupling coefficient which determines the coupling efficiency and is defined as :

$$\kappa \equiv \frac{\omega}{4}\langle a|\Delta\varepsilon|b\rangle = \frac{\omega\varepsilon_0}{4}\iint_{-\infty}^{\infty}\varepsilon_a^*(x,y)\Delta n^2(x,y)\varepsilon_b(x.y)dxdy \quad (4)$$

where $\Delta n^2(x,y)$ represents the perturbation in the dielectric coefficient ($\Delta\varepsilon = \varepsilon_0\Delta n^2$). This indicates that κ is dependent on ω, Δn^2, ε_a, and ε_b.In addition, one can expect the maximum power coupling from one waveguide to the other is occurred at $z = L_c \equiv (2m+1)\pi/(2\sqrt{\kappa^2+\delta^2})$, where m=0,1,2… and the maximum power fraction of coupling is $\kappa^2/(\kappa^2+\delta^2)$. As the designed three-waveguides coupler structure is the case of symmetric directional couplers ($\delta = 0$), the power in one waveguide can be fully transferred to the other ones and the minimum coupling length can be determined as$L_c = \pi/(2\kappa)$. From this relation, coupling coefficient κ is function of ω, Δn^2, ε_a, and ε_b. So the optical modulation process can be achieved by controlling those factors. For the proposed device, we directly change the refractive index of neighboring waveguide using free carrier plasma dispersion effect (FCPD) as shown in Fig. 2(b).

Here is the operation principle. At first, to make symmetric three-waveguides structure, *p*-doped region is covered whole waveguide structure. Then, light coupled to each waveguide with same coupling coefficient. By controlling of waveguide length, we can decide the switching state at the end of coupled waveguide structure. Then, by employing *pn* junction which is located only one waveguide structure to change refractive index of one waveguide structurewith applied forward bias, refractive index of WG_1 can be decreased and coupling coefficient can be changed which can change the waveguide coupling condition. Finally, it can switch the state of end of modulator structure.

The proposed structure was simulated using the 3D-BPM simulation. The waveguide and coupler structure is determined as same as above Fig. 1(a). Without change of refractive index of each waveguides, the incident light with operation wavelength of 1550 nm propagates to the WG_0 with TE-like fundamental mode. When the meet the neighboring waveguide structure, the evanescent field is coupled to the both sides of waveguidesWG_1 and WG_2 with same coupling coefficient due to all the waveguides are symmetric and identical, maximum power coupling is occurred at the coupling length point. As shown in Fig. 2. (a), this structure has normally-off state at the end of waveguide coupling structure. By directly change of refractive index of $WG_1$with +0.008, thenthe coupling coefficient between WG_1 and WG_0 would be different from the coupling coefficient between WG_2 and WG_0, causing the different coupling lengths. Finally we confirmed the switching from off-state to on-state can be occurred by the refractive index change.

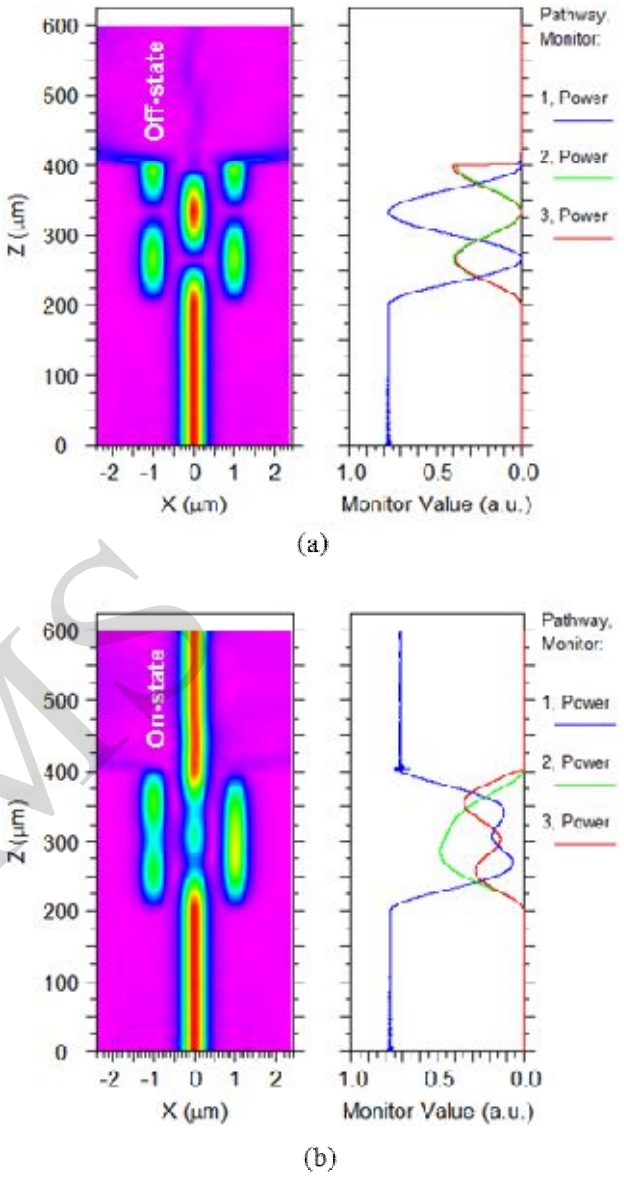


Fig.2: The 3D-BPM simulation results with change of refractive index: (a) with silicon refractive index of WG_0 = 3.45, WG_1= 3.45 and WG_2= 3.45 (b) with silicon refractive index of WG_0 = 3.45, WG_1= 3.458 and WG_2= 3.45.

III. Device Fabrication

The proposed Si-photonic modulator based on three-waveguides coupler was fabricated on 8-inch SOI wafer, which has a 250 nm-thick top silicon layer and a 2μm-thick buried oxide layer using standard Si-CMOS compatible process. The three-waveguides were formed as rib waveguide structure having a slab height of 130 nm, using 248 nm deep ultra-violet lithography. The waveguide coupler structure is fabricated with width of 500 nm and each gap distance among waveguides of 500 nm as shown in Fig. 3(a). For the controllable region, *pn*

IJSMS

diode is formed using ion implantation process with boron doping concentration of 5.5 × 10^{19} cm^{-3} and phosphorous doping concentration 6.1 × 10^{19} cm^{-3} respectively. The *pn* junction is located at the center of WG_1 to only change the refractive index of WG_1. Heavily doped p^+ and n^+ region as ohmic contacts were formed 1 μm away from WG_1 and WG_2 to avoid free carrier absorption loss. The top clad with 1 um-thick oxide layer was deposited. The Al metal electrode is formed through the cladding layer, connecting p^+ region with signal electrode and n^+ region with ground, as shown as Fig. 3(b). The fabricated devices shows the total footprint of ~ 2.5μm (W) × 200 μm (L).

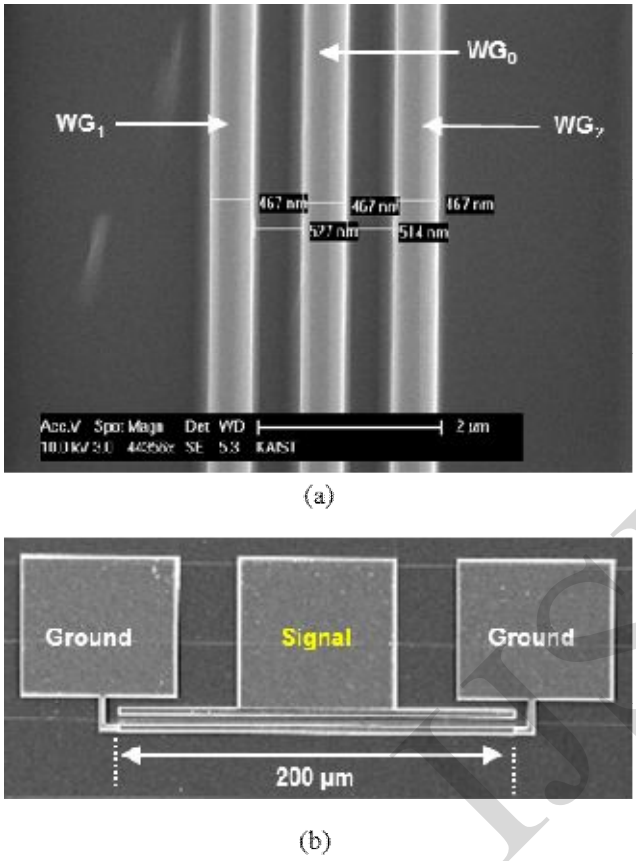


Fig. 3: The SEM images of fabricated device: (a) measured three-waveguides structure, and (b) fabricated Si-photonic modulator using three-waveguides coupler which has total footprint about ~500 μm^2.

IV. Experimental Results

The fabricated device characterized with fiber-to-fiber measurement using tunable light source from 1520 nm to 1630 nm. For the light coupling, grating couplers were used with vertical fiber coupling with incident angle of 15°. For the change of refractive index, Kithely current source is used to apply bias voltage on a *pn* diode. Fig. 4 shows its transmission spectrum with different applied bias voltage. With forward bias of 1.2 V, transmission spectrum is red-shifted with achievement of π-phase shift. From this measurement, $V_{sw} \cdot L$ is calculated as 0.24 V·mm.

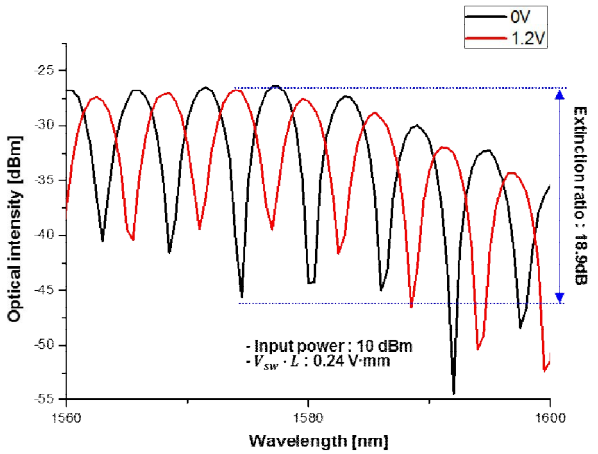


Fig.4: The Measured Transmission Spectrum With Change Of Applied Bias Voltage Using Free Carrier-Injection In *Pn* Diode.

The operation speed of proposed device is measured with Agilent high-speed pulse-pattern-generator covering up to 12.5 Gbps and Agilent oscilloscope. Using PRBS signal with length of 2^{23}-1, it shows the capability to operation speed of 3 Gbps with extinction ratio of 3 dB. It is relatively faster than conventional modulator structure with *p-i-n* diode structure.

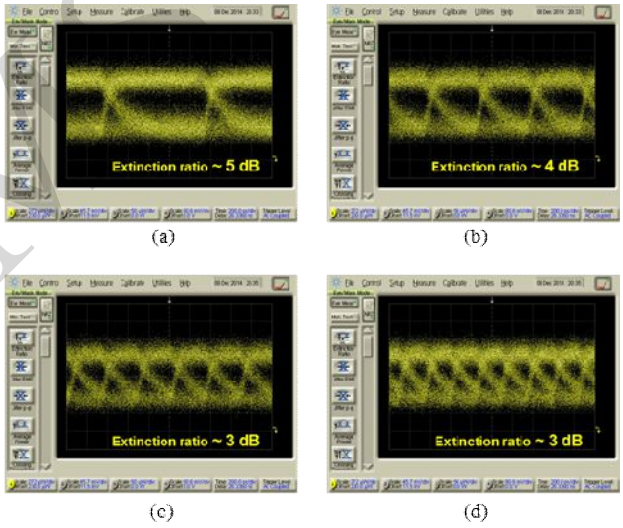


Fig.5: The measured eye-diagram with various operation speed and its extinction ratio: (a) 1 Gbps, (b) 2 Gbps, (c) 3 Gbps, and (d) 4 Gbps.

V. Conclusion

We proposed the Si-modulator using three-waveguides coupler structure contrary to conventional directional coupler structure for the first time. It shows the compact device size about ~500 μm^2 which is much smaller than MZI modulator structure. In addition, it can affordable for the operation speed up to 3 Gbps using carrier injection of *pn* diode by applying forward bias. We expect that this device can enhanced using more sophisticated fabrication process and can be used for the new structure of Si-photonic modulator.

ISMC

ACKNOWLEDGMENT

This work was supported by the Center for Integrated Smart Sensors funded by the Ministry of Science, ICT & Future Planning as Global Frontier Project (CISS-2012M3A6A6054191). The authors thank to NNFC for the device fabrication.

REFERENCES

[1] G. T. Reed, G.Mashanovlch, F.Y. Gardes and D.J. Thomson, "Silicon optical modulators," nature photonics review, pp. 518-526, July 2010 .

[2] D. J. Thomson, F. Y. Gardes, J.-M. Fedeli, S. Zlatanovic, Y. Hu, B. P. Kuo, E. Myslivets, N. Alic, S. Radic, G. Z. Mashanovich and G.T. Reed, "50Gb/s silicon optical modulator," IEEE Photonics technology letters, vol. 24, No . 4 , February 2012.

[3] A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, "A high-speed silicon optical modulator based on a Metal-oxide-semiconductor capacitor," nature, pp 615-618, September 2003.

[4] G. Li, X. Zheng, J. Yao, H. Thacker, I. Shubin, Y. Luo, K. Raj, J. E. Cunningham, and A. V. Krishnamoorthy, " 25Gb/s 1V-driving CMOS ring modulator with integrated thermal tuning," Optics Express, vol. 19, No. 21, October 2011.

[5] J.-S. Kim and J. T. Kim, "Silicon electro-optic modulator based on an ITO-integrated tunable directional coupler," Applied Physics, vol. 49, no. 7, January 2016.

[6] M.-D. He, K.-J. Wang, L. Wang, J.-B. Li, J.-Q. Liu, Z.-R. Huang, L. Wang, L. Wang, W.-D. Hu, and X. Chen, "Graphene-based terahertz tunable plasmonic directional coupler," Applied Physics Letters, vol. 105, no. 8, August 2014.

[7] W.-P. Huang, "Coupled-mode theory for optical waveguides: an overview," J. Opt. Soc. Am. A, vol. 11, pp963-983, 1994.

[8] G. T. Reed, Silicon Photonics: The State of the Art, 1st ed. John Wiley & Sons, pp233-235, 2008.

IJSMS