طراحی و مشخصه یابی یک مدولاتور نوری سیلیکونی جدید

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چکیده – در این مقاله، یک ساختار جدید برای مدولاتور نوری سیلیکونی مبتنی بر تخلیه حامل با نرخ انهدام dB ۷.۸۱ و تلفات نوری کم dB ۰.۵۶ در بایاس معکوس ۹ ولت ارائه شده است. مدولاتور از ۱۰۰ نانومتر ناحیه با ناخالصی بسیار زیاد به منظور ایجاد هر اتصال اهمی استفاده می کند و مدولاتور با پروفایل چگالی کم ناخالصی در ناحیه فعال به عنوان شیفت دهنده فاز به گونه ای طراحی شده است تا تلفات نوری را کاهش دهد. نمودار چشم عملکرد جیتر ps ۷.۱۳ و نقطه تصمیم گیری ps ۲۲.۰۷ را نشان می دهد.

کلید واژه- اثر پراکندگی پلاسما، تخلیه حامل، مدولاتور نوری سیلیکونی

Design and Characterization of a Novel Silicon Optical modulator

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Abstract- *A new structure for the carrier depletion based silicon optical modulator is proposed with the extinction ratio of 7.81 dB and the low optical loss of 0.56 dB/mm at 9 V reverse bias. The modulator uses 100nm of heavily doped regions for each ohmic contact. The Modulator itself is designed with low impurity concentration doping profile in the active area as the phase shifter in order to reduce the optical loss. The eye diagram shows the jitter performance of 7.13 ps and the decision point of 22.07 ps.*

Keywords: carrier depletion, plasma dispersion effect, silicon optical modulator

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1 Introduction

Among the basic elements in optical communication systems optical modulators are for light encoding [1]. Silicon based modulators are used in optical applications such as data center communications, and interconnect communications [2, 3]. Optical modulators work is based on plasma dispersion effect [4] to modulate the incoming light [5]. Two important figures of merit of optical modulators are optical loss and extinction ratio determining the device performance. The mentioned devices employ carrier depletion as a result of reverse bias application to manipulate the semiconductor refractive index for phase variation of propagating light [6]. Several depletion mode silicon optical modulators have been suggested which can have data transmission of tens of Giga-bit per seconds [7-10]. In this paper, a new modified structure for the depletion mode silicon optical modulator presented in [3] is proposed which has increased the extinction ratio and reduced the optical loss. Verification results of both figures of merit of modulator: optical loss and phase shift are demonestrated in section 2 while the results of the new proposed modulator is presented in section 3.

2 Verification and Modulator Structures

The proposed modulator cross section in [3] is shown in Fig.1(a), and this work proposed structure is shown in Fig.1(b). The Si based modulator is working on a silicon on insulator (SOI) wafer, with Al metals and heavily doped p and n regions beyond to realize ohmic contacts. By applying a DC reverse bias to the contacts, a depletion region is created [11].

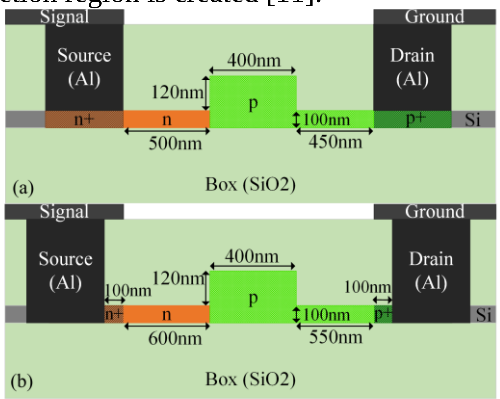

Figure 1. (a) Modulator cross section presented in [3]. (b) new proposed modulator cross section.

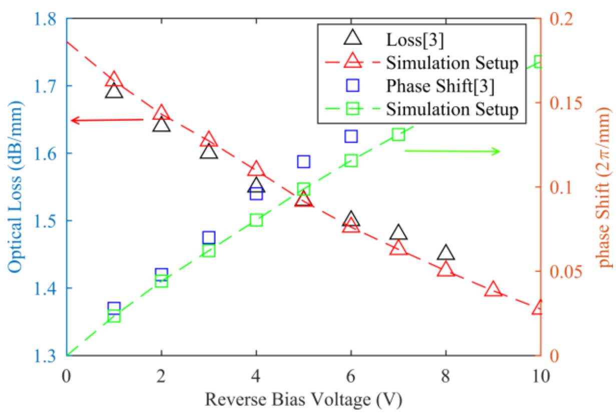

Figure 2. Optical loss and phase shift vs reverse bias voltage for [3] and this work simulation setup results.

Fig.2 shows the results for optical loss and phase shift of [3] comparing with the same structure simulated in this work simulation setup for verification purposes.

3 Simulation Results and Discussion

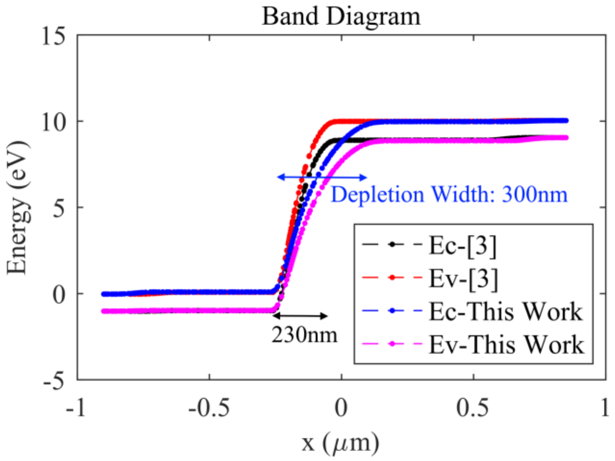

Figure 3. Semiconductor region band diagram of the phase shifter in 9V reverse bias for [3] and new proposed structure.

In order to simulate the optical and electrical behavior of the modulator a commercially available software package is employed [12]. Both Fermi-Dirac and Klaassen's [13] models are employed for charge carrier statistics in electrical simulation and Poisson's equation with carrier continuity equation are solved to obtain electrical characteristics of the device. As can be seen from Fig.3 though depletion region width for [3] is 230nm, for the new proposed modulator structure is 300nm. The advantage of the new proposed structure is that there is no need for extra heavily doping regions beyound the contacts and it just needs 100nm heavily doped region for making an ohmic contact. Also, in the new structure the amount of n and p type impurity is changed to $9\times e^{17}$ cm^{-3} and $1\times e^{17}$ cm^{-3}, respectively. In this case, as carrier concentrations are decreased because of the wider depletion region in compare with [3], the change in imaginary part of the refractive index has a significant reduction as can be seen from Fig.4.

Furthermore, the modulator optical loss is achieved with the change of absorption coefficient (imaginary part of refractive index); Consequently, by modifying the carrier concentration of the device, the modulator can have lower optical loss which can be observed from Fig.5. The obtained optical loss at -9 V is 0.56 dB/mm.

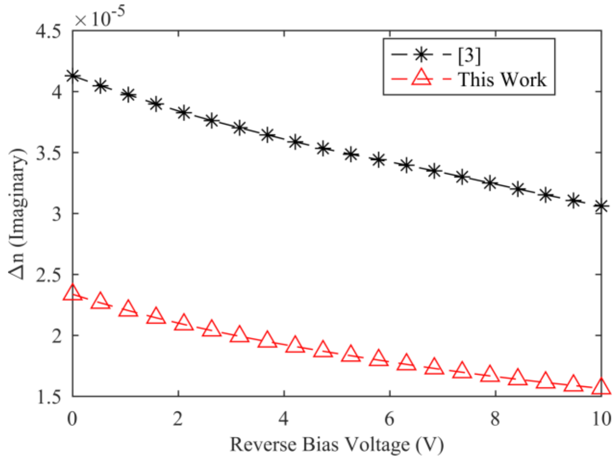

Figure 4. Refractive index imaginery part as a function of reverse bias voltage.

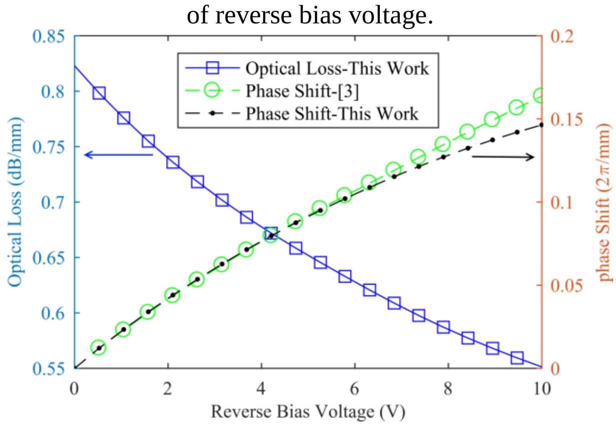

Figure 5. Optical loss and phase shift efficiencies vs reverse bias voltage, in the proposed modulator. The π radian phase shift is achieved in -9 V (V_π = -9 V).

The change in carrier concentrations contributes to change in real part of the refravtive index and consequently phase shift of the propagating light along the modulator and make a phase modulation. The phase shift of the new structure is less than [3] as shown in Fig.5. The phase shift efficiency ($V_\pi L$) is calculated as 3.15 V·cm where L is the modulator length which is similar to [3]. To show the fundamental mode propagating behavior along the modulator, an optical mode profile is needed. For this reason, the finite difference algorithm method is used. Fig. 6 shows the optical profile indicating that the most part of the light is confined in the phase shifter active area. The measured eye diagram of the new proposed modulator structure is shown in Fig. 7 which has the extinction ratio (ER) of 7.81 dB showing the ratio between maximum and minimum transmitted power levels and it's more than ER of 7 measured in [3]. The jitter metric is 7.13 ps which means that the modulator timing signal displays a small variation of few picoseconds and the decision point which

determines "0" or "1" position of the signal is measured as 22.07 ps.

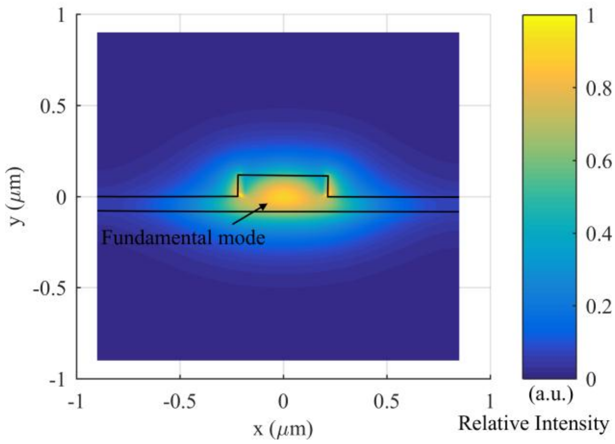

Figure 6. Phase shifter active area optical mode profile.

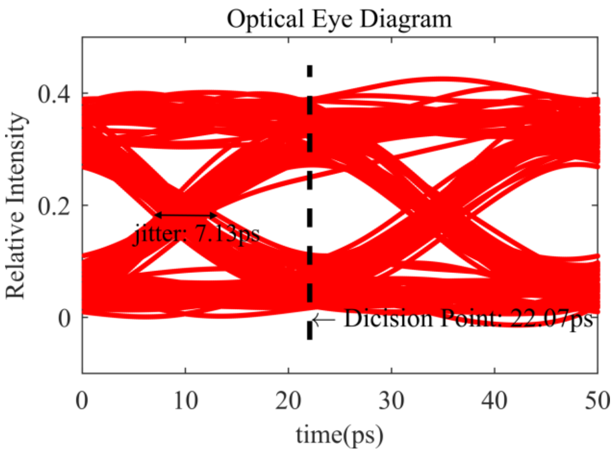

Figure 7. Optical eye diagram of the proposed modulator structure at 40 Gbit/s.

Table1. Comparison of the proposed modulator and other silicon optical modulators.

References / Figure of merits	[1]	[3]	[8]	This Work
V_π (V)	-6	-8	-7	-9
ER (dB)	4.1	7	5.56	7.81
Phase shift efficiency (V·cm)	3.1	2.7	2.67	3.15
Optical loss (dB/mm)	1.75	1.45	1.04	0.56
Jitter (ps)	---	---	---	7.13

4 Conclusion

A new modulator structure is proposed which has two optimized figure of merit optical loss of 0.56 dB/mm at -9 V and ER of 7.81 dB. The presented optical modulator has an open eye diagram with 7.13 ps jitter and decision point of 22.07 ps has been obtained. The proposed modulator designed in a way of needing just 100nm high dopant regions and also low impurity concentrations in the phase shifter active area which makes a straight manufacturing process.

References

[1] H. Xu, X. Li, X. Xiao, Z. Li, Y. Yu, and J. Yu, "Demonstration and characterization of high-speed silicon depletion-mode Mach–Zehnder modulators," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, pp. 23-32, 2014.

[2] D. Pérez-Galacho, D. Marris-Morini, E. Cassan, C. Baudot, J.-M. Fédéli, S. Olivier, *et al.*, "Comparison among Silicon modulators based on Free-Carrier Plasma Dispersion Effect," in *Transparent Optical Networks (ICTON), 2015 17th International Conference on*, 2015, pp. 1-4.

[3] S. T. Lim, M. J. Sun, and C. E. Png, "Silicon optical modulator simulation," *Frontiers in Physics*, vol. 3, p. 27, 2015.

[4] R. A. Soref and B. R. Bennett, "Kramers-Kronig analysis of electro-optical switching in silicon," in *Cambridge Symposium-Fiber/LASE'86*, 1987, pp. 32-37.

[5] A. Chen and E. Murphy, *Broadband optical modulators: science, technology, and applications*: CRC press, 2011.

[6] D. Thomson, F. Gardes, Y. Hu, G. Mashanovich, M. Fournier, P. Grosse, *et al.*, "High contrast 40Gbit/s optical modulation in silicon," *Optics express*, vol. 19, pp. 11507-11516, 2011.

[7] P. Dong, L. Chen, and Y.-k. Chen, "High-speed low-voltage single-drive push-pull silicon Mach-Zehnder modulators," *Optics express*, vol. 20, pp. 6163-6169, 2012.

[8] X. Tu, T.-Y. Liow, J. Song, X. Luo, Q. Fang, M. Yu, *et al.*, "50-Gb/s silicon optical modulator with traveling-wave electrodes," *Optics express*, vol. 21, pp. 12776-12782, 2013.

[9] Y. H. D. Lee, J. Cardenas, and M. Lipson, "Linear silicon PN junction phase modulator," in *CLEO: 2015*, San Jose, California, 2015, p. SW3N.5.

[10] X. Xiao, H. Xu, X. Li, Z. Li, T. Chu, J. Yu, *et al.*, "60 Gbit/s silicon modulators with enhanced electro-optical efficiency," in *Optical Fiber Communication Conference*, 2013, p. OW4J. 3.

[11] G. T. Reed, G. Z. Mashanovich, F. Y. Gardes, M. Nedeljkovic, Y. Hu, D. J. Thomson, *et al.*, "Recent breakthroughs in carrier depletion based silicon optical modulators," *Nanophotonics*, vol. 3, pp. 229-245, 2014.

[12] L. Solutions, "FDTD Solutions Manual Release 7.5," *Vancouver, BC*, 2011.

[13] D. Klaassen, "A unified mobility model for device simulation," in *Electron Devices Meeting, 1990. IEDM'90. Technical Digest., International*, 1990, pp. 357-360.