High Bandwidth All Silicon MOS-Capacitor Ring Modulators

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Abstract *We demonstrate silicon/SiO_2/polysilicon lateral MOS Capacitor ring modulators operating up to 50GHz with a substantial plasma absorption effect, which leads to enhanced electro-optical modulations by loss modulation mechanism in resonators and reduced one-level insertion loss down to 1dB for modulation extinction ratio >3dB. ©2023 The Author(s)*

Introduction

Silicon photonics technology is now one of the most competitive solutions to address the demands of high bandwidth communication for data centre based applications. So far, high-speed silicon photonics transceivers can deliver 224 Gb/s PAM-4 signals with co-designed or dedicated electronics drivers [1, 2], and make it possible to upgrade current 100 Gb/s PAM-4 based 1.6 Tbps silicon photonics circuits [3] to 3.2 Tbps. Silicon photonics transmitters based on ring modulators are advantageous for WDM deployment in a single channel benefiting from the nature of their multi resonances, which can further increase the bandwidth of 16-channel based optical transceivers. Together with co-packaged optics (CPO) development, silicon ring modulators will be able to address the future challenges of bandwidth density and power efficiency when scaling the next generation data centres.

Here we report a carrier accumulation effect based silicon MOS-Capacitor (MOSCAP) ring modulators, which not only benefit from the phase change effect, that silicon depletion ring modulators highly relied on, but also a significant carrier absorption effect that uniquely exists in MOS based waveguides. Thanks to the combination of the plasma dispersion and absorption effect, the MOSCAP ring modulators can circumvent the bottleneck of the conventional depletion ring modulators, i.e., the modulation extinction ratio (ER) costs higher insertion losses at faster operating speeds. Here we demonstrate MOSCAP ring modulators can be operated to 50 GHz (100Gb/s NRZ), and the concurrent of phase and loss modulation allows the one-level insertion loss (IL_{one}) of the ring modulators down to 1(2) dB for DC(high speed) modulation with an ER > 3 dB. This largely reduces the optical power budget and allows sufficient optical modulation amplitude (OMA) at the detector side.

Lateral MOS-Capacitor Modulator

Here we fabricated MOSCAP ring modulators [4] with a radius of 15μm, consisted of half original SOI single crystalline silicon, half polysilicon and in-between silicon dioxide with sub 7nm thickness (t_{ox}), as depicted in Fig.1(a). The polysilicon part was doped as p-type (Fig.1.(b)). The phase change efficiency ($V_\pi L$) and loss modulation of the MOSCAP waveguide have been calculated based on the equation-(1,2), which predict more accurate plasma effects [5] at the wavelength ~ 1550 nm:

$$-\Delta n=5.4\times10^{-22}\Delta N_e^{1.011}+1.53\times10^{-18}\Delta N_h^{0.838} \quad (1)$$

$$\Delta\alpha=8.8\times10^{-21}\Delta N_e^{1.167}+5.84\times10^{-18}\Delta N_h^{1.109} \quad (2)$$

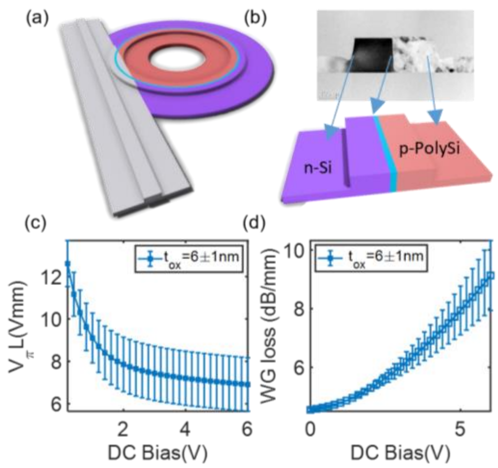

Fig. 1:(a) Schematic design of the MOSCAP ring modulator; (b) Schematic and TEM cross-section of the MOSCAP waveguide of the ring modulator; (c) phase change efficiency and (d) absorption modulation induced by the applied gate voltage.

The plasma absorption equation-(2) interprets the nature of superlinear absorption due to the accumulated high concentration carriers in the centre of the MOS waveguide, of which the density is on the order of $10^{20}/cm^3$. The loss coefficient $\Delta\alpha$ has a difference of a factor of 2 in comparison with the linear absorption model [6].

The calculated $V_\pi L$ agrees well with the experimental values, and is shown in Fig.1(c), and has an upper limit of 7 Vmm for t_{ox} = 6nm. The loss modulation induced by the applied gate voltage (V_g, 0-6V) is about 5 dB/mm, consistent with the extracted loss values based on the ring resonance spectra, as shown in Fig.2(a). The MOSCAP waveguides loss (α_{wg}) is modulated from 4.5 dB/mm to 9.5 dB/mm, which corresponds to a value range of (0.95 to 0.9) for the optical attenuation coefficient (a, $a^2=exp(-\alpha_{wg}L)$) of the ring resonator, as shown in Fig.2(b). Thanks to such a large modulation of a, the coupling condition between the bus waveguide and MOSCAP ring modulator can be altered by the applied DC and RF voltages.

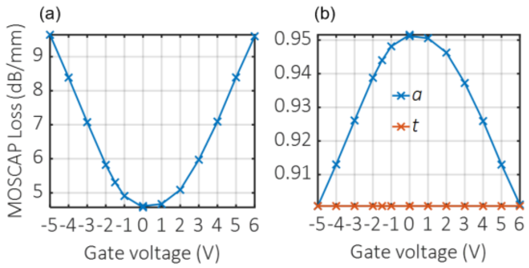

Fig. 2: (a) Experimental results of the waveguide absorption/ loss resulting from the accumulated high density free carriers in MOSCAP waveguides; (b) Extracted all pass MOSCAP ring resonator coefficients, self-coupling coefficient *a* and *t*.

Concurrent phase and loss modulation

As explained above loss modulation is significant within MOSCAP ring modulators. This causes substantial detuning of the coupling states of ring modulators from over-coupling to critical coupling, or critical coupling to under coupling, as shown in Fig.3 and Fig4, respectively. When plotting transmission spectra in dB scale for modulation ER estimation, the resonance depth change is about 20 dB for a gate voltage change of 3V, which allows a DC ER of 6dB and OMA=0.42 for an IL_{one} of 2dB and a DC ER of 3.5 dB and OMA =0.3 for an IL_{one} of 1.2 dB. Here the OMA (P1-P0) is defined by the difference between one (P1) and zero (P0) levels after normalization to the input laser power at an off-resonance wavelength. When operating at a low insertion loss point, the ring modulator can benefit from a higher bandwidth than the value limited by the optical *Q*-factor thanks to the optical peaking effect. For the devices based on the spectra in Fig.3 and Fig.4, we have been able to demonstrate up to 50 Gbit/s operation with a bit error rate (BER) below 1×10^{-12} with feed-forward equalization (FFE) at an average power insertion loss (IL) of 3.5 dB for an achieved ER of at least 3dB at cost ~ 2dB IL_{one}.

We also confirmed the enhanced optical modulation wavelength range (on the left, blue) and suppressed modulation wavelength range (on the right, orange) as depicted in Fig.3&4, which is more pronounced when the transmission spectra are drawn in linear scale. Considering the thermal effects of ring behaviour, the enhancement ideally can be beneficial even at high input optical power by setting the operating wavelength at the left side of the resonances. Experimentally, we demonstrate that such an enhancement exists with a modulation ER of 6dB measured on the enhancement side, and only 3 dB ER measured on the suppressed side in high-speed operation at same optical IL loss [4].

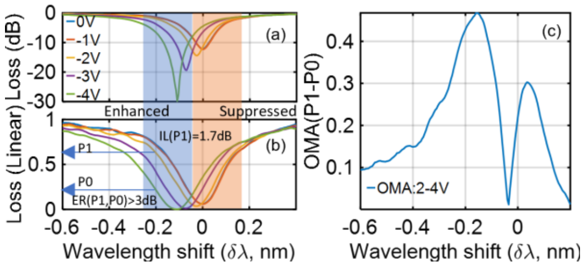

Fig. 3: Coupling detuning from over-coupling to critical coupling induced by the applied gate voltage. (a) Transmission spectra with the shift of resonance and the change of depth in dB scale. (b) Transmission loss in linear scale normalized to the power at a wavelength 1 nm away. (c) Modulation OMA for applied gate voltage change from 2-4 V.

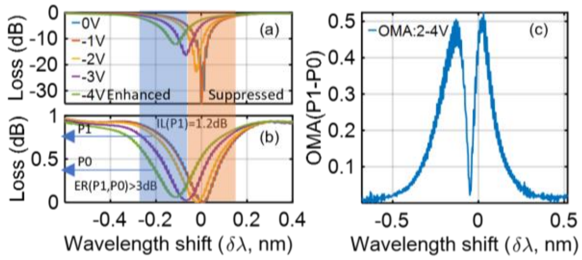

Fig. 4: Coupling detuning from critical coupling to under coupling induced by the applied gate voltage. (a) Transmission spectra with the shift of resonance and the change of depth in dB scale. (b) Transmission loss in linear scale normalized to the power at a wavelength 1 nm away. (c) Modulation OMA for applied gate voltage change from 2-4 V.

The suppression and enhancement originate from the fact that loss modulation increases the linewidth of the resonance at the same time when plasma dispersion induces wavelength blue shifts. Hence, the left side of the resonance shows larger shifts, and the right side suffers less shifts.

Bandwidth

In MOSCAP waveguides, the carrier

accumulation effect starts to dominate the modulation when the applied DC voltage is above flat band voltage ~ 0.8V, and at the same time, a higher but nearly constant junction capacitances co-exist. Here we characterized the electro-optical (EO) bandwidth of the MOSCAP ring modulators with different active lengths (*L*). For L=83µm, the EO bandwidth can reach 50 GHz at V_g=1V. By reducing the driving segment length down to 25 µm, the EO bandwidth is beyond 50 GHz for V_g=1V and close to 50 GHz for V_g = 2V, as shown in Fig.5.

As seen from the modulation enhancement in Fig.3, when detuning the coupling condition from over coupling to critical coupling, both the ER and OMA are improved, which is preferred for high-speed modulation. In such a scenario, we have achieved 100 Gb/s NRZ modulation with a BER of 1×10^{-6} by driving the 83 µm long active segment with V_g = 1V (the inset of Fig.5).

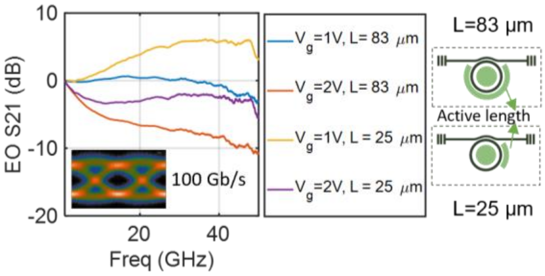

Fig. 5: EO bandwidth of the MOSCAP ring modulators. Different segment lengths have been analyzed for 50 GHz operation.

To further reach even higher bandwidth operation, the segmented approach, with short segments loads, as in Fig.5, can be considered to achieve high bandwidth PAM-4 operation. Reducing the ring radius, whilst properly controlling the oxide thickness and loss modulations can allow low capacitance modulators to be formed. Alternatively, flip-chip integration with dedicated CMOS drivers with lower source impedance can also lead to higher bandwidth operation.

Conclusion

To our knowledge, we demonstrated the first silicon MOSCAP ring modulator that exploits the loss modulations and with EO bandwidth 50 GHz and 100 Gb/s NRZ operation. The high-density of carriers present in the MOS junction leads to superlinear absorption in silicon. Thanks to the significant carrier absorption, concurrent with the plasma dispersion effect, the MOSCAP ring modulators show advantages of reducing the IL_{one} to 1 dB for >3dB ER modulation by DC measurement, and in high-speed operation, we demonstrate IL_{one} ~ 2 dB with an average power insertion loss 3.5 dB for a modulation ER ⩾3dB and a BER < 1×10^{-12} at data rate of 50 Gb/s.

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