64 Gb/s silicon QPSK modulator with single-drive push-pull traveling wave electrodes

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Abstract: We demonstrate a silicon QPSK modulator consisting of two nested Mach-Zehnder interferometers with 3.5 mm long traveling-wave electrodes. 64 Gb/s QPSK modulation is achieved with an EVM of 24.4% and power consumption of 7.1 pJ/bit.

OCIS codes: (060.1660) Coherent communications; (250.7360) Waveguide modulators; (130.0250) Optoelectronics

1. Introduction

Silicon photonics offers the key merits of small footprint, agile functionalities, and compatibility with integrated microelectronic circuits. As a key component for signal conversion from electrical to optical domain, silicon modulators have become the research highlight in recent years. 70 Gb/s on-off keying (OOK) modulation has been realized on silicon platform by optimizing the traveling wave electrode (TWE) and the interleaved p-n junctions [1]. The next generation optical networks require a high channel data rate of 100 Gb/s, due to the rapid expansion of communication capacity. Advanced modulation formats together with polarization multiplexing can be applied to satisfy the high transmission capacity requirement. More recently, 128 Gb/s silicon PM-QPSK modulation has been accomplished by nested Mach-Zehnder modulators (MZMs) with dull-drive push-pull TWEs [2]. In this paper, we report a 64 Gb/s silicon QPSK modulator with single-drive push-pull TWE. The single-drive push-pull TWE can improve the data quality at a high modulation speed, as the loaded capacitance of the TWE is reduced to half compared to the regular dull-drive push-pull TWE [3]. The modulator is more compact due to the single-drive design and the number of RF ports is also reduced by half, facilitating chip package. Moreover, we use four thermo-optic phase shifters to set the biases while the literature reports all use six thermo-optic phase shifters, which makes our device even more compact.

2. Device structure

Fig. 1(a) shows the structure of the QPSK modulator consisting of two nested MZMs. Each MZM contains a 3.5 mm long single-drive push-pull TWE and two 50 μm long thermo-optic phase shifters. Fig. 1(b) shows the cross-sectional view of the thermo-optic phase shifter. It is formed by the heavily n^+ doped silicon slab separated from the waveguide by 0.8 μm to avoid free carrier absorption loss. Deep air trenches surround phase shifters to improve thermal tuning efficiency and reduce thermal crosstalk. Fig. 1(c) shows the cross-sectional view of one MZM. The heavily p^+ doping regions are placed at the outer sides of the Mach-Zehnder interferometer (MZI), and connected to the signal (S) and ground (G) lines of the TWE. The heavily n^+ doping regions are placed in between the MZI arms, and connected to the DC bias electrode. The fabrication was done using the IME standard CMOS process. Fig. 1(d) shows the optical image of the fabricated device after wire bonding.

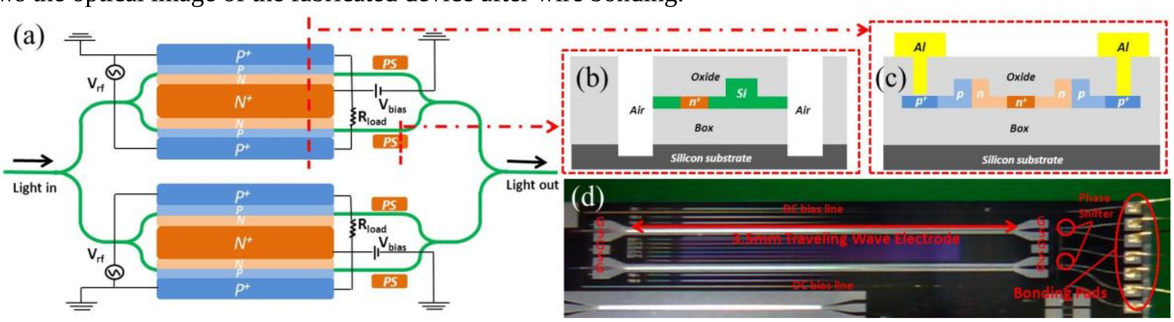

Fig. 1(a) Device structure of the QPSK modulator. PS: phase shifter. (b) Cross-sectional view of the thermo-optic phase shifter. (c) Cross-sectional view of the single-drive push-pull TWE. (d) Optical image of the fabricated silicon QPSK modulator.

3. Experimental results

We first characterized the modulation efficiency of the TWE. The lowest transmission was obtained by adjusting the four thermo-optic phase shifters. The bias voltage on one arm of a nested MZM was increased while the transmission spectrum was measured as shown in Fig. 2(a). The maximum transmission occurs at -4 V, indicating the π-phase shift voltage is $V_\pi \approx -4$ V ($V_\pi L \approx 1.4$ V cm). The static extinction ratio (ER) of the MZM is about 21 dB. Fig. 2(b) shows the electro-electro (EE) S_{21} responses of one MZM measured by a vector network analyzer (VNA) at various DC biases. Electrical transmission notches are present at ~13 and ~24 GHz, which is mainly affected by the coupled-slotline mode [4]. The S_{21} 6-dB bandwidth of the TWE increases with reverse bias and reaches 23 GHz at -5 V.

We next characterized the high speed performance of the modulator. Fig. 2(c) shows the experimental setup. We used two pseudo-random binary sequence (PRBS) signals with a length of 2^{23}-1 and a peak-to-peak voltage (V_{pp}) of 6 V to drive the modular. The TWEs were terminated with two external 50-ohm resistors. The modulated optical signal was measured by an optical oscilloscope and an optical modulation analyzer (OMA). The input light wavelength was fixed at 1550 nm. The four thermo-optic phase shifters from top to bottom were set to 0, π, 0.5π and 1.5π phases, respectively. The DC biases for nested MZMs were set to -3 V. The measured on-chip insertion loss is ~8 dB. Fig. 2(d) shows the eye diagram of the QPSK signal at a bit rate of 64 Gb/s. Three transition levels can be distinguished. Fig. 2(e) shows the optical spectra in a 50 GHz frequency span limited by the OMA. Fig. 2(f) shows the decoded 32 Gb/s in-phase (I) and quadrature (Q) eye diagrams with the Q-factors being 6.1 (I) and 5.9 (Q), respectively. Fig. 2(g) shows the constellation diagram of the 64 Gb/s signal, indicating a magnitude error of 16.7 %, a phase error of 10.7° and an error vector magnitude (EVM) of 24.4%. The bit error rate (BER) deduced from the EVM is 2.1×10^{-5} at a received optical power of -10 dBm.

Finally, we estimated the power consumption of the QPSK modulator. ~40 mW power was applied on the thermo-optic phase shifter to achieve π-phase shift. Therefore, the power consumption on the four phase shifters is P_1=0+20+40+60=120 mW. The characteristic impedance of the TWE is ~54 ohm, extracted from the smith chart, and hence the power consumption on the TWEs is estimated to be $P_2=2\times1/4\times V_{pp}^2/R$= ~333 mW. Therefore, the total power consumption is $P=P_1+P_2$=453 mW, corresponding to 7.1 pJ/bit for the 64 Gb/s QPSK modulation.

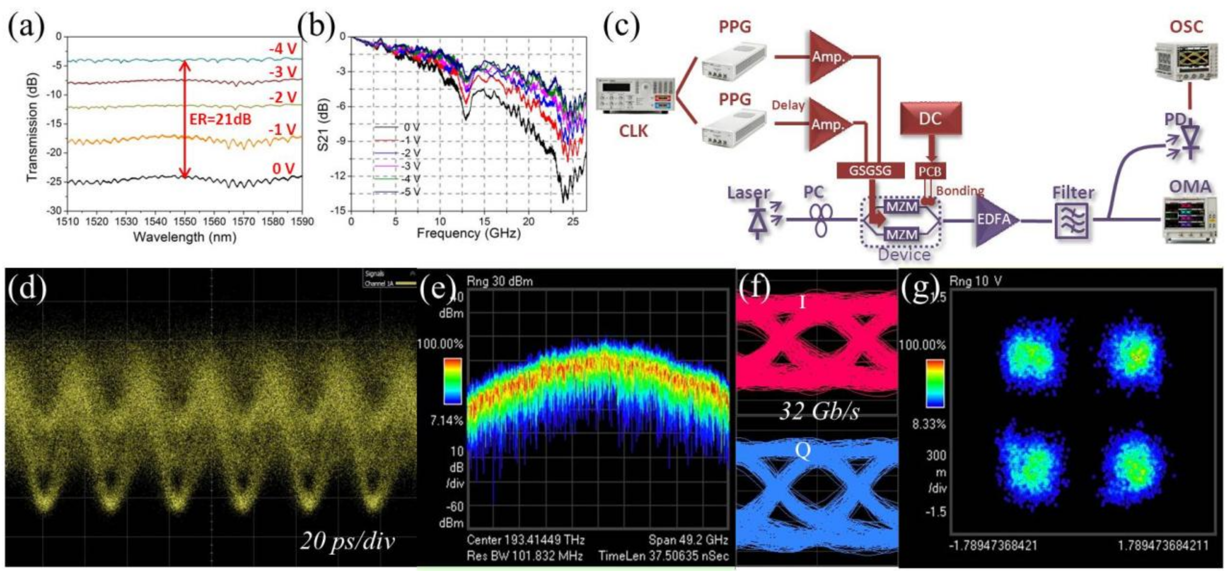

Fig. 2 (a) Transmission spectrum at various reverse biases. (b) EE S_{21} responses of the TWE. (c) Experiment setup for high speed measurement. (d)-(g) Measurement results of the QPSK modulator working at 64 Gb/s modulation speeds. (d): eye diagrams; (e): optical power spectra; (f): decoded in-phase and quadrature eye diagrams; (g): constellation diagrams.

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