High-speed silicon micro-ring modulator at 2-μm waveband

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Abstract: Silicon micro-ring modulator with 18-GHz electro-optic bandwidth and <1-V‧cm modulation efficiency was reported, achieving 50-Gbps highest-speed signaling at 1960 nm. Better endurance of two-photon absorption at 2 μm leads to significantly improved high-speed performances. © 2021 The Author(s)

1. Introduction

Recent years, in virtue of hollow-core fiber [1] with low loss and low latency, and thulium-doped fiber amplifier (TDFA) [2] with broadband gain, 2-μm waveband has been considered as a promising communication window, especially for the short-reach optical interconnection and capacity/latency-hungry scenarios like data centers [3-4].

Thanks to the acceptable absorption loss of silicon at 2-μm wavelength, conventional silicon-on-insulator (SOI) is still a preferred platform for 2-μm wavelength integrated devices/systems [5]. Electro-optic modulators, which play key roles in optical communication systems, are also in urgent need to be extended towards 2 μm. Till now, several silicon modulators at the 2-μm wavelength have been reported, such as high-speed Mach-Zehnder modulator (MZM) up to 80 Gbps [6-7] and micro-ring modulator (MRM) with 3-Gbps data rate [8]. However, the current modulation efficiency, bandwidth and data rates still have a long way to go, to meet the demands of high-speed 2-μm-wavelength transmission, especially for low-power-consumption MRM.

Besides, weaker two-photon absorption (TPA) [9] and stronger free-carrier dispersion (FCD) [10] at longer wavelength make it more attractive for 2-μm-wavelength silicon modulators. Particularly, when it comes to MRM, TPA effect accumulated in the resonator brings in the distortion in both the time and frequency domain, i.e. self-pulsation (SP) and optical bi-stability (BI), therefore results in deterioration of high-speed performances [11]. Weaker TPA coefficient makes 2-μm silicon MRM more tolerant to the high optical launching power, so as to achieve better high-speed performances.

In this work, we report the state-of-art high-speed silicon integrated MRM working at the 2-μm waveband. The proposed MRM presents 18-GHz electro-optic bandwidth at 4V reverse bias, and modulation efficiency of 0.85 V‧cm. Up to 50-Gbps none-return-to-zero on-off-keying (NRZ-OOK) modulation is realized with a bit error rate (BER) under 3.8e-3. TPA induced spectrum distortion is observed in the 2-μm MRM, and so is the impact on eye performances. However, 2-μm MRM shows ~3 dB higher power threshold of TPA compared with MRM in the C band, so as to achieve better high-speed performances at higher launching power. This work fills the blank space of high-speed silicon MRM at 2-μm, and also is the first time to observe and analyze the TPA effect in 2-μm MRM. It shows the promising perspective of high-speed silicon integrated circuits at the 2-μm waveband.

2. Static characterization

The silicon 2-μm-wavelength MRM is designed on the 220-nm SOI wafer with 2-μm-thick buried oxide layer. The rib waveguide with 90-nm-thick slab is 600-nm wide propagating at 2 μm wavelength. The phase shifter in MRM is designed with a L-shaped PN junction in order to increase the modulation efficiency [12]. The doping concentrations are 8e17 cm−3, 1e18 cm−3, 1e20 cm−3, and 1e20 cm−3 for the n, p, n++, and p++ doping regions, respectively. The device was fabricated by MPW run in AMF, Singapore. Fiber-to-chip coupling via inverse tapers has ~5 dB/facet loss at 2 μm. A fiber laser source with a fixed single wavelength near 1960 nm and the ASE broadband source centered at 1850 nm were employed to measure the transmission spectrum of MRM. The resonant spectrum is plotted in Fig. 1(a), showing free spectrum range of 16.75 nm, full width at half maximum of 0.94 nm and the extinction ratio (ER) near 1960 nm over 15 dB.

Due to the lack of a tunable laser at 2 μm, the operation point of MRM was tuned by applying a voltage to the heater and shifting the resonance close to the laser wavelength. Thus, we mapped the resonance shift with the heating power, as shown in Fig. 1(b), abstracting the thermal tuning efficiency of 0.15 nm/mW. By using the single-frequency laser source, power meter at 2 μm, and sweeping the heating power, we obtained the resonant
spectra under diverse optical launching powers indicating TPA induced bi-stability, as depicted in Fig. 1(d). And it needs to note that the spectra recovered by thermal tuning shown here are reverse from the real spectra. It’s clear to see that the resonances under high launching power red shift and become asymmetric since the input power higher than 6 dBm. And when it increases to 10 dBm, the resonance is extremely sharp in the red side and the ER is reduced to 10 dB. The distortion of resonance induced by TPA makes it more unstable and difficult to load signals at the red side of resonance, and also decreases the ER and hence the optical modulation amplitude of signals.

Fig. 1. (a) Resonant spectrum of 2-μm MRM, (b) shifted spectra under heating power, (c) S21 frequency response, (d) resonances at different input power, (e) shifted resonances at different reverse bias.

By means of the same method, resonances under different reverse biases are revealed as Fig. 1(e), and the modulation efficiency is measured as 62.1 pm/V with the corresponding $V_{\pi}L$ of 0.85 V‧cm, which is improved by near 5 times compared with the previous results reported in [8]. The frequency responses (S21) under various reverse biases are measured by the Agilent 67GHz vector network analyzer (VNA), as plotted in Fig. 1(c). The 3-dB EO bandwidth is beyond 18 GHz at -4V DC bias, which is currently the record of high-bandwidth MRMs at 2 μm wavelength.

3. High-speed verification

In the high-speed verification, a pseudorandom binary sequence (PRBS) signal was generated by the arbitrary waveform generator (AWG) with sample rate of 92 GSa/s, amplified to ~4.5 Vpp, then combined with -4V DC bias by a bias-tee and loaded onto the electrodes of MRM. Another pairs of heating electrodes were also used to shift the resonance near to the laser frequency and adjust the proper operation point of MRM. The modulated optical signal is amplified via TDFA and then received by a 20-GHz photodetector (PD) and a real-time oscilloscope for off-line digital signal processing (DSP) or a digital communication analyzer for eye diagram measurement.

In order to observe the TPA’s impact on high-speed performances, we firstly introduced 10 Gbps OOK signals onto the MRM under different optical launching powers, and held the same system parameters including driving voltage, reverse bias and the received optical power after TDFA. The measured ERs and signal-to-noise ratios (SNR) of the 10 Gbps signals are shown in the Fig. 2(a), with the corresponding eye diagrams under different input
powers. The SNRs keep rising up as the launching power increases, which is straightforward that TDFA brings more noises for the lower input power. However, the ERs firstly go up along with the increased power, but reach a bottleneck and then fall down at the high launching power of 10 dBm, which can find the proof from Fig. 1(d) (the distorted resonant with lower ER at 10 dBm input). This phenomenon indicates that there exists an optimal launching power, which not only alleviates the ASE noises brought by high-gain TDFA under low input power, but also prevent the strong TPA induced ER reduction under high input power.

As for the high-speed transmission system, the higher the optimal launching power, the better the ERs and SNRs of received signals. In this case, thanks to the lower TPA coefficient, 2-μm waveband in SOI platform reflects natural advantages compared to the conventional transmission window C band. To prove this, optical bi-stability (BI) in silicon MRM induced by thermo-optical (TO) effect, TPA and other nonlinear effects is theoretically analyzed by coupled mode theory and linear stability analysis method [13]. Taking account of the higher Kerr effect, lower TPA, stronger FCD and free-carrier absorption (FCA) effect at 2 μm contrast to C band, and setting the identical parameters of MRMs in the two wavebands, we obtained the BI boundaries in the map of input power and wavelength detuning. As shown in Fig. 2(b), both the upper and lower thresholds of launching power present 3 dB higher at 2 μm than that in C band, which means the silicon MRM at 2 μm can endure much higher input power, holding high-quality high-speed transmission and keeping unaffected by TPA. These results illustrate the superior application prospects of silicon integrated circuits at 2 μm, especially for the high-speed interconnect systems with hungry power penalty.

After adjusting the operation point of MRM to get rid of TPA, eye diagrams of 20 and 30 Gbps OOK signals were observed on the sampling oscilloscope, as shown in Fig. 3(a-b), appearing clear open eyes with the ERs of 2.659 dB and 2.125 dB respectively. A higher data rate can be achieved by applying a root raised cosine filter and feed-forward equalization (FFE) at the transmitter/receiver side. The BER curves of the 40-Gbps and 50-Gbps OOK signals are plotted in Fig. 3(c). The 40-Gbps OOK signal has a BER under 7% forward error correction (FEC) threshold (3.8e-3) at > -5 dBm received optical power, and the 50-Gbps OOK signal shows a BER of 4.4e -4 at 3 dBm. The corresponding post-FFE eye diagrams are also depicted.

Fig. 3. (a-b) Eye diagrams of 20 and 30 Gbps signals, (c) BER curves of 40 and 50 Gbps signals.

4. Conclusion
The state-of-art high-speed silicon micro-ring modulator working at 2-μm waveband was demonstrated with 18-GHz bandwidth, high modulation efficiency and up to 50-Gbps signaling. TPA induced spectrum distortion and deterioration of high-speed signals were observed in the 2-μm MRM. And theoretical studies reveal the higher threshold of launching power at 2-μm MRM so as to avoid TPA’s impact on high-speed transmission. Thus, silicon MRM at 2 μm waveband shows promising perspective in the high-speed optical interconnect systems.

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