Universal Silicon Depletion Ring Resonator for an Error Free Transmission Link

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Abstract *We report a universal silicon depletion ring resonator with detection responsivity of 0.56-A/W, dark current <700 nA and 9dB optical modulation extinction ratio, enabling C band 50-Gb/s NRZ communication link with BER ⩽ 3×10^{-12}.*

Introduction

Silicon photonics technology has been widely used to support the fast-growing bandwidth demand in data centers. Recently, all-silicon ring based optical transmission links have drawn a lot of attention due to their advantages of CMOS compatibility, low cost, and compactness. Multiple rings can also be formed on a single bus waveguide to directly implement a WDM system with high bandwidth density and power efficiency for next generation communication applications. As two indispensable building blocks of an all-silicon optical transceiver link, enormous efforts have been made to develop high-performance all-silicon ring modulators (MODs) and photodetectors (PDs) individually [1,2]. Owing to its small size and resonance enhancement, silicon micro-rings can improve high-density integration with reduced power consumption [3] and optical power in micro-ring waveguides [4]. However, the design differences required for PDs and MODs can significantly increase the complexity and cost of fabrication, and the electrical circuit design for wavelength control and stabilization, which is the most challenging part for the resonating devices and requires a small technology node in 300 mm wafers [5].

In this paper, we report a C band universal silicon depletion ring resonator with resonance bandwidth from 1525 nm to 1565nm, and designed to perform simultaneously as an avalanche photodetector (APD) and an optical modulator towards an error-free transmission link that is less dependent on driver, TIA, and DSP chips. As an optical modulator, 10 dB extinction ratio (ER) is possible with an RF driving voltage of 2.5V_{pp}. The photodetection performance shows a high responsivity of 0.56 A/W and high dark current <700 nA. The co-designed device allows a large enough modulation ER to overcome its high noise limited photodetection performance, achieving a bit-error-rate (BER) of 2×10^{-12} at 40 Gb/s directly without DSP or filters, and an BER of 3×10^{-12} (1×10^{-11}) at 50 (56) Gb/s with 3 taps forward-error-correction (FFE) at the detection sides. This work provides a universal C band silicon depletion ring resonator design capable of performing as either of a photodetector and a modulator simplifying fabrication and supporting error free communication without DSP techniques for next generation high-speed all-silicon optical transmission applications.

Co-design of optical modulation and photodetection

The universal ring design is based on a 10µm-radius micro-ring structure with an active doping region around 73% of its circumference, which can work as an APD or MOD by applying a reverse bias (V_{bias}) voltage of 6.1V and 1V, respectively, as shown in Fig. 1. The co-designed PN junction is formed with an L-shape doping profile with the purpose of having a large overlap between the depletion region and optical mode, in order to get better modulation and detection efficiency. The measured transmission spectra are shown in Fig. 1, in which the Q-factors of the ring resonances are about 4200, the DC ERs are ~ 20dB, and the free spectral range (FSR) is ~10nm. The fabricated devices show high insertion losses between grating to grating, about 20dB, because of the modifications of standard foundry process flow, which can be overcome by optimized fabrication.

The ring shows broadband resonances in C band, and the measured micro-ring modulator (MR-MOD) resonance shifts with applied voltage bias are depicted in Fig. 1(b). With a $2V_{pp}$ swing and $\sim 1V_{bias}$, a large DC ER 10 dB can be achieved with one level insertion loss (IL) of about 4dB. While working as an APD, the measured dark and total current of the micro-ring avalanche photodetector (MR-APD) are shown in Fig. 1(c). The measured total photocurrent increases with the injected optical power at the resonance wavelength. The measured total photocurrent increases with the injected optical power at the resonance wavelength. The responsivity decreases with injected optical power when close to 0dBm. The dark current is about 700nA and the responsivity about 0.56A/W at a DC bias of $6.1V_{bias}$ before reaching saturation.

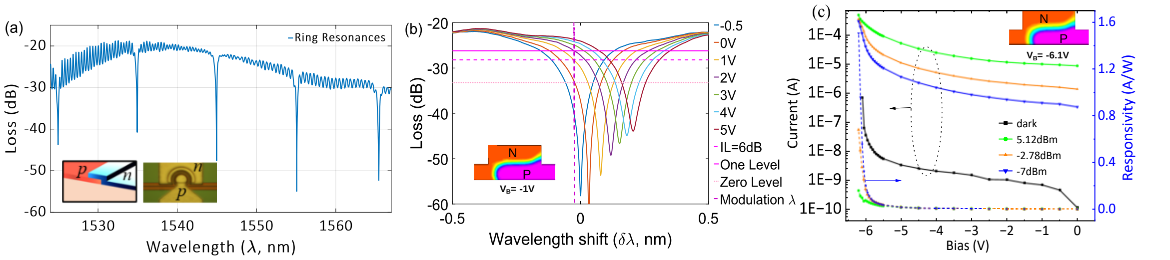

Fig. 1: Measured (a) transmission spectrum of the fabricated micro-ring, (b) DC electro-optical wavelength shifts of MR-MOD, (c) dark current, total current, and responsivity versus bias voltage of MR-APD.

Bandwidth of the universal silicon depletion ring

The bandwidth of the depletion ring is first estimated by characterizing the EO response. 80Gb/s optical APD detection eye diagrams (with pattern averaging), and 112Gb/s optical modulation eye diagrams can be achieved, as shown in Fig.2(a, b, d). The optical eye diagram quality is mainly limited by the electrical eye diagram degradation as shown in Fig. 2(c) for optical modulation performance. When operating as a MR-APD, the bandwidth measurement is limited by the intrinsic noises and the 40GHz lithium niobate modulator used to generate the high-speed optical signal. Without the help of a dedicated low noise TIA, low noise filters or other equipment, we still show that a low BER $\sim 1\times10^{-12}$ can be achieved without using electrical DSP techniques.

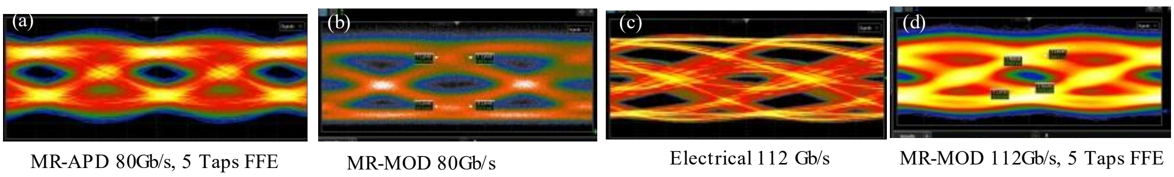

Fig. 2: Measured eye diagrams of MR-APD at (a) 80Gb/s; The applied RF voltage is 1.8 V_{pp}, and optimized ERs are about 4-5 dB for data rate of (b) 80 Gb/s and (d)112 Gb/s of MR-MOD. The applied electrical eye diagrams start to degrade after 64 Gb/s, the electrical eye diagrams supplied for the devices at 112 Gb/s is shown in (c).

Optical communication link

For the performance measurement of the MR-APD, a CW laser light (1550nm) firstly went through a polarization controller (PC), and then was modulated by a lithium niobate Mach-Zehnder interferometer modulator (LN MZI-MOD). The modulated signal then was amplified with a two-stage erbium-doped fiber amplifier (EDFA) before it was coupled to the MR-APD through a second PC. Photocurrent signal was then collected by a combination of a 67 GHz RF open probe, bias tee and a 60 GHz RF linear amplifier, and then sent to the 80GHz electrical port of a Keysight Digital Communication Analyzer (DCA-X 86100D + Agilent 86116C-040). The BER characterization is done in the jitter mode.

The measured 40Gb/s, 50Gb/s, and 56Gb/s eye diagrams of the MR-APD with input bus waveguide optical power of 5.4dBm, 6.2dBm and 6.3dBm at $6.1V_{bias}$ are shown in Fig. 3(a-c), with a BER of 2×10^{-12} at 40Gb/s (no FFE), 3×10^{-12} (3 taps FFE), and 1×10^{-11} at 56Gb/s (3 taps FFE). To reach a BER of 2×10^{-12} or even lower at 40 Gb/s, the required optical power (average power of the modulated signal from LN MZI-MOD) is 5.4 dBm and the required optical modulation ER is about 8 dB. In comparison, by sending same modulated optical signal from LN MZI-MOD to the reference PD of the 65GHz optical detector of Keysight DCA (with noise filter off), the required optical power is about 2 dBm to reach a BER level of $\sim 1\times10^{-12}$, as shown in Fig.3(j). At same circumstances, to reach BER of ~1×10^{-12} at 50 Gb/s, the required optical power to the bus waveguide of the MR-APD is about 6.5 dBm.

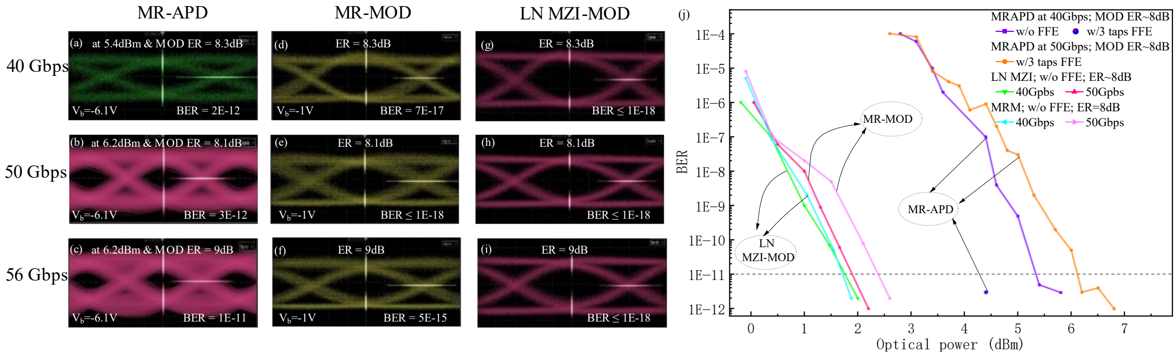

Fig. 3. Measured eye diagrams of MR-APD with the bit rate of (a) 40Gb/s, Pin = 5.4dBm, and MOD ER = 8.3dB; (b) 50Gb/s, Pin = 6.2dBm, and MOD ER = 8.1dB, with 3 taps FFE; (c) 56Gb/s, Pin = 6.2dBm, and MOD ER = 9dB, with 3 taps FFE. The eye diagrams of MR-MOD with the bit rate of (d) 40Gb/s, ER = 8.3dB; (e) 50Gb/s, ER = 8.1dB; (f) 56Gb/s, ER = 9dB. The eye diagrams of LN MZI-MOD with the bit rate of (g) 40Gb/s, ER = 8.3dB; (h) 50Gb/s, ER = 8.1dB; (i) 56Gb/s, ER = 9dB. (j) Measured 40Gb/s and 50Gb/s NRZ BER with different optical power of MR-APD, MR-MOD, and LN MZI-MOD.

The performance of the MR-MOD is compared with LN-MZI-MOD as shown in Fig.3(d-j) at different data rates, the measured optical power VS BER is close to each other, and both can reach high optical ER > 8dB and very low BER < 3×10^{-15} for data rate 40–56 Gb/s. To have a high optical ER, the MR-MOD is biased at 1V and driven with an RF voltage of 2.5V_{pp}. The injected power to the bus waveguide is 12 dBm and the average optical power loss is about 6 dB, which means that about 6 dBm of power is coupled out from the MR-MOD. As discussed above, the modulated high power (6dBm) is large enough to have low BER ~1×10^{-12} for the MR-APD. Based on the performance analysis of the MR-APD and the MR-MOD, an error free communication link can be built by simply using the co-designed universal depletion ring resonator with coupled optical power of about 12 dBm. By integration with a low noise TIA with matched impedance can further improve the high-speed performance of the whole communication link.

Conclusion

We have demonstrated a co-designed high-performance MR-MOD and MR-APD towards error-free communication links operation up to 50Gb/s with single all-silicon depletion universal ring. Based on our current demonstration results, the MR-APD needs at least 5.5dBm optical power and optical ER of 8dB to generate OE conversion with a BER <1×10^{-12}, indicating that the link requires a laser source with ≥11.5 dBm output power in consideration of the 6dB average power IL. The co-designed MR-MOD can fulfil the high-power operation with low BER<3×10^{-15} and high modulation ER
>8dB. Our work proves the principle of using a universal ring device to form a high-speed error-free communication link (modulator + photodetector), providing a simplified all ring-based platform for WDM communication applications.

Acknowledgements

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