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SHORT COMMUNICATIONS

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Broadband PZT electro-optic modulator

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As the demand for computing power in data centers continues to grow, balancing data transmitting speed and energy efficiency has emerged as a critical challenge. High-bandwidth, low-power interconnection schemes are increasingly recognized as core requirements for next-generation intelligent computing center designs[1, 2]. For short-range optical interconnections of intra-chip and inter-chip—typically covering tens of meters or less—microring resonant modulators (MRM) are emerging as an ideal solution. Their advantages, such as a small footprint, low power consumption, and compatibility with large-scale integration, make them highly suitable for addressing high-density and high-capacity demands through wavelength division multiplexing (WDM) technology[3, 4]. Additionally, for intra-data center and inter-data center optical interconnections using intensity-modulated direct-detection (IMDD) strategies, Mach–Zehnder modulators (MZM) play a pivotal role. Their superior linearity and broadband response secure their dominance in the market for 400 G and beyond optical module applications[5].

Traditionally, the silicon photonics (SiPhs) platform has been valued for its superior complementary metal–oxide–semiconductor (CMOS) integration capability and cost-effectiveness. However, the centro-symmetric crystal structure of silicon lacks a linear electro-optic (EO) response. Additionally, the linearity of plasma dispersion modulation is poor, and it is associated with high optical losses. The parasitic capacitance and resistance of doped pn junctions further degrade the device bandwidth[6]. As for thin film lithium niobate (TFLN) based modulators, they exhibit high EO bandwidth, good linearity and low optical loss, but the inherent low EO coefficient (r_{33} = 30.9 pm/V) limits the cooperative optimization of driving voltage and device size[7]. In this work, we show the advanced lead zirconate titanate ($Pb(Zr_xTi_{(1-x)})O_3$, PZT) based modulators with broadband bandwidth and high modulation efficiency, due to the high Pockels coefficient (>100 pm/V)[8]. The manufactured MZM demonstrates a modulation efficiency of $V_\pi L$ = 1.3 V·cm and support an on-off keying (OOK) modulation rates of 80 Gb/s. The MRM exhibits EO tunability of 41 pm/V, corresponding to a modulation efficiency of $V_\pi L$ = 0.56 V·cm and support an OOK modulation rates of 64 Gb/s.

Three-dimensional electromagnetic field simulations reveal the electric field intensity distribution across the waveguide, as depicted in Fig. 1. The device is fabricated on a silicon substrate with a 5 μm BOX layer and a 320 nm PZT waveguide layer. A rib waveguide is formed by etching to a depth of 150 nm, with a width of 1 μm and electrode thickness of 300 nm. Prior to EO test, the waveguide is polarized by applying a 20 V/μm voltage across the electrodes for 10 min, followed by −1 V for 1 min to remove surface charge accumulation. This process is repeated several times to facilitate polarization[9], as illustrated in Fig. 2. Fig. 3(a) illustrates the schematic of the MZM, featuring a ground-signal-ground (GSG) electrode configuration for a push–pull operation, with an electrode spacing of 6 μm and a device length of 2 mm. Fig. 3(b) depicts the relationship between the transmitted optical power and the applied electrode voltage. The MZM exhibits a modulation efficiency of 1.3 V·cm. The EO frequency response of the S_{21} parameter, as shown in Fig. 3(c), reveals a flat response across the measured spectrum, indicating a 3 dB bandwidth exceeding 70 GHz. A dip in EO response between 1 and 10 GHz is observed, which may be attributed to the substrate-interface effects and necessitates further investigation. Fig. 3(d) presents the eye diagram of the MZMs under OOK modulation at 80 Gb/s, demonstrating the modulator's high-speed performance. In Fig. 4(a), the MRMs have a ring radius of 17 μm and electrodes spaced 5 μm apart along the axial direction. Fig. 4(b) shows the static transmission spectrum of the PZT MRM under forward and reverse bias after linear polarization. According to the transmission spectrum, it can be found that the free spectral range (FSR) of the micro ring is 8.86 nm. After polarization process, the EO tunability of the MRMs is 41 pm/V. The modulation efficiency is calculated by the formula $V_\pi L = \frac{\mathrm{FSR}\cdot L_{\mathrm{seg}}}{2\Delta\lambda/\Delta V}$ [10], and the modulation efficiency $V_\pi L$ is 0.56 V·cm. Fig. 4(c) shows the EO response curves of the modulator at different operating wavelengths, with a 3 dB EO bandwidth of approximately 53 GHz. The eye diagram obtained by the MRM under OOK signal modulation at a rate of 64 Gb/s is shown in Fig. 4(d).

In conclusion, we successfully demonstrate high-band-

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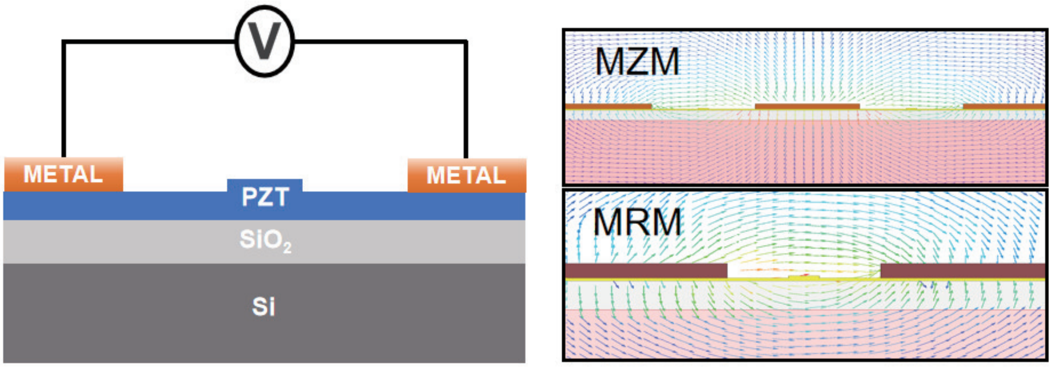

Fig. 1. (Color online) Electric field distribution of PZT modulators.

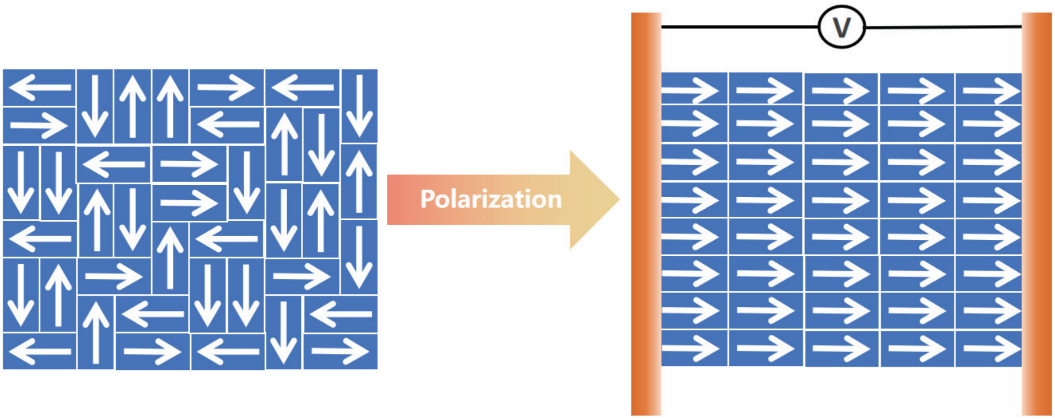

Fig. 2. (Color online) Illustration of PZT polarization.

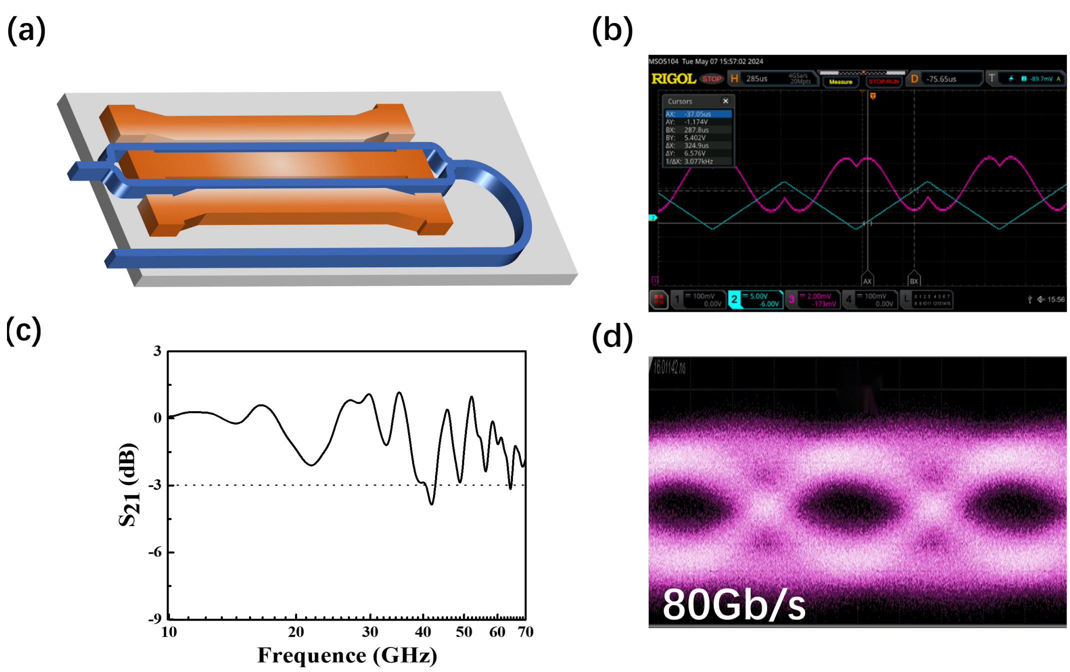

Fig. 3. (Color online) Schematic diagram of MZM and EO test results. (a) Schematic diagram of the MZM. (b) Modulation efficiency result ($V_\pi L$ = 1.3 V·cm). (c) Measured EO bandwidth of 70 GHz. (d) Eye diagram of the PZT MZM, measured using OOK modulation with a peak-to-peak drive voltage of 3 V.

width, high-efficiency MZM and MRM devices on the PZT optical platform. The devices achieve modulation efficiencies of 1.3 and 0.56 V·cm, with demonstrated OOK modulation rates of 80 and 64 Gb/s, respectively. These results underscore the practical potential of the PZT optical platform for high-speed optical communications, attributed to its high performance and CMOS compatibility, holding promise for advancing next-generation photonic technologies.

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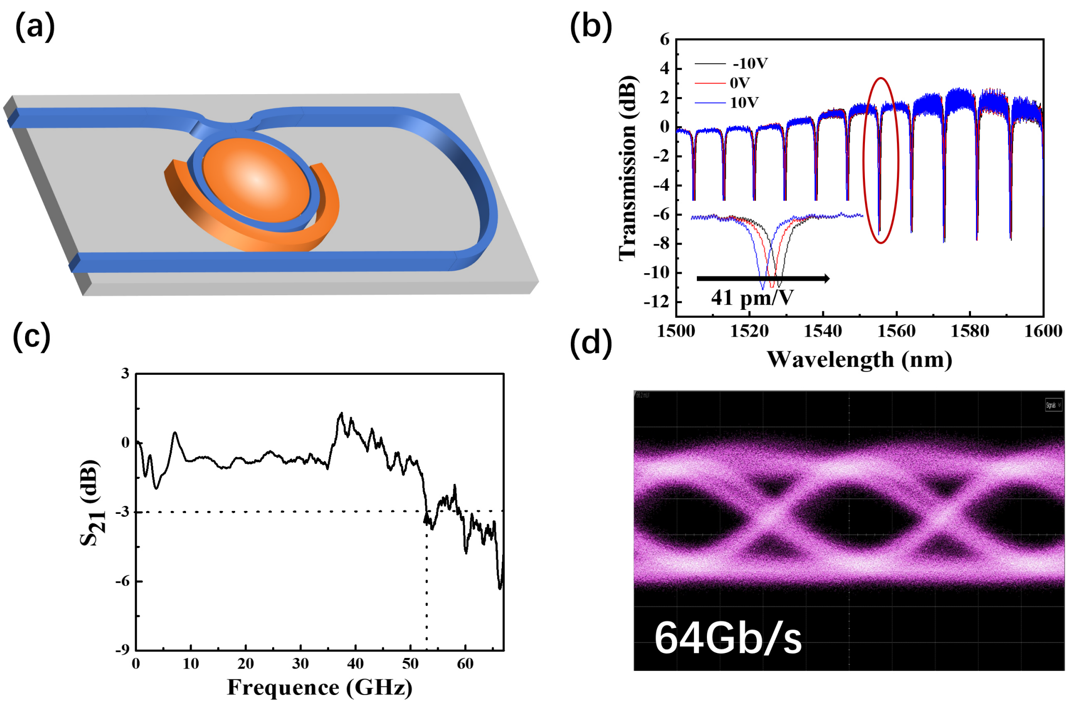

Fig. 4. (Color online) Schematic diagram of MRM and EO test results. (a) Schematic diagram of the MRM. (b) Modulation efficiency result ($V_\pi L$ = 0.56 V·cm). (c) Measured EO bandwidth of 53 GHz. (d) Eye diagram of the PZT MRM, measured using OOK modulation with a peak-to-peak drive voltage of 3 V.

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