120 Gb s^{-1} Hybrid Silicon and Lithium Niobate Modulators with On-Chip Termination Resistor

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Abstract: We demonstrated hybrid silicon and lithium niobate Mach-Zehnder modulators with on-chip termination resistor. The device shows high electro-optic bandwidth up to 60 GHz, low V_π of 2.25 V and low insertion loss of 2 dB.
OCIS codes: (130.3730) Lithium Niobate; (130.4110) Modulator; (060.4510) optical communications.

1. Introduction

Future high-speed optical transmission links demand high-performance optical modulators with ultra-high electro-optic (EO) bandwidth, low drive voltages, low insertion loss and low cost [1]. Silicon photonics technology on the silicon-on-insulator (SOI) becomes the first choice considering the low cost and mature Si CMOS fabrication process [2,3]. Unfortunately, the EO modulation mainly rely on the free-carrier dispersion effect which intrinsically absorptive and nonlinear degrades the performance of modulators [4,5]. Lithium niobate ($LiNbO_3$, LN) has been the ideal material for modulator because of its large EO coefficient, linear EO response, high intrinsic bandwidth, wide transparency window and good stability [6]. In recent years, LN-on-insulator platform (LNOI) has emerged as a promising candidate to enable integration and increase the EO modulation efficiency [7]. Modulators based on LNOI with a low drive voltage and ultrahigh EO bandwidth have been demonstrated [8]. To combine the scalability of silicon photonics with the superior modulation performance of LN, hybrid integration of LN membranes onto SOI has been demonstrated [9]. The modulators show a large V_π due to the unpatterned LN membranes which compromise the modulation efficiency.

Recently, we demonstrated a hybrid Si/LN modulator with etched LN waveguides based on benzocyclobuten (BCB) adhesive die-to-wafer bonding technology [10]. The devices show a high EO bandwidth and modulation efficiency, but the V_π of 5.1 V still remain too high for future modulators. In this paper, we demonstrate a hybrid Si/LN Mach-Zehnder modulator (MZM) integrated with an on-chip termination resistor formed by NiCr. The integration of the modulator with termination resistors can efficiently decrease the complexities of packaging and testing. Furthermore, this approach can provide a high flexibility for designing to realize complex modulator configuration. The device here shows high EO bandwidth up to 60GHz, low V_π of 2.3 V and low insertion loss of 2 dB. On-off keying (OOK) modulation up to 100 Gbits^{-1} and four-level pulse amplitude (PAM-4) modulation up to 120 Gbits^{-1} are successfully demonstrated.

2. Si/LN hybrid MZM with termination resistor

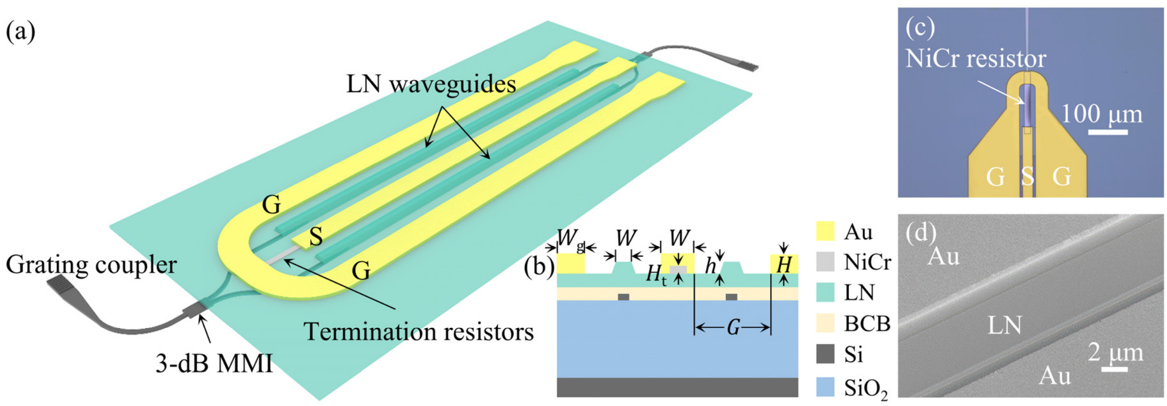

Fig. 1: (a) Schematic of the hybrid silicon and LN MZM with on-chip termination resisitor. (b) Cross-section view of the high-speed modulation

region and termination resisitor. (c) Optical image of NiCr on-chip termination resistor. (d) SEM image of Au electrodes and LN optical waveguide.

Fig. 1(a) shows the schematic of the Si/LN hybrid MZM with on-chip termination resistor. The modulator can be divided into silicon layer, LN layer and mental layer. The first layer is silicon optical I/O circuit including grating couplers, 3-dB multimode interference (MMI) and silicon optical waveguides formed by standard electron beam lithography (EBL) and inductively coupled plasma reactive ion etching (ICP RIE). Then, a commercially available x-cut LNOI substrate (NANOLN) with a 600-nm thick LN membrane is bonded on the top surface of the silicon layer via BCB bonding technology. The LN waveguides are formed along the y axis of $LiNbO_3$ membranes while the gold electrodes creating a horizontal electric field along the z axis of $LiNbO_3$. As a result, the electric field has opposite direction across the two waveguides where the Pockels effect happened, thus inducing an optical phase difference between them. A vertical adiabatic coupler promise a high coupling efficiency (loss of ~0.19 dB) between the silicon and LN layer. Fig. 1(d) shows the SEM image of the modulation region consists of low loss LN optical waveguides (<0.5 dB/cm) formed by dry etch process and travelling-wave electrodes with ground-signal-ground configuration. To achieve high modulation efficiency and low optical loss, the fabricated LN waveguides have a top width of W = 4.2 μm, a rib height of h = 300 nm, the gap between the waveguides and electrodes is set to 1.55 μm correspond to the gap between the signal and ground electrodes of G = 7.3 μm. The thickness of electrodes was set to H = 900 nm, the width of signal and ground electrodes were designed as W_s = 23.1 μm and W_g = 120 μm, respectively (Fig. 1(b)). A thickness of H_t = 200 nm NiCr is deposited via electron beam evaporation under the Au electrodes at the end of modulator, the width and length are set to 14 μm and 100 μm respectively to promise 50 Ω precise resistance of termination resistor. The optical microscope image of the on-chip termination resistor is shown in Fig. 1(c).

We first characterized the stability of the termination resistor. For the NiCr resistor with width and thickness of 14 μm and 200 nm respectively, the fusing current can be 110 mA from the testing results. The V_π measurements are performed with a 100 kHz triangular voltage sweep on a modulator without termination resistor considering the fusing current. Fig.2 (a) shows the response for the 12 mm long device, the device shows a low V_π of 2.25 V. The insertion loss of the modulator with termination resistor is 2 dB. Next, we measured the bandwidth of the modulator using the setup described in [10], the EO response (Fig. 2 (b)) were recorded through S_{21} analysis using a vector network analyzer (VNA). The measured 3-dB EO bandwidth is up to 60 GHz for 12 mm long device. It should be noted that the device still shows a low attenuation nearby 3 dB at 67 GHz which is the limiting frequency of the VNA.

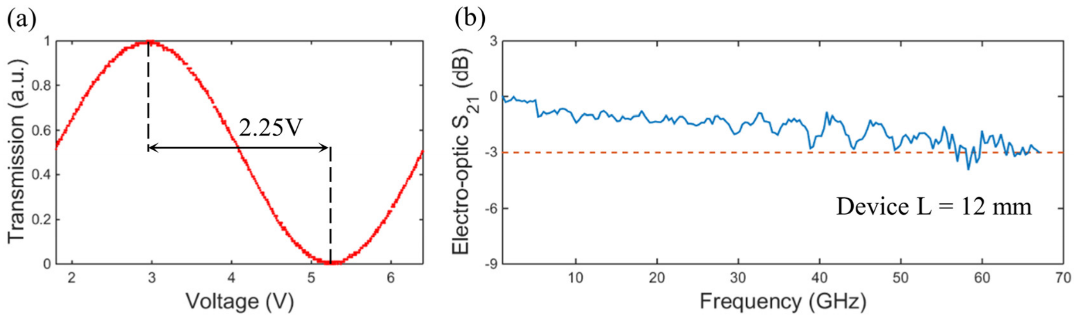

Fig. 2: (a) Normalized optical transmission as a function of applied voltage on travelling-wave electrodes, showing the V_π of 2.25 V for 12 mm long device. (b) Measured EO S_{21} parameter as a function of the frequency for the RF signal, the result shows high 3-dB bandwidth up to 60GHz for 12 mm long device.

3. Data transmission testing

Fig. 3 shows the performance of the modulator with termination resistor for high-speed digital data transmission. As depicted in Fig.3 (a), the amplitudes of the RF signal from arbitrary waveform generator are amplified by an RF amplifier (SHG S807). The MZM are biased at quadrature point via the applied voltage on the bias tee. Only one probe used in testing cause the integration of modulator with on-chip termination resistor. This approach shows a good flexibility for high-speed transmission testing. First, the OOK modulations were applied on the modulator. Fig. 3(b) (c) shows the optical diagrams at 80 and 100 Gb s^{-1}, the measured extinction ratios are 9.5 and 6.0 dB respectively. It is noteworthy that at 100 Gb s^{-1} the whole measurement system is already limited by the bandwidth pf the RF probe and cables. We also carried out the PAM-4 modulation experiments with the same setup. The optical PAM-4 eye-diagrams at 40 Gbaud and 60 Gbaud are shown in Fig. 3(d) (e). The back to back (B2B) bit-error rate (BER) at 60 Gbaud are measured and the curve is shown in Fig. 3(f). The purple curve represents the BER as a function of the received optical power. No error floor is observed in the measured power range, and all the error rates are well below the hard-FEC limit of 3.8×10^{-3}. The results show the devices have the capacity for higher speed transmission.

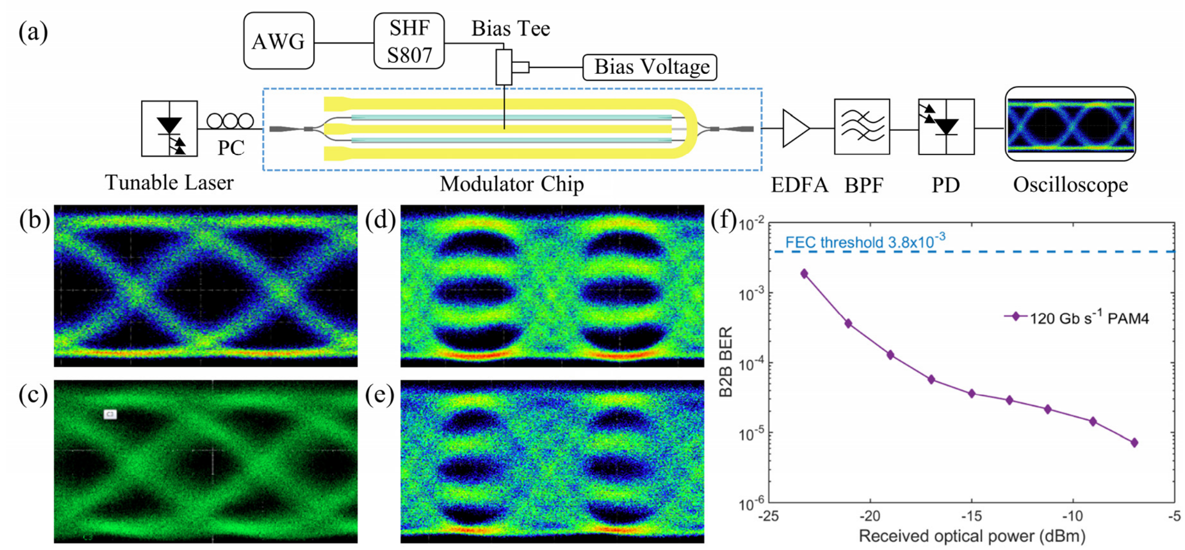

Fig. 3: (a) Schematic of the experimental setup. Signals from arbitrary waveform generator (AWG) are fed to the MZM via microwave probes after amplified by an RF amplifier (SHG S807). The modulated light is amplified by an erbium-doped fiber amplifier (EDFA), filtered using a bandpass filter (BPF), and detected by a high-speed PD connected with a real-time oscilloscope for recording diagrams. (b) (c) Optical eye diagrams for OOK signal at date rate of 80 Gb s^{-1} and 100 Gb s^{-1}. The dynamic extinction ratios are 9.5 dB and 6.0 dB. (d) (e) Measured PAM-4 modulation optical eye diagrams at 40 Gbaud (80 Gb s^{-1}) and 64 Gbaud (128 Gb s^{-1}). (f) Measured curves of BER versus the received optical power for 60 Gbaud (120 Gb s^{-1}) PAM-4 signal.

4. Conclusion

We demonstrated a hybrid silicon and LN modulator with high bandwidth of 60 GHz, low V_π of 2.25 V and low insertion loss of 2 dB. In addition, we integrated an on-chip termination resistor with the high performance modulator. The device shows a stable and satisfactory performance for all parameters. The termination resistor can provide more convenience for testing and packaging and more flexibility for designing. Based on the device, we show data operations up to 120 Gb s^{-1} for PAM-4 modulations. The results show the efficacy of hybrid Si/LN modulators in satisfying the demand of future high-speed optical transmission links.

5. References

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