Demonstration of low power penalty of silicon Mach–Zehnder modulator in long-haul transmission

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Abstract: We demonstrate error-free 80km transmission by a silicon carrier-depletion Mach-Zehnder modulator at 10Gbps and the power penalty is as low as 1.15dB. The devices were evaluated through the bit-error-rate characterizations under the system-level analysis. The silicon Mach-Zehnder modulator was also analyzed comparatively with a lithium niobate Mach-Zehnder modulator in back-to-back transmission and long-haul transmission, respectively, and verified the negative chirp parameter of the silicon modulator through the experiment. The result of low power penalty indicates a practical application for the silicon modulator in the middle- or long-distance transmission systems.

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OCIS codes: (230.4110) Modulators; (060.4510) Optical communications.

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1. Introduction

Silicon photonics has attracted significant attention in the last decade for its advantages in high bandwidth and low energy consumption, its ability in monolithically integration with microelectronic circuits on one platform, and its potential application in optical communication, interconnects and computing [1–6]. Silicon modulators as essential components of optoelectronic circuits have been extensively studied for its capability of small footprint, high speed, as well as compatible with complementary metal-oxide-semiconductor (CMOS) fabrication processes [7–10]. High-performance silicon modulators, such as resonator modulator (microring modulator) [9] and interferometer modulator (Mach-Zehnder interferometer modulator (MZM)) [10], have already been studied in interconnection [9]. Recently, long haul transmission based on silicon resonator modulators has been demonstrated [11, 12].

Comparing with the resonator modulator, MZM has a broader bandwidth, which is better for wavelength division multiplexing (WDM) systems [13]. The sensitivity of a symmetrically configured MZM to changes in temperature is theoretically very small [7]. Thus, MZM is considered a more practical device for long-haul communications. However, the study of MZM for medium- and long-haul optical communications remains largely unexplored.

In this work, to the best of our knowledge, we demonstrated, for the first time, a low power penalty, 80km error-free transmission using a Si MZM at 10Gbps and performed a system level analysis using BERs characterizations. A performance comparison between a Si MZM and a lithium niobate (LiNbO3) modulator in long haul transmission is also conducted.

2. Si MZM modulator design

Figure 1(a) and 1(b) illustrate the cross section of the phase shifter and the schematic of Si MZM. Reversed PN junction is applied in our 2mm long phase shifter in both arms of the Si MZM in order to keep the absorption balance in MZM. An offset of 100nm is used to enhance the modulation efficiency [14]. The waveguides are 220nm high and 600nm wide. The waveguide of phase shifter have a 60nm slab that is doped to form the PN diode structure for electrical contracts. An intrinsic gap of 50 nm between n-type and p-type regions is adopted to decrease the capacitance of the diode. The P and N doping concentrations are about 1 × 10^{17}/cm³. The P + + and N + + doping concentrations are about 1 × 10^{20}/cm³ to form a good ohmic contact. Both the P + + and N + + regions are 500nm away from the edge of the waveguide to minimize the optical absorption loss. The length difference is 100µm between the two arms and a Y-splitter is used to split and recombine the optical beam in the MZM. A coplanar waveguide (CPW) has been applied to drive the phase shifters with 10µm width and 6.4µm gap. We used the commercial software package to simulate the CPW impedance about 30Ω [15]. A large extinction ratio (ER) is designed in order to get good...
signal quality for intensity modulation. The spectra of the Si MZM is measured seen Fig. 1(c), where the on-off extinction ratio is about 20dB when driving voltage increases from 0v to 6v. The modulation efficiency $V_{πL}$ is about 1.52V cm, and the 3dB-bandwidth of Si MZM is 7.5GHz. The insertion loss for the Si MZM is about 20dB including 4dB per facet coupling loss, 6dB propagation loss in 4mm shifter and 3dB per Y junction; while the insertion loss ~8dB for LiNbO₃ modulator.

![Fig. 1. (a) Schematic of the cross section of the phase shifter. (b) Schematic of Si MZM. (c) Spectra of the Si MZM with different voltages.](image)

3. Experimental setup

Before long haul transmission, the performance of the Si MZM is characterized at different modulation rates. The Si MZM experiment is performed with the following setup in Fig. 2(a). A tunable laser (TLS) source generated a CW 1538nm light wave. Digital polarization controller (PC) is used to adjust the polarization of the light, and light is amplified by an erbium-doped fiber amplifier (EDFA) then coupled into waveguide through taper fiber. The light wave is modulated on chip using the MZM, which is driven by a pulse pattern generator (PPG) generating a $2^{7–1}$ pseudo-random bit sequence (PRBS). The optical signal is then coupled into fiber. A variable optical attenuator (VOA) is connected to the fiber to control the optical power. The same light was measured by a power meter (PM) as the one received by 10G photoreceiver after a 3dB splitter. The photoreceiver consists of a high-speed PIN photodiode and transimpedance amplifier (PIN-TIA) followed by a limiting amplifier (LA). Finally, the electrical signal is evaluated using a bit-error-rate tester (BERT). Both the PPG and the BERT are synchronized to the same clock.

To demonstrate the Si MZM long-haul transmission, the experimental setup is shown in Fig. 2(b). After the light wave is modulated, the optical signal passes through an EDFA with 12dB magnification and the tunable filter ($λ$) before long haul transmission. G. 652 standard single-mode optical fiber (SSMF) were set to 0-, 26-, 53-, 80-km long. The rest of the links are same as the one in Fig. 2(a).
4. Experiment and analysis for different modulation rate

The different modulation rates are measured to evaluate the performance of Si MZM. Also, a commercial LiNbO\textsubscript{3} MZM was tested as the reference, which has a 3dB-bandwidth about 10GHz. The PPG was set to generate the 4Gbps, 8Gbps, 10Gbps and 12Gbps NRZ data. Light wave is modulated by microwave and then loaded with signal on chip as in Fig. 2(a). After that the modulated optical signal is fed into a digital communication analyzer (Agilent DCA 86100A) with a 20GHz optical receiver module for eye diagram measurement, as shown in Fig. 3, under the best conditions for both Si MZM and LiNbO\textsubscript{3} MZM.

For the Si MZM, it is reversely biased at 3.3 V and the driving voltage swing is amplified to 7V. The eye diagrams for Si MZM describe more noise and more thick eyelids when modulation rates were increased. For the LiNbO\textsubscript{3} MZM, the driving voltage swing is 7.1 V with a forward bias voltage of 5 V. The eye diagrams slowly deteriorate with the increased modulation rates. This is because the limited bandwidths of modulators bring more noise for higher modulation rate and deteriorate signal. And the LiNbO\textsubscript{3} modulator’s 3dB-bandwidth (10GHz) is larger than the Si MZM’s (7.5GHz), the better eye diagram of LiNbO\textsubscript{3} is obtained as ER = 9.97dB and S/N = 11.13 compared to ER = 8.17dB and S/N = 5.95 for Si MZM at 10Gbps.
Then the performance of BER was measured using the experimental setup depicted in Fig. 2(a). Error-free operation (defined as less than $10^{-12}$ BERs) is tested, and the BER curves as the function of the receiver optical power (ROP) shown in Fig. 4(a). We further analyze the difference between Si MZM and LiNbO$_3$ MZM at the $10^{-10}$ BER and draw the curves of ROP as the function of modulation rates shown in Fig. 4(b). From the curves, it is obtained that the larger ROP were required with the higher modulation rate, because the optical receiver needs to collect enough number of photons to judge out “1”. At the same modulation rate, the ROP of Si MZM is a little higher than the one of LiNbO$_3$ MZM. It is suggested that there are three reasons. One is that absence of high-density low-loss microwave package introduces additional microwave loss. Secondly, traveling wave electrode impedance ($30\Omega$) does not match the load ($50\Omega$), increasing the microwave reflection and reducing the quality of modulation. Finally, the experimental setup are same for Si MZM and the LiNbO$_3$ MZM except that the pre-EDFA is not used for LiNbO$_3$ to insure the same output optical power (~$-5.5$dBm) after modulation. Although the pre-EDFA could introduce the amplified spontaneous emission (ASE) noise, the presence of pre-EDFA in setup could not affect the signal to noise (S/N) degradation because it was placed before Si MZM as power amplifier. The higher modulation rate, the larger ROP difference between Si MZM and LiNbO$_3$ MZM, because the bandwidth of Si MZM is lower than the one of LiNbO$_3$ MZM. These can be improved by optimizing the CPW, integrating appropriate on-chip termination resistors and reducing the insert loss.

5. Experiment and analysis for different transmission distances

Under the experimental setup shown in Fig. 2(b), the MZMs are driven at the same condition in Fig. 3. The 10Gbps modulated optical signal is imported into SSMF lengths of 0-, 26-, 53-, 80-km with the same output optical power (~$-5.5$dBm) after passing through EDFA and filter ($\lambda$). The eye diagrams are shown in Fig. 5. As we can see, as distance increasing, both eye diagrams for Si MZM and LiNbO$_3$ MZM turn worse and the intersection of the signal “1” and “0” go down gradually, which is caused by the chromatic dispersion effects. Note that the eye diagram of LiNbO$_3$ MZM is better than that of Si MZM in the case of 0km transmission, but it turn to worse in the case of 80km transmission. This interesting change of signal quality can also be observed by comparing the S/N parameters in results shown in Fig. 5.
Fig. 5. Eye diagrams in long-haul transmission for different distances, Si MZM (A) 0km, (B) 26km, (C) 53km, (D) 80km; LiNbO3 (E) 0km, (F) 26km, (G) 53km, (H) 80km.

We further carry on BER measurements with the experimental setup depicted in Fig. 2(b) to specifically describe the performance in long-haul transmission for our Si MZM at 10Gbps. The data was drawn in Fig. 6(a) and the curves of ROP as the function of distance is described in Fig. 6(b). The power penalties are $-0.55$, $-0.4$, and $1.15\text{dB}$ for 26km, 53km and 80km at the BER of $10^{-10}$. It is smaller than the one of LiNbO3 MZM, which is $1.1\text{dB}$, $1.6\text{dB}$ and $3.65\text{dB}$, respectively. Up to 80km transmission, the Si MZM can reach $10^{-10}$ BER with $-12.35\text{dBm}$ ROP while LiNbO3 MZM requires a higher ROP ($-11.75\text{dBm}$).

Fig. 6. Experimentally-measured system-level performance characterization of varying propagation distances compared Si MZM and LiNbO3 MZM at 10Gbps modulation rate. (a) BER curves as the function of ROP; (b) ROP vs. propagation distance under $10^{-10}$BER.

The reason for the small power penalty is the negative chirp parameter of the Si MZM in single arm modulation [16, 17], while LiNbO3 MZM with positive chirp parameter in single arm modulation [18, 19]. The chirp was generated from the electro-optical effect of material and the intensity transmission of the modulator structure. In our case, the negative chirp is coming from both the plasma dispersion effect in Si and the intensity transmission in MZM. The average chirp parameter was calculated about $-0.8$ based on the spectra shift in Fig. 1(c). The negative chirp has an effect to compress pulse, and was used to compensate the pulse broadening from the dispersion introduced through the long-haul transmission. The broadening of the pulse will initially be decreased (compressed) to minimum at proper
distance, and then increase along the longer distances [20]. As a result, the narrowing of modulated chirped pulses make the smaller ROPs at shorter distance as red curve in Fig. 6(b). After about 30km, the ROP turn to increase with the broadened pulses. On the other hand, the positive chirp intensifies pulse broadening, resulting in more serious inter-symbol interference and larger power penalty as well as dispersion effect as black curve in Fig. 6(b). Thus, a small ROP was obtained at 80km using our Si MZM. The experiments results are consistent with the theory and experimental analysis in Ref [16, 17].

6. Conclusions

We have demonstrated an error-free transmission for a distance up to 80km at 10Gbps and showed a minimum power penalty of 1.15dB. After a system level comparative study between our Si MZM and a commercial LiNbO3 MZM, the negative chirp parameter of the Si MZM is verified in the experiment, which compensated the dispersion deterioration and led to a low power penalty in long-haul transmission. Therefore, Si MZM is veritably a practical photonic device for the future middle- or long-haul WDM transmission systems.

Acknowledgments

This work is partially supported by the National High Technology Research and Development Program of China (863 Program) (Grant No. 2011AA010302), and China Postdoctoral Science Foundation Funded (Grant No. 2011M500005 and No. 2012T50022).