Characterization of Silicon Mach-Zehnder Modulator in 20-Gbps NRZ-BPSK Transmission

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SUMMARY 20-Gbps non-return-to-zero (NRZ)—binary phase shift keying (BPSK) using the silicon Mach-Zehnder modulator is demonstrated and characterized. Measurement of a constellation diagram confirms successful modulation of 20-Gbps BPSK with the silicon modulator. Transmission performance is characterized in the measurement of bit-error-rate in accumulated dispersion range from -347 ps/nm to +334 ps/nm using SMF and a dispersion compensating fiber module. Optical signal-to-noise ratio required for bit-error-rate of $10^{-3}$ is 10.1 dB at back-to-back condition. It is 1.2 dB difference from simulated value. Obtained dispersion tolerance less than 2 dB power penalty for bit-error-rate of $10^{-3}$ is -220 ps/nm to +230 ps/nm. The symmetric dispersion tolerance indicates chirp-free modulation. Frequency chirp inherent in the modulation mechanism of the silicon MZM is also discussed with the simulation. The effect caused by the frequency chirp is limited to 3% shift in the chromatic dispersion range of 2 dB power penalty for BER $10^{-3}$. The effect inherent in the silicon modulation mechanism is confirmed to be very limited and not to cause any significant degradation in the transmission performance.

key words: silicon modulator, silicon photonics, phase shift keying, optoelectronic integrated circuit

1. Introduction

Mach-Zehnder modulators (MZMs) are key devices in telecommunications. The MZMs with push-pull operation provide modulation without frequency chirp, which causes degradation of the signals due to chromatic dispersion in optical fibers [1]. The MZMs are used for not only conventional on-off-keying (OOK) formats, but also phase shift keying (PSK) formats. The PSK formats have an advantage of improved receiver sensitivity [2]. The differential PSK (DPSK) is suitable for ultra-long transmissions in such as transoceanic distance [3]. Moreover, advanced formats such as quadrature PSK (QPSK) and dual-polarization QPSK (DP-QPSK) have been received intensive attentions due to its high spectral efficiency and are being introduced in the long-haul networks. Though such PSK modulations can be realized using a single phase shifter, the chirp-free modulation using MZMs has an advantage of high tolerance to driving conditions in addition to the tolerance to the chromatic dispersion [2]. The single MZM and the nested MZM can realize high-quality modulation [4]. Such MZMs have been realized using lithium niobate (LN) with Pockels effect, and have been widely introduced to the current optical fiber networks.

Recent increasing data traffic in telecommunication networks requires more cost reduction in addition to the high-speed modulation format. However, the cost reduction of the LN modulator is limited by its large footprint and small wafer size.

Silicon MZMs are good candidates for the requirements because of their feature such as small foot print and low cost fabrication using CMOS-compatible process. A lot of high-speed modulators have been well developed and some of them have achieved high bitrate of 50 Gbps in the OOK format [5], [6]. Regarding the PSK format, a few studies are also reported [7]–[10]. The silicon MZMs can thus correspond to the PSK format including the advanced format such as QPSK. However, there is a significant difference from the LN modulators in physics for the modulation. In the silicon MZMs, phase shift in each arm is realized through plasma dispersion effect, which also induces amplitude modulation by free carrier absorption [11]. The amplitude modulation in each arm causes imbalances to the push-pull operation of MZMs and results in the frequency chirp of the signals. The frequency chirp in the silicon MZM is not obvious and needs to be characterized for commercial use.

The frequency chirp of the silicon MZM is discussed with the fabricated devices [8], [12]–[14]. We also discussed the effect to the binary PSK (BPSK) format and demonstrate the chirp-free performance in the measurement of constellation diagrams [8]. In this paper, we demonstrate the single mode fiber transmission of 20-Gbps DPSK using the silicon MZM and discuss the effect of the frequency chirp to the transmission performance.

The paper is organized as follows. In Sect. 2, we present a design and fabrication of the silicon modulator investigated. In Sect. 3, we show the experimental setup and its results. In Sect. 4, we discuss the frequency chirp inherent in the modulation mechanism of the silicon modulator using the simulation. Then, we summarize the discussions in Sect. 5.

2. Design of Silicon MZM

The silicon MZM studied here is fabricated using the CMOS-compatible process with KrF (248 nm) excimer laser

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The wafer is a 8-inch silicon-on-insulator (SOI) wafer with 2-μm buried oxide layer and 220-nm top silicon layer. The top view of the fabricated silicon MZM is shown in Fig. 1. The silicon MZM is composed of MZ interferometer with silicon rib-waveguide phase shifters of 4 mm length \( l_p \). The core of the phase shifter is fabricated in the top layer of the SOI wafer. The rib thickness \( r_t \) is 220 nm, the rib width \( r_w \) is 600 nm, and the slab thickness \( s_t \) is 95 nm. The core has lateral PN junctions and provides high-speed phase shift under reverse bias conditions. The electrode on top of the silicon rib-waveguide is coplanar traveling-wave electrode made of aluminum. The two silicon phase shifters are connected with combiner and splitter of Y-branch. The MZ interferometer is asymmetric for experimental purpose, which allows the operating point of the MZM to be controlled by adjusting the wavelength.

The fiber-to-fiber loss of the silicon MZM is lower than 10.5 dB in C- and L-bands. The phase shifter loss is less than 3.2 dB. The \( V_\pi \) of the phase shifter is about 7 V.

3. Modulation Characteristics of the Silicon MZM

In this section, we investigate characteristics of modulated signals generated by the silicon MZM.

3.1 Experimental Setup

Figure 2 illustrates the experimental setup for measurement of phase shift keying format.

As shown in Fig. 2(a), the silicon MZM was driven with RF signals of opposite polarity (Data, \( \overline{Data} \)) in each arm for push-pull operation. The RF signals were pseudo-random binary sequence (PRBS) \( 2^{31} - 1 \) generated in pulse pattern generator (PPG). They were amplified and applied to the phase shifters from one side of the traveling wave-electrode through probes. DC biases for reverse bias conditions were applied from the opposite side of the electrode through bias-tee. The driving voltage of each arms are 8Vpp and the reverse bias is \( -5 \) V.

The continuous-wave (CW) light is input through lensed PANDA fiber and modulated signals were coupled to the other lensed fiber. The wavelength of the CW light is slightly shifted from 1550 nm in the range of 3 nm for adjusting the operating point of asymmetric MZ interferometer.

As shown in Fig. 2(b), the modulated optical signals from the MZM were amplified in a erbium-doped fiber amplifier (EDFA) and passed through a band-pass filter of 1.0 nm for reduction of ASE noise. The signals were converted to the electric signals of in-phase and quadrature (IQ) components using a coherent receiver composed of 90-degree optical hybrid (OH) and balanced PD. The laser light input to the modulator is also utilized for the local oscillator (LO) under test for homodyne coherent detection. Constellation diagrams including trajectory of transition between the symbols were obtained with the real-time oscilloscope with 32 GHz electrical bandwidth.

3.2 BPSK Modulation Using the Silicon MZM

Figure 3 shows the measured constellation diagram of 22.3-
Gbps NRZ-BPSK signals. The eye-diagram of modulated signals shown in Fig. 3(b) was obtained using sampling oscilloscope. The eye-diagram has clear typical pattern for BPSK and the two symbol states indicated as the dark (blue) points are clearly divided. The clear 20-Gbps BPSK modulation are realized in the silicon MZM. The bit-error-rate (BER) is confirmed less than $10^{-6}$ and it can be said the signals successfully generated. The spectrum without carrier peak in Fig. 3(c) also indicates the successful generation of the BPSK format.

The light (green) line shown in Fig. 3(a) indicates the trajectory between two symbol states. The straight trajectory along the real axis means the signal has modulated without frequency chirp. From the results, we confirmed the silicon MZM realizes NRZ-BPSK modulation with low frequency chirp.

3.3 Transmission Characteristics

As we found the silicon modulator realized the BPSK modulation successfully, we investigate the transmission characteristics using differential PSK (DPSK) configuration.

Figure 2(c) shows the experimental setup for DPSK signal detection. The driving conditions of the signals were the same as the measurement of constellation diagrams. For DPSK detection, balanced photodetectors incorporated with 1-bit delay interferometer were utilized. For investigation of the transmission characteristics under chromatic dispersion, the single mode fiber (SMF) and a dispersion compensating fiber module (DCFPM) are used. Combining 5/10/15-km SMF and a DCFM for 20-km SMF, investigated dispersion range was $-347 \text{ ps/nm}$ to $+334 \text{ ps/nm}$ at a wavelength of 1550 nm. In the BER measurement, the noise was added by EDFA. By adjusting the input power to the EDFA with a variable optical attenuator (VOA), optical signal-to-noise ratio (OSNR) was changed. OSNR was measured at the input of the bandpass filter using optical spectrum analyzer with 0.1-nm noise bandwidth. The input power to the PD in the receiver was kept constant in the measurement. The bitrate is 22.3 Gbps.

Figure 4 shows the experimental results obtained in 22.3-Gbps DPSK transmission. Figure 4(a) shows the waveforms with both in positive and negative dispersion. Two
waveforms in the opposite dispersion have the similar shape to each other. The same effect by positive and negative dispersion means the modulated signals has chirp-free characteristics. Figure 4(b) shows the BER under each dispersion condition. At back-to-back, the OSNR required for achieving BER less than 10^{-3} (OSNR_{req} is 10.1 dB. As OSNR_{req} is 11.7 dB in case of 42.7-Gbps NRZ-DPSK by the simulation reported in [4], it is estimated 8.9 dB at 22.3 Gbps. The difference from the simulation is considered to be 1.2 dB. Dispersion tolerance is measured through path penalty shown in Fig. 4(c). The smooth line is polynomial fitting. The path penalty becomes symmetric to the zero-point. It also indicates the chirp-free characteristics of the modulated signals. The accumulated chromatic dispersion which yields a 2-dB penalty in OSNR_{req} is \( \Delta \phi = -220 \text{ps/nm} \) to \( 230 \text{ps/nm} \). From the simulation at 42.7 Gbps, the value at 22.3 Gbps is estimated to 273 ps/nm. Further improvement of the bandwidth of the modulator will reduce the difference from the simulation.

4. Frequency Chirp of the Silicon MZM

In this section, we investigate the effect to the transmission performance of the frequency chirp inherent in the modulation mechanism of the silicon modulator using the simulation.

In MZMs, the frequency chirp arises from some reasons such as imbalance of the power splitting to the arms, and applied electrical signal amplitude [16]. These are common problem between the MZMs made of various materials. On the other hand, there is the specific reason inherent in the modulation mechanism. Here we evaluate the frequency chirp inherent in the modulation mechanism of the silicon MZMs using simulations.

The refractive index of the doped silicon is affected by the free carriers through plasma dispersion effect. In the silicon phase shifter, free carrier distribution in the PN junction is changed by applying biases from the electrode. Thereby the effective refractive index of the phase shifter is controlled through plasma dispersion effect. In the modulation mechanism, there are two major differences from the conventional LN modulator. One is loss change in the phase shifter through free carrier absorption accompanied with the effective refractive index change. Another is nonlinear relation between applied bias and phase shift. In the LN modulator, the phase shift is linearly changed through Pockels effect and it does not induce any loss to the phase shifter.

The electric field of the output signal generated in the MZM is expressed in

\[
E = E_0/2 \exp(j\phi_e - \alpha_e) \cdot [\exp(j\Delta\phi(V_A) - \Delta\alpha(V_A)) + j\phi_0 + \exp(j\Delta\phi(V_B) - \Delta\alpha(V_B))], \tag{1}
\]

where \( E_0 \) is the amplitude of the electric field in the input waveguide, \( \phi_e \) and \( \alpha_e \) are the phase shift and optical loss common in both arms respectively, \( \Delta\phi \) and \( \Delta\alpha \) are the phase shift and loss change induced by the applied bias \( V_A \) and \( V_B \), \( \phi_0 \) is the constant phase difference between two arms. The difference of the silicon MZM from LN MZMs is included as the applied bias dependence of \( \Delta\phi \) and \( \Delta\alpha \). We obtained these value from the DC measurement of the silicon phase shifter. Figure 5 shows the phase shift and loss in the phase shifter under each reverse bias condition. The phase shift is extracted from the spectrum of asymmetric MZ interferometer using the expression, \( \Delta\phi = 2\pi\Delta\lambda/\text{FSR} \), where FSR (Free Spectral Range) is a wavelength difference between two peaks in the transmission spectrum of the asymmetric MZ interferometer. While, the loss is obtained through the comparison of the transmittance between the waveguides of different lengths. The smooth lines are polynomial fittings.

For evaluation of the frequency chirp, \( \alpha \)-parameter is frequently used [1]. It represents the frequency chirp of the modulated signals in various types of modulators. For MZMs, \( \alpha \)-parameter at the state with phase difference of \( \pi/2 \) between two arms, \( \alpha_0 \), is useful [16]. From the phase and loss dependence in Fig. 5, \( \alpha_0 \) in the silicon modulator is calculated to be \(-0.14 \) with push-pull operation condition for BPSK. If we consider one of the two major effects, either the loss change or the nonlinear relation between applied bias and phase shift, \( \alpha_0 \) becomes \(-0.02 \) without the nonlinearity or \(-0.12 \) without the loss change. The nonlinearity between applied bias and phase shift is thus main reason of the frequency chirp in the silicon modulator. In comparison with the common imbalance of the power splitting to the arms, \( \alpha_0 \) of \(-0.14 \) corresponds to the imbalance with extinction ratio of 23 dB, which is comparable to the specification of the commercial LN modulators.

\( \alpha_0 \) is useful for simple comparison between modulators, however, it represents only a part of modulated signal. In order to evaluate direct influence on optical transmissions, we simulated the optical transmissions using the modulator with the phase and loss dependence in Fig. 5. For comparison, an ideal MZM which does not have any imbalances was also simulated. The optical simulator OptSim by Synopsys was used. The 22.3-Gbps NRZ-DPSK transmission was simulated under the push-pull operation with \( V_z \) driving voltage on each arm. We thereby investigated the
difference inherent only in the modulation mechanism of the silicon MZM.

The simulated dispersion penalty is shown in Fig. 6. Here the OSNR_{req} is plotted. Comparing the silicon MZM to the ideal MZM, the silicon MZM has better tolerance to the positive chromatic dispersion and worse to the negative dispersion than that of the ideal MZM. It indicates that the modulated signals by silicon MZM has a slight negative frequency chirp. The accumulated dispersion ranges which requires the power penalty less than 2 dB for OSNR_{req} is from −252 ps/nm to +268 ps/nm. Though the slight shift of 8 ps/nm from the center is observed, the amount of positive and negative range of 520 ps/nm is the same as that in the ideal MZM. At the back-to-back, there is no difference in the OSNR_{req} between the two. Thus the effect to the transmission caused by the modulation mechanism difference is limited to the small (3%) shift of the dispersion tolerance, and the required OSNR and the amount of the dispersion tolerance are not affected.

As discussed in Sect. 3.3, the measurement results shows the slight shift of the range for a specific dispersion penalty towards positive dispersion direction. It is a good agreement with the simulated result. Thus, both in the experiments and the simulation, the distortion inherent in the silicon modulation mechanism is confirmed to be very limited and not to cause any significant degradation in the transmission performance.

5. Conclusion

In this paper, we fabricated the silicon MZM for 20-Gbps BPSK format and investigated its transmission performance. The observed constellation diagram indicates the chirp-free modulation by the silicon MZM and it was also confirmed by the symmetric dispersion tolerance observed in the transmission using DPSK configuration. The observed accumulated dispersion range at 2 dB power penalty in OSNR required for achieving BER 10^{-3} was from −220 ps/nm to +230 ps/nm. At the back to back, the required OSNR is 10.1 dB, which is only 1.2-dB difference from the simulated value. The slight differences in the OSNR_{req} at back-to-back and dispersion tolerance from the simulation will be reduced with further improvement of the bandwidth of the silicon modulator.

For understanding the frequency chirp inherent in the modulation mechanism of the silicon MZM, transmission characteristics are also investigated using the simulation. The simulated transmission characteristics results that the distortion of the silicon MZM is limited to the slight shift of the range of dispersion tolerance. The silicon modulation mechanism is confirmed not to cause any significant degradation in the transmission performance.

Thus, the silicon modulator has the transmission performance close to the conventional modulators in 20-Gbps BPSK format. The silicon MZM can be a good candidate of the low-cost and compact modulator for PSK formats in the telecommunications.

References


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