Compatibility of Silicon Mach-Zehnder Modulators for Advanced Modulation Formats

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***Abstract*—Silicon photonics which is compatible with mature complementary metal oxide semiconductor (CMOS) fabrication process has been extensively demonstrated for monolithic integration of photonic and electrical circuits. We show that an integrated silicon Mach-Zehnder modulator (MZM) may be used for advanced modulation formats despite the nonlinear dependence of refractive index change with applied voltage in the free-carrier depletion modulator. We experimentally demonstrated the use of a silicon MZM for direct detection optical orthogonal frequency division multiplexing (DDO-OFDM) modulation with advanced data formats of quadrature phase-shift keying (QPSK), 8 phase-shift keying (8PSK) and 16-quadrature amplitude modulation (16-QAM). The measured bit error rate performance of the back-to-back and 50 km single mode fiber transmission of each format is well below the forward error correction limit.**

***Index Terms*—Advanced modulation, orthogonal frequency division multiplexing, silicon modulator.**

I. Introduction

The continuing exponential growth in bandwidth required for data networks has made it important to make efficient use of the optical spectrum. Spectrally efficient modulation schemes [1] in coherent optical communications and the use of spatial division multiplexing are thus of growing importance for optical communications. Over the last decade, silicon photonics has advanced significantly and can now integrate photonic devices such as lasers [2]–[4], (de)multiplexers [5], switches [6], [7], receivers [8]–[11] and modulators [12]–[15]. Unlike conventional optical modulators which make use of the linear electro-optic effect to produce a change in the refractive index that is linearly proportional to the applied voltage, silicon modulators rely on the change in free carrier density in the waveguide to change the refractive index [16]. Thus silicon modulators have a nonlinear transfer function between applied voltage and refractive index change. Silicon modulators do offer potential advantages of requiring a smaller driving voltage and footprint when compared with conventional lithium niobate modulators. Silicon modulators were first demonstrated in [12] with on-off keying modulation. Advanced modulation was achieved afterwards with binary phase-shift keying (BPSK) using a single ring modulator [13] and quadrature phase-shift keying (QPSK) modulation using two ring modulators with a phase shifter to induce a $\pi/2$ phase offset [14]. However, phase modulation usually needs a larger electrical driving power than amplitude modulation and the structure becomes quite complicated for multi-level modulations. Recently, single carrier QPSK and quadrature amplitude modulation (QAM) using ring assisted Mach-Zehnder modulator (MZM) was demonstrated at symbol rates of less than 50 Msymbol/s [15].

One of the possible approaches to achieve high spectral efficiency is to use advanced modulation formats with digital signal processing. Orthogonal frequency division multiplexing (OFDM) is an example of a more spectrally efficient advanced modulation format. OFDM offers the potential advantages of robustness to chromatic dispersion (CD) and polarization mode dispersion (PMD), and has been considered for use in high speed optical transport networks (OTN). Coherent optical OFDM has been widely studied because of the higher spectrum efficiency and receiver sensitivity [17]. For some cost sensitive applications, direct detection optical OFDM (DDO-OFDM) based on amplitude modulation is more attractive because of the reduced complexity of the transceiver compared with coherent optical OFDM [18], [19].

In this paper, we investigate for the first time, the compatibility of silicon modulator for advanced modulations based on DDO-OFDM technique. We evaluate the modulation of QPSK, 8 phase-shift keying (8 PSK) and 16-QAM and measured their bit error rate (BER). The BER of both back-to-back and 50 km single mode fiber (SMF) transmission is well below the forward error correction (FEC) threshold of 3.8×10^{-3} with 7% hard decision FEC overhead.

II. Design and Fabrication

The MZM used in this application is formed by a sub-micron rib waveguide in a Mach-Zehnder configuration. One of the arms is embedded with a $\mathrm{p}^+ - \mathrm{p} - \mathrm{n} - \mathrm{n}^+$ diode and its cross section schematic diagram is shown in Fig. 1(a). The waveguide is 500 nm wide and has a height of 220 nm. The fundamental mode and the carriers are confined in an effective area of 0.17 $\mu\mathrm{m}^2$. The shallow etched (70 nm etching depth) grating coupler is used to couple the light in and out of the chip. The light is then split into two arms by a 3 dB multi-mode interferometer (MMI) coupler. The modulator is operated under reverse bias

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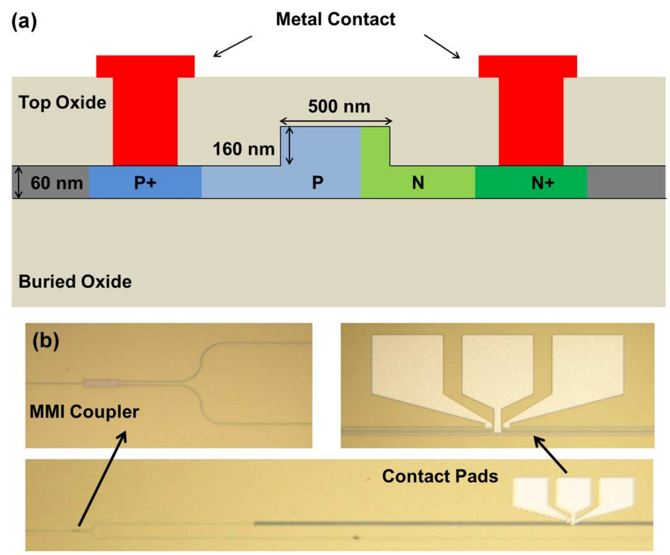

Fig. 1. (a) Schematic diagram of the active arm of the proposed silicon MZM cross section. (b) Top-view micrograph of the fabricated MZM.

for free-hole depletion due to the larger refractive index change and smaller absorption loss compared with electron. The distance from the waveguide to the heavy doped region is 600 nm: the optimum distance involves a trade off between the modulation speed and the waveguide loss. The arm which was doped as a phase shifter has an active length of 1500 μm. To enable a wavelength independent operation, the two paths of the MZM were designed to be nominally the same length. The top-view micrograph of the device is shown in Fig. 1(b).

The device was fabricated on silicon-on-insulator (SOI) substrate with 220 nm top silicon and 2 μm buried oxide. The grating coupler and the waveguide were defined by UV photolithography and followed by anisotropic dry etching. After the active area was patterned, the p-type (Boron) and n-type (Phosphorus) implantation is performed. The doping level of the $p+$, p, $n+$, n were 7×10^7, 5×10^7, 5×10^7 and 3×10^7, respectively. The implanted dopants in silicon were activated using a rapid thermal anneal at 1030°C for 5s prior to deposition of a thick SiO_2 layer. The following step was contact via opening and the electrical contact to the device was made by deposition of aluminum metal connects [20].

III. Experimental Results and Discussions

The TE polarized transmission characteristic of the MZM was measured by a narrow linewidth tunable laser with 0.01 nm resolution and 0 dBm output power, as shown in the "0 V" trace in Fig. 2(a). As the path difference of the MZM is designed to be zero, the MZM can be operated for a wide range of wavelength within the grating coupler bandwidth. The maximum coupling efficiency is found to be at a wavelength longer than 1565 nm. The fiber-to-fiber insertion loss of the device at 1560 nm is $\sim$17 dB. The coupling loss from the two grating couplers is $\sim$10 dB. The coupling loss will be significantly reduced by using apodized grating design [21]. The transmission response of the MZM is also plotted as a function of the applied voltages shown by Fig. 2(b).

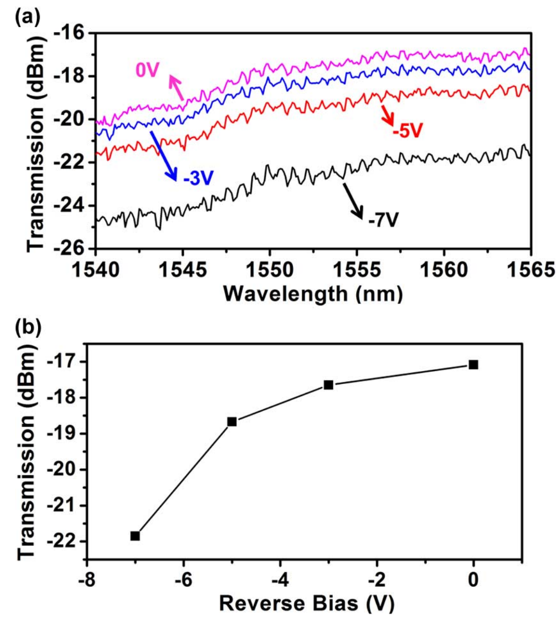

Fig. 2. (a) DC response of the silicon MZM with an input power of 0 dBm. The spectra are measured by a narrow linewidth laser with 0.01 nm resolution. (b) Measured transmission as a function of the applied voltages.

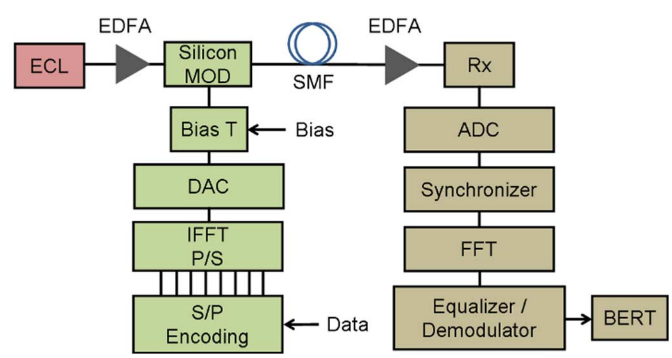

Fig. 3. Experimental setup for the OFDM transmission system.

Besides, by changing the period of the grating coupler, the maximum coupling efficiency can be optimized at 1550 nm. The transmissions of the light under different reverse biases are shown in Fig. 2. The transmission loss increases with $\sim$4.8 dB under -7 V bias compared with 0 V which indicates $\sim$4.8 dB extinction ratio. The measured 3-dB bandwidth of the silicon modulator is 9 Hz.

A DDO-OFDM signal is applied to the modulator and the experimental setup is shown in Fig. 3. The external cavity laser (ECL) output has a wavelength of 1560 nm. The optical power is boosted by an erbium doped fiber amplifier (EDFA) to 14 dBm before coupled into the silicon modulator to compensate for the grating coupler insertion loss. The baseband OFDM signal is generated by an arbitrary waveform generator (Tektronix AWG 7082C with sampling rate of 8 GS/s) with MATLAB program. The pseudo-random binary sequence (PRBS) is first converted from serial to parallel (S/P) and followed by symbol encoding with data formats of QPSK, 8 PSK, and 16-QAM. Afterwards, inverse fast Fourier transform (IFFT) with a size of 512, insertion with cyclic prefix (CP) of 1/32, and digital-to-analog conversion (DAC) were performed. The generated baseband RF

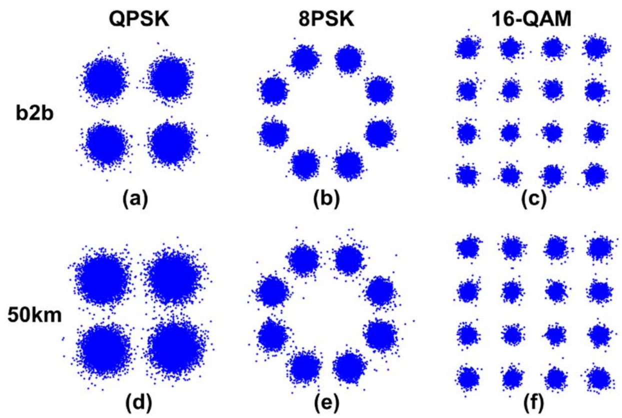

Fig. 4. Measured constellation of the received signals: (a)–(c) B2b measurements of QPSK, 8PSK, and 16-QAM signals; (d)–(f) 50 km SMF transmission of QPSK, 8PSK, and 16-QAM, respectively.

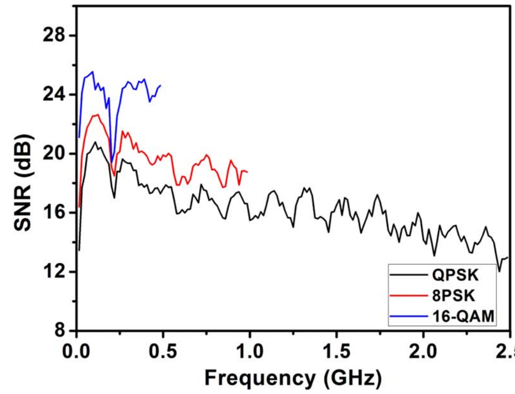

Fig. 5. Measured back-to-back SNR of each subcarrier for QPSK, 8PSK, and 16-QAM.

signal is amplified and coupled onto the silicon modulator with DC bias through a bias tee and a high speed RF probe. The subcarriers used for QPSK, 8PSK, and 16-QAM are 159, 63 and 31, respectively. The effective data rates (after subtracting the CP and the training sequence) of QPSK, 8PSK and 16-QAM are 4.38 Gb/s, 2.60 Gb/s and 1.71 Gb/s, respectively.

The modulated optical signal is transmitted through 50 km SMF. As the 50 km SMF used in this experiment consists of three reels of SMFs with different length thus it has a relatively higher loss than the theoretical value. Hence, the signal is amplified by another EDFA prior to the receiver. The received optical signal is detected by a commercial photodetector and the waveform is captured by a real time oscilloscope. The off-line signal processing program consists of analog-to-digital conversion (ADC), synchronization, fast Fourier transform (FFT), equalization, and symbol decoding.

As shown in Fig. 4, the constellation diagrams of the QPSK, 8PSK, and 16-QAM signals are measured at a receiver power of -9.5 dBm, -8.5 dBm and -8.5 dBm, respectively. The signal to noise ratio (SNR) of the b2b measurement is sufficient for all the three data formats. After 50 km SMF transmission, the SNR degradation is negligible for the 8PSK and 16-QAM signals while the QPSK signal shows a small degradation in SNR. Though QPSK has a larger phase margin, the symbol rate used for QPSK is much higher than the 8PSK and 16-QAM in this experiment, thus the QPSK signals are easier affected by dispersion. The measured b2b SNR of each subcarrier for all the three formats is shown in Fig. 5. The QPSK signals have a lowest SNR and occupy a bandwidth of $\sim$2.5 GHz. The dip at $\sim$0.24 GHz is caused by the impedance mismatch in the electrical driving circuit and further optimization of the electrode design is needed to overcome this. The signal quality can be improved by minimizing the insertion loss of the silicon MZM which will enhance the optical SNR. According to the state-of-art coupling efficiency [21], the insertion loss can be reduced to less than 10 dB which may help to improve the modulation performance.

The BER of the received signal is calculated from the measured SNR assuming the noise is Gaussian as shown in Fig. 6. For QPSK signal, forward error correction (FEC) threshold of 3.8×10^{-3} can be achieved when the receiver optical power is higher than -12 dBm. As the maximum modulation bandwidth of the AWG is 3.2 GHz and for a proof of concept demonstration, we did not push to higher speed. Though the SNR at frequencies above 2.5 GHz might be lower than 12 dB seen from Fig. 5, we would expect that the data rate can go higher while keeping the BER still below the FEC threshold, because we observe BER of 10^{-7} when the launched optical power is -8.5 dBm. The power penalty of the 50 km transmission measured at FEC threshold is $\sim$1 dB. For 8PSK and 16-QAM signals, BER is well below the FEC limit when the receiver power is higher than -13.5 dBm. There is also much potential to achieve higher data rates as the BER for both two formats were 10^{-6}. The power penalty of the 50 km transmission is negligible for both 8PSK and 16-QAM. For all the modulation formats under test, no error floor was observed when the BER goes down to 10^{-7}. We believe that they can achieve error-free operation $(\mathrm{BER} < 10^{-9})$ when the launched optical power increased.

The high peak-to-average power ratio (PAPR) of the OFDM signals usually requires the modulator and the amplifier to have linear response over a wide range to avoid distortion. Thus it may be an advantage for silicon modulator which is based on carrier density modulation rather than linear electro-optic effect. In this experiment, the modulator driving power is below 20 dBm in order to avoid a large distortion. The linearity of the silicon modulator used in this experiment is one of the key factors which limit the modulation performance. To achieve higher level modulation, the linearity needs to be further optimized. Ring(s) assisted MZM has been previously found to enhance the modulator linearity [22], [23] which may help to improve the modulation performance on OFDM signals. We may also rely on the nonlinear free carrier modulation effect in silicon diode to achieve an overall linear response of the MZM [24].

IV. Conclusion

We fabricated and evaluated the use of an integrated silicon MZM for advanced modulation formats. We experimentally show that the modulator may be used for DDO-OFDM modulation with formats of QPSK, 8PSK, and 16-QAM. The measured BER is well below the FEC threshold with b2b and 50 km transmission for all the three formats. The data rate can be further increased and higher level modulation can be

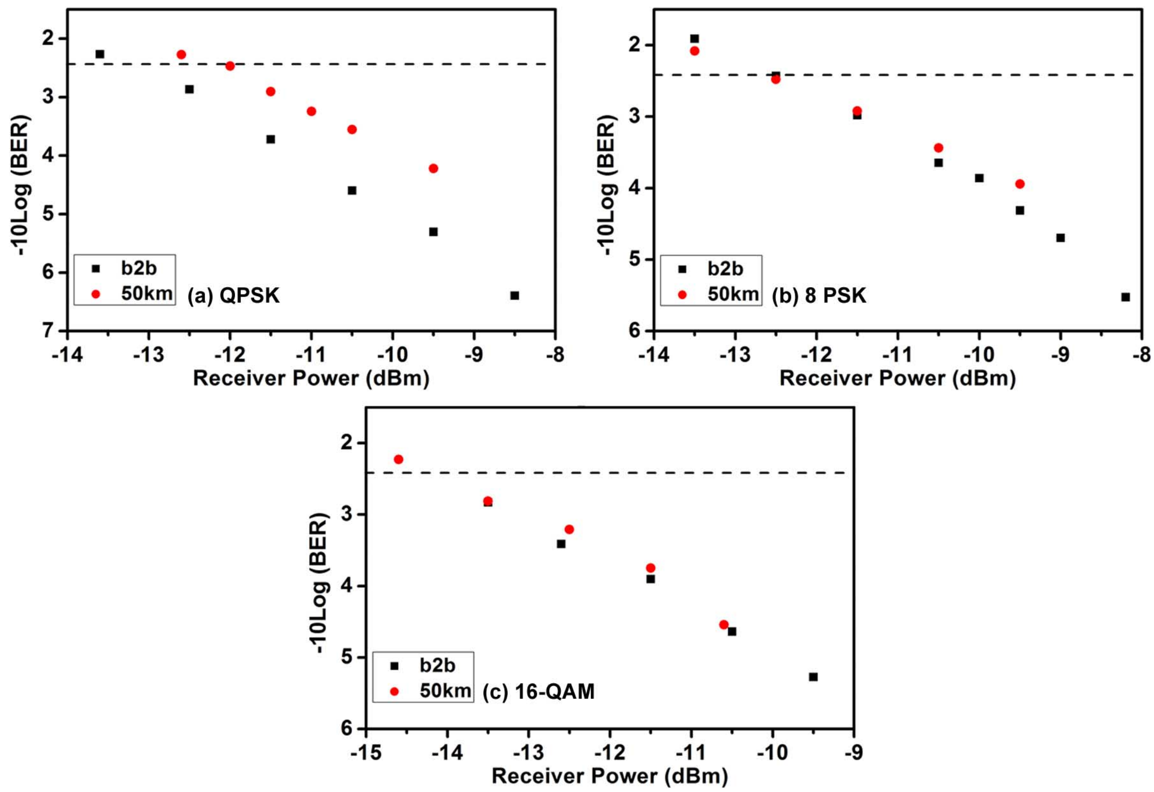

Fig. 6. Measured BER performances for b2b and 50 km transmission of OFDM signals with (a) QPSK, (b) 8PSK, and (c) 16-QAM modulation.

achieved if the modulator linearity and the frequency response are optimized.

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