# Silicon Photonic Modulators for High-Capacity Coherent Transmissions

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# Silicon Photonic Modulators for High-Capacity Coherent Transmissions

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*(Invited paper)*

**Abstract:** We discuss system-orientated design and optimization of all-silicon modulators for high-baud-rate (up to 84GBaud) coherent transmissions. We achieved single-carrier net-600Gb/s DP-32QAM and DP-16QAM over 1520km; and 800Gb/s super-channel using a silicon-modulator optical frequency comb. 

**OCIS codes:** (130.4110) Integrated Modulators; (060.1660) Coherent communications; (250.0250) Optoelectronics; (060.233) Fiber optics communications.

## 1. Introduction

Photonic integrated circuits are a key enabler of future ultra-high-capacity optical transmission systems. Using densely integrated high-bandwidth optical transceivers, the footprint and power consumption of WDM systems will be dramatically reduced compared to current solutions using bulky discrete optical components. High-baud-rate, single-carrier transmission has been extensively explored on photonic integration platforms, such as InP [1,2], thin film polymer on silicon [3] and organic hybrid [4]. Compared to other platforms, silicon photonics (SiP) leverages mature CMOS technology and offers a smaller form factor, leading to lower-cost mass production and large-scale photonic integration [5–7]. All-silicon modulators are preferred as they are readily integrated with other photonic functions, such as wavelength and polarization multiplexers, optical equalization, and Ge photodectors, on the same fabrication process. Over the last decade, we have seen significant progress in silicon modulators for pulsed amplitude modulation (PAM) links [6] and coherent transmissions [7]. Here we review our recent progress in silicon-modulator-based coherent transmitters for high-baud-rate quadrature amplitude (QAM) and on-chip optical frequency comb generation for flexible, bandwidth-efficient optical transmission systems.

## 2. Silicon IQ-modulator for QAM

Figure 1(a) shows the schematic of our silicon IQ modulator consisting of a pair of traveling-wave Mach-Zehnder modulators (MZMs) with phase shifters in lateral p-n junctions working in the depletion mode. A series push-pull driving configuration is adopted to reduce the capacitance for a higher bandwidth that is dominated by RF losses [8]. As shown in Fig. 1(b), the MZM is designed based on a 220-nm-thick silicon-on-insulator (SOI) platform with two metal and six doping layers, for which details can be found in [9].

The system-level performance of a silicon modulator in a transmission link can be characterized by the modulator power penalty (MPP) with contributions from 1) optical attenuation in doped silicon waveguides, 2) modulation loss due to a voltage swing smaller than $V_\pi$, and 3) intersymbol interference (ISI) due to limited electro-optic bandwidth. These three penalty sources are intricately intertwined. Therefore, an optimal design for a give process can only be achieved by minimizing the total penalty. We recently proposed a bandwidth-aware figure of merit (FOM) for silicon modulators in a pulse-amplitude modulation (PAM) link [10] to minimize this penalty. A numerical approach, rather than an analytic FOM, was used for modulator design optimization (minimum MPP) for coherent transmissions. In either case, we first designed a unit-length MZM for a 50-Ω RF transmission line with a microwave traveling velocity matched to the optical group velocity. Then the phase-shifter length $L$ and the bias voltage $V_b$ were optimized to minimize the MPP. Figure 1(c) shows the simulated MPP as a function of $L$ at various $V_b$. We can see that the the minimum value ($\sim 10.7$dB) is achieved at $V_b = 0.75$V near $L = 4.5$ mm that was chosen in our design.The device was fabricated through a CMC-IME MPW run. The measured frequency response of the MZM (Fig. 1(d)) shows a bandwidth of 22 GHz and 35 GHz at zero bias and $V_b = -3$V, respectively. However, the best modulation performance was achieved at $V_b = 0.75$V, as shown in Fig. 1(e), due to the optimal trade-off between modulation efficiency and bandwidth as predicted in Fig. 1(c). The back-to-back (B2B) bit error rates (BERs) for 60 GBaud 16-QAM with $2V_{pp}$ without pre-compensation are shown in Fig. 1(f). Again, $V_b = 0.75$V shows the best performance thanks to the lowest MPP.

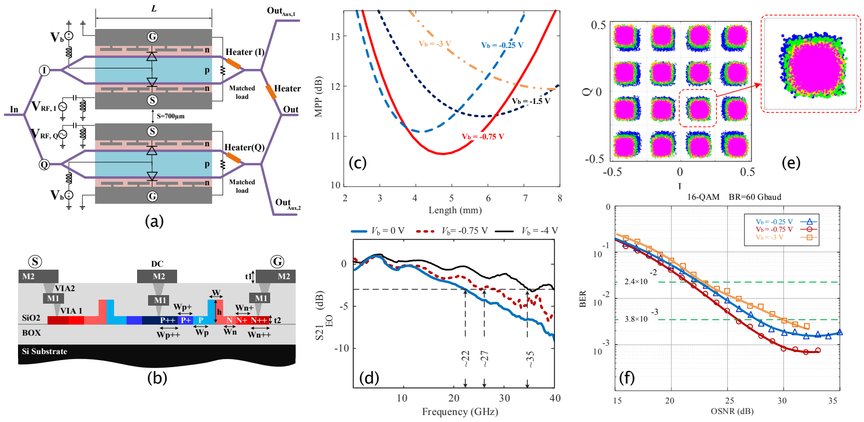


Fig. 1: (a) Schematic of the silicon IQ modulator. (b) Cross section of the silicon MZM. (c) Simulated MPP as a function of the phase-shifter length $L$ for 16-QAM at 60 Gbaud. (d) Frequency response at various bias for $L = 4.5$mm. (e) Post-emulated constellation diagrams of 30-GBaud 16-QAM at various bias. (f) BER performance at 60-Gbaud without pre-compensation.

## 3. High-baud-rate transmission

Using the silicon IQ modulator, we performed single-carrier dual-polarization QAM transmissions for up to 720 Gb/s. The experimental setup is the same as that in [9], plus a physical polarization division multiplexing emulator for dual-polarization operation. Pre-emphasis was applied to compensate the limited transmitter bandwidth due to the digital-to-analog converter ($\sim$17 GHz) and the silicon modulator ($\sim$27 GHz at $V_b = 0.75$V). The use of an optical filter can reduce the burden of the digital pre-emphasis and lower quantization noise. However, independently designed digital and optical filters cannot achieve the best trade-off of DAC quantization noise and SNR degradation across the signal frequency band. We have developed a joint optimization procedure of optical and digital pre-emphasis filters [9], illustrated in Fig. 2(a), that can effectively improve the signal quality. Figure 2(b) shows constellations of 84-Gbaud 16-QAM and 70-Gbaud 32-QAM signals. B2B BER performance vs. received optical signal-to-noise ratio (OSNR) is shown in Fig. 2(c). Performance for propagation in a standard single mode fiber is shown in Fig. 2(d). For 400 Gb/s transmission, we achieved 60-Gbaud dual-polarization (DP)-16QAM reaching a distance of 1,520 km. We meet the BER threshold for 20% forward error correction overhead, at 72 Gbaud DP-32QAM (720 Gb/s) transmitted over 160 km and 84 Gbaud DP-16QAM (672 Gb/s) transmitted over 720 km, achieving net rates of 600 Gb/s and 576 Gb/s, respectively. To the best of our knowledge, these results are the highest single-carrier bit rate and the highest spectral efficiency (up to 8.3 bits/Hz) achieved to date using a CMOS-compatible technology.

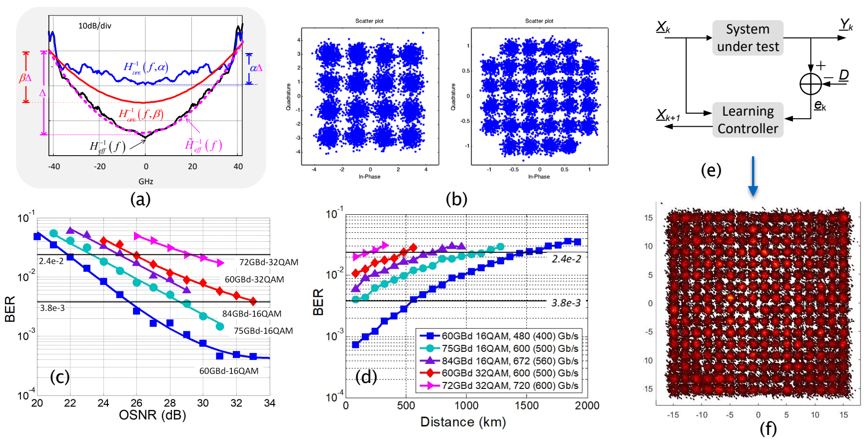


Fig. 2: (a) Pre-emphasis frequency responses of optical ($H_{OPE}^{-1}$), digital ($H_{DPE}^{-1}$), total with ($\widetilde{H}_{eff}^{-1}$) and without smoothing($H_{eff}^{-1}$); $\alpha$ and $\beta$ are the weighting factors for a maximal excursion of $\widetilde{H}_{eff}^{-1}$. (b) Constellations of 84-Gbaud 16-QAM and 70-Gbaud 32-QAM. (c) BER v.s. OSNR curves for 60/75/84 Gbaud 16QAM and 60/72 Gbaud 32QAM. (d) BER for 60/75/84 Gbaud 16QAM and 60/72 Gbaud 32QAM for swept transmission distance. (e) Block diagram of ILC method. (f) 20 Gbaud/256QAM with the ILC predistortion.

Silicon modulators also suffer from nonlinear pattern-dependent behavior that causes signal distortion in the presence of very high order modulations or large driving voltages. To address this issue, we recently demonstrated [11] a predistortion method based on the iterative learning control (ILC) technique using quasi-real-time adaptation with hardware-in-the-loop; see Fig. 2(e)). Applying this method with the silicon IQ modulator, we achieved 20-Gbaud 256-QAM (Fig. 2(f)) and 40-Gbaud 128-QAM with an power-sensitivity improvement of up to 5 dB.

## 4. Frequency comb for super-channel transmission

Modulator-based optical frequency combs provide a flexible solution for generation of optical carriers, especially for applications such as flexible-grid WDM or super-channel, where a tunable frequency spacing is preferred. Using the same fabrication process as the IQ modulator, we developed a dual-drive silicon MZM (Fig. 3(a)) for on-chip frequency comb generation [12]. As shown in Fig. 3(b), five comb lines were achieved with 20 GHz spacing. The worst case tone-to-noise ratio is greater than 40 dB after one stage of optical amplification. Using this on-chip frequency comb generator, we achieved 5 × 16-GBd DP-32QAM for a 800 Gb/s Nyquist-WDM super-channel meeting a 20% FEC overhead. We also achieved 5×20 Gbaud DP-16QAM with a BER well below the 7% FEC threshold. This super-channel without guard band gives a seamless spectrum, as shown in Fig. 3(c), indicating the good stability of the comb. It is challenging to achieve a larger number of comb lines due to the relatively high $V_\pi$ ($\sim$ 3.5 V). However, for an aggregate Tb/s data rate, a few sub-carriers should be sufficient for a super-channel using high-speed modulators.

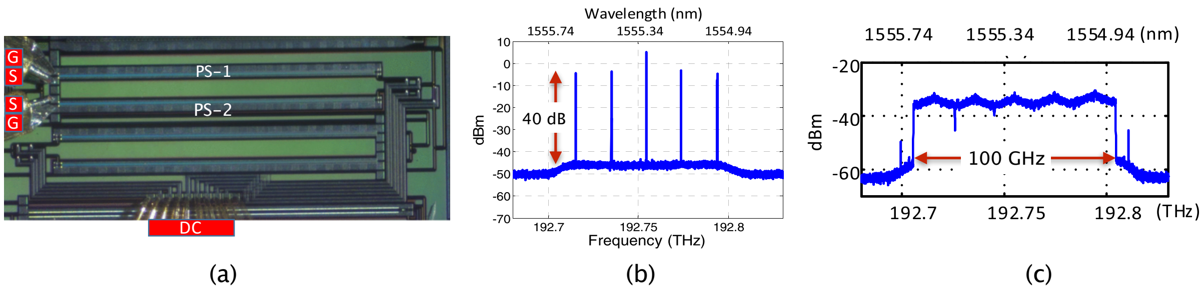


Fig. 3: (a) Micro-image of a dual-drive silicon MZM with 4.5-mm-long phase shifters. (b) Spectrum of a 20-GHz optical frequency comb after one-stage EDFA amplification (100 MHz resolution). (c) A seamless 800-Gb/s super-channel in 5 × 20 Gbaud 16-QAM Nyquist-WDM.

## 5. Conclusion

We have experimentally established the suitability of an all-silicon optical modulator to support ultra-high-capacity coherent optical transmission links beyond 400 Gb/s. Silicon modulators also provide a flexible solution for on-chip, few-carrier optical frequency comb generation. Monolithic integration of the flexible optical frequency comb and IQ modulators provides a promising solution for Tb/s super-channel transmitters.

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