Reconfigurable Silicon Photonic Transmitter for Space Based Communications Nodes

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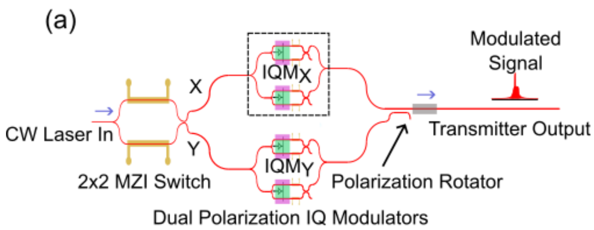
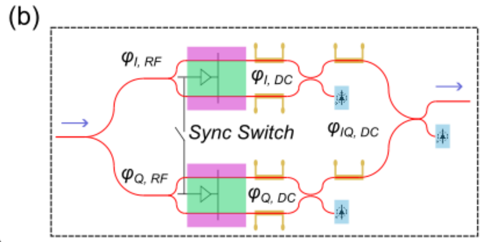
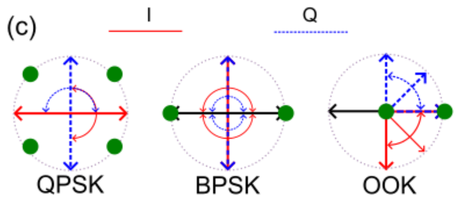
Abstract: We present the first reconfigurable silicon-photonic link capable of both coherent and intensity modulation/direct detection (IM-DD). We experimentally demonstrate error free OOK, BPSK, and QPSK modulated signals all on a single transmitter.

1. Introduction

Optical wireless communications (OWC) play a pivotal role in modern telecommunications, enabling widespread access to high-speed connectivity [1]. Recently, there has been growing interest in utilizing wavelengths in the mid-infrared range [2], driven by their compatibility with fiber-based transmission, to facilitate the seamless integration of high-capacity wired and wireless networks. The application of OWC systems is exemplified in inter-satellite and satellite-to-earth communications. In the realm of space communications, low-earth orbit (LEO) satellites are an especially appealing application of OWC technology due to their relatively low latency and path loss [3]. However, despite the proliferation of LEO constellations, the novelty of many of these systems and the advanced technology required for OWC in space have led to the emergence of numerous incompatible communication standards in the modulation rate, format and multiplexing. These standards mismatches hinder satellites from effectively communicating with one another, creating a bottleneck in achieving more ubiquitous connectivity [4]. Specifically, optical inter-satellite links (OISLs) must possess the capability to transmit and receive various protocols for both intensity and coherent modulation [5] to enable effective communication between these systems. To meet this critical demand, we introduce the first, fully reconfigurable silicon-photonic transmitter, designed to seamlessly execute both coherent and intensity modulation, thus tackling the intricate demands of space-based OWC systems.







(d)

	$\varphi_{I,RF}$	$\varphi_{Q,RF}$	$\varphi_{I,DC}$	$\varphi_{Q,DC}$	$\varphi_{IQ,DC}$
QPSK	$\pm\frac{\pi}{2}$	$\pm\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0
BPSK	$\pm\frac{\pi}{2}$ (Sync)		$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$
OOK	$\pm\frac{\pi}{4}$ (Sync)		0	0	$\frac{\pi}{2}$

Fig. 1. (a) Schematic of full transmitter link. (b) Schematic of individual reconfigurable IQ modulator with nested MZMs. (c) Phasor representation of signals for different modulation formats. (d) Table showing ideal phase swing and bias points needed for reconfigurability.

2. Operating Principle and Experimental Results

Figure 1 outlines our proposed architecture. Light from a continuous-wave (CW) laser source is coupled into our photonic integrated circuit (PIC) via a polarization maintaining fiber (PMF). Using a Mach-Zehnder interferometer (MZI) based switch, the optical signal can be split into two paths (for dual-polarization), and sent to our complex IQ modulators. The IQ modulators, seen in Figure 1b, are built using two differential-drive travelling wave Mach-Zehnder modulators (TW-MZMs). Following the I and Q MZMs, the modulated optical signal can then be delayed using additional thermo-optic (TO) phase shifters to set the correct bias points for the various modulation formats our architecture supports. Finally, after recombination via a 3 dB 2x2 coupler, the signals from the different polarization paths are recombined using a polarization rotator/splitter (PSR) before coupling back out into a single mode fiber (SMF).

To achieve a fully reconfigurable operation, our architecture leverages both the DC phase bias produced by the TO phase shifters as well as the inherent $\pi/2$ shift from the 3 dB couplers. A summary of the different formats and their corresponding ideal phase bias points is seen in Figures 1c and 1d. For both coherent modulation formats, a differential signal with phase swing of $\pm\pi/2$ is applied to both MZMs. For on-off keying (OOK), a differential swing of $\pm\pi/4$ is applied to both MZMs ($\phi_{*,RF}$). For OOK and binary phase shift keying (BPSK), these signals are sent synchronously to both the I and Q channels, and for quadrature phase shift keying (QPSK), they are sent independently. For QPSK and BPSK modulation, a $\pi/2$ phase shift is applied to both $\phi_{I,DC}$ and $\phi_{Q,DC}$ resulting in a π phase difference between the two arms of the MZMs at the default state. If no bias applied to ϕ_{IQ}, then after the Q branch is rotated by $\pi/2$ from the 3 dB coupler during the final recombination, the transmitter output will have 4 quadrature points, at 0, $\pi/2$, π, and $3\pi/2$ corresponding to QPSK modulation. For BPSK, if a $\pi/2$ phase bias is applied to ϕ_{IQ}, the outputs of both MZMs constructively interfere resulting in 2 quadrature points (0 and π). Finally, for OOK modulation, $\phi_{I,DC}$ and $\phi_{Q,DC}$ are set to zero, resulting in a $\pi/2$ phase difference for both arms at the default state. Thus, the I and Q branches produce intensity modulated signals that can constructively interfere during recombination if ϕ_{IQ} is again biased at $\pi/2$. For all cases, if the ideal small signal phase swing is not achieved, the transmitter can still produce perfect extinction ratios by tuning the bias points accordingly.

Figure 2a shows a high level schematic of the setup we use in this experiment. The transmitter photonic integrated circuit (PIC) is fabricated from the TowerJazz Photonics multi-project wafer (MPW) service. It is fully packaged onto a printed circuit board (PCB), which includes die attach, wirebonding, and fiber-attach. The TW-MZMs are built using lateral junction depletion mode PN phase shifters and Titanium Nitride TO phase shifters that are a part of the TowerJazz PH18MA process development kit (PDK). The TO phase shifters used are undercut resulting in a P_π of just 2.5 mW, suitable for low-power control mechanisms.

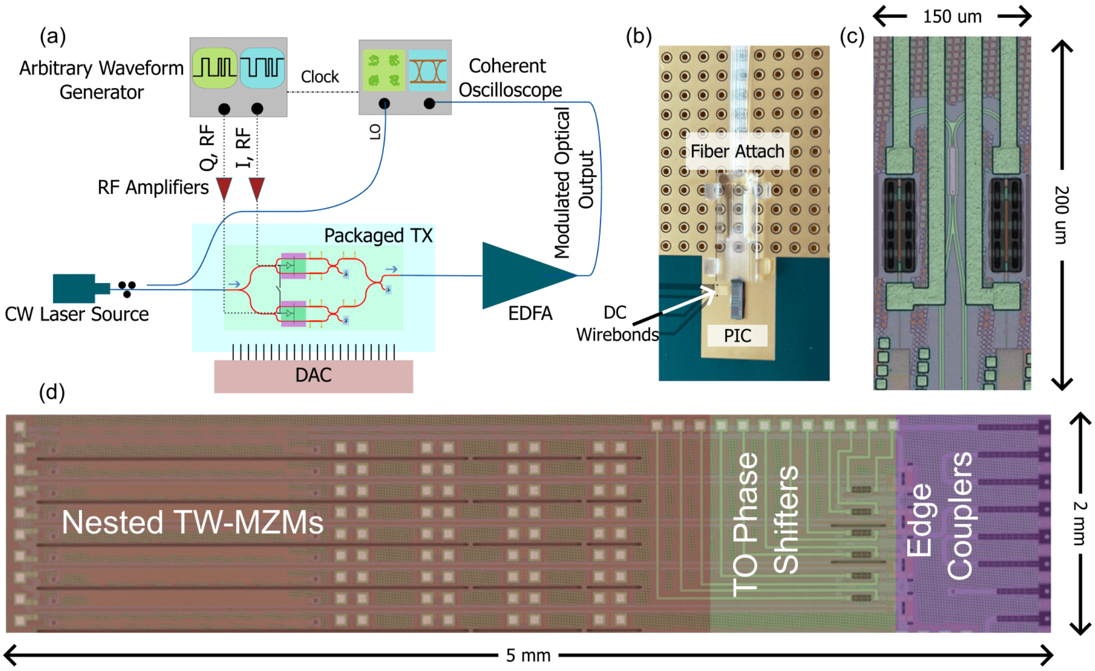


Fig. 2. (a) Full experimental setup. (b) Packaged PIC with DC wirebonds, die-attach, and fiber-attach. (c) Undercut TO phase shifters (d) Microscope image of full transmitter PIC.

The TW-MZMs are driven with high speed RF 50 Ω G-S probes that are connected to a Tektronix Arbitrary Waveform Generator (AWG). The AWG produces a high speed differential signal that is amplified and sent to the probes. The DC connections to the TO phase shifters are wirebonded onto the PCB and routed to a digital to analog converter (DAC) that controls the transmitter. The modulated optical output of the PIC is then sent to a commercial coherent receiver with a built in local oscillator to analyze the signal integrity and measure the overall spectrum. As seen in Figure 3, the transmitter successfully produces QPSK, BPSK, and OOK signals at speeds up to 5 GBaud. Our transmitter produces signals with error vector magnitudes as low as 10%, which can be even further improved by employing sophisticated digital signal processing (DSP) methods at the coherent receiver [6].

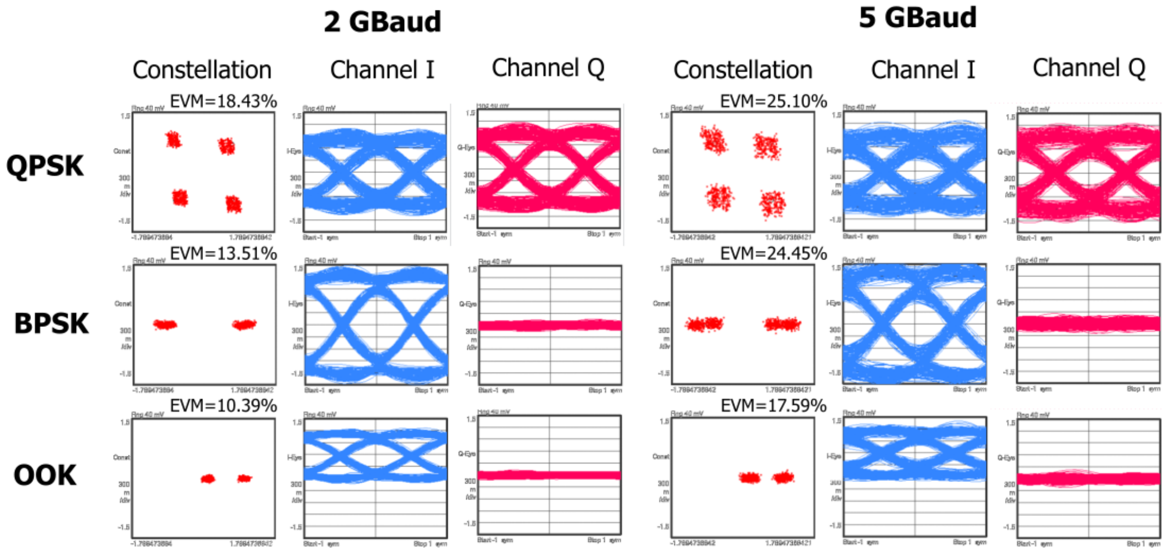


Fig. 3. Constellation and eye diagrams at PIC output for QPSK, BPSK, and OOK at 2 GBaud and 5 GBaud

3. Conclusion

To the best of our knowledge, this work is the first demonstration of a fully reconfigurable transmitter capable of both coherent and IM-DD modulation. We achieve error free modulation at 5 GBaud for QPSK, BPSK, and OOK. Importantly, it is completely foundry compatible and can be built using standard PDK components implying mass scalability and high yield. Future work will entail improving device level design to enable higher bandwidths, as well as direct integration with electronic integrated circuits, paving a way for low-latency, high throughput connectivity for inter-satellite communications.

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