

Ultra-Short Silicon-Organic Hybrid (SOH) Modulator for Bidirectional Polarization-Independent Operation

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Abstract: We propose a bidirectional, polarization-independent, recirculating IQ-modulator scheme based on the silicon-organic hybrid (SOH) platform. We demonstrate the viability of the concept by using an SOH Mach-Zehnder modulator, operated at 10 GBd BPSK and 2ASK-2PSK.

Introduction

Future converged metro-access networks demand high capacity at low cost especially for the subscriber. In such WDM systems, lasers need a tight wavelength control even at each optical network unit (ONU). It could be more cost effective, if all lasers would be concentrated at the central office. To this end, remotely seeded schemes are proposed¹⁻³. However, at the ONU the polarization of the remotely supplied optical carrier is random, requiring polarization-insensitive device concepts. This renders the use of silicon photonic devices challenging, even though the technology would be ideally suited for low-cost mass production of transceivers for optical access networks. It has been demonstrated that the intrinsic polarization dependence of silicon photonic modulators can be overcome with bidirectional modulation schemes³. However, conventional travelling-wave modulators⁴ are constructed for unidirectional operation with co-propagating (co) electrical and optical waves. For bidirectional operation, when electrical and optical waves are also counter-propagating (ctr), the bandwidth is limited to a few GHz³.

In this paper we demonstrate a polarization-independent silicon-based bidirectional modulator relying on ultra-short phase shifters for a high e/o bandwidth. The phase shifters are based on the silicon-organic hybrid (SOH) platform which combines strongly guiding slot waveguides with electro-optic organic cladding materials⁵. This allows us the fabrication of a MZM with 250 μm long phase modulator (PM) sections, and a 2ASK-2PSK (bipolar 4ASK) NRZ operation at 10 GBd. Our results demonstrate that silicon-based broadband bidirectional IQ-modulators would be feasible for use in next-generation optical access networks.

Bidirectional Modulator Design

The design of the envisioned bidirectional IQ-modulator is sketched in Fig. 1(a). A polarization-splitting grating coupler^{6,7} maps the two orthogonal linear polarization states $E_x^{(in)}$ and $E_y^{(in)}$ of the fiber to the quasi-TE modes of two independent on-chip waveguides. The light from both polarizations then co-propagates (co) or counter-propagates (ctr) through the device with respect to the electrical modulation signal, and is simultaneously modulated with the very same data. The unmodulated co-propagating field $E_{x,co}^{(in)}$ becomes a modulated fiber field $E_{y,co}^{(out)}$, and the unmodulated counter-propagating field $E_{y,ctr}^{(in)}$ becomes a modulated fiber field $E_x^{(out)}$. If the seed laser launched linearly x-polarized light, now y-polarized light would be received. In this case, the light outgoing from the modulator and the light incoming into the modulator could be separated by a simple polarization beam splitter (PBS)⁸.

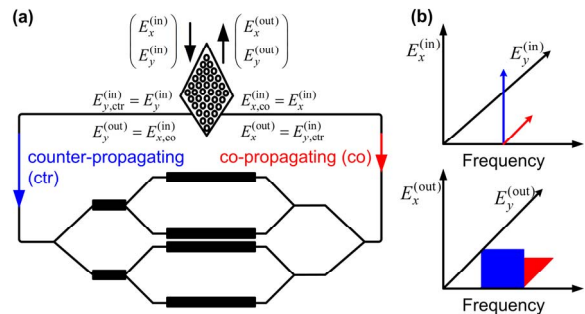


Fig. 1: (a) Envisioned bidirectional photonic integrated circuit (PIC); (b) input and output signal of the chip. The light is coupled to the chip and polarizations are separated by e.g. a 2D grating coupler⁶. The light from both polarizations then co-propagates (co) or counter-propagates (ctr) through the device with respect to the electrical modulation signal and is modulated with the very same data. The unmodulated co-propagating field $E_{x,co}^{(in)}$ becomes a modulated fiber field $E_{y,co}^{(out)}$, and the unmodulated counter-propagating field $E_{y,ctr}^{(in)}$ becomes a modulated fiber field $E_x^{(out)}$. If the seed laser launched linearly x-polarized light, now y-polarized light would be received.

The modulator requires short phase-shifters with identical modulation sensitivity for co-propagating and counter-propagating light. As mentioned before, this excludes travelling-wave modulators. For a simple separation of outgoing and incoming light with a PBS, matched optical path lengths are mandatory, which can be adjusted with proper phase align sections.

Experimental Setup

We demonstrate the feasibility of the concept by a series of experiments with devices fabricated by IMEC. In a first experiment, we measure the unidirectional performance of a 250 μm long MZM having a π -voltage of 2.5 V, and do the same for a 1.5 mm long IQ-modulator with a π -voltage 0.8 V. In a second experiment, we show bidirectional operation of the MZM.

The setup for bidirectional operation is depicted in Fig. 2. The intended PIC is schematically sketched in Fig. 1(a) and emulated by an assembly of discrete fiber-optic components and a silicon photonic chip (device under test, DUT). The aforementioned stable path length matching is not feasible with discrete components, primarily because of thermal drifts. The receiver operates differently, whether the data in both polarizations are correlated or uncorrelated. To avoid this change-over point of operation, we de-correlate the modulated signals and employ polarization demultiplexing at the receiver.

An external cavity laser (ECL) serves as optical source and local oscillator (LO) for homodyne coherent detection. To compensate the unduly high insertion loss of 25 dB of the DUT, the optical carrier was boosted to 18 dBm. An optical circulator separates the signals propagat-

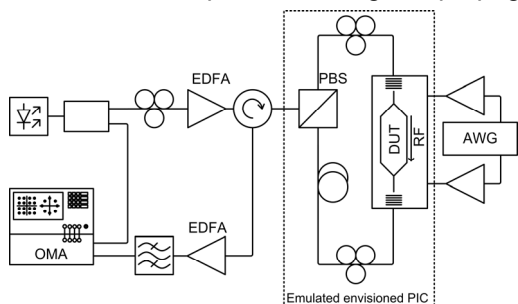


Fig. 2: Experimental setup for bidirectional measurement. The box displays the bidirectional modulator, which we envision to build on a photonic integrated circuit (PIC). Light of an external cavity laser (ECL) is boosted and passes a circulator, which separates input and output of the PIC. The output is split by a polarization beam splitter (PBS). Both outputs are aligned to the polarization of the grating coupler. The SOH modulator (device under test, DUT) modulates the signal with 10 GBd data stored in an arbitrary waveform generator (AWG). The modulated signals travel back to the circulator, are amplified, filtered by a 2 nm optical bandpass filter, and coherently received with an optical modulation analyzer (OMA). The polarization controller between ECL and circulator tests the polarization sensitivity. For unidirectional operation the respective output of the DUT is directly

connected into and out of the chip. A polarization beam splitter (PBS) separates two orthogonal polarization states, which are manually aligned to ensure efficient coupling to the quasi-TE mode of the DUT waveguides. After propagating through the DUT, the light is coupled back to the PBS, which recombines the two polarizations. The signal is amplified by an erbium doped fiber amplifier (EDFA), followed by a 2 nm bandpass filter. An optical modulation analyzer (OMA) demultiplexes the polarizations and receives the data. For unidirectional measurements, the lower part of the loop (counter-propagating incoming light) is opened and directly connected to the OMA. An arbitrary waveform generator (AWG) followed by electrical amplifiers drives the DUT. Its peak-to-peak voltage is 1.8 V_{pp} for the MZM and 0.8 V_{pp} for the IQ-modulator. Due to memory restrictions of the AWG, we use a PRBS of length $2^{15}-1$.

Experimental Results

We measure the electric-optic-electric (EOE) frequency response of the DUT using a vector network analyzer. The curves for co-propagating and counter-propagating light are nearly identical up to the 6 dB bandwidth of 11 GHz, see Fig. 3(a), indicating that NRZ symbol rates up to 17 GBd would be possible.

A. Unidirectional Operation

For unidirectional operation, we measure the performance for co-propagating and counter-propagating light separately, see Fig. 3(b). We use a Mach-Zehnder modulator (MZM) to generate BPSK and 2ASK-2PSK signals with a symbol rate of 10 GBd. The left column of Fig. 3(b) is for co-propagating light, the right column for counter-propagating light. The error vector magnitude (EVM) is 6.9% (co) and 7.6% (ctr) for BPSK, and to 10.8% (co) and 13.2% (ctr) for 2ASK-2PSK. During the measuring time of 5 min, BPSK signals did not produce errors, indicating a BER of $< 10^{-13}$.

Using an SOH IQ modulator at a symbol rate of 5 GBd, Figure 3(c) shows the QPSK constellation diagrams for co-propagating and counter-propagating light. The EVM was 16% (co) and 20.3% (ctr). Again, the BER was smaller than 10^{-13} . The non-circular shape of the constellation points reflects a superposition of rhombus-shaped constellations, which stem from the drifting quadrature phase that is set by the optical wavelength.

B. Bidirectional Operation

For bidirectional operation, we vary the polarization state before the PBS to prove polarization-independent operation. At the receiver, we

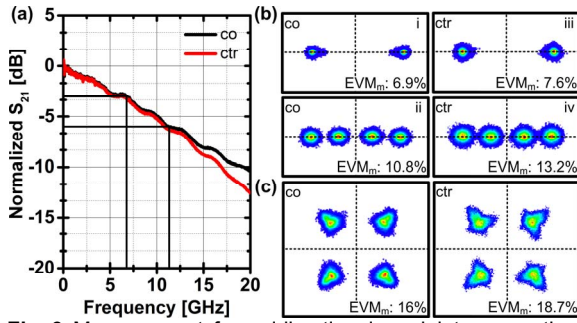


Fig. 3 Measurement for unidirectional modulator operation. (a) Electro-optic-electric small signal response of a 1 mm long silicon-organic hybrid Mach-Zehnder modulator (MZM) for co-propagating (black) and counter-propagating light (red). The small-signal responses are identical up to the 6dB bandwidth of 11 GHz. (b) Constellation diagrams for a 250 μm long MZM modulated with 10 GBd BPSK and 2ASK-2PSK with co-propagating (co, i & ii) and counter-propagating light (ctr, iii & iv), respectively. (c) Constellation diagrams for a 1.5 mm long IQ-modulator modulated with 5 GBd QPSK for co-propagating (co) and counter-propagating light (ctr). The strange shapes reflect a superposition of rhombus-shaped constellations, which stem from the drifting quadrature phase that is set by the optical wavelength.

perform digital polarization demultiplexing with the OMA and plot the EVM of the better polarization state, Fig. 4. The EVM ranges between 17% and 20% for BPSK, except for one single point. For 2ASK-2PSK we found an EVM between 16% and 20%. For the OMA dual-polarization demultiplexing algorithm the constellation must not be confined to a line or a point^{9,10}. This explains the noticeable decrease in performance compared to the two unidirectional cases where a single-polarization algorithm without this constraint is used.

For a single, arbitrary input polarization state for the modulator (#6 (i) for BPSK and #3 (ii) for 2ASK-2PSK) we perform digital polarization demultiplexing, compensate the delay between the polarization states and combine them. The resulting constellation diagrams Fig. 4 represent the outcome as would be expected from an integrated bidirectional modulator as in Fig. 1(a).

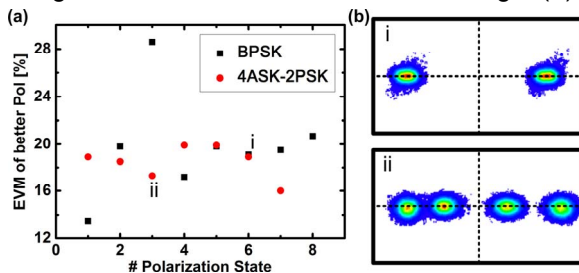


Fig. 4 Measurement for bidirectionally operated Mach-Zehnder modulator. (a) EVM of the best performing polarization for 8 arbitrarily chosen input states of polarization into the polarization beam splitter, see Fig. 2. Despite certain difficulties in polarization demultiplexing, we found for BPSK typical EVM values below 20%. (b) Two constellation diagrams, (i) for BPSK, and (ii) for 2ASK-2PSK are reconstructed by a digital compensation of the de-correlation delay in Fig. 2. The polarization states (i) and (ii) are marked in Subfigure (a).

This concept of a bidirectional modulator is transferable to IQ-modulators. However, the insertion loss of the PIC must be low enough so that unavoidable reflections at the fiber-chip coupling interfaces do not dominate. Unfortunately, with our present IQ-modulators, this requirement was not fulfilled. In the next-generation of the PIC, the PBS will be on-chip with matched lengths in the two arms, and even better results than those presented in Fig. 4 can be expected.

Conclusion

For laserless remotely seeded subscriber units, we propose a bidirectional, polarization-independent IQ-modulator scheme for future optical access networks. As a first step, we demonstrated QPSK modulation with a 1.5 mm long IQ-modulator at 5 GB in a counter-propagating configuration. We then performed polarization-independent bidirectional modulation with a 250 μm long SOH modulator using 10 GBd BPSK and 2ASK-2PSK signals.

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