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# Advanced modulation format using silicon modulators in the O-band

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## ABSTRACT

This paper review our recent work on silicon modulators based on free carrier concentration, working in the O-band of optical communications (1260 nm - 1360 nm) for short distance applications. 25 Gbit/s OOK modulation is obtained using a driving voltage of  $3.3 V_{pp}$ , and QPSK dual-drive Mach-Zehnder modulator (DDMZM) operating in the O-band is demonstrated for the first time.

**Keywords:** silicon modulator, advanced modulation format, QPSK, Mach Zehnder

## 1. INTRODUCTION

Significant research effort has been dedicated over the past years to the development of silicon-based photonic technologies [1-2]. Developing high performance silicon modulators based on the free-carrier plasma dispersion (FCPD) effect has been an important milestone. These modulators are commonly based on carrier depletion in PN junctions and outstanding performances have already been demonstrated [3-4]. However, in order to keep up with the growing bandwidth demand in datacom applications, it is necessary to move from binary on-off keying (OOK) modulation format to more advanced formats such as 4-level pulse amplitude modulation (PAM-4) or quadrature phase-shift keying (QPSK). Advanced modulation formats using silicon modulators have already been demonstrated [5-8]. However, most of these demonstrations have been carried out in the C-band of optical communication systems (1530 nm - 1570 nm) where the FCPD is stronger. Nevertheless, it is believed that silicon photonics is the best suited for next generation of short range optical fiber communications, where current standards favor the use of the O-band (1260 nm - 1360 nm) in order to exploit the zero-dispersion region of standard single-mode fibers. In this work we present results on high performance silicon modulators operating in the O-band, including efficient OOK modulation and the first demonstration of a QPSK silicon-based dual-drive Mach-Zehnder modulator (DD-MZM) operating in the O-band.

## 2. SILICON MODULATOR DESIGN

The active region of the Mach Zehnder modulator is illustrated in Fig 1. (a). It is based on a PN diode embedded in a silicon-on-insulator (SOI) waveguide. The waveguide width and height are 400 nm and 300 nm, respectively, while its slab height is 50 nm. The PN diode is obtained by boron and phosphorus implantation of the waveguide. Targeted doping concentrations are  $P = 5 \times 10^{17} \text{ cm}^{-3}$  and  $N = 1.4 \times 10^{18} \text{ cm}^{-3}$ . The junction interface is 25 nm shifted from the center of the waveguide to benefit from larger effective index variation. Highly doped  $P^{++}$  and  $N^{++}$  regions are used away from the optical mode to reduce access resistance without increasing optical losses. The modulators were fabricated using the 300 mm DAPHNE technological platform from STMicroelectronics [9].

The phase shifter efficiency was estimated by measuring the transmission of ring resonators embedding the phase shifter inside the ring, as a function of the applied voltage. The results was a  $V_{\pi} L_{\pi}$  product between 0.95 V-cm and 1.15 V-cm for a reverse applied voltage range from 1 V to 4 V [10]. These values are the highest reported modulation efficiencies of

carrier depletion based modulators in the O-Band.

Mach-Zehnder modulators are using a dual drive configuration, as schematically illustrated in Fig 1. (b). Phase shifter lengths of 1 mm or 2 mm have been used in both arms of symmetric Mach-Zehnder structures. Multi-mode interference (MMI) couplers are used as input/output splitter and combiner. Metallic heaters form low speed/high efficiency static phase shifters, in order to tune the direct current (DC) phase shift  $\Phi$  between both arms. The radio frequency (RF) signals are applied on each PN phase shifter independently, using GSGSG coplanar waveguides, while DC tips are used to apply the static phase shift (Fig 1. (c)).

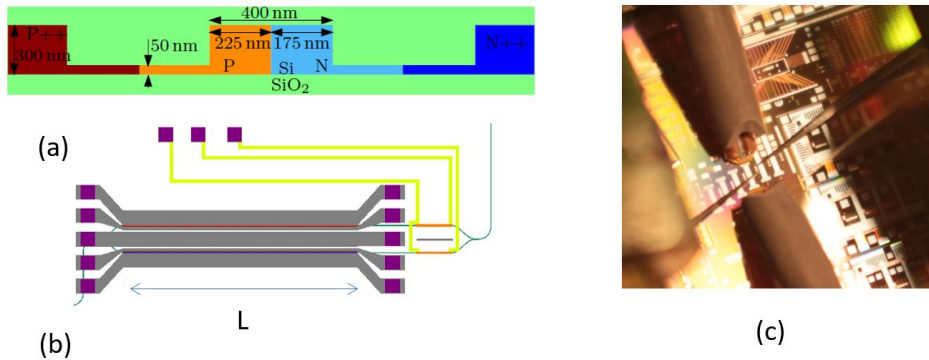


Figure 1. (a) Phase shifter design: a PN diode is located in the SOI rib waveguide; (b) layout of the dual-drive Mach Zehnder modulator; (c) picture of the device under test.

### 3. OOK MODULATION

The set-up used for OOK modulation characterization is schematically reported in Fig 2. Both arms of the 1 mm long DD-MZM were driven in push-pull configuration, i.e. one arm is driven with the PRBS data signal and the other with its complementary. The heaters were used to set the interferometer to the quadrature point. Thanks to the push-pull configuration and the high efficiency of the active region, it has been possible to reduce the voltage swing down to  $3.3 V_{pp}$ , with a DC bias of 1.7 V. The corresponding eye diagram at 25 Gbps is reported in Fig. 3. An extinction ratio (ER) of 5 dB was obtained, while the total on-chip losses were 3.6 dB at this operating point.

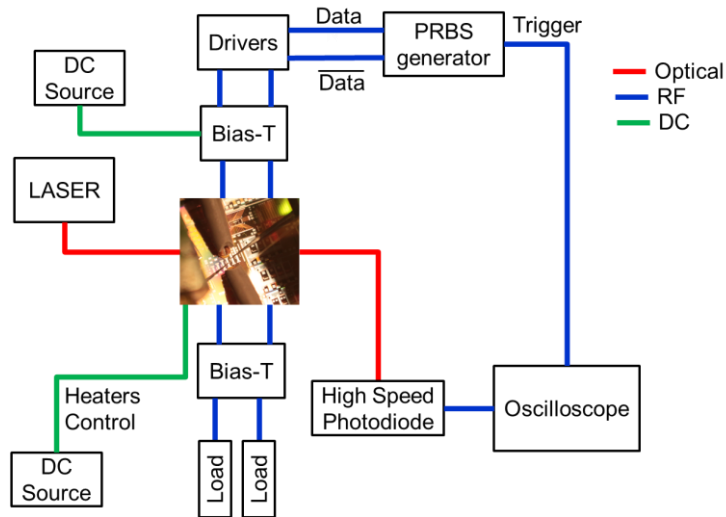


Figure 2. Schematic representation of the set-up used for OOK-modulation characterization.

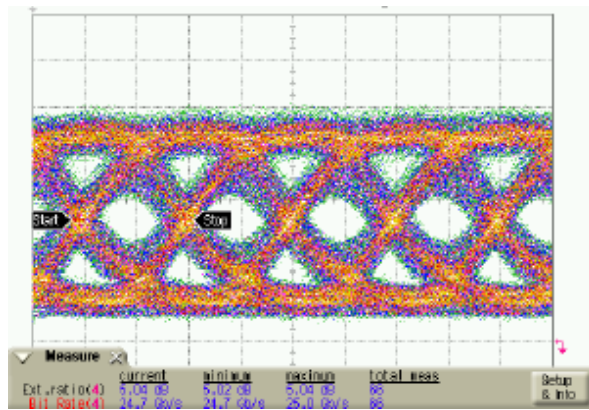


Figure 3. Measured eye diagram at 25 Gbps of the 1 mm long DD-MZM with an applied voltage swing of 3.3 Vpp and 1.7 V DC bias.

#### 4. QPSK MODULATION

DD-MZMs can also be used to generate QPSK signals with a simpler structure than standard IQ modulators based on nested MZMs [11-12]. Furthermore, this scheme allows a reduction of the driving voltage applied to the transceiver and thus to the power consumption to generate the QPSK constellation, offering a better power efficiency and scalability that

are key advantages for short distance intra data center communications. The set-up used for QPSK modulation characterization at 20 Gbps (10 Gbaud) is reported in Fig 4.

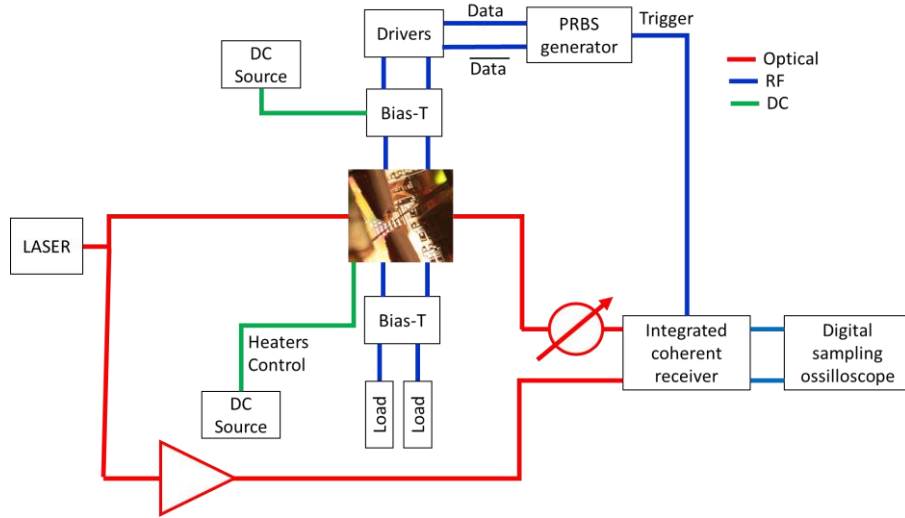


Figure 2. Schematic representation of the set-up used for QPSK-modulation characterization. Two  $2^{15}-1$  long de-correlated pseudo random binary sequences are applied on each of the MZ arm.

Two  $2^{15}-1$  long de-correlated pseudo random binary sequences (PRBSs) at 10 Gbps were amplified to reach a swing voltage  $V_{pp}$  of 7 V and applied to each of the phase shifters in order to achieve a peak-to-peak phase modulation of  $\pi$  in each arm, while the phase-shift introduced by the heater is adjusted to operate the DD-MZM at the quadrature point ( $\Phi=\pi/2$ ). TE-polarized light from an O-band external cavity laser followed by a fiber polarization controller was coupled to the photonic integrated circuit using a single polarization grating coupler (GC). The same laser was also used as local oscillator (LO). The modulated optical signal was then sent to the coherent receiver through a variable optical attenuator in order to adjust the received power. The I/Q signals of the receiver were fed to a 40 Gbps digital sampling oscilloscope (DOS) with 16 GHz electrical bandwidth. Blocks of  $10^5$  symbols were acquired and then processed offline. An adaptive finite impulse response (FIR) filter with decision-directed least mean square (DD-LMS) tracking was used as digital signal processing (DSP). The processed samples were used to obtain the constellation diagrams and to compute bit error rate (BER). The BER was calculated over five blocks of  $10^5$  symbols.

For QPSK modulation characterization, a 2 mm-long MZM was used, as it is necessary to achieve a  $\pi$  phase variation on each arm of the MZM. On-chip optical losses are estimated below 3.8 dB, corresponding to 2.6 dB for the 2 mm-long active region, while losses below 0.6 dB are estimated for each MMI couplers. After DSP, a classical QPSK constellation diagram was obtained, as illustrated in Fig 5. (a) for a receiver input power of -22 dBm. The measured BER performance of the Si DD-MZM is reported in Fig 5. (b), and compared with that obtained with a LiNbO<sub>3</sub> modulator in a standard IQ configuration and a LiNbO<sub>3</sub> modulator in a DD-MZM configuration. It can be seen that a penalty of 5 dB occurs between the LiNbO<sub>3</sub> IQ modulator and the LiNbO<sub>3</sub> DD-MZM for a BER of  $10^{-3}$ . This power penalty is thus inherent to this

generation scheme. Interestingly the power penalty of the silicon DD-MZM is only 1.5 dB with respect to its LiNbO<sub>3</sub> counterpart.

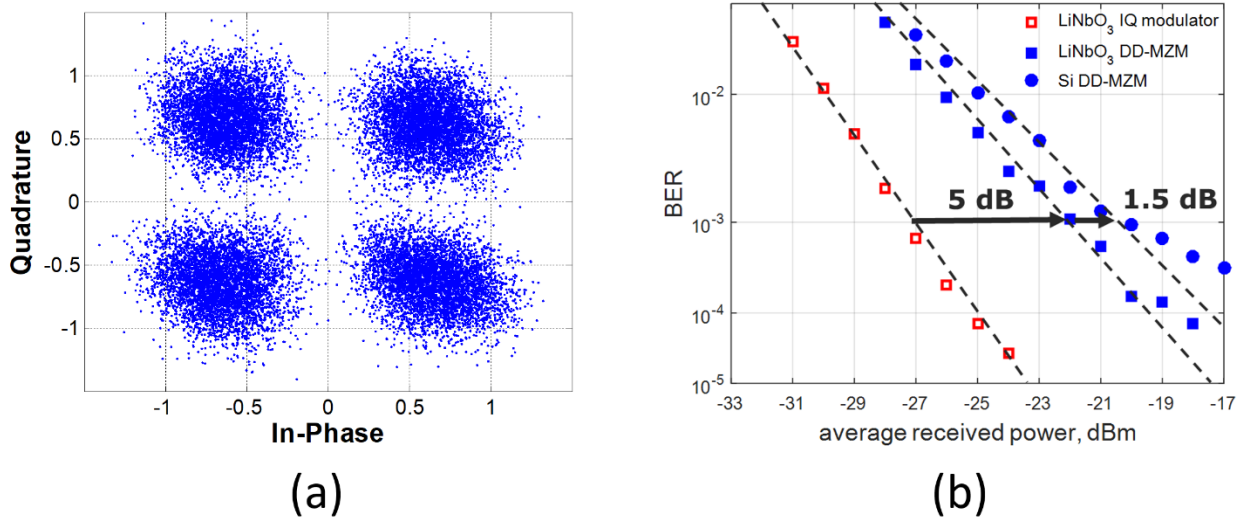


Figure 5. (a). Typical QPSK constellation diagram after DSP of the Si DD-MZM modulator at 10 Gbaud (20 Gbps), (b) Measured BER as a function of the average received power for the Si DD-MZM under investigation, and comparison with LiNbO<sub>3</sub> modulator in DD-MZM configuration and LiNbO<sub>3</sub> IQ modulator.

## 5. CONCLUSION

In this paper we reported our recent work on Si modulators working in the O-band, targeting short range communications. The design of high performance silicon modulators is challenging at this wavelength because the free carrier plasma dispersion effect is weaker than in the C-band. However 25 Gbit/s OOK operation is demonstrated using a push pull configuration, with a reduced peak-to-peak voltage of 3.3 V, and on chip optical loss of only 3.6 dB at the operating point. A DD-MZM can also be used to generate QPSK modulated signals. We thus demonstrated for the first time the use of a silicon DD-MZM to generate a QPSK signal in the O-band.

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