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Simulative Analysis of InP-based Dual Polarization IQ Mach-Zehnder Modulators

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Abstract: A realistic model of an Indium-Phosphide DP-IQ Mach-Zehnder modulator supported by experimental measurements is introduced within an accurate time-domain simulator. BER vs OSNR results show the effect of model's non-linearities increasing the modulation format complexity at different symbol rates. The intrinsic modulator SNR is estimated.

Keywords: *Mach-Zehnder modulator, photonic integrated circuits, Indium Phosphide.*

1. Introduction

The advent of photonic integrated circuits (PICs) is strongly impacting optical network market focusing on the Indium Phosphide (InP) technology for the realization of integrated electro-optical Mach-Zehnder modulators (MZM), considered a promising semiconductor for PICs evolution related to the exponential increase of photonic chip complexity [1]. Considering the need of an accurate simulation environment to emulate and control realistic physical layer effects in software-defined (SD) optical networks, the goal of this work is to introduce a novel and scalable model of an InP DP-IQ-MZM within an accurate time-domain simulator for quality of transmission (QoT) estimation, integrating measurements performed on a real modulator sample to faithfully reproduce the component non-linear effects. The intrinsic signal-to-noise ratio (SNR) introduced by the modulator is estimated to evaluate the MZM impact on transmission performance.

2. Physical Model & Simulation Results

The InP MZM model which has been considered in the simulation framework presents a voltage-dependent transfer function $T(V)$ and a non-linear phase response $\phi(V)$ which introduce two novel parameters with respect to the legacy modulators, a transmission absorption parameter c and a phase non-linearity parameter b [2], expressed as:

$$T(V) = \left(1 + exp\left[\frac{V-c}{0.8}\right]\right)^{-1.25} \quad (1) \qquad \phi(V) = \left(\frac{2b \cdot V_{CM} \cdot V_{\pi} - \pi}{V_{\pi}}\right) \cdot V - b \cdot V^2 \quad (2)$$

where V is the input bias voltage applied to the electrode, c is the transmission absorption parameter, V_{CM} is the common mode DC bias voltage present on each MZM electrode, V_{π} is the voltage required for inducing a phase variation of π and b is the phase non-linearity parameter The InP MZM model has been developed to realistically reproduce the component behaviour via simulation. In addition, the custom low pass filter of an InP modulator sample provided by Lumentum Company has been characterized in laboratory, measuring the response of drivers' electrodes, and integrated in the model. This module takes into account the component non-linearities in terms of bandwidth limitation. The simulation framework in use for a single polarization IQ-MZM is represented in Fig. 1: the two red building blocks represent the novel SD InP MZM module, while the blue ones are part of a time-domain simulator used as a QoT estimator [3] for a back-to-back (B2B) simulation of the modulator model.

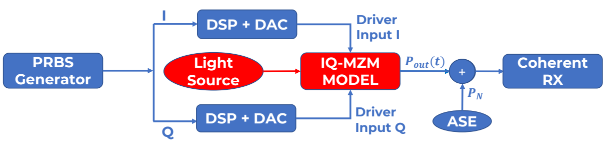

Fig. 1: Block scheme of the simulation framework.

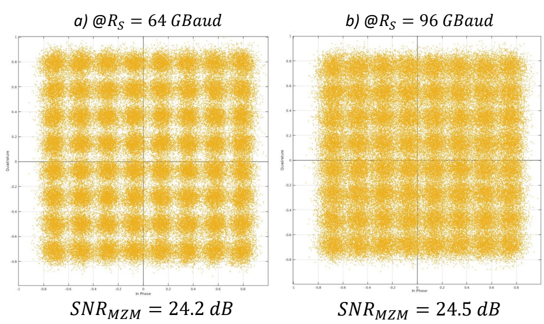

Fig.2: DP-64-QAM constellations after CPE (receiver side): a) 64 GBaud, b) 96 GBaud.

Simulations have been performed for a dual polarization (DP) InP IQ-MZM considering a pseudo-random binary sequence (PRBS) generation (PRBS17, with $2^{17} - 1$ bits) and setting the digital signal processing (DSP) and digital-to-analog converter (DAC) elements with realistic parameters in order to perform a correct pulse shaping to produce a Nyquist shaped spectrum. The custom low pass filter has been modeled thanks to the electrodes' characterization of the modulator sample for the generation of the electric fields sent to the in-phase

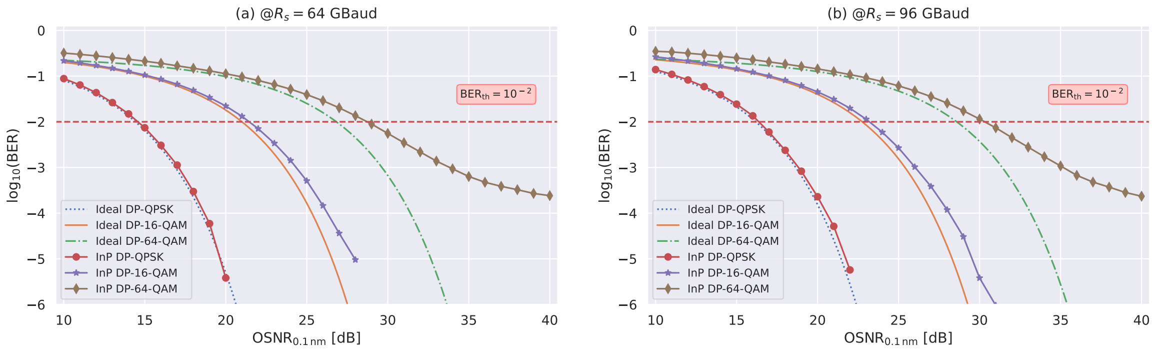

Fig. 3: Comparison of BER vs OSNR ideal curves with respect to the SSFM simulated InP MZM Model curves for different modulation formats at a) 64 GBaud and b) 96 GBaud.

and quadrature sections of the modulator. In the novel modulator model, a realistic laser light source has been centered at 193.414 THz, with 3 dBm power and a phase noise of 1 MHz. InP MZM parameters has been set considering a slightly non-linear behavior ($b = 0.01$) and an affordable absorption effect ($c = 12.0$). To introduce further realistic effects of the model, also a light unbalance of 5 dB has been introduced on the extinction ratio of the two I and Q arms of the modulator. In order to draw bit-error-rate (BER) versus optical signal-to-noise ratio (OSNR) curves, the DSP of the coherent receiver of the time-domain simulator has been configured to introduce an amplified spontaneous emission (ASE) noise loading at the modulator output. The B2B simulation of the modulator has been performed considering three different modulation formats (DP-QPSK, DP-16-QAM and DP-64-QAM) and two different symbol rates (64 and 96 GBaud), R_S, to cover different transceiver standards, starting from 200 G and going towards 1000 G and beyond. For the ASE loading at the optical output of the modulator, an increasing OSNR (0.1 nm noise bandwidth) from 10 to 40 dB is considered. A constant-phase-estimator (CPE) aided DSP processed result has been exploited for the error counting. As a term of comparison for the realistic InP modulator model, theoretical ideal modulator models have been considered [4]. Simulation results are shown in Fig. 3, where the pre-FEC BER vs OSNR curves of the different configurations of the InP MZM are depicted with respect to the ideal relationships. Increasing the cardinality of the modulation format, the behavior of the curves differs more evidently from the ideal ones. Considering DP-64-QAM modulation for both symbol rates under test shown in Fig. 2, it can be observed that pre-FEC BER floors around 10^{-4}, due to the non-linearity introduced in the InP MZM model and the electric noise inserted by the band-cut of the drivers on I and Q arms. Taking into account the electric noise introduced by the modulator and considering it in an additive white Gaussian noise (AWGN) channel, it can be considered as an intrinsic, additive SNR_{MZM} of the modulator with respect to the overall GSNR of the AWGN channel [5]. This intrinsic SNR_{MZM} has been evaluated for both the symbol-rates under test, obtaining two values around 24 dB for both the configurations (Fig. 2). In fact, observing Fig. 3, InP MZM behavior starts to divert with respect to the ideal one for OSNR values larger than SNR_{MZM} . Considering the obtained results, the introduction of this novel DP-IQ-MZM InP model within a validated simulative environment can be a powerful approach to analyse and predict non-linear effects introduced by this kind of components, also in the perspective of considering a full SD network scenario.

3. Conclusion

The aim of the presented work is to introduce a novel InP DP-IQ-MZM model, supported by a real device characterization, within a time-domain simulator for B2B simulations. Considering the measured band-cut given by the electrodes of the modulator and the non-linearity introduced by the integrated InP MZM model for a more accurate emulation of the component behaviour, BER vs OSNR results show a clear modification of the device performance increasing the complexity of the modulation format. Isolating the MZM impact from the other effects in transmission thanks to AWGN channel properties, also the intrinsic SNR_{MZM} of the modulator has been evaluated, obtaining an almost constant value around 24 dB for all the configurations under test. This simulation instrument presents its potentialities in both accuracy and scalability of the framework, enabling further investigations on different and isolated effects of other components inserted in the PIC, as the impact of semiconductor optical amplifiers (SOA), or the propagated effects of the device on a SD network through SSFM simulations.

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