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Modeling of MZM-Based Photonic Link Power Budget

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Abstract: An accurate methodology for analyzing the Mach-Zehnder modulator (MZM) based optical link power budget is presented. It optimizes the transceiver's system-level performance to meet the specifications of the optical links with N-level (N=2,4,8) pulse amplitude modulation format for high-speed signaling.

1. Introduction

Silicon-based photonic integration has emerged as a promising solution to meet the ever increasing transfer bandwidth requirement in the computing industry. Escalating the modulation format from PAM-2 to PAM-4, even to PAM-8 requires an analytic model to analyze the trade-off among the electrical-to-optical (EO) channel loss over the sacrificed signal-to-noise ratio, the circuits design complexity, the chip area and the power consumption [1].

MZM is by far the most reliable indirect optical modulator in silicon photonic platform, though its footprint is large and thus requires relatively more power from the drivers [2]. The extinction ratio (ER) of MZM at the transmitter (TX) side is determined by optical modulation amplitude (OMA), MZM's average output power (P_{ave}), the MZM device characteristic and the modulation scheme. An optimized optical link requires a suitable ER at the TX side to achieve a target receiver bit error rate (BER) performance with the least optical laser/electrical driver power consumption. Fig. 1 describes the proposed MZM-based photonic link power budget model. The key parameters of photonic devices, optical channel, and the specifications of the electrical driver and receiver circuitry are tabulated. By satisfying the boundary condition shown in Fig. 1, the model derives the power-optimized photonic parameters (e.g. laser power and MZM specs) according to the specified receiver specifications. This model is applicable to multiple-level pulse-amplitude modulation schemes.

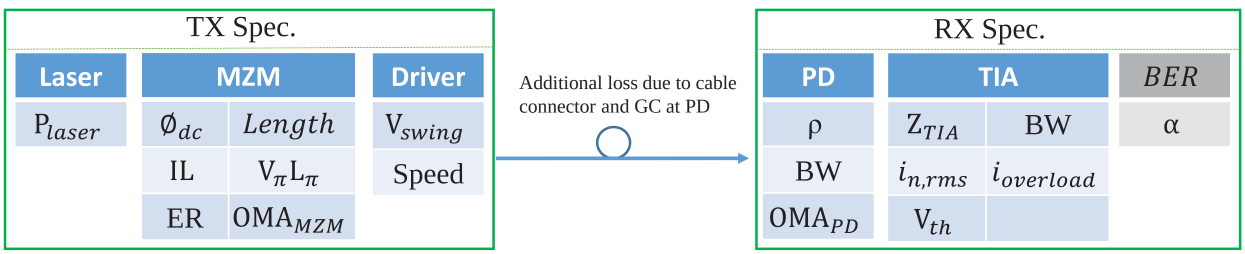
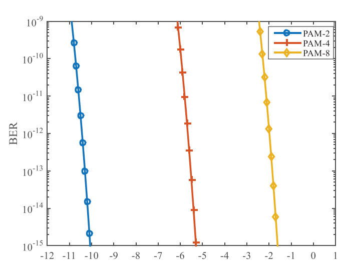


Fig. 1. MZM-based optical link specifications.

2. Deriving OMA for the Receiver

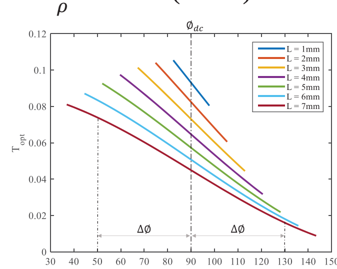
The receiver front-end circuit, TIA, when being connected to the PD, needs to provide high gain, large bandwidth and high sensitivity to achieve the desired BER at high-speed data rate. BER=0.5erfc(0.5α/$\sqrt{2}$)) is the complementary error function of the scaling factor, α [3]. By substituting α into Eq.(1), BER as a function of OMA_{min} at the PD's input can be plotted in Fig. 2. In Eq.(1), N stands for PAM-N. $i_{n,rms}$ is the TIA's input referred rms current noise. V_{th} is the decision threshold for the circuits seen at the output of the TIA. Z_{TIA} is the TIA's transimpedence gain. All the parameters value used for plotting the BER vs. OMA_{PD} curve can be found in the caption of Fig. 2. In order to achieve a BER of 10^{-12}, the minimum OMA_{PD} has to be larger than -10.1 dBm, -5.4 dBm and -1.7 dBm for PAM-2, PAM-4 and PAM-8, respectively.

$$OMA_{PD} = (N-1)\frac{\alpha i_{n,rms} + V_{th}/Z_{TIA}}{\rho} \quad \text{(Watts)} \qquad (1)$$



BER	PAM-N	Min. OMA_{PD} (dBm)
10^{-10}	2	-10.7303
	4	-5.9590
	8	-2.2793
10^{-12}	2	-10.1782
	4	-5.4070
	8	-1.7272
10^{-15}	2	-10.0627
	4	-5.2915
	8	-1.6117

Fig. 2. PAM-2/4/8 receiver sensitivity based on a 32 Gb/s TIA in 16nm FinFET CMOS process ($i_{n,rms} = 4\mu A, V_{th} = 20\ mV, Z_{TIA} = 58\ dB\Omega, \rho = 0.9\ A/W$).



$$\frac{V_\pi L_\pi}{180°} = \frac{V_{swing} Length}{\Delta\emptyset}$$

$$ER = 10\log_{10}\frac{T_{opt}(\emptyset_{dc} - \Delta\emptyset)}{T_{opt}(\emptyset_{dc} + \Delta\emptyset)}\ (dB)$$

$$P_{ave} = P_{laser} + 10\log_{10} T_{opt}(\emptyset_{dc})\ (dBm)$$

$$OMA_{MZM} = P_{laser} + 10\log_{10}\left(T_{opt}(\emptyset_{dc} - \Delta\emptyset) - T_{opt}(\emptyset_{dc} + \Delta\emptyset)\right)\ (dBm)$$

Fig. 3. Optical power transfer function of the MZM in 130nm SOI CMOS process with different arm lengths (an effective phase shift of 7.58$^\circ/mm$ is extracted when operating at 32 Gb/s).

3. Deriving MZM ER and OMA from the Optical Power Transfer Function

ER, which correlates the OMA with the average power, is an important specification for optical modulators. The optical power transfer function (T_{opt}) of the MZM is analyzed and given in Eq.(2). It is more accurate than those given in [4][5], in which the authors didn't consider the device length dependent static and dynamic insertion loss introduced by the optical elements. The T_{opt} is plotted in Fig.3 for the MZM in a 130nm SOI CMOS process with different arm lengths. In this plot, MZM is driven by a push-pull driver with 1.8 V_{PP} swing on both arms. k is the mismatch factor between two arms. $\emptyset_1$ and $\emptyset_2$ are the absolute phases of MZM's two arms. The two branches of optical power before entering the combiner is represented by P_1 and P_2. The two most significant insertion losses are introduced by the grating coupler and the high-speed phase modulator, respectively. An IL_{GC} of 3 dB is used for the analysis. Moreover, losses introduced by other optical elements (e.g. the Y-junctions, silicon waveguides and the PIN phase modulators) have been included in the MZM model. Thus, the ER and OMA can be accurately derived from the T_{opt}. The corresponding equations are shown along with the T_{opt} plot in Fig.3.

$$T_{opt} = \frac{P_1 k + P_2(1-k) + 2\sqrt{P_1 P_2 k(1-k)}\cos(\emptyset_1 - \emptyset_2)}{P_{laser} 10^{\left(IL_{Y-junc.} + IL_{WG} + IL_{GC}\right)/10}} \tag{2}$$

4. Correlation between Transmitter and Receiver

The OMA after the coupling at the RX PD side needs to be guaranteed to meet the BER requirement for PAM-N signaling. This is plotted in Fig.4 (a) with varying the input laser power from 5 to 14 dBm (denoted in red at the side of each curve). The three horizontal dash-dotted lines indicate the minimum required OMA for PAM-2/4/8, respectively. The overload current, which is set by the average power of MZM and the ρ of the PD, is plotted in Fig.4 (b). The TIA needs to be able to tolerate certain amount of overload current. Thus the more overload current is required to be cancelled, the more the input current noise will be introduced, which in turn raises the minimum required OMA_{min} at the RX side. It can be observed that there is an optimal ER for this specific MZM, which is around 8 dB. In order to meet the OMA_{min} for PAM-4 and PAM-8 RX sensitivity requirement, it doesn't help to increase the ER by using longer MZM length. The input laser power needs to be increased to compensate the excessive loss due to the long MZM.

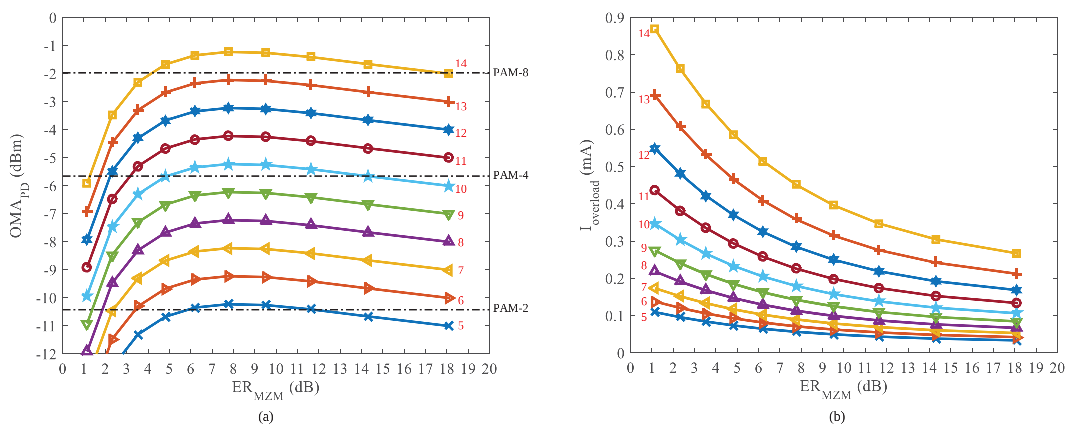


Fig. 4. (a) OMA_{PD} versus ER with varying input laser power, the dash-dotted horizontal lines are the minimum required OMA at the PD for PAM-N signaling derived from the parameters used in Fig. 2; (b) The overload current seen from the TIA versus ER.

5. Conclusion

A complete full link power budget analysis model is presented for the MZM-based optical link with PAM-2/4/8 modulation format. Once the optimal ER at certain laser power is determined, the driver power requirement can be optimized at the electrical side depending on the driver's topology. This budget analysis model can be potentially extended to other types of the optical links (e.g. micro-ring modulator or VCSEL-based).

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