Intuitive Analytical Model Relating Electrical Crosstalk in Mach-Zehnder Modulators to Performance Degradations

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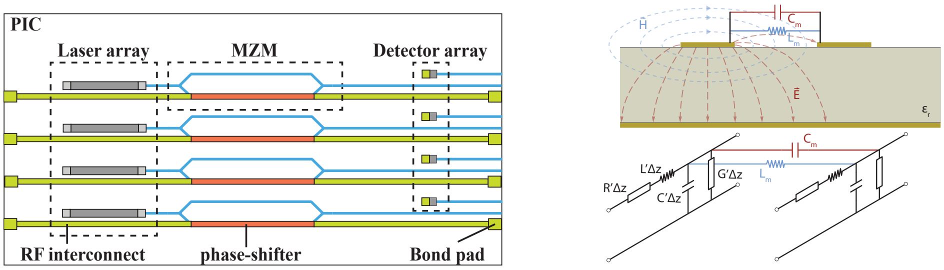
WDM transmitters are increasingly realized as photonic integrated circuits where arrays of lasers and modulators are monolithically integrated in a parallel channel architecture. With increasing integration density electrical crosstalk emerges as a phenomenon that impairs transmitter performance. We present an intuitive analytical description of how coupling inside and between Mach-Zehnder modulators can affect their dynamic extinction ratio and introduce power penalties to the transmission. Based on the model we derive a crosstalk threshold of around -30 dB above which degradation starts to become visible. The results will be useful in establishing design rules to avoid crosstalk induced impairments.

Introduction

Large-scale photonic integrated circuits are regarded as the most promising technology to overcome the present capacity limits in our telecom and datacom networks and to sustain the on-going capacity growth in the future. Monolithically integrated optical transceivers, as illustrated in Fig. 1a, can offer low cost, low power consumption at a small foot-print with the flexibility of up-scaling in both number of production units and number of transmit channels. However, they become increasingly more complex with a large number of components per chip, leading to a very high integration density. This results in a number of proximity effects that influence device performance, namely electrical, thermal and optical crosstalk [1, 2]. Especially electrical coupling between RF lines and high-speed modulators, as illustrated in Fig. 1b, has been found to degrade the transmitter performance [3] and numerical models based on electro-magnetic simulations were previously suggested to account for such effects [4]. In this paper, we focus on an analytical and simple model that relates the amount of electrical crosstalk to performance degradation in Mach-Zehnder (MZ) modulators. The intuitive model is flexible and can be extended to many MZ modulator configurations. We illustrate that by analyzing crosstalk between two single-drive MZ modulators and compare it to crosstalk effects on an individual dual-drive parallel push-pull MZ modulator.



(a) (b)

Figure 1: (a) Parallel WDM transmitter circuit with array of lasers, modulators and detectors. (b) Electric and magnetic field coupling between electrodes causes crosstalk between modulators.

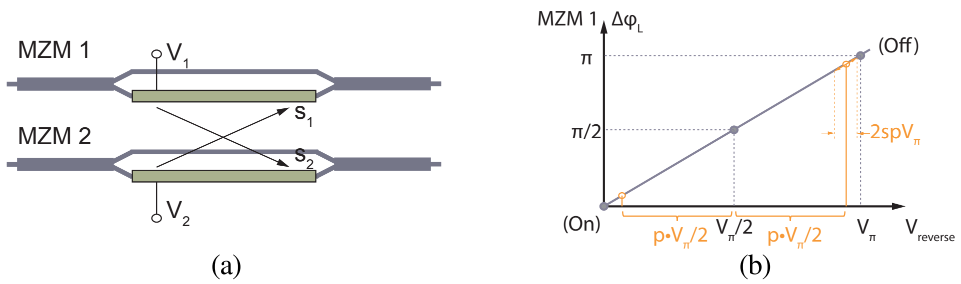


Figure 2: (a) Coupling s_1 and s_2 between two single-drive MZ modulators. (b) MZ transfer function with electrical coupling s and drive voltage reduction p.

Inter Mach-Zehnder Modulator Crosstalk

The model can be explained by referring to Fig. 2a, which shows two single-drive MZ modulators. For the sake of simplicity, the analysis is performed under the assumption of a lumped electrode operation condition. Each modulator is driven with the voltages V_1 and V_2 respectively and we can introduce a factor p that represents the attenuation of the drive voltage from its ideal peak-to-peak swing, so that the available voltage is pV_{pp}. Each modulator is biased at its quadrature point using the bias voltage $V_{bias} = V_\pi/2$. Depending on the information pattern $sig(t)$ which can take values of ± 1, the voltage on the first modulator's electrode can be written as

$$V_1 = \frac{V_\pi}{2} + sig(t) p \frac{V_\pi}{2}. \tag{1}$$

The phase change experienced by the optical signal in that modulator arm will have the values

$$\Delta\phi_1 = \frac{\pi}{2} + sig(t) p \frac{\pi}{2}, \tag{2}$$

when we assume a linear phase-voltage relationship as depicted in Fig. 2b so that the destructive ($\Delta\phi_1 = \pi$) and constructive ($\Delta\phi_1 = 0$) interference points are reached in case of an ideal $p = 1$ drive condition.

In presence of electrical crosstalk, a coupling factor s_1 and s_2 can be introduced that represents the voltage coupling from the first modulator to the second and vice versa. It can be assumed that $s_1 = s_2$ due to reciprocity and when secondary coupling is neglected. The drive voltage on the first modulator then reduces by a factor of $(1-s)$ and experiences noise from the second modulator of magnitude spV_π. The voltage values for the worst case scenario when the crosstalk noise acts against the modulating voltage for the "off" and "on" states are shown in Fig. 2b and can be written as

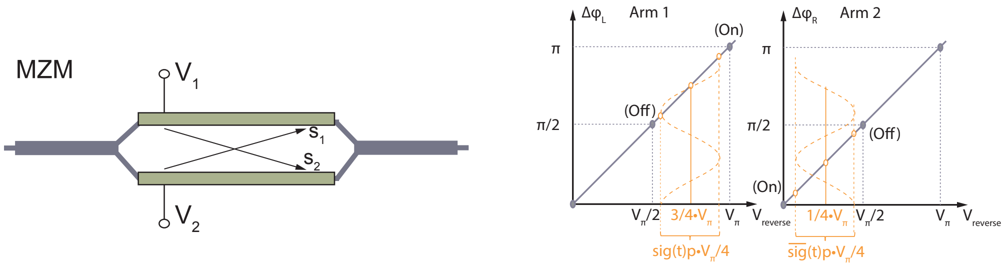
$$V_{OFF,ON} = \frac{V_\pi}{2} \pm (1-s) p \frac{V_\pi}{2} \mp spV_\pi. \tag{3}$$

The corresponding phase differences in the first modulator then have the values

$$\Delta\phi_{OFF,ON} = \frac{\pi}{2} \pm (1-s) p \frac{\pi}{2} \mp sp\pi. \tag{4}$$

One can show that the intensity transfer function of the Mach-Zehnder modulator depends on the phase difference between the two arms $\Delta\phi$ in the form of

$$P = \frac{E_0^2}{2} e^{-\alpha L} (1 + cos(\Delta\phi)) \tag{5}$$



(a)

(b)

Figure 3: (a) Single Mach-Zehnder modulator with two electrodes in parallel dual-drive mode. (b) Voltage values on each of the two electrodes.

where α denotes the optical attenuation and L the modulator length. This phase change $\Delta\phi$ now deviates from its ideal value in presence of crosstalk as shown in equation (4) and leads to a degradation of the optical extinction ratio, defined as the ratio $ER = P_{on}/P_{off}$ between the intensities in "on" and "off" state. One can write the extinction ratio using equation (5) then as

$$ER = \frac{1+cos\left[\frac{\pi}{2}(1+p-3sp)\right]}{1+cos\left[\frac{\pi}{2}(1-p+3sp)\right]} \tag{6}$$

depending on the crosstalk coupling s and the drive voltage reduction p.

Intra Mach-Zehnder Modulator Crosstalk

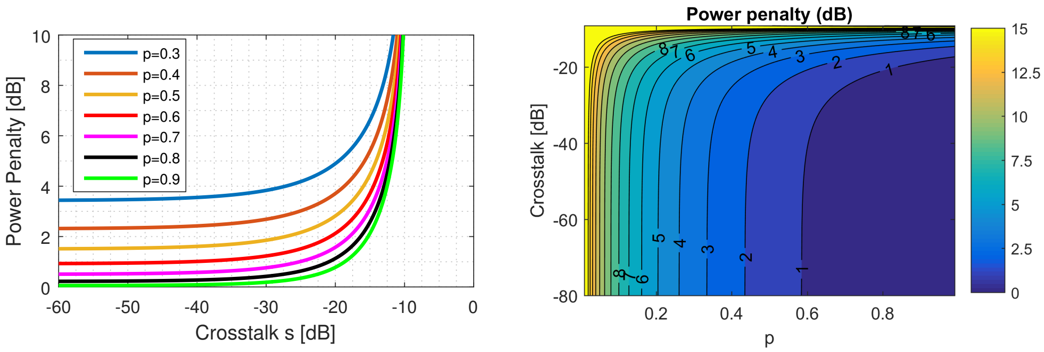
Above analysis was performed for the case of two modulators which are placed close to each other, both operating in a single-drive mode. In this section, we investigate the effect of electrical crosstalk on an individual modulator, which is operated in dual-drive push-pull mode with the corresponding voltages on each of the two arms as shown in Fig. 3. This configuration can be often found in transmitters utilizing IQ vector modulation and is therefore of significant interest. Here, electrical crosstalk can lead to coupling from one arm to the other and vice versa. By following a similar reasoning as in the previous section, a noise term $sp\frac{V_\pi}{2}$ can be added to the modulating voltage on each arm. The sign of that term can be chosen to represent the worst case situation, i.e. reducing the effective drive voltage, so that the values are furthest away from the ideal values needed for ON and OFF states. The extinction ratio can be derived to be again

$$ER = \frac{1+cos\left[\frac{\pi}{2}(1+p-3sp)\right]}{1+cos\left[\frac{\pi}{2}(1-p+3sp)\right]}. \tag{7}$$

It is interesting to observe that above term is the same as for the case of two single-drive modulators. It can be understood by taking into account the fact that in the dual-drive situation, the drive voltage on each arm is half the value of the single-drive case, but the electrical coupling affects twice the modulation output as both crosstalk receivers are part of the same modulator.

From the calculated extinction ratio the power penalty value δ can be determined which gives the amount of additional power needed at the receiver to obtain the same bit-error rate with respect to the ideal extinction ratio case [5]:

$$\delta = 10\log_{10}\frac{1+ER}{1-ER}. \tag{8}$$



(a) (b)

Figure 4: (a) Power penalty introduced due to unideal drive voltage p and crosstalk s. (b) Contour plot of power penalty versus p and s.

Calculation Results

The calculated results for the power penalty for both the inter MZ modulator and intra MZ modulator crosstalk cases are shown in Fig. 4a for varying drive voltage reduction p and crosstalk s values. Here, s can be obtained experimentally by measuring appropriate crosstalk test structures as shown in [3] and it represents the voltage coupling from one modulator to the other. The factor p simulates the effects of microwave attenuation, reflections and a general reduction of the drive voltage from its ideal value. It can be observed, that additional power penalty is introduced if $p \neq 1$ which corresponds to a reduction of the optical extinction and correspondingly eye opening in case of modulated output signals. Furthermore, crosstalk results in additional increase in power penalty. One notices the onset of degrading impact of crosstalk when its level rises above -30 dB. The power penalty then increases rapidly so that at -10 dB crosstalk, we have more than 10 dB power penalty already.

Conclusions

The results indicate that electrical crosstalk can lead to significant performance degradation of the modulated output signal and according to the analytical model, effects are visible for crosstalk levels above -30 dB. In practice, there are many other factors that determine the modulation output signal quality, starting from imperfections in the RF path, optical imbalance of the MZ interferometer, reaching to laser source imperfections so that accordingly, supplementary effort is required to incorporate all related effects into the modeling. Above analysis can act as an initial guideline and clearly illustrates the negative effect of electrical crosstalk on optical modulation.

References

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