Design and simulation of a series push-pull Mach-Zehnder modulator in a generic photonic integration platform

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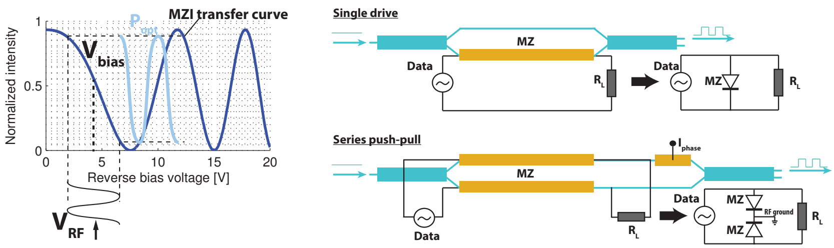
In this paper we report on the design and simulation of a series push-pull Mach-Zehnder modulator for a generic photonic integration platform. Detailed travelling-wave electrode design considerations for high-speed operation in the generic platform are given. Additionally, numerical simulations are presented that indicate an improved performance over conventional single-drive modulators.

Introduction

Photonic integration technology plays a key role in today's capacity-driven telecommunication and data communication applications. The demand for small form-factor transmitters and receivers with high bandwidth and low power consumption points to the use of photonic integrated circuits (PICs) that offer high integration density and performance on a small chip. To increase accessibility to this technology and decrease chip costs, the generic foundry approach has been adopted successfully to photonic integration [1]. Within the generic integration scheme basic functional components are established by a foundry that can be freely combined on a circuit level to form the desired PIC. One particularly important component for transmitter chips, is the electro-optical modulator as it dictates overall chip capacity and signal quality. Conventional single-drive Mach-Zehnder modulators (MZM) with a traveling-wave electrode design have been previously used in the COBRA generic integration process, showing clear NRZ-modulation up to 10 Gbps [2]. In this paper, we report on an improved COBRA modulator design based on a series push-pull driving scheme, that offers a potentially up to 4 GHz higher modulation bandwidth compared to the previous design. Additional advantages of the new modulator include low chirp, low imbalance and high break-down voltage and make it promising for high-speed modulation in long-distance applications. We first describe the series push-pull driving scheme with its advantages, then focus on the high-speed modulator electrode design and finally conclude with modulator performance simulations

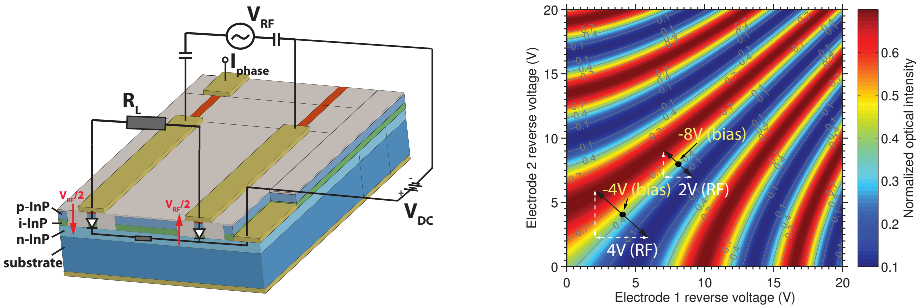
Working Principle

In the conventional single-drive mode, one arm of the MZM is designed as an electro-optical phase-shifter. The RF data signal is fed from one side of the electrode and co-propagates with the optical signal, changing its phase along the path and introducing zero or a π phase difference between the two arms. Thus, the optical output intensity varies as a results of constructive or destructive interference and is dependent on the electrical



(a) (b)

Figure 1: (a) MZM transfer function for single-drive case. (b) Electrical circuit for single drive and series push-pull configuration. In series push-pull a phase shifter is needed to introduce an additional $\pi/2$ phase difference between the two arms.

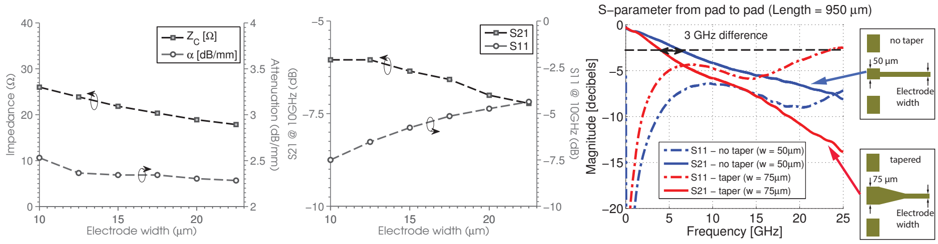


(a) (b)

Figure 2: (a) Schematic showing the MZM cross section with biasing circuit and n-contact metalization. (b) MZM transfer function showing optical output intensity depending on drive voltage on both arms, incorporating additional $\pi/2$ phase shifter.

input signal as shown in the intensity-voltage transfer function in Figure 1a. This driving scheme is simple in design but has several drawbacks that impairs the modulator's performance. Due to the single-sided drive, a power imbalance between the two arms and chirp of the optical output signal are introduced, limiting the extinction ratio and bandwidth-length product of the modulator [3].

A series-push pull driving scheme as shown at the bottom of Figure 1b can overcome those problems [4]. Both arms of the MZM are designed as EO-phase-shifters and the RF signal is applied between the inputs of the two electrodes. This is illustrated on the device's cross section in Figure 2a. Because the two optical waveguides share the same n-doped bottom cladding layer, they are electrically connected and can be viewed as two p-i-n diodes in series. The input RF drive voltage is then divided in half along each arm, but with opposite signs, so that each arm of the MZM only needs half the voltage as compared to the single-drive case to achieve a π phase difference between them, doubling the overall efficiency. Furthermore, the chirp introduced by one arm is compensated by the other arm, allowing for chirp free modulated output. Finally, the modulation speed can be enhanced due to the fact that the line capacitance in push-pull is reduced due to the series connection of the individual junction capacitances through the n-layer. Based on this driving scheme, we have designed a series push-pull modulator in the COBRA



(a) (b) (c)

Figure 3: (a) Measured S21 and S11 coefficients and (b) characteristic impedance and microwave attenuation at 10 GHz for a 1 mm long electrode depending on its width. (c) S-parameter measurement of optimized and non-optimized probing pad geometries.

generic process. An additional $\pi/2$ phase shift between the two arms is necessary for NRZ operation and can be realized through an extra DC phase shifter, as indicated in Figure 2a. The modulator's output intensity as a function of applied voltage to both arms can then be computed and is shown in Figure 2b. Depending on the bias point, the input RF voltage swing can be reduced slightly due to the quadratic electro-optical effect.

High-speed Electrode Design

The modulation bandwidth is strictly determined by the electrical bandwidth of the phase-shifter electrode, so that its careful design for high-speed operation is required. Optimization of the metal-insulator-semiconductor microstrip line for modulators in the COBRA process has been presented in [5] based on a full-wave 3D-EM approach. It has been found that 10 µm wide electrodes show the best trade-off between microwave loss and impedance mismatch. Measurements on phase-shifter test electrodes with different width values from the COBRA process agree with the simulation results. The measured characteristic impedance, microwave loss, electrical transmission and reflection at 10 GHz are shown as a function of electrode width in Figure 3a and Figure 3b. It can be observed, that as electrode width decreases, the reflection decreases as well due to better impedance match to 50 Ω. However, microwave loss increases due to conductor losses, so that we chose 10 µm as the optimum value for the modulator design.

As the modulators need to be fed via RF probes or through wire bonds, we have studied the effect of different pad geometries on its electrical bandwidth. We have chosen to use 50 µm wide pads with abrupt transition to the 10 µm wide phase-shifter electrode, because they show superior RF performance compared to 75 µm wide pads with taper section. Figure 3c shows the measured S21 and S11 curves for 950 µm long transmission lines applying both pad types. A narrower pad has a higher characteristic impedance, so that less reflections occur at the the interface to the 50 Ω probes whereas a taper section increases the effective length of this impedance mismatch, so that by omitting a taper, its effect is reduced.

Performance Simulation

To investigate the performance of the proposed series push-pull modulator, numerical simulations based on a hybrid 3D-EM and circuit approach have been performed. Both electrodes in the push-pull configuration are represented by a cascade of scattering pa-

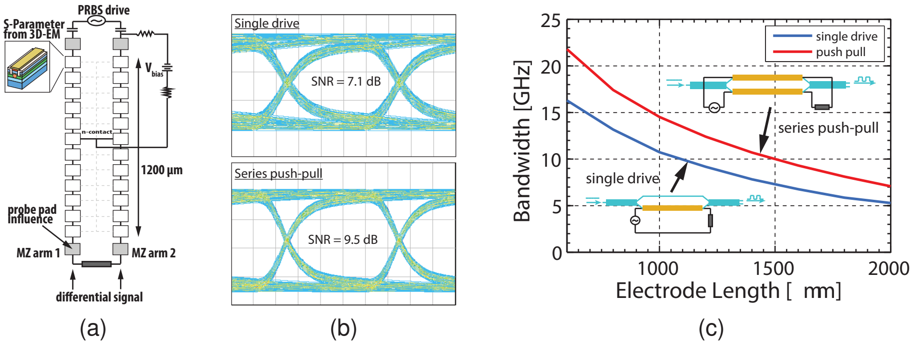


Figure 4: (a) Simulation model utilizing S-parameters from 3D solver. (b) Simulated electrical eye diagram for single drive and push-pull case (V_{pp} = 4 V, L = 1200 µm). (c) Simulated electrical 6 dB bandwidth depending on electrode length for both cases.

rameter blocks (L=100 µm), obtained from full-wave simulations as described in [5], to form a total length of 1200 µm. The circuit representation is given in Figure 4a and implemented in the Advanced System Design (ADS) circuit simulator by adding a driving bit sequence to the start, a termination to the end of the electrode and additional biasing elements. Figure 4b shows the simulated 10 Gbps eye diagram for the single-drive and push-pull configuration. An improvement in the eye opening and 2.4 dB better signal-to-noise ratio can be observed in the latter case. Figure 4c shows the simulated 6 dB electrical bandwidth of both driving schemes. For a given electrode length, the push-pull scheme allows for 2 to 4 GHz higher bandwidth and for typical lengths of 1.2 mm it shows an electrical bandwidth of 12.5 GHz.

Conclusion

We have presented a series push-pull Mach-Zehnder modulator for the COBRA generic photonic integration process and detailed its working principle and high-speed electrode design. Numerical simulations indicate that it is superior to a single-drive MZM showing up to 12.5 GHz electrical bandwidth and thus suitable for high-speed long-distance applications.

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