Microwave Modeling and Analysis of an InP based Phase Shifter from a Generic Foundry Process

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Theoretical analysis and numerical simulations on the microwave properties of a III-V integrated phase shifter are presented and compared with experimental results. A 3D-electro-magnetic model of the phase shifter is used to study the effect of geometrical and material parameter changes on the modulator's transmission line parameters including its bias voltage dependency. The model predictions match well with measurements on phase shifter structures fabricated in a generic integration process and can be used to analyze electrical crosstalk between modulators in high-capacity WDM transmitter chips.

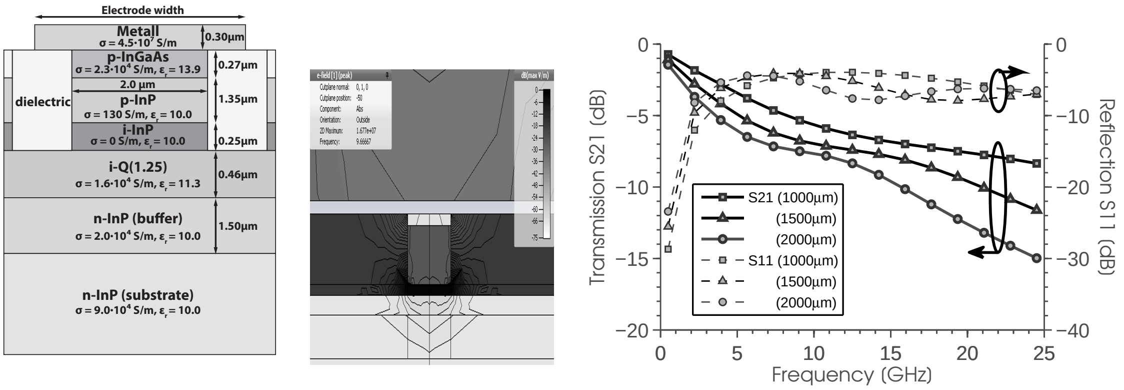
Introduction

Monolithically integrated high capacity multichannel transmitters are becoming more and more attractive, e.g. in optical interconnect or access network applications. Fabrication of such transmitters through a generic foundry approach stands to reason due to reduced development time and cost [1]. A steady demand for higher capacity, channel count and smaller chip size gives rise to many design and fabrication challenges. One such challenge lies in the design of electro-optical phase shifters for high speed modulation and in the electrical crosstalk between them due to small separation distances on chip. High frequency losses and reflections in phase shifters affect the electrical signal propagation and degrade their performance whereas crosstalk introduces noise and distortions. Therefore, careful analysis of their microwave characteristics is required. This paper studies those based on a 3D solver approach, similar to [2], and extends the model to account for crosstalk effects.

Phase Shifter Model and Simulation

The phase shifter structure is shown in figure 1(a) and consists of a shallow optical waveguide with a top metal electrode and trenches on each side with dielectric filling for passivation. Propagation of the microwave signal along the top electrode is described by transmission line theory and defined through the propagation constant $\gamma = \alpha + j\beta$, where α is the attenuation and β the phase constant, and the characteristic impedance Z_C [2]. The full-wave solver CST MWS is used here to model the phase shifter cross section and determine the microwave parameters. Its electric field solution is shown in figure 1(b) and corresponds to a microstrip mode with a quasi-TEM behaviour, centered around the depletion area between the intrinsic layer and the p-doped cladding. Bias dependency is incorporated through variation of the depletion thickness.

Electrical scattering parameters have been calculated for three different phase shifter lengths and are presented in figure 1(c). The 1500µm long phase shifter shows an elec-



(a) (b) (c)

Figure 1: (a) Phase shifter cross section; (b) its quasi-TEM field solution; (c) simulated scattering parameters for three different lengths (20 µm width).

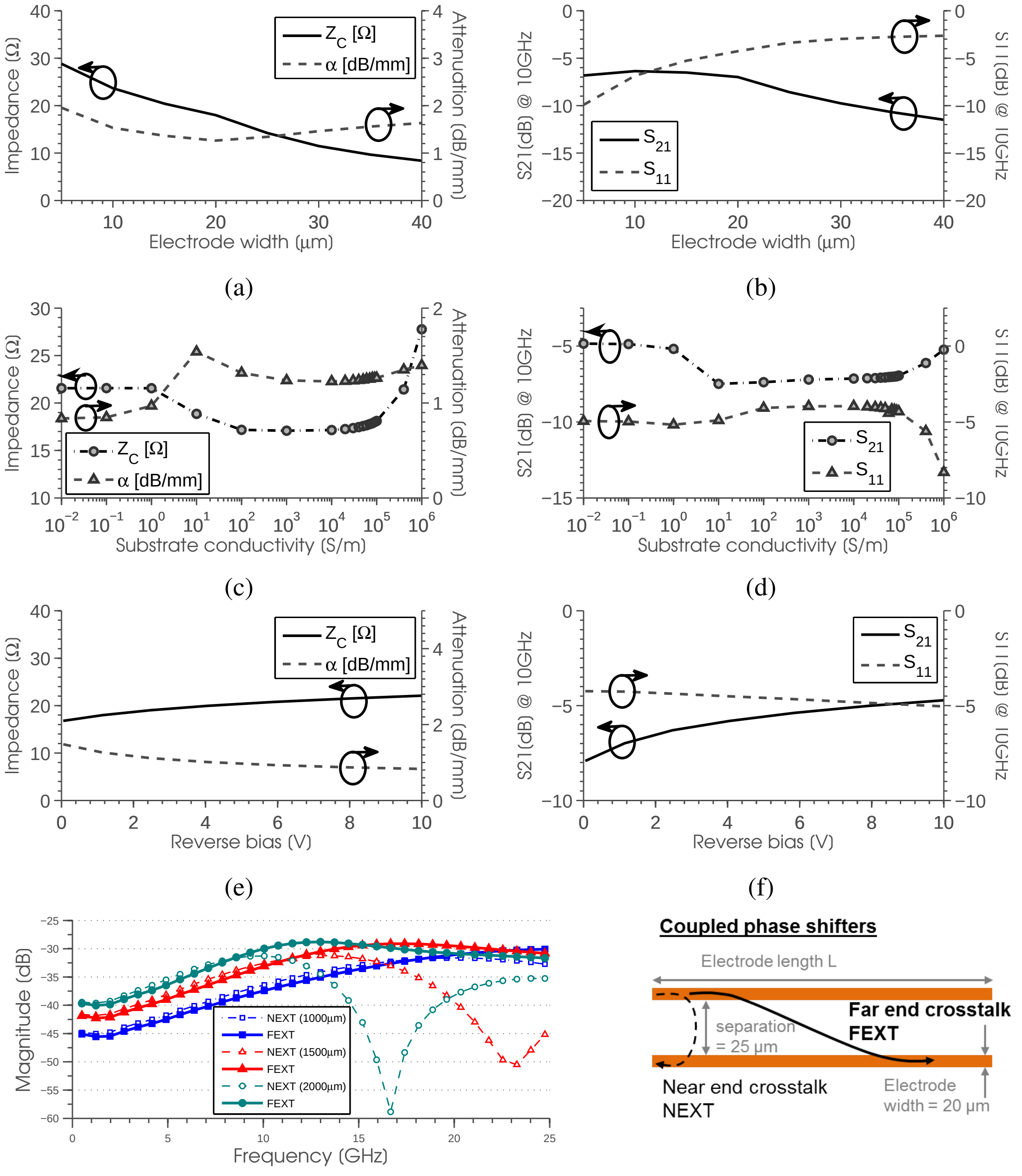
trical -6dB bandwidth of 7GHz allowing for 10GBit/s operation. The bandwidth can be improved by decreasing the length in exchange for less phase shift per applied voltage.

Microwave Properties and Crosstalk

In this section, the dependence of the phase shifter's properties on the electrode width, the substrate conductivity and applied reverse bias are analyzed. Figure 2(a) and 2(b) show the influence of changing electrode width on its characteristic impedance, attenuation and scattering parameters at 10 GHz. The attenuation is lowest for 20 µm and increases towards smaller and higher widths. For small widths, the electric field is located more at the lossy p-doped cladding area and the metal cross section is smaller, increasing the dielectric and conductor losses. For high width values, the metal extends over the trench area and lies on a thin dielectric on top of the p-i-n layers, increasing the conductor loss again. Best transmission is obtained for widths between 10 µm and 20 µm.

Depending on the substrate conductivity, different kinds of mode propagation (skin-effect, slow-wave and dielectric) can occur in a microstrip line [3]. This can be observed in figure 2(c) and 2(d), where the influence of substrate conductivity on the microwave properties are shown. At high conductivities, the substrate behaves like a lossy conductor resulting in higher attenuation and impedance (skin-effect mode) and at very low conductivities, the substrate acts as a dielectric with very low losses. Inbetween lies the slow-wave region. Transitions between those three propagation regions typically show attenuation peaks [3] which are observed also here. For the n-doped substrate used in the COBRA generic integration process ($\sigma \sim 10^5$), propagation occurs in the transition region between slow-wave mode and skin-effect mode. The transmission is low because of low impedance and high attenuation in the slow-wave region. Therefore, a highly conductive or a semi-insulating substrate would result in better microwave performance.

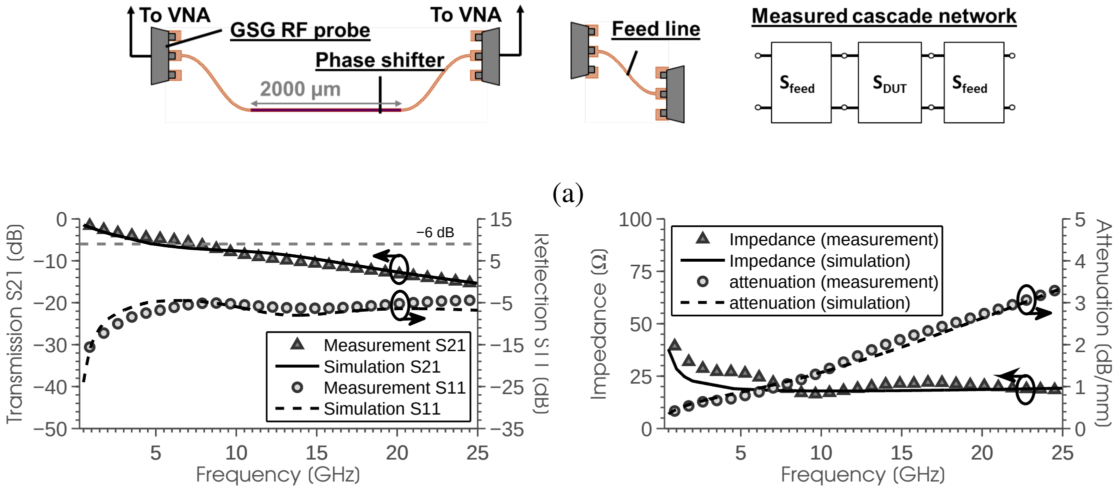
The effect of applied reverse bias on the phase shifter is shown in figure 2(e) and 2(f). As the reverse bias increases, the depletion area gets thicker, increasing the effective thickness of the microstrip and therefore Z_C, and allowing for more field to penetrate dielectric instead of conductive material, reducing the attenuation. However, large bias voltages are not preferred in general as the optical waveguide loss and electrical power consumption is also increased.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 2: Influence of electrode width (a), substrate conductivity (c) and reverse bias (e) on the characteristic Impendance Z_C, microwave attenuation α , and their influence on scattering parameters (b), (d), (f) of a 1500 µm long phase shifter (values are from simulations at 10 GHz). (h) Configuration of two coupled phase shifters; (g) their NEXT and FEXT for different coupling lengths.

Near end and far end crosstalk from two coupled phase shifters (see figure 2(h)) at a distance of 25 µm have been analyzed for three coupling lengths by extending the simulation approach to the coupled structure and are shown in figure 2(g). Crosstalk is higher for longer coupling lengths and reaches -30 dB at 10 GHz for the 2000 µm structure. FEXT is more dominant at higher frequencies but starts to roll off due to high



(a)

(b)

(c)

Figure 3: (a) Illustration of phase shifter with de-embedding configuration. S-parameters (b) and transmission line characteristics (c) of a 2000 µm long, 20 µm wide phase shifter.

frequency attenuation whereas NEXT shows periodic minima at resonance frequencies.

Experimental Results

Phase shifter test structures have been fabricated in the generic process and characterized using a 2-port vector network analyzer for model verification. De-embedding of the probe pad and feeding lines from the RF measurements has been performed using a cascade network approach as indicated in figure 3(a). The characteristics of the phase shifter section $\mathbf{S_{DUT}}$ can be extracted from the measurement when the feed line network $\mathbf{S_{feed}}$ is known. The measured scattering parameters of a 2000 µm long phase shifter are shown in figure 3(b) and match well with the simulated values. Extracted microwave parameters in figure 3(c) show an impedance around 25 Ω and attenuation of 1.5 dB/mm at 10GHz.

Conclusion

Microwave characteristics of an optical phase shifter have been analyzed for different electrode widths, substrate conductivities and reverse bias voltages and the model predictions have been verified by measurements on fabricated phase shifters. The 3D-EM model has been used to analyze crosstalk between two coupled phase shifters. Suitable testing structures need to be designed and measured in future work for further comparison with the crosstalk results.

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