Simulation and Design of a 40 GHz Mach-Zehnder Modulator on InP

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Based on a rigorous vectorial analysis, a fast traveling-wave Mach-Zehnder modulator is modelled and designed. The cross-section of the semiconductor layer stack and the lossy electrodes are carefully modelled using the Method of Lines in order to investigate propagation characteristics, velocity and losses. In order to enhance the modulation efficiency, design curves are derived and the cross-sectional dimensions for minimum microwave loss are determined. The loss of the optimized modulator agrees very well with Small Signal measurements up to 40 GHz. The layerstack of the fabricated device is suitable for integration with InP multi-wavelength lasers.

Introduction

For 40 Gb/s transmission systems and beyond, high speed modulators are of great interest. The most commonly used materials for modulators are $LiNbO_3$ and the III-V semiconductor compounds GaAs and InP. Whereas the former has the advantage of a low insertion loss and recently also a low driving voltage [1], the semiconductor substrates have the advantage of possible integration with amplifiers [2]. It is well known that modulators using lumped metal contacts are limited in frequency by the RC time constant and that this problem can be overcome by using a travelling wave design [3]. A travelling wave Mach-Zehnder modulator has been realized, e.g., by Walker on GaAs [4] and by Mörl [5] and Krähenbühl [6] on InP.

However, little has been published about the microwave design considerations that are to be taken into account in the design of a high-speed travelling wave Mach-Zehnder modulators on InP. Highly accurate design data are necessary for these devices because of the long and costly fabrication process. Hence a rigorous model is needed that includes the main limiting factors: the velocity mismatch between the optical wave and the microwave as well as the microwave loss.

The waveguide structure of the modulator considered by the authors is composed of several semiconductor layers with a step index profile and lossy metallic electrodes (fig. 1). Conventional analyses use a model with homogeneous dielectric layers and infinitely thin electrodes, which does not take the conductor losses into account. This yields an error in the microwave phase velocity and an incorrect electric field.

In this paper, the used model fully accounts for the microwave and optical properties of the inhomogeneous layer stack. The loss in the modulating electrodes and in the semiconductor layers is considered by means of a complex dielectric constant. In this way, the slow wave propagation caused by the semiconductor layers is included as well.

The model structure is analyzed by the Method of Lines (MoL), which has been efficiently used for the simulation of various planar waveguides for microwave integrated circuits and integrated optics by Pregla, Pascher and others [7, 8, 9]. The MoL takes advantage of the planar layer stack

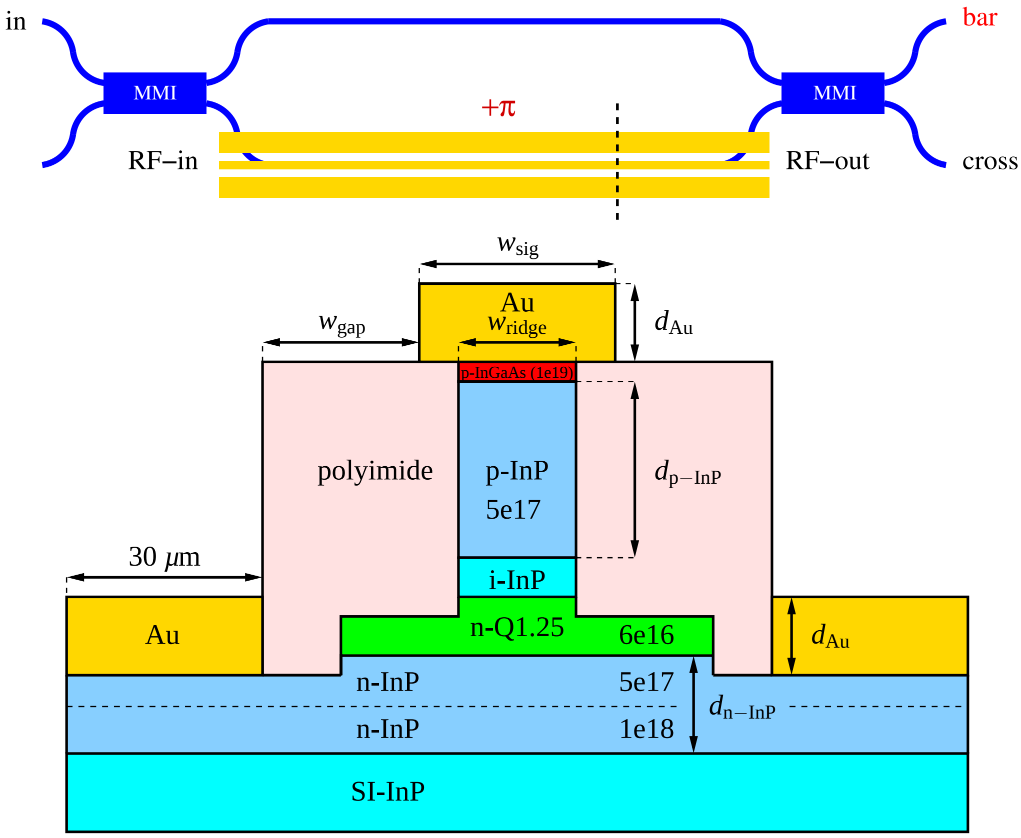

Figure 1: *Top view and cross-section (at dashed line) of a travelling-wave electro-optic modulator.*

by discretizing the wave equation in the direction parallel to the interfaces of the layers, whereas an analytical solution is retained in the vertical direction. Thus, highly accurate results are obtained at a comparatively small numerical effort.

In this paper, we present MoL simulations to optimize the electric field across the reverse biased diode of the modulator. The results were confirmed by HFSS (High-Frequency Structure Simulator) and by measurements.

Simulation and Measurement Results

The travelling wave modulator has been simulated by the MoL according to the cross-section in figure 1. The biggest electro-optic effect is obtained when the electric field is highest in the region where the light is confined. From a microwave point of view, it would be favourable to put the electrodes just above and below this region. However, an InP-ridge is needed not only to get the right optical confinement, but also to prevent optical absorption in the metal. Due to this latter argument and additional technical constraints, also the ground contacts must be placed at a certain minimum distance from the ridge.

To make use of the pin-diode structure of the ridge, doping of the InP-ridge is necessary. Unfortunately, doped semiconductors have a conductivity that is much lower than that of metals. Therefore, the amount of doping in the cladding influences the RF-attenuation due to varying resistivity. Figure 2 shows the attenuation is linear with the ridge width and the cladding thickness, and thus with the amount of p-doped material in between the signal line and the depletion-zone edge. Both plots were simulated at 40 GHz. Furthermore, the higher the doping, the more metal-like the resistive semiconductor gets. The doping of the p-InP cladding was set to 5e17 cm^{-3}. Figure 2 also shows

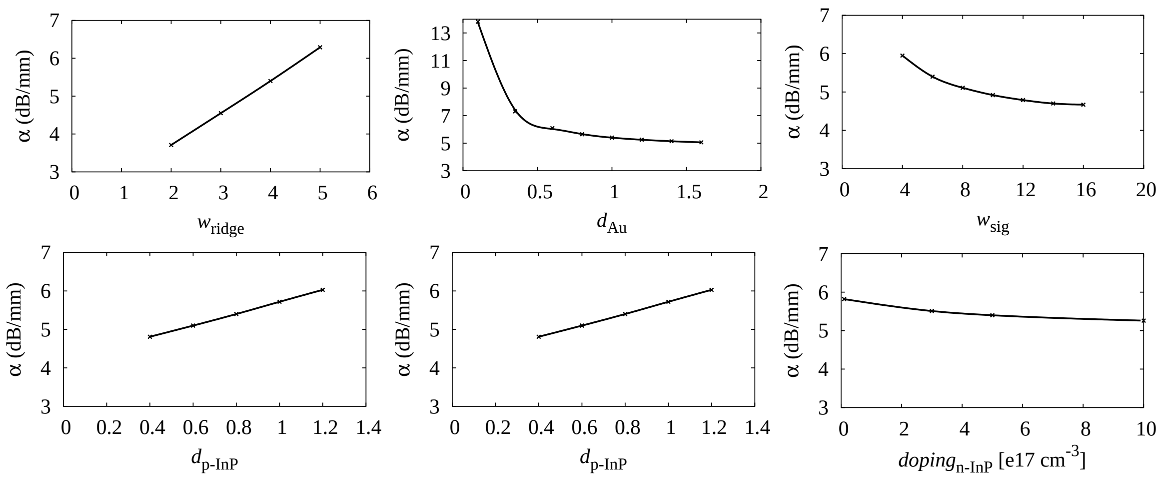

Figure 2: *RF-attenuation at 40 GHz as a function of ridge width (top left), gold thickness thickness (top middle), signal line width (top right), p-cladding thickness (bottom left), buffer thickness (bottom middle) and buffer doping (bottom right). Other parameters are as in the optimized design.*

the effect of the width of the signal line on the RF-attenuation. A wider signal line reduces the RF propagation loss, because a bigger part of the electric field is concentrated in the air instead of the semiconductor material. The attenuation is also reduced if the gold thickness is increased. Since the skin depth of Au is about 385 nm at 40 GHz, especially at thin Au thicknesses the attenuation increases dramatically. For the optimized design we chose for a Au thickness d_{Au} of about 1.5 μm . Since a minimal thickness of the p-layer is needed to avoid excessive optical absorption in the InGaAs-layer, an 800 nm p-doped cladding d_{p-InP} was grown. The minimal ridge width w_{ridge} was set by fabrication limitations to 4 μm. The thickness of the n-buffer layer d_{n-InP} in figure 1 was set to 1 μm.
HFSS simulations have been performed using the same structure as for the MoL simulations. HFSS (Ansoft) is a 3-dimensional finite difference EM field solver. The structure is discretised in tetrahedra and the EM field components are calculated on the vertices and edges of these elements using appropriate boundary conditions. The mesh is refined adaptively at the locations where a large gradient exists. The output of a simulation is a.o. the impedance at the ports and the S-parameters. From these, the complex propagation constant of the structure was calculated.

Comparison with measurements

The device was fabricated in several variants close to the optimized design. Figure 3 shows the attenuation data of a structure with a signal line width of 6 μm. The measured values for the phase-shifting section have been extracted using the thru-reflect-line (TRL) method [10]. Depicted are the values measured through small signal (SS-) measurements and those calculated by both the MoL and HFSS. Comparison with measured values is very good. It can be noted that the loss curve does not follow a $\sqrt{f}$ law, since the losses are mainly determined by the absorption in the substrate and not by the skin depth of the electrodes.
Figure 3 also shows the real part of the microwave index of a structure with a signal line width of 6 μm. One of the causes for the offset between simulation and measurement of the effective index could be the lack of reliable data of the used polyimide at RF-frequencies. Also, since the calculated values of the MoL and HFSS agree very well, we believe another source of error is the uncertainty of the doping levels in the different layers, which has not been measured. A different

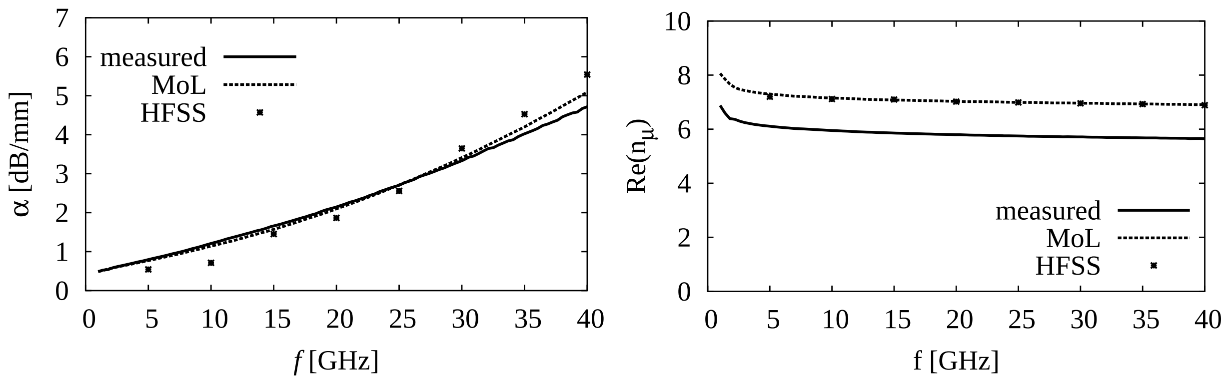

Figure 3: *Measurements (solid line), MoL-simulations (dashed line) and HFSS-simulations (crosses) of the microwave attenuation* α *(left) and of the microwave index* n_μ *(right) for a phase-shifter with a signal line width* w_{sig} *of 6 µm.*

doping profile would not only change the conductivities, but also the thickness of the depletion layer. Attenuation and effective index plots for a structure with a signal line width w_{sig} of 12 μm showed similar behaviour.

Conclusions

The Method of Lines has been employed to model and design a fast travelling-wave electro-optic modulator. Field distributions and design curves have been presented and discussed in view of an optimized component with minimum microwave loss. The small-signal measurements of the fabricated device show very good agreement (within 0.3 dB/mm) with the MoL modelling and with HFSS simulation results.

Acknowledgements

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