Low loss transmission lines in COBRA generic photonic integration platform

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ABSTRACT

Delivering unperturbed radio-frequency signal to the components on densely packed photonic integrated chip is an important aspect for circuits needed to operate at high bit rates. Efficient, low-loss routing of a high-speed electrical signal from the driver to the photonic chip can be a challenge. Therefore, the design of transmission lines for intra-chip connection, with low microwave loss and matched characteristic impedance to the rest of the circuit is important. We have characterized transmission lines on two different substrates, n-InP doped and semi-insulating. Low-loss transmission lines in the COBRA generic integration platform are fabricated and measured up to 65 GHz.

Keywords: transmission line, radio-frequency, n-doped substrate, semi-insulating substrate, microwave loss, characteristic impedance

1. INTRODUCTION

The integration of a large number of optical components on a single chip is currently one of the main research objectives for data communications and networking applications. Radio-frequency (RF) propagation on photonic integrated circuits (PICs) has received substantial attention with the bandwidth scaling up. The use of on-chip transmission lines enables important design freedom for highly integrated PICs [1]. Keeping the electrical losses low and the characteristic impedance (Z_C) of the lines matched to the driver input ensures efficient propagation of the electrical signals. As most commercially-available, broad-bandwidth drivers are standardized to 50 Ω, it is desired that the on-chip lines have the same value.

Providing electrical signals to components on a photonic chip is often done via bond pads placed at the edge of the chip. However, with increasing component densities, also the distance of some components to the edge of the chip is increasing. To bridge the distance, electronic interconnects are needed, but especially for RF-components, this may degrade the signal quality.

The properties of the substrate play a key role in this degradation, as it determines the microwave loss of transmission lines and the parasitic capacitance of access pads [2]. A doped substrate is preferred when it comes to biasing lasers and modulators, as it offers straightforward current/voltage application. However, it introduces more losses for the radio-frequency signal. We investigated different designs of transmission lines in the COBRA generic integration platform [3], on n-doped and semi-insulating (SI) substrate, demonstrating very low losses in a large frequency range for the SI-substrate.

2. TRANSMISSION LINE DESIGN

An ideal transmission line is an interconnect whose conductors are perfect with zero resistance and a lossless dielectric. In this scenario, a voltage at the input of the ideal transmission line would propagate without distortion or attenuation [4]. However, in reality each type of transmission line exhibits a certain attenuation, yet depending on its type this can be minimized.

Two types are mostly in use: microstrip line due to its simple fabrication, and coplanar waveguide (CPW) exhibiting lower losses as the mode propagates partly in air. The corresponding electro-magnetic field is shown in Figure 1. The microstrip mode is confined between the upper metal line and the highly doped n-InP substrate acting as a conductor, $\varepsilon_r = 12.5$, while the CPW mode is propagating between the metals on top of the dielectric, $\varepsilon_r = 3.5$, and partially in the air. Design parameters for microstrip line are signal width (w) and dielectric height (h) and for CPW line are signal width (w) and signal-ground separation (g), as indicated in Figure 1. In order to realize the CPW transmission line, the signal-ground separation needs to be smaller than the height of the dielectric. This is not always possible due to fabrication limitations, therefore we examine transmission line design on two different substrates, aiming at low-losses and matched characteristic impedance at 25 GHz operation.

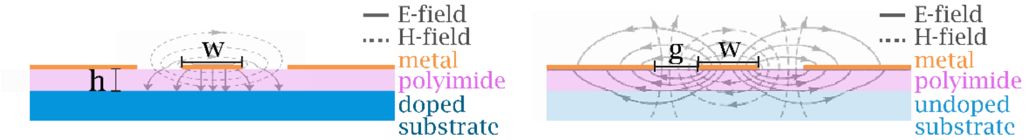

Figure 1: Microstrip (left) and coplanar waveguide (right) transmission line behaviour, with the important parameters for their design.

2.1 N-doped substrate

For a n-doped substrate in the COBRA platform, the transmission line acts as a microstrip line, as the condition $g < h$ cannot be satisfied due to fabrication limitations. In the COBRA platform, the nominal height of the polyimide is $h = 2 \pm 0.5$ µm, depending on the position on the wafer and neighbouring topology. We examine the influence of this tolerance on the characteristic impedance, shown in in Figure 2 [5]. We observe that for a change of ± 0.5 µm, Z_C changes by ± 5 Ω. Aiming at $Z_C = 50\ \Omega$ and fixing the polyimide height at 2 µm, the signal width needs to be as narrow as 4 µm. However, this value is dependent on the exact dielectric height.

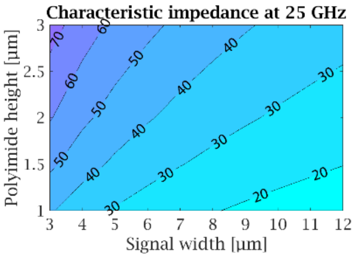

Figure 2: Microstrip line characteristic impedance dependence on w *and* h *at 25 GHz.*

Another problem which exists with the doped substrate is the high parasitic capacitance of the access pad. The design of the access pad is made in ground-signal-ground (GSG) configuration, in order to transfer the ground plane via wire bonds to the photonic chip and to allow direct on-chip measurements with RF probes. For a pad of 60×60µm^2, the value of pad capacitance is about 60 pF and can limit the bandwidth of the photonic components.

2.2 Semi-insulating substrate

In order to solve the problem of the access pad parasitic capacitance, we have also designed the transmission lines on semi-insulating substrate. Elimination of the parasitic capacitance of the pad is solved by placing it directly onto the SI-substrate. As the line is placed on top of a polyimide (Figure 1), there is a transition between the pad and the transmission line, bringing the metal gradually from the substrate to the top of the polyimide layer.

The parameters which influence the characteristic impedance of the line are signal width (w) and signal-ground gap (g). Previous work on electro-refractive modulators in the COBRA platform has showed that for a combination of values w = 10 µm and g = 10 µm, the obtained loss was minimal and the characteristic impedance was around 30 Ω [6]. Here we examine slight variations of this case, having the same mask set for both n-doped and semi-insulating substrate. Keeping the gap constant at g = 10 µm, we change the signal width w = 4-10 µm to obtain the optimal performance for both substrates.

3. TRANSMISSION LINE CHARACTERIZATION

The fabrication on both substrates is done through the JePPIX foundry services [7]. We used a 2-port vector network analyser to obtain the scattering (S) parameters of the network. The ABCD de-embedding technique [8] allows us to extract parameters of the line: Z_C, losses and microwave propagation index. Transmission lines on 2 µm polyimide with a gap g = 10 µm and varying signal widths w were characterized. The extracted microwave loss and characteristic impedance are shown in Figure 3.

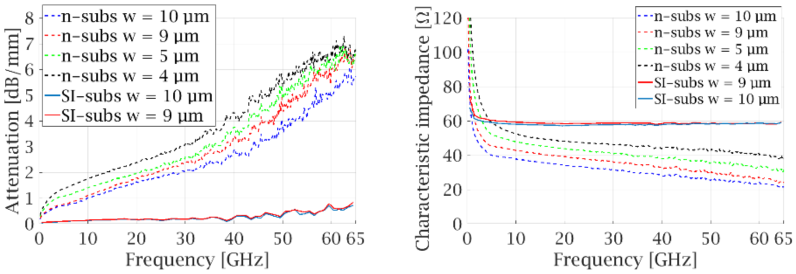

Figure 3: Extracted microwave loss (left) and characteristic impedance (right) of transmission lines on two different substrates from the measured S-parameters.

The microwave losses on n-doped substrate are 2-3 dB/mm at 25 GHz, rising up to 6-7 dB/mm at 65 GHz. Two origins are responsible for these losses: electrical loss, coming from the fact that the conductor is not perfect, and dielectric losses, as the mode is confined. With the frequency increase the microstrip line is dispersive and the characteristic impedance is frequency dependent on n-substrate. For the microstrip line the characteristic impedance changes rapidly with the geometry change: varying *w* by 5 µm Z_C changes by 10 Ω.

The main advantage of the semi-insulating compared to the doped substrate is low microwave loss, as low as 0.2-0.6 dB/mm in the whole measured frequency range, for *w* = 10µm and *g* = 10 µm. This value is an order of magnitude lower than the one obtained for the doped substrate. Additionally, the characteristic impedance is independent of the frequency, and in our case is 58 Ω. In the interest of reaching exactly 50 Ω, the gap needs to be lowered.

Owing to low losses, transmission lines can be made long up to several mm, therefore facilitating the design of compact photonic circuits adding a level of freedom in placing the components anywhere on the chip, while maintaining the integrity of driving signal.

4. CONCLUSION

Transmission lines for intra-chip connection in COBRA generic integration platform have been designed, fabricated and characterized on two different type of substrate, n-doped and semi-insulating. The choice of substrate highly influences the performance of the high frequency signal on chip, as the electrical signal propagates differently.

In case of a doped substrate, the line behaves as a microstrip waveguide and the optimal value for loss is *w* = 10 µm and *h* = 2 µm in COBRA platform. Nevertheless, its characteristic impedance slightly depends on the frequency and the losses are 2 dB/mm at 25 GHz. On the other side, the transmission line on SI-substrate acts as a coplanar waveguide, with parameters *w* = 10 µm and *g* = 10 µm, showing as low as 0.2 dB/mm loss at 25 GHz.

Another important aspect of undoped substrate is the removal of the access pad parasitic capacitance. All of this together will allow more freedom in placing other building blocks in the platform which operate at high speed, as the introduction of a transmission line on SI-substrate will not degrade the transmitted electrical signal to the component.

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