RF-interconnections on InP

J.H. den Besten[1], R. Pahuta[1], A.W. Roodnat[2], X.J.M. Leijtens[3], M.K. Smit[3]

[1]Delft University of Technology, Faculty of Information Technology & Systems,
Photonic Integrated Circuits Group, P.O. Box 5031, 2600 GA Delft, The Netherlands
Tel. +31 015 2781752, Fax +31 015 2784046, Email: J.H.denBesten@ITS.TUDelft.NL

[2]TNO Physics and Electronics Laboratory
P.O. Box 96864, 2509 JG The Hague, The Netherlands

[3]Eindhoven University of Technology
P.O. Box 513, 5600 MB, Eindhoven, The Netherlands

We report first results on RF-interconnections on SI-InP wafers. Coplanar waveguides (CPWs) with different lengths and widths, and waveguide bends were fabricated and characterized. Propagation losses for narrow CPWs are lower than 6 dB/cm at 40 GHz and for broad CPWs even as low as 1.5 dB/cm. Bending losses are negligible even for bending radii of 200 µm. Reflections at the waveguide bends are below –19 dB at frequencies up to 40 GHz.

Introduction

The increasing interest in 40 Gb/s transmission requires high quality RF-interconnections on Photonic Integrated Circuits containing components like detectors or RF-modulators. The most commonly used materials to make high-speed modulators are $LiNbO_3$ and III-V compound semiconductors as GaAs and InP. $LiNbO_3$ Mach-Zehnder (MZ) modulators with coplanar waveguides (CPW) are reported up to 40 GHz with a low inserting loss, but with a high driving voltage (~7 V) [1]. Multiple quantum well (MQW) III-V electro absorption (EA) modulators on the contrary can have a driving voltage as low as 1.8 V [2], but suffer from high insertion losses. An advantage of III-V modulators is that amplifiers or lasers can be integrated [3]. We realized MZ-optical switches with losses below 2 dB and an extinction ratio as high as 20 dB [4]. Intrinsic speed of these devices is very high. Electrode and bondpad capacitance limited their bandwidth for RF-application to 500 MHz. Our goal is to improve the bandwidth by designing them as a traveling wave (TW) MZ-modulator on InP, with a low inserting loss as well as a low driving voltage.

As a first step we performed an investigation into the propagation and reflection properties of gold coplanar waveguides on semi-insulating (SI-) InP. Simulated results obtained with the HFSS (High-Frequency Structure Simulator) simulation tool were used to design CPW structures of different lengths, widths and curvatures. In order to minimize reflections, all CPWs were set to have a characteristic impedance of 50 Ω.

Design

Modulators using lumped metal contacts are limited in frequency by the RC time constant. A well-known approach to overcome this problem is the traveling wave design. In this case the electrode is designed as a transmission line. Because its capacitance is distributed, it does not limit the modulation speed. The electro-optical effect can be integrated along the length of the modulator, which is thousands of wavelengths long. The effect will be optimal when the velocity of the modulating electrical signal travels with the same speed as the optical signal. Matching of the group

velocities is considered to be the most efficient; because the electrodes are not dispersive, the electrical group velocity is equal to its phase velocity [5].
In terms of refractive indices, the group index N of the modulated optical wave must equal the effective index n_μ of the modulating microwave. For lithium niobate N is less than n_μ, while for InP N is larger than n_μ. In the typical waveguide-structures we use, N is around 3.6. For semi-insulating InP the dielectric constant in the frequency range of 4 to 18 GHz has been measured to be within 0.5 % of 12.55 [6]. This corresponds to an n_μ of 3.55. Simulations indicated however that in the ridge-waveguide structure we use for our switches the n_μ will be in the order of 2. No attempt was made at this stage to reach velocity-match.
The characteristic impedance of the transmission line should be matched to that of the driver, usually 50 Ω. If the electrode is not properly matched, a frequency dependent standing-wave pattern will emerge on the electrode. Especially at low frequencies the backward traveling waves will contribute significantly to the modulation and decrease the modulation efficiency [7]. The complex characteristic impedance is given by

$$Z_0 = \sqrt{\frac{i\omega L + R}{i\omega C + G}} \,. \tag{1}$$

A cross section and a top view of the coplanar waveguides we fabricated is shown in figure 1. Their Z_0 is a function of the ratio of the width of the central stripline over the width of the gap. An HFSS simulator was used to determine this ratio in our case. As a substrate we used a 350 µm thick SI-InP wafer that had a resistivity of $1{\cdot}10^7$ Ω·cm.

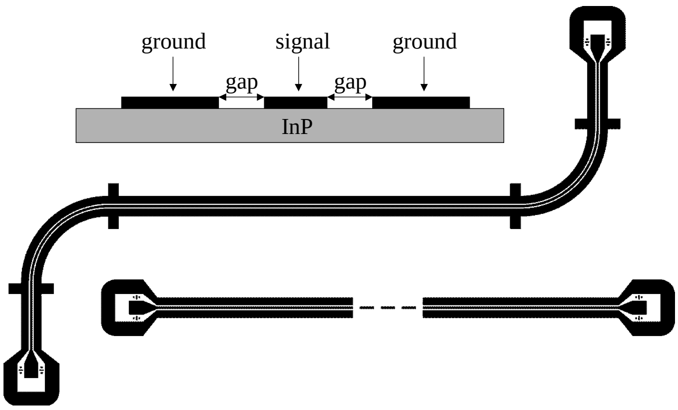
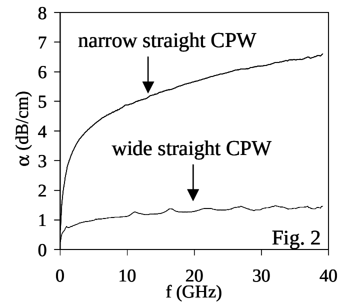


Fig. 1. Cross-section and top view of the coplanar waveguides. The width of the signal stripline and the width of the gap determine the Z_0. The losses are influenced by the dimensions of the metalization pads.

A variety of coplanar stripline structures has been made with different lengths, tapers and curves. The simulator tool was used to determine the minimal curve radius. If the radius of a curve is too small, slot line modes are excited and will add losses. Extra gold strips before and after the curves make it possible to eliminate these modes by bonding. The coplanar waveguide pattern was transferred into a 2 µm thick negative resist, after which the Ti-Au contacts were defined by lift-off. The gold-layer had an approximate thickness of 250 nm.

Experiments

A network analyzer was used to measure the electrical response of the CPWs up to 40 GHz. In figure 2 the losses in dB/cm are shown for both a narrow and a wide CPW. The narrow one had a center conductor width of 15.4 µm, a gap of 10 µm and a ground electrode width of 55 µm. The wide CPW had a center conductor width of 100 µm a gap of 62.8 µm and a ground electrode width of 300 µm. Both had a length of 1.340 cm. Losses of 6 dB/cm at 40 GHz for the narrow CPW are comparable with the losses measured with coplanar electrodes on GaAs [7]. Because the losses at higher frequencies for the wide CPW are only 1.5 dB/cm, reflections between the probes give a ripple with a period of about 5 GHz (corresponding with a probe spacing of around 1 cm). Figure 3 compares the losses of the same narrow CPW with those of a similar U-curved CPW with bending radii of 200 µm. Because the losses are comparable we see no need for bondwires or airbridges to eliminate slot line modes.



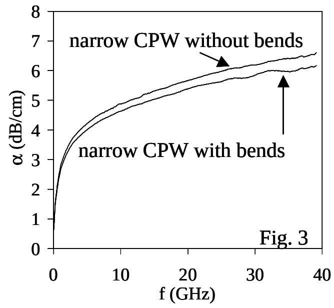
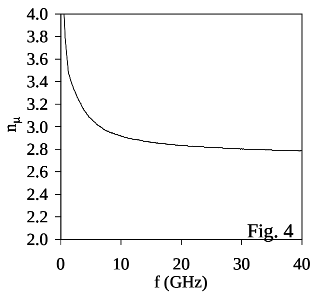
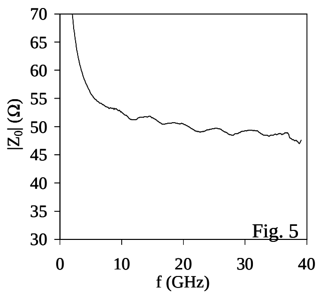


Fig. 2. The losses versus frequency of a narrow and wide, straight CPW.
Fig. 3. The losses versus frequency of a straight and U-curved, narrow CPW

Figure 4 shows the n_μ for the straight CPW. The value of around 2.8 at 40 GHz is clearly significantly lower than the optical group index N mentioned above. The absolute value of Z_0 is depicted in figure 5. The aimed at impedance of 50 Ω is fairly well hit and gives low reflections and thus a low S_{11}-parameter, which is equal for the narrow CPW with and without curves (see fig. 6).





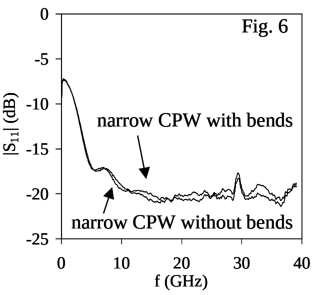


Fig. 4. Microwave n_μ versus frequency of a narrow, straight CPW.
Fig. 5. Absolute value of Z_0 versus frequency of a straight CPW.
Fig. 6. The S_{11}-parameter versus frequency for a straight and U-curved, narrow CPW.

In formula (1) R represents the series resistance and is related to the dimensions and conductivity of the metallic conductors. Because of the skin-effect, it is also a function of frequency. The skin-effect is given by:

$$\delta_s = \frac{1}{\sqrt{\pi f \mu_R \mu_0 \sigma}}, \qquad (2)$$

in which δ_s is the effective field penetration depth, and has a value of 383 nm at 40 GHz for Au-metalization. Since we only had a gold thickness of 250 nm, R is relatively big. It causes the impedance at low frequencies to be proportional with:

$$Z_0 \propto \sqrt{\frac{1}{f}}. \qquad (3)$$

This explains why in figure 6 the impedance close to zero increases rapidly. Because the loss coefficient $\alpha(f)$ is a function of the dimensions of the CPW, a thicker gold layer would lower the propagation losses for the lower frequency range. In future experiments gold electroplating will be used to get a metallization thickness of three times the skin depth.

Conclusions

We measured coplanar waveguides fabricated on semi-insulating InP. A straight coplanar waveguide with a central conductor width of 15.4 µm showed losses of less than 6 dB/cm and an n_μ of 2.8 at 40 GHz. Losses for this CPW with sharp curves are comparable, and for a bigger CPW even as low as 1.5 dB/ cm. These first measurement data look promising for use in broadband, TW MZ-modulators on InP.

References

[1] W.K. Burns, M.M. Howerton, R.P. Moeller, R. Krähenbühl, R.W. McElhanon and A.S. Greenblatt, “Low Drive Voltage, Broad-Band $LiNbO_3$ Modulators With and Without Edge Ridges”, Journal of Lightwave Technology, vol. 17, no. 12, pp. 2551-2555, Dec. 1999.

[2] K.Satzke, D. Baums, U. Cebulla, H. Haisch, D. Kaiser, E. Lach, E. Kühn, J. Weber, R. Weinmann, P. Wiedemann and E. Zielinski, “Ultrahigh-bandwidth (42 GHz) polarization-independent ridge waveguide electroabsorption modulator based on tensile strained InGaAsP MQW”, Electronic Letters, vol. 31, no. 23, pp. 2030-2032, 1995.

[3] C. Rolland, “InGaAsP-based Mach-Zehnder modulators for high-speed transmission systems”, in Proceedings of the OFC ’98, 1998. pp. 283-284.

[4] T. Uitterdijk, H. van Brug, F.H. Groen, H.J. Frankena, C.G.M. Vreeburg and J.J.G.M. van der Tol, “Integrable polarization insensitive InGaAsP/InP Mach-Zehnder switch”, in Proceedings Integrated Photonics Research ‘96, 1996, pp. 486-489.

[5] R. Spickermann, S.R. Sakamoto and N. Dagli, “In traveling wave modulators which velocity to match?”, in Proceedings IEEE/LEOS ’96, 1996, pp. 97-98.

[6] R.E. Neidert, S.C. Binari, T.Weng, “Dielectric constant of semi-insulating indium phosphide”, Electronic Letters, vol. 18, pp. 987-988.

[7] N. Dagli, “Wide-Bandwidth Lasers and Modulators for RF Photonics”, IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 7, July 1999.

[8] N.A.F. Jaeger, F. Rahmatian, H. Kato, R. James, E. Berolo, Z.K.F. Lee, “Velocity-Matched Electrodes for Compound Semiconductor Traveling-Wave Electrooptic Modulaters: Experimental Results”, Microwave and Guided Wave Letters, vol. 6, no. 2, 1996.