A Velocity-Matched Traveling-Wave Mach-Zehnder Modulator on InP

J.H. den Besten[1], D. Caprioli[1], R. van Dijk[2], F.E. van Vliet[2], W. Pascher[3], J.J.M. Binsma[4], B. Smalbrugge[1], T. de Vries[1], X.J.M. Leijtens[1] and M.K. Smit[1]

[1]COBRA, Eindhoven University of Technology
Den Dolech 2, P.O. Box 513, 5600 MB, Eindhoven, The Netherlands
Tel. (+31) 40 2473420, Fax (+31) 40 2448375, E-mail: j.h.d.besten@tue.nl
[2]TNO Physics and Electronics Laboratory, The Hague, The Netherlands
[3]Allg. und Theoretische Elektrotechnik, FernUniversität Hagen, Germany
[4]JDS Uniphase, Eindhoven, The Netherlands

We report a traveling-wave Mach-Zehnder (MZ) modulator on InP that is both velocity- and impedance-matched. The V_π of a device with 2-mm-long phase shifters was measured to be 6 V and the static extinction ratio to be higher than 20 dB at 1550 nm. Its measured 3-dBe bandwidth is 9 GHz. This is much lower than simulated (>50 GHz). The discrepancy can partly be attributed to an unexpectedly high electrode contact resistance, the cause of which has been identified.

Introduction

Since the direct modulation speed of semiconductor lasers is limited to about 40 GHz, external modulators are needed to reach even higher bandwidths. Integration of both devices reduces (expensive) fiber-chip couplings. Integrated laser-MZ-modulator chips have been reported for instance in [1, 2]. To have the most efficient interaction in a traveling-wave Mach-Zehnder modulator, the modulating microwaves should travel along the phase-shifter with a low attenuation and at the same speed as the optical carrier. The Mach-Zehnder modulator we described in [3] was suitable for integration with semiconductor optical amplifiers but was bandwidth limited to about 20 GHz mainly by its microwave attenuation and impedance mismatch. The microwave attenuation can be greatly reduced by narrowing the ridge waveguide width. In addition, this enables a velocity- and impedance matched design. We realized these improvements in a modulator described in this paper, to obtain possible operation beyond 50 GHz.

Design

In [4], we discussed the layerstack design of the fabricated Mach-Zehnder, consisting of two 2×2 multi-mode interference couplers connected by two phase shifters (Fig. 1).

Figure 1: Photograph of the realized Mach-Zehnder modulator. Size: 4.6×0.75 mm.

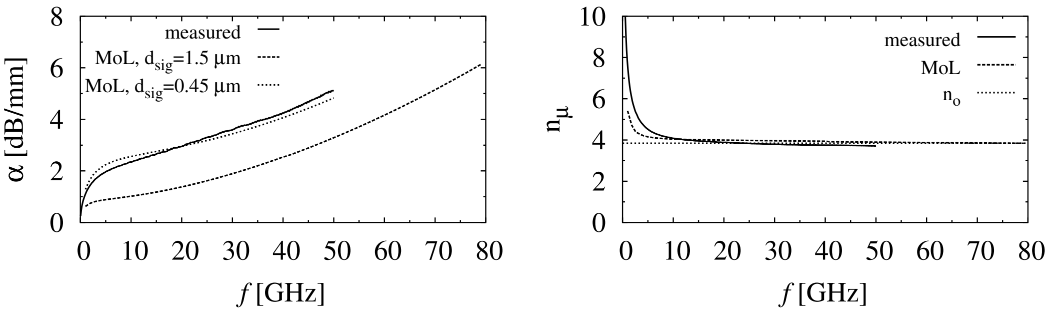

Figure 2: Measurements (up to 50 GHz, at 8 V reverse bias) and Method-of-Lines simulations (up to 80 GHz) of the microwave attenuation α (*left*) and microwave index n_μ (*right*). The also plotted optical group index n_o indicates a good velocity match.

The three main parameters that influence the microwave loss in an InP-based traveling wave modulator are the waveguide width (dielectric loss) and gold thickness and signal line width (metallic loss). They also determine the microwave index and characteristic impedance. The impedance goes up with decreasing waveguide width, since the capacitance decreases as well. A reduced conductor loss causes the impedance to decrease if the signal line is made wider. Finally, a bigger gap between signal and ground increases the impedance because of a lower conductance in the buffer layer. As a compromise between all parameters, we chose a ridge width of 1 μm with a signal line of 2 μm wide and a signal-ground gap of 8 μm. Then, the microwave attenuation is lowest, the velocity match is almost perfect and the impedance match is good.

From an optical point of view, reducing the waveguide width has both an advantage and a disadvantage. A ridge width of 1 μm is smaller than the cut-off width for the fundamental optical mode in a shallowly-etched waveguide. Therefore, a deeply-etched waveguide must be used. Changing from a 4-μm-wide shallowly etched waveguide [3] to a 1-μm-wide deeply etched waveguide will increase the optical insertion loss, but will reduce the microwave index and increase the optical group index from 3.66 to 3.84, enabling an easier to achieve velocity match.

With the optimized parameters discussed above, we simulated the structure (dashed lines in Fig. 2). Since the simulated microwave index matches the optical group index, the modulator will only be limited by the microwave attenuation. The 3 dBe bandwidth will then be reached at the frequency where the driving signal has decreased by 6.41 dB at the end of the modulating section [5]. For a 2-mm-long modulator, this will be at a frequency > 50 GHz.

Experiments

Fig. 3 (*left*) shows the measured switching curves for a modulator with 2-mm-long phase shifters. The switching voltages are 6 and 8 V for TE- and TM-polarisation, respectively. High scatter losses from very rough waveguide side walls cause both polarisations to suffer from high insertion losses. Small-signal S-parameters were measured from 45 MHz to 50 GHz. Fig. 3 (*right*) shows typical results of a 950-μm-long phase shifter including bond pads. From the low S_{11} and S_{22} values (< -15 dB), it can be concluded that the impedance is matched well. Extracted transmission line components are $R = 35\ \Omega$/mm,

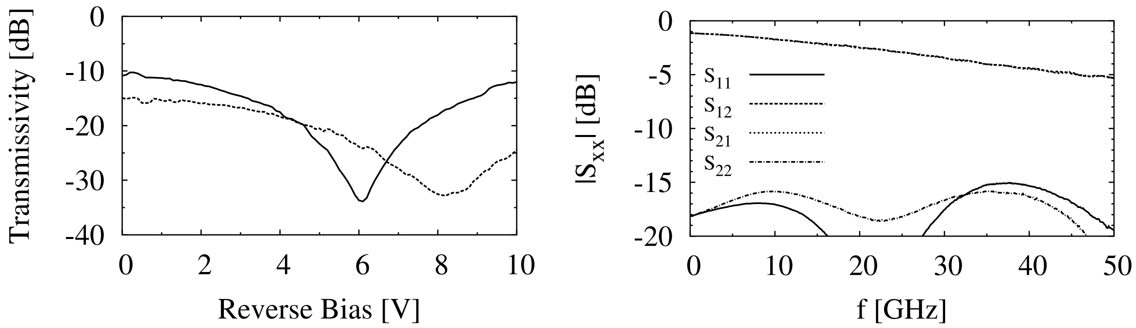

Figure 3: *Left*: DC switch characteristic for the cross port of a 2-mm-long 2×2 MZI modulator oriented in the $[1\bar{1}0]$ direction. The solid and dashed lines represent TE- and TM-polarization, respectively. *Right*: Measured small-signal S-parameters of a modulator with an active length of 950 nm.

$L = 630 \cdot 10^{-12}$ H/mm, $C = 0.207 \cdot 10^{-12}$ F/mm and $G = 0.31 \cdot 10^{-6}$ S/(GHz·mm). From these, we calculated an impedance value of about 55 Ω for higher frequencies. To obtain the de-embedded microwave attenuation and index, we compared two phase-shifters of differents lengths but with equal probe pads [6]. Fig. 4 shows both parameters are depending on the amount of reverse bias. Since a higher reverse bias causes a bigger depletion region and thus a smaller volume of doped material in the waveguide ridge, the microwave absorption will decrease when the reverse bias is increased. Therefore, it is favourable for the obtainable bandwidth if the non-modulated arm of the Mach-Zehnder modulator is biased as well. Then, the modulation arm can be driven at a higher reverse bias to put the modulator in the quadrature point. An increase in reverse bias reduces the microwave index at the same time due to the lower attenuation. This is because of the slow-wave character of the transmission line.

To compare the measurements with the simulations, we inserted two measured curves in Fig. 2. It is clear that the microwave losses are much higher than expected. We discovered that this was caused by fabrication imperfections. First of all, the plated gold is not a solid block but contains little holes. This forces the microwave current running along the signal line to take a longer path. The microwaves therefore experience an increased resistance and attenuation. At the same time, the velocity is much less affected by the spongy morphology since the field is flowing outside the metal. In addition, the plated gold was much thinner (0.85 μm) than aimed at (1.5 μm). Measured values of the signal line series resistance confirmed that the effective (= solid) signal electrode thickness is varying from 370 to 643 nm. It is clear that this increased metallic loss has a huge impact on the modulator bandwidth.

Finally, we determined the electro-optical bandwidth using a back-to-back 18-GHz photodetector. The measured relative optical response is shown in Fig. 4 (solid line). The 3 dBe bandwidth is 9 GHz, although typically we obtained values around 5 GHz. This is much lower than simulated with a designed signal line thickness of 1.5 μm (> 50 GHz, dashed line) and calculated from the extracted microwave parameters (> 30 GHz, dotted line). We discovered that during fabrication, the highly-doped InGaAs contactlayer underneath the signal electrode was removed. This introduces a high contact resistance and thus a big series resistor in front of the diode, in the order of 1 kΩ·mm. As a consequence, part of the modulating voltage will be over this resistor, instead of over the depletion region.

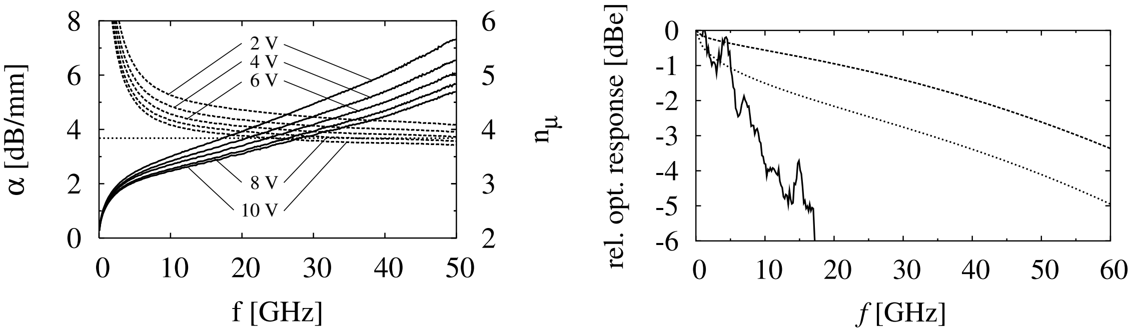

Figure 4: *Left*: Microwave attenuation (solid lines) and index (dashed lines) for different reverse biases extracted from SS-measurements. The straight, dotted line represents the optical group index. *Right*: Relative optical response for a modulator with 2-mm-long phase shifters: simulated (3 dB bandwidth > 50 GHz, dashed line), calcaluted from ss-measurements (> 30 GHz, dotted line) and measured (9 GHz, solid line).

Especially at higher frequencies, when the impedance of diode capacitance decreases, the optical response suffers from this.

Conclusions

We realized a traveling-wave Mach-Zehnder modulator on InP that is both velocity- and impedance-matched. The V_π was measured to be 6 V and the static extinction ratio < 20 dB at 1550 nm. Unfortunately, the measured 3 dBe bandwidth was reduced by fabrication imperfections: a poor quality of plated gold and an the absence of the contact layer reduced the bandwidth from > 50 GHz (simulations) to 30 GHz (S-parameter measurements) and 9 GHz (electro-optic measurement).

Acknowledgements

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