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Highest Performance Open Access Modulators on InP Platform

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Abstract *High-speed (80 Gbps), low drive-voltage ($V_\pi L$ = 0.9 V-cm), low insertion loss (IL = 11 dB) travelling wave electrodes based Mach-Zehnder modulators are presented on an open-access InP platform. ©2022 The Authors*

Introduction

With the increase in demand for streaming services and cloud storage platforms, large-capacity optical fibres are becoming ever more important in short- and middle-reach links, such as those in datacentre networks [1]. Coherent transceivers with fast modulators are key in fulfilling this demand and realizing them on an open access integrated platform provides a cost effective solution. [2] reported an introduction of integrated InP phase modulators (PMs) with a lumped electrode design on an n-doped substrate with a bandwidth of 30 GHz. This works presents the inclusion of travelling wave electrodes based electro-optic phase modulators to the HHI open access InP platform. To this end, a dedicated multi quantum well (MQW) based stack was developed. The performance of the modulator (3 dB bandwidth/ V_π) presented here is 15 GHz/V. It is better than [2] (3.75 GHz/V) and the proposed design in [3] (13.6 GHz/V). This paper is organized in the following way: Section 2 describes the design for the high-speed phase modulator; Section 3 presents the Mach-Zehnder Modulator (MZM) performance and finally, Section 4 concludes the paper.

Device design

The core of the electro-optic PM is a deep ridge waveguide with p-i-n diode configuration fabricated on a semi-insulating InP substrate, in which the corresponding low electrical losses result in higher bandwidths compared to n-doped substrate. The intrinsic part of the diode consists of MQWs fundamentally different from that used in actives (gain, absorption). Together with the passive stack (optimized for propagation), there are three waveguide architectures in the platform. To connect the different waveguide architectures efficiently and with low reflections, high-density butt-joint transition elements are developed [4]. The insertion loss of the butt-joint transition element from passive waveguide to the modulator waveguide is about 1.5 dB. In order to achieve additive contributions of the electro-optic effects (Pockels effect and quantum-confined Stark effect) for TE input, the crystal orientation is changed from the existing [110] to [1$\bar{1}$0].

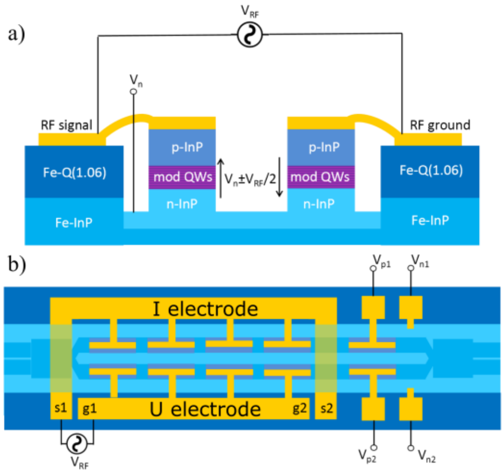

Figure 1. a) Schematic of the cross-section of an electro-optic phase modulator on the HHI open access InP platform. The circuit illustrates the push-pull scheme b) Top view of the capacitively loaded TWEs.

The high-speed modulator is comprised of twin modulator waveguides (Fig. 1a). The periodically capacitively loaded transmission lines (TL) (adapted from [5]) are designed to have an equivalent characteristic impedance of 50 Ohm in order to be impedance matched to commercial driver electronics and test equipment, and therefore minimize reflections. Fig. 2 shows the measured reflections (S11) for a 3 mm long MZM. The reflections are below -10 dB at least until 60 GHz.

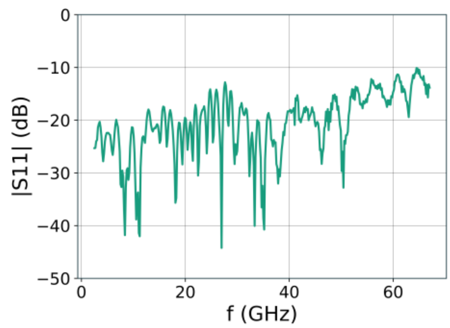

Figure 2. Measured S11 amplitude of a 3mm long MZM.

The high-speed modulators are implemented with a travelling wave electrode (TWE) and are driven in a push-pull scheme which offers two advantages:

1. When the optical and electrical waves are velocity matched, the device bandwidth is only limited by the electrical propagation losses as opposed to RC constants in conventional lumped electrode designs.
2. It results in a series connection of the two diodes and as such, halves the capacitance. This means twice as much diode area can be contacted for a given length in order to achieve 50 Ohm transmission lines compared to a single-driven TWE modulator. This finally results in half the $V_\pi L$ for a push-pull driven device.

In general, TWE sections offer a rich design space for parameter tuning (for ex., waveguide width, RF track width, etc.) compared to lumped electrode design where independent parameter tuning is not possible.

250 µm long TWE sections with a fill factor of 0.75 make up the electro-optic phase modulator (EOPM). Without add-ons, the EOPM acts as a pure phase modulator, while a MZM is formed by adding multimode interference (MMI) couplers at the input and output of the EOPM (Fig. 1b). For biasing purposes, the MZM is also equipped with independent DC phase control electrodes (V_{p1}, V_{p2} in Fig. 1b) that have a length of 500 µm and fill factor of 1 but are otherwise similar to the modulator sections in the TWE. For convenience, a MZM with x mm long TWE section will be referred to as x mm long MZM in this paper.

Device Performance

For the DC characterization, TE polarized input light is coupled into a 6 mm long MZM and the power from one of the output arms is recorded. Reverse bias voltage applied on the U and I electrodes (as labelled in Fig. 1b) is varied with one of the n-pads (V_{n1}, V_{n2}) contacted as ground. Fig. 3 shows the resulting extinction ratio map.

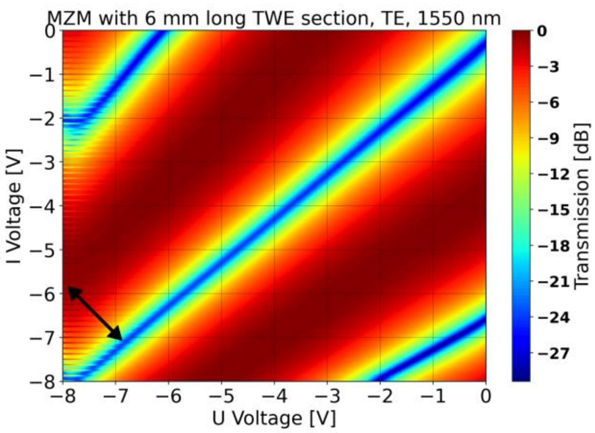

Figure 3. DC extinction ratio map of a MZM with 6 mm long TWE section. The black line indicates the working point of -7 V bias voltage giving a V_π of 1.5 V.

The V_π can be deduced from the plot to be 1.5 V at a bias of -7 V (as indicated by the black line in Fig. 3), which translates to a $V_\pi L$ of 0.9 V-cm. The extinction ratio is better than 25 dB.

The small signal 3 dB bandwidth is measured using a lightwave component analyzer (LCA). An electrical GS probe is used for applying the high-speed signal to one electrode end of the modulator. The other electrode end is terminated with a 50 Ohm resistor. A constant voltage source is used for biasing the MZM to the working point of 8 V. The measured small signal RF response of a 3 mm long MZM (12 TWE sections) is plotted in Fig. 4. The 3 dB BW for the MZM is around 45 GHz. Also, the insertion loss of the MZM, including 2 butt joint transitions and fibre coupling, is measured to be 11 dB.

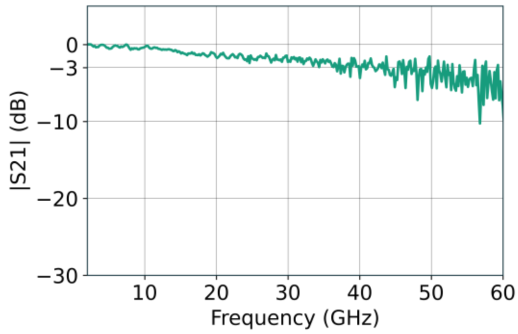

Figure 4. Small signal RF response of a 3 mm long MZM. The 3 dB BW is ~ 45 GHz.

The effective index of the optical wave (n_{opt}) is estimated to be 3.8 and for the electrical wave (n_μ) is evaluated to be 4.2. Eq. 1 can be used to evaluate the achievable bandwidth f_{3dB} for a modulator of length L [6]:

$$f_{3dB} = \frac{1.4c}{L\pi(n_\mu - n_{opt})} \quad (1)$$

where c is the speed of light. For the 3 mm long MZM, f_{3dB} is 112 GHz. This means the bandwidth is currently limited by electrical losses rather than velocity mismatch.

The 3 dB bandwidth and V_π are crucial parameters to gauge the performance of the phase modulator and both are dependent on the modulator length. The figure of merit, 3 dB bandwidth/V_π, eliminates the length dependence of the individual parameters. For the 3 mm long MZM, this figure is 15 GHz/V.

For large signal characterization, non-return to zero (NRZ) sequences are input to the MZM. To boost the bit pattern generator output voltage (0.5 V), a 66 GHz amplifier was used. Fig. 5 shows the measured optical eye diagrams for 3 mm long and 5 mm long MZMs at bit rates of 80 Gbps and 64 Gbps respectively. The extinction ratio for the two cases is 5.9 dB and 8.1 dB respectively.

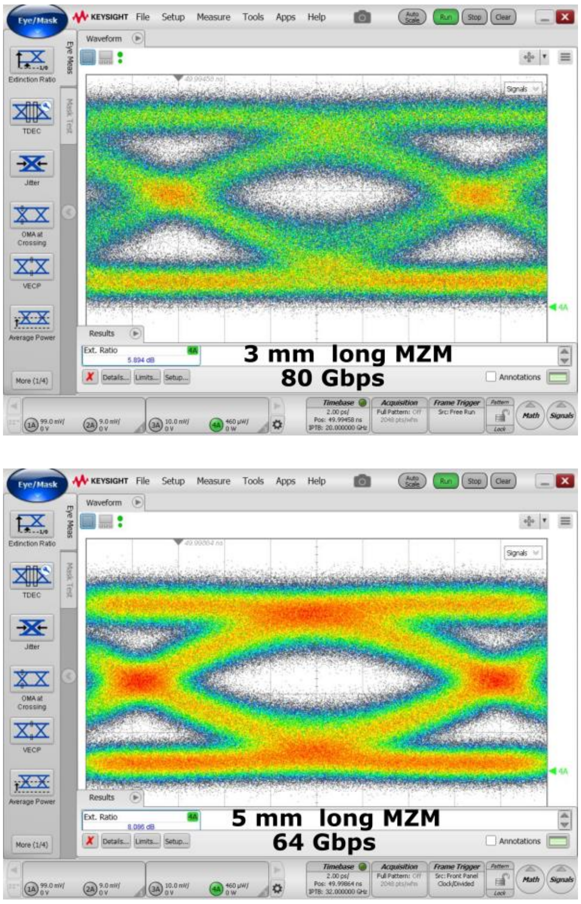

Figure 5. Eye diagrams of a 3 mm long MZM at a bit rate of 80 Gbps and a 5 mm long MZM at a bitrate of 64 Gbps.

Conclusions and Outlook

The highest performance modulators (15 GHz/V) available in open access InP platforms have been presented. NRZ operation up to 80 Gbps has been demonstrated for a 3 mm long MZM. The MZM has a small signal 3 dB bandwidth of 45 GHz, a V_π of 3 V and an insertion loss of 11 dB (including fibre coupling). We believe that the insertion loss can still be significantly lowered with improvements in waveguide lithography and the active-passive butt joint transition. The high-speed modulators that are now available on the open access platform can help achieve complex multi-level coherent transmission systems on an InP photonics integrated circuit.

Acknowledgements

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