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High Bandwidth InP based Mach-Zehnder Modulator for 112 Gbps Transmission

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Abstract

A very high speed InP Mach-Zehnder modulator based on quantum-confinement Stark effect in push pull configuration is proposed. This travelling-wave electrode provides modulator with extremely low electrical and optical loss. The device exhibits a 3 dB electro-optic BW of over 90 GHz and a Vπ of 2.0 V which enables 112 Gbps data transmission with very low power consumption and low optical loss.

Introduction

Low power consumption, high speed and compact modulators are highly in demand in the modern data transmission networks to meet the requirements from further rapid growth of internet and multimedia data transfers. Realizing a higher baud rate requires higher speed coherent optics such as a transmitter and a receiver as well as the management of RF loss. Regarding the optical transmitter, a high-speed modulator photonics integrated circuit (PIC) alone can have very high RF loss because of velocity and Impedance mismatch from the driver signal, so it must be assembled very close to a high-speed driver ASIC in one package commonly known as co-packaged optics (CPO) to reduce RF loss. Current optical modulators used are mainly the type using the electrooptic effect in dielectric materials such as LiNbO3 and the type using the electro-absorption effect of the semiconductors. The Electro-absorption modulator is small, can be operated with a low-voltage drive, and enable the monolithic integration with a laser diode. However, EAMs have higher optical loss and there are several problems in the LiNbO3 modulators, such as a large module size of 15 x 120 mm, large driving voltage of 3 to 8 V, and” DC drift” in which the driving condition is varied due to application of the DC voltage. Mach Zehnder Modulators based on indium phosphide (InP) have shown higher 3-dB bandwidths and lower driving voltages and the benefit of monolithic integration capability. In this paper, we present a push-pull travelling wave MZM on InP which can operate up to 112Gb/s. This paper has two sections about the transmitter design, one explaining Modulator design and other one explaining Fabrication.

Mach-Zehnder Modulator Design

Proposed design Exploits QCSE and Franz-Keldysh effect to introduce change in real and imaginary refractive index in the waveguide. Because of the big refractive index change based on QCSE compared with other Electro-optic effects, such as the Kerr's effect, Pockels effect and free carrier absorption effect, the InP-based MZM operates at a low driving voltage. The excitonic absorption characteristic changes in response to an induced field, which results in an effective index change in the MQWs through Kramer's-Kronig relations. This effect is called Quantum Confined Stark Effect, and can be observed in below figures. Figure 1 shows the tilting of bands (QCSE Effect) when reverse biased.

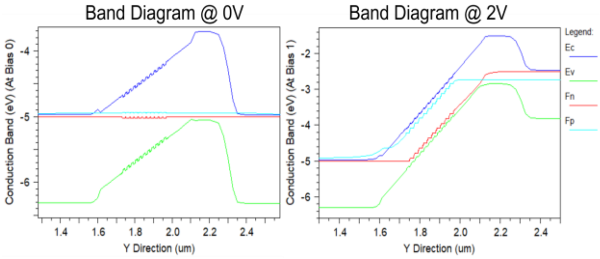

Fig. 1: Illustration of QCSE Effect of current design

Figure 2 shows the change in refractive index in the MQW explaining Kramer's-Kronig relations.

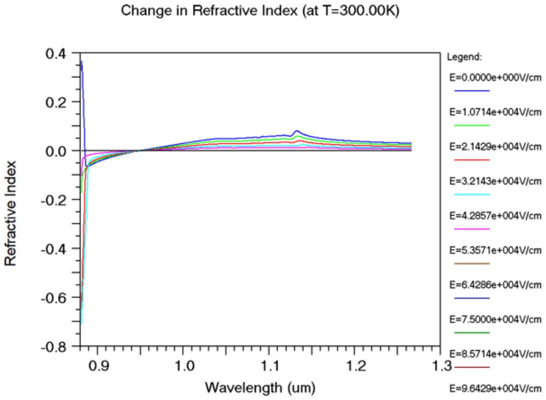

Fig. 2: Change in RI because of QCSE

The design has n-i-p-n configuration since the main obstacle to higher speed modulation with an InP-based MZM is the high series resistance of the semiconductor. In particular, a p-doped InP layer has contact and bulk resistances that are about one order of magnitude higher than those of an n-doped InP layer. Therefore, the resistance of the p-doped cladding layer must be lower if we are to extend the BW without degrading other properties such as the V_π and the optical propagation loss. So, P doped cladding layer has been replaced with a thick n doped InP layer and a thin p doped layer is introduced above intrinsic region to block electron and leakage current, so that the electric field can be induced which also decreases the capacitance of device due to carrier blocking. The doping levels in the waveguide have been chosen such a way that the loss due to electrons and holes is minimized close to the optical mode and still manage to induce large electric field in intrinsic region.

The Device contains 11 InGaAsP MQWs having QWs thicker than the barriers with band-gap sufficiently away from the operating wavelength 1310nm to ensure low loss transmission, two separate confinement heterostructure layers, an Fe-doped SI-InP substrate (Semi-Insulating InP layer), and an n-InP cladding on top of SI-InP substrate. To avoid losses of the electrical signal and the optical signal caused by the p-type semiconductor layer, both the signal and ground electrode layers are made with n-type semiconductor layers in which the loss is about 1/20 of that in the p-type. The design is based on Coplanar strip line configuration to enable the differential operation for push pull and fabrication simplicity also CPS structure provides higher bandwidth and better impedance matching compared to co-planer waveguide (CPW) structure.

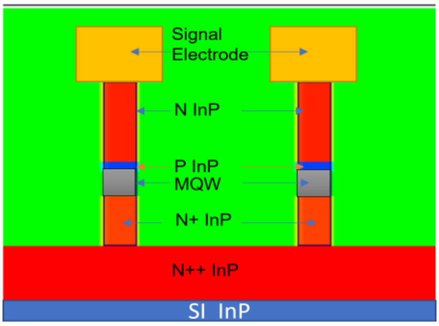

Fig. 3: Proposed Design

The dimensions of the modulator have been optimized to achieve the best performance and fabrication ease. Most critical factors in the device design are the waveguide width, signal to ground gap, length, doping levels and etch depth. the structure is shown in figure 3

Simulation Results

The modulator is to be operated in push pull mode. There's a trade-off between the Vπ and the bandwidth of modulator. Insertion loss of the modulator is around 2.6 dB to 3 dB and extinction coefficient is 17.4 db. Figure 4 shows the modulation response of the modulator. The Q point can be chosen at 1 V. Vπ of the MZM is 2 V but in push pull it'll be less, normally it should be half the single end Vπ but since we have n-i-p-n structure the arms have different effects when bias is reversed.

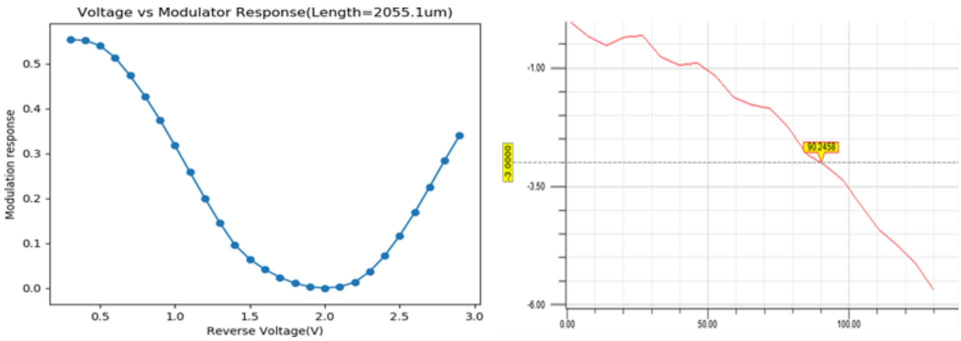

Fig. 4: Modulation and frequency response of MZM

Figure 4 shows the modulation and frequency response of the modulator. The bandwidth of this modulator is simulated to be above 90 GHz. L* Vπ of the modulator is constant and is 4.11 V.mm.

The device has been modelled as a complete transceiver device for transmission up to 112 Gbps with custom made driver and photo-diode specs in Active Optical cable circuit. Figure 5 shows different eye diagrams at different data rates. Estimated BER and Extinction ratio at 112 Gbps data rate is approximately $1*10^{-7}$ and 10 dBm respectively.

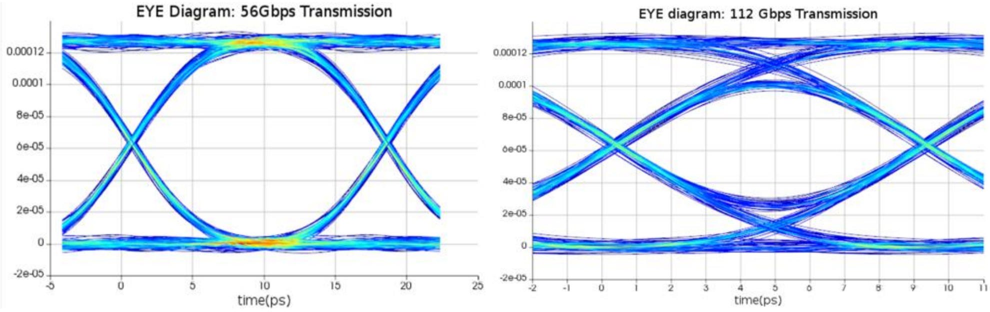

Fig. 5: Eye diagrams of 56 Gbps and 112 Gbps data transmission.

MZM Fabrication

The fabrication of the MZM (Mach-Zehnder Modulator) involves a precise 4-step lithography process, with two of these steps being particularly critical. The process commences with the thorough cleaning of the wafer, utilizing O_2 plasma for this purpose, followed by the removal of the native oxide layer using a solution of 1:10 $H_3PO_4 : H_2O$. Subsequently, a layer of SiN_x is deposited through Plasma-Enhanced Chemical Vapor Deposition (PECVD). The deposition of a hard mask follows, during which the thickness and refractive index of the SiN_x layer are rigorously examined for any variations using tools like the reflectometer (as depicted in Figure 6) and spectroscopic ellipsometry.

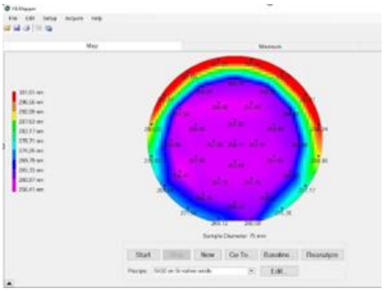

Fig. 6: Screenshot of the reflectometer measurement where we are mapping the thickness of the SiNx layer on the wafer. In this example we deposited 260nm of SiNx, the deposition rate of SiNx is increased at the edges compared to the center of the wafer.

For the initial lithography step, we employ Electron Beam Lithography, using the newly introduced high-plasma-etching-resistant photoresist CSAR 0.13. Following the lithography step, we proceed with the etching of the SiN_x hard mask, using CHF_3 as the etchant. Subsequently, we perform the etching of the semiconductor, employing Cl_2 gas for the InP/InGaAsP layers. SEM images of the etched MESAs are presented in Figures 7 and 8. Our etching process yields an impressive etch depth of $3.5\mu m$ with exceptionally straight walls. The MESA maintains its orthogonal shape throughout the entire etching process of the InP/InGaAsP layers.

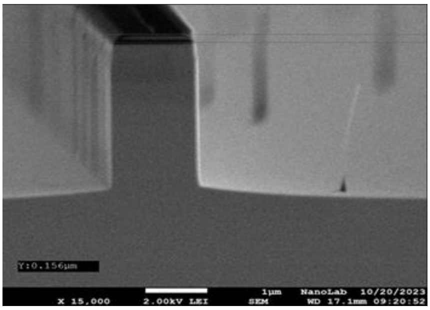

Fig. 7: MESA structure

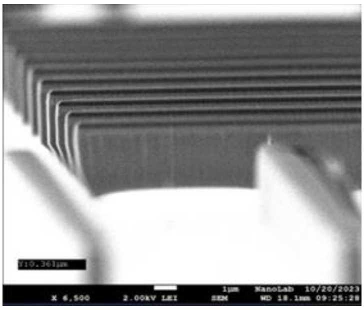

Fig. 8: SEM picture of an array of waveguides

This SEM image displays a MESA structure with an etch depth of $3.5\mu m$. The uppermost dark layer, which measures 200nm in thickness, is the SiNx hard mask utilized for deep etching. The etched structure adheres closely to the designed specifications with a linewidth of 1.5um and exceptionally straight walls. Notably, the wall exhibits minimal roughness, measuring less than 50nm. In the background, you may observe wire-like features, which are artifacts resulting from the (EBL) exposure process and represent the cross-section of the electron beam used during the exposure.

The subsequent step in our process, following the removal of the hard mask from the MESAs, involves the deposition of a passivation layer made of SiO_2. For this purpose, we employ the same PECVD chemistry mentioned earlier. Additionally, we utilize bisbenzocyclobutane (BCB) for planarization, primarily as mechanical support for our structures. After planarization, we proceed with the etching of the BCB, followed by creating openings at the tops of the MESAs for metallization. We use Ti/Pt/Au for the p-type metallization at the MESA's summit. This step necessitates lithography, and we employ the EVG aligner along with the MAN-440 photoresist, a negative and thick photoresist utilized for the lift-off process. Figure 9 provides a visual representation of the metal layer, which is deposited in the center of the arches and atop the MAN-440 before the lift-off process.

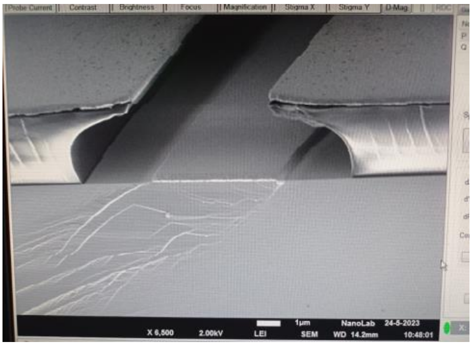

Fig. 9: This SEM image captures the MAN-440 photoresist just prior to the lift-off process. A layer of Ti/Pt/Au has been deposited, both on top of the MAN-440 and in the central region where the metal layer is needed. The MAN-440 has a thickness of $3.5\mu m$. Notably, the overhangs on the left and right sides are strategically designed openings essential for the subsequent lift-off process.

Conclusion

We have designed an n-i-p-n heterostructure MZM with travelling wave electrode that can enable 112 Gbps data transmission without the need of any high format modulation schemes. This device promises reduced RF loss compared to a conventional p-i-n mzm. A 100 Gb/s NRZ modulation with a dynamic ER of over 10 dB was successfully demonstrated. The fabrication is currently in progress, but simulated results show this modulator can be of great use as active optical cables in data centers and for optical communication.

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References and Footnotes

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