High Speed Travelling Wave Carrier Depletion Silicon Mach-Zehnder Modulator

Christopher T. DeRose[1], Douglas C. Trotter[1], William A. Zortman[1] and Michael R. Watts[2]
[1]*Applied Photonic Microsystems*
Sandia National Labs, P.O. Box 5800, Albuquerque, NM 8718, USA
[2]*Massachusetts Institute of Technology Research Laboratory of Electronics*
77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
cderose@sandia.gov

Abstract: We present the first demonstration of a travelling wave carrier depletion Mach-Zehnder modulator impedance matched to 50 Ω. This device has a bandwidth of 24 GHz and a halfwave voltage length product of 0.7 V-cm, placing it among the best in its class.

1. Introduction

Over the last 25 years optical links have grown from a solution for long haul telecommunication to a solution for data communication over distances of a few tens to hundreds of meters. As optical data communications systems become the solution for tens of meter and shorter distance links, the cost per Gbps will ultimately become the driving performance metric. Due to its high yield and the high volume manufacturing infrastructure, silicon is an excellent candidate for future low cost optical data communications device components. Here we present a high speed, travelling wave silicon carrier depletion Mach-Zehnder modulator (MZM).

2. Device Fabrication and Theory

The MZM was fabricated on a silicon-on-insulator (SOI) wafer with 3 µm of buried oxide and an initial 250 nm thick silicon layer. The devices were defined using an ASML deep ultra-violet (DUV) laser scanner and silicon etch. Arsenic and Phosphorous implants were used to achieve an *n*-type and *p*-type doping level of $\sim5\times10^{18}/cm^3$ in the sp-n junction. Electrical contact from the device to aluminum bus lines was made through tungsten vias. A cross-section of the active part of the device can be seen in Fig. 1.

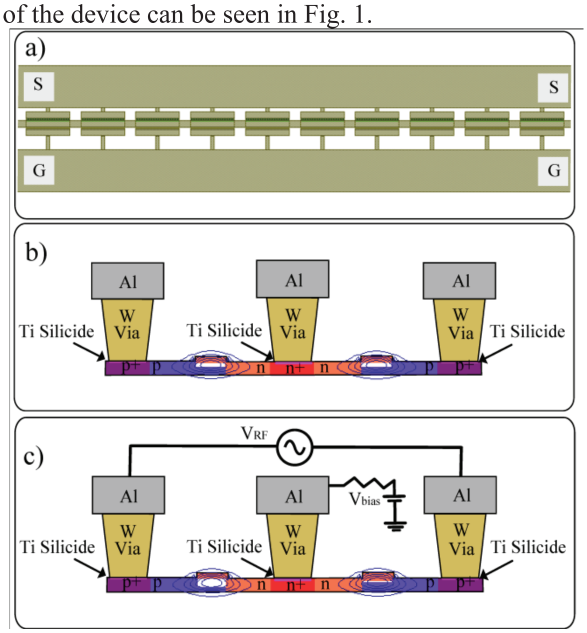

Fig. 1 a) Schematic of the capacitively loaded slot line b) push-pull carrier depletion MZM with no applied RF signal, the depletion region is represented by white, a contour plot of the Ex field for the mode of each arm of the device is also shown c) with an applied RF voltage, the effective index in one arm of the device is increased (depletion region widens) while it is decreased in the other (depletion region shrinks).

There have been several previous demonstrations of silicon MZMs [1-3]. Previously reported devices have had low impedance due to the high capacitance of the p-n junction and relatively high $V\pi$-L products. The MZM we present here was designed as a push-pull segmented travelling wave device. Using this approach we were able to able to achieve both impedance matching to 50 Ω and velocity matching to the waveguide mode for the first time.

In a segmented design, the active p-n junctions are attached periodically to a high impedance travelling wave electrode. By periodically adding the capacitive p-n junctions both impedance and velocity matching can be

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achieved simultaneously [4]. The simultaneous impedance and velocity matching can be seen with a simple analysis. The impedance and microwave velocity index of an unloaded electrode are given by

$$Z_0 = \sqrt{\frac{L_0}{C_0}} \text{ and, } n_0 = c\sqrt{L_0 C_0} \quad (1)$$

where, Z_0 is the impedance of the unloaded line, n_0 is the microwave velocity index, L_0 is the inductance of the unloaded line, C_0 is the capacitance of the unloaded line and c is the speed of light. Adding additional capacitance results in

$$Z_L = \sqrt{\frac{L_0}{(C_0+C_L)}} \text{ and, } n_L = \sqrt{L_0(C_0+C_L)} \quad (2)$$

where, Z_L is the impedance of the loaded line, n_L is the microwave velocity index of the loaded line and C_L is the loading capacitance. By requiring $n_L Z_L = n_0 Z_0$ where Z_L is 50 Ω and n_L is the group index of the optical mode achieves impedance matching and by simultaneously enforcing $C_L = (n_L^2 - n_0^2)/(cZ_L n_L)$ velocity matching is achieved.

The unloaded travelling wave electrode was a slot line with an impedance of 95 Ω and was fabricated in metal1 which is a 1μm Ti/TiN/AlCu/TiN stack the slot line had a microwave index of 2.3. The p-n junctions which were connected in series had a capacitance of 0.41 fF/μm at 0V bias . In order to achieve velocity matching to the optical mode which has a group index of 4.5 we fabricated our device with 50 μm active segments and a fill factor of 0.6.

3. Experimental Results

The electrical S-parameters and modulator bandwidth for MZMs with effective active lengths of 0.5, and 1.5 mm were measured with an Agilent E8364B vector network analyzer. We found 3dB bandwidths of 24 GHz and 14 GHz for the 0.5mm and 1.5 mm long modulators respectively. We found that the devices had better than 20 dB return loss up to 30 GHz, showing excellent impedance matching to 50 Ω. Furthermore, a half-wave voltage of 0.7 V-cm was measured for a 2 mm long modulator.

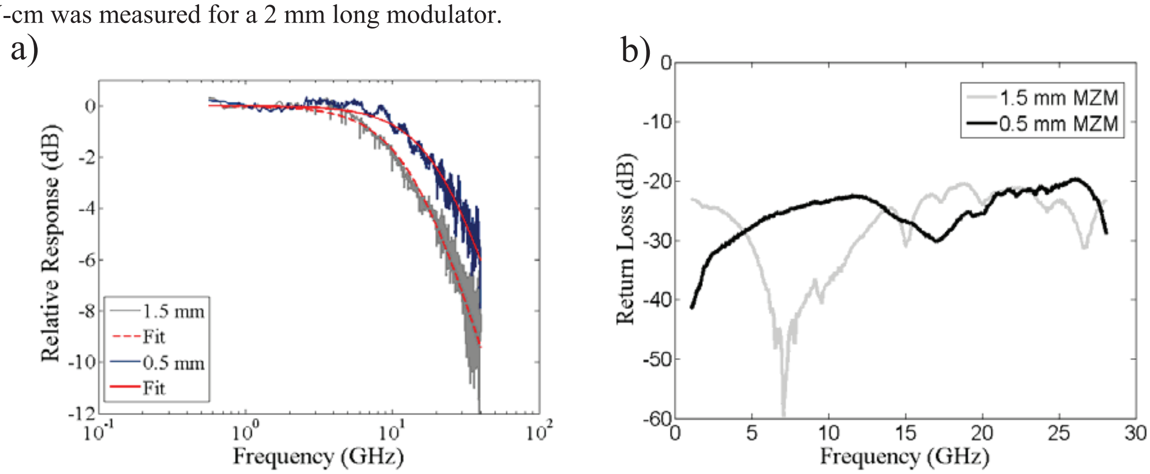

Fig. 2 a) measured bandwidth of 1.5 and 0.5 mm capacitively loaded MZM b) electrical S11 of same modulators showing better thand 20 dB return loss up to 30 GHz.

4. Conclusions

We have demonstrated a capacitively loaded push-pull travelling wave carrier depletion silicon MZM which was impedance matched to 50 Ω for the first time. We measured a bandwidth of 24 GHz for a 0.5 mm modulator and 14 GHz for a 1.5 mm modulator placing the bandwidth of this device among the best in its class. Furthermore, a Vπ∗L of 0.7 V-cm was measured for a 2 mm modulator, which to the best of the authors knowledge is the best yet reported for this class of modulator. Finally, the device bandwidth is currently limited by series resistance in the p-n junction and can be improved in future designs.

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5. References

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