Traveling Wave Electrodes for Wide-Bandwidth Substrate-Removed Electro-Optic Modulators

Selim Dogru and Nadir Dagli
Electrical and Computer Engineering Department, University of California at Santa Barbara, Santa Barbara, CA
e-mail: dagli@ece.ucsb.edu

Abstract: Traveling wave electrodes suitable for wide bandwidth substrate removed electro-optic modulators containing buried electrodes are reported. Experimental results indicate modulator bandwidths in excess of 35 GHz along with sub volt drive voltage.

1. Introduction

Optical modulators are essential components for fiber optic communication, optical signal processing, RF photonics and instrumentation. Low drive voltage and wide bandwidth operation are highly desirable. Substrate removal techniques allow creation of very high vertical index steps. This results in very strong vertical confinement. Furthermore, very strong external fields overlapping very well with the optical mode can be applied using buried electrodes made out of thin doped semiconductor layers. This results in very efficient modulation. In our previous work, we demonstrated 0.3 V V_π Mach Zehnder Modulators (MZMs) using substrate removal technology in bulk GaAs [1] and 0.8 V V_π in InP using multi quantum well cores [2]. However wide bandwidth operation of such devices has not been demonstrated yet. In this paper, we describe a traveling wave version of such modulators and present experimental results showing modulator electrical to optical bandwidths in excess of 35 GHz.

2. Device description

The top and cross sectional schematic of the modulator is shown in Figure 1. It is a traveling wave Mach-Zehnder intensity modulator based on loaded line approach. Modulator electrode consists of a coplanar line which is periodically loaded with small capacitive elements made out of modulator arms. Modulator arms are formed in a compound semiconductor epilayer removed from its substrate and glued onto a transfer substrate using the polymer Benzocyclobutane (BCB) as the glue. Epilayer is etched away except in the gap of the coplanar electrode. Both sides of the epilayer are processed resulting in a so called staircase waveguide of width *w*. This is just like a rib waveguide but each side of the rib is etched on one side of the epilayer. Doped *n*-InP layers are used as buried electrodes. A *p* layer in between these *n* layers forms two back to back *p-i-n* diodes and prevents conduction between *n*-InP buried electrodes. Electrically isolated active modulator sections are formed in the interferometer arms using boron implantation. Cross section of an active part of an interferometer arm is shown Figure 1. These are 100 μm long and can be modeled using lumped circuit elements. We can take slices of Δx wide in the cross section and each slice can be modeled using appropriate resistance and capacitance per unit length as shown in Figure 1. Entire equivalent circuit of the electrode is also given in this figure. Here L_u, C_u, R_u and G_u are the inductance, capacitance, resistance and conductance per unit length of the unloaded coplanar line. Y_M is the admittance of the RC circuit representing each active section due to the loading of active modulator sections.

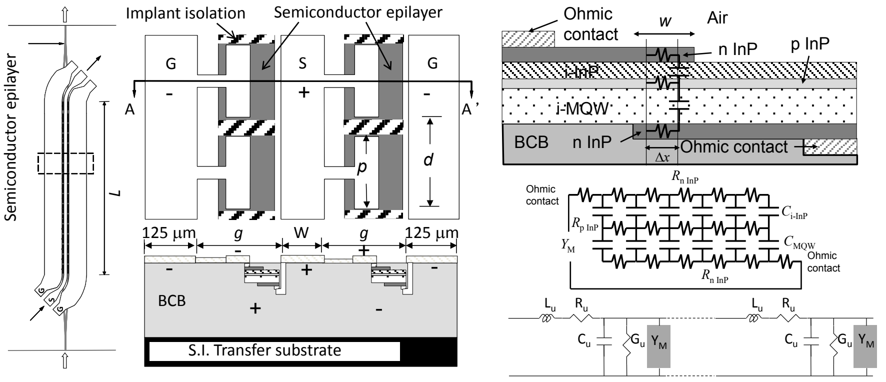

Figure 1: Top and cross sectional schematics along AA' of the traveling wave modulator and detail of one of the interferometer arms. Electrical equivalent circuit of the electrode as well as the detail of Y_M are also shown. w = 1 μm, W = 64 μm, p = 90 μm, d = 100 μm and g = 18 μm.

3. Results and discussion

Microwave performance of these electrodes was measured using an automatic network analyzer up to 35 GHz. Using measured s-parameters, electrode phase velocity, v_{ph}, characteristic impedance, Z_c, and attenuation coefficient, α, were determined [3]. Modulator small signal modulation response was calculated using these parameters and well known expressions [4]. These results are shown in Figure 2.

978-1-61284-0733-9/12/$26.00

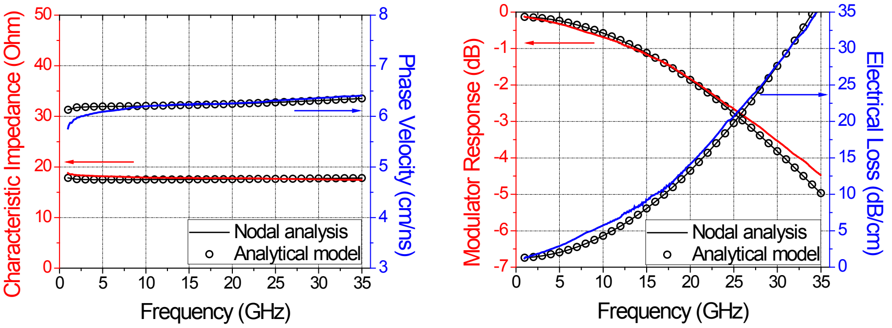

Figure 2: Electrode phase velocity, v_{ph} , characteristic impedance, Z_c , and attenuation coefficient, α and small signal modulation response of a modulator with 2 mm long electrode.

We also calculated these parameters using the equivalent circuit shown in Figure 1. L_u, C_u, R_u and G_u are determined independently using well known coplanar line equations. In the calculations we used independently measured parameters for the resistances and capacitances shown in the ladder network that model the admittance Y_M of active modulator sections that periodically load the coplanar line. Sheet and contact resistances were measured using TLM patterns on the fabricated chip as 500 and 250 $\Omega/\square$ for upper and lower n-InP layers respectively and $5\text{x}10^{-6}$ Ohm.cm^2 for upper and lower contacts. Capacitance of the active modulator section was also measured using large area diodes and a CV meter as 45 nF/cm^2. This agrees with independently measured single arm capacitance of 4.5 pF/cm for MZM. This measured capacitance is the series combination of the capacitances of the top and bottom *p-i-n* diodes or $C_{\text{i-InP}}$ and C_{MQW} . In this design *i*-InP layer of the top *p-i-n* is much thinner (10 nm) compared to i region of the bottom *p-i-n* containing the MQW layer (150 nm). Hence $C_{\text{i-InP}} >> C_{\text{MQW}}$ and the measured capacitance is essentially C_{MQW} . This also shows that the actual resistance of the *p*-InP layer does not matter. At frequencies above a few GHz, the impedance of $C_{\text{i-InP}}$ sections become very low. So to a very good approximation every node on the branch containing $R_{\text{p-InP}}$ elements is shorted to the node above of the branch made out of $R_{\text{n-InP}}$ elements. Therefore we get parallel combination of two resistive branches. Since $R_{\text{n-InP}} << R_{\text{p-InP}}$, overall resistance of the path that brings the contact voltage to top side of the MQW region is dominated by the resistance of the *n*-InP layer and the actual resistance of the *p*-InP layer does not matter. We verify this by modeling the data in two ways. One way is to solve the equivalent circuit shown for Y_M using a nodal analysis numerically. The other way is to assume that $C_{\text{i-InP}}$ paths are short circuits and only resistive branches made out of $R_{\text{n-InP}}$ exist on both sides of the MWQ region represented by C_{MQW} elements. In this case, an analytical expression can be found for Y_M . Results of modeling this way are labeled as analytical model in Figure 2. It is seen that these two models agree very well both with each other and experimental data. The electrical to electrical (3 dB) bandwidth of this modulator is 27 GHz. Electrical to optical bandwidth (6 dB) is in excess of 35 GHz. The drive voltage is not given since measurements are under way but earlier results on very similar modulators in which arms are connected in series yielded 2 V V_π for 1.8 cm long electrode. Hence this design in which arms are connected in parallel should have a V_π of less than 1 V.

4. Summary

Traveling wave electrodes for ultra-low voltage substrate removed electro-optic modulators are reported. These electrodes are based on loaded line approach and consist of a regular coplanar line periodically loaded with active modulator sections. Modulation response based on experimental results indicates bandwidths in excess of 35 GHz with sub volt drive voltage. Furthermore, experimental results are modeled to very good accuracy using independently determined process parameters which makes further engineering and optimization possible.

Acknowledgement: This work is supported by a DARPA STTR grant.

References

[1] JaeHyuk Shin, Yu-Chia Chang, and Nadir Dagli, "0.3 V Drive Voltage GaAs/AlGaAs Substrate Removed Mach-Zehnder Intensity Modulators" Appl. Phys. Lett., vol.92, 201103, 2008.

[2] Selim Dogru, Jae Hyuk Shin and Nadir Dagli, "InGaAlAs/InAlAs Multi Quantum Well Substrate Removed Electro-optic Modulators", Proceedings of IEEE Photonics Society Annual Meeting (IEEE Photonics 2011), Paper ThJ2, pp. 739-740, Arlington, VA, 9-13 October 2011.

[3] JaeHyuk Shin, Steven R. Sakamoto, and Nadir Dagli, "Conductor Loss of Capacitively Loaded Slow Wave Electrodes for High Speed Photonic Devices," IEEE/OSA J. of Lightwave Technology, vol. LT-29, No. 1, pp. 48-52, Jan. 2011.

[4] Nadir Dagli," Wide Bandwidth Lasers and Modulators for RF Photonics," IEEE Trans. Microwave Theory Tech., vol. MTT-47, No. 7, pp. 1151-1171, July 1999.