Novel Transmission Lines for 32 Gbit/s Si MZI Modulator

F. Merget, S. Sharif Azadeh, J. Mueller, B. Shen, M. P. Nezhad, J. Hauck, and J. Witzens
Integrated Photonics Laboratory, RWTH Aachen University, Sommerfeldstraße 24, 52074 Aachen, Germany

We present MZI Silicon Photonics modulators with an advanced transmission line design which overcomes bandwidth limitations arising from crosstalk and improves linear RF-losses. A -3.66 dBc electro-optic bandwidth of 16.2 GHz with a 50 Ω matched dual drive voltage of 4 V is experimentally validated for a 4 mm long device.

I. INTRODUCTION

Over the last decade, increasing demand for higher bandwidth and reach in datacenters has motivated externally modulated single mode subsystems and their realization with silicon technology [1]. One of the key components of such interconnect systems is the electro-optic modulator [2-5]. Various technologies and architectures have been investigated in Silicon Photonics (SiP) technology such as plasma modulators in both injection and depletion mode [6,7], polymer modulators [8], and strained silicon modulators based on the non-linear $\chi^{(2)}$ effect [9,10]. Amongst the aforementioned technologies, modulators based on plasma dispersion in a reverse biased pn-junction with Mach-Zehnder Interferometer (MZI) architecture have proven so far to be the most reliable and robust approach for high-speed operation in thermally unstable environments. The bandwidth of such modulators is mainly limited by the signal attenuation in the transmission line due to the combined resistive and capacitive loading from the pn-junction inside the phase modulators [11]. Therefore, in the present work our focus is on improving the characteristics of the RF transmission lines. We incorporate two architectural improvements to the transmission lines [12]: 1) An advanced driving scheme that suppresses the cross-talk between the complementary signals applied to the two adjacent arms of an MZI modulator driven in push-pull configuration. 2) Signal line extensions that reduce the resistance between the metal lines and the waveguide with minimal effect on phase matching, transmission line impedance and waveguide losses. The design modifications have been experimentally validated.

II. ADVANCED SIGNAL DRIVING SCHEME

As illustrated in Fig. 1, the fabricated modulators are based on an MZI architecture where each of the two interferometer arms consist of individual phase modulators operated in push-pull configuration. The phase modulators have a length of $L = 4$ mm. They are each driven by a ground-signal (GS) transmission line with a targeted impedance of 50 Ωhm. From the measured phase shifts vs. applied voltage, we extract a $V_gL = 4.0 \text{ V cm}$ and $V_{C2}L = 1.6 \text{ V cm}$ for single ended operation resulting in full extinction for a 4 V dual drive in push-pull configuration. The total optical loss of the modulator (waveguide to waveguide) is measured to be 8.8 dB. The signal lines of the two arms are adjacent to each other (GSSG electrode configuration). In a typical push-pull configuration, the cathodes of both diodes are connected to the signal lines. To ensure push-pull operation, data-

Fig. 1. Left: Top view (a), cross-sectional schematic (b) and microscope image (c) of the investigated modulator. Right: Signals for the conventional (d) and the advanced driving scheme (e).

signal ‘S’ as well as the complementary data signal ‘$\overline{S}$’ are required. Since S and $\overline{S}$ are different signals from an RF point of view, cross-talk between the signal lines can become an issue unless the two SG transmission lines are separated by a significant distance [7]. Since cross-talk is frequency dependent, it directly affects the modulation bandwidth. In our modulators, we are driving both signal lines with the same RF signal, thus making cross-talk a non-issue. In order to operate the MZI in push-pull operation, we flip the polarity of one of the diodes. Furthermore,
in order to maintain reverse biasing of the pn-diodes, we add a DC bias to one of the signal lines. The signals applied to the two arms are depicted in Fig. 1(e). Using this driving scheme we demonstrate a -3 dBe electro-optic bandwidth of 16.2 GHz (Fig. 2(c), blue curve) limited by RF-losses resulting from a direct trade-off with optical insertion losses driven by the implant concentrations, as well as by residual phase mismatch [12].

III. ADVANCED CONTACTING SCHEME FOR PN-JUNCTION

The RF signal loss $\alpha$ of the transmission line is the primary factor fundamentally limiting the bandwidth of the modulator once cross-talk has been suppressed. It is primarily generated by the Ohmic losses resulting from the current flowing through the silicon between the metal lines to the pn-junction. These losses (Fig. 2(a)) depend on the linear series resistance $R_{\text{WG}}$ ($\Omega$ m) and the linear capacitance $C_{\text{WG}}$ (F/m) of the pn-diode [11]:

$$
\alpha(f) = \alpha_0 \sqrt{\frac{f}{f_0}} + R_{\text{wg}}(2\pi \cdot f \cdot C_{\text{wg}}) \cdot Z_s = \alpha_0 \sqrt{\frac{f}{f_0}} + \alpha_1 f^2
$$

where $f$ is the RF frequency, $Z_{\text{TL}}$ is the transmission line impedance and $\alpha_0$ corresponds to losses induced by the resistance of the metal lines. At higher frequencies, the second term becomes dominant. In order to reduce the losses and thus extend the bandwidth of the modulator, we introduced metal extensions from the signal and the ground lines as depicted in Fig. 2(b). A low resistance path is thus provided between the metal lines and the pn-junction. The current flow is forced to be transverse in the widely spaced (10 μm) electrode extensions, and the extensions are interdigitated to reduce the excess capacitive load. Thus, the metal extensions have only minimal impact on the transmission line impedance $Z_{\text{TL}}$ and phase velocity $v_{ph}$ of the transmission lines as compared to placing the metal electrodes closer to the waveguide.

Fig. 2. (a) Conventional design of a loaded transmission line versus (b) design with interleaved electrode extensions. (c) Electro-optic transmission coefficient of the modulator with (green) and without (blue) interleaved electrode extensions. Dashed lines are measured and solid lines are fits taking RF-losses (eq. (1)) and phase-mismatch into account. (d) 32 Gbit/s eye diagram (PRBS 7) of the modulator (2 $V_{\text{ph}}$ dual drive) measured with a 40 GHz receiver from U2T visualized with a 20 GHz real time oscilloscope.

Fig. 2(c) compares the electro-optic transmission coefficients $S_{21}$ of the modulator with and without electrode extensions (both have the driving scheme with suppressed cross-talk). The solid lines show a fit based on equation (1) and taking phase mismatch into account. The introduction of the electrode extensions improved the electro-optic bandwidth from 14.5 GHz to 16.2 GHz (-3 dBe crossing of the VNA data corrected for cable losses and receiver bandwidth). The 11% improvement was reduced from the expected 27% due to residual phase mismatch [12] that could be significantly improved in a second device iteration.

IV. CONCLUSION

With the aid of two structural improvements in the RF transmission line design of MZI-based silicon photonics modulators, i.e., the addition of interdigitated electrode extensions and a modification of the signal driving scheme, the bandwidth of the modulators has been significantly increased. These improvements are implemented independently of design constraints related to phase and impedance matching. The authors would like to acknowledge funding by the European Research Council (ERC) under contract no. 279770 and by the German Ministry for Research and Education (BMBF) under contract no. 16BP12504. The devices were fabricated via the shuttle service OpSiS at Singapore’s Institute of Microelectronics (IME).

REFERENCES