40 Gbit/s silicon optical modulator for high-speed applications

L. Liao, A. Liu, D. Rubin, J. Basak, Y. Chetrit, H. Nguyen,
R. Cohen, N. Izhaky and M. Paniccia

A high-speed silicon optical modulator based on the free carrier plasma dispersion effect is presented. It is based on carrier depletion of a *pn* diode embedded inside a silicon-on-insulator waveguide. To achieve high-speed performance, a travelling-wave design is used to allow co-propagation of the electrical and optical signals along the length of the device. The resulting modulator has a 3 dB bandwidth of ∼30 GHz and can transmit data up to 40 Gbit/s.

Introduction: Owing to its promise of low cost, high yield, and device integration, silicon (Si) was first explored as a platform for integrated photonics more than two decades ago [1]. While high-speed modulation is an essential requirement of any optical communications link, achieving it in Si had been challenging because the material does not exhibit any appreciable electro-optic effect. It was not until 2004 that modulation in the gigahertz range was first realised in Si [2]. Since then there has been significant progress in further performance improvements of the Si modulator [3–5]. In this Letter, we discuss the design, characterisation, and recent high-speed performance of a Si optical modulator based on the free carrier plasma dispersion effect. This device has 30 GHz bandwidth and can transmit data up to 40 Gbit/s. Such high-speed modulation is unprecedented in Si and will enable integrated Si photonic chips for next generation communication networks as well as future high performance computing applications.

Design: To date, the most proven way to achieve high-speed optical modulation in Si is via the free carrier plasma dispersion effect, where a change in free carrier density results in a change in the refractive index of the material, which, in turn, modifies the optical phase of light passing through it. Modulation speed, as a result, is determined by how fast the free carriers can be injected into or removed from the area in which the optical mode is travelling. Three device configurations, namely, MOS capacitor [2, 3], reverse-biased *pn* diode [5], and forward-biased *pin* diode [4], have been proposed to achieve phase modulation in Si. The optical modulator presented here is based on a reverse-biased *pn* diode. This design is chosen because its device capacitance is much reduced compared to that of the MOS capacitor and its electric-field induced majority carrier dynamics is inherently faster than the carrier generation and/or recombination processes of the forward-biased *pin* diode.

Fig. 1*a* is a top-down schematic of the Si modulator. It is based on an asymmetric Mach-Zehnder interferometer (MZI) with a *pn* diode embedded in each of the two arms. The waveguide splitter and combiner are 1×2 multimode interference (MMI) couplers. Fig. 1*b* is a schematic of the *pn* diode phase shifter. It comprises a p-type doped Si rib waveguide having rib width of 0.6 µm, rib height of 0.5 µm, and an etch depth of 0.22 µm, along with an n-type doped Si cap layer 1.8 µm wide. This thin (0.1 µm thick) cap layer is formed using an epitaxial Si growth process and is used for *pn* junction formation and electrical contact. To ensure ohmic contact between Si and metal, the thin cap layer ∼0.3 µm away from the rib edge and two slab regions ∼1 µm away from both sides of the rib edge are heavily doped for the N-contact and P-contacts, respectively. Because of the ultrafast transverse movement of the carriers in response to the reverse-bias voltage, the modulator speed is governed by the resistance capacitance (RC) time constant of the device and metal contact parasitics. To minimise the RC limitation, a single sided Si cap layer design is used to reduce the capacitance of the phase shifter. Furthermore, a travelling-wave electrode design based on a coplanar waveguide structure, as shown in Fig. 1*b*, is used. The RF travelling-wave coplanar waveguide and modulator optical waveguide are carefully designed so that both electrical and optical signals co-propagate along the length of the phase shifter with similar speeds, while, at the same time, the RF attenuation is kept as small as possible. The RF signal is coupled to the travelling-wave electrode from the optical input side and termination load is added to the output. To realise high-speed performance, it is critical to optimise the termination impedance. Two techniques are used to terminate the modulators. In the first approach, the modulator chip is flip-chip bonded to a printed circuit board (PCB) with low-loss RF connectors. The PCB is designed for high-speed performance with PCB traces having ∼0.3 dB/cm RF loss at 40 GHz. Surface mount resistors, serving as device terminations, are then bonded to PCB traces to which the output ends of the travelling-wave electrodes have been electrically connected. In a second approach, titanium nitride (TiN) resistors are monolithically integrated with the Si modulator. Fig. 2 is a microscope image showing the TiN resistor connected to the output end of the travelling-wave electrode.

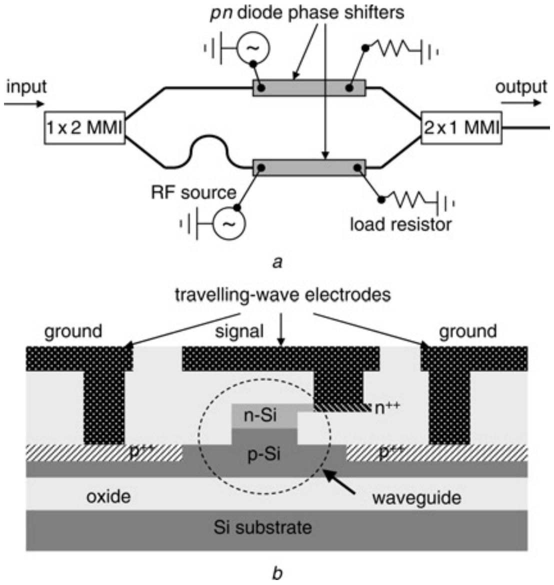


Fig. 1 *Top view of asymmetric MZI Si modulator and schematic cross-section of pn diode waveguide phase shifter*

a Top view of asymmetric MZI Si modulator
b Schematic cross-section of *pn* diode waveguide phase shifter

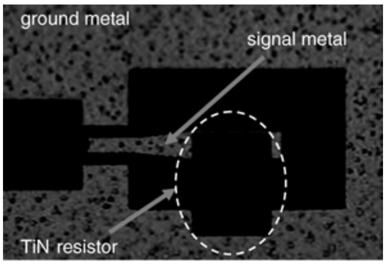


Fig. 2 *Optical microscope image of TiN resistor monolithically integrated with Si modulator*

Experimental results: The MZI Si modulators used for high-speed experiments have a 1 mm-long *pn* diode phase shifter embedded in each arm. The total on-chip optical loss is less than 4 dB. It includes 1 dB passive waveguide transmission loss, 0.5 dB MMI coupler loss, and 1.8 dB phase shifter loss, which can be attributed primarily to the dopants in the *pn* diode. The current devices do not have optical tapers integrated, so coupling loss to and from optical fibre is ∼9 dB/facet. Device phase efficiency, defined as V_π (where V_π is the bias voltage required for π-rad phase shift and L is the device length), is <4 V cm. Note that the current device has not been optimised in terms of minimising optical loss. Simulation shows that lower doping concentrations can be used to reduce phase shifter loss to less than 1 dB without significant impact on optical phase efficiency or device bandwidth. Furthermore, optical tapers have been designed and tested which should improve coupling loss to ∼3 dB/facet.

The high-speed performance of the Si modulator is characterised by measuring both its 3 dB frequency roll-off and its data transmission capability. To measure frequency roll-off, a signal generator is swept from 100 MHz to 50 GHz. This RF signal is combined with a DC voltage using a bias Tee to ensure reverse-bias operation for the entire AC voltage swing. The DC-coupled signal after the bias Tee, which is the input drive voltage to the Si modulator, is first measured against frequency using a digital communications analyser (DCA) electrical module with 63 GHz bandwidth. This RF signal is then connected to the travelling-wave electrode of one of the phase shifters to induce optical modulation. For a modulator whose termination resistor is mounted onto the PCB, the RF signal is supplied to the PCB connector. For a modulator integrated with the TiN resistor, the drive signal is sent to the electrode using a high-speed RF probe. The modulator is biased at quadrature by tuning the DC voltage applied to the other phase shifter. A continuous-wave laser beam at ~1550 nm is coupled into the Si modulator via a lensed fibre. The modulated optical output is collected using another lensed fibre and is connected to a DCA optical module with a 53 GHz photo-receiver. To obtain the frequency response of the Si modulator for a constant input drive voltage, the photo-receiver output is normalised by the measured drive voltage for all frequencies. A detailed study of bandwidth performance is performed by varying the termination resistance. Although the high-frequency characteristic impedance of the modulator is 20 Ω, the highest modulation bandwidth is obtained with ~14 Ω termination. We believe the reason for this is that because a 50 Ω drive is used, the RF reflections resulting from the multiple impedance mismatches may actually serve as pre-emphasis of the RF signal and equalise the losses at high frequencies. The normalised frequency response data for two modulators, one with a surface mount termination resistor and the other with an on-chip TiN resistor, is given in Fig. 3. In both cases, the termination resistance used is ~14 Ω, and the resulting 3 dB roll-off frequency is ~30 GHz.

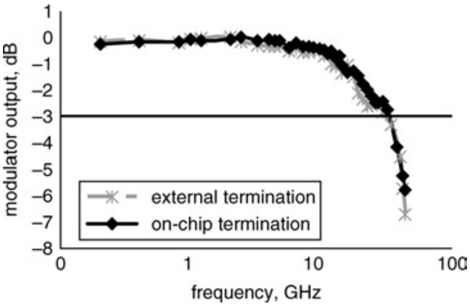
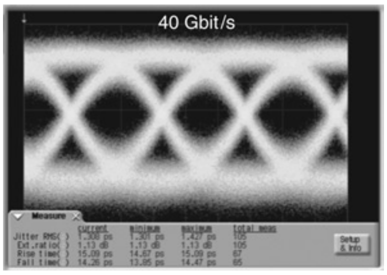


Fig. 3 *Normalised optical response of two MZI Si modulators against RF frequency*

To study the data transmission performance of the modulator, RF signal from a pseudorandom bit sequence (PRBS) generator with $[2^{31} - 1]$ pattern length is first amplified using a commercially available 50 Ω modulator driver. The amplified output of 6 V_{pp} is combined with 3 V_{DC} to again ensure reverse-bias operation for the entire AC voltage swing. This DC-coupled signal is connected to the input of the travelling-wave electrode of one of the phase shifters. Nonetheless, one can drive phase shifters in both of the MZI arms in push-pull configuration. With the optimal termination resistance of 14 Ω, a clearly open optical eye diagram at a bit rate of 40 Gbit/s is obtained, as shown in Fig. 4. The measured extinction ratio (ER) of the optical eye is 1.1 dB, close to the expected value of 1.2 dB given the 4 V cm phase efficiency of the device and that >35% of the drive voltage is lost owing to the driver-modulator (50–20 Ω) impedance mismatch. To increase ER without impacting speed, one approach is to place multiple segments of 1 mm phase shifters in a chain and drive them individually with the correct delay.



	current	minimum	maximum	total meas
Jitter RMS( )	1.308 ps	1.301 ps	1.427 ps	105
Ext.ratio( )	1.13 dB	1.13 dB	1.13 dB	105
Rise time( )	15.09 ps	14.67 ps	15.09 ps	67
Fall time( )	14.26 ps	13.85 ps	14.47 ps	65

Fig. 4 *Optical eye diagram of MZI Si modulator (shows data transmission at 40 Gbit/s)*

Conclusion: A Si modulator based on a reverse-biased *pn* diode design is presented. By employing travelling-wave electrodes with both external and on-chip termination, we achieved 30 GHz 3 dB bandwidth and 40 Gbit/s data transmission. Such high-speed modulation is unprecedented in Si and represents another significant step forward in realising Si photonic solutions for future high-speed communication and computing applications.

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L. Liao, A. Liu, J. Basak, H. Nguyen and M. Paniccia (*Intel Corporation, 2200 Mission College Blvd, SC12-326, Santa Clara, CA 95054, USA*)

E-mail: ling.liao@intel.com

D. Rubin, Y. Chetrit, R. Cohen and N. Izhaky (*Intel Corporation, S.B.I Park Har Hotzvim, Jerusalem 91031, Israel*)

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