High-Speed Silicon-Organic Hybrid (SOH) Modulator with 1.6 fJ/bit and 180 pm/V In-Device Nonlinearity

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Abstract We report on a 40 Gbit/s silicon-organic hybrid (SOH) modulator with 11 dB extinction ratio. A novel electro-optic chromophore with record in-device nonlinearity of 180 pm/V leads to $V_\pi L = 0.5$ V mm and a low energy consumption of 1.6 fJ/bit at 12.5 Gbit/s.

Introduction Energy-efficient silicon electro-optic modulators are key components for future short-distance interconnects in data centers and high-performance computers [1]. Targeted energy consumptions are tens of fJ/bit for dense off-chip connections, and a few fJ/bit for global on-chip connections [1]. Over the last years, a variety of silicon modulators has been demonstrated based on free-carrier depletion, or injection in pn-diodes, or based on metal-oxide-semiconductor (MOS) structures [2, 3]. Carrier injection devices have typically very small voltage-length products of $V_\pi L = 0.36$ V mm [4], but the large carrier lifetime calls for pre-emphasis and limits the modulation speed to 20 GHz. The modulation energy per bit is usually in the pJ-range due to the forward bias of the diode. Carrier depletion modulators, in contrast, have been demonstrated to operate at data rates of up to 50 Gbit/s [5], but typically with $V_\pi L > 10$ V mm for non-resonant devices. Extinction ratios (ER) range from 3 dB to 8 dB at high data rates, and the lowest reported energy consumption is 200 fJ/bit [6]. Modulation energies can be significantly reduced by using resonant structures, such as ring resonators, microdisks or photonic crystal waveguides. The lowest energy consumption reported to date for a silicon-based modulator amounts to 3 fJ/bit with an ER of 3.2 dB [7]. However, both carrier injection and depletion type modulators are subject to an inherent coupling of amplitude and phase modulation, and resonant structures suffer from strong wavelength dependence and temperature sensitivity.

In this paper, we pursue a fundamentally different approach by combining silicon slot waveguides with electro-optic cladding materials in a non-resonant silicon-organic hybrid (SOH) device. Pure phase modulation is achieved by exploiting the linear electro-optic effect in the cladding, where we reached an in-device material nonlinearity of $r_{33} = (180\pm20)$ pm/V—the highest in-device value reported so far. For a 1 mm long device this leads to a $\pi$-voltage of $V_\pi = 0.5$ V measured at DC. At 12.5 Gbit/s we demonstrate data transmission with record-low peak-to-peak drive voltages of 125 mV pp, corresponding to an energy consumption of 1.6 fJ/bit. This is, to the best of our knowledge, the lowest energy consumption reported so far for silicon-based MZI modulators, a value that compares well even with best-in-class resonant devices. We further show that our device can be operated at symbol rates of at least 40 GBd, where an ER of better than 10 dB is achieved.

Silicon-Organic Hybrid Modulator

The schematic of a phase modulator is depicted in Fig. 1(a). It consists of a slot waveguide electrically connected to a coplanar transmission line through 60 nm thick doped silicon strips. The voltage applied to the transmission line drops across the narrow slot, resulting in a high electric field that strongly overlaps with the optical mode, Fig. 1(a). The waveguide is covered and the slot is filled with the electro-optic chromophore DLD164, see inset of Fig. 1(a). Modulation energies can be significantly reduced by using resonant structures, such as ring resonators, microdisks or photonic crystal waveguides. The lowest energy consumption reported to date for a silicon-based modulator amounts to 3 fJ/bit and has been achieved with a microdisk modulator operated at a data rate of 12.5 Gbit/s with a drive voltage of 1 V pp and an ER of 3.2 dB [7]. However, both carrier injection and depletion type modulators are subject to an inherent coupling of amplitude and phase modulation, and resonant structures suffer from strong wavelength dependence and temperature sensitivity.

In this paper, we pursue a fundamentally different approach by combining silicon slot waveguides with electro-optic cladding materials in a non-resonant silicon-organic hybrid (SOH) device. Pure phase modulation is achieved by exploiting the linear electro-optic effect in the cladding, where we reached an in-device material nonlinearity of $r_{33} = (180\pm20)$ pm/V—the highest in-device value reported so far. For a 1 mm long device this leads to a $\pi$-voltage of $V_\pi = 0.5$ V measured at DC. At 12.5 Gbit/s we demonstrate data transmission with record-low peak-to-peak drive voltages of 125 mV pp, corresponding to an energy consumption of 1.6 fJ/bit. This is, to the best of our knowledge, the lowest energy consumption reported so far for silicon-based MZI modulators, a value that compares well even with best-in-class resonant devices. We further show that our device can be operated at symbol rates of at least 40 GBd, where an ER of better than 10 dB is achieved.

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bearing pendant coumarin side groups is applied to the slot waveguide. These side groups both stabilize the glassy matrix and significantly enhance the poling efficiency [10].

Silicon waveguides are fabricated in IMEC by 193 nm deep-UV lithography on a 220 nm SOI wafer with a 2 µm thick buried oxide. The Mach-Zehnder interferometer (MZI) modulator, Fig. 1(c), consists of an MZI with two identical 1 mm long phase-modulators, Fig. 1(a). The two phase modulators are driven in push-pull operation by a coplanar waveguide (CPW, ground-signal-ground, GSG) as depicted in Fig. 1(c). The CPW consists of 600 nm thick copper lanes linked to the silicon modulator by 900 nm thick tungsten vias. The metallization stack is locally opened to expose the slot waveguide. Fig. 1(b) shows an SEM image of the fabricated phase modulator with its metal stack. We measure a slot width of 160 nm and a rail width of 210 nm. The electro-optic cladding is poled at elevated temperatures by applying a DC voltage across the ground electrodes. The voltage-length product of the MZI modulator was measured to be \( V_{CL} = 0.5 \ \text{V/mm} \) in the low-frequency limit. Taking into account the measured waveguide dimensions we calculate the corresponding in-device nonlinearity of the cladding to be \( r_{33} = (180\pm20) \ \text{pm/V} \). The fiber-to-fiber loss is 16.5 dB. The on-chip loss is approximately 6 dB for maximum transmission of the modulator.

**On-Off Keying Experiments**

A pseudorandom bit pattern generator (PPG) with a PRBS length of \( 2^{31}-1 \) drives the MZI modulator using a GSG picoprobe. A bias voltage of 2 V is applied at the same GSG electrodes by using a bias-T. A 50 Ω resistor terminates the CPW via a second picoprobe. Light from an external cavity laser (1550 nm, 5 dBm) is coupled to the silicon chip and modulated. The data signal is amplified and fed to a digital communications analyzer (DCA) and a bit-error ratio (BER) tester. A gate field of up to 250 V/µm is applied as depicted in Fig. 1(c) for increasing the conductivity of the thin silicon slabs [9].

Fig. 2 depicts NRZ OOK eye diagrams for data rates between 12.5 Gbit/s and 40 Gbit/s at a drive voltage of 950 mVpp. The ER exceeds 10 dB for all data rates. At 12.5 Gbit/s and 30 Gbit/s we measure Q²-factors of 22 dB and 19 dB, respectively, and the BER is below \( 1\times10^{-11} \). At 40 Gbit/s we measure a Q² of 15 dB and a BER of \( 1\times10^{-8} \). In a second experiment, we reduce the drive voltage of the modulator. Measured BER are depicted in Fig. 3(a) for data rates of 12.5 Gbit/s and 25 Gbit/s. The measured BER stays below the hard-decision \( 2^{nd} \) generation FEC threshold of \( BER = 2.3\times10^{-3} \) for drive voltages of 190 mVpp \((7 \ \text{fJ/bit})\) and 150 mVpp \((9 \ \text{fJ/bit})\) for 25 Gbit/s and 12.5 Gbit/s, respectively, when the modulator CPW is terminated. Due to the short 1 mm length, the device can also be operated without termination (“lumped”) at a data rate of 12.5 Gbit/s.

Next, we estimate the energy consumption of the modulator. As common in the field, we do this by calculating the dissipated RF power. Therefore, power consumption of laser, optical amplifier and electrical drivers is not included in these numbers. The estimated energy consump-
Currents flowing due to bias and gate voltages are measured to be below 2 nA and below 100 fA, respectively, contributing a negligible energy consumption of less than 1 aJ/bit. For a drive voltage such that we remain below the FEC-threshold in Fig. 3(a), the lowest energy-per-bit value is \((1.6 \pm 0.1)\) fJ/bit. This is obtained for a unterminated modulator operated at a mean drive voltage of \(125 \text{mV}_{pp}\) \((V_{\text{scope}} = 70 \text{mV}_{pp})\) at a data rate of 12.5 Gbit/s. At 80 mV\text{pp} drive voltage, a BER of \(2.7 \times 10^{-3}\) is measured, still very near the hard-decision (and certainly below the soft-decision) FEC threshold with an energy consumption of only 0.6 fJ/bit. These are the lowest values reported so far for nonresonant silicon modulators, comparing well with the energy required by resonant structures.

**Conclusions**

We experimentally demonstrate a high-speed silicon-organic push-pull MZI modulator with a very low energy consumption of 1.6 fJ/bit. The device is successfully operated at data rates up to 40 Gbit/s. Drive voltages can be as low as 125 mV\text{pp} due to hybridization of a silicon slot waveguide and a novel highly nonlinear organic chromophore that has an in-device nonlinearity of \(\gamma_{33} = (180 \pm 20) \text{ pm/V} \) after poling.

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**References**