40 Gbit/s Silicon-Organic Hybrid (SOH) Phase Modulator

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Abstract *A 40 Gbit/s electro-optic modulator is demonstrated. The modulator is based on a slotted silicon waveguide filled with an organic material. The silicon organic hybrid (SOH) approach allows combining highly nonlinear electro-optic organic materials with CMOS-compatible silicon photonics technology.*

Introduction

Silicon-on-insulator (SOI) photonics is considered a promising option for lowest-cost highly integrated photonic circuits. Actual research is oriented towards CMOS fabrication compatibility and complementing the optical toolbox. A fast, inexpensive modulator with low RF power requirements is one of the key components in the integrated optics toolbox that still needs more attention. So far successful silicon photonics high-speed approaches are based on the plasma effect [1, 2]. However fundamental speed limitations related to carrier injection and removal are likely to become limiting factors in these techniques.

To circumvent limits imposed by the Silicon itself a silicon-organic hybrid (SOH) approach has been suggested. It combines silicon waveguides with a highly $\chi^{(2)}$-nonlinear electro-optic (EO) organic material [3-8]. This technology allows the choice among a variety of highly nonlinear electro-optic materials with significantly larger $\chi^{(2)}$–susceptibility than $LiNbO_3$ [8-11].

This work presents the first successful implementation of a silicon EO modulator with 40 Gbit/s modulation speed. The modulator potentially operates at low voltages due to the slot-and-socket structure, Fig. 1. It combines strong optical field enhancement inside the low-index slot that is filled with the nonlinear material, and an efficient application of the RF modulation voltage via the doped sockets. The modulator operates over the entire C-band in contrast to resonant devices.

Design and Fabrication

The cross-section of the phase modulator is shown in Fig. 1(left). It comprises a slotted silicon waveguide on a buried oxide layer. The slot is filled with an electro-optic cover material. Due to the high index contrast between cover and silicon the horizontally oriented electric field is strongly enhanced. The slotted waveguide is connected to two AlCu electrodes via doped silicon sockets with high conductivity, so almost the entire voltage of the RF modulating signal drops across the narrow slot leading to an exceptionally strong electric RF field. The combination of optical field enhancement and RF field concentration together with a proper choice of the EO material opens the route to modulators with exceptionally low operation voltages [3-6].

The samples were fabricated within the ePIXfab framework by CEA-LETI in a CMOS line based on an SOI wafer from SOITEC. The slotted socket waveguides in Fig. 1 are 220 nm in height, have a slot width of 120 nm, and connect via slot-to-rib transformers to 450 nm wide rib waveguides with attached gratings for a convenient fiber-to-chip coupling. Shallow-etched conductively-doped sockets having a width of 6 µm and a height of 70 nm connect the slot waveguide to AlCu electrodes well outside the

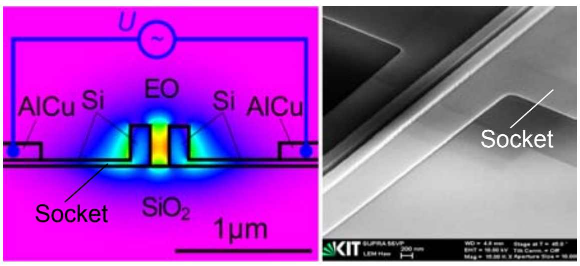

Fig. 1: Phase modulator (PM) (**left**) Cross section of SOH socket waveguide with color-coded quasi-TE field magnitude. The slot is filled with a $\chi^{(2)}$-nonlinear electro-optic (EO) material, the socket is doped to increase its conductivity. (**right**) SEM image of a PM without metallization. The doped regions appear in darker shade due to the larger conductivity.

light-guiding region. Both electrodes form a coplanar line with a nominal impedance of 50 Ω.

Prior to metal deposition, a 600 nm thick silica mask has been deposited and subsequently structured. The metal deposition and removal was performed according to standard techniques of the microelectronic industry. The slot waveguides are to be filled with an organic nonlinear material. To this end, a new process has been developed for the opening of the silica hard mask after metallization. This process is responsible for the increase of the fibre-to-fibre insertion loss from 23 dB (measured after the ion implant and before metallization) to 39 dB (2 × 5 dB of which are due to the grating couplers). We are working on reducing losses.

The nonlinear electro-optic organic material is a polymer with embedded chromophores with a nonlinear coefficient of r_{33} = 150 pm/V [9] as used in the GigOptix production line. As the deposition procedure is similar to standard lithographic processes, it can be easily adapted to mass production. Subsequent to deposition, the material is poled by applying a voltage through the same RF electrodes used for modulation. The poling of the nonlinear material has been tested on different waveguide systems and is routinely performed on an entire wafer.

The PM section has a length 1.7 mm. Due to the remarkably short length, the walk-off between the optical and electrical signals is tolerable up to 100 GHz [5].

Experimental characterization

Frequency response

For measuring the PM frequency response we applied a sinusoidal voltage with frequencies between 15 GHz and 40 GHz. The chip was contacted with a ground-signal RF probe. The RF power before the probe was kept constant to 10 dBm. The resulting phase modulation index η was determined by evaluating the ratio between optical carrier and first optical sideband intensities, $[J_0/(\eta)/J_1(\eta)]^2$ (Bessel function $J_\nu(\eta)$ of first kind and order ν), see Fig. 2.

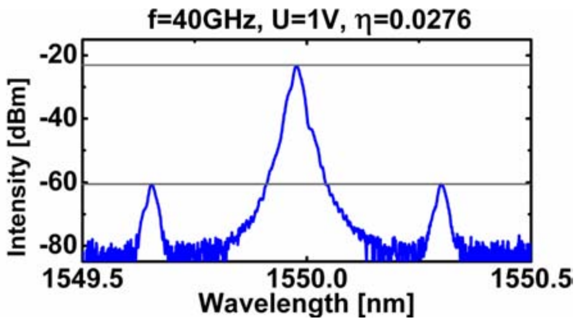

Fig. 2: Optical spectrum for 40 GHz sinusoidal modulation with RF amplitude U = 1 V.

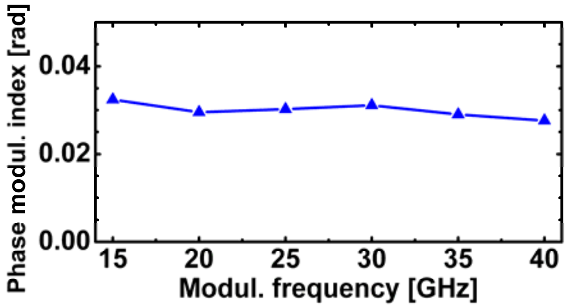

Fig. 3: Modulation index η as a function of the modulation frequency for a constant RF probe amplitude of 1 V is varying less than 13 % showing high speed capability.

With a photodiode placed after the PM we checked that no intensity modulation was present.

The results in Fig. 3 show a variation of the modulation index smaller than 13% over the entire modulation frequency range. This demonstrates the high-speed capability of our device.

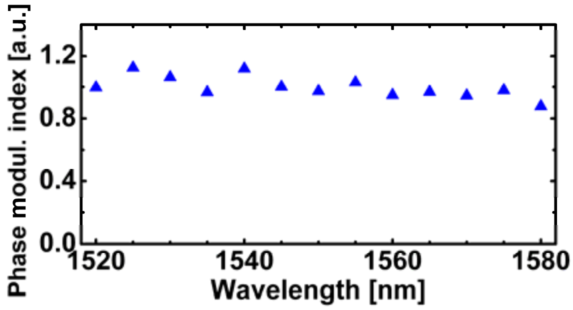

Fig. 4: Modulation index η as a function of wavelength is constant over more than the entire C band. Fixed modulation frequency (20 GHz) and amplitude.

The modulator is also optically broadband. Figure 4 demonstrates a constant modulation index over the entire C-band.

Modulation with PRBS data

For demonstrating the capabilities of the PM, it was driven with a 42.7 Gbit/s data signal (PRBS length 2^7-1). The experimental setup is shown in Fig. 5. Data is generated using a 4 × 10 Gbit/s pulse pattern generator and multiplexed in a 4:1 electrical multiplexer. The amplified 42.7 Gbit/s data signal has a swing of 10 V p-p (**A**) for driving the PM. The optical carrier at a wavelength of 1550 nm is amplified, filtered and variably attenuated. After modulation (**B**), optical signal is amplified by an EDFA. The phase modulated signal is then converted to amplitude modulation using an optical delay interferometer (**C**). The converted signal is then detected using a preamplified receiver. The eye diagrams (**D**) are measured using a 70 GHz photodiode and 70 GHz electrical sampling heads. The signal quality is Q^2 = 12.7 dB. The BER is measured using a 70 GHz photodiode and a 42.7 Gbit/s error ratio tester (BERT) and is found to be of

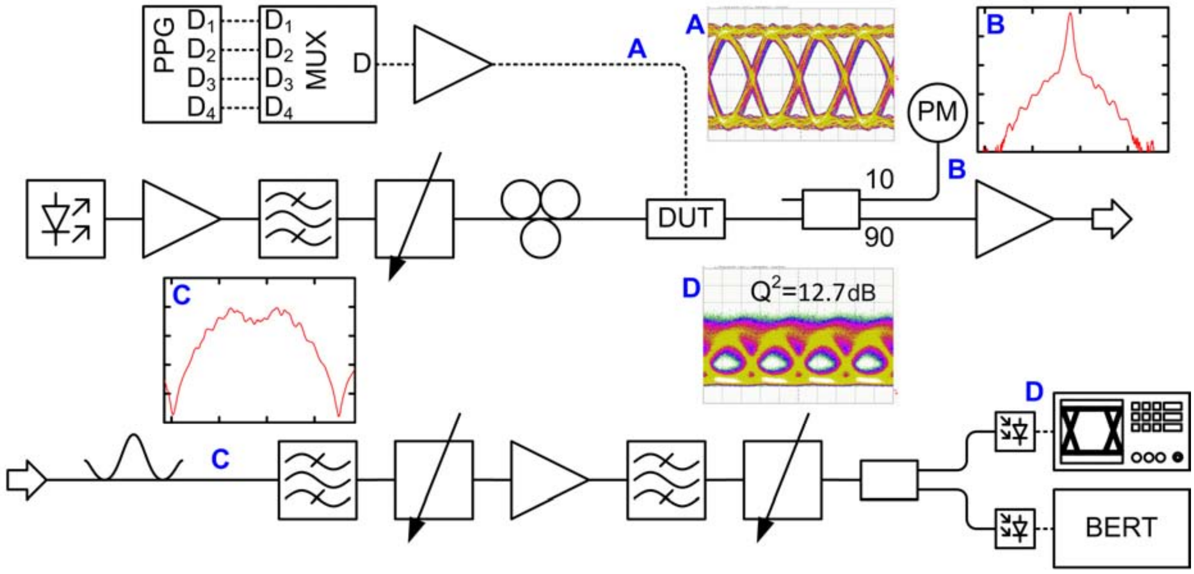

Fig. 5: Characterization setup. The 42.7 Gbit/s data is generated by a 4×10 Gbit/s pulse pattern generator (PPG), and are electrically multiplexed using a 4:1 electrical multiplexer (MUX). The signal is amplified (**A**) and drives the device under test (DUT). A CW-laser is amplified, filtered, attenuated and adjusted in polarization to be modulated in the DUT. The phase modulated signal (**B**) is converted to an amplitude modulated signal (**C**) using a delay interferometer. The amplitude modulated signal is then detected using a pre-amplified receiver.

the order of 10^{-6}, well below the FEC threshold of 2×10^{-3}.

Conclusions

We demonstrated a phase modulator based on silicon-organic hybrid (SOH) technology. At a data rate of 42.7Gbit/s we achieved a BER of 2×10^{-6} and a signal quality of Q^2 = 12.7 dB. With a sinusoidal modulation we observed a flat response in a frequency range up to 40 GHz. The device exhibited the same degree of phase modulation over the complete C-band.

Acknowledgements

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