Silicon-Organic Hybrid (SOH) Electro-Optical Devices

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Abstract: Silicon-organic hybrid (SOH) integration enables electro-optical devices that combine high modulation speed with low power consumption. We give an overview on SOH modulator concepts, underlying material systems, and recent experimental demonstrations.

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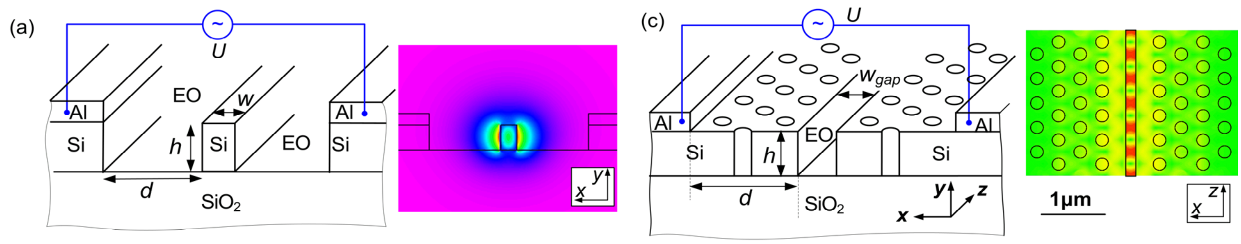
1. Introduction

Silicon-on-insulator (SOI) offers various features that make the material system well suited for large-scale nanophotonic integration, but falls short of certain optical properties that would be needed for highest-performance optical data transmission systems. In particular, due to crystal symmetry, silicon does not possess any appreciable second-order nonlinearities, and electro-optical devices are currently relying on free-carrier dispersion. Using forward-biased pin-junctions integrated into nanophotonic rib waveguides, $U_\pi L$ figures of merit of 0.36 V mm modulation energies of 5 pJ/bit have been demonstrated, but bandwidth is limited by the slow recombination dynamics of the minority carriers [1]. Carrier depletion in reverse-biased pn-junctions can enable bandwidths up to 30 GHz and data rates of 40 Gbit/s, but $U_\pi L$ rises by about two orders of magnitude [2]. In addition, the presence of free carriers changes both the refractive index and the absorption of the waveguide, and phase modulation is hence inevitably accompanied by amplitude fluctuations [3]. Therefore, plasma-effect modulators are not well suited for generating complex quadrature-amplitude modulation (QAM) formats, where independent information is encoded on the phase and the amplitude of a signal.

The deficiencies of silicon can however be overcome by combining SOI waveguides with functional organic cladding materials [4], [5]. All-optical signal processing in silicon-organic hybrid (SOH) slot waveguides [6] has been demonstrated at data rates of 170 Gbit/s [7]. Electro-optical SOH devices show the potential of operating at data rates beyond 100 Gbit/s with power consumption below 1 pJ per bit [4], [8]. Electro-optic interaction in SOH slot waveguides [9] was demonstrated with half-wave voltages as low as 0.25 V [10], but speed was limited by large *RC* time constants. A bandwidth of 3 GHz and $U_\pi L$ figures of merit of 8 V mm have been demonstrated in silicon strip-loaded slot waveguides [11]. Using slotted photonic crystal waveguides [14], electro-optic interaction at modulations speeds of 40 GHz could be observed [12]. We have recently reported on the first data transmission experiment with an SOH modulator in which data rates of 42.7 Gbit/s were achieved [13]. Here, we give an overview on SOH electro-optical device concepts, the underlying material systems, and recent advances in the experimental demonstration of broadband electro-optic modulation.

2. SOH electro-optic modulator concepts

Figure 1 shows schematic views of SOH electro-optic modulator concepts. Light is guided by nanophotonic SOI structures that are covered with organic electro-optic cladding materials (EO), and the electrical signal is applied to metal lines running in parallel to the optical waveguides. Field discontinuities at the high index-contrast core-cladding interfaces of the optical waveguide enable strong interaction of the guided mode with the electro-optic material, see field plots in Figure 1. When using a simple optical strip waveguide, Figure 1 (a), travelling-wave propagation can be achieved by matching the group velocities of the optical and the electrical signal. There is no inherent limitation to the electrical bandwidth, but the spacing between the metal electrodes (~2*d*) must be chosen large enough (typically > 2.5 µm) to avoid optical loss which results in rather high operation voltages. This can be overcome by using a slotted waveguide structure where light is guided by two parallel silicon strips that are spaced by a narrow (typically 100 nm) gap, Figure 1 (b). The silicon strips are electrically connected to the metal lines by thin conductive silicon slabs. A voltage applied to the electrodes induces a strong electric field and a large electro-optic index change within the slot region where the optical mode field is concentrated. The slot capacitance *C* has to be charged via the resistance *R* of the slabs, and the bandwidth is limited by the corresponding *RC* time constant. This structure has the potential to support data rates beyond 100 Gbit/s if appropriate measures are taken to increase the conductivity of the slab regions [4], [8]. If the thin silicon slabs are replaced by properly designed photonic crystal (PhC) structures, Figure 1 (c), the group velocity of the optical signal can be reduced to 4 % of the vacuum velocity of light over a bandwidth of 1 THz [14]. This allows for a drastic reduction in device length, but the bandwidth of the device is limited to ~ 80 GHz by walk-off effects [14].



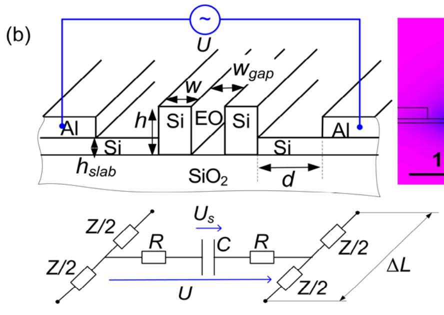


Figure 1: Three basic SOH device concepts comprising nanophotonic SOI waveguides and organic electro-optic cover materials (EO). The electric field distributions are depicted on the right-hand side. **(a)** Optical strip waveguide with metal transmission lines (Al). By matching the group velocities of the optical and the electrical signal, travelling-wave propagation can be achieved, and there is no inherent limitation of the electrical bandwidth. **(b)** Slot waveguide structure: The silicon strips are electrically connected to metal lines by conductive silicon slabs. The slot capacitance C has to be charged via the resistance R of the slab regions, and the bandwidth is limited by the corresponding RC time constant. **(c)** Photonic crystal (PhC) slot waveguide structure: By appropriate design of the PhC, slow light propagation is possible. This enhances electro-optic interaction. The electrical bandwidth is then limited by walk-off.

3. Organic electro-optic materials

There are two main classes of organic electro-optic cladding materials: Single-crystalline films that can be grown either from solutions or melts of organic molecules, and polymer-based guest-host systems, where electro-optic chromophores are embedded into a polymer matrix. The most prominent crystalline material is the stilbazolium salt DAST (4-N, N-dimethylamino-4'-N'-methyl-stilbazolium tosylate), providing an electro-optic coefficient of $r_{11} \approx 50$ pm/V at 1550 nm. Comparable values have been measured for the phenolic configurationally-locked polyene crystal OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene)malononitrile) [15]. For these materials, the orientation of the functional electro-optic groups is defined by the crystal lattice. For guest-host systems, however, chromophores are initially randomly oriented and need to be aligned by applying an external electrical field (typically between 100 V/µm and 200 V/µm) at elevated temperatures (100 °C - 150 °C). The efficiency of this so-called poling procedure, i.e. the degree to which chromophores can be aligned, depends heavily on the ambient conditions, and the electro-optic coefficients achieved by in-situ poling in an electro-optical device are often much lower than the values achieved by poling of thin films [10], [11]. A poling efficiency of 100 % has been demonstrated with AJC146 chromophores in a PMMA-AMA (poly(methyl methacrylate-co-9-anthrylmethyl methacrylate)) polymer matrix that was cross-linked by a bismaleimide (BMI) agent after poling. In this experiment, electro-optic coefficients r_{33} of up to 170 pm/V could be achieved at a wavelength of 1550 nm – six times larger than the values for the $LiNbO_3$ reference [16].

Long-term stability of organic electro-optic materials is crucial for any commercial device applications. Thermal stability for over 5000 h at 85 °C has been demonstrated for LDP-80 chromophores in an amorphous polycarbonate (APC) matrix [17]. Enclosed in hermetically sealed packages, the devices showed photochemical stability under high optical power (500 mW @ 1550 nm). Polymer-based electro-optic modulators have previously been shown to comply with Telcordia reliability standards [18].

4. Device fabrication and experimental testing

Figure 2 (a) shows a cross-sectional view of a fabricated SOH electro-optic modulator. The SOI slot waveguide structures (240 nm strip width, 120 nm slot width) were realized within the European silicon photonics platform ePIXfab using DUV lithography and dry etching. The silicon slabs adjacent to the slot waveguide have a thickness of 60 nm. The waveguide structures were subsequently overcladded with a guest-host electro-optic material which was

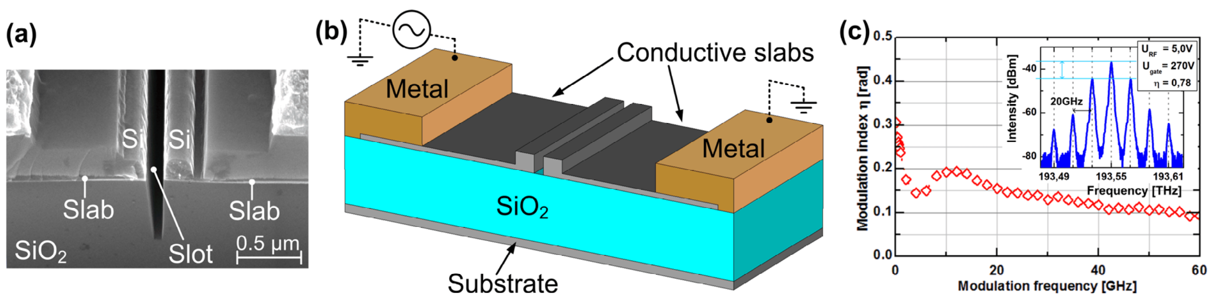


Figure 2: SOH phase modulator. **(a)** Cross-sectional SEM view of the fabricated device. The slot has accidentally been etched 1 µm deep into the buried oxide (SiO_2) **(b)** Electro-optic waveguide section: Two metal lines are running in parallel to the silicon slot waveguides. The silicon strips are electrically connected to the lines by conductive silicon slabs. **(c)** Modulation index as a function of modulation frequency. The amplitude of the RF modulation signal is kept constant at 1 V. The inset shows the optical power spectrum the phase-modulated optical signal at a modulation frequency of 20 GHz.

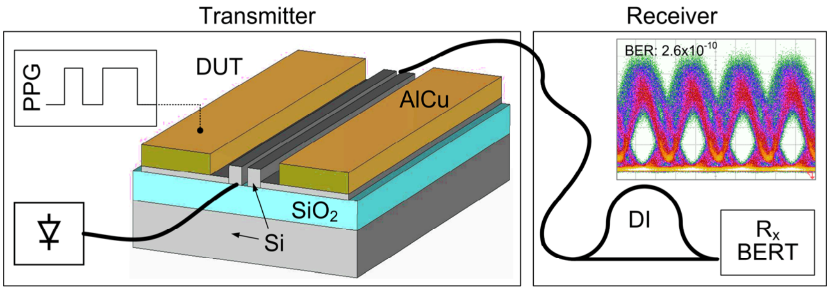


Figure 3: Data transmission experiment: Laser light is launched into the SOH slot waveguide, and an electrical 42.7 Gbit/s signal is fed to the electrodes. This generates a purely phase-modulated signal. On the receiver side, phase-to-amplitude conversion is achieved by feeding the signal into a delay interferometer (DI) that superimposes optical waves from subsequent bit slots. DUT = device under test. BERT = bit-error ratio tester

poled by applying a DC voltage to the slot waveguide. The electrical drive signal is applied to the metal lines running in parallel to the slot waveguide, Figure 2 (b). For sinusoidal modulation signals, the phase modulation index η was derived from the optical power spectrum. The frequency characteristic of the modulation index is plotted in Figure 2 (c). Above 2 GHz, the frequency response is essentially flat with a resonance peak at ~10 GHz which is attributed to imperfect impedance matching of the 50 Ω transmission line. The frequency response of the device suggests that data streams well beyond 40 Gbit/s can be achieved.

5. Data transmission

For an experimental demonstration of data transmission, 1550 nm light was coupled to the waveguide and the modulator was driven with a 42.7 Gbit/s electrical signal (amplitude of 4.1 V measured before the probe, PRBS length 2^{31}-1), Figure 3. This produces a purely phase-modulated signal, which is detected using a one-bit delay interferometer at the receiver. Clear and open eye diagrams are found with bit error ratios as low as 2.6 x 10^{-10} [13]. The power consumption was estimated to be approximately 4 pJ/bit, and the data rate was only limited by the available pulse pattern generator, not by the device itself. This experiment represents the first experimental demonstration of data encoding using an SOH electro-optic modulator. Even though the device is a first-generation sample with significant potential for further improvement, it can already well compete with state-of-the art carrier-injection phase modulators both in terms of power consumption [1] and bandwidth [2].

6. Summary

Silicon-organic hybrid (SOH) electro-optic modulators combine highest modulation speed with lowest power consumption. First-generation demonstrators show characteristics that already outperform state-of-the-art carrier injection modulators. Opportunities for further improvements abound.

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7. References

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