Progress in Silicon-Organic Hybrid (SOH) Integration

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Abstract: We give an overview on our recent achievements in the field of SOH integration, covering in-device electro-optic coefficients r_{33} in excess of 200 pm/V, highly efficient Mach-Zehnder modulators, IQ modulators, and modulator-based frequency comb generators.
Keywords: Silicon photonics, electro-optic modulators, photonic integrated circuits, nonlinear optical devices

1. Introduction

Silicon electro-optic (EO) modulators are key building blocks of highly integrated photonic-electronic circuits. Due to the absence of a linear EO effect (Pockels effect) in unstrained silicon, silicon modulators mostly rely on the plasma dispersion effect, leading to challenges when targeting non-resonant fast devices that feature low drive voltage and small footprint simultaneously. Alternatively, high-speed modulators with low drive voltage can be realized by silicon-organic hybrid (SOH) integration [1], [2]. Here, light is guided in a silicon waveguide core, and linear EO effects are realized by interaction of the evanescent part of the guided light mode with an EO organic cladding. Until recently, the performance of these modulators was limited by small in-device EO coefficients r_{33}, typically in the range of 20 pm/V to 50 pm/V [3], [4].

In this paper, we give an overview on our recent progress in SOH EO devices, such as Mach-Zehnder modulators (MZM) with in-device EO coefficients of 230 pm/V and small π-voltage-length products of $U_\pi L = 0.5$ Vmm, IQ modulators suitable for data rates of up to 112 Gbit/s, and modulator-based frequency comb generators that allow for superchannel transmission at terabit/s data rates.

2. Silicon-organic hybrid (SOH) devices

The cross section of an SOH MZM is illustrated in Fig. 1(a). The MZM comprises two SOH phase modulators that are driven in push-pull mode by a single coplanar transmission line in ground-signal-ground (GSG) configuration [5]. Each of the phase modulators consists of a slot waveguide [6] that confines a large portion of the guided light in a 160 nm-wide slot, which is filled with an organic EO material, see Fig. 1(b). In addition, the copper strips of the transmission line are electrically connected to the rails of the phase modulators by tungsten vias with a height of 900 nm and *n*-doped 60 nm thick silicon slabs, see Fig. 1(c). A voltage applied to the

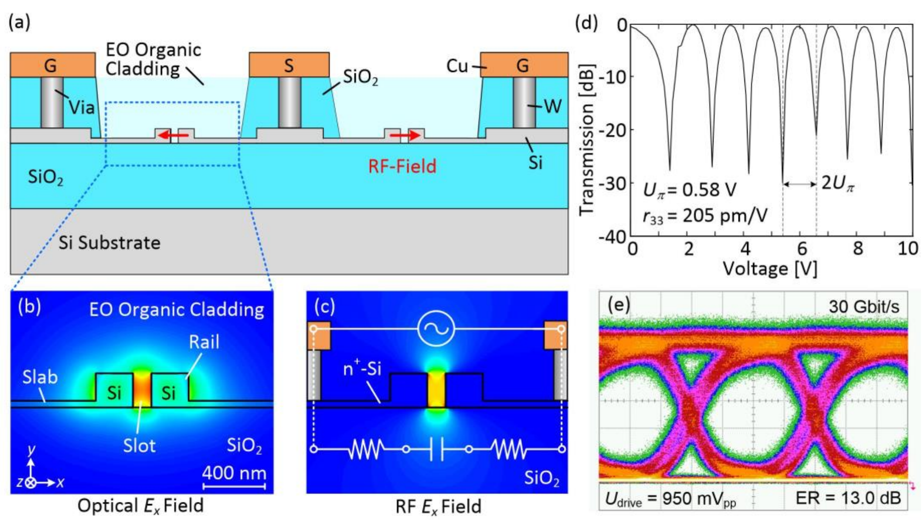

Fig. 1: Silicon-organic hybrid (SOH) Mach-Zehnder modulator (MZM). **(a)** Cross section of the MZM. The device consists of two slot waveguide phase modulators, driven in push-pull by a single coplanar ground-signal-ground (GSG) transmission line [5] **(b)** Cross-sectional view and simulated optical mode of one phase modulator (slot width 160 nm, rail width 210 nm). The light is strongly confined to the slot due to electric-field discontinuities at the slot sidewalls [6]. The slot is filled with an organic EO material. **(c)** Simulated RF mode field of the slot waveguide. The modulation voltage drops across the narrow slot resulting in a high modulation field that has a strong overlap with the optical mode. **(d)** Voltage-dependent transmission of a 1 mm-long MZM with $U_\pi L = 0.5$ Vmm. The π-voltage is measured at a DC bias > 5 V to remove the effect of free charges in the cladding that lead to partial field screening at small DC fields [4]. **(e)** Eye diagram for 30 Gbit/s OOK with a 1 mm-long MZM at a drive voltage of 950 mV_{pp}. An extinction ratio (ER) of 13 dB is measured. [modified after [5] © 2014 IEEE].

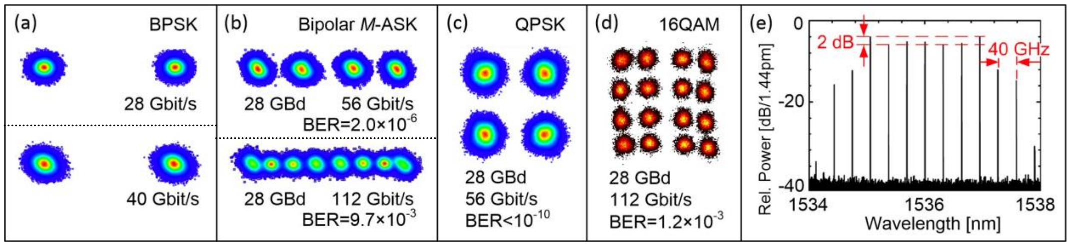

Fig. 2: Experimental demonstrations of SOH electro-optic modulators. **(a)** Constellation diagrams of BPSK signals at symbol rates of 28 GBd and 40 GBd [9]. **(b)** Bipolar 4ASK (56 Gbit/s) and 8ASK (84 Gbit/s) at a symbol rate of 28 GBd. [9] **(c,d)** Constellation diagrams of QPSK and 16QAM signals for data rates of 28 GBd. For the 16QAM-signal, pre-emphasis was used to generate the electric drive signal [10]. **(e)** MZM-based frequency comb generation. A 40 GHz sinusoidal drive signal with a peak-to-peak voltage of $3.4\times U_\pi$ is used to create a comb with 7 lines and a spectral flatness of 2 dB [11]. [Fig. 2(a,b) modified after [9] © 2013 IEEE, (c,d,e) after [10], [11] © 2013/14 OSA]

transmission line drops across the narrow slot, resulting in a high modulation field that strongly overlaps with the optical quasi-TE mode. We demonstrated that in-device EO coefficients of the organic material can be as high as 230 pm/V [4] when using monolithic materials or binary chromophore systems instead of conventional chromophore-polymer guest-host systems [7], [8]. This enables building Mach-Zehnder modulators (MZM) with low π-voltage-length products of $U_\pi L = 0.5$ Vmm. An exemplary voltage-dependent transmission characteristic of a 1 mm-long SOH MZM with binary chromophore cladding PSLD41/YLD124 is depicted in Fig. 1(d). SOH MZM are well suited for on-off-keying (OOK) at data rates up to 40 Gbit/s [9], [8]. A recorded 30 Gbit/s eye diagram of a 1 mm-long terminated MZM with a peak-to-peak drive voltage of 950 mV_{pp} is depicted in Fig. 1(e). The data rate of the modulator can be further increased by using higher-order modulation formats. We demonstrated data rates up to 40 Gbit/s using binary phase-shift keying (BPSK), Fig. 2(a), and up to 84 Gbit/s using bipolar amplitude-shift keying (ASK), Fig. 2(b), employing a 1 mm-long MZM [9]. Also, 1.5 mm-long SOH IQ modulators were demonstrated [10] and found to be suitable for 56 Gbit/s QPSK modulation and 112 Gbit/s 16QAM modulation, see Fig. 2(d,e).

Moreover, an SOH MZM can be used as a broadband frequency comb source for wavelength-division multiplexed (WDM) data transmission [11]. To this end, the MZM is operated with a 40 GHz sinusoidal drive signal. Due to the high EO efficiency of the device, the modulation spectrum comprises a multitude of modulation sidebands. A comb featuring 7 lines within a spectral flatness of 2 dB is achieved by driving the two phase modulators of the Mach-Zehnder with a modulation depth of 3.6π and 2.7π, respectively, see Fig. 2(e). The viability of SOH comb sources was demonstrated in a series of data transmission experiments, where different line spacings, symbol rates, pulse shapes, and modulation formats were exploited [11]. A total line rate of 1.152 Tbit/s and a net spectral efficiency of 4.9 bit/s/Hz were achieved by using a comb with a 25 GHz line spacing.

3. Summary

We review recent progress in silicon-organic hybrid (SOH) electro-optic modulators. Novel cladding materials with large electro-optic coefficient enable highly efficient devices that operate at data rates up to 112 Gbit/s. Furthermore, we show that an SOH MZM can be operated as a frequency comb generator that enables superchannel transmission at terabit/s data rates.

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