# Silicon-Organic Hybrid (SOH) — A Platform for Ultrafast Optics

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**Abstract** *Silicon signal processing at bitrates beyond 100 Gb/s is demonstrated. A new enabling platform is reviewed, which relies both on silicon-based CMOS technology for waveguide fabrication, and on an organic cladding providing nonlinearity for switching.*

## Introduction

Silicon-on-insulator (SOI) photonics holds promise for convergence of photonic and electronic integrated circuit on one CMOS-compatible platform. As a matter of fact it is a likely path towards cost-effective mass-producible, ultra-compact and power efficient multi-functional optoelectronic integrated circuits. Until recently, the mayor obstacle towards photonic integration in silicon were waveguide losses. Yet, there has been tremendous progress in the field of silicon photonics such that we now are able to fabricate compact low-loss components [1]. Indeed, a whole industry has worked on providing a complete library of optical components. Some of these components are lowest-loss waveguides [2][3], tapers [4] and grating couplers [5], filters [6] or photonic crystal devices offering dispersion and slow light functionalities [7], to name just a few. While all of the aforementioned devices are passive building blocks, active devices such as lasers, amplifiers and modulators are needed to complement the library. And indeed, by wafer-bonding III-V heterostructures onto silicon-on-insulator (SOI) waveguides, continuous-wave (cw) lasers [8][9], and optically and electrically pumped amplifiers [10][11] have been realized. Yet, electrical and optical modulation is still an issue. As a matter of fact, electrical and optical signal processing suffer from two-photon absorption (TPA) and free carrier absorption (FCA) related speed limitations [12], which require special measures to keep such speed limitations within limits.

In this paper, we review the silicon-organic hybrid (SOH) platform [13]. The SOA platform combines the advantages of silicon with the ultra-fast performance of organic Kerr ($\chi^{(3)}$) and electro-optic ($\chi^{(2)}$) nonlinear materials. To be more precise, the silicon wire guides the optical mode, and an organic cladding provides the nonlinearity for electrical and optical modulation up to highest speed. This approach has recently led to high-quality 120 Gbit/s [14] and 170 Gbit/s [15] signal processing. In addition, ultra-low power electro-optic switching has been predicted [16][17] and more recently confirmed by experiment as well [18].

## The Platform and its Waveguide Structures

In the SOH approach, all active and passive waveguides, couplers and filters, are fabricated as silicon waveguides, Fig. 1. The nonlinear optical functionality, however, comes in through the organic material in the cladding.

Here, we discuss the three nonlinear waveguide structures depicted in Fig. 1 with respect to their suitability as Kerr-nonlinear waveguides. An in-depth

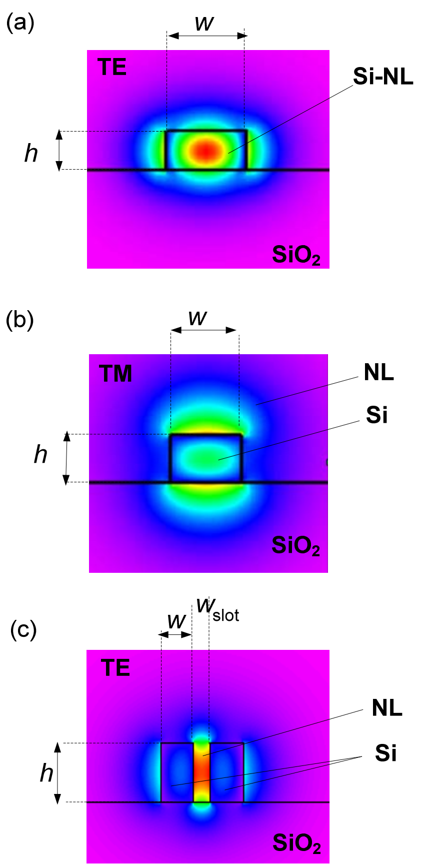


Fig. 1: Waveguide structure and electric field amplitude of three silicon-wire structures. (a) The conventional silicon strip waveguide providing core nonlinearity from silicon for strong TE input signals , (b) Cover nonlinear waveguide in a strip waveguide where an organic cladding provides strong nonlinearity to a TM signal, and (c) cover nonlinearity in a slot waveguide where an organic material may provide strong nonlinearity to a TE-polarized signal.

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discussion may be found in Ref. [17] and [19] for the electro-optic and the Kerr effect, respectively.

The strength of the Kerr nonlinearity is best described by the nonlinearity coefficient $\gamma$,

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}^{(3)}} .$$

The equation shows that $\gamma$ can be maximized by using materials with a strong nonlinear index coefficient $n_2$ and the smallest possible third-order nonlinear effective interaction area $A_{eff}^{(3)}$. Yet, this number does not tell all. The efficiency – and even worse the ultrafast time constants – might be impeded by TPA (two-photon absorption). A frequently used figure of merit (FOM), which relates the nonlinear phase shift to the associated TPA intensity change, is

$$\mathrm{FOM} = \frac{1}{\lambda}\frac{n_2}{\alpha_2},$$

where $\alpha_2$ is the nonlinear absorption coefficient.

In the more conventional approach depicted in Fig. 1(a), the dimensions of a silicon strip-waveguide have been chosen to provide a maximum confinement of the optical mode. This way the silicon nonlinearity with a nonlinear index coefficient $n_2$=6 x $10^{-18}$ m$^2$/W may be exploited. While this structure provides a high nonlinearity, it also comes along with considerable TPA. In Fig. 1(b) we have depicted a nonlinear Kerr-waveguide with cover nonlinearity. In this structure the waveguide provides guiding but is designed to push the optical mode as far as possible into the cladding layer above the waveguide. As a cladding we have chosen the organic molecule DDMEBT with a nonlinear coefficient $n_2$=2 x $10^{-17}$ m$^2$/W, a material which has no TPA absorption [20]. The only TPA that is left stems from the light which remains in the silicon wire. A further improvement is obtained with the slot-waveguide structure from Fig. 1(c). Here the optical mode is mostly confined to the narrow slot. The field enhancement across the slot is maximum, and TPA is negligible [19].

### Fabrication of Waveguide Structures

We have fabricated the three structures of Fig. 1 in order to compare them for their nonlinear efficiency.

Waveguide templates have been produced on a 200 mm CMOS pilot line using 193 nm deep-UV (DUV) lithography and a chlorine-based reactive ion etching process [21]. The thickness of the waveguide height amounts to $h$ = 220 nm, and the buried oxide is 2 µm thick. The strip (slot) widths $w$ ($w_{slot}$) range from 160 nm to 220 nm (150 nm to 250 nm). The waveguide templates were functionalized by vapor deposition of a 950 nm thick amorphous organic film consisting of DDMEBT [20].

After deposition, cross-sectional profiles of the waveguides have been produced by focused ion beam (FIB) milling using a Carl Zeiss CrossBeam system. A high homogeneity of the organic cover layer over its whole cross section was found, and it could be confirmed that the organic substance fills even the slot homogeneously, see Fig. 2.

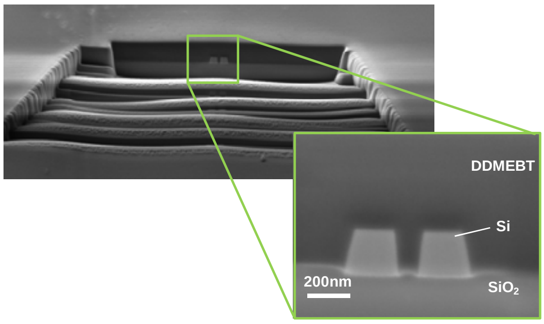


Fig. 2: SEM picture showing cross-section of slot-waveguide structure. The organic material as homogenously covered the waveguide and even filled the slot.

### Characteristics of the Nonlinear Waveguides

In order to characterize the waveguides for their amplitude and phase dynamics, we performed heterodyne pump-probe measurements [22]. Fig. 3 shows the temporal phase dynamics of the three respective structures for different pump powers.

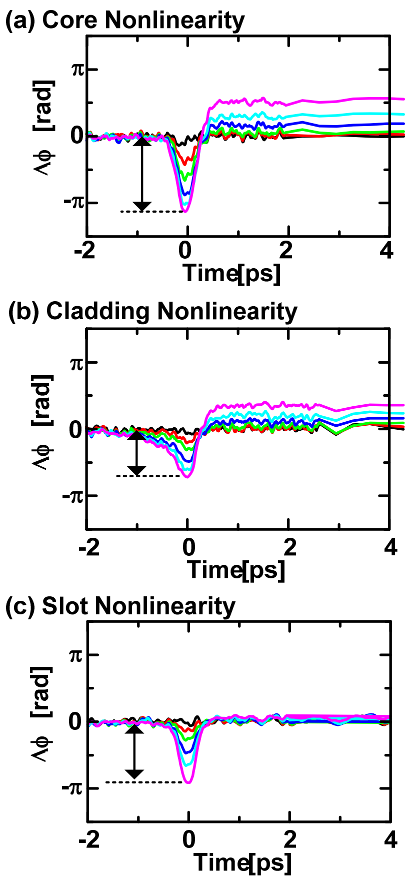


Fig. 3: Phase response dynamics $\Delta\phi_{NL}$ of the 3 structures from Fig. 1. The silicon core-nonlinear waveguide (a) has a large nonlinearity with a slow relaxation of the nonlinear effect. The waveguide with cladding nonlinearity (b), shows a strong nonlinearity with a some slow relaxation. The slot waveguide (c) shows pure Kerr nonlinearity with nearly no TPA-related slow tail.

The structure with strip-waveguide, optimized for a core nonlinearity, shows a strong Kerr-effect. Yet, it also shows a strong TPA absorption, which leads to free carriers that in turn generate a plasma effect related refractive index with a long lifetime. This carrier induced slow relaxation is vastly reduced in the cladding-nonlinear structure of Fig. 3(b), and completely vanishes for the slot waveguide depicted in Fig. 3(c). The slot waveguide shows a pure instantaneous phase response and no degradation from TPA.

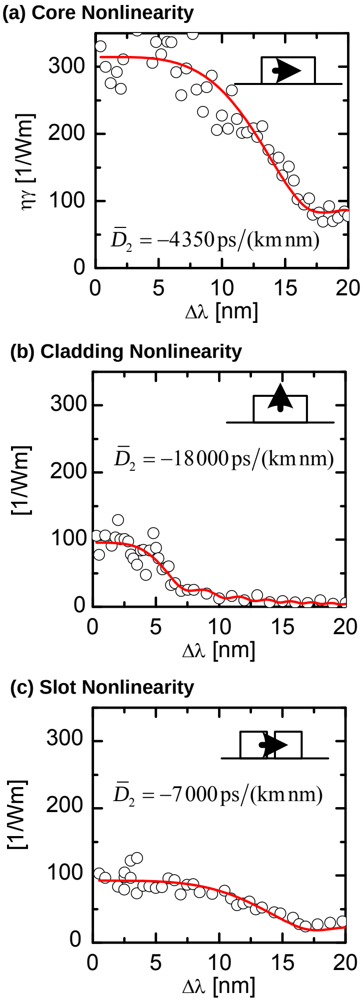


Fig. 4: Dependence of FWM conversion efficiency on the wavelength detuning $\Delta\lambda$; measurement (°) and fit (-). The largest nonlinearity is found for (a), (b) and (c) provide similar nonlinearity coefficients.

The nonlinearity coefficient $\gamma$ and the waveguide dispersion have been measured across a 20 nm spectral range for all three structures, see Fig. 4. The largest nonlinearity in the order of 300 000/(Wkm) is found for the strip waveguide with core nonlinearity. The waveguides with cladding and slot nonlinearity feature nonlinearity coefficients of 100 000/(Wkm). With a narrower slot the slot nonlinear waveguide will outperform all the other structures.

The results of the experiment are summarized in the Table below.

**Table:** Measured Parameters of Fig. 1 waveguides

| **Design** | **Core** | **Cladding** | **Slot** |
|---|---|---|---|
| $\gamma$ [1/(W km)] | 307 000 | 108 000 | 100 000 |
| $\mathrm{FOM_{TPA}}$ | 0.38 | 1.21 | 2.19 |
| Height [nm] | 220 | 220 | 220 |
| RibWidth [nm] | 360…400 | 360…400 | 220 |
| SlotWidth [nm] | - | - | 160…200 |

### Experiments

Experiments have been performed to test the silicon-organic hybrid waveguides for their speed.

A first experiment demonstrating 42.7 Gbit/s all-optical wavelength conversion in a 4 mm long slot waveguide is shown in Fig. 5**Error! Reference source not found.**. Here, the nonlinear Kerr effect in the slot waveguide has been exploited to perform wavelength conversion with retiming functionality by means of four-wave mixing a 42.7 Gbit/s signal at 1559 nm and a 42.7 GHz clock signal at 1550 nm to generate a new signal at 1541 nm. It is worth noting that the pulse sequence depicted at the bottom of **Error! Reference source not found.** shows no pattern dependence [23]. Tests with all kinds of patterns up to PRBS lengths of $2^{15}$-1 have been performed without an indication for pattern dependence. Input power levels for the data signals were 11.3 dBm and 21 dBm for the clock. (Power levels measured at the input on the chip.)

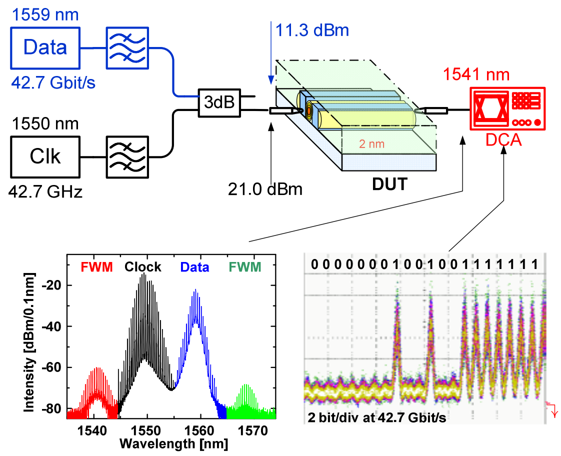


Fig. 5: All-optical wavelength conversion by menas of FWM in a SOH slot-waveguide. The FWM spectra and an example of a pattern with long sequences of ”1” and some single ”1” shows no pattern dependence.

A 120 Gbit/s to 10 Gbit/s demultiplexing experiment is shown in Fig. 6. This experiment has been performed with a SOH slot-waveguide of 6 mm length [14] . More recently, the same device has demonstrated demultiplexing from 170.8 to 42.7 Gbit/s [15].

### Conclusions

A new silicon-organic hybrid platform has been introduced. The platform allows for the first time to overcome the inherent speed-limitations of silicon as demonstrated with signal processing experiments.

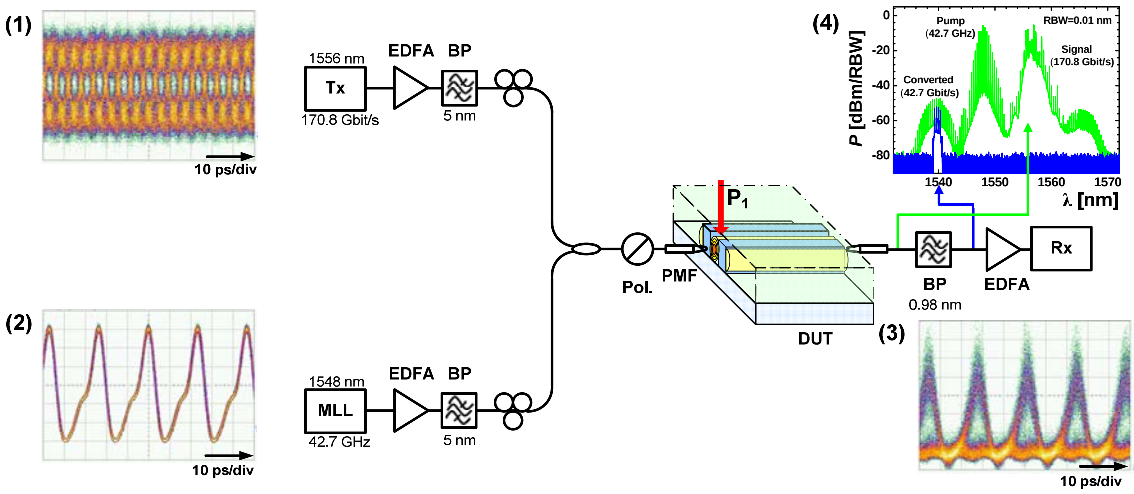


Fig. 6: Experimental setup of the 120 to 10 Gbit/s demultiplexing experiment. MLL1, MLL2 = mode-locked lasers, Mod = data modulator, OTDM-Mux = optical time-division multiplexer, EDFA = erbium-doped fiber amplifier, Att = attenuator, PM = power meter, Pol = polarizer, PMF = polarization maintaining fiber, DUT = device under test, DCA = digital communication analyzer. Insets: (1) 120 Gbit/s signal, (2) 10 GHz pump, (3) demultiplexed 10 Gbit/s signal, (4) Spectrum at the output

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