Nonlinear Nano-Photonics

W. Freude[1,2,*], L. Alloatti[1], D. Korn[1], M. Lauermann[1], A. Melikyan[1], R. Palmer[1], J. Pfeifle[1], P. C. Schindler[1], C. Weimann[1], R. Dinu[4], J. Bolten[5], T. Wahlbrink[5], M. Waldow[5], S. Walheim[6,7], P. M. Leufke[6], S. Ulrich[8], J. Ye[8], P. Vincze[6], H. Hahn[6], H. Yu[9], W. Bogaerts[9], V. Brasch[10], T. Herr[10], R. Holzwarth[11,12], K. Hartinger[12], C. Stamatiadis[13], M. F. O'Keefe[14], L. Stampoulidis[15], L. Zimmermann[16], R. Baets[9], Th. Schimmel[6,7], I. Tomkos[17], K. Petermann[13], T. J. Kippenberg[10], C. Koos[1,2], J. Leuthold[1,2,3]

[1]Institute of Photonics and Quantum Electronics (IPQ-KIT), Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
[2]Institute of Microstructure Technology (IMT-KIT) – [3]Now with Swiss Federal Institute of Technology (ETH), Zürich, Switzerland
[4]GigOptix Inc., Switzerland and GigOptix Bothell, Washington, USA – [5]AMO, Aachen, Germany
[6]Institute of Nanotechnology (INT-KIT) – [7]Institute of Applied Physics (IAP-KIT) – [8]Institute of Applied Materials (IAM-AWP-KIT)
[9]Photon. Res. Group, Ghent Univ. – IMEC, Dpt. of Informat. Technol. (INTEC) & Center of Nano- and Biophoton. (NB-Photon.), Gent, Belgium
[10]Ecole Polytech. Federale de Lausanne (EPFL) – [11]MPQ Garching, Germany – [12]Menlo Systems, Martingsried, Germany
[13]Joint Lab Silicon Photonics HFT4, Technische Universität Berlin, Germany – [14]u2t Photonics, Sedgefield, UK
[15]Constelex Technology Enablers, Corallia Microelectronics Innovation Center, Athens, Greece
[16]IHP Frankfurt (Oder), Germany – [17]Athens Information Technology Center, Athens, Greece
**E-mail: w.freude@kit.edu — Web: http://www.ipq.kit.edu*

Abstract: We discuss electro-optic modulators (up to 64QAM at a data rate 150 Gbit/s), waveguides for efficient sum and difference frequency generation, comb line generation with a Kerr-nonlinear ring resonator, and a surface plasmon polariton modulator.

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1. Introduction

Nonlinear effects support a large variety of methods for processing optical signals near wavelengths of 1.55 µm. Especially the silicon-on-insulator (SOI) platform — typically a 220 nm thin Si slab with refractive index $n_{\mathrm{Si}} \approx 3.5$ on top of a thick SiO_2 layer residing on a Si substrate — allows strong field confinement in high index-contrast nano-scaled waveguides (WG). However, Si lacks a $\chi^{(2)}$-nonlinearity, while its high $\chi^{(3)}$-nonlinearity is impeded by two-photon absorption (TPA) and free-carrier absorption (FCA). The addition of organic materials (silicon-organic hybrid, SOH) provides what silicon has not: A $\chi^{(2)}$-nonlinearity, and a $\chi^{(3)}$-nonlinearity without TPA and FCA. Also GaAs as a material platform is an option. Alternatively, if the photonic Si layer of the SOI stack is replaced by silicon nitride (SiN) with $n_{\mathrm{SiN}} \approx 2$, the guided fields do not suffer from TPA for $\lambda > 600$ nm, and FCA has no impact in this dielectric. A different approach for electro-optic modulators is to combine Si waveguiding with plasmonic structures. Choosing from a multitude of nonlinear nano-photonic devices, we discuss a WG for efficient $\chi^{(2)}$-nonlinear frequency generation, present results for $\chi^{(2)}$-nonlinear high-speed SOH and GaAs modulators, illustrate the capabilities of a plasmonic modulator, and demonstrate comb line generation with a $\chi^{(3)}$-nonlinear SiN ring resonator.

2. SOH double slot waveguide for $\chi^{(2)}$-nonlinear frequency generation

Efficient second-harmonic generation as well as sum and difference frequency generation (DFG) or optical parametric amplification require a $\chi^{(2)}$-nonlinear medium with phase matching over a wide frequency range. In Fig. 1(a),(c) the layout of a suitable silicon-organic hybrid (SOH) double slot multimode WG is displayed, dispersion-engineered for phase matching the modes for pump, Fig. 1(a),(b), signal and idler, Fig. 1(c),(d) [1]. With a linear electro-optic coefficient of 230 pm/V for the organic cladding and a CW pump power of 20 dBm, we predict for large device lengths L a relative power gain $G(L + 1\ \mathrm{cm}) / G(L)$ of 14.7 dB/cm. For $L = 1$ cm, $\lambda_p = 1.5$ µm (*p*ump, 20 dBm), $\lambda_s = 3.1$ µm (*s*ignal, −10 dBm), $\lambda_i = 2.9$ µm (no *i*dler input), we expect output idler and signal powers of 0.68 mW (−1.7 dBm) and 0.78 mW (−1.1 dBm), respectively.

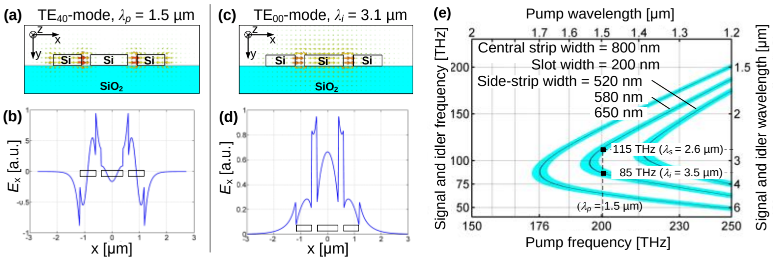

Fig. 1. Silicon organic-hybrid (SOH) double slot multimode waveguide (a), (c) for $\chi^{(2)}$-nonlinear DFG. Propagation constants for quasi-TE$_{40}$ pump (b) as well as for for quasi-TE$_{00}$ signal (λ_s = 2.9 µm) and idler mode (d) can be matched. Slots are filled with a poled nonlinear organic cover. (e) For three different geometries, the signal and idler frequencies that satisfy energy conservation as well as mode phase-matching conditions $k_s + k_i - k_p = 0$ for *s*ignal, *i*dler and *p*ump propagation constants, are depicted as a function of pump frequency (black solid lines). The cyan-shaded regions indicate a coherent buildup length of $L_{\mathrm{coh}} = 2 / (k_s + k_i - k_p) \geq 1$ cm. [Modified from [1] © 2012 OSA]

3. Modulators

For advanced *M*-QAM (quadrature amplitude modulation) transmission formats, in-phase / quadrature (IQ) modulators must access any of the *M* points in a constellation diagram of the complex field plane. IQ modulators are built from two single Mach-Zehnder modulators [2] (MZM) nested in the two $\pi / 2$ phase-shifted arms of an outer MZ interferometer. The cross-section of one SOH slot-WG MZM is shown in Fig. 2(left). The slots are filled with a poled $\chi^{(2)}$-nonlinear organic material. The WG refractive indices are controlled by electrical signals propagating on an externally terminated 50 Ω electrical coplanar ground-signal-ground WG. An 28 GBd 16QAM data stream, Fig. 2(right), with a rate of 112 Gbit/s [3] could be modulated on an optical carrier at $\lambda = 1.545$ µm using an 8-tap pre-emphasis, but no receiver equalization. The measured bit error ratio $\text{BER} = 1.2\times10^{-3}$ allows hard decision forward error correction. With a driving voltage of 5 V_{pp}, the modulator consumes 620 fJ/bit, which could be as low as 320 fJ/bit [4] for on-off keying at 10 Gbit/s.

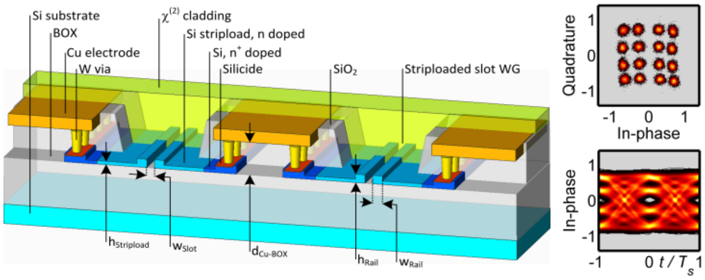

Fig. 2. SOH IQ modulator. (**left**) Cross-section of one MZM with two slot-WG phase modulator sections (1.5 mm long) filled with a $\chi^{(2)}$-nonlinear organic cladding. Rails are connected to GSG Cu electrodes by tungsten vias, a silicide layer and the Si striploads. Crossings of optical and electrical paths are possible. (**right**) Constellation (top) and eye diagram (bottom) of a 16QAM 28 GBd 112 Gbit/s data stream using an 8-tap pre-emphasis without receiver equalization. $\text{BER} = 1.2\times10^{-3}$, $\text{EVM} = 10.3$ %. [Modified from [3] © 2013 OSA]

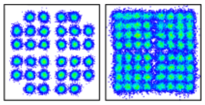

Fig. 3. GaAs modulator (150 Gbit/s, 30 mm long). (**left**) 32QAM, EVM = 6.3 %, $\text{BER} = 5\times10^{-5}$ (**right**) 64QAM, EVM= 6.9 %, $\text{BER} = 1.1\times10^{-2}$ [Modified from [5] © 2013 OSA]

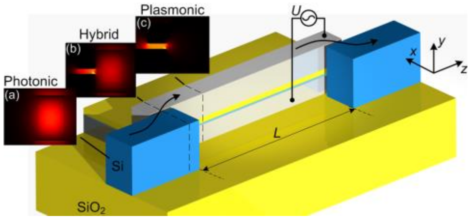

Fig. 4. Surface plasmon polariton (SPP) absorption modulator (L = 10 µm long). With a directional coupler, light is coupled from a silicon nanowire into the active plasmonic section. It consists of stacked layers of silver (Ag, grey), indium tin oxide (ITO, 10 nm, light blue), and SiO$_2$ (yellow). The SPP absorption is modulated by a voltage U between the silver electrodes. [Modified from [6] © 2011 OSA]

Using GaAs as the electro-optic material, an IQ modulator for the formats 4QAM, 16QAM, 32QAM and 64QAM IQ was demonstrated to have a single-polarization bit rate of up to 150 Gbit/s, Fig. 3 [5].

For greatly reducing the modulator footprint, an electrically controlled ultra-compact surface plasmon polariton (SPP) modulator [6] [7] [8] could be the first step. The device as depicted in Fig. 4 and can be as short as 10 µm, depending on the required extinction ratio and the acceptable loss. It comprises a stack of metal / insulator / metal-oxide / metal layers, which supports a strongly confined SPP in the 1.55 µm wavelength region. The SPP absorption coefficient is modulated by electrically changing the free carrier density in the intermediate metal-oxide layer. The typical RC time constant in a 50 Ω environment is 35 fs. The limited extinction ratio of a prototype [6] could be subsequently improved to 1 dB/µm [7].

4. Comb line generation in a $\chi^{(3)}$-nonlinear ring resonator

Kerr-nonlinear ring resonators have previously been used as comb generators for data transmission, but only isolated, carefully selected lines could be used due to their tendency to develop a multiplet character [10] (see also previous work by T. Herr *et al.*, Ref. 8 in [9]). To find low phase-noise comb states without multiplet spectral lines using the setup shown in Fig. 5, the pump power, the polarization, and the detuning between pump frequency and ring resonance have to be carefully adjusted [9] [10]. Using QPSK and 16QAM modulation formats, an aggregate data rate of 392 Gbit/s is transmitted on 6 neighbouring comb lines [9].

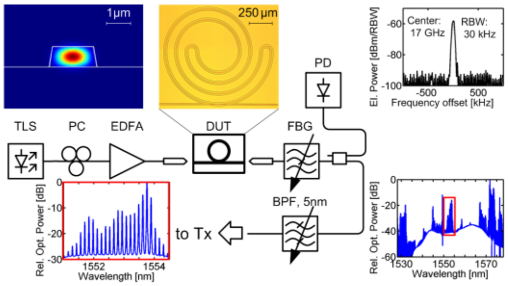

Fig. 5. Comb line generation with a SiN spiral-shaped ring resonator (2 µm × 750 nm). A tunable laser source (TLS, 37 dBm, near 1549.4 nm) pumps the ring. A fibre Bragg grating (FBG) suppresses the pump by 20 dB. A photodiode mixes the comb lines (black photocurrent spectrum). A bandpass filter (BPF, 5 nm) selects the optical lines (red-framed blue spectra) used for data transmission. [Modified from [9] © 2013 OSA]

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