All-Optical Wavelength Conversion at 42.7 Gbit/s in a 4 mm Long Silicon-Organic Hybrid Waveguide

T. Vallaitis, C. Heine, R. Bonk, W. Freude, J. Leuthold
Institute of Photonics and Quantum Electronics, University of Karlsruhe, 76131 Karlsruhe, Germany.
Tel. : +49 721 608-7170, Fax: +49 721 608-2786, e-mail:t.vallaitis@ipq.uni-karlsruhe.de

C. Koos
Carl Zeiss AG, Corporate Research and Technology, 73447 Oberkochen, Germany

B. Esembeson, I. Biaggio
Department of Physics, Lehigh University, Bethlehem, PA 18015. USA

T. Michinobu, F. Diederich
Laboratorium für Organische Chemie, ETH Zürich, Honggerberg, HCI, CH-8093 Zurich, Switzerland

P. Dumon, R. Baets
Photonics Research Group, Ghent University-IMEC, Dept. of Information Technology, B-9000 Gent, Belgium

Abstract: All-optical wavelength conversion at 42.7 Gbit/s over 18 nm in a passive 4 mm long silicon-organic hybrid waveguide is demonstrated based on four-wave mixing. No patterning effects are observed.

OCIS codes: (130.7405) Wavelength conversion devices; (190.2620) Harmonic generation and mixing;

1. Introduction

Wavelength conversion is one of the corner stones of all-optical signal processing. While devices like semiconductor optical amplifiers or highly nonlinear fibers have been successfully used for some time [1], the research effort for silicon compatible wavelength converters that offer on-chip integration has been considerably increased [2–4]. However, all pure silicon implementations to date suffer from two-photon absorption (TPA) and free-carrier absorption (FCA) effects. Additional technological measures like a p-i-n structure are needed to mitigate these effects and scale to bit rates of 40 Gbit/s [5]. Combining the waveguiding properties of silicon with third order nonlinearities from organic cladding materials offers a technologically feasibly alternative that avoids free-carrier effects completely [6].

In this paper, we demonstrate all-optical wavelength conversion based on four-wave mixing in a 4 mm long silicon-organic hybrid waveguide. No patterning effects are observed and the signal quality is only limited by OSNR, which could be overcome by increasing the input power. Silicon-organic hybrid waveguides provide CMOS compatible nonlinearities for all-optical signal processing at highest bit rates.

2. Sample Structure

The highly nonlinear silicon-organic hybrid slot waveguides are based on silicon-on-insulator technology in a 193 nm process [7] offered by ePIXfab [8]. On a buried oxide buffer a 157 nm wide slot waveguide is formed by two silicon ribs of height 220 nm and width 216 nm. The waveguides are filled and covered with molecular beam deposited DDMEBT (2-[4-(dimethylamino)phenyl]-3-{[4-(dimethylamino)phenyl]ethynyl}buta-1,3-diene-1,1,4,4-tetracarbonitrile), an off-resonant Kerr-type nonlinear organic cladding with a refractive index of n = 1.8 [9,10].

Due to the discontinuity of the normal electric field at the interface, the nonlinearity of the slot waveguides is further enhanced [11], up to a record value of $\gamma = 10^5\ \mathrm{W^{-1}km^{-1}}$ [12]. Because of the slot-geometry, losses due to two-photon absorption and free-carrier absorption can be avoided [6]. Waveguide facets are as cleaved and no anti-reflection coating is applied, leading to a coupling loss of 6.2 dB per facet. The linear propagation loss is 1.55 dB/mm. For a device of 4 mm length this amounts to a total fiber-to-fiber loss of 18.6 dB. The device is operated without any cooling or temperature control.

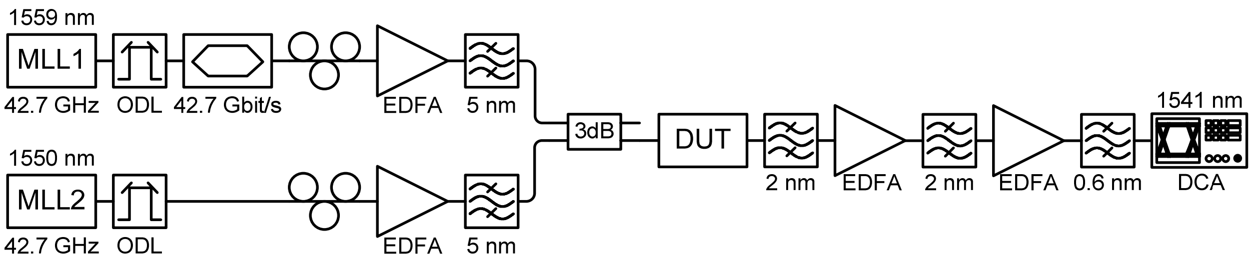

Fig. 1 Experimental setup of the wavelength conversion experiment. Mode-locked laser (MLL1) pulses are modulated at 42.7 Gbit/s. A second mode-locked laser (MLL2) provides a clock signal. Optical delay lines (ODL) are used to synchronize the pulse streams. Both signals are amplified, band-pass filtered and launched into the device under test (DUT) using polarization-maintaining lensed fibers. The four-wave mixing signal is amplified, band-pass filtered and detected with a digital communications analyzer (DCA).

3. Wavelength Conversion Experiment

Degenerate four-wave mixing is a parametric process that can efficiently generate new waves [13] at frequencies $\omega_{FWM} = 2\omega_1 - \omega_2$. Fig. 1 shows the setup of the wavelength conversion experiment. Mode-locked laser (MLL1) pulses at 1559 nm are modulated with a pseudorandom (2^{31}-1 bit) RZ signal at 42.7 Gbit/s ($Q^2 > 21$ dB). A second mode-locked laser (MLL2) at 1550 nm provides the clock pulses at a repetition rate of 42.7 GHz. The pulse width of both sources is approximately 2.2 ps. Optical delay lines (ODL) are used to synchronize the pulse streams. Both signals are amplified and band-pass filtered to suppress the strong amplified spontaneous emission (ASE) from both booster amplifiers. Using polarization-maintaining lensed fibers the TE polarized pulses are launched into the device under test (DUT), reaching maximum on-chip power levels of 21.0 dBm for the clock and 11.3 dBm for the data signal. Fig. 2(a) shows the optical spectrum at the output of the nonlinear waveguide. Both four-wave mixing signals can be clearly observed. In order to avoid cross-talk from the strong data signal, the converted signal at 1541 nm is then amplified and filtered with a 0.6 nm narrow band-pass, resulting in the spectrum shown in Fig. 2(b). A digital communications analyzer (DCA) with a bandwidth of 53 GHz is used to detect the signal.

The measurement results for the wavelength-converted signal are shown in Fig. 3. The eye diagram in Fig. 3(a) shows an open eye with a quality factor of $Q^2 = 11.3$ dB. Distortions of the 0-rail are due to the limited bandwidth of the DCA and weak cross-talk from the clock. For the bit sequences (PRBS of 2^{15}-1 bit) shown in Fig. 3(b)-(d) no pattern dependence is observed, which can be fully explained by the absence of free-carrier effects. The signal quality is only limited by OSNR degradations due to amplifier noise. This limitation could be easily overcome by increasing the input power to the nonlinear waveguide.

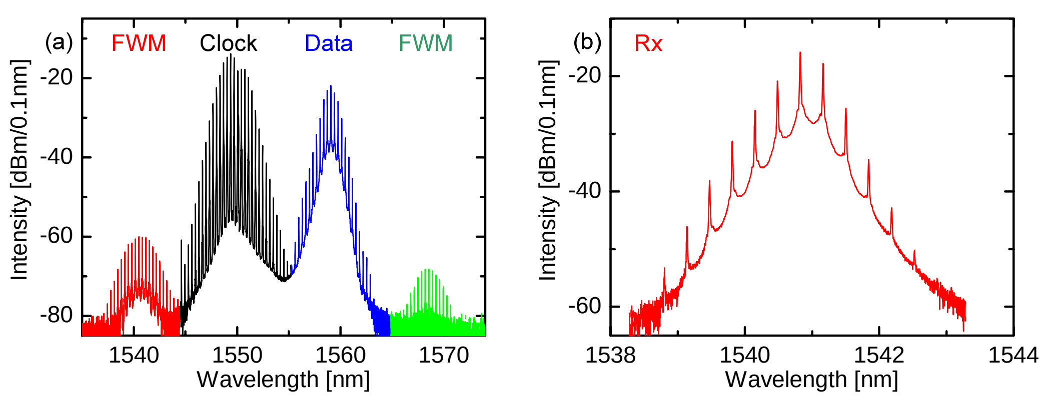

Fig. 2 Optical spectra of the four-wave mixing (FWM) experiment, measured (a) at the output of the nonlinear waveguide and (b) in the receiver after both band-pass filters. The FWM signal at 1541 nm was chosen to avoid cross-talk from the strong data pulses.

4. Summary

All-optical wavelength conversion at 42.7 Gbit/s over 18 nm in a passive 4 mm long CMOS-compatible device has been demonstrated. The quality of the received signal was only limited by amplifier noise and reached a value of $Q^2 = 11.3$ dB. No pattern effects have been found. Increasing the input power will enable error free operation and allow nonlinear silicon-organic hybrid slot waveguides to scale to highest bit rates.

This work was supported by the European FP6 program, TRIUMPH (grant IST-027638 STP), the DFG Center for Functional Nanostructures of the University of Karlsruhe, the EU ePIXnet network of excellence, and the ETH Research Council. We acknowledge partial support from the Commonwealth of Pennsylvania, Ben Franklin Technology Development Authority, technological support by ASML Netherlands B.V., and equipment loan from Siemens Portugal and from Optoelectronics Research Centre (ORC) in Southampton, UK.

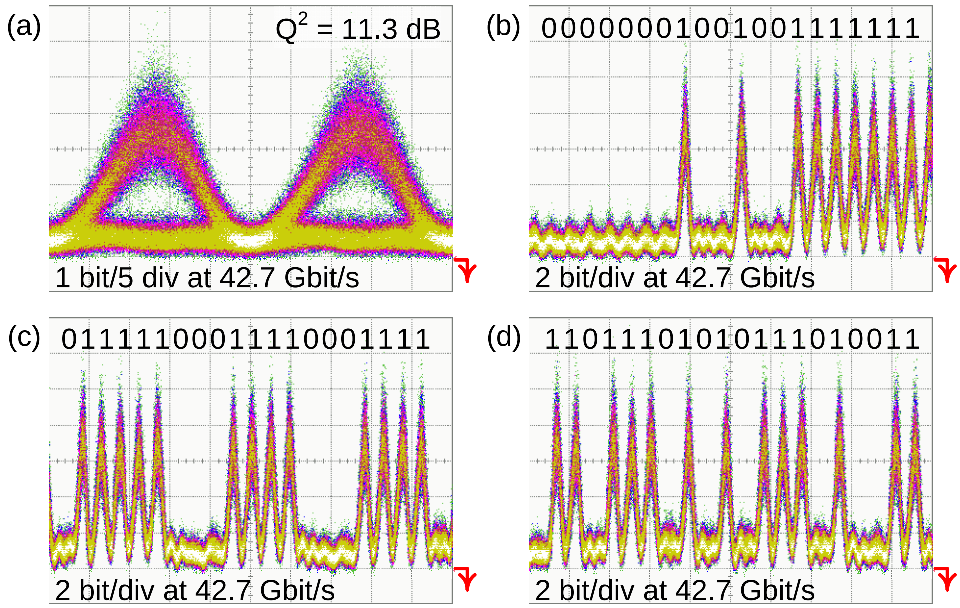

Fig. 3 (a) Eye diagram of the four-wave mixing signal at 1541 nm with a quality factor of $Q^2 = 11.3$ dB. Distortions of the 0-rail are due to the limited bandwidth of the DCA and weak cross-talk from the clock. (b)-(c) Bit sequences with different characteristics. No pattern dependence is observed. The eye quality is only limited by the OSNR due to amplifier noise.

5. References

[1] E. Ciaramella, G. Contestabile, F. Curti, and A. D'Ottavi, "Fast Tunable Wavelength Conversion for All-Optical Packet Switching," IEEE Photon. Technol. Lett. 12, 1361-1363 (2000)

[2] H. Fukuda, K. Yamada, T. Shoji, M. Takahashi, T. Tsuchizawa, T. Watanabe, J. Takahashi, and S. Itabashi, "Four-wave mixing in silicon wire waveguides," Opt. Express 13, 4629-4637 (2005).

[3] R. L. Espinola, J. I. Dadap, R. M. Osgood Jr., S. J. McNab, and Y. A. Vlasov, "C-band wavelength conversion in silicon photonic wire waveguides," Opt. Express 13, 4341-4349 (2005).

[4] W. Mathlouthi, H. Rong, and M. Paniccia, "Characterization of efficient wavelength conversion by four-wave mixing in sub-micron silicon waveguides," Opt. Express 16, 16735-16745 (2008).

[5] Y.-H. Kuo, H. Rong, V. Sih, S. Xu, ,M. Paniccia, and O. Cohen "Demonstration of wavelength conversion at 40 Gb/s data rate in silicon waveguides," Opt. Express 14, 11721-1726 (2006).

[6] T. Vallaitis, C. Koos, B. Esembeson, I. Biaggio, T. Michinobu, F. Diederich, P. Dumon, R. Baets, W. Freude, and J. Leuthold, "Highly Nonlinear Silicon Photonics Slot Waveguides without Free Carrier Absorption Related Speed-Limitations," Proc. 34th European Conf. Opt. Commun. (ECOC'08), Brussels, Belgium, 4, Th.2.D.6 (2008).

[7] W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, and D. Van Thourhout, "Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology," J. Lightwave Technol. 23, 401–412 (2005).

[8] http://www.epixfab.eu

[9] T. Michinobu, J. C. May, J. H. Lim, C. Boudon, J.-P. Gisselbrecht, P. Seiler, M. Gross, I. Biaggio, and F. Diederich, "A new class of organic donor–acceptor molecules with large third-order optical nonlinearities," Chem. Commun. 737-739 (2005).

[10] B. Esembeson, M. L. Scimeca, T. Michinobu, F. Diederich, and I. Biaggio, "A high-optical quality supramolecular assembly for third-order integrated nonlinear optics," Adv. Mat. 20, (2008) online. http://dx.doi.org/10.1002/adma.200801552

[11] T. Baehr-Jones, M. Hochberg, G. Wang, R. Lawson, Y. Liao, P. A. Sullivan, L. Dalton, A. K.-Y. Jen, and A. Scherer , "Optical modulation and detection in slotted silicon waveguides," Opt. Express 13, 5216-5226 (2005).

[12] C. Koos, P. Vorreau, P. Dumon, R. Beats, B. Esembeson, I. Biaggio, T. Michinobu, F. Diederich, W. Freude, and J. Leuthold, "Highly-nonlinear silicon photonics slot waveguide," Optical Fiber Commun. Conf. (OFC'08), Postdeadline Paper PDP25 (2008).

[13] G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, San Diego, 1989), Chap. 10.