



**HAL**  
open science

## All-optical signal processing using silicon devices

Leif Katsuo Oxenløwe, Minhao Pu, Yunhong Ding, Hao Hu, Francesco da Ros, Dragana Vukovic, Asger Sellerup Jensen, Hua Ji, Michael Galili, Christophe Peucheret, et al.

► **To cite this version:**

Leif Katsuo Oxenløwe, Minhao Pu, Yunhong Ding, Hao Hu, Francesco da Ros, et al.. All-optical signal processing using silicon devices. 40th European Conference on Optical Communication (ECOC 2014), Sep 2014, Cannes, France. pp.We.2.5.1, 10.1109/ECOC.2014.6964241 . hal-01069414

**HAL Id: hal-01069414**

**<https://hal.science/hal-01069414>**

Submitted on 29 Sep 2014

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# All-Optical Signal Processing using Silicon Devices

L.K. Oxenløwe<sup>(1)</sup>, M. Pu<sup>(1)</sup>, Y. Ding<sup>(1)</sup>, H. Hu<sup>(1)</sup>, F. Da Ros<sup>(1)</sup>, D. Vukovic<sup>(1)</sup>, A. Sellerup Jensen<sup>(1)</sup>, H. Ji<sup>(1)</sup>, M. Galili<sup>(1)</sup>, C. Peucheret<sup>(2)</sup>, K. Yvind<sup>(1)</sup>

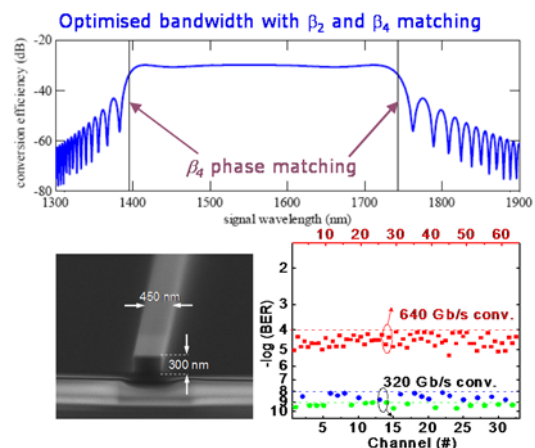
<sup>(1)</sup> DTU Fotonik, Ørstedes Plads 343, Kgs. Lyngby, Denmark, [lkox@fotonik.dtu.dk](mailto:lkox@fotonik.dtu.dk)

<sup>(2)</sup> FOTON Laboratory, CNRS UMR 6082, ENSSAT, University of Rennes 1, 22305 Lannion, France

**Abstract** This paper presents an overview of recent work on the use of silicon waveguides for processing optical data signals. We will describe ultra-fast, ultra-broadband, polarisation-insensitive and phase-sensitive applications including processing of spectrally-efficient data formats and optical phase regeneration.

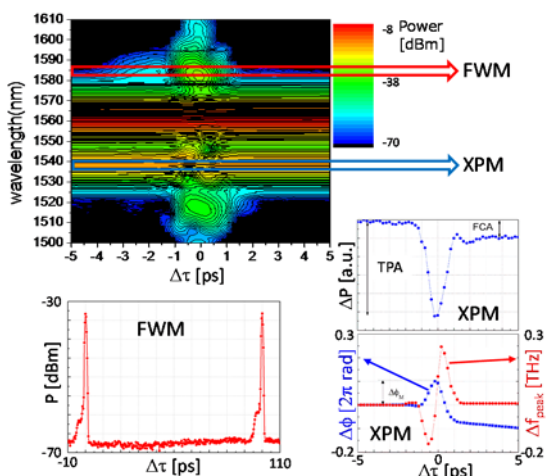
## Introduction and background

As the Internet traffic maintains its double-digit percentage growth, the need for novel and more energy- and spectrally efficient processing technologies never subsides. With the (re-) introduction of coherent communications and advanced modulation formats strongly bound to electronic digital signal processing (DSP), a whole range of transmission impairment mitigation techniques have become possible. These include in particular dispersion compensation, and to some degree nonlinear transmission impairment compensation by e.g. digital back-propagation<sup>1</sup>. Alongside these very successful DSP endeavours, optical signal processing (OSP) has been undergoing a tremendous development, though still short of commercial penetration. Over recent years, OSP has been demonstrated to allow for phase-sensitive amplification for phase regeneration<sup>2</sup>, ultra-broadband flexi-grid light sources<sup>3</sup>, add/drop multiplexing of spectrally intertwined data channels like OFDM<sup>4</sup>, time lens based linear transmission impairment compensation<sup>5</sup>, optical phase conjugation and optical twin-wave transmission for nonlinear transmission impairment compensation<sup>6-7</sup>, and many other



**Fig. 2:** Ultra-broadband FWM bandwidth available with dispersion-engineered silicon nanowire. Lower right: Example of FWM-based broadband OSP: Wavelength conversion, up to 640 Gbit/s<sup>26,28</sup>.

exciting functionalities. The foundation of OSP is efficient optical nonlinearities, and many materials are being investigated today. The most successful materials platform today is undoubtedly highly nonlinear fibres (HNLF), where the nonlinearity may be accumulated over a large length of fibre. HNLF, however, needs special efforts to reduce stimulated Brillouin scattering and increase the OSP bandwidth, which may be improved on by Al-doping, strain and stable dispersion designs like the SPINE-HNLF<sup>8</sup>. Compact waveguide platforms are also very interesting, in particular because of the very stable dispersion properties, allowing for ultra-broadband OSP bandwidths, as demonstrated e.g. in silicon nanowires<sup>9</sup>. Other platforms include chalcogenide (ChG) waveguides<sup>10</sup>, III-V photonic wires<sup>11</sup>, periodically poled Lithium Niobate (PPLN)<sup>12</sup> and semiconductor optical amplifiers (SOAs)<sup>13</sup>. This paper will focus on silicon optical signal processing and mostly on crystalline silicon (c-Si). However, c-Si waveguides suffer from two-photon absorption (TPA) at 1550 nm, and hence other related materials are heavily researched today—such as amorphous silicon<sup>14</sup> with reduced TPA allowing for more efficient lower power OSP<sup>15-18</sup>, as well



**Fig. 1:** Ultra-fast FWM and XPM in a silicon nanowire<sup>24</sup>

as Hydrex glass and silicon nitride<sup>19-21</sup>, as well as III-V wires<sup>11</sup>. One other approach is to apply a p-i-n junction across ones wire and apply a reverse voltage to reduce the steady state density of free carriers, thus strongly reducing the nonlinear absorption loss<sup>22-23</sup>.

**Ultra-fast and ultra-broadband OSP in c-Si**

Fig. 1 shows an experimental spectrogram<sup>24</sup> of a pump-probe characterisation in a c-Si nanowire. This shows that there is indeed no memory effect in FWM in c-Si, and that XPM has both a fast red and fast blue shift, allowing for dual-copy wavelength conversion<sup>25</sup>. Fig. 2 shows how proper nano-engineering by waveguide dimensioning can match  $\beta_2$  and  $\beta_4$  to yield an ultra-broadband FWM bandwidth extending over several hundred nm<sup>26-27</sup>. Thus c-Si nanowires may be used for both ultra-fast and ultra-broadband OSP. Fig. 2 also shows an example of ultra-fast wavelength conversion of an up to 640 Gbit/s serial data signal<sup>28</sup>. Other broadband demonstrations include 640 Gbit/s serial-to-parallel conversion<sup>29</sup>, OSP of 1.28 Tbit/s data<sup>30</sup>, BER-confirmed OOK all-optical regeneration<sup>31-33</sup>], Fig. 3 shows a very recent experiment, where wavelength conversion of the very spectrally efficient data format Nyquist-OTDM was demonstrated at 320 Gbit/s<sup>34</sup>.

**Polarisation-insensitive OSP in c-Si**

All the above functionalities are based on polarisation sensitive processes, so it is very important to find polarisation-insensitive solutions. Fig. 4 shows an integrated polarisation-diversity chip using two c-Si nanowires with a polarisation splitter and rotator (PSR) in either end<sup>35</sup>. An integrated polarisation-insensitive optical ring resonator based DPSK demodulator was implemented in a similar way<sup>36</sup>. In<sup>35</sup>, as shown in Fig. 4, 40 Gbit/s polarisation-independent optical phase conjugation was accomplished allowing for 160 km transmission.

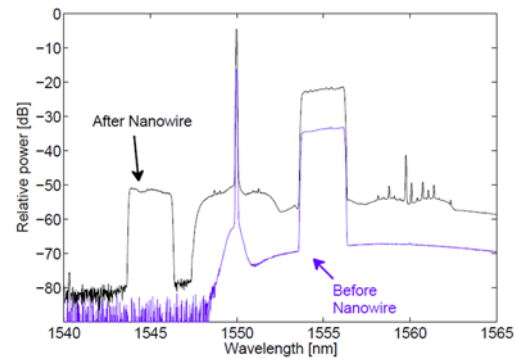


Fig. 3: Ultra-fast FWM-based wavelength conversion of a 320 Gbit/s Nyquist-OTDM data signal<sup>34</sup>.

Other similar approaches are demonstrated in SOAs<sup>37</sup> and PPLN<sup>38</sup>.

**Phase-sensitive amplification in c-Si**

Fig. 5 shows results from<sup>39</sup> with the first phase-regeneration using silicon. A c-Si nanowire in a p-i-n junction<sup>22</sup> is employed to reduce accumulation of TPA-generated free carriers. With this device it is possible to increase the pump power and use longer waveguides (4 cm) enabling a very high CW conversion efficiency of minus a few dB with -25 V bias<sup>40</sup>. This high efficiency enable a phase-sensitive extinction ratio (ER) up to a record 20 dB for a chip with CW operation, and this in turn allows for a demonstration of 10 Gbit/s DPSK phase regeneration with a 14 dB receiver sensitivity improvement. Other chip-based investigations count Si photonic crystal waveguides with 11 dB ER<sup>41</sup>, ChG<sup>42</sup> and PPLN<sup>43</sup>.

**Conclusions**

We have attempted to provide an overview of major milestones achieved using crystalline silicon nanowires for optical signal processing. Nanowires have the benefit of allowing for ultra-fast and ultra-broadband OSP, and may in addition be made polarisation-independent and with very high conversion efficiency allowing for phase-sensitive applications.

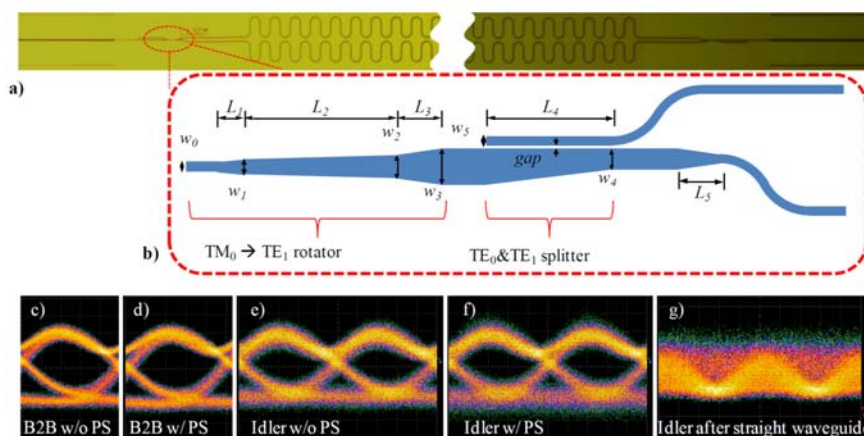


Fig. 4: Polarisation-insensitive FWM device with integrated silicon nanowires<sup>35</sup>.

**Acknowledgements**

A. Gajda, L. Zimmermann, B. Tillack, K. Petermann for Si p-i-n collaboration, ERC SOCRATES, VKR NATEC, FTP NESTOR, FTP Terabit on Silicon, FTP SIMOF.

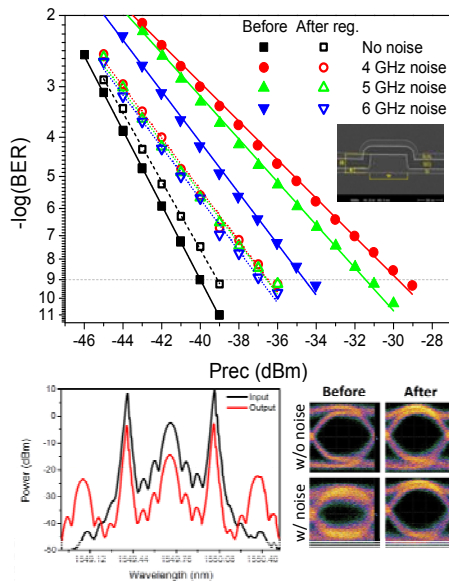


Fig. 5: Phase-regeneration in a crystalline silicon nanowire in a p-i-n junction<sup>39</sup>.

References

[1] E. Ip et al, "Compensation of dispersion and nonlinear impairments using digital back propagation," J. Lightwave Technol. 26, 3416–3425 (2008)

[2] R. Slavik et al, "All-optical phase and amplitude regenerator for next-generation telecommunications systems," Nat. Photonics 4, 690–695 (2010).

[3] A. Vahid et al, Flex-grid Compatible Ultra Wide Frequency Comb Source for 31.8 Tb/s Coherent Transmission of 1520 UDWDM Channels, OFC 2014, Th5B.7

[4] T. Richter et al, "Coherent In-line Substitution of OFDM Subcarriers Using Fiber-Frequency Conversion and Free-Running Lasers", OFC 2014, paper Th5B.6

[5] M. Nakazawa et al, "Ideal distortion-free transmission using optical Fourier transformation and Fourier transform-limited optical pulses," Photon. Technol. Lett., Vol. 16, No. 4, pp. 1059-1061, 2004.

[6] H. Hu et al, Fiber Nonlinearity Compensation of an 8-channel WDM PDM-QPSK Signal using Multiple Phase Conjugations, OFC 2014, paper M3C.2

[7] X. Liu et al, "Phase-conjugated twin waves for communication beyond the Kerr nonlinearity limit," Nature Photon. 7, 560-568 (2013).

[8] <http://ofscatalog.specialtyphotonics.com>

[9] N. Ophir et al, "Wavelength conversion and unicast of 10-Gb/s data spanning up to 700 nm using a silicon nanowaveguide." Opt. Express, Vol. 20, No. 6, (2012).

[10] B.J. Eggleton et al, Chalcogenide Photonics, Nature Photonics 5, 141-148, doi:10.1038/nphoton.2011.309

[11] J.J. Wathen, "Efficient continuous-wave four-wave mixing in bandgap-engineered AlGaAs waveguides" Optics Letters, Vol. 39, No. 11 (2014)

[12] A. Bogoni et al, "640 Gb/s all-optical regenerator based on a periodically poled Lithium Niobate waveguide," J. Lightwave Technol., Vol. 30, No. 12, pp. 1829-1834, 2012

[13] H. C. H. Mulvad et al, "640 Gbit/s OTDM lab-transmission and 320 Gbit/s field-transmission with SOA based clock recovery," OFC 2008, paper OWS2, 2008.

[14] B. Kuyken et al, "Nonlinear properties of and nonlinear processing in hydrogenated amorphous silicon waveguides," Opt. Express., Vol. 19, No. 26, 2011.

[15] K-Y Wang et al, Ultralow power continuous-wave frequency conversion in hydrogenated amorphous silicon waveguides, Optics Lett., Vol. 37, No. 8 (2012)

[16] K-Y Wang et al, ultralow-power all-optical processing of high-speed data signals in deposited silicon waveguides, Optics Express, vol 20, no 22, (2012)

[17] S. Suda et al, Pattern-effect-free all-optical wavelength conversion using a hydrogenated amorphous silicon waveguide with ultra-fast ..., Opt. Lett., 37(8) (2012)

[18] C. Grillet et al, amorphous silicon nanowires combining high nonlinearity, FOM and optical stability, Optics Express, vol 20, no 20, (2012)

[19] D.J. Moss et al, New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics, NPHOT, DOI: 10.1038/NPHOTON.2013.183

[20] Y. Okawachi et al, Octave-spanning frequency comb generation in a silicon nitride chip, Opt. Lett., 36(17) 2011

[21] J. F. Bauters et al, "Ultra-low-loss high-aspect-ratio Si3N4 waveguides," Opt. Express 19(4), 3163–3174 (2011)

[22] A. Gajda et al, "Highly efficient CW parametric conversion at 1550 nm in SOI waveguides by reverse biased p-i-n junction," Opt. Express 20, 13100–13107 (2012).

[23] R. Jones et al, Net continuous wave optical gain in a low loss silicon-on-insulator waveguide by stimulated Raman scattering, Optics Express, ol 13, no 2, (2005)

[24] M. Ma et al, "Detailed time-resolved spectral analysis of ultra-fast four-wave mixing in silicon nanowires," Proc IPC 2011, paper TuV2, 2011.

[25] H. Ji et al, "Two-copy wavelength conversion of an 80 Gbit/s serial data signal using cross-phase modulation in a silicon nanowire and detailed pump-probe characterisation" ECOC 2012, Paper We.2.E.3.

[26] H. Hu et al, "Ultra-high-speed wavelength conversion in a silicon photonic chip," Opt. Exp., 19(21), 2011.

[27] M. Pu et al, "15-THz tunable wavelength conversion of picosecond pulses in a silicon waveguide." IEEE Photonics Technology Letters, vol. 23, no. 19, 2011.

[28] H. Hu et al, "Silicon Chip based Wavelength Conversion of Ultra-High Repetition Rate Data Signals", OFC 2011, postdeadline paper PDPA8

[29] H. C. Hansen Mulvad et al, "Ultra-high-speed optical serial-to-parallel data conversion in a silicon nanowire," ECOC' 2011, Paper Th.13.A.2 (postdeadline paper)

[30] L.K. Oxenløwe et al, "Silicon Photonics for Signal Processing of Tbit/s serial data signals", IEEE J. Select. Topics Quantum Electron., Special Issue, vol 18 no 2, pp996-1005, March/April 2012 (invited paper)

[31] H. Ji et al, "40 Gbit/s serial data signal regeneration using self-phase modulation in a silicon nanowire," IPC 2012, paper ThQ1

[32] A. S. Jensen et al, "All-optical 40 Gbit/s regenerative wavelength conversion based on cross-phase modulation in a silicon nanowire", OECC 2013, 2013. Paper ThM1-2.

[33] R. Salem et al, "Signal regeneration using low-power four-wave mixing on silicon chip," Nature Photonics 2, 2008.

[34] A. S. Jensen et al, "Wavelength Conversion of a 320-Gbit/s Nyquist DPSK Signal using Four-Wave Mixing in a Silicon Nanowire" submitted

[35] D. Vukovic et al, Polarization-insensitive wavelength conversion of 40 Gb/s NRZ-DPSK signals in a silicon polarization diversity circuit, Opt. Express, 22(10), (2014)

[36] Y. Ding et al, "Polarization diversity DPSK demodulator on the silicon-on-insulator platform with simple fabrication," Opt. Express 21(6), 7828–7834 (2013).

[37] C. M. Gallep et al, "Polarization independent dual wavelength converter based on FWM in a single semiconductor optical amplifier," OFC 2010, OWP2.

[38] I. Brener et al, "Polarisation-insensitive wavelength converter based on cascaded nonlinearities in LiNbO3 waveguides," Electron. Lett. 36(1), 66–67 (2000).

[39] F. da Ros et al, Phase regeneration of DPSK signals in a silicon waveguide with reverse biased p-i-n junction, Optics Express, vol 22, no 5 (2014)

[40] F. Da Ros et al, "Continuous wave phasesensitive four-wave mixing in silicon waveguides with reverse-biased p-i-n junctions," ECOC 2013, paper P.2.11

[41] Y. Zhang et al, "Phase-sensitive amplification in silicon photonic crystal waveguides," Opt. Lett. 39, (2014).

[42] R. Neo et al, "Phase-sensitive amplification of light in a  $\chi(3)$  photonic chip using a dispersion engineered chalcogenide ridge waveguide," Opt. Express 21, (2013)

[43] B. J. Puttnam et al, "Large phase sensitive gain in periodically poled lithiumniobate with high pump power," IEEE Photon. Technol. Lett. 23, 426–428 (2011).