All-optical signal processing using silicon devices

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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-01069414v1

Submitted on 29 Sep 2014

All-Optical Signal Processing using Silicon Devices

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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 [1]. 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 [2], ultra-broadband flexi-grid light sources [3], add/drop multiplexing of spectrally intertwined data channels like OFDM [4], time lens based linear transmission impairment compensation [5], optical phase conjugation and optical twin-wave transmission for nonlinear transmission impairment compensation [6-7], and many other 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* [8]. 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 [9]. Other platforms include chalcogenide (ChG) waveguides [10], III-V photonic wires [11], periodically poled Lithium Niobate (PPLN) [12] and semiconductor optical amplifiers (SOAs) [13]. 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 [14] with reduced TPA allowing for more efficient lower power OSP [15-18], as well

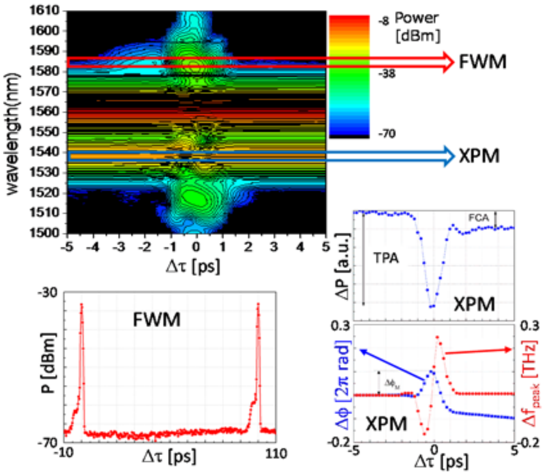

Fig. 1: Ultra-fast FWM and XPM in a silicon nanowire [24]

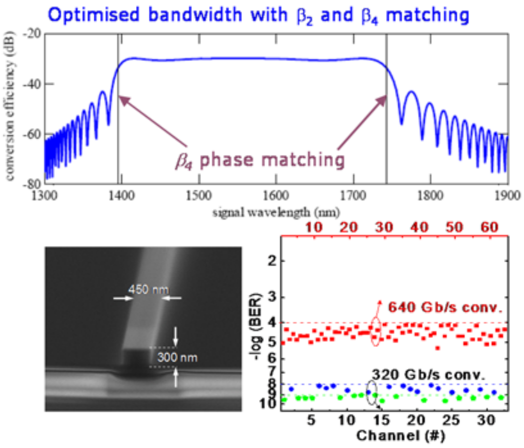

Fig. 2: Ultra-broadband FWM bandwidth available with dispersion-engineered silicon nanowire. Lower right: Example of FWM-based broadband OSP: Wavelength conversion, up to 640 Gbit/s [26-28].

as Hydex glass and silicon nitride [19-21], as well as III-V wires [11]. 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 [22-23].

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

Fig. 1 shows an experimental spectrogram [24] 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 [25]. Fig. 2 shows how proper nano-engineering by waveguide dimensioning can match β_2 and β_4 to yield an ultra-broadband FWM bandwidth extending over several hundred nm [26-27]. 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 [28]. Other broadband demonstrations include 640 Gbit/s serial-to-parallel conversion [29], OSP of 1.28 Tbit/s data [30], BER-confirmed OOK all-optical regeneration [31-33]], 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 [34].

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 [35]. An integrated polarisation-insensitive optical ring resonator based DPSK demodulator was implemented in a similar way [36]. In [35], as shown in Fig. 4, 40 Gbit/s polarisation-independent optical phase conjugation was accomplished allowing for 160 km transmission.

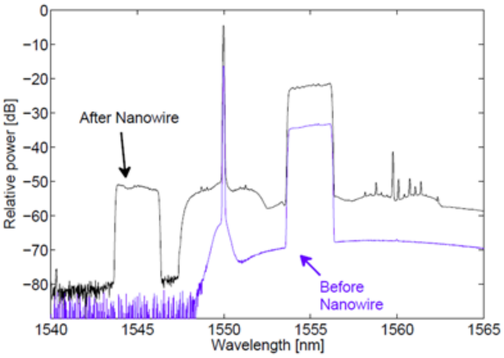

Fig. 3: Ultra-fast FWM-based wavelength conversion of a 320 Gbit/s Nyquist-OTDM data signal [34].

Other similar approaches are demonstrated in SOAs[37] and PPLN [38].

Phase-sensitive amplification in c-Si

Fig. 5 shows results from [39] with the first phase-regeneration using silicon. A c-Si nanowire in a p-i-n junction [22] 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 [40]. 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 [41], ChG [42] and PPLN [43].

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.

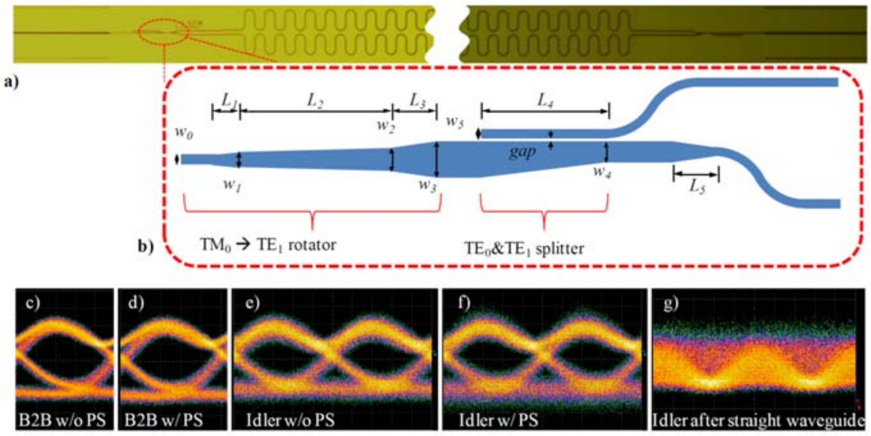

Fig. 4: Polarisation-insensitive FWM device with integrated silicon nanowires [35].

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.

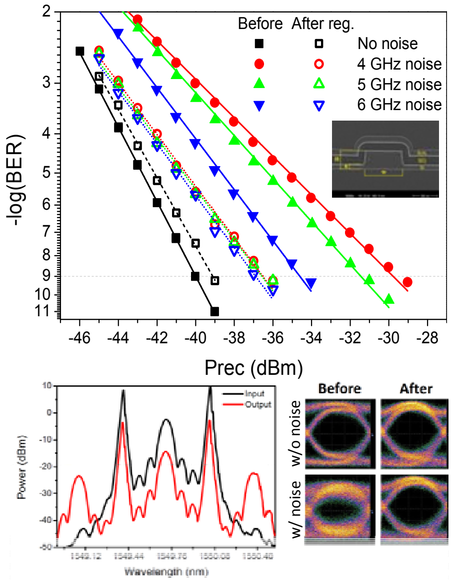

Fig. 5: Phase-regeneration in a crystalline silicon nanowire in a p-i-n junction [39].

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