Polarization Insensitive Wavelength Conversion in a Low-Birefringence SiGe Waveguide

Mohamed A. Ettabib, Alexandros Kapsalis, Adonis Bogris, Francesca Parmigiani, Victor J. F. Rancaño, Kyle Bottrill, Mickael Brun, Pierre Labeye, Sergio Nicoletti, Kamal Hammani, Dimitris Syvridis, David J. Richardson and Periklis Petropoulos

***Abstract*—We report the first demonstration of a single-pass dual-orthogonal-pump FWM-based wavelength conversion scheme in a silicon-based waveguide. The silicon germanium (SiGe) waveguide used was designed to exhibit strong TE/TM mode similarity across a broad wavelength range as well as a large nonlinear coefficient. A polarization dependent loss (PDL) of just 0.42 dB was measured and the conversion of 40 Gb/s DPSK signals was demonstrated with 1.5 dB power penalty at a bit error ratio (BER) of 10^{-9}.**

***Index Terms*—Silicon Photonics, Wavelength Converters, Four-Wave Mixing, Phase Shift Keying, Optical Waveguide, Integrated Optics, Nonlinear Optics.**

I. Introduction

All-optical wavelength converters (WCs) are anticipated to form a fundamental part of future ultra-high speed spectrally-efficient wavelength division multiplexed (WDM) networks, promising to reduce network complexity and cost and offer greater flexibility [1]. Among the various wavelength conversion technologies [2-4], four-wave mixing (FWM)-based WCs have attracted significant research attention in recent years. Their transparency to bit rate and modulation format makes FWM-based WCs highly compatible with the increasingly high-bandwidth high-speed communication networks.

While highly nonlinear fibers (HNLFs) represent the most mature technology for implementing FWM-based WCs, silicon photonic devices have recently emerged as an alternative technological competitor to HNLFs [5-7]. The compatibility of Si technology with CMOS infrastructure has made it an attractive option for low cost large-scale production. In addition, it is possible to engineer Si devices that benefit from both the ultra-high nonlinear refractive index of silicon and the tight confinement of light into micro- or nano-scale Si waveguides. Such waveguides exhibit a third order nonlinear coefficient which can be up to 4-5 orders of magnitude larger than that achievable using silica-based HNLF technology [5], making highly nonlinear Si devices an attractive platform for implementing efficient wavelength conversion systems. Indeed, a number of demonstrations of broadband low-power and efficient silicon-based WCs have already been reported [6-8].

In addition to these attributes, a practical wavelength conversion system should also be independent of the polarization of the signal. While FWM is an inherently polarization-dependent process requiring accurate control of the state of polarization of the mixing waves, implementations that achieve polarization insensitive operation have been proposed. Such schemes employing either two orthogonally polarized pumps [9] or polarization diversity [10] have already been widely demonstrated in fiber-based devices, but their adoption in silicon-based systems is still rather limited [11, 12]. Polarization diversity is widely used in photonics to overcome the strong birefringence of devices. In the context of FWM, care must be taken to minimize the relative delay between the two different polarizations of the generated idler beams when recombining them. Similarly, any backscattering reflections can degrade system performance when a polarization diversity loop is adopted. The dual orthogonal pumps scheme on the other hand, offers a simpler single-pass configuration but requires similar dispersive and nonlinear characteristics for the TE and TM modes of the device. Thus, it necessitates precise structural engineering of the waveguide to ensure low birefringence behavior.

In this Letter, we expand on the work reported in [13] where we demonstrated the first dual-orthogonal-pump silicon-based ($Si_{0.8}Ge_{0.2}$) WC with only 0.42 dB polarization-dependent loss (PDL). We present a numerical study showing the dependence of the modal and nonlinear properties of SiGe waveguides on their dimensions, and which justifies the choice of a waveguide exhibiting strong TE and TM modal symmetry and a large nonlinear coefficient over the entire S+C+L bands. We also

This work was supported by the European Communities Seventh Frame-work Programme FP7/2007-2013 under Grant 288304 (STREP CLARITY) and the Photonics Hyperhighway Programme Grant (EPSRC grant EP/I01196X). The data for this paper can be found at 105258/SOTON/386211

M. A. Ettabib, F. Parmigiani, V. J. F Rancaño, K. Bottrill, D. J. Richardson and P. Petropoulos are with the Optoelectronic Research Centre, University of Southampton, SO17 1BJ, Southampton, United Kingdom (email: mae206@orc.soton.ac.uk, frp@orc.soton.ac.uk, vjfr1u10@orc.soton.ac.uk, krhb1g12@soton.ac.uk, djr@orc.soton.ac.uk, pp@orc.soton.ac.uk).

A. Kapsalis, A. Bogris and D. Syvridis are with Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Panepistimiopolis, Ilissia, 15784, Athens, Greece (email: alex@di.uoa.gr, abogris@di.uoa.gr, dsyvridi@di.uoa.gr). Adonis Bogris is also with the Department of Informatics, Technological Educational Institute of Athens, Aghiou Spiridonos, Egaleo, 12243, Greece.

M. Brun, P. Labeye, S. Nicoletti are with CEA-Leti MINATEC Campus, 17 rue des Martyrs 38054 Grenoble Cedex 9, France (email: mickael.brun @cea.fr, pierre.labeye@cea.fr, sergio.nicoletti@cea.fr)

K. Hammani is with Laboratoire Interdisciplinaire Carnot de Bourgogne, Université de Bourgogne Franche-Comté, 9 av. A. Savary, BP 47870, 21078 Dijon Cedex, France (email: kamal.hammani@u-bourgogne.fr)

report the conversion of 40 Gb/s differential phase-shift keying (DPSK) signals with 1.5 dB power penalty at a BER of 10^{-9}.

II. Polarization Insensitive FWM

FWM-based wavelength conversion is a polarization-dependent process. As such, the strength of the generated idler is dependent on the relative alignment of the states of polarization of the input pump(s) and signal beams and the maximum conversion efficiency is achieved for co-polarized input waves. However, polarization insensitive WC can be achieved by implementing a simple single-pass FWM scheme based on the use of two orthogonally polarized pumps (Fig. 1). Figure 1 illustrates the particular case of two linearly polarized orthogonal pumps, where the state of polarization of the generated idler is orthogonal to that of the linearly polarized signal [14, 15].

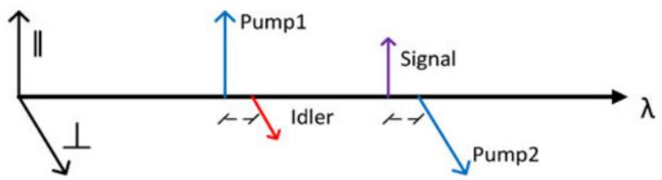

Fig. 1. A schematic illustrating a dual-orthogonal-pump FWM-based wavelength converter.

A key requirement for implementing such a scheme is the use of a low-birefringence nonlinear medium. Similar optical characteristics for the TE and TM modes of the medium ensure the achievement of good linear and nonlinear phase matching simultaneously among all beams propagating along the two orthogonal axes of the device [16]. This is in contrast to the angled pump scheme [11] where phase matching conditions are satisfied separately in each orthogonal projection (TE and TM) and adjustment of the state of polarization of the pump(s) is subject to both the pump power and wavelength,

In this work, the nonlinear device used was a $Si_{0.8}Ge_{0.2}$ strip waveguide embedded in Si (the choice of Ge concentration was based on our earlier characterization study concluding that a Ge concentration of 20% results in the highest nonlinear figure of merit for the majority of waveguide widths studied). A full waveguide analysis was carried out by means of a Finite Elements Method (FEM) solver to study the optical characteristics of waveguide. Various aspect ratios (width/height) of the waveguide were analyzed to study the impact of the waveguide structural geometry on birefringence and nonlinearity. The model aimed to yield a waveguide design exhibiting identical (or very similar) TE and TM effective mode indices and a high nonlinearity [17]. Figure 2 plots the difference in dispersion between the TE and TM modes as a function of waveguide width for a fixed waveguide height of 1.7µm. (Merely practical considerations relating to the fabrication run restricted us to this value). The figure shows that the waveguide exhibits the lowest birefringence for a width of 1.5 µm. The fundamental mode profile of this waveguide structure exhibits two nearly identical transversal modal field components (E_x and E_y). However, all widths between 0.7-2.2µm included in the study can be considered as viable design options, since the largest difference in dispersion between the two modes in any waveguide within this range is only approximately $6\cdot10^{-5}$ ps/nm for a 2-cm long device. The absolute value of dispersion of waveguides with these dimensions is approximately -800 ps/nm/km. This low birefringence behavior is facilitated by the use of a buried device structure (i.e. encapsulating the waveguide in a Si layer) which allows obtaining the necessary symmetry in the effective refractive index for the TE and TM modes [8].

The real part of the nonlinear coefficient $\mathrm{Re}(\gamma) = n_2\omega/cA_{eff}$ of waveguides with the same height and varying width is plotted in Fig. 2 for the TM mode (the TE mode exhibits similar values). As expected, waveguides with smaller widths exhibit larger nonlinear coefficients due to a tighter mode confinement. This holds until the waveguide dimensions become too small for the mode to be contained within it. The plot shows that the nonlinear coefficient approaches its maximum value at a waveguide width of 1µm, which was eventually chosen for the implementation of the polarization insensitive WC.

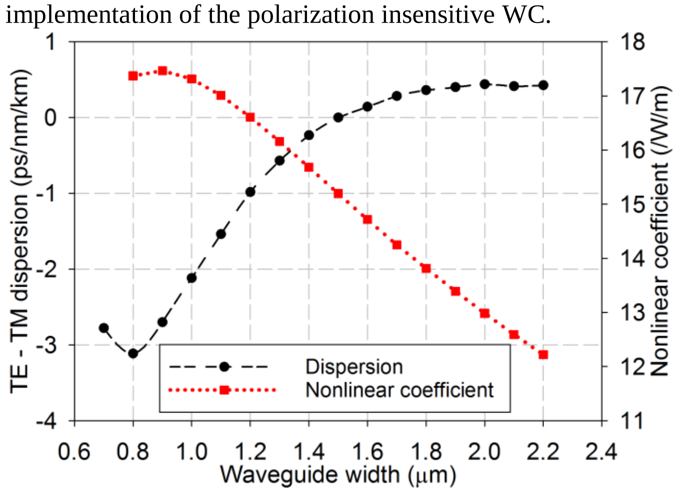

Fig. 2. A plot of the difference in chromatic dispersion between TE and TM modes (circles, dashes) – and of the nonlinear coefficient (squares, dots) as a function of waveguide width. for a waveguide height of 1.7µm at 1550nm .

III. Waveguide Fabrication and Characterization

The fabrication method of the $Si_{0.8}Ge_{0.2}$ strip waveguide that was used in this work consisted of realizing a 1.7 µm thick SiGe layer directly on a 200 mm Si substrate. The layer was epitaxially grown by reduced pressure chemical vapor deposition (RP-CVD) to control precisely the Ge concentration and uniformity. The strip was etched using inductively coupled plasma reactive ion etching (ICP RIE) and encapsulated by a 12-µm Si cladding layer with the same RP-CVD technique. Coupling to the waveguide was facilitated through a 2-µm taper at its entrance. Note that other than improving the coupling efficiency, the 0.5-mm long taper did not affect the guidance of the wave. The length of the waveguide was 20 mm. Figure 3 (top) displays a scanning electron microscope (SEM) image of the waveguide cross-section before and after encapsulation. The propagation loss of the fabricated waveguide was measured to be 1.4 dB/cm for both TE and TM modes (please refer to [17] for the measurement technique). The calculated dispersion curves as well as the nonlinear coefficient of the two polarization axes of the waveguide over a wide wavelength region around 1.55 µm are shown in Fig. 3 (bottom). As can be seen in the figure, the two polarization modes were predicted to exhibit very similar dispersion and nonlinearity across the 1.40 – 1.70 µm band.

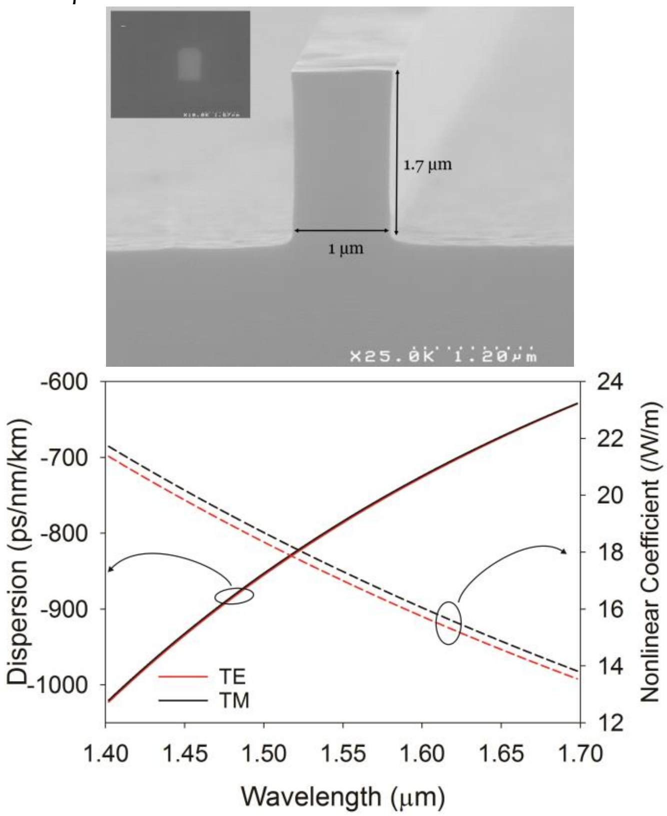

Fig. 3: Dispersion and nonlinear coefficient curves for the structure under investigation as a function of wavelength. Inset: 1µm wide SiGe strip waveguide before and after encapsulation in a 12µm Si cladding layer.

IV. Experimental Setup and Results

The experimental setup used for the polarization insensitive WC is shown in Fig. 4 (top). Two CW lasers, operating at 1558.5 nm (Pump 1) and 1564.5 nm (Pump 2), were combined together in the same fiber through a 50/50 coupler. A third CW beam at 1563.5 nm was fed to a polarization scrambler in order to randomize its state of polarization. The signal was then coupled together with the two pumps through a second 50/50 coupler. The three waves were amplified in an erbium-doped fiber amplifier (EDFA) and coupled to the $Si_{0.8}Ge_{0.2}$ waveguide. The signals were launched into the device using a commercial lensed fiber with a spot size of 2 µm, exhibiting an overall coupling loss of approximately 8 dB. In all of our measurements, the total pump power at the input of the waveguide was approximately 390mW (equally shared between the two pumps to optimize the PDL). Following the work reported in [17], we estimate this power to be around one order of magnitude below the TPA threshold of the waveguide. The state of polarization of the two pumps was made to be orthogonal to each other by adjusting the polarization controllers PC1 and PC2 and minimizing the undesired pump-to-pump FWM at the output of the waveguide using an optical spectrum analyzer (OSA) (see Fig. 5). At the output of the sample, the wavelength-converted signal was selected using a 1-nm bandwidth filter and coupled into an optical detector. The variations in the signal power represented the degree of polarization sensitivity of the FWM process achieved by the SiGe waveguide. A maximum PDL of 0.42 dB was detected.

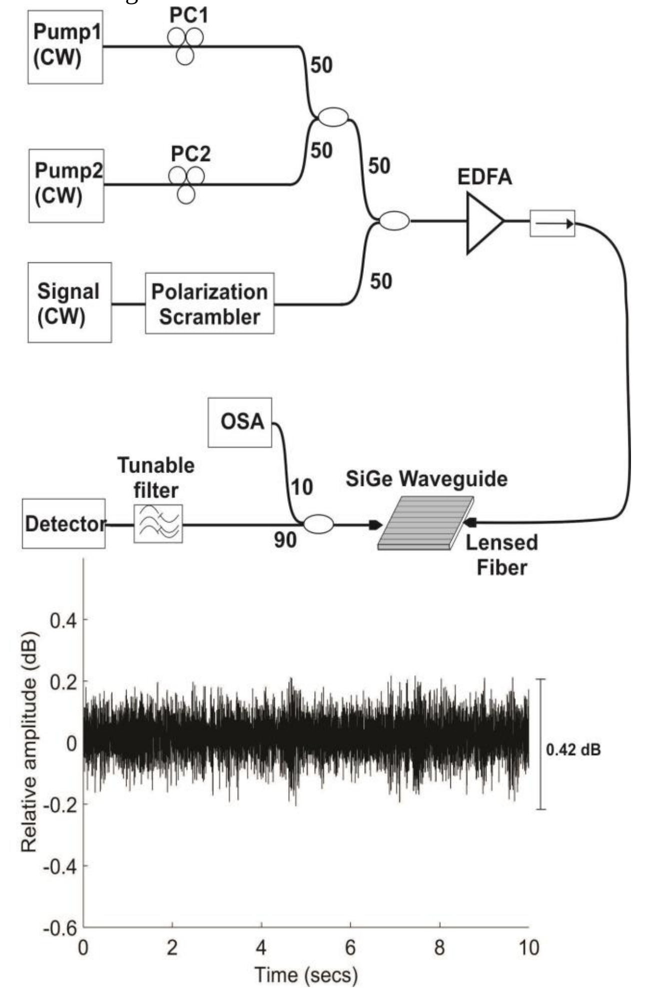

Fig. 4. Top: Experimental setup of the WC using a SiGe waveguide. Bottom: polarization sensitivity as a function of time.

The performance of the SiGe-based WC was then assessed using modulated data signals. An amplitude modulator was introduced in place of the polarization scrambler to generate a 40 Gb/s non-return-to-zero DPSK 2^{31}-1 pseudo-random bit sequence (PRBS). A typical spectrum obtained at the output of the waveguide is shown in Fig. 5. The FWM conversion efficiency (CE) (defined as the ratio of the power of the converted idler to the output signal power) was -27 dB and the optical signal to noise ratio (OSNR) of the converted signal was 24 dB. As expected, the orthogonal alignment of the pumps resulted in a reduced CE compared to that of a scalar (co-polarized) pumping scheme [8]. At the output of the sample, the wavelength-converted signal was compared to the original in terms of eye diagrams and BER tests (Fig.6). For this purpose, the signals under test were demodulated in a 1-bit delay line interferometer (DLI) and directly detected using an optically pre-amplified photodiode.

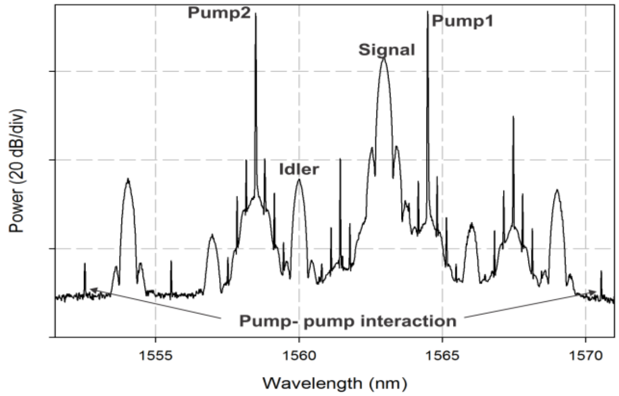

Fig. 5. Spectral trace measured at the output of the sample.

BER measurements showed an approximately 1.5 dB power penalty (at a BER of 10^{-9}) as compared to the back-to-back (B2B) operation (Fig. 6) and a clear and open eye was also recorded for the converted signal (insets of Fig. 6). We believe that much of the BER conversion penalty should be attributed to the ASE noise of the EDFA used to amplify the signals prior to the sample. The use of a lower-noise EDFA, in conjunction with improved filtering throughout the setup should improve the overall performance of the WC.

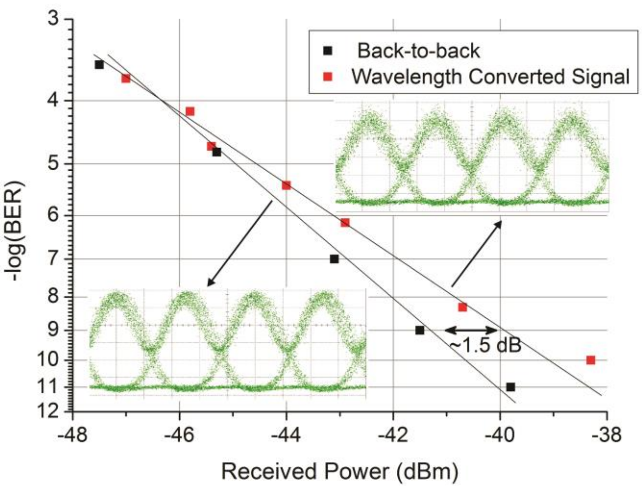

Fig. 6. BER curves and demodulated eye diagrams (insets) for the original signal (B2B) and the wavelength converted signal.

V. Conclusion

This Letter reported the first demonstration of a single-pass polarization insensitive wavelength converter in a 20-mm long silicon germanium waveguide. The design process of the SiGe device has yielded a highly symmetrical TE/TM behavior and a large nonlinear coefficient. Utilizing FWM with two orthogonally polarized pumps, the wavelength conversion of a 40-Gb/s DPSK signal was demonstrated, achieving a PDL of just 0.42 dB, a conversion efficiency of approximately -27 dB and a conversion penalty of 1.5 dB at a BER of 10^{-9}.

The results reported here further demonstrate the emergence of SiGe devices as a competitive all-optical signal processing technology. The inclusion of Ge in the waveguides facilitates flexible dispersion engineering and enhances the effective nonlinear coefficient, making SiGe technology a versatile choice for a wide range of nonlinear applications [17-19].

References

[1] G. Contestabile, M. Presi, and E. Ciaramella, "Multiple wavelength conversion for WDM multicasting by FWM in an SOA," PTL. **16**(7), 1775-1777 (2004).

[2] Junfeng Zhang, Yuping Chen, Feng Lu, and Xianfeng Chen, "Flexible wavelength conversion via cascaded second order nonlinearity using broadband SHG in MgO-doped PPLN," Opt. Express **16**, 6957-6962 (2008).

[3] Jianjun Yu; Jeppesen, P., "80-Gb/s wavelength conversion based on cross-phase modulation in high-nonlinearity dispersion-shifted fiber and optical filtering," in IEEE Photon. Technol. Lett., vol.13, no.8, pp.833-835, Aug. 2001.

[4] Durhuus, T.; Mikkelsen, B.; Joergensen, C.; Danielsen, S.L.; Stubkjaer, K.E., "All-optical wavelength conversion by semiconductor optical amplifiers," in Lightwave Technology, Journal of , vol.14, no.6, pp.942-954, (1996).

[5] C. Koos , P. Vorreau , T. Vallaitis , P. Dumon , W. Bogaerts , R. Baets , B. Esembeson , I. Biaggio , T. Michinobu , F. Diederich , W. Freude and J. Leuthold "All-optical high-speed signal processing with silicon-organic hybrid slot waveguides", Nat. Photon. **3**(4), 216 -219 (2009).

[6] M. A. Foster, A. C. Turner, J. E. Sharping, B. S. Schmidt, M. Lipson, and A. L. Gaeta, "Broad-band optical parametric gain on a silicon photonic chip," Nature 441, 960-963 (2006).

[7] B. Lee, A. Biberman, A. Turner-Foster, M. Foster, M. Lipson, A. Gaeta, and K. Bergman, "Demonstration of broadband wavelength conversion at 40 gb/s in silicon waveguides," IEEE Photon. Technol. Lett., **21**(3), 182-184 (2009).

[8] M. A. Ettabib, K. Hammani, F. Parmigiani, L. Jones, A. Kapsalis, A. Bogris, D. Syvridis, M. Brun, P. Labeye, S. Nicoletti, P. Petropoulos, "FWM-based wavelength conversion of 40 Gbaud PSK signals in a silicon germanium waveguide," Opt. Express **21**(14), 16683–16689 (2013).

[9] J. Lu, L. Chen, Z. Dong, Z. Cao, and S. Wen, "Polarization insensitive wavelength conversion based on orthogonal pump four-wave mixing for polarization multiplexing signal in high-nonlinear fiber," J. Lightwave Technol. **27**(24), 5767–5774 (2009).

[10] K. K. Chow, C. Shu, C. L. Lin, and A. Bjarklev, "Polarization-insensitive widely tunable wavelength converter based on, four-wave mixing in a dispersion-flattened nonlinear photonic crystal fiber," IEEE Photonics Technol. Lett. **17**, 624-626 (2005).

[11] M. Pu, H. Hu, C. Peucheret, H. Ji, M. Galili, L. Oxenløwe, P. Jeppesen, J. Hvam, and K. Yvind,"Polarization insensitive wavelength conversion in dispersion-engineered silicon waveguide," Opt. Express **20**, 6374-6380 (2012).

[12] D. Vukovic, Y. Ding, H. Hu, H. Ou, L. Oxenløwe, and C. Peucheret, "Polarization-insensitive wavelength conversion of 40Gb/s NRZ-DPSK signals in a silicon polarization diversity circuit," Opt. Express **22**, 12467-12474(2014).

[13] M. A. Ettabib, V. Rancaño, F. Parmigiani, A. Kapsalis, A. Bogris, K. R. Bottrill, M. Belal, M. Brun, P. Labeye, S. Nicoletti, K. Hammani, D. Syvridis, D. J. Richardson, and P. Petropoulos, "Polarization Insensitive Wavelength Conversion of 40 Gb/s DPSK Signals in a Silicon Germanium Waveguide," in Optical Fiber Communication Conference 2015, paper Tu2F.1.

[14] V. J. F. Rancano, F. Parmigiani, P. Petropoulos and D. J. Richardson, "100-GHz Grid-Aligned Multi-Channel Polarization Insensitive Black-Box Wavelength Converter, " J. Lightwave Technol. **32**(17), 3027-3035 (2014).

[15] Qiang Lin and Govind P. Agrawal, "Vector theory of four-wave mixing: polarization effects in fiber-optic parametric amplifiers," J. Opt. Soc. Am. B 21, 1216-1224 (2004)

[16] C. McKinstrie and S. Radic, "Phase-sensitive amplification in a fiber," Opt. Express **12**, 4973-4979 (2004).

[17] Kamal Hammani, Mohamed A. Ettabib, Adonis Bogris, Alexandros Kapsalis, Dimitris Syvridis, Mickael Brun, Pierre Labeye, Sergio Nicoletti, David J. Richardson, and Periklis Petropoulos, "Optical properties of silicon germanium waveguides at telecommunication wavelengths," Opt. Express 21, 16690-16701 (2013).

[18] M. A. Ettabib, F. Parmigiani, A. Kapsalis, A. Bogris, M. Brun, P. Labeye, S. Nicoletti, K. Hammani, D. Syvridis, d. Richardson, and P. Petropoulos, "Record Phase Sensitive Extinction Ratio in a Silicon Germanium Waveguide," in CLEO 2015, paper STh1O.8.

[19] M. A. Ettabib, L. Xu, A. Bogris, A. Kapsalis, M. Belal, E. Lorent, P. Labeye, S. Nicoletti, K. Hammani, D. Syvridis, D. P. Shepherd, J. H. V. Price, D. J. Richardson, and P. Petropoulos, "Broadband telecom to mid-infrared supercontinuum generation in a dispersion-engineered silicon germanium waveguide," Opt. Lett. **40**, 4118-4121 (2015).