

Nonlinear Optics on a Silicon Platform for Broadband Light Generation and Ultrafast Information Processing

Bart Kuyken, Raphael Van Laer, Francois Leo, Dries Van Thourhout, Roel Baets, Gunther Roelkens
Photonics Research Group, Department of Information Technology
Ghent University – imec
Ghent B-9000, Belgium
Bart.Kuyken@intec.ugent.be

Takuro Ideguchi, Simon Holzner, Ming Yan, Theodor W. Hänsch, Stéphane Coen, Peter Verheyen, Joris Van Campenhout, Simon-Pierre Gorza, Sylvain Combrie, Alfredo De Rossi, Fabrice Raineri, William M. J. Green, Nathalie Picqué,

Abstract— With the help of the strong nonlinear optical response in silicon nanophotonic wire waveguides complex sources and devices can be integrated on a chip. We demonstrate mid-infrared wavelength translators and frequency combs. Furthermore, we open up the possibility for the integration of nonlinear optical functions at telecom wavelengths by exploiting more exotic nonlinear interactions in silicon waveguides as well as new waveguide platforms.

Keywords Nonlinear optics, four-wave mixing; Nonlinear optics, integrated optics

1. INTRODUCTION

The high confinement of integrated waveguides, made out of high refractive index semi-conductor materials, can enhance nonlinear optical processes incredibly. Furthermore, the nonlinear refractive index of semi-conductor materials such as silicon or InGaP itself is very high. Hence, nonlinear optical interactions can become very efficient in semi-conductor waveguide platforms made out of these materials. These interactions can be used for a set of applications.

One application is the development of broadly tunable or broadband sources in the mid-infrared. These sources would meet the demand of sources needed for mid-infrared sensing. Mid-infrared sensing exploits the strong and specific absorption lines of many molecules in the mid-infrared wavelength region [1], sometimes referred to as the “molecular fingerprint region”. This would enable chip-scale optical sensors with a high sensitivity and selectivity. Through nonlinear optical mixing broadly tunable sources and devices can potentially be integrated on the silicon-on-insulator platform. Specifically, the absence of two-photon absorption beyond $2.2 \mu\text{m}$ - hampering efficient nonlinear interactions at telecom wavelengths - allows for efficient nonlinear interactions in the mid-infrared in silicon waveguides.

Another traditional application of nonlinear optics is ultrafast signal processing. However, because of the high two photon absorption at telecom wavelengths, crystalline silicon does not seem to be the ideal candidate here. Nonetheless, by shifting towards materials with a wider bandgap, two-photon absorption can be suppressed or eliminated at telecom wavelengths enabling efficient nonlinear interactions. We show that InGaP and a-Si:H on insulator nanowire waveguides can be used to obtain efficient nonlinear interactions in the telecom window with no or less parasitic two-photon absorption.

Lastly, we show that even in the presence of two-photon absorption at telecom wavelengths the photon-phonon interaction can be made efficient in silicon waveguides. The latter paves the way for making e.g. high quality all optical RF-filters on a CMOS platform.

All these demonstrations show how integrated platforms are very efficient for doing nonlinear optics at different wavelengths for different applications.

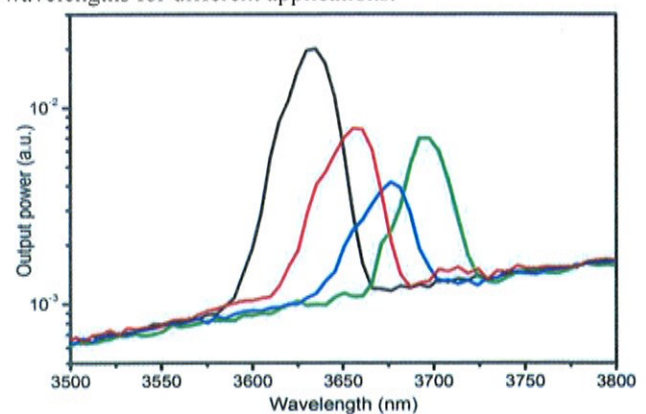


Fig. 1. Down converted signals of respectively a telecom signal at 1565 nm (black), 1559 nm (red), 1554 nm (blue), and 1550 nm (green) in a telecom wavelength translator.

II. SILICON BASED MID-IR DEVICES

The (crystalline) silicon devices presented here are based on waveguides fabricated on a 200 nm silicon-on-insulator wafer with a 400 nm thick device layer. The relatively thick layer allows for operating the waveguides at mid-ir wavelengths. Contrary to waveguides fabricated in "standard" 220 nm thick layers they are not in cut-off nor leak towards the silicon substrate at these long wavelengths. Furthermore, the nonlinear parameter is found to be $\sim 40 \text{ (Wm)}^{-1}$ at a wavelength of about 2200 nm. A first demonstration of the efficient nonlinear interactions of these waveguides is a so called wavelength translator [2,3]. This translator can link the telecom band with the mid-infrared wavelength region. For example, we show that a pump centered at 2190 nm, can down convert signals over more than an octave from the telecom band to ~ 3700 nm. In a second experiment, a waveguide is used to generate an octave spanning frequency comb. In the experiment a 1600 nm wide waveguide is pumped with fs pulses [4]. The fs pulses centered at 2290 nm are broadened in the waveguide. The output spectrum, a supercontinuum, (see Figure 2) covers an octave spanning from ~ 1550 nm up to ~ 3250 nm. Moreover, the coherence of the obtained supercontinuum is verified by beating it with a narrow linewidth CW laser on a fast photodiode. The obtained beat notes have a linewidth in the order of 50 kHz, limited by the instabilities of the pump optical parametric oscillator. The narrow bandwidth beatnotes show that the supercontinuum consists out of a set of narrow line width lines and is as such a frequency comb.

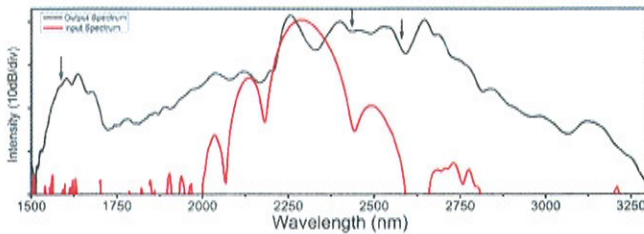


Fig. 2. The input and output spectrum of the short pulses travelling through the 1 cm long silicon waveguide. The arrows indicate at which wavelength the coherence is measured.

III. NON CRYSTALLINE SILICON INTEGRATED PLATFORMS FOR ALL-OPTICAL SIGNAL PROCESSING

The detrimental nonlinear absorption in silicon waveguides at telecom wavelengths hampers efficient nonlinear interactions. For all-optical signal processing applications one wants to work at telecom wavelengths. So other materials are sometimes preferred over crystalline silicon for these applications. These materials should have a wide band-gap to avoid the two photon absorption. Ideally, they should also have a high linear and nonlinear refractive index. The combination allows for high confinement waveguides made out of a material with a high nonlinear refractive index. We have explored the use of hydrogenated amorphous silicon [5]

and InGaP [6] for making highly nonlinear waveguides. Because of the relatively wide band-gap of these materials, the fabricated structures show no or only weak two photon absorption. Nonetheless, the waveguides show a strong nonlinear response. Figure 2 shows a cross section of a fabricated InGaP waveguide. As can be seen in the figure the dimensions of the waveguide (250 nm high, 630 nm wide) are very similar than those for crystalline silicon waveguides at telecom wavelengths.

IV. STRONG PHOTON-PHONON COUPLING IN CRYSTALLINE SILICON WAVEGUIDES

Strong photon-phonon coupling has been demonstrated in integrated structures such as photonic crystals before. Lately, however, the photon-phonon coupling has been investigated in silicon waveguides as well [7]. In a first demonstration researchers described the coupling between photons in a waveguide and phonons in a silicon nitride membrane adjacent to the waveguide. Recently, we have observed even stronger photon-phonon coupling by confining the photons and phonons in the same photonic wire [8]. By doing so we achieve a nonlinear interaction which can be stronger than the interactions arising from the nonlinear refractive index of silicon. We show a strong interaction of light and sound with frequencies around 10 GHz. Although the bandwidth of the interaction is much smaller than the Kerr effect, the scheme can be used for Radio Frequency signal processing.



Fig. 3. A SEM cross-section of an InGaP waveguide with measured dimensions of 630 nm x 250 nm

V. CONCLUSION

In short, the high optical nonlinear response of integrated semi-conductor waveguides allows for making complex devices in the mid-infrared such as an optical wavelength translator as well as an octave spanning mid-infrared frequency comb. Despite the success of (crystalline) silicon platforms, InGaP and a-Si:H platforms are more suitable for doing ultrafast signal processing in the telecom band. Lastly, by tailoring the strong phonon-photon coupling new applications such as novel RF filters are within reach

REFERENCES

- [1] J. G. Crowder, et al., "Infrared methods for gas detection," in Mid-Infrared Semiconductor Optoelectronics. New York: Springer-Verlag, 2006.

- [2] X. Liu, et al., "Bridging the mid-infrared-to-telecom gap with silicon nanophotonic spectral translation," *Nature Photonics* 6, 667-669 (2012).
- [3] B. Kuyken et al., "Generation of 3.6 μ m radiation and telecom-band amplification by four-wave mixing in a silicon waveguide with normal group velocity dispersion," *Optics Express* (2014).
- [4] B. Kuyken, et al., "An octave spanning mid-infrared frequency comb generated in a silicon nanophotonic wire waveguide," *Nature Communications* 6, 6310 (2014).
- [5] B. Kuyken, et al., "Nonlinear properties of and nonlinear processing in hydrogenated amorphous silicon waveguides", *Optics Express*, 19, p.B146-B153 (2011).
- [6] U.D. Dave, et al. "Nonlinear properties of dispersion engineered InGaP photonic wire waveguides in the telecommunication wavelength range", *Optics Express* 23, p.4650 (2015).
- [7] Shin, Heedeuk, et al. "Tailorable stimulated Brillouin scattering in nanoscale silicon waveguides " *Nature communications* 4 (2013).
- [8] R. Van Laer, et al. "Interaction between light and highly confined hypersound in a silicon photonic nanowire", *Nature Photonics* 9, 199-203 (2015).

08:30 - 09:00 **JTHE.11**
Invited

Germanium Compounds for Future Photonic Systems

F. Y. Gardes, C. G. Littlejohns, M. Nedjalkov, I. Budo Dominguez,
J. Soto Perales, C. J. Mitchell, A. Z. Korkmaz, G. T. Reed, G. Z. Mashanovich
Optoelectronics Research Centre, University of Southampton, United Kingdom

09:00 - 09:30 **JTHE.12**
Invited

New Materials and Devices for Optical Interconnect

D. Van Thourhout¹, Z. Wang², B. Tian³, Y. Hu⁴, J.P. Georghis, J. Beeckman,
M. Panfiliere⁵, C. Menckhof⁶, I. Asselbergher, S. Dem⁷, P. Absil, H. Mich-Hsang⁸,
J. Van Campenhout⁹
¹ Photonics Research Group, IMTEC, Belgium; ² Department of Electronics and
Information Systems, Belgium; ³ Center for Nano- and Biophotonics Ghent University,
Ghent, Belgium; ⁴ MEC Heverlee, Belgium

09:30 - 09:45 **JTHE.13**

A Simple Fabrication Process for SiN/SiO₂ Waveguide Based on Sidewall Oxidation of Patterned Silicon Substrate

Yanan Wang, Jian Wang, Changzheng Sun, Bing Xiong, Y. Luo, Zhibao Hao,
Yanlin Han, Lei Wang, Hongtao Li
Tsinghua University, China

09:45 - 10:00 **JTHE.14**

Broadband, Polarization-Insensitive Superconducting Single-Photon Detectors Based on Waveguide-Integrated Ultra-Narrow Nanowires

Xuedan Zhu, Chao Gu, Yuhao Cheng, Xiaodong Hu
Tsinghua University, China

Nonlinear photonic devices

Fraenck Gardes
University of Surrey, United Kingdom

10:30 - 12:15

10:30 - 11:00 **JTHE.21**
Invited

Mid-Infrared Integrated Photonics on a SiGe Platform

L. Carletti, C. Blawiecki, D. Aifoux, C. Morier, R. Ouedraoui, P. Rigbi-Rimmo, Z. Liu,
C. Lemaire, J.L. Leducq, P. Viktorovitch, X. Letangier, C. Gertler, M. Brun, S. Orliz,
P. Lebeve, S. Nicollet, P. Mar, Y. Yu, B. Luther-Daems, D. Husson,
S. Maccioni, M. Simeoni, D. J. Moss¹
¹ University of Lyon, France; ² CEA-Lab MINATEC Campus, GRENOBLE, France;
³ QUNOS Laser Physics Centre, Australian National University, Australia
⁴ RMIT University, Australia

11:00 - 11:30 **JTHE.22**
Invited

Nonlinear Optics on a Silicon Platform for Broadband Light Generation and Ultrafast Information Processing

Bart Kuyken
Ghent University - imec, Belgium

11:30 - 11:45 **JTHE.23**

High-efficiency and Broadband Wavelength Conversion in a Slot Waveguide with the Periodic Structure Altering the Phase-Mismatch

Feiya Zhou¹, Liwei Zhang², Yanyan Wang³, Jing Ding⁴, Deming Liu⁵
¹ Heilongjiang University of Science and Technology, China
² National Engineering Laboratory for Next Generation Internet Access System, China

11:45 - 12:15 **JTHE.24**
Invited

Silicon Nanowires for Ultra-fast and Ultrabroadband Optical Signal Processing

Huan Ji, Hao Hu, Jianbo Pu, Yinhong Ding, Asger Jensen, Michael Galati,
Krzysztof Wond, Lutz Osvieske
DTU Photonik, Department of Photonics Engineering, Technical University of Denmark
Denmark

14:00 - 14:15 **JTHE.31**

SOI Slot Photonic Crystal Cavities on SiO₂ From $\lambda = 1.3 \mu\text{m}$ to $1.6 \mu\text{m}$

Tri Hong Cam Hoang¹, Michel Zhang², Samuel Sema³, Charles Cser⁴,
Xavier Le Roux⁵, Laurent Vivien⁶, Eric Cassan⁷
¹ Institut d'Electronique Fondamentale, France; ² Laboratoire Charles Fabry,
Institut d'Optique, CNRS, France; ³ IBM Research - Zurich Laboratory, Switzerland

14:15 - 14:30 **JTHE.32**

A Novel Variable Optical Attenuator Based on Two Detuned Coupled Rings

Heng Zhang, Hongchuan Yu, Minghua Chen, Sgung Yang, Hongwei Chen,
Sizhong Xie
Department of Electronic Engineering, Tsinghua National Laboratory for Information
Science and Technology (TNIST), China

14:30 - 14:45 **JTHE.33**

Compact Waveguide Resonator Filter for Wavelength-Selective Reflection and Rejection in Silicon Waveguides

Chang-Joon Chae¹, Duk-Yong Choi², Efstathios Sifertsis³, Yong-Tak Lee⁴
¹ Advanced Photonics Research Institute, Korea; ² Laser Physics Center, Australian
National University, Australia; ³ Department of EEE Engineering, University of
Melbourne, Australia

14:45 - 15:00 **JTHE.34**

Coupled-cavity Fabry-Pérot Semiconductor Lasers for Single-mode Operation

Xiu-Wen Ma, Yue-De Yang, Yong-Zhen Huang, Jin-Long Xiao, Bo-Wen Liu,
Hong Long, Ling-Xu Zou
State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors,
Chinese Academy of Sciences, China

15:00 - 15:15 **JTHE.35**

Investigation of Loss Mechanism of SOI Slot Waveguide Ring Resonators

Mehmet Zihang, Samuel Sema, Xavier Le Roux, Laurent Vivien, Eric Cassan
Institut d'Electronique Fondamentale, Université Paris-Sud, France
Xiangdong Li, Xue Feng, Xian Xiao, Yihang Li, Kaiyu Cui, and Yiding Huang
Tsinghua University, China

15:15 - 15:30 **JTHE.36**

Tunable Silicon Slot Micro-Ring Operating At 1000 nm

Xiangdong Li, Xue Feng, Xian Xiao, Yihang Li, Kaiyu Cui, and Yiding Huang
Tsinghua University, China





OECC2015

The 20th OptoElectronics and Communications Conference

June 28 - July 2, 2015
Everbright Convention Center, Shanghai, China



ORGANIZERS



上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

TECHNICAL CO-SPONSORS



区域光纤通信网与新型光通信系统国家重点实验室



JOINT INSTITUTE
交叉研究中心



INDUSTRY SPONSORS:
A&P INSTRUMENT®
科豪儀器



OECC