



HAL
open science

Nonlinear third order silicon photonics enabled by dispersion and subwavelength engineering

Christian Lafforgue, Samuel Serna, Sylvain Guerber, Hongtao Lin, Joan Manel Ramirez, Guillaume Marcaud, Carlos Alonso-Ramos, Xavier Le Roux, Kathleen Richardson, Nicolas Dubreuil, et al.

► **To cite this version:**

Christian Lafforgue, Samuel Serna, Sylvain Guerber, Hongtao Lin, Joan Manel Ramirez, et al.. Non-linear third order silicon photonics enabled by dispersion and subwavelength engineering. Opto-electronic Devices and Integration, 2019, Wuhan, China. pp.OW1C.2, 10.1364/oedi.2019.ow1c.2 . hal-04475728

HAL Id: hal-04475728

<https://universite-paris-saclay.hal.science/hal-04475728>

Submitted on 23 Feb 2024

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.

Nonlinear third order silicon photonics enabled by dispersion and subwavelength engineering

Christian Lafforgue ¹, Samuel Serna ^{1,2}, Sylvain Guerber ^{1,3}, Hongtao Lin ², Joan Manel Ramirez ¹, Guillaume Marcaud ¹, Carlos Alonso-Ramos ¹, Xavier Le Roux ¹, Kathleen A. Richardson ⁴, Nicolas Dubreuil ⁵, Delphine Marris-Morini ¹, Juejun Hu ², Frédéric Boeuf ³, Sébastien Cremer ³, Stéphane Monfray ³, Eric Cassan ¹, Laurent Vivien ¹

¹ Centre de Nanosciences et de Nanotechnologies (C2N), CNRS, Univ. Paris-Sud, Université Paris Saclay, C2N, 91120, Palaiseau, France

² Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

³ Technologie R&D, STMicroelectronics, SAS, 850 rue Jean Monnet, 38920 Crolles, France

⁴ College of Optics and Photonics-CREOL, University of Central Florida, Orlando, Florida 32816, USA

⁵ Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Université Paris Saclay, 2 Avenue Augustin Fresnel, 91127 Palaiseau cedex, France

e-mail: laurent.vivien@u-psud.fr

ABSTRACT

Integrated photonics has for several years included in its panoply the development of functions based on third-order non-linear optical phenomena, from the generation of supercontinuum or frequency comb sources to metrology or spectroscopy on chip applications. This natural evolution, after the development of high-speed transceivers in the last few years, particularly in silicon photonics, is based on a number of compromises and still has to solve problems, particularly concerning the integration of nonlinear materials on silicon and their exploitation. The work we present addresses two directions. The first is oriented towards the development of a supercontinuum source using Nitrogen-rich photonic circuits from an industrial CMOS platform, while the second aims at the development of hybrid highly nonlinear waveguides significantly reducing the impact of two-photon absorption in the telecom window around 1,55 μm by exploiting silicon slot waveguides infiltrated by chalcogenide glasses (As_2S_3).

Keywords: Silicon photonics, nonlinear photonics, chalcogenides, slot waveguides

1. INTRODUCTION

Silicon photonics is now the preferred integration platform for the realization of complex circuits of high integration density [1-5]. At the same time, silicon, which is a material with a high Kerr index, has a bandgap energy (around 1,1eV) that makes it very sensitive to the phenomenon of two-photon absorption (TPA) in the telecom band around 1.55 μm and at shorter wavelengths. To make concrete progress towards the realization of non-linear functions in CMOS technology, or at least compatible with an approach to the deposition of an optical substrate in back-end technology, the problem of silicon TPA must be addressed in the first approach [6].

We first report supercontinuum generation [7-9] in nitrogen-rich silicon nitride waveguides fabricated through back-end CMOS compatible processes on a 300mm platform. By pumping in the anomalous dispersion regime at a wavelength of 1200nm, two-octaves spanning spectra covering the visible and near-infrared ranges were obtained. Numerical calculations were performed and show that the nonlinear index of nitrogen-rich silicon nitride is the same order of magnitude than that of stoichiometric silicon nitride despite a decreasing of light confinement. Nitrogen-rich silicon nitride then appears to be a promising candidate for nonlinear devices compatible with back-end CMOS processes.

In a second approach, we demonstrate a novel class of highly nonlinear hybrid waveguide structures based on infiltration of As_2S_3 chalcogenide glass into silicon slot waveguides. The nonlinear properties of the hybrid waveguides were precisely quantified via a bidirectional top-hat D-Scan method, enabling a direct comparison between different device geometries. Furthermore, we experimentally verify that it is possible to have waveguides with TPA figure of merit larger than 1 ($FOM_{\text{TPA}} > 1$), which allows nonlinear phase shifts larger than π with minimal loss, opening the possibility for large scale, efficient and robust ultrafast all-optical devices and circuits.

2. SUPERCONTINUUM GENERATION IN NITROGEN-RICH SiN WAVEGUIDES PUMPED AT $\lambda \sim 1200\text{nm}$

Stoichiometric SiN (Si_3N_4) is an interesting nonlinear material that reconciles several of the above issues. It has a Kerr index $n_2 = 2,6 \times 10^{-19} \text{m}^2 \text{W}^{-1}$ and SiN on SiO_2 waveguides can be characterized by low to ultralow propagation losses ($\ll 1\text{dB/cm}$), yet strongly depending on the considered fabrication process. However, most of the reported SiN devices were fabricated using high temperature processes such as low pressure chemical vapor deposition (LPCVD) or annealing steps to avoid cracks in the films and achieve ultra-low linear losses. Such high temperature fabrication steps are not compatible with back-end CMOS processes, hindering the

integration of SiN devices on electronic-photonic integrated circuits for large scale and low cost production. Plasma enhanced chemical vapor deposition (PECVD) addresses this issue since it is a low temperature deposition method ($<500^\circ$) widely used to deposit SiN films in CMOS foundries. Nonetheless this deposition method involves the use of precursor gas such as silane resulting in N-H dangling bonds in the SiN film responsible for strong absorption at wavelengths around $1.5\mu\text{m}$. Recently results have been published indicating the possibility to reduce drastically the linear losses at 1550nm by employing deuterated SiN. This method can be a back-end compatible solution for nonlinear photonics in the C-band, but still no advances has been showed to cover the O-band ($1260\text{nm}-1360\text{nm}$) with similar processes. In addition, the development of shorter wavelength light sources in the visible is of great interest from an application point of view. Here we report a two octave spanning SCG covering the visible range and the O-band in N-rich SiN waveguides fabricated on a 300mm platform at STMicroelectronics. First a thermal oxidation of a silicon substrate was performed to obtain a 600nm thick silicon dioxide (SiO_2) layer. Two tetraethyl orthosilicate (TEOS) deposition steps were carried out to form a $2\mu\text{m}$ thick oxide layer. Then a 600nm thick N-rich SiN film was deposited with low-temperature PECVD. Finally a deep-UV lithography step followed by an etching to define the waveguide were operated.

The chromatic dispersion of the waveguides were optimized to show abnormal dispersion throughout the O band around 1300nm . We carried out a set of experiments to characterize the effective non-linear response of these waveguides. After measuring their linear transmission to around 0.6dB/cm for 700nm width and 0.4dB/cm for the 1200nm width waveguides at 1300nm wavelength, we performed nonlinear characterization on straight waveguides using a 130fs 1MHz pulsed laser with a tunable OPA to pump the device of pulse peak power ranging from 250W to 9.5kW . The pump wavelength was set to 1200nm . To estimate the nonlinear coefficient of N-rich SiN, numerical simulations were performed to fit the experimental data.

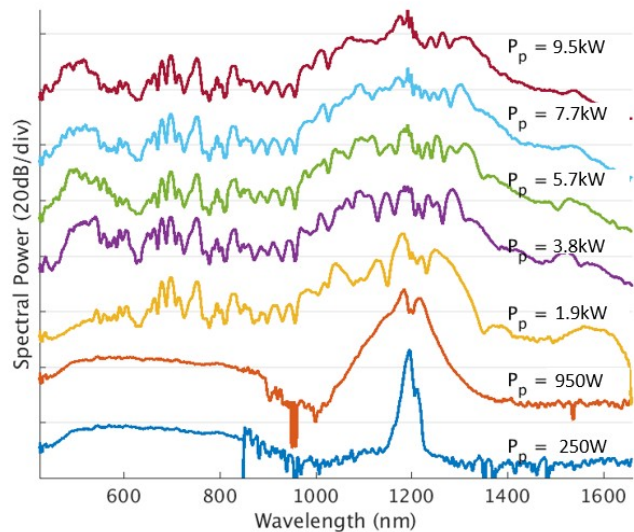


Fig. 1. Experimental and simulated results for different peak powers.

The simulations consisted in solving the generalized nonlinear Schroedinger equation using a 4th order Runge-Kutta in the interaction picture method. The carried out experiments demonstrated a two octave spanning supercontinuum generation covering the visible range and the O-band using N-rich SiN fabricated through low temperature back-end CMOS compatible processes (see Fig. 1). Experimental results were validated by numerical simulations and opened opportunities to integrated nonlinear photonics for telecommunications in the O-band, spectroscopy, or biosensing.

3. ENGINEERING THIRD ORDER OPTICAL NONLINEARITIES IN HYBRID CHALCOGENIDES-ON-SILICON WAVEGUIDES

We also explored the development of hybrid slot waveguides to partially bypass silicon's TPA in the telecom band around 1500nm . We experimentally demonstrated complete filling of nano-slot in silicon waveguides with As_2S_3 glass using a simple thermal reflow process. The devices were fabricated on SOI wafers (SOITEC) with a 220nm -thick silicon layer over $2\mu\text{m}$ of buried SiO_2 . Patterns were defined in ZEP-520A resist (Zeon Chemical Co.) by 80 kV e-beam lithography Nanobeam NB-4 system followed. The resist patterns were then transferred to the Si layer by an inductively coupled plasma (ICP) reactive ion etching process using SF_6 and C_4F_8 gases. Following this, thin films of As_2S_3 were prepared using single-source thermal evaporation. The film deposition was performed using a custom-designed system (PVD Products, Inc.) [10]. The devices were then annealed for 1 min at 250°C in an inert gas atmosphere. Fig. 2 shows a typical view of two different hybrid slot waveguides characterized by 70nm and 200nm slot widths, respectively.



Fig. 2. Views of two different hybrid slot waveguides characterized by 70nm and 200nm slot widths, respectively.

To measure the figure of merit of different devices, we used our previously developed bidirectional top hat D-Scan technique [11]. As a temporal domain analog of the well-known Z-scan technique, the D-scan method allows direct measurement of the waveguide coupling coefficients as well as the effective real and imaginary nonlinear coefficients. With this approach, we estimated the nonlinear effective waveguide factor of merit (FOM_{TPA}) characterizing the Kerr over TPA compromise of third-order nonlinear effects and given in bulk materials by:

$$FOM_{TPA} = \frac{n_2}{(\beta_{TPA} \times \lambda)}$$

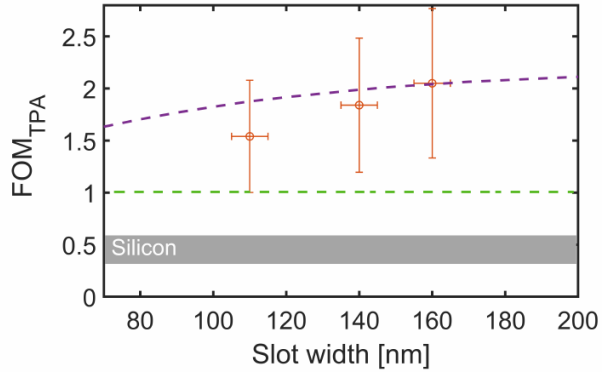


Fig. 3. Nonlinear factors of merit of the characterized hybrid chalcogenide on-Si slot waveguides [12]

We showed experimentally that it is possible to have different effective nonlinearities by changing the slot sizes. Our results illustrated the potential for the development of dispersion engineered slotted structures for efficient ultra-fast all-optical nonlinear photonics in chip-scale platforms.

4. CONCLUSION.

As a conclusion, Silicon non-linear optics offers interesting opportunities in the 400nm-1700nm spectral range provided that the problem of two-photon absorption (TPA) can be solved or at least partially bypassed. We present here two approaches contributing to this objective, based either on an alternative materials, nitrogen-rich nitride on SiO₂, or on the development of hybrid chalcogenide on silicon waveguides whose effective non-linearity can be enhanced with benefit by the use of slot waveguide geometries.

These results will be presented in detail at the conference, as well as their perspectives.

REFERENCES

- [1] L. Vivien and L. Pavesi, Handbook of silicon photonics (Taylor & Francis, 2016).
- [2] A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, Nature 427, 615 (2004).
- [3] Q. Du, C. Wang, Y. Zhang, Y. Zhang, T. Fakhru, W. Zhang, C. Goncalves, C. Blanco, K. Richardson, L. Deng et al., ACS Photonics 5, 5010 (2018).
- [4] L. Vivien, M. Rouvière, J.-M. Fédéli, D. Marris-Morini, J.-F. Damlencourt, J. Mangeney, P. Crozat, L. El Melhaoui, E. Cassan, X. Le Roux et al., Opt. express 15, 9843 (2007).
- [5] J. Justice, C. Bower, M. Meitl, M. B. Mooney, M. A. Gubbins, and B. Corbett, Nat. Photonics 6, 610 (2012).
- [6] J. Leuthold, C. Koos, and W. Freude, Nat. photonics 4, 535 (2010).
- [7] M. Sinobad, C. Monat, B. Luther-davies, P. Ma, S. Madden, D. J. Moss, A. Mitchell, D. Allieux, R. Orobitchouk, S. Boutami, J.-M. Hartmann, J.-M. Fedeli, and C. Grillet, Optica. 5, 360 (2018).
- [8] Y. Okawachi, M. Yu, J. Cardenas, X. Ji, A. Klenner, M. Lipson, and A. L. Gaeta, Opt. Lett. 43, 4627 (2018).
- [9] H. Zhao, B. Kuyken, S. Clemmen, F. Leo, A. Subramanian, A. Dhakal, P. Helin, S. Severi, E. Brainis, G. Roelkens, and R. Baets, Opt. Lett. 40, 2177 (2015).
- [10] Q. Du, Z. Luo, H. Zhong, Y. Zhang, Y. Huang, T. Du, W. Zhang, T. Gu, and J. Hu, "Chip-scale broadband spectroscopic chemical sensing using an integrated supercontinuum source in a chalcogenide glass waveguide," Photonics Res. 6, 506–510 (2018).
- [11] S. Serna and N. Dubreuil, "Bi-directional top-hat d-scan: single beam accurate characterization of nonlinear waveguides," Opt. Letters 42, 3072–3075 (2017).
- [12] S. Serna, H. Lin, C. Alonso-Ramos, C. Lafforgue, X. Le Roux, K. Richardson, E. Cassan, N. Dubreuil, J. Hu, and L. Vivien, Opt. Lett. (In review), 2019.