Dispersion Trimming for Mid-Infrared Supercontinuum Generation in Silicon-Germanium on Silicon Waveguides

(Student paper)

Alberto Della Torre[1], Milan Sinobad[1,2], Rémi Armand[1], Barry Luther-Davies[3], Pan Ma[3], Stephen Madden[3], Sukanta Debbarma[3], Khu Vu[3], David J. Moss[4], Arnan Mitchell[2], Jean-Michel Hartmann[5], Jean-Marc Fedeli[5], Christelle Monat[1], Christian Grillet[1]

[1] Université de Lyon, Institut des Nanotechnologies de Lyon (INL), 69131 Ecully, France
[2] School of Engineering, RMIT University, Melbourne, VIC 3001, Australia
[3] Laser Physics Center, Australian National University, Canberra, ACT 0100, Australia
[4] Centre for Microphotonics, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[5] Université Grenoble Alpes, CEA-Leti, 38054 Grenoble Cedex 9, France
e-mail: alberto.della-torre@ec-lyon.fr

ABSTRACT

We report octave spanning mid-infrared supercontinuum generation in a highly nonlinear silicon germanium-on-silicon ridge waveguide. We show that, by adding a chalcogenide cladding, it is possible to trim *a posteriori* the waveguide's dispersion profile which, in turn, governs the properties of the generated supercontinuum. In particular, we experimentally show that a shift from anomalous to normal dispersion takes place when a 1.26 µm thick cladding layer of $Ge_{11.5}As_{24}Se_{64.5}$ is added. Finally, we show that the group velocity dispersion of the waveguide can be precisely controlled by changing the thickness of the cladding layer. This demonstrates that the heterogeneous integration of materials can be used as a post-processing technique to precisely control the supercontinuum properties.

Keywords: Supercontinuum generation; nonlinear optics; integrated optics; mid-infrared; dispersion trimming.

1. INTRODUCTION

On-chip mid-infrared (mid-IR, between 3 µm and 20 µm) supercontinuum (SC) generation is a technological challenge that is promising to have a strong impact in many different fields such as bio imaging, environmental sensors and security [1-5]. The prediction of great nonlinear properties, wide transparency window from 3 to 15 µm and CMOS compatibility of germanium have attracted a growing interest toward germanium-based platforms [6,7]. An octave spanning supercontinuum generation up to 8.5 µm has been already demonstrated by our group in a SiGe on Si waveguide [8-10]. The bandwidth and the coherence properties of the generated SC are mainly determined by the waveguide's dispersion profile. In general, the dispersive properties are set at the design stage and cannot be adjusted once the device has been fabricated. However, fabrication inaccuracies, surface roughness, surface contamination and the presence of defects may lead to a deviation from the targeted dispersion profile. Therefore, post-process mechanisms to post-trim the waveguide dispersion depending on the actual structure produced by fabrication are of great interest.

Here we demonstrate mid-IR supercontinuum generation in a SiGe and in a hybrid chalcogenide/SiGe waveguide with shifted dispersion. We show that it is possible to fine tune the dispersion profile *a posteriori* by changing the chalcogenide cladding thickness, introducing a simple post-processing tool to control the supercontinuum dynamics and its properties.

2. SUPERCONTINUUM GENERATION AND DISPERSION TRIMMING

2.1 Supercontinuum generation

A 7 cm long 3.75 x 2.7 µm^2 cross-section $Si_{0.6}Ge_{0.4}$/Si waveguide (Fig. 1a) was coated with a 1.26 µm thick layer of chalcogenide $Ge_{11.5}As_{24}Se_{64.5}$ (Fig. 1b). Numerical simulations show that the group velocity dispersion shifts from anomalous (air clad, Fig. 2a top) to normal (chalcogenide clad, Fig. 2b top) when the coating layer is added. The waveguide, operating in TE single mode, was pumped before and after the deposition of the chalcogenide layer with ~200 fs pulses at 4 µm (air clad) and 4.15 µm (chalcogenide clad) delivered from a MIROPA-fs optical parametric amplifier with 63 MHz repetition rate. Fig. 2a (bottom) and 2b (bottom) shows the experimental (and theoretical) SC generated out of the air clad and chalcogenide clad waveguide respectively. In the former case the resulting SC, spanning from 2.63 up to 6.18 µm, shows asymmetric profile and uneven amplitude across the spectrum, both typical of SC generation in the anomalous dispersion regime. In the latter case a narrower and smoother spectrum (with a -30 dB bandwidth extending from 3.1 to 5.5 µm), typical of SC generation in normal

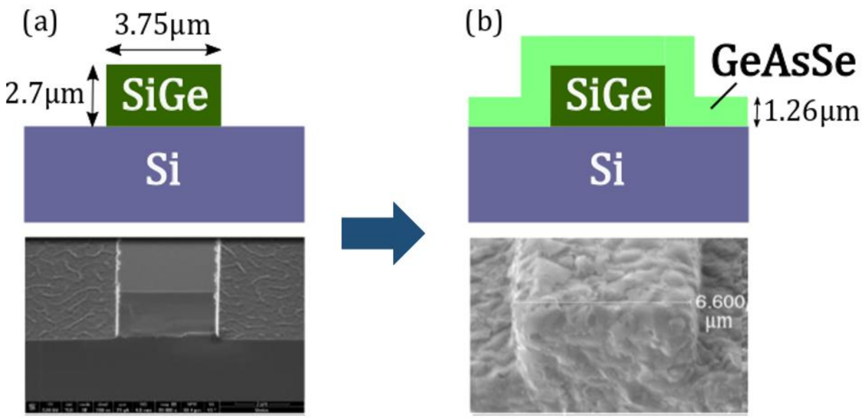

Figure 1. Schematic (top) and Scanning Electron Microscope image (bottom) of the air clad (a) and the chalcogenide clad (b) waveguide.

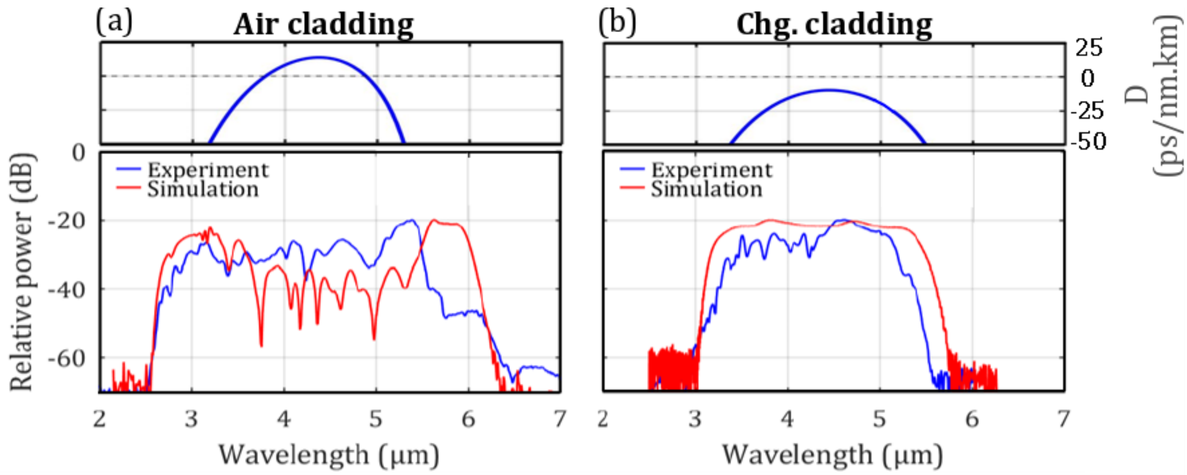

Figure 2. Calculated group velocity dispersion for air clad (a top) and chalcogenide clad (b top) waveguide with the same 3.75 x 2.7 μm2 core cross-section. Experimental (blue) and simulated (red) spectra out of the air cladded (a bottom) and chalcogenide cladded (b bottom) waveguide. The waveguides were pumped by 200 fs pulses at 4 and 4.15 μm respectively with 2.35 kW coupled peak power.

dispersion regime, was obtained. The SC generation process was simulated by numerically solving the nonlinear Schrödinger equation, obtaining a good agreement with experiments.

2.2 Dispersion trimming

We have experimentally demonstrated that the addition of a chalcogenide layer on top of a SiGe/Si waveguide leads to a change in the dispersion, shifting, in our particular example, from an anomalous to normal dispersion. In order to clarify the impact of the chalcogenide thickness on the dispersion GVD profile, we have numerically calculated the dispersion curve for four different thicknesses, from 0.25 to 1.26 µm (Fig. 3). As the chalcogenide thickness increases, the overall dispersion gradually decreases, eventually reaching normal values for thicknesses higher than 500 nm. Moreover, the dispersion profiles converge as the thickness approaches 1 µm, in agreement with the confinement of the mode in the waveguide core. Along with the dispersion shift, a variation of the zero dispersion wavelengths and a flattening of the profile take place. As a flat profile of the dispersion is generally targeted for SC generation, both in the anomalous and in the normal dispersion regime, the possibility of controlling the dispersion profile and the position of the zero-dispersion wavelengths by simply changing the thickness of the chalcogenide layer (with a reasonable resolution of around 100 nm) is a convenient post-process dispersion engineering tool.

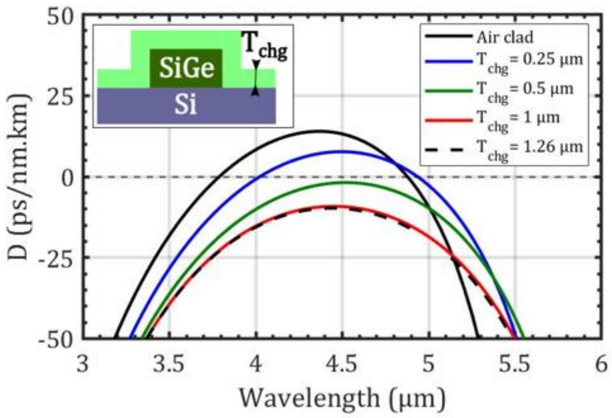

Figure 3. Calculated group velocity dispersion for different thicknesses of the chalcogenide layer. The dashed black line indicates the zero dispersion. The inset show a schematic of the waveguide (adapted from [11]).

3. CONCLUSIONS

In summary, we report the addition of a top chalcogenide layer as a simple post-processing technique to fine tune the dispersion profile of a nonlinear SiGe on Si waveguide for integrated SC generation. We experimentally show that, by adding a chalcogenide top layer to a ridge waveguide, anomalous-to-normal dispersion shift takes place and we numerically study the impact of the chalcogenide layer thickness on the group velocity dispersion.

ACKNOWLEDGEMENTS

We acknowledge the support of the International Associated Laboratory in Photonics between France and Australia (LIA ALPhFA), the Agence Nationale de la Recherche (MIRSICOMB, ANR-17-CE24-0028) and the European Research Council (ERC) under the European Union's Horizon 2020 program (GRAPHICS 648546).

REFERENCES

[1] R. Soref: Mid-infrared photonics in silicon and germanium, *Nature Photonics*, vol. 4. pp. 495-497, 2010.

[2] N. K. Hon, R. Soref and B. Jalali: The third-order nonlinear optical coefficients of Si, Ge, and $Si_{1-x}Ge_x$ in the midwave and longwave infrared, *J. Appl. Phys.*, vol. 110. pp. 011301, 2011.

[3] G. Z. Mashanovich, *et al*.: Germanium Mid-Infrared Photonic Devices, *J. Light. Technol.*, vol. 35. pp. 624–630, 2017.

[4] K. Hammani, *et al*.: Towards nonlinear conversion from mid- to near-infrared wavelengths using Silicon Germanium waveguides, *Opt. Lett.*, vol. 40. pp. 4118-4121, 2015.

[5] M. A. Ettabib, *et al*.: Broadband telecom to mid-infrared supercontinuum generation in a dispersion-engineered Silicon Germanium waveguide, *Opt. Lett.*, vol. 40. pp. 4118-4121, 2015.

[6] J. M. Ramirez, *et al*.: Low-loss Ge-rich $Si_{0.2}Ge_{0.8}$ waveguides for mid-infrared photonics, *Opt. Lett.*, vol. 42. pp. 105-108, 2017.

[7] J. M. Ramirez, *et al*.: Graded SiGe waveguides with broadband low-loss propagation in the mid infrared, *Opt. Express,* vol. 26. pp. 870-877, 2018.

[8] L. Carletti, *et al*.: Nonlinear optical response of low loss silicon germanium waveguides in the mid-infrared, *Opt. Express*, vol. 23. pp. 8261-8271, 2015.

[9] L. Carletti, *et al*.: Mid-infrared nonlinear optical response of Si-Ge waveguides with ultra-short optical pulses, *Opt. Express*, vol. 23. pp. 32202-32214, 2015.

[10] M. Sinobad, *et al*.: Mid-infrared octave spanning supercontinuum generation to 8.5µm in silicon-germanium waveguides, *Optica*, vol. 5. pp. 360, 2018.

[11] M. Sinobad, *et al*.: Dispersion trimming for mid-infrared supercontinuum generation in a hybrid chalcogenide/silicon-germanium waveguide, *J. Opt. Soc. Am. B,* vol. 36. pp. 98–104, 2019.