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# Coherent Mid-Infrared Supercontinuum Sources in Silicon-Germanium Waveguides

Alberto Della Torre,<sup>1,6</sup> Milan Sinobad,<sup>1,2</sup> Rémi Armand,<sup>1</sup> Barry Luther-Davis,<sup>3</sup> Pan Ma,<sup>3</sup> Stephen Madden,<sup>3</sup> Sukanta Debbarma,<sup>3</sup> Khu Vu,<sup>3</sup> David J. Moss,<sup>4</sup> Arnan Mitchell,<sup>2</sup> Jean-Michel Hartmann,<sup>5</sup> Jean-Marc Fedeli,<sup>5</sup> Christelle Monat,<sup>1</sup> and Christian Grillet<sup>1</sup>

<sup>1</sup>Université de Lyon, Institut des Nanotechnologies de Lyon (INL), 69131 Ecully, France

<sup>2</sup>School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

<sup>3</sup>Laser Physics Center, Australian National University, Canberra, ACT 0100, Australia

<sup>4</sup>Centre for Microphotonics, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

<sup>5</sup>Université Grenoble Alpes, CEA-Leti, 38054 Grenoble Cedex 9, France

<sup>6</sup>e-mail : alberto.della-torre@ec-lyon.fr

**Abstract:** We report coherent mid-infrared supercontinuum generation in silicon-germanium waveguides. We show that the degree of coherence can be controlled by either employing an air clad configuration or a hybrid chalcogenide/silicon-germanium system. © 2020 The Author(s)

**OCIS codes:** (320.6629) Supercontinuum generation; (190.4390) Nonlinear optics, Integrated optics; (140.3070) Infrared and far-infrared lasers.

## 1. Introduction

In the last decades, supercontinuum (SC) sources have found numerous applications owing to their unique feature of combining high brightness and ultra-broad spectral bandwidth. Mid-infrared (mid-IR, 2-20  $\mu\text{m}$ ) sources have attracted particular interest for spectroscopic and sensing applications, due to the strong molecular fingerprint in this spectral region [1,2]. The integration of mid-IR SC sources in a CMOS compatible platform is a technological challenge that would allow to leverage the already existing manufacturing infrastructure to develop high volume, low cost sensing technology. On-chip SC can be generated via nonlinear effects that broaden the spectrum of a pulse injected in an optical waveguide. By exploiting the promising nonlinear properties and wide transparency window (from 3 to 15  $\mu\text{m}$ ) of germanium [3,4], we recently demonstrated SC generation from 3 to 8.5  $\mu\text{m}$  in a silicon-germanium on silicon platform [5]. For many applications, however, in addition to a wide spectral bandwidth, it is crucial that the SC pulses maintain high shot-to-shot stability in both amplitude and phase, i.e. a high degree of temporal coherence [6].

Here, we study the coherence properties of mid-IR SCs that are experimentally generated in silicon-germanium ( $\text{Si}_{0.6}\text{Ge}_{0.4}$ ) on silicon waveguides. We showed that a  $3.75 \times 2.7 \mu\text{m}^2$  cross-section air clad waveguide, pumped in the anomalous dispersion regime, maintains high coherence at the extreme parts of the spectrum [7], thereby allowing for pulse stabilization via  $f$ -to- $2f$  self-frequency referencing for high precision spectroscopy applications. Yet, many spectroscopy and imaging techniques, such as coherent Raman spectroscopy, anti-stokes Raman spectroscopy and optical coherence tomography, require high coherence across the entire spectrum [6]. We show that we can trim the coherence properties of the SC by simply depositing a chalcogenide cladding layer, generating a fully coherent mid-IR SC.

## 2. Coherent Supercontinuum generation

$\text{Si}_{0.6}\text{Ge}_{0.4}$  waveguides were pumped in the TE polarization at  $\sim 4 \mu\text{m}$  by a MIROPA-fs (Hotlight Systems) optical parametric amplifier delivering nearly transform-limited  $\sim 200$  fs pulses with 63 MHz repetition rate. A  $3.75 \times 2.7 \mu\text{m}^2$  cross-section, 7 cm long air clad waveguide was pumped with 2.35 kW coupled peak power pulses in the anomalous dispersion regime (fig. 1(a), left), generating a SC spanning more than one octave (-30dB bandwidth from 2.63 up to 6.18  $\mu\text{m}$ , fig. 1(a), right). The SC generation process was simulated by numerically solving the generalized nonlinear Schrodinger equation and the degree of first-order coherence  $g^{(1)}_{12}$  was calculated from 40 independent simulations with random input noise. The right hand side of fig. 1(a) shows the good agreement between experimental and simulated spectra. We attribute the discrepancy beyond 5.5  $\mu\text{m}$  to water vapor absorption [8] that takes place along the free-space path from the chip output to the spectrometer. The coherence is high ( $>0.99$ ) at the extreme parts of the spectrum, at  $f$  ( $\lambda=5.8 \mu\text{m}$ ) and  $2f$  ( $\lambda=2.9 \mu\text{m}$ ), but not across its whole bandwidth. The high coherence is preserved thanks to a careful design of the waveguide's dispersion profile, which inhibits the amplification of noise [7].

The same waveguide was then covered with a 1.26  $\mu\text{m}$  thick cladding layer of  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  chalcogenide glass, shifting the dispersion curve to all-normal (fig. 1(b), left) [9]. This allowed to generate a slightly narrower SC (spanning from 3.1 to 5.5  $\mu\text{m}$ ), but fully coherent across the entire spectrum (fig. 1(b), right).

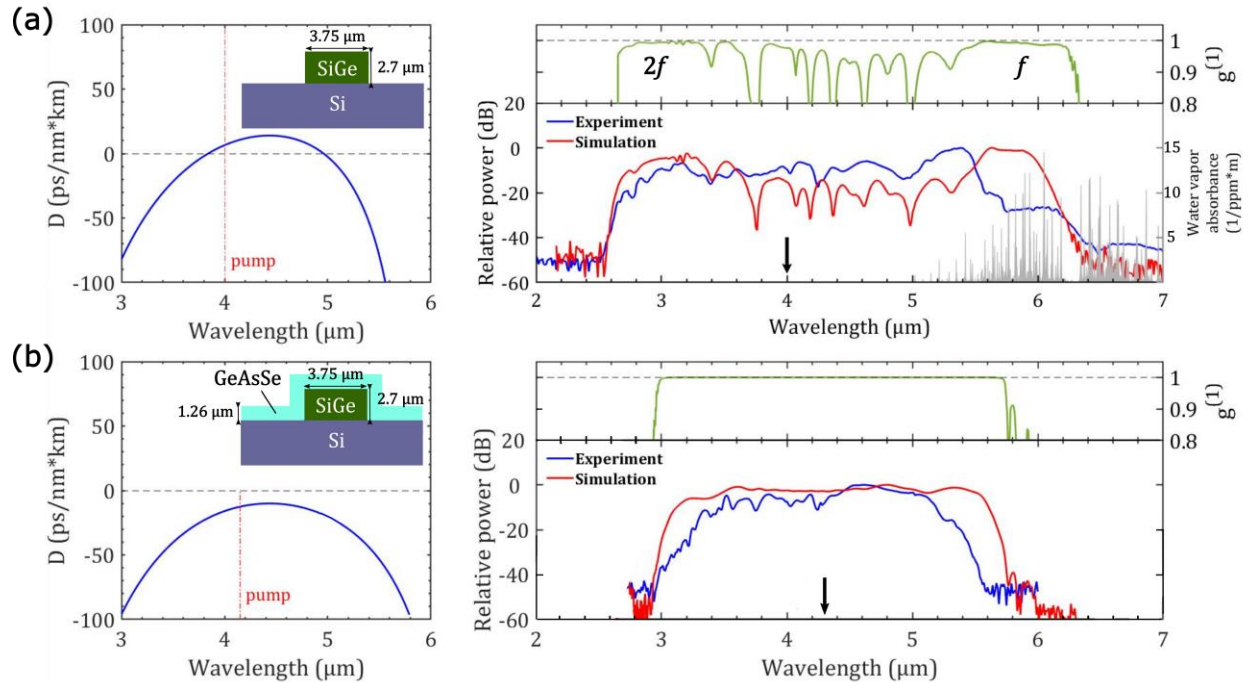


Fig. 1. (a) Left: dispersion profile and cross section (inset) of the  $3.75 \times 2.7 \mu\text{m}^2$  air clad waveguide; right: corresponding experimental (blue) and simulated (red) SC at 2.35 kW coupled peak power, water absorbance beyond  $5 \mu\text{m}$  (grey) [8] and calculated first-order coherence (green). (b) Left: dispersion profile and cross section (inset) of the  $3.75 \times 2.7 \mu\text{m}^2$  chalcogenide clad waveguide; right: corresponding experimental (blue) and simulated (red) SC at 2.32 kW coupled peak power and calculated first-order coherence (green). The black arrows on the spectra indicate the pump wavelengths.

### 3. Conclusion

In summary, we demonstrate on-demand control of the spectral and coherence properties of on-chip mid-IR SCs. We show that either high coherence at  $f$  and  $2f$  or full coherence can be achieved in a highly nonlinear SiGe waveguide, with potential spectroscopic, sensing and imaging applications.

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