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Mid-Infrared Supercontinuum Generation in a Pure Germanium-on-Silicon Ridge Waveguide

Alberto Della Torre,^{1,6} Milan Sinobad,¹ Rémi Armand,¹ Barry Luther-Davies,² Pan Ma,² Stephen Madden,² David J. Moss,³ Arnan Mitchell,⁴ Jean-Michel Hartmann,⁵ Vincent Reboud,⁵ Jean-Marc Fedeli,⁵ Christelle Monat,¹ and Christian Grillet¹

¹Université de Lyon, Institut des Nanotechnologies de Lyon (INL), 69131 Ecully, France

²Laser Physics Centre, Australian National University, Canberra, ACT 0100, Australia

³Optical Sciences Centre, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

⁴School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

⁵Université Grenoble Alpes, CEA-Leti, 38054 Grenoble Cedex 9, France

⁶e-mail : alberto.della-torre@ec-lyon.fr

Abstract: We experimentally demonstrate mid-infrared supercontinuum generation (from 3.53 up to 5.83 μm) in a pure germanium on silicon waveguide. We attribute the long wavelength limit of the supercontinuum to free-carrier absorption. © 2020 The Authors

1. Introduction

In the last two decades, germanium has played a key role in group-IV photonics. Germanium was at first used in integrated photonic devices operating in the near-infrared [1,2]. More recently, however, the wide transparency window up to 15 μm [3] and theoretical predictions of attractive nonlinear properties [4] led researchers to explore germanium as a promising material for mid-infrared (from 3 to 15 μm) photonics. In terms of fabrication, tremendous progress has been made in recent years, with several demonstrations of low-loss germanium on silicon waveguides in the mid-infrared [1].

Mid-infrared devices can for instance be used for the detection and recognition of molecules, in particular organic species, with strong fundamental absorption lines in this band [3]. A broadband source, such as a supercontinuum, is a fundamental element in integrated sensing platforms. It indeed enables the parallel detection of multiple gas species [5]. On-chip mid-infrared supercontinuum generation has been demonstrated in several group-IV platforms [5-8]. Our group reported supercontinuum generation up to 8.5 μm in silicon-germanium on silicon waveguides [7]. We have also demonstrated the possibility, with this platform, of precisely controlling the supercontinuum coherence properties [9-11]. The great potential of germanium-based platforms for on-chip mid-infrared supercontinuum generation was recently confirmed, with the demonstration of a supercontinuum extending from 3 up to 13 μm in a germanium-rich graded index silicon-germanium on silicon waveguide [12]. To achieve such a broad spectrum, however, the waveguide was pumped at 7.5 μm , whereas short wavelength pumps are preferable in fully integrated broadband sources.

Here, we show that a supercontinuum can be generated in a pure germanium waveguide and we investigate the origins of the bandwidth limitations when pumping at shorter wavelengths. To those ends, we pumped a germanium on silicon air-clad waveguide with ~ 200 fs pulses at 4.6 μm and generate a supercontinuum extending from 3.53 to 5.83 μm , with milliwatt-level on-chip power. With the help of numerical simulations, we attribute the long wavelength extension limit of the supercontinuum to absorption from free-carriers, generated by three-photon absorption. Owing to the transparency of the atmosphere between 3 and 5 μm and to the strong absorption of hazardous and greenhouse gases such as CO (~ 4.5 μm), CO₂ (4.2, 4.3 μm) and CH₄ (3.45 μm), our source has potential applications in free-space communications and environmental monitoring.

2. Mid-infrared Supercontinuum Generation

We designed a 4.46 μm wide, 2.57 μm thick air-clad germanium on silicon waveguide (Fig. 1a inset) to achieve low dispersion beyond 4 μm (Fig. 1a). The waveguide exhibited low propagation losses of ~ 1.25 dB/cm between 3.5 and 4.5 μm , thanks to the extremely low threading dislocation density ($\sim 10^7$ cm⁻²) and reduced sidewall roughness.

We pumped the waveguide at 4.6 μm in the normal dispersion regime (Fig. 1a), with ~ 200 fs TE polarized pulses from a mid-infrared MIROPA-fs optical parametric amplifier at a repetition rate of 63 MHz. When pumping with 22 mW coupled average pump power (corresponding to a 3.3 kW coupled peak power), we generated a supercontinuum with 2.3 μm bandwidth (3.53–5.83 μm) at -30 dB level (Fig. 1b, top). Thanks to transmission measurements, we

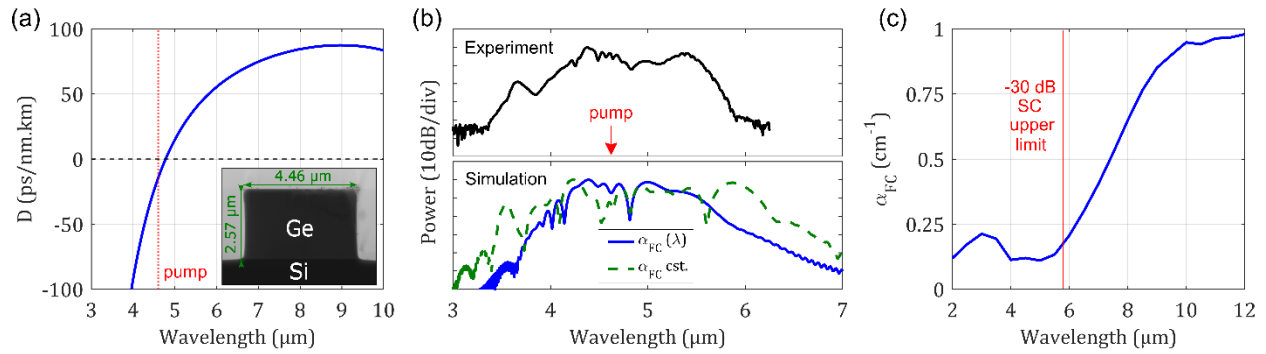


Fig. 1. (a) Dispersion parameter of the germanium on silicon waveguide with a $4.46 \mu\text{m} \times 2.57 \mu\text{m}$ cross-section. A Scanning Electron Microscope image of the waveguide is shown in the inset. (b) Top: output experimental supercontinuum for 22 mW (3.3 kW) coupled average (peak) power. Bottom: simulated supercontinuum considering wavelength dependent (continuous blue line) and constant (dashed green line) free-carrier absorption. (c) Free-carrier absorption coefficient as a function of wavelength at 1 cm length along the waveguide.

showed that the on-chip supercontinuum power was 4.4 mW, exceeding the milliwatt-level required for spectroscopic applications. Our supercontinuum covers the 3-5 μm atmospheric transparency window, making it particularly interesting for free-space communications and environmental monitoring.

Our modeling work shows that the long wavelength boundary is mainly limited by the high free-carrier absorption beyond 6 μm [13]. Free-carriers are generated in the waveguide as a consequence of three-photon absorption. By carefully modeling the wavelength dependence of free-carriers absorption, we numerically reproduced the experimental supercontinuum (Fig. 1b bottom, blue continuous line). On the contrary, the simulated supercontinuum extends up 7 μm if the free-carrier absorption is supposed to be constant and equal to the value at the pump wavelength (Fig. 1b bottom, green dashed line), well beyond the upper boundary observed experimentally. Figure 1c shows the free-carrier absorption coefficient at 1 cm length along the waveguide. The sharp increase of free-carrier absorption at $\sim 6 \mu\text{m}$ exactly corresponds to the -30 dB upper limit of the experimental supercontinuum.

3. Conclusion

In conclusion, we have succeeded in generating a supercontinuum in a germanium waveguide, with milliwatt-level on-chip power. The supercontinuum covers the 3.53–5.83 μm band, making it interesting for free-space communications and environmental monitoring. We attribute the long wavelength boundary to free-carrier absorption.

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