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Mid-Infrared Supercontinuum Generation in Germanium-on-Silicon Waveguides

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Abstract: We report the first experimental supercontinuum generation (from 3.53 to 5.83 μm) in a pure germanium waveguide. By optimizing the design, we envision to generate a supercontinuum extending up to almost 10 μm . © 2020 The Author(s)

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 the theoretical prediction of attractive nonlinear properties [4] have 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 region [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 for integrated sensing platforms since it allows for parallel detection of multiple gas species [5]. On-chip mid-infrared supercontinuum generation has been demonstrated in several group-IV platforms [5-8]. Supercontinuum generation up to 8.5 μm has been demonstrated by our group in silicon-germanium on silicon waveguides, reaching the onset of the absorption from the silicon substrate [7]. We have also demonstrated the possibility, with this platform, of precisely controlling the supercontinuum coherence properties [9,10]. Due to their a priori wider transparency windows [11], pure germanium on silicon waveguides are anticipated to overcome the current limits of other group-IV platforms. So far, however, supercontinuum generation in germanium waveguides has been limited to numerical demonstrations.

Here we report the first experimental demonstration of supercontinuum generation in a pure germanium waveguide. We pumped a 4.46 μm x 2.57 μm cross-section germanium on silicon air-clad waveguide with $\approx 200\text{fs}$ pulses at 4.6 μm , generating a supercontinuum extending from 3.53 to 5.83 μm . 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) [12], our source has potential applications in free-space communications and environmental monitoring.

2. Supercontinuum Generation

A 4.46 μm wide, 2.57 μm thick air-clad germanium on silicon waveguide (fig. 1a inset) was designed to have low dispersion beyond 4 μm (fig. 1a). We measured propagation losses of ≈ 1.25 dB/cm between 3.5 and 4.5 μm .

Our nonlinear characterization of the platform suggested that the supercontinuum generation would be optimized when pumped at long wavelengths. Supercontinuum generation was achieved by pumping the waveguide with $\approx 200\text{fs}$ TE polarized pulses from a mid-infrared MIROPA-fs optical parametric amplifier at a repetition rate of 63 MHz. By pumping at 4.6 μm (currently, the longest wavelength achievable by the MIROPA-fs) in the normal dispersion regime, we obtained the spectra shown in fig 1b. When pumped with 22 mW coupled average pump power (corresponding to 3.3 kW coupled peak power), a 2.3 μm bandwidth (3.53–5.83 μm) at -30 dB level was achieved. Our modeling work shows that this long wavelength boundary is mainly limited by the high free-carrier absorption beyond 6 μm [13]. Yet, our supercontinuum covers the 3-5 μm atmospheric transparency window, already making it particularly interesting for free-space communications and environmental monitoring.

We believe that improvements could be achieved if we could increase the pump wavelength to 5 μm . This should reduce the multiphoton absorption and therefore the generation of free-carriers [14]. Experimentally, our pump laser can be slightly modified to produce pulses around 5 μm . A 6 μm wide by 2 μm thick Ge waveguide

Figure 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) Output spectra for different coupled average powers.

Figure 2: (a) Dispersion parameter of germanium on silicon waveguide with a $6\ \mu\text{m} \times 2\ \mu\text{m}$ cross-section (inset). (b) Numerical input (red) and output spectra (blue) for a 1.2 cm long waveguide pumped with 4.5 kW coupled peak power.

(fig. 2 (a), inset) exhibits low dispersion from 4 to 11 μm with zero dispersion at 5 μm (fig. 2 (a)). With a 1.2 cm long waveguide pumped with a 4.5 kW coupled peak power, we numerically predict a supercontinuum extending over a 6 μm bandwidth (3.5-9.5 μm) at the -30 dB level (fig. 2 (b)). These predictions will form the basis of our next experiments.

3. Conclusion

In conclusion, we have demonstrated the first experimental supercontinuum generation in a pure germanium waveguide. The supercontinuum covers the 3.53–5.83 μm band. The multiphoton absorption and therefore the generation of free-carriers could be reduced by pumping at longer wavelengths, potentially enabling to generate a supercontinuum extending up to almost 10 μm .

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References

- [1] D. Marris-Morin *et al.*, "Germanium-based integrated photonics from near- to mid-infrared applications," *Nanophotonics* **7**, 1781–1793 (2018).
- [2] V. Reboud *et al.*, "Germanium based photonic components toward a full silicon/germanium photonic platform," *Prog. Cryst. Growth Charact. Mater.* **63**, 1–24 (2017).
- [3] R. Soref, "Mid-infrared photonics in silicon and germanium," *Nat. Photonics* **4**, 495–497 (2010).
- [4] N. K. Hon, R. Soref, and B. Jalali, "The third-order nonlinear optical coefficients of Si, Ge, and $\text{Si}_{1-x}\text{Ge}_x$ in the midwave and longwave infrared," *J. Appl. Phys.* **110**, 011301 (2011).
- [5] E. Tagkoudi *et al.*, "Parallel gas spectroscopy using mid-infrared supercontinuum from a single Parallel gas spectroscopy using mid-infrared supercontinuum from a single Si_3N_4 waveguide," *Opt. Lett.* **45**, 2195–2198 (2020).
- [6] N. Singh, *et al.*, "Midinfrared supercontinuum generation from 2 to 6 μm in a silicon nanowire," *Optica* **2**, 797 (2015).
- [7] M. Sinobad, *et al.*, "Mid-wavelength Infrared Supercontinuum Generation Spanning 1.4 Octaves in a Silicon-Germanium Waveguide," *Optica* **5**, 360 (2018).
- [8] N. Nader *et al.*, "Infrared frequency comb generation and spectroscopy with suspended silicon nanophotonic waveguides," *Optica* **6**, 1269–1276 (2019).
- [9] M. Sinobad *et al.*, "Dispersion trimming for mid-infrared supercontinuum generation in a hybrid chalcogenide/silicon-germanium waveguide," *J. Opt. Soc. Am. B* **36**, A98 (2019).
- [10] M. Sinobad, *et al.*, "High coherence at f and $2f$ of mid-infrared supercontinuum generation in silicon germanium waveguides," *IEEE J. Sel. Top. Quantum Electron.* **26**, 1–8 (2019).
- [11] G. Z. Mashanovich, *et al.*, "Group IV mid-infrared photonics [Invited]," *Opt. Mater. Express* **8**, 1040–1043 (2018).
- [12] V. M. Lavchikov and B. Jakoby, "Photonics in the Mid-Infrared: Challenges in Single-Chip Integration and Absorption Sensing," *IEEE J. Sel. Top. Quantum Electron.* **23**, (2017).
- [13] M. Nedeljkovic, R. Soref, and G. Z. Mashanovich, "Predictions of free-carrier electroabsorption and electrorefraction in germanium," *IEEE Photonics J.* **7**, (2015).
- [14] D. Seo, *et al.*, "Multiphoton absorption in germanium using pulsed infrared free-electron laser radiation," *Phys. Rev. B - Condens. Matter Phys.* **83**, 1–6 (2011).