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Broadband and Flat Mid-Infrared Supercontinuum Generation in a Varying Dispersion Waveguide for Parallel Gas Spectroscopy

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Abstract: We report optimized mid-infrared supercontinuum generation in a silicon-germanium on silicon waveguide with varying dispersion. We employ the generated supercontinuum for a proof-of-principle demonstration of free-space parallel gas spectroscopy.

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1. Introduction

Mid-infrared (MIR, from 3 to 13 μm) supercontinuum (SC) sources are of great interest for high precision and high throughput spectroscopy [1,2]. The MIR band is known as the molecular fingerprint region. Many important molecules (e. g. pollutants and greenhouse gases) have fundamental roto-vibrational modes absorbing in the MIR region. Therefore, molecule detection and spectroscopy in the MIR can have orders of magnitudes higher sensitivity than in the near-infrared and visible regions, where only weak overtones of the fundamental absorption lines are present. However, commercial MIR technology is still relatively bulky and expensive. The last ten years have seen a quest to develop compact and cheaper sensing and spectroscopic devices with high performances. An integrated MIR SC is an ideal source for such devices, since it can provide broadband, fast, and high resolution measurements.

Germanium-based waveguides are particularly interesting for integrated MIR SC generation, since they combine a wide transparency window in the MIR (up to 8.5-13 μm , depending on the germanium content) [3], and high nonlinearity [4]. In addition, the use of group IV materials is particularly important for future commercial applications, since it allows to leverage the well-developed microfabrication technologies of the electronic industry for cost-effective mass production of the final devices. In the last years, we have demonstrated SC generation in silicon-germanium and pure germanium waveguides [5,6], as well as the ability to control the properties of the generated SC [7–9]. SC generation in silicon-germanium waveguides covering the entire molecular fingerprint region has also been demonstrated [10]. The properties of the generated SC strongly depend on the group velocity dispersion profile of the underlying waveguide. Typically, a waveguide pumped in the anomalous dispersion region generates a broader SC with, however, low spectral flatness and poor coherence. On the other hand, high spectral flatness and coherence can be achieved in a waveguide operating in the all-normal dispersion regime, but at the cost of reducing the SC bandwidth. High resolution, multi-species parallel absorption spectroscopy would greatly benefit from a SC that combines high spectral flatness and a broad spectral coverage, i.e. from a design that allows to overcome this trade-off.

Here, we employ an air-clad silicon-germanium on silicon (SiGe/Si) two-stages inverse-tapered waveguide to enhance the efficiency, the spectral flatness, and the spectral coverage of our SC. We harness the spectral quality of our SC for a proof-of-principle demonstration of parallel free-space spectroscopy of water vapor and carbon dioxide.

2. Supercontinuum Generation and Parallel Gas Spectroscopy

Our waveguide consist of a 3.3 μm thick air-clad $\text{Si}_{0.6}\text{Ge}_{0.4}$ core on a silicon substrate (fig. 1a). At the input side, the waveguide is 3.25 μm wide and has a 3 mm long straight section, followed by an inverse-tapered section which increases the waveguide width up to 9 μm at the output side. We pumped the waveguide at 3.9 μm , in the anomalous dispersion regime (fig. 1b, blue curve), with 200 fs pulses at 63 MHz repetition rate at 60 mW average power. The top part of figure 1c shows the generated SC, recorder with a Fourier transform interferometry based optical spectrum analyzer. The small cross straight section at the input enhances the efficiency of the nonlinear

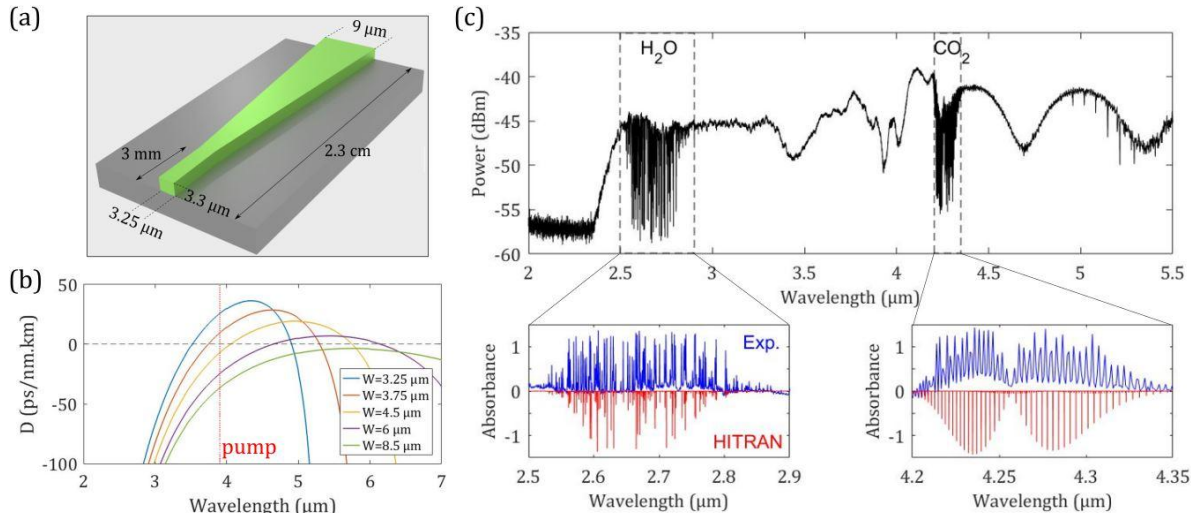


Fig. 1. (a) Schematic of the SiGe/Si waveguide. (b) Dispersion profile for selected waveguide widths. (c) Experimental SC (top), absorbance of water vapor (bottom left) and carbon dioxide (bottom right) as retrieved from the measured spectrum (blue) and from the HITRAN database (red). The latter was inverted for clarity.

spectral broadening, which is maximized by the anomalous dispersion profile. The inverse-tapered section allows to continuously shift the position of the two zero dispersion wavelengths (fig. 1b), and therefore the spectral location of the generated dispersive waves, resulting in a flat and broadband spectrum. The SC extension at the long wavelength side is limited by the detection band of our spectrum analyzer, which is sensitive up to 5.5 μm . The absorption from water vapor and carbon dioxide in the free-space path between the waveguide output and the spectrum analyzer are clearly visible in the spectrum. In particular, the improved spectral flatness in the 2.5-3 μm region, resulting from our particular design, allows to well resolve the absorption lines of water. The bottom part of figure 1c shows the absorbance of water (left) and carbon dioxide (right) as retrieved from our measurements (blue) and compared to the HITRAN database (red). The agreement is relatively good, and it is limited by the resolution, of our spectrum analyzer.

3. Conclusion

In conclusion, we have demonstrated efficient MIR SC generation in a SiGe/Si waveguide. The waveguide was designed to generate a broadband and flat spectrum. We harnessed the spectral quality of our SC for a proof-of-principle demonstration of multi-species parallel gas spectroscopy.

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References

- [1] M. Vainio and L. Halonen, "Mid-infrared optical parametric oscillators and frequency combs for molecular spectroscopy," *Phys. Chem. Chem. Phys.* **18**, 4266–4294 (2016).
- [2] 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 (2020).
- [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] M. Sinobad *et al.* "Mid-infrared octave spanning supercontinuum generation to 8.5 μm in silicon-germanium waveguides," *Optica* **5**, 360–366(2018).
- [6] A. Della Torre *et al.* "Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide," *APL Photonics* **6**, 016102 (2021).
- [7] 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).
- [8] 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).
- [9] M. Sinobad *et al.* "Mid-infrared supercontinuum generation in silicon-germanium all-normal dispersion waveguides," *Opt. Lett.* **45**, 5008–5011 (2020).
- [10] M. Montesinos-Ballester *et al.* "On-Chip Mid-Infrared Supercontinuum Generation from 3 to 13 μm Wavelength," *ACS Photonics* **7**, 3423–

