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Mid-Infrared Supercontinuum Generation in a Silicon-Germanium Waveguide for Multi-Species Parallel Gas Spectroscopy

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Abstract: We report efficient, broadband, and flat mid-infrared supercontinuum generation in a silicon-germanium on silicon waveguide. We employ the generated supercontinuum for a proof-of-principle demonstration of parallel spectroscopy of water vapor and carbon dioxide.

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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]. 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 mid-infrared technology is still relatively bulky and expensive. The last ten years have seen a quest to develop compact and cheap sensing and spectroscopic devices with high performances. An integrated broadband source, such has a SC, is a key element of such devices. SC sources can be broader than one octave, and they are constituted of hundreds of thousands closely spaced emission lines. Therefore, they are an ideal source for high precision parallel detection and spectroscopy of multiple molecular species.

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) [2], and high nonlinearity [3]. Indeed, SC is typically generated by pumping the waveguide with high intensity pulses, and the spectrum of the pump laser is broadened by a combination of nonlinear effects. Therefore, highly nonlinear waveguides enable efficient SC generation. 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 low cost and mass production of the final devices. In the last years, we have demonstrated SC generation in silicon-germanium and pure germanium waveguides [4,5], as well as the ability to control the properties of the generated SC [6–8]. SC generation in silicon-germanium waveguides covering the entire molecular fingerprint region has also been demonstrated [9].

Here, we report MIR SC generation in a silicon-germanium on silicon (SiGe/Si) waveguide which is designed to efficiently generate a broadband and flat spectrum. We harness the spectral quality of our SC for a proof-of-principle demonstration of parallel spectroscopy of water vapor and carbon dioxide.

2. Supercontinuum Generation and Parallel Gas Spectroscopy

Our waveguide consist in a 3.3 μm thick air-clad $\text{Si}_{0.6}\text{Ge}_{0.4}$ core on a silicon substrate (fig. 1a, left). 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 (fig. 1a, right). 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. 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 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 wavelength (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

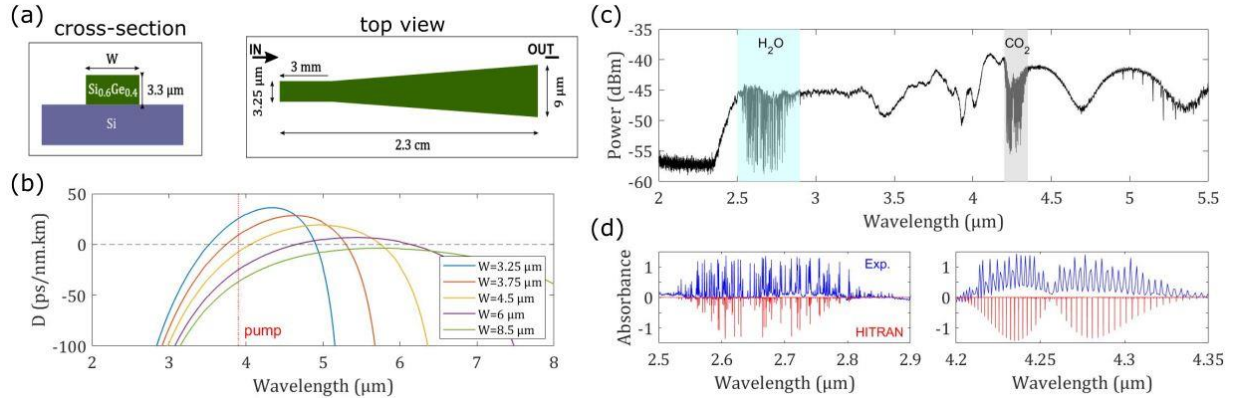


Fig. 1. (a) Waveguide cross-section (left) and top view (right). (b) Dispersion profile for selected waveguide widths. (c) Experimental SC. (d) Absorbance of water vapor (left) and carbon dioxide (right) as retrieved from the measured spectrum (blue) and from the HITRAN database (right). The latter was inverted for clarity.

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 (respectively highlighted by the cyan and grey areas in fig.1c). 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. Figure 1d 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.

In particular, in the case of carbon dioxide, we can observe the double branch profile typical of roto-vibrational modes in linear molecules.

3. Conclusion

In conclusion, we have demonstrated efficient MIR SC generation in a SGe/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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