Mid-Infrared Supercontinuum Generation in a Tapered SiGe/Si Waveguide for Multi-Species Gas Spectroscopy

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We report the experimental generation of a broadband and flat mid-infrared supercontinuum in a silicon-germanium-on-silicon inverse tapered waveguide. The supercontinuum extends from 2.4 to 5.5 µm, only limited by the long wavelength detection limit of our spectrum analyzer. We exploit the enhanced flatness of our supercontinuum for a proof-of-principle demonstration of gas spectroscopy of water vapor and carbon dioxide.
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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.

RESULTS

Our waveguide consists of a 3.3 µm thick air-clad $Si_{0.6}Ge_{0.4}$ 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. The small cross straight section at the input enhances

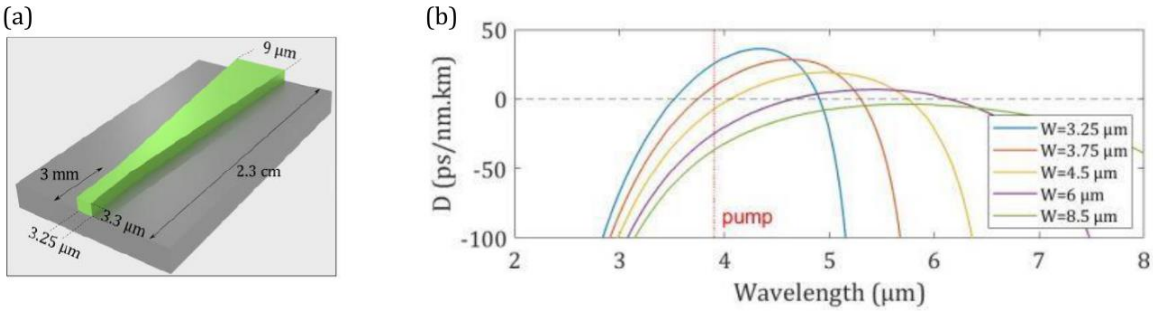

Fig. 1. (a) Schematic of the tapered SiGe/Si waveguide. (b) Dispersion profile for selected waveguide widths.

the efficiency of the nonlinear spectral broadening, which is maximized by the anomalous dispersion profile (fig. 1b, blue curve). The inverse-tapered section enables 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.

Figure 2a shows a schematic of the free-space experimental setup. We pumped the waveguide at 3.9 µm, in the anomalous dispersion regime (fig. 1b, blue curve), with 200 fs TE polarized pulses at 63 MHz repetition rate and 60 mW average power, delivered by a tunable Optical Parametric Amplifier (OPA, Hotlight Systems MIROPA-fs). We used a set of two polarizers and a half wave-plate to control the input power and polarization. Light was coupled to the waveguide and the output was collected with the help of two MIR lenses, a visible camera (Dino-lite) and a MIR camera (Lynred). The top part of figure 2b shows the generated SC, recorded using an Optical Spectrum Analyzer (OSA, Thorlabs OSA205) sensitive from <2 µm to 5.5 µm. The SC extends over more than an octave, from 2.4 to 5.5 µm. The extension at the long wavelength side is limited by the detection band of our spectrum analyzer. Numerical simulations show that the SC could reach 7.8 µm wavelength. The continuous spectral shift of the zero dispersion wavelengths, and therefore of the dispersive waves, given by the waveguide tapering results in the filling of the 2.4-3 µm and 6-7.8 µm spectral regions, leading to a flatter SC in the tapered than in waveguides with constant width (the spectra recorded for the latter are not shown here).

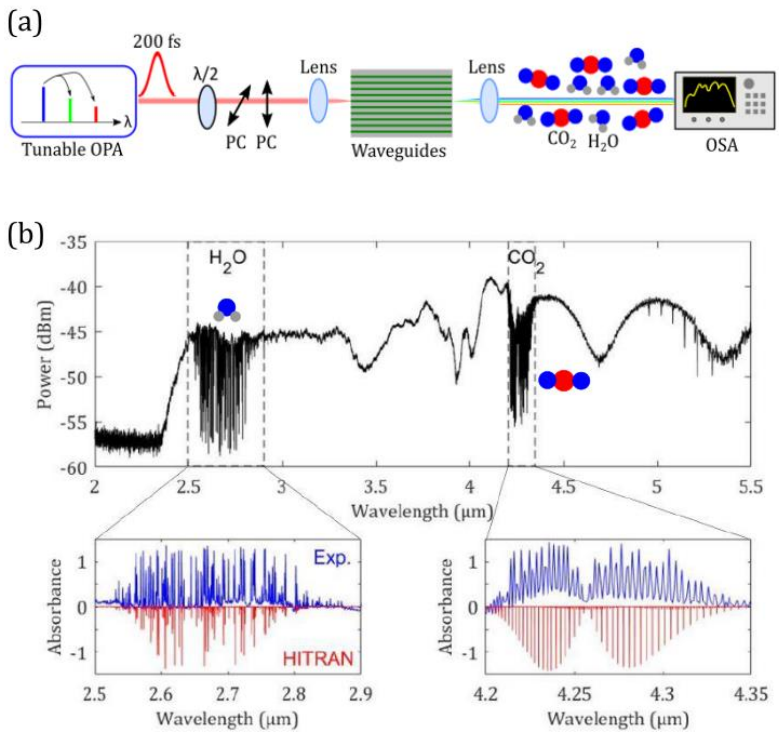

Fig. 2. (a) Schematic of the experimental setup. (b) Experimental SC (top), absorbance of water vapor (bottom left) and carbon dioxide (bottom right) as retrieved from the measured spectrum (blue) and from the HITRAN database (red). The latter was inverted for clarity.

The absorption from water vapor and carbon dioxide in the 55 cm long free-space path between the waveguide output and the spectrum analyzer (see fig. 2a) are clearly visible in the spectrum. In particular, the increased flatness given by out tapered design at the blue end of the spectrum leads to better resolution of the dips due to water absorption at around 2.7 µm. Similar dips are also visible at around 4.2 μm due to the absorption from CO_2. The bottom part of figure 2b 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. We can notice that, in the case of CO_2, we obtain the double branch absorption spectrum typical of roto-vibrational modes in linear molecules. In the case of water, which is not a linear molecule, the absorption lines have a more complex pattern.

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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