

# Octave Spanning Mid-Infrared Frequency Comb Generation in Silicon Nanophotonic Wire Waveguides

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**Abstract:** A mid-infrared octave spanning frequency comb is generated in a silicon waveguide. By beating the generated comb on a photodetector with a narrow linewidth lightsource the linewidth of the lines is measured to be <100kHz.

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**OCIS codes:** (190.4380) Nonlinear optics, four-wave mixing; (190.4390) Nonlinear optics, integrated optics

## 1. Introduction

The mid-infrared spectral region is a domain of interest to many areas of science and technology [1] including molecular fingerprinting, trace gas sensing, thermal imaging, and biomedical diagnostics. Laser frequency combs, which emit a broad spectrum consisting of discrete, evenly spaced narrow lines, have the potential to significantly expand the performance of precision spectroscopy and broadband molecular sensing in this region. Extension of frequency comb techniques to the mid-infrared spectral region is thus currently under exploration [2]. The recent significant progress [3,4] in developing mid-infrared photonics platforms in Si, which is highly transparent in the mid-infrared, offers exhilarating perspectives for versatile frequency comb generation, due to CMOS compatibility and the ease of fabrication. Here we demonstrate an octave spanning mid-infrared frequency comb through supercontinuum generation in silicon wire waveguides. We verify the phase coherence of the comb generated in a photonic wire waveguide by monitoring free-running beat notes between the supercontinuum and narrow linewidth lasers.

## 2. Experimental results

The 1 cm-long silicon nanophotonic wire used in the experiment is fabricated in imec's CMOS pilot line, on a 200 mm silicon-on-insulator (SOI) wafer consisting of a 390 nm silicon waveguide layer on a 2  $\mu\text{m}$  buried oxide with no top cladding. The dimensions of the photonic wire are shown in the inset of Figure 1 a). The waveguide is slightly over etched by 10 nm. Using a cutback method, the propagation loss in the 2200-2400 nm band is estimated to be < 0.2 dB/cm.

For the experiment the quasi TE mode of the waveguide is excited by a home-made femtosecond optical parametric oscillator (OPO) with a repetition frequency of 100 MHz. When the center wavelength of the output pulses of the optical parametric oscillator is tuned to a center wavelength of 2290 nm, about 70-fs long pulses are produced. The average output power coming out of the OPO is 25 mW. The pulses are coupled to the chip using a high numerical aperture (NA) chalcogenide lens. The coupling loss to the chip is 12 dB resulting in an on-chip peak power of 264 W. The output of the photonic chip is coupled via a high NA lens to a Fourier transform infrared spectrometer (FTIR). The output spectrum of the chip recorded with the FTIR is shown in Figure 1 b). The spectrum of the input pulses is also shown in the figure in red. As can be seen in Figure 1 b), the supercontinuum generated in the 1 cm silicon photonic wire spans from 1.55  $\mu\text{m}$  up to 3.3  $\mu\text{m}$ . The broadening is achieved by pumping the silicon wire waveguide in the anomalous dispersion region, close to the zero dispersion wavelength of the photonic wire waveguide as shown in Figure 1 b).

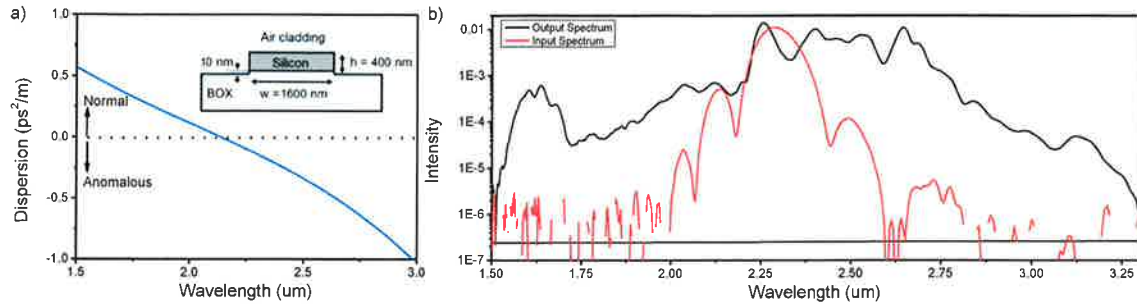


Figure 1: a) The second order dispersion of the photonic wire waveguide. The inset in figure a) shows the geometry of the silicon photonic wire used. The black curve in Figure 1 b) shows the output spectrum of the silicon photonic wire waveguides, an octave spanning supercontinuum from 1.55  $\mu\text{m}$  to 3.3  $\mu\text{m}$  is generated. The input and output spectra are in arbitrary units.

### 3. Phase coherence of the generated supercontinuum

Spectral broadening in a highly nonlinear waveguide can introduce noise causing a loss of coherence in the spectrum. We thus characterize the phase coherence of the spectrum at the output of the chip by measuring free-running beat notes between the output of the chip and narrow line-width continuous wave lasers at different frequencies across the octave spanning spectrum. First the supercontinuum beats with a continuous wave (cw) narrow linewidth fiber laser at 1586 nm (Koheras Adjustics E15, line-width  $\sim 1$  kHz at 120  $\mu\text{s}$ ) on a fast InGaAs photodetector. A portion of the resulting radiofrequency (RF) spectrum of the output of the photodetector is shown in Figure 2 a). A resolution bandwidth of 10 kHz is chosen to limit the spread in beat-note frequency due to variation in the unlocked optical sources. The same experiment was performed in the mid-infrared and we present the beat note measurement of the supercontinuum and a mid-infrared cw tunable optical parametric oscillator (Argos, Aculight, line-width  $\sim 60$  kHz at 500  $\mu\text{s}$ ) when the cw OPO is tuned to a wavelength of 2418 nm (Fig.2b) and 2580 nm (Fig. 2c) respectively. For these two measurements, a 100-MHz InGaAsSb photodiode (D124, Redwave Labs) is used. In all these cases, the narrow line-width beat note shows that the generated supercontinuum is coherent. All beat notes exhibit about the same line-width of 50-70 kHz and no broadening of the beat signals involving the comb modes at the chip output is observed relative to the femtosecond OPO pump (not shown in the figure). The results demonstrate good phase coherence of the broadened spectrum generated by the Si chip.

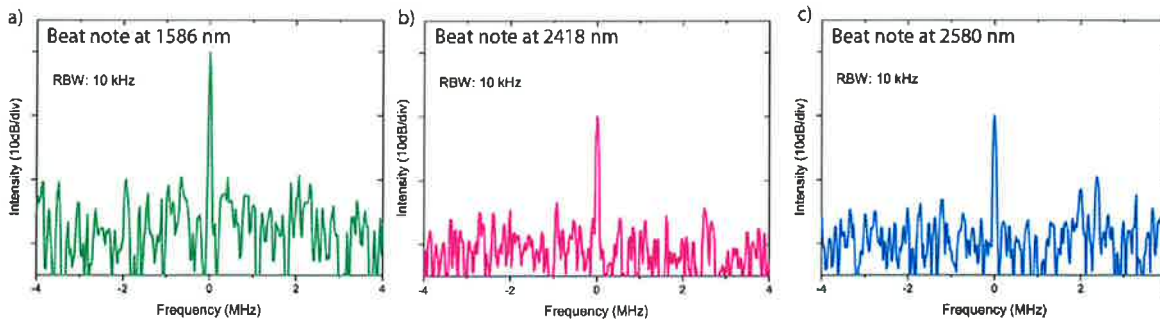


Figure 2: The RF spectrum of a photodetector measuring the beat note of the supercontinuum comb and a cw narrow linewidth laser at a) 1586 nm, b) 2418 nm, c) 2580 nm. No other lines are observed in the measurement with a frequency span equal to half the repetition frequency. All free-running beat notes are measured with a resolution bandwidth (RBW) of 10 kHz.

### 4. Acknowledgements

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**Abstract**

A mid-infrared octave spanning frequency comb is generated in a silicon waveguide. By beating the generated comb on a photodetector with a narrow linewidth light source the linewidth of the lines is measured to be  $\approx 100$  kHz.

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