Octave spanning supercontinuum generation in silicon from 1.1 μm to beyond 2.4 μm

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Abstract: We demonstrate an octave spanning coherent supercontinuum generated in a silicon waveguide covering the near to shortwave IR (SWIR) region. The measured -20 dB SC span ranges from 1.124 μm to 2.4 μm.

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Supercontinuum (SC) has been significant for applications such as, molecular spectroscopy, ultrashort pulse generation, signal processing, and optical frequency synthesis [1, 2]. To become mainstream in nanophotonics SC devices need to leverage on CMOS compatible material, such as silicon. Silicon is a highly nonlinear material with Kerr coefficient (n_2), 30 and 400 times higher than silicon nitride and silica, respectively [3]. However, two-photon absorption (TPA) has impeded its potential as a nonlinear platform in the telecom window [4]. This has restricted researchers to mid infrared for generating an octave spanning SC in silicon where TPA is absent [5].

In this work we show for the first time, to the best of our knowledge, over an octave spanning supercontinuum from silicon's transparency edge 1.1 μm, to beyond 2.4 μm (limited by the optical spectrum analyzer (OSA)), as shown in Fig.1. The SC is quite flat with -20dB bandwidth spanning 1.1 octaves. We designed and fabricated a 5 mm long silicon-on-insulator rib waveguide with width of 920 nm, slab thickness 65 nm and height 315 nm, as shown in Fig 1 (inset). This geometry has its 1st zero dispersion wavelength (ZDW) at 1.67 μm and ensures dispersive wave generation below 1.2 μm. The waveguide was pumped at 1.9 μm with a moded-locked laser (centered at 1550 nm) which was coherently shifted to 1.9 μm with a highly nonlinear fiber (Menlo Systems). We chose 1.9 μm because the n_2 of the silicon is two times higher than that at 1550 nm and TPA is 3 times lower. The coupled average power was 5 mW (25pJ), with repetition rate of 200 MHz and a pulse width of 50 fs. The light was coupled in with a black diamond-2 aspheric lens (NA~0.56), and the signal was collected by butt coupling an InF_3 multimode fiber to the waveguide. To measure such a broad signal two different OSA's were used, Yokogawa - AQ6370D and AQ6375B.

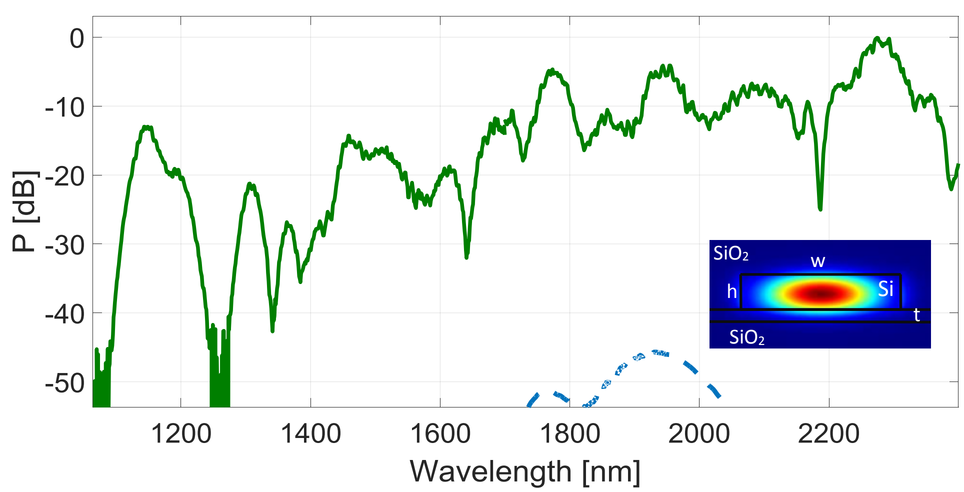

Fig.1. Measured SC from the 5 mm long waveguide with the pump spectrum (not the actual signal level) shown in dash blue. Inset: The fundamental mode in the waveguide with dimensions: slab thickness, t = 65nm, height, h = 315nm, width, w = 920nm.

To investigate how fluctuations in the input pulse influence the intensity and phase stability of the SC, we calculated the degree of first order coherence ($|g_{12}|$) of the SC by solving nonlinear Schrodinger equation (NLSE) using split step Fourier method [6]. In the simulation, 1.5% intensity noise and one photon per mode quantum noise (shot noise) of the input source was included. The $|g_{12}|$ was calculated by taking an ensemble average of 100 individually generated SC pairs in the presence of input noise. As shown in Fig. 2a, the coherence is high, except near 1.29 μm and 2.36 μm which can be improved by reducing the soliton fission length (by reducing dispersion length) and the physical length of the waveguide before significant amplification of input noise by modulation instability can occur [6]. The parameters we used in the simulations are: effective mode area - 0.28 μm^2, TPA coefficient - 0.5×10^{-11}m/W, soliton number - 21. The temporal evolution of the pulse along the waveguide is seen in Fig. 2c, where, following the soliton fission near 0.3 mm, part of the pulse splits (carrying dispersive waves) and lags by 4 ps at the end of the waveguide. The weak leading part of the pulse cannot be observed by our OSA as it mostly belongs to the signal close to the 2nd ZDW which is beyond our OSA's measurable bandwidth.

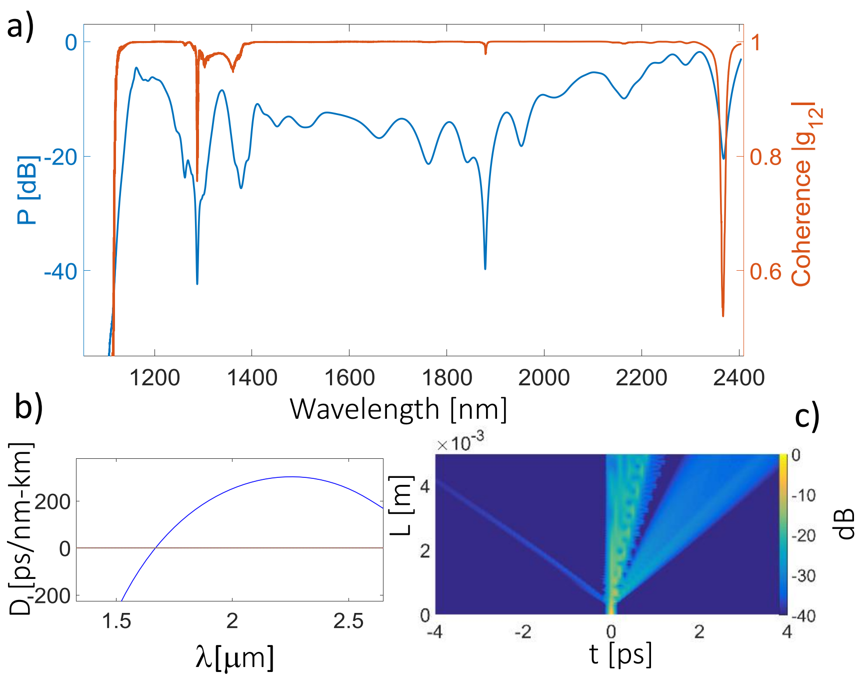

Fig.2. a) Simulation of the SC and the first order coherence $|g_{12}|$ of the spectrum, b) is dispersion of the waveguide with ZDW at 1.67 μm, and c) is the temporal evolution of the pulse along the waveguide.

This work paves the way for an all-silicon CMOS-compatible optical frequency synthesizer. Our SC device can be incorporated with the second harmonic generator based on silicon [7], to perform f to 2f conversion for locking the f_{ceo} frequency of the moded-locked laser and stabilizing the octave spanning frequency combs. This will have applications in chip scale precise frequency synthesis, optical atomic clocks, and sensing.

In conclusion, we have demonstrated over an octave spanning coherent supercontinuum in the important infrared window (NIR to SWIR) by pumping an appropriately dispersion engineered silicon waveguide in the high n_2 and low TPA region. *This work was supported under the DARPA DODOS project, contract number HR0011-15-C-0056.*

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