Mid-Infrared Generation by Frequency Down-Conversion Across 1.2 Octaves in a Normally-Dispersive Silicon Wire

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Abstract: Using four-wave mixing in normally-dispersive mid-infrared silicon nanophotonic waveguides, we demonstrate the conversion of light across more than 1.2 octaves, from the telecom band to a wavelength of 3630 nm.

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

1. Introduction

The long-wavelength transparency of the silicon-on-insulator (SOI) wire waveguide platform up to ~4 µm [1], limited by the absorption of the silicon oxide, has recently been leveraged to expand the application of the platform beyond the traditional telecom space. A new set of mid-infrared spectroscopic applications arise from the specific and strong absorption lines of many molecules within this "molecular fingerprinting" wavelength region [2], which enable the development of chip-scale optical sensors with high sensitivity and high selectivity. Previous work has exploited the intrinsically high third-order nonlinearity and strong optical confinement of silicon wire waveguides to generate the mid-infrared radiation required for such chip-scale sensors. Recent demonstrations have shown that four-wave mixing-based nonlinear optical functions including supercontinuum generation [3], optical parametric amplification [4,5], and wavelength conversion [6-8], can be integrated in compact mid-infrared silicon photonic integrated circuits. In this paper, we demonstrate generation of mid-infrared radiation near 3630 nm by mixing a high-power pump at 2190 nm with a telecom signal at 1564 nm, within a silicon photonic wire engineered to have normal dispersion. Simultaneously, we illustrate that the telecom band signal is amplified by up to 13.1 dB for a peak pump power of 18.3 W. To the best of our knowledge, this is the first time that wavelength conversion across more than an octave has been demonstrated in silicon waveguides.

2. Phase-matching in a silicon waveguide

The phase-matching condition for the degenerate four-wave mixing process in a waveguide is given by

$$\beta_2 \Delta\omega^2 + \frac{1}{12}\beta_4 \Delta\omega^4 + 2\gamma P = 0 \qquad (1)$$

Here, γ is the effective nonlinearity parameter of the waveguide, $\Delta\omega$ is the frequency detuning between pump and signal (or idler), β_2 and β_4 are the second- and fourth-order dispersion coefficients respectively, evaluated at the pump frequency, and P is the pump peak power. The higher-order dispersion terms are necessary when conversion over a wide band is envisaged. In this particular photonic wire the second-order dispersion is normal, e.g. positive, such that the fourth-order dispersion β_4 has to be negative to achieve phase-matching. This facilitates phase-matching far from the pump [9]. For an air-clad wire waveguide 1650 nm wide and 400 nm thick (as shown in the inset of Fig. 1, having $\gamma = 20\ W^{-1}m^{-1}$), the phase-matched idler and signal solutions of Eq. (1) are plotted in Fig. 1, for pump wavelengths between 2100 nm and 2400 nm. A fixed pump peak power of 20W is assumed. Pumping within the normal dispersion regime at 2190 nm, the simulation in Fig. 1 predicts that an input signal near 1700 nm can be down-converted to a band near 3076 nm.

3. 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 SOI wafer consisting of a 400 nm silicon waveguide layer on a 2 µm buried oxide. The dimensions of the photonic wire match those shown in the inset of Fig. 1. For the experiment, a picosecond pulse train (FWHM ~ 2 ps, repetition rate = 76 MHz) generated by a tunable optical parametric oscillator (OPO) is coupled to a single-mode optical fiber, and used as the pump. A telecom tunable CW laser is used as a probe. Coupling into/out of the SOI photonic wire is accomplished using lensed fibers. Signal and pump are combined by a 90/10 fused silica fiber coupler. A polarization controller is used to excite the TE polarized waveguide modes of both the pump and the probe. The waveguide loss is measured at <0.2 dB/cm at both the telecom and pump wavelengths. The fiber coupling loss at each facet is 8.5 dB ± 1dB. The waveguide output spectrum up to 2500 nm is characterized with a mid-infrared optical spectrum analyzer, at 1 nm spectral resolution. For spectral analysis at wavelengths longer than 2500 nm, a Fourier Transform Infrared spectrometer (FTIR) equipped with a liquid-nitrogen cooled InAs detector is used. In this case, the light is coupled out of the waveguide and collimated into the FTIR with a high numerical aperture (NA) chalcogenide lens.

In a first experiment, the peak wavelength of the spontaneous parametric fluorescence (modulation instability: MI) excited by the high peak power pulses was recorded as a function of the input pump wavelength. The MI peaks indicate the wavelength bands at which phase-matching is achieved. The wavelengths at which the MI peaks appear on the blue side of the pump are shown as the red triangles in Fig. 1, as a function of pump wavelength. The red stars correspond to the energy-conserving wavelengths on the red side of the pump. As illustrated by the dashed line in Fig. 1, for a pump tuned to 2190 nm we expect phase-matching between signals near 1700 nm and 3076 nm. Experimentally, an input probe signal at 1565 nm is phase-matched for efficient wavelength conversion to 3635 nm. Fig. 2 (a) shows the optical spectrum at the waveguide output in this case, as recorded by the FTIR. A long pass filter is used at the FTIR input to suppress the transmitted pump pulses. In addition to the residual 2190 nm pump, Fig. 2 (a) also exhibits a converted idler peak at 3630 nm protruding above the thermal background radiation floor. Figure 2 (b) plots the on-chip parametric gain as a function of the telecom band signal wavelength, for a pump wavelength of 2190 nm and a peak pump power of 18.3 W. Following the measurement procedure outlined in [4], the figure shows that net gain is observed from 1550 nm up to 1585 nm, with a peak value of 13.1 dB at 1564.4 nm. The conversion gain at 3635 nm is estimated to be 9.2 dB according to the Manley-Rowe relations. The lack of an appropriate tunable laser source prevents a similar set of measurements for up-conversion of wavelengths near 3635 nm to the telecom band.

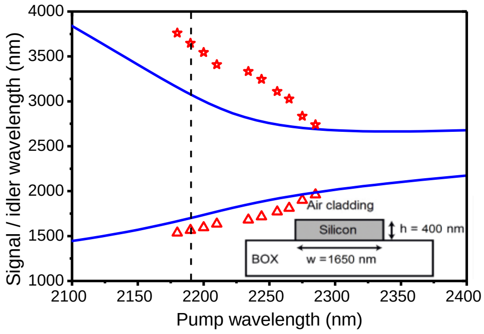

Figure 1: Phase-matched idler and signal wavelength as a function of pump wavelength. The blue curve shows the simulated phase-matched wavelengths, for a peak pump power of 20 W. The red triangles label the positions of the experimentally observed modulation instability peaks on the blue side of the pump, while the red stars correspond to the energy-conserving wavelengths on the red side of the pump.

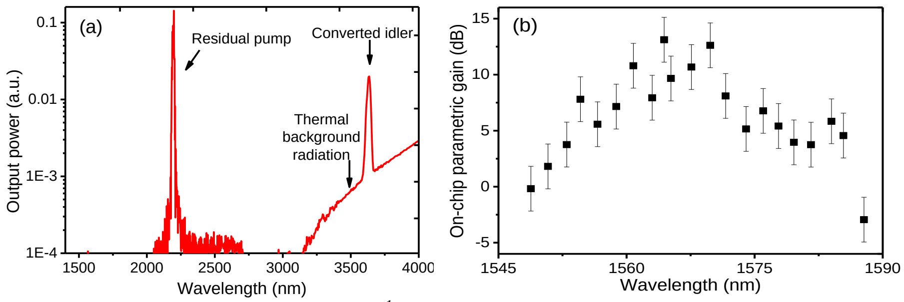

Figure 2: (a) Optical spectrum recorded with an FTIR (16 cm^{-1} resolution) when the waveguide is pumped at 2190 nm with a peak power of 18.3 W, and probed by a telecom signal at 1565 nm. The converted idler is seen at 3635 nm, above the thermal background radiation signal. (b) On-chip gain for the telecom CW probe as a function of wavelength in the 1 cm-long silicon wire waveguide for 18.3 W pump pulses centered at 2190 nm. Error bars originate from the +/- 1 dB uncertainty in the value of the pump power coupled into the waveguide.

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[1] M. Milosevic, et al., "Silicon waveguides and devices for the mid-infrared," Applied Physics Letters **101**, 121105-121105 (2012).
[2] J. G. Crowder, et al., “Infrared methods for gas detection,” in Mid-Infrared Semiconductor Optoelectronics. New York: Springer-Verlag, 2006.
[3] B. Kuyken, et al., "Mid-infrared to telecom-band supercontinuum generation in highly nonlinear silicon-on-insulator wire waveguides," Optics Express **19**, 20172-20181 (2011).
[4] X. Liu, et al., “Mid-infrared optical parametric amplifier using silicon nanophotonic waveguides,” Nature Photonics **4**, 557–560 (2010).
[5] B. Kuyken, et al., "50 dB parametric on-chip gain in silicon photonic wires,” Optics Letters **36**, 4401-4403 (2011).
[6] S. Zlatanovic, et al., "Mid-infrared wavelength conversion in silicon waveguides using ultracompact telecom-band-derived pump source," Nature Photonics **4**, 561-564 (2010).
[7] Q. Lin, et al., "A proposal for highly tunable optical parametric oscillation in silicon micro-resonators," Optics Express **16**, 10596-10610 (2008).
[8] X. Liu, et al., "Bridging the mid-infrared-to-telecom gap with silicon nanophotonic spectral translation," Nature Photonics **6**, 667-669 (2012).
[9] R.K. Lau, et al., "Continuous-wave mid-infrared frequency conversion in silicon nanowaveguides," Optics Letters **36**, 1263-1265 (2011).