Mid-Infrared Nonlinear Optics in Silicon Nanostructures

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Abstract

We report continuous-wave wavelength conversion from the telecom band to the mid-infrared via four-wave mixing in silicon nanowaveguides. We convert a 1636-nm signal to produce a 2384-nm idler, demonstrating a parametric bandwidth of 748 nm.

A highly promising research area that recently has emerged is nonlinear optics using silicon photonics. Since the birth of nonlinear optics, researchers have continually focused on developing efficient nonlinear optical devices that require low optical powers. The strong light confinement in silicon waveguides results in a high effective nonlinearity and enables tuning of the waveguide dispersion, which is essential for phase matching of parametric nonlinear optical processes such as four-wave-mixing (FWM) [1]. However, silicon devices based on FWM in the telecom band are fundamentally limited by the nonlinear optical loss mechanisms of two-photon absorption (TPA) and the resulting free-carrier absorption (FCA). It is known that the TPA coefficient decreases with increasing wavelength beyond 1.7 μm and drops to zero for wavelengths beyond 2.2 μm [2]. As a result, previous demonstrations of silicon photonic devices designed to operate in the mid-infrared (MIR) region beyond 2.2 μm have exhibited relatively large amplification [3] and broadband conversion [4] using a pulsed pump source. However, there are a number of applications where the use of a continuous-wave (CW) pump is desirable, such as in free-space communications, since it facilitates wavelength conversion of a continuous data stream, and in high-resolution spectroscopy, since it enables the generation of narrow-linewidth sources.

In this paper, we describe our recent results on CW wavelength conversion from the telecom band to the MIR via FWM in silicon nanowaveguides. We measure a parametric bandwidth of 748 nm by converting a 1636-nm signal to produce a 2384-nm idler and show continuously tunable wavelength conversion from 1792 nm to 2116 nm. Lastly, we are able to produce broadband frequency combs by using FWM parametric oscillation in ring resonators which offers the possibility of CMOS-compatible multiple-wavelength sources and all-optical clocks.

The nanowaveguides were fabricated on a silicon-on-insulator wafer with a 3-μm buried oxide and a 500-nm silicon layer. The TE polarization mode is selected for the pump and signal beams using a polarization beamsplitter cube and polarization controller, respectively. The nanowaveguide is 940 nm wide, 280 nm high, and 1 cm long. We estimate the propagation loss and input/output coupling loss to be -1.7 dB/cm and -3 dB/facet, respectively. The pump laser for FWM is a high-power CW thulium fiber laser centered at 1940 nm, and the signal is a second CW thulium fiber laser, tunable from 1790 nm to 1930 nm. As the signal is tuned from 1792 nm to 1928 nm, we generate an idler over wavelengths from 1953 nm to 2116 nm. The measured conversion bandwidth of 324 nm is limited only by the tuning range of the signal laser. With approximately 25

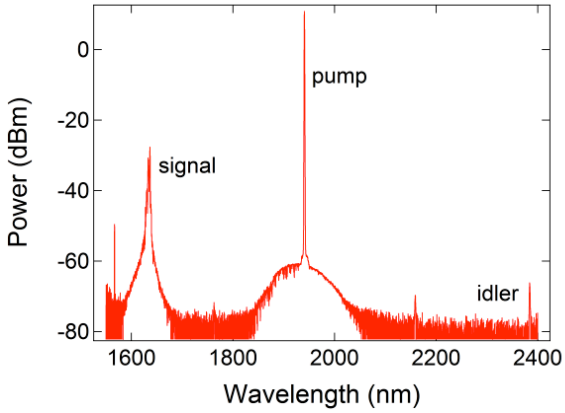

Fig. 1. Measured FWM spectra showing broadband wavelength conversion across 748 nm. The signal, pump, and idler wavelengths are 1636 nm, 1940 nm, and 2384 nm, respectively.

mW of pump power within the nanowaveguide, the conversion efficiency ranges from -31.7 dB to -34 dB, varying less than 3 dB across the entire tuning range of the signal. As we increase the pump power to approximately 160 mW, we measure a maximum conversion efficiency of -17.8 dB.

Theoretically, the full conversion bandwidth for these experimental conditions is predicted to be 936 nm, from 1579 nm to 2515 nm. We demonstrate that this larger conversion bandwidth is possible by using a U-band Fabry-Perot laser diode at 1636 nm as the CW signal source. As expected, we observe wavelength conversion to 2384 nm, demonstrating a parametric bandwidth of at least 748 nm. The FWM output spectrum showing the signal, pump, and idler is shown in Fig. 1.

In conclusion, we have designed and fabricated a silicon nanowaveguide capable of broadband, CW parametric-mixing in the MIR. We generate a 2384-nm idler and measure a conversion bandwidth of 748 nm. Additionally, we observe continuously tunable wavelength conversion across 324 nm. This demonstration indicates that the advantages of silicon photonics may be extended to the MIR to create chip-scale devices for applications such as infrared spectroscopy, biochemical sensing, free-space communications, and astronomy.

References

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