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Mid-Infrared Light Sources Using Parametric Amplification in Silicon Nanophotonic Wires

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Abstract: Progress toward realizing silicon-based mid-IR light sources will be reviewed. Using silicon nanophotonic wire parametric amplifiers as compact high-gain elements, synchronously-pumped wavelength-tunable mid-IR optical parametric oscillators and broadband supercontinuum sources have been demonstrated.

OCIS codes: (130.3120) Integrated optics devices, (190.4970) Parametric oscillators and amplifiers

1. Introduction

The silicon-on-insulator (SOI) nanophotonic platform has been proposed as an excellent system for integrated mid-infrared optical devices, on account of the long-wavelength transparency of silicon and many associated CMOS-compatible materials [1]. Advantages including strong optical confinement, ultra-compact device area, and the availability of advanced manufacturing tools make this platform suitable for low-cost mid-IR integrated circuits. Given the presence of distinct molecular absorption bands in the mid-IR, such circuits could address applications in the molecular spectroscopy space, including environmental sensing [2] and rapid medical diagnostics [3].

An important component of any such spectroscopy circuit is a light source, which for integrated systems would preferably be silicon-based. To maximize its spectral range of application, this source would also ideally have widely tunable and/or broadband emission characteristics. These performance characteristics can be satisfied by making use of efficient four-wave mixing (FWM) in silicon nanophotonic wires to generate light within the short-wave IR and mid-IR spectral range. Nonlinear interactions in short silicon wires can be highly efficient, as a result of both the high nonlinear index of silicon and the high optical confinement [4]. These properties can be fully exploited by working at photon energies near one half the bandgap of silicon where two-photon nonlinear absorption (TPA) is strongly suppressed ($\lambda \sim 2200$ nm, [5-7]), facilitating the development of mid-IR light sources derived from high-gain optical parametric amplifiers [8]. This presentation will review our recent experiments demonstrating long-wavelength light sources using nonlinear optical effects in silicon nanophotonic wires.

2. Silicon-based mid-IR light sources

SOI silicon nanophotonics wires with cross-sectional dimensions of 900 nm x 220 nm can be dispersion-engineered to produce anomalous dispersion characteristics which satisfy the FWM phase-matching conditions over a broad spectral region near silicon's TPA threshold. The combination of a large effective nonlinearity coefficient ($\gamma \sim 150$ $W^{-1}m^{-1}$), and low linear propagation losses (~ 1-2 dB/cm near $\lambda \sim 2200$ nm) have facilitated the demonstration of broadband mid-IR optical parametric amplification and wavelength conversion in 2 cm long silicon wires, with on-chip gain exceeding 50 dB [9]. By enclosing such a mid-IR parametric amplifier within a fiber feedback loop as shown in the inset of Fig. 1(a), a silicon-based synchronously pumped optical parametric oscillator (OPO) has been constructed [10]. Figure 1(a) illustrates that single-pass parametric gain and wavelength conversion efficiency as large as 54 dB and 58 dB, respectively, are achieved when the wire pumped by a picosecond pulse-train at 2175 nm. Parametric oscillation occurs within the spectral regions where the parametric gain exceeds the round-trip loss shown by the blue curve. Exploiting dispersion selection by tuning the pump wavelength, the oscillation wavelength can be tuned by more than 160 nm by tuning the pump over only 60 nm, as shown in Fig. 1(b). The OPO can also be tuned by adjustment of the delay between the pump and the loop-circulating pulses, as demonstrated in Fig. 1(c).

Non-resonant configurations for silicon nonlinear mid-IR light sources are also possible. Using a nearly identical 2 cm long dispersion-engineered silicon nanophotonic wire, but without the fiber optical feedback path, we have demonstrated generation of a supercontinuum spanning from the C-band at 1530 nm up to 2550 nm [11]. In this experiment, the wire is pumped with a picosecond pulse-train at 2120 nm, at which the wire exhibits the higher-order dispersion conditions producing to the broadest possible output spectrum. As shown in Fig. 1(d), the supercontinuum originates from the cumulative superposition of several nonlinear effects, including modulation instability, Raman scattering, dispersive wave generation, and self-phase modulation.

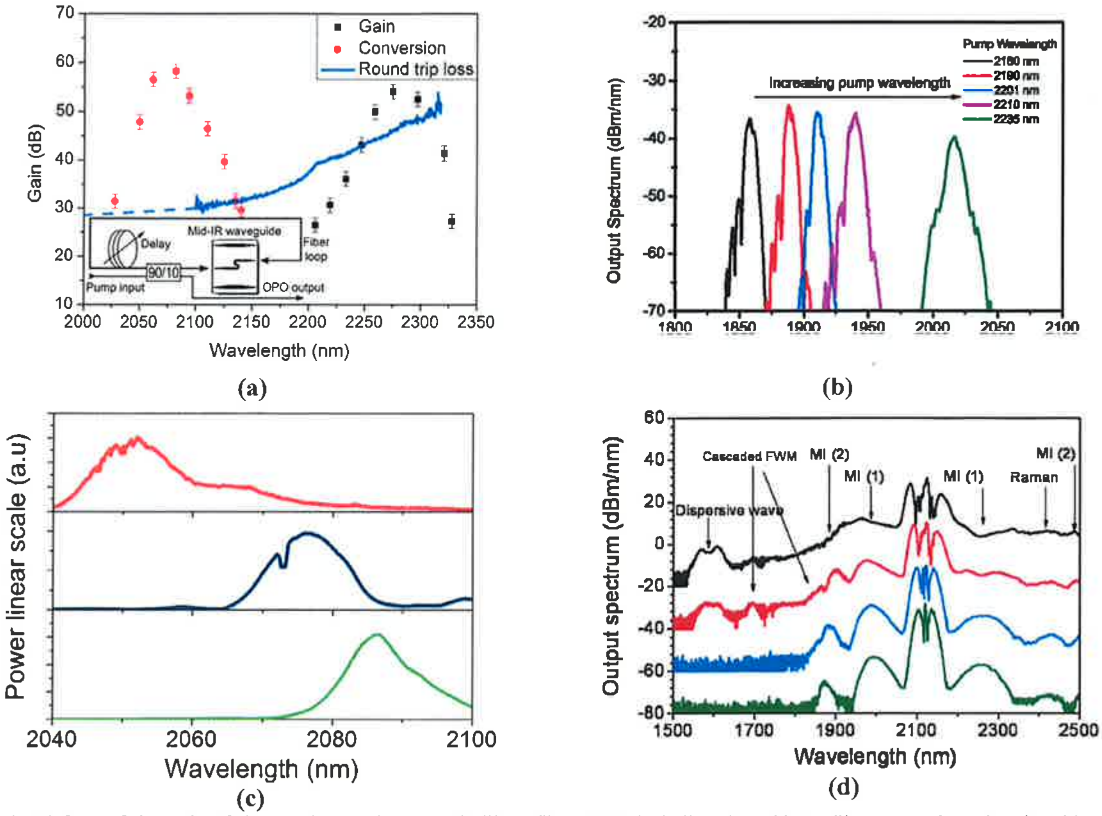

Fig. 1. (a) Inset: Schematic of the synchronously-pumped silicon-fiber OPO, including the mid-IR silicon nanophotonic wire chip, the external fiber loop, the optical delay line, and the 90/10 fiber directional coupler. Single-pass parametric gain (black squares) and conversion efficiency (red circles) obtained along the 2 cm long silicon nanophotonic wire, when pumped by a picosecond pulse-train at 2175 nm with a peak power of 24 W. The blue curve depicts the round-trip loss through the external fiber loop feedback path. The significantly lower round-trip loss near the 2075 nm conversion gain peak makes this region preferable for parametric oscillation with low threshold. Nevertheless, oscillation was observed on both the blue and the red sides of the pump. (b) Tuning of the OPO operating wavelength by adjustment of the phase-matching conditions, via selection of the pump wavelength. The OPO output wavelength is red-shifted from 1855 nm to 2020 nm while the pump is tuned from 2180 nm to 2235 nm. (c) Tuning of the OPO operating wavelength using the variable optical delay within the external fiber loop. The output wavelength is blue-shifted from 2086 nm to 2052 nm for increasing values of the round-trip delay within the fiber loop. (d) Spectra of supercontinuua generated in a 2 cm long nanophotonic wire pumped with a picosecond pulse-train at 2120 nm. The various spectral peaks contributing to the supercontinuum are labeled. Output spectra are shown for increasing values of coupled input peak power: 3.1 W (green), 4.3 W (blue), 7.9 W (red) and 12.7 W (black). The spectra are vertically offset by multiples of 20 dB for clarity.

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