Mid-infrared Raman-enhanced four-wave mixing in silicon waveguides

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Four-wave mixing (FWM) is an important nonlinear process for wavelength conversion and photon-pair generation. Owing to the high third-order nonlinearity and tight optical confinement, integrated silicon waveguides have emerged as convenient platforms for the observation of FWM processes using continuous-wave (CW) pump sources with optical powers typically employed in communication systems [1]. However, without resorting to pulsed pump sources or complex resonator geometries, the conversion efficiencies in these chip-based systems are typically very low [2]. An alternative solution to enhance the conversion in FWM interactions is coupling the parametric nonlinear process with the resonant Raman response of the material [3]. This is particularly useful when extending the operation into the mid-infrared (MIR) region where the pump powers can be low, and where there is interest for applications in free space communications, optical imaging, and sensing [4].

In this paper we investigate a Raman-enhanced FWM (RE-FWM) process within silicon waveguides designed for operation in the mid-infrared region for the first time. The waveguides are based on a low-loss single-mode rib structure. Two waveguide widths (W) are used to investigate the influence of phase-matching on the FWM process, 1490 nm and 1515 nm, with the remaining dimensions fixed as: rib height (H) = 500 nm, etch depth (h) =250 nm, and length = 2 cm. The optical transmission losses are ~2 dB/cm. The signal was set at λ=1950 nm and the CW pump was tuneable within the range of 2165-2172 nm, to cover the full Raman scattering bandwidth. A schematic of the experimental setup and waveguide design are shown in Fig. 1a. The output spectra were recorded with a mid-infrared optical spectrum analyser to estimate the conversion efficiency ($CE = P_{\text{idler}}/P_{\text{signal}}$). Thanks to the strong enhancement, the measured CE curves show a clear peak when the pump wavelength matches with the peak of the silicon Raman shift for the given signal wavelength (Fig. 1b). Simulation results obtained using the generalised nonlinear Schrödinger equation (GNLSE) are in good agreement with the measured data [3]. The results show that a maximum CE of -35 dB (1490 nm) and -25 dB (1515 nm) can be obtained for the two waveguides with a pump power as low as 46 mW. We attribute the higher CE for the 1515 nm waveguide to the fact that zero dispersion wavelength is closer to the pump, resulting in a more efficient FWM conversion [5]. However, in both cases the CE enhancement due to the Raman coupling is as high as ~8 dB, presenting a significant improvement of processing. Through further optimization of the waveguide width ($W = 1540\ nm$), we estimate that the CE could be as high as -11 dB for pump powers of 100 mW, considerably higher (~8 dB) than previous FWM result [6]. These results highlight the potential to build high-efficiency wavelength conversion in the MIR region through coupling of the strong Raman response to the FWM process.

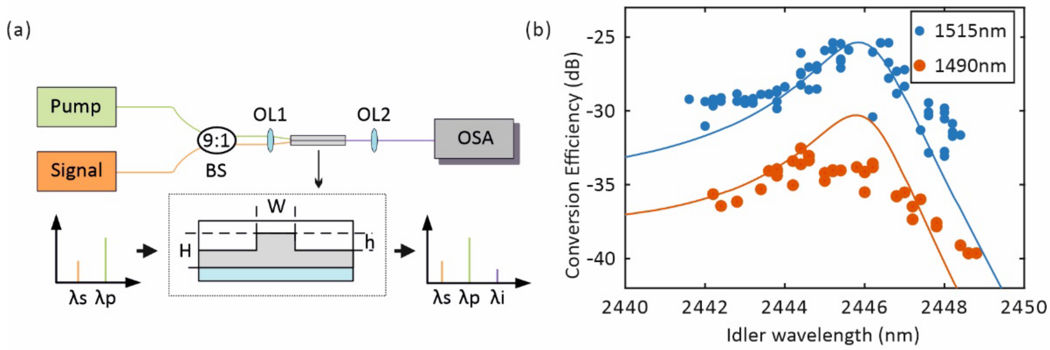

Figure. 1 (a) Experimental setup and waveguide profile. **(b)** Simulation results (solid lines) and experimental results (solid points) for the two width waveguides given in the legend.

References

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