Nonlinear Silicon Nanophotonics for Mid-Infrared Applications

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***Abstract* – The silicon nanophotonic wire platform can be applied toward development of integrated optical devices for the generation and processing of mid-infrared light signals. The demonstration of a mid-infrared optical parametric amplifier will be reviewed, and recent work aimed at expanded gain bandwidth and reduced pump power requirements will be presented.**

I. INTRODUCTION

Within the mid-infrared (mid-IR) spectral region near λ = 2200 nm, the silicon nanophotonic wire platform has potential to be used in constructing room temperature, highly efficient, ultra-compact devices for light generation and amplification through coherent nonlinear optical processes [1-3]. This platform could be an ideal host for a variety of mid-IR applications including molecular spectroscopy, free-space communication and environmental monitoring [4, 5]. Strong optical confinement in silicon not only enhances the effective nonlinearity by means of reduced modal area, but also provides flexibility in the control of waveguide dispersion that is necessary for processes such as four-wave mixing (FWM) [6].

II. MID-INFRARED OPTICAL PARAMETRIC AMPLIFIER

We have recently demonstrated the first silicon photonic wire mid-IR optical parametric amplifier (OPA) [1]. The OPA exhibits net off-chip gain of 13 dB in addition to on-chip gain as large as 25.4 dB (Fig. 1), while having a length of only 4 mm. By positioning the pump wavelength in the mid-IR near one-half the band-gap wavelength (λ ~ 2200 nm), the majority of parasitic TPA-related absorption is eliminated [7-9]. It is therefore possible to exploit the extremely large enhancement of the effective third-order nonlinearity γ (Fig. 1b) afforded by high-confinement silicon photonic wire waveguides, being as much as 10^5 times larger than that in conventional silica single-mode fiber [10], in order to facilitate efficient parametric processes. Moreover, waveguide dispersion engineering concepts [6, 11, 12] have been applied to achieve a total on-chip gain bandwidth exceeding 220 nm (Fig. 1d).

III. BROADBAND MODULATION INSTABILITY AND RAMAN-ENHANCED FWM GAIN

Building upon the initial mid-IR OPA demonstration described above, recent work has produced silicon wires with cross-sectional dimensions of w = 900 nm by h = 220 nm,

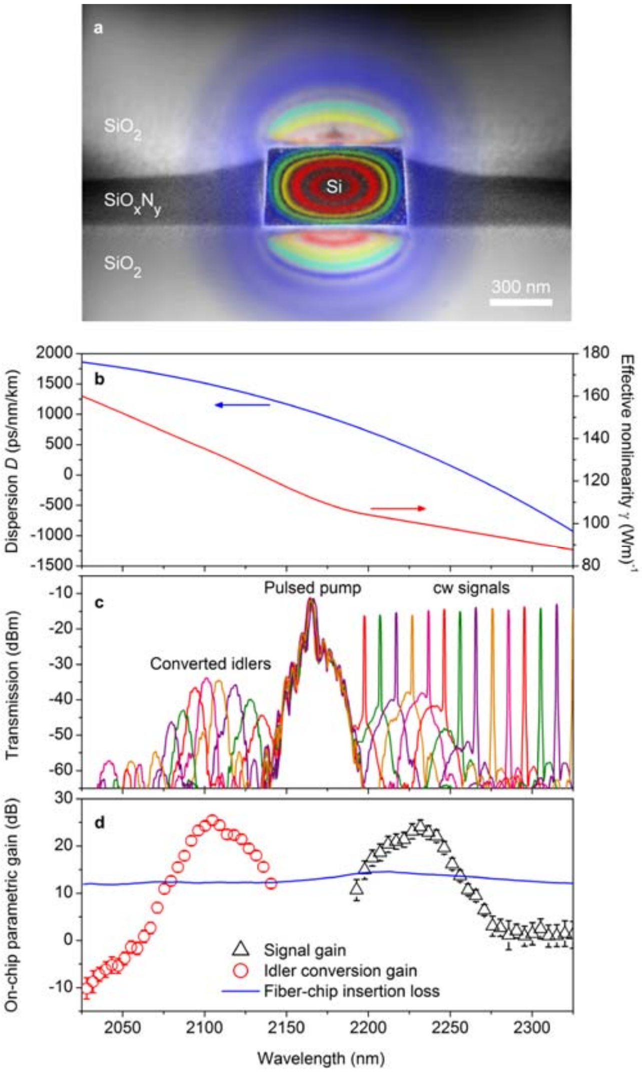

Figure 1. Engineered silicon nanophotonic waveguide characteristics, mid-IR FWM experiments, and broadband on-chip optical parametric amplification. a) SEM cross-section of the 700 nm x 425 nm silicon waveguide. The colour-map illustrates the E_y component of the fundamental quasi-TM mode at λ=2200 nm. b) Simulated dispersion coefficient D (blue curve) and effective nonlinearity parameter γ (red curve). c) Series of FWM spectra taken at the output of the 4 mm-long waveguide. The peak pump power is P_{pump} ~ 27.9 W. d) On-chip parametric signal gain (black triangles) and idler conversion gain (red circles), with bandwidth ~220 nm, and peak values >25 dB. Net off-chip gain results where amplification exceeds fiber-chip insertion losses (blue line), with maximum value ~13 dB.

which are both longer (2 cm) to enhance the total cumulative FWM effects, as well as dispersion-optimized for ultra-broadband phase matching [13, 14]. The wires have anomalous GVD ($\beta_2 < 0$) at wavelengths from 1800 nm to 2400 nm, in addition to small positive 4th-order dispersion ($\beta_4 > 0$) within the same range. Small β_4 is critical for achieving broadband phase matching and expanding the parametric gain bandwidth.

Figure 2a) illustrates that when the silicon wire is pumped with a peak input power of ~13.5 W, the output spectrum is characterized by a strong broadband modulation instability (MI) spectrum extending from 1911 nm to 2486 nm. In addition, a prominent Raman Stokes peak rides on top of the MI spectrum at a wavelength of 2411 nm, frequency down-shifted from the pump by a Stokes shift of 15.6 THz [7]. Moreover, a frequency up-shifted Raman anti-Stokes [15] peak at a wavelength of 1950 nm is visible. The visibility here of a strong MI background suggests that the on-chip mid-IR parametric gain available is far larger than demonstrated in previous studies [1], where MI was not observed. As illustrated in Fig. 2b), the intense MI correlates with very large values of on-chip parametric gain, exceeding 40 dB. Moreover, we demonstrate that on-chip gain can exceed 50 dB in narrow bands assisted by stimulated Raman scattering. In comparison with prior work [1], the peak operating pump power is reduced to less than half. At the same time, the maximum on-chip gain obtained using the 2 cm-long wire here shows an improvement of more than 25 dB, while the on-chip gain bandwidth (> 580 nm) is increased by more than 2.5x.

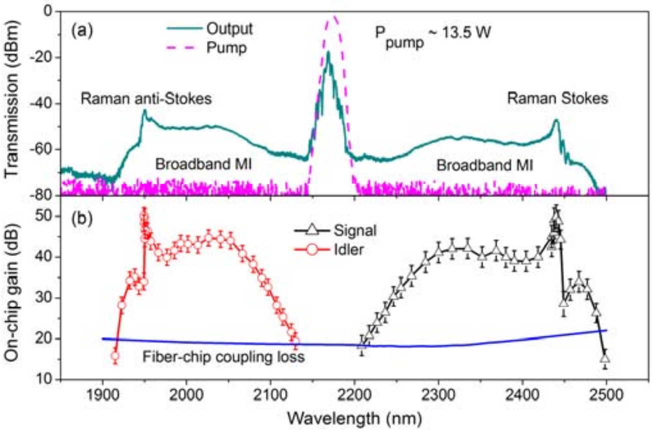

Figure 2. a) Input (dashed magenta curve) and transmitted (solid cyan curve) pump spectra, illustrating broadband MI and Raman Stokes/anti-Stokes peaks. b) On-chip parametric gain, exhibiting broadband on-chip amplification over a bandwidth > 580 nm, maximum Raman-assisted gain values of ~ 50 dB, unassisted FWM parametric gain of ~ 40 dB, peak net off-chip gain > 30 dB.

IV. CONCLUSION

These results provide a foundation for the construction of silicon-based room-temperature mid-IR light sources including tunable chip-scale parametric oscillators [16-18], optical frequency combs [19], and supercontinuum generators [20]. In this manner, silicon nanophotonic technology may be extended to an entirely new class of mid-IR applications [4, 5] including biochemical detection, environmental monitoring, and free-space communication, in which an integrated on-chip platform can be of significant technological benefit.

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