Optical parametric amplification in silicon nitride waveguides for coherent Raman imaging

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Abstract: Waveguide-based optical parametric amplification by stimulated four-wave mixing in silicon nitride waveguides is presented. The high nonlinearity leads to reduced necessary pump energies and waveguide length. The light source was applied for narrow-band Raman imaging.

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1. Introduction

Silicon nitride (Si$_3$N$_4$) waveguides offer a versatile on-chip platform with a two orders of magnitude higher nonlinearity in comparison to photonic crystal fibers. Therefore, nonlinear processes such as four-wave mixing (FWM) can be driven very efficiently [1, 2]. The result is a significant reduction of requirements, i.e., a lowering of pump energy and orders of magnitude shorter interaction lengths. For an experimental demonstration of these advantages, we present tunable waveguide-based optical parametric amplification (WOPA) by stimulated FWM in Si$_3$N$_4$ waveguides for narrowband coherent anti-Stokes Raman scattering (CARS) imaging, with the potential to be set up as an all-integrated device.

2. Scheme and experimental setup

In the experiments, Si$_3$N$_4$ waveguides (950 nm high and 7 mm long) with different widths were pumped with a fiber laser (Fig. 1(a)) emitting 800 fs pulses with a repetition rate of 1 MHz and centered at 1033 nm wavelength to generate spontaneous FWM (Fig. 1(b), dashed line). Additionally, a tunable cw radiation from a titanium:sapphire laser was coupled into an exemplary waveguide with a width of 1300 nm to stimulate the FWM process (Fig. 1(b), solid line). The pump energy and seed power were set to 3 nJ and 4 mW, respectively, resulting in an enhancement of the FWM idler wave by 35 dB. The generated idler output energy was approx. 65 pJ, which corresponds to an external conversion efficiency of $-16.6$ dB. The spectral bandwidth of the stimulated FWM signal was determined by the bandwidth of the pump laser and turned out to be approx. 85 cm$^{-1}$, however, we show that a better spectral resolution can be achieved with longer pump pulse durations. An external pump beam with a pulse energy of 7.3 nJ was used as the pump wave together with 30 pJ idler energy as the Stokes wave for following CARS imaging experiments.
3. Wavelength tuning and CARS imaging

Wavelength tuning of the idler wave was accomplished on the one hand by the choice of waveguide width, which determines the coarse wavelength range of the FWM gain (Fig. 2(a)), and on the other hand by the seed wavelength for fine tuning. Exemplary measurements in a 1400 nm wide waveguide demonstrate the tunability, where the seed source was tuned from 818 nm to 896 nm generating stimulated FWM idler wavelengths from 1220 nm to 1400 nm (Fig. 2(b)). These idler wavelengths enable label-free and chemically-selective CARS imaging from the fingerprint to the CH-stretch region. To demonstrate the applicability of the light source, CARS images of a cross-sectional cut of a leaf of chlorophytum comosum, soaked in dimethyl sulfoxide-d$_6$ (dDMSO), were acquired with lock-in detection (Fig. 2(c)). The measured image contained 1024 × 1024 pixels, each with a pixel dwell time of 10 µs.

![Fig. 2. (a) Spontaneous FWM spectra for three different waveguide widths. (b) Wavelength tuning of the stimulated FWM by wavelength tuning of the seed source (818 nm to 896 nm). (c) CARS image of a chlorophytum comosum leaf soaked in dDMSO.](image)

4. Conclusion

Waveguide-based optical parametric amplification for narrowband coherent anti-Stokes Raman scattering was presented, enabling label-free and chemically-selective imaging with both low pump energy (3 nJ) and seed power (4 mW) for stimulated FWM in a Si$_3$N$_4$ waveguide. With an external pump energy of 7.3 nJ and 30 pJ of idler energy coherent Raman imaging in the silent region was demonstrated. In contrast to experiments with photonic crystal fibers two orders of magnitude shorter medium length as well as lower pulse energy was used [3, 4]. Furthermore, by integrating the seed laser source on the chip [5], as well as the spectrometer for detecting the CARS signal [6], the experimental setup has a high potential to be miniaturized.

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