

High Efficiency CARS Conversion in Silicon

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Abstract: We experimentally demonstrate unprecedented wavelength conversion efficiency of 58% from coherent anti-Stokes Raman scattering (CARS) in a silicon waveguide. CARS is modeled by incorporating Raman scattering and free carrier effects into the nonlinear Schrödinger equation.

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1. Introduction

Wavelength conversion in silicon chips has significant potential for applications. For example, the transfer of information from one wavelength channel to another is important for optical packet routing, which is necessary for silicon-based optical communications and data processing. Silicon's excellent thermal conductivity and high optical damage threshold also make it an attractive medium for high-power optical wavelength conversion. Specifically, practical silicon-based wavelength converters could offer a robust, low-cost solution for generating intense light at wavelengths that are currently difficult to reach. Coherent anti-Stokes Raman scattering (CARS) has been studied as a means to address these needs in silicon photonics. Unfortunately, efficient transfer of information in CARS based wavelength conversion depends on the phase matching between the optical waves that participate in it. Thus, the conversion efficiencies that have been reported in silicon-based CARS are extremely low. Here, we experimentally demonstrate highly efficient CARS wavelength conversion in a silicon waveguide without the need for phase matching. Using intense optical pulses, we measure a CARS conversion efficiency that is orders of magnitude greater than previously published values.

2. Conceptual Background

Stimulated Raman Scattering has been used to create optical amplifiers and lasers in silicon [1,2]. In silicon, the Raman Stokes signal is downshifted by ~ 15.6 THz from the pump wavelength. The nonlinear Raman susceptibility also couples the Stokes field to the anti-Stokes wavelength—15.6 THz upshifted from the pump—through a four-wave mixing (FWM) process (cf. Figure 1). This process has been utilized to demonstrate the transfer of information from the 1550 nm band to the 1310 nm band [3]. As in any FWM process, the efficiency of the generation of anti-Stokes signal strongly depends on the phase matching between the pump, Stokes, and anti-Stokes fields. For a given phase mismatch, the conversion efficiency may be increased by increasing the intensity of the pump signal. Of course, for a continuous-wave (CW) pump, there is a practical limit to the amount of optical power that can be used. Furthermore, in silicon, increasing the CW pump intensity causes an increase in the generation of free carriers generated through two-photon absorption (TPA). These carriers deplete the pump, Stokes, and anti-Stokes fields, and limit the CARS conversion efficiency. However, if optical pulses are used to pump CARS, carrier accumulation can be reduced, which minimizes their impact on the fields. In order to achieve this improvement, the pulse width must be shorter than the carrier lifetime, which must in turn be shorter than the pulse repetition rate. Here, we employ pulses with optical intensities as high as ~ 2 GW/cm² to observe conversion efficiencies close to 60% without phase matching.

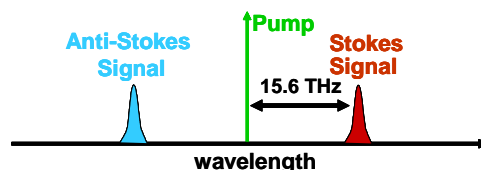


Fig.1 Wavelength conversion through CARS in Silicon

3. Experimental Results

Optical pulses (3 ps duration) from a mode-locked laser operating at 1550 nm are split by a power coupler to produce pump and probe pulses. One component is stretched, amplified with an Erbium Doped Fiber Amplifier (EDFA), and compressed to generate 40 ps pump pulses with peak power as high as 260 W. The other component is

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sent through another EDFA to generate a flat optical continuum centered around 1685 nm, the Stokes wavelength in silicon for a pump at 1550 nm. The pump and Stokes waves are combined in free space and coupled to a silicon waveguide with modal area of around $2.8 \mu\text{m}^2$, through a microscope objective. The input coupling loss of the setup, including the reflection and mode mismatch loss, is estimated to be approximately 6.6 dB. The 2 cm long optical waveguide has a linear propagation loss of $\sim 0.5 \text{ dB/cm}$. An optical delay line in the path of the Stokes signal is used to adjust the relative delay between the pump and Stokes pulses, which is critical for optimizing the CARS efficiency. At the output of the waveguide, the Stokes and the anti-Stokes signals are separated using a WDM splitter and measured using optical spectrum analyzers.

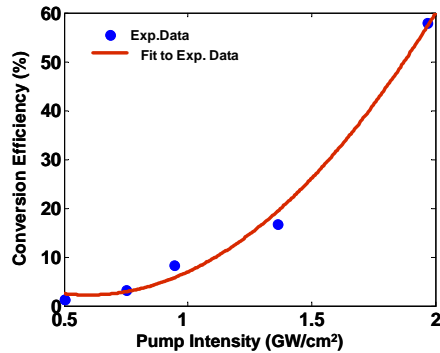


Fig. 2 Variation of conversion efficiency with pump intensity

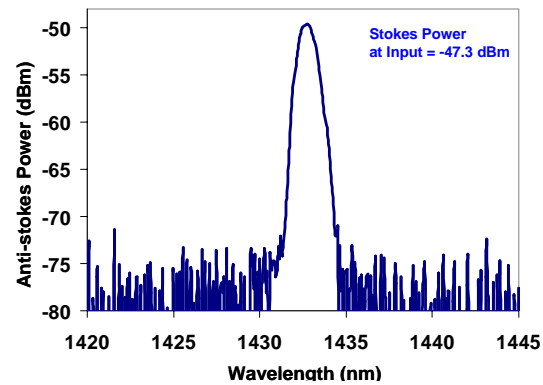


Fig.3 Anti-stokes spectra at 58% conversion

The variation of the conversion efficiency as a function of the optical intensity is shown in fig. 2. As expected, the conversion efficiency increases with the pump intensity. We observe a conversion efficiency of about 58% at approximately 2 GW/cm^2 . The CARS spectrum corresponding to the maximum conversion efficiency is shown in fig. 3. To the best of our knowledge, this is the largest efficiency reported for CARS wavelength conversion in *any* optical medium. The CARS conversion was numerically simulated by solving the nonlinear Schrodinger equation, taking the effects of free carrier dynamics into account for the pulse widths used in our experiments. Simulation results in fig.4 clearly show that the conversion efficiencies observed experimentally are possible using the optical intensities used in our measurements. Also, the simulations validate the experimentally observed super-linear variation of the conversion efficiency with pump intensity.

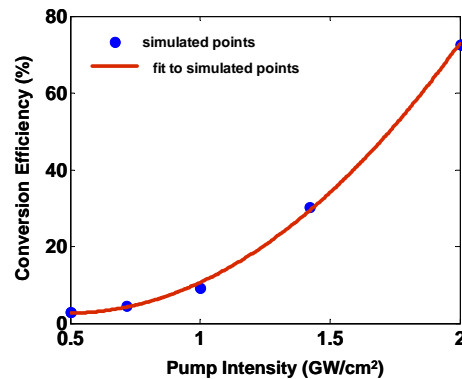


Fig. 4 Numerical simulation of the variation of conversion efficiency as a function of pump intensity

In summary, we have demonstrated an unprecedented CARS conversion efficiency of 58% in silicon waveguides without phase matching. This value is orders of magnitude higher than previously reported values. Our pump-probe measurements also represent the first measurements of the entire CARS spectrum of silicon at once, without any wavelength tuning.

References

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