Role of Phase-matching on Raman-enhanced FWM in Silicon Core Fibers

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Abstract: Raman-enhanced four-wave mixing is investigated in silicon core fibers that have been tapered to control the phase-matching conditions. The large estimated conversion efficiencies (~1 dB) will be useful for high-power amplification of telecom signals.

1. Introduction

Four-wave mixing (FWM) has been widely investigated in silicon photonics platforms for use in wavelength conversion, amplification and regeneration of optical data signals [1]. However, there are challenges to increasing the total gain that can be achieved via this process when operating in the telecom band owing to the strong two-photon absorption (TPA) and subsequent free carrier absorption (FCA), and typically pulsed pump sources [2] or integrated p-i-n diodes are employed to reduce these losses [3]. An alternative route to increasing the FWM gain whilst retaining a CW telecom pump is to couple the parametric nonlinear process with the resonant Raman response. Although such nonlinear coupling has been investigated in silicon platforms, to date the focus has been on coherent anti-Stokes Raman scattering (CARS) processes, resulting in low conversion efficiencies [4]. Here we investigate Raman-enhanced FWM of the Stokes beam using our tapered silicon core fiber (SCF) platform. Specifically, by making use of the fiber tapering process to adjust the SCF core size, we can explore the role of phase-matching on the gain enhancement [5]. Our experiments show that we can achieve a Raman enhancement of ~15dB to the FWM conversion efficiency for a pump power of only 28mW, when the pump is positioned close to the zero-dispersion wavelength (ZDW) of the tapered SCF. Moreover, simulations show that the gain can be increased further when using higher pump powers and perfect phase matching (~20dB), allowing for conversion efficiencies to the Stokes wave of ~1dB, opening a route for high-power amplification of telecom signals.

2. Theory and Results

The nonlinear processes that contribute to the gain at the Stokes wavelength are depicted in the energy level diagrams of Fig. 1(a), where (1) is degenerate FWM, (2) is stimulated Raman scattering (SRS), and (3) is inverse Raman scattering (IRS). FWM is the foundation of the enhanced process with two pump photons (ω_p) being consumed to generate a signal photon (ω_s) and an idler photon (ω_i). Once the FWM induces idler photons at the Stokes wavelength, SRS can take place, which leads to enhancement of the conversion efficiency. However, due to the presence of the FWM enhanced anti-Stokes wavelength, strong IRS can also occur, resulting in a transfer of energy back to the pump. This compensation of the pump can thus further increase the conversion efficiency of the Stokes wavelength via the FWM and SRS processes.

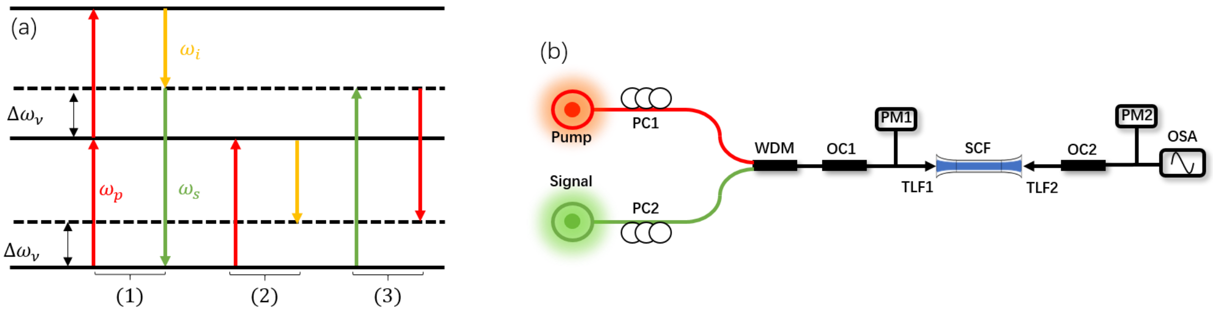

Fig. 1 (a) Energy level diagrams. (b) Experimental setup for Raman-enhanced FWM. PC, polarization controller; WDM, wave-division multiplexer; OC, optical coupler; PM, power meter; TLF, taper lens fiber; OSA, optical spectrum analyzer.

The experimental setup to study the interaction between the FWM and Raman processes is shown in Fig. 1(b), where a tunable CW pump centered at 1545nm is combined with a CW signal beam, positioned at the anti-Stokes wavelength of 1431nm, before launching into the tapered SCFs. To investigate Raman-enhanced FWM under different phase-matching conditions, SCFs were tapered to obtained core diameters of 860nm and 750nm over a length of 10mm. Both SCFs exhibited propagation losses of ~2dB/cm and the group velocity dispersion (GVD) parameters at the pump wavelength are β_2=-0.15ps^2/m and -0.52 ps^2/m for the core diameters of 860nm and 750nm, respectively. The experiments were conducted with a pump power of 28mW and a signal power of only 2mW and the measured conversion efficiencies are shown as the circles in Fig. 2(a). The results show that as the pump wavelength is tuned to overlap the FWM process with the peak of the Raman gain (λ_i-Λ_R=0), there is an order of magnitude enhancement of the conversion efficiency associated with the coupling of the nonlinear processes. Moreover, the maximum conversion efficiency is greater for the larger core SCF, due to the smaller GVD and thus better phase-matching for the FWM process. To better understand the observed enhancements, the experiments were compared with simulations using the nonlinear Schrödinger equation (NLSE) conducted both with and without the Raman term turned on [6]. As can be seen, the simulations with Raman are in good agreement with our experiments. We also see that there is a 15dB enhancement of the conversion efficiency due to Raman coupling for the 860nm core SCF, but this drops to 9dB due to the larger phase-mismatch as the core size decreases to 750nm.

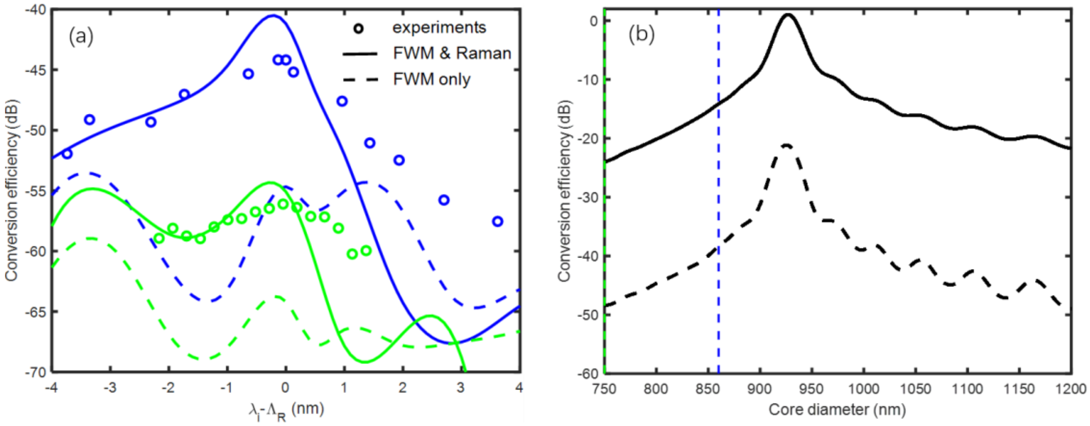

Fig. 2 (a) Conversion efficiency comparison between two SCF core diameters, 860nm (blue) and 750nm (green), compared to simulations of the NLSE. (b) Simulated conversion efficiency as a function of SCF core diameter, both with (solid) and without (dashed) Raman.

To further understand the role of the core size on the enhanced conversion efficiency, additional simulations are presented in Fig. 2(b) for a pump wavelength of 1545nm. To compensate for the changing core diameter, the simulations were conducted with fixed pump intensity of 8.6×10^{11}W/m^2, which corresponds to a peak power of 340mW for a diameter of 860nm and signal power of 2mW. We note that for these simulations higher pump powers were chosen such that they allowed for the maximum conversion efficiency to be achieved, even though TPA and TPA-induced FCA are no longer negligible. It is clear that there is an optimum core diameter that satisfies the phase-matching conditions, allowing for large conversion efficiencies of up to ~1dB. Comparing to simulations conducted without the Raman term, the average gain enhancement due to the nonlinear coupling can reach over 20dB.

4. Conclusion

This work has investigated the role of phase-matching on the Raman-enhanced FWM conversion in SCFs when pumped with CW laser sources. Experimental enhancements of up to 15dB have been obtained, with simulations indicating the conversion efficiency could reach up to ~1dB when phase-matching and pump power are optimized.

5. References

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