Stimulated Raman Scattering in a Tapered Submicron Silicon Core Fiber

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Abstract: Raman scattering is observed for the first time in a tapered silicon core fiber. Both spontaneous and stimulated effects are presented, with a gain up to 0.8 dB achieved with a 58.5 mW telecom pump.

1. Introduction

Nonlinear silicon photonics has experienced significant attention over the past two decades as it offers low cost, high speed solutions for optical communication systems [1]. However, there are on-going challenges to producing efficient all-optical systems using silicon materials due to its indirect bandgap and the difficulties in connecting nanoscale planar waveguides to micron-sized fibers and pump lasers. In attempt to address the first issue, Raman scattering has been explored in various planar structures to provide optical gain across the telecoms band [2,3]. Regarding interconnection, recently an alternative platform has emerged in the form of polycrystalline silicon core fibers (SCFs) fabricated from the molten core drawing method, in which it is possible to exploit the excellent nonlinear properties of the crystalline semiconductor material directly within the fiber geometry [4]. These SFCs are typically post-processed using a tapering procedure to achieve submicron core dimensions with low transmission losses required to observe efficient nonlinear processing [4,5]. In this work, we provide the first observation of spontaneous and stimulated Raman scattering in a 13.5 mm long tapered SCF with a submicron core. A peak Raman gain of 0.8 dB is obtained using a 1431 nm pump laser with a continuous wave power of 58.5 mW. We anticipate that with continued efforts to reduce the transmission and coupling losses, these SCFs can provide new possibilities for all-fiber laser sources and amplifiers.

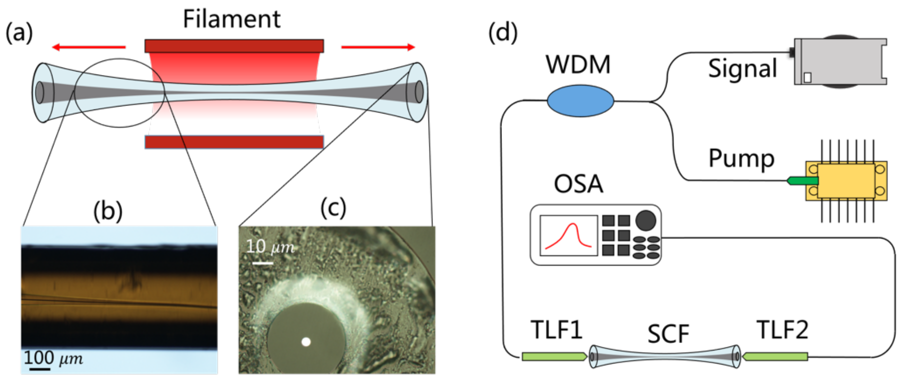

Fig. 1. (a) Schematic of the tapering process to produce low loss SCFs. (b) Image of tapered SCF after packaging with a protective capillary. (c) The input facet of SCF after polishing. (d) Schematic illustration of the experiment setup.

2. Fiber design and experiment results

To enhance the nonlinear performance, we taper the dimensions of the as-drawn SCF to have a core diameter of ~ 900 nm using a two-step process detailed in Ref. [4]. Compared with single step tapering, the filament temperature used in this two-step process is much lower, which allows for the production of a continuous silicon core with large crystalline grains and reduced residual stress over ~1cm lengths. As the SCFs are clad in silica, a conventional glass processor workstation (Vytran GPX-3300) could be used for the tapering. The tapered SCF was inserted into a capillary for strengthening before the end facets were polished for optical coupling, as shown in Fig.1(b) and Fig.1(c). The total length of the tapered SCF was 13.5 mm, which includes a uniform straight waist region of 10 mm and two transition regions, a down-taper transition and up-taper transition, respectively. The transition regions were maintained as larger cores at the taper input and output help to improve the coupling efficiencies. The linear loss of the SCF at 1550 nm was estimated to be around 2.4 dB/cm by subtracting the coupling losses (7 dB) from the total transmission loss (10.2 dB).

Fig. 1(d) shows a schematic of the experimental setup for Raman characterization, where the light is coupled into and out of the SCF using conventional tapered lensed fibers (TLF). To characterize the spontaneous Raman scattering, we start by coupling a 1431 nm diode laser pump source (FITEL FOL1439) into the SCF. The optical power was measured by a power meter (Thorlab S148C) and the spectrum was recorded with an optical spectrum analyzer (YOKOGAWA AQ6370D). Fig. 2(a) shows the recorded spectra of the stokes signals as the pump power is increased. The generated stokes signals are centered at 1546.3 nm, which corresponds to the Raman shift of 15.6 THz for crystalline silicon. Spontaneous Raman scattering can be observed when the pump power is as low as 0.6 mW. Note the bandwidths of the Stokes signals are slightly larger than the theoretical bandwidth of 105 GHz for silicon, which is due to the finite bandwidth of the pump source [2]. The Raman gain coefficient has been evaluated using the methodology provided in Ref. [2] as $g_s = 34\ cm/GW$, which agrees well with the number measured in crystalline silicon waveguides [5]. To investigate stimulated Raman amplification, a signal laser (TUNICS T100S) was injected into the SCF together with the pump by using a WDM. The signal wavelength was scanned from 1542 nm to 1550 nm at a constant power of 0.1 mW. Fig. 2(b) shows the on-off gain curve at a pump power of 58.5 mW. A peak gain of 0.8 dB was obtained. This value is similar to what has been reported in planar silicon waveguides [5], which suggests the material quality of the SCF is close to single crystal.

The experimental results have also been verified numerically by solving the nonlinear Schrödinger equation using the waveguide and material parameters from Ref. [4,5] and the predetermined linear loss. As seen from Fig. 2(c), the calculated Raman spectra agree very well with our experiments. The measured peak gain of 0.8 dB also matches the stimulated gain curve for the 10 mm long SCF shown in Fig. 2(d), which is labeled by a black square. These simulations also indicate that a maximum gain of 2.5 dB could be realized by increasing the SCF length to 20 mm and pumping with 150 mW. However, for higher powers it is clear that the influence of two photon absorption (TPA) and associated free carriers absorption (FCA) present at the telecom wavelengths will limit the achievable gain, though this could be mitigated by moving the pump wavelength beyond the TPA edge (2.2 μm).

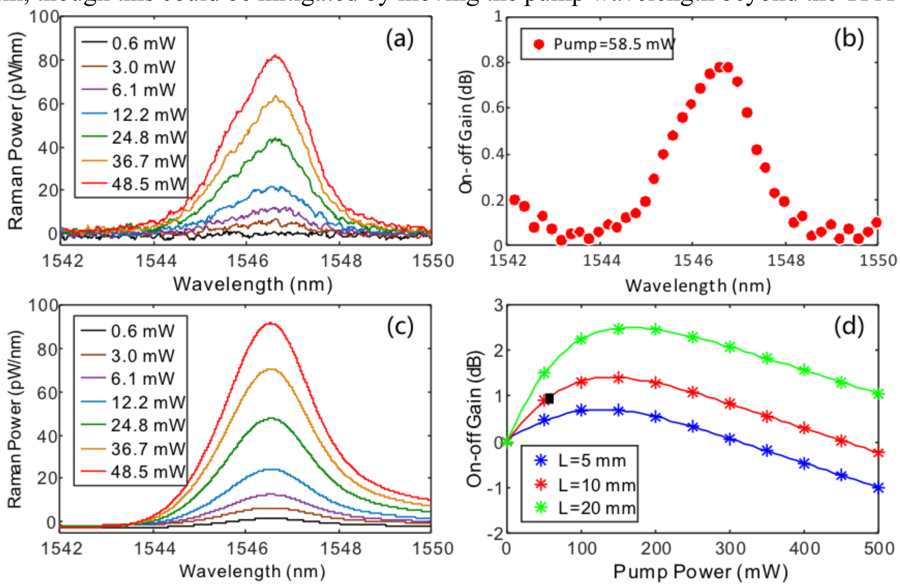

Fig. 2. (a) Experimental spectra of spontaneous Raman gain for a 1431 nm pump. (b) Stimulated Raman gain curve for 1431 nm pump and tunable signal. (c) Simulated spontaneous Raman spectra corresponding to (a). (d) Simulation results of on-off gain for different fiber lengths.

3. Conclusions

In conclusion, this work reports the first measurement of spontaneous and stimulated Raman scattering in a tapered SCF with a submicron core size. A Raman gain coefficient of $g_s = 34\ cm/GW$ has been evaluated and a peak on-off gain 0.8 dB was achieved at a Stokes wavelength of 1546.3 nm. Simulation results have shown that a peak gain of 2.5 dB could be obtained by increasing the SCF length. By exploiting the SCF compatibility with conventional fiber infrastructures, these results could be used to achieve an all-fiber integrated Raman amplifier or laser [7].

4. Reference

[1] W. N. Ye, et al., "Review of silicon photonics: history and recent advances," Journal of Modern Optics, **60**(16), 1299-1320 (2013).
[2] R. Claps, et al., "Observation of Raman emission in silicon waveguides at 1.54 µm," Optics Express, **10**(22), 1305-1313 (2002).
[3] H. Rong, et al., "A continuous-wave Raman silicon laser," Nature, **433**(7027), 725-728 (2005).
[4] F. H. Shuailin, et al., "Tapered polysilicon core fibers for nonlinear photonics," Optics Letters, **41**(7), 1360-1363 (2016)
[5] W. Dong, et al., "Four-Wave Mixing-Based Wavelength Conversion and Parametric Amplification in Submicron Silicon Core Fibers," Journal of Selected Topics in Quantum Electronics, **27**(2), 1-11 (2020).
[6] S. Mahdi, et al., "Raman Scattering and Gain in Silicon-on-Insulator Nanowire waveguides," Journal of Nonlinear Optical Physics & Materials, **21**(2), 1250021 (2012).
[7] H. Ren, et al., "Tapered silicon core fibers with nano-spikes for optical coupling via spliced silica fibers," Optics Express, **25**(20), 24157-24163 (2017).