Supplementary Information:

Mid-infrared Raman Amplification in Silicon Core Fiber

M. HUANG[1], S. SUN[1], T. S. SAINI[1], Q. FU[1], L. XU[1], D. WU[1], H. REN[2], L. SHEN[3], T. W. HAWKINS[4], J. BALLATO[4], AND A. C. PEACOCK[1]

[1]Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom
[2]School of Optoelectronic Engineering and Instrumentation Science, Dalian University of Technology, Dalian, 116024, China
[3]Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, 430074, China
[4]Center for Optical Materials Science and Engineering Technologies and Department of Materials Science and Engineering, Clemson University, Clemson, South Carolina 29634, USA

Contents

I. Propagation loss estimation.

To characterise the propagation loss of the tapered SCF, the insertion loss of the device was measured with the picosecond laser at 1.99 μm, using the lowest power setting to minimise the effect of nonlinear absorption. The measured insertion loss for this SCF was 12.8 dB and the loss contributions are summarized in *Table 1*.

Table 1 Summary of loss contribution in the insertion loss measurement

Contributor	Details	Loss (dB)
OL1	M40 Newport (NA 0.65, lens diameter 5 mm)	2
OL2	M60 Newport (NA 0.85, lens diameter 5 mm)	1.5
Coupled-in loss	OL1 to input facet	3.5
Coupled-out loss	Output facet to OL2	1.5
Facet reflection	Air to silicon or silicon to air	1.5
Fiber propagation	0.2 dB/cm over a length of 6.5 cm	1.3

Here the coupled-in and out loss are estimated through calculating the overlap between the focused beam size of lenses and the profile of fundamental mode in SCF using Mode Solution.

II. Fiber parameters and generalized nonlinear Schrödinger equation (GNLSE).

Table 2 Parameters for spontaneous simulation.

Parameter	Label	Value	Parameter	Label	Value
Core size	D_w	1.6 μm	Input loss	α_{in}	7.5 dB
Linear loss	α_l	0.2 dB/cm	Output loss	α_{out}	4 dB
GVD	β_2	$0.003\ \mathrm{ps^2/m}$	Nonlinear index	n_2	$6 \times 10^{-18}\mathrm{m^2/W}$
TOD	β_4	$-7.23 \times 10^{-7}\mathrm{ps^4/m}$	Linear loss	α	0.2 dB/cm
Effective mode area	A_{eff}	$1.17\ \mathrm{\mu m^2}$	phonon lifetime	τ_1	7.5 ns
TPA coefficient	β_{TPA}	0.3 cm/GW	damping time	τ_2	3.5 ps
Free carrier loss	σ	$1.45 \times 10^{-21}\mathrm{m^2}$	Response function	f_R	0.038
Free carrier dispersion	μ	5.87			

Simulations were conducted by using the generalized nonlinear Schrödinger equation (GNLSE) [1]:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - i\sum_{n=1}^{\infty}\frac{i^n\beta_n}{n!}\frac{\partial^n A}{\partial t^n} - \frac{\sigma}{2}(1+i\mu)N_c A = \mathrm{i}(\gamma(\omega_0) + \mathrm{i}\gamma_1\frac{\partial}{\partial t})(\mathrm{A(z,t)}\int_0^{\infty} R(t')|A(z,t-t')|^2 d\,t').$$

Here A is the pulse amplitude; α is the linear propagation loss; β_n is the *n*th order dispersive term; $\gamma = \omega_0 n_2/cA_{eff} + i\,\beta_{TPA}/2A_{eff}$ is the nonlinearity, n_2 is the nonlinear refractive index, A_{eff} is the effective mode area; $\gamma_1 = (d\gamma/d\omega)_{\omega=\omega_0}$; σ is the free carrier loss , μ is the free carrier dispersion. N_c is the free carrier density which is governed by the following equation:

$$\frac{\partial N_c(t)}{\partial t} = \frac{\beta_{TPA}}{2\hbar\omega_0}\frac{|E(t)|^4}{A_{eff}^2} - \frac{N_c(t)}{\tau}.$$

Here β_{TPA} is the two-photon absorption coefficient and τ is the free-carrier lifetime. The nonlinear response function $R(t)$ is given by:

$$R(t) = (1 - f_R)\delta(t) + f_R h_R(t),$$

where $f_R = g_R\Gamma_R/(n_2 k_0 \Omega_R)$ represents the fractional contribution of the delayed Raman response to the nonlinear polarization in which g_R is the Raman gain, Γ_R/π is the gain bandwidth, $\Omega_R/2\pi$ is the peak gain frequency shift. Raman response function is given by: $h_R(t) = (\tau_1^{-2} + \tau_2^{-2})\tau_1 \exp(-t/\tau_2)\sin(t/\tau_1)$, in which τ_1 and τ_2 is the Raman damping time of Raman vibrations.

III. The influence of fiber dispersion for Raman efficiency.

a. Figure 1 plots the simulated group velocity dispersion (GVD) profiles in the SCFs. For the fiber core size (D = 1.6 μm) we used in experiment, the pump wavelength is very close to the zero-dispersion wavelength (ZDW), where the four-wave mixing (FWM) process could be strong [2]. However, as we can see in Figure 2, the ZDW can be shifted by varying the core diameter.

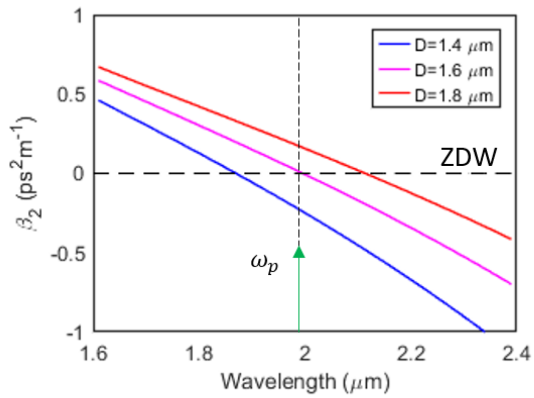

Figure 1 Calculated group velocity dispersion (GVD) for the SCF with different core diameters shown in the legend.

b. By using the parameters from Table 2 and the calculated values of the dispersion, Figure 2 shows the output peak power of Stokes waves as a function of fiber core diameter. The Stokes waves are generated via spontaneous cascaded Raman scattering, assuming the peak power of the pump is 10 W, and the pulse duration is 125 ps, as used in the experiments. The cascaded Raman scattering reaches a minimum for a core diameter of 1.58 μm. This is attributed to the strong competition with the FWM process, which overlaps with the Raman bandwidth [2]. However, when increasing the core diameter to 1.7 μm, even the 5^{th} order Stokes wave (4.1 μm) can achieve maximum output power. Although increasing the core diameter further, allows for the observation of the 6^{th} order Stokes wave (>5.5 μm), the converted powers for all the other waves are significantly reduced. Therefore, 1.7 μm was chosen for long wavelength generation through cascaded Raman processes in the additional simulations.

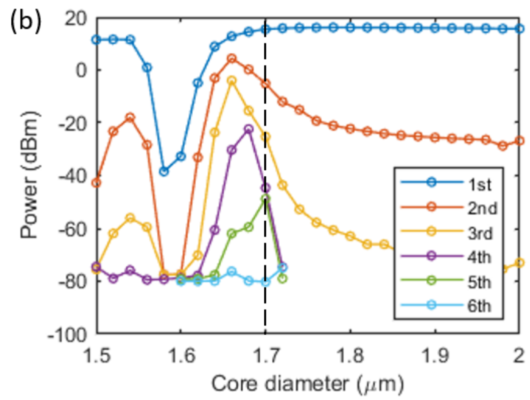

Figure 2 Cascaded Raman scattering output Stokes power as a function of fiber core diameter, for the Stokes order given in the legend.

IV. Raman efficiency simulation as a function of pulse width.

When pumping at 2 μm with a fixed peak power of 10 W, Figure 3 shows the output Stokes peak powers from cascaded Raman scattering as a function of pump pulse width for a 1.7 μm core diameter fiber. As we can see, the high-order Stokes waves (2nd, 3rd, 4th, 5th) achieve a maximum output power when decreasing the pulse width to 40 ps. Therefore, we choose a pulse width of 40 ps (FWHM) width for simulations of cascaded Raman scattering for the 2 μm pump.

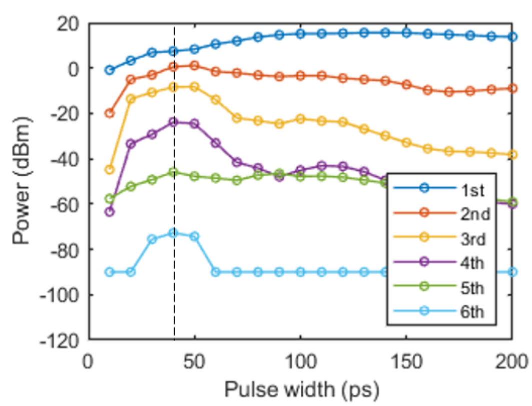

Figure 3 Cascaded Raman scattering output Stokes powers as a function of pulse width, for the Stokes order given in the legend.

Supplementary reference:

1. G. P. Agrawal, "Nonlinear fiber optics," in *Nonlinear Science at the Dawn of the 21st Century* (Springer, 2000), pp. 195-211.
2. Q. Lin, J. Zhang, P. M. Fauchet, and G. P. Agrawal, "Ultrabroadband parametric generation and wavelength conversion in silicon waveguides," Optics Express **14**, 4786-4799 (2006).