Beam cleanup of the stimulated Raman scattering in grade-index multi-mode fiber

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In order to study the beam cleanup effect of the stimulated Raman scattering (SRS) in the graded-index multi-mode fiber (GIMF), a continuous wave all-fiber laser at 1117.8 nm and a pulsed fiber amplifier at 1064 nm are built up as the seed and pump source in the Raman fiber amplifier (RFA). In unseeded SRS process, a pump beam with $M^2_x = 6.7$ and $M^2_y = 6.7$ is transferred into a Stokes beam with $M^2_x = 1.5$ and $M^2_y = 1.7$ in the multi-mode fiber with a 62.5 μm graded-index core (numerical aperture =0.29). In the RFA, a seed light with $M^2_x = 6.7$ and $M^2_y = 7.3$ is amplified to a signal light with $M^2_x = 1.8$ and $M^2_y = 2.0$. The experimental results are explained by the simulation on the mode evolution during SRS procession and Raman amplification in the GIMF. The results show that both the SRS and Raman amplification effect in the GIMF have beam cleanup effect.

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The simplest solution for boosting output power of the rare-earth-doped fiber lasers is to increase the size of the core by replacing single-mode to multi-mode fibers. Unfortunately, multi-mode fibers support numerous transverse modes, and as a result beam quality degrades dramatically[1–3]. However, high power lasers with poor beam quality resulted in excess beam divergence and low irradiance at a potential target. Thus, it is important to enhance the brightness of the high power laser beams.

Recently, new techniques of brightness enhancer based on nonlinear process have been demonstrated, such as stimulated Brillouin scattering[4] and stimulated Raman scattering (SRS)[5,6]. This type of brightness enhancement is also known as "beam cleanup"[7]. A multi-mode pump beam is converted into a diffraction limited output beam at the Stokes wavelength. In 2010, Junhua *et al.*[8] used the 40 m long double-clad fiber with diameters of 40/107/350 μm for core, inner cladding, and outer cladding as the Raman gain fiber to enhance the beam quality M^2 factor of pulse from 3.5 to 1.37. In 2006, Flusche *et al.*[9] achieved the combination and cleanup of four laser beams via SRS using a multi-port fiber combiner and large multi-mode fiber. They were able to take a pump beam with an M^2 of 26.1, and produced a Stokes beam with M^2 of only 2.4 in the multi-mode fiber with 100 μm core diameter. Meanwhile, they produced a beam of $M^2 = 2.6$ from a pump of $M^2 = 42.1$ in the fiber with 200 μm core diameter. It should be noted that these experiments were all unseeded configurations and employed free-space launching construction.

We built a core-pump Raman all-fiber amplifier system to study the beam cleanup effect of the SRS in the graded-index multi-mode fiber (GIMF). The pump source was self-made high peak power pulse with the wavelength of 1064 nm, while the seed source was a self-made continuous wave (CW) of 1117.8 nm fiber laser. Despite the highly multi-mode nature of the pump and seed lights, the Stokes lights are generated in specific modes of the fiber, confirming substantial beam cleanup during the SRS process.

The core-pump Raman fiber amplifier (RFA) structure diagram is shown in Fig. 1. The CW 1117.8 nm signal light and pulse 1064 nm pump light were coupled together by the single-mode wavelength division multiplexing (WDM). In order to verify the beam cleanup effect, it is preferred that the beam quality of the input light is as low as possible. Therefore, we employed a 2 m long double-clad fiber to degrade the beam quality with diameters of 40/140 μm and numerical apertures (NAs) of 0.09/0.46 for core and inner cladding, respectively. The single-clad GIMF was utilized as the Raman gain fiber, which had a length of 1.0 km, a core diameter of 62.5 μm and a core NA of 0.29, which characterizes a near parabolic-index profile in the core. To minimize backreflection, the output facet was angle cleaved to 8°. The output beam of the amplifier was collimated by lens provided by Thorlab Inc. (USA). The pump and signal lights were separated by using a dichroic mirror. The beam quality measurements were carried out by M2-200S beam quality analyzer (Ophir-Spricon Inc., USA).

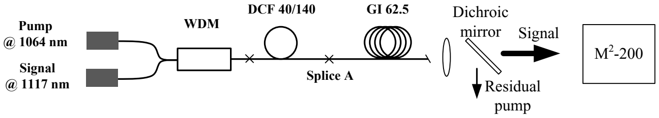


Fig. 1. Experimental setup of Raman fiber amplifier.

The signal source was a self-made fiber laser oscillator, which produces as much as 136.7 mW output power with an optical-to-optical conversion efficiency of 27.4%. The center wavelength was at 1117.8 nm and the full-width at half-maximum (FWHM) was 0.07 nm.

The pulse fiber laser utilized the master oscillator power amplifier configuration. The seed of this amplifier was a pulsed laser diode at 1064 nm, which had a pulse repetition frequency of 50 kHz and a pulse width of 50 ns. The seed pulse was amplified by the single-mode Yb-doped fiber amplifier. The maximum average output power of the pump source was 154.7 mW with the peak power of 2 kW. The center wavelength of the output light was 1064.0 nm with the FWHM of 1.95 nm.

The M^2 value is a general metric to characterize the beam quality of the laser beams. So the M^2 value of the pump and signal lights in the RFA were measured, respectively. While there was only pump light with the average power of 40 mW and no SRS excited in the RFA, the beam quality of the output pump light was measured as $M^2_x = 6.7$ and $M^2_y = 6.7$. Then, when there was only the signal light with the power of 50 mW and no SRS excited in the RFA, the beam quality of the output signal light was measured as $M^2_x = 6.7$ and $M^2_y = 7.3$. The measured results are shown in Fig. 2.

The signal and pump lights were near-diffraction limited because the output fiber of the source was single-mode fiber. However, the beam quality was degraded after propagating through the RFA due to the multi-mode fiber in the RFA.

Keeping the signal off, the power of the pump light improved. When only the pump light was injected with an average power of 154.7 mW, the output light spectrum was as shown in Fig. 3(a). It is shown that the unseeded SRS process occurred in the Raman gain fiber. The first Stokes center wavelength was 1116.0 nm with 3 dB linewidth of 4.34 nm. There were some residual pump light and the second-order Stokes was excited. The residual pump light intensity was 25 dB lesser than the first-order Stokes, and the second-order Stokes spectral intensity was 35 dB lesser than the first-order Stokes. Therefore, these two light components can be ignored. The beam quality of the first-order Stokes light was measured. The results are shown in Fig. 3(b) as $M^2_x = 1.5$ and $M^2_y = 1.7$. A near-diffraction-limited Stokes beam was obtained from a severely aberrated pump beam. It indicated that the SRS in the multi-mode fiber had beam cleanup effect.

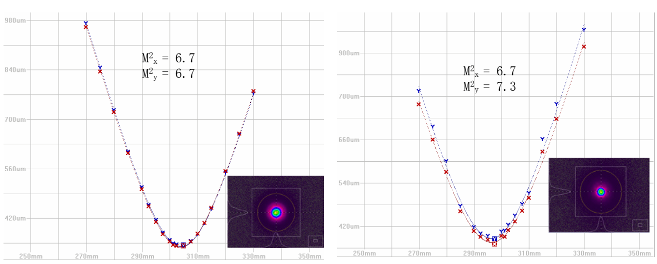


Fig. 2. Beam quality results in the fiber system: (a) signal light and (b) pump light.

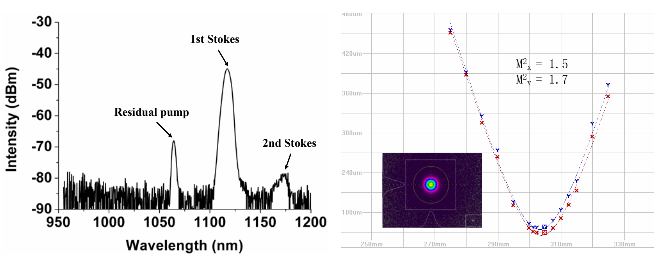


Fig. 3. Output characteristics of the unseeded SRS process: (a) output spectrum and (b) beam quality.

If we maintained the pump light but add 50 mW signal, the output light spectrum was as illustrated in Fig. 4(a). The center wavelength of the amplified signal was 1117.8 nm with 3 dB linewidth of 0.32 nm. In addition, there were also some residual pump light and the second-order Stokes light in the output beam. However, both light components can be ignored as well, because their light intensities were 30 dB lesser than that of the first-order Stokes. The beam quality of the amplified signal light was measured. The results are shown in Fig. 4(b) as $M^2_x = 1.8$ and $M^2_y = 2.0$. It has been significantly improved as compared with aberrated pump and signal lights, showing that the Raman amplification in the multi-mode fiber had beam cleanup effect.

Comparing the two processes, the bandwidth of the Stokes beam is much narrower for the RFA than that in the single-pass SRS experiment. The center wavelength of output light was decided by the signal light in RFA, whereas it was determined by the Raman gain coefficient distribution of the fiber in the single-pass SRS experiment. The contrast between these two spectra is completely analogous to that between the amplifier line spectrum and that of amplified spontaneous emission.

Based on the above experimental results, both SRS and Raman amplification in GIMF have the beam cleanup effect, so we can take advantage of it to enhance the beam quality of the severely aberrated light. Why this phenomenon occurred in the GIMF is attributed to two reasons. On one hand, the lower order modes have better overlap with the multi-mode pump beam, so they can consume most of pump power along

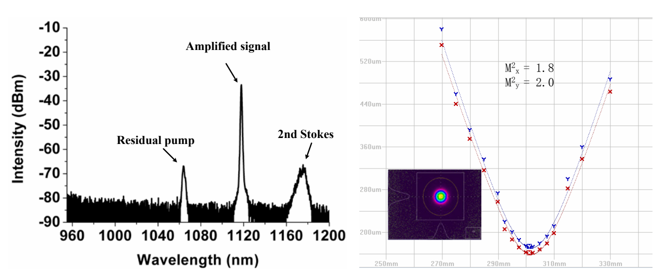


Fig. 4. Output characteristics of the RFA: (a) output spectrum and (b) beam quality.

the fiber. On the other hand, due to the near parabolic GeO_2 doping concentration in the core of the GIMF, there is a higher Raman gain coefficient in the center of the core. As a result, the lower mode distributed in the center of the core extracted higher Raman gain at the first Stokes than the other modes. These reasons can be quantitatively explained by the mode competition during the SRS process as follows:

Assume that the pump pulse has a rectangle pulse shape, the peak power evolution in the RFA can be treated as a CW. The mode evolution in the Raman amplifier can be simulated by using the coupled differential equations which describe the interaction of the pump and Stokes waves during the SRS process[10]. For Raman fiber devices, it is desired that almost all the pump light can convert into the first Stokes whereas the second or higher order Stokes is not excited. However, the higher order stokes are always inevitable in ordinary RFA. Here, only the first and second Stokes lights, together with the pump light are considered. Taking the Raman gain distribution across the transverse section, we can obtain the coupled equations as follows:

$$\frac{dP(z,\lambda_0,l)}{dz} = -a(\lambda_0,l)P(z,\lambda_0,l) - P(z,\lambda_0,l) \frac{\lambda_1}{\lambda_0}\sum_{m=1}^{N_1}\left(P(z,\lambda_1,m)\left(\frac{g_R(\lambda_0,\lambda_1)}{A_{eff}(\lambda_0,\lambda_1)}\right)_{lm}\right), \qquad (1)$$

$$\frac{dP(z,\lambda_1,m)}{dz} = -a(\lambda_1,m)P(z,\lambda_1,m) + P(z,\lambda_1,m) \sum_{l=1}^{N_0}\left(P(z,\lambda_0,l)\left(\frac{g_R(\lambda_0,\lambda_1)}{A_{eff}(\lambda_0,\lambda_1)}\right)_{lm}\right) - P(z,\lambda_1,m)\frac{\lambda_2}{\lambda_1}\sum_{n=1}^{N_2}\left(P(z,\lambda_2,n)\left(\frac{g_R(\lambda_1,\lambda_2)}{A_{eff}(\lambda_1,\lambda_2)}\right)_{mn}\right), \qquad (2)$$

$$\frac{dP(z,\lambda_2,n)}{dz} = -a(\lambda_2,n)P(z,\lambda_2,n) + P(z,\lambda_2,n) \sum_{m=1}^{N_1}\left(P(z,\lambda_1,m)\left(\frac{g_R(\lambda_1,\lambda_2)}{A_{eff}(\lambda_1,\lambda_2)}\right)_{mn}\right), \qquad (3)$$

where the variable $P(z, \lambda_i, l)$ represents the power of the mode l with the wavelength λ_i at the distance z. The subscript index i stands for the pump ($i = 0$), first Stokes ($i = 1$), and second Stokes ($i = 2$). The Raman gain coefficient $g_R(\lambda_i, \lambda_j)$, corresponding to the pump wavelength λ_i, signal wavelength λ_j, is determined by the material distribution and composition inside the transverse section. The variable $\alpha(\lambda_i, l)$ is referred to as the background loss at wavelength λ_i with mode l. The background loss is supposed not to vary along the fiber. Finally, N_j is the number of modes that can be supported at the wavelength λ_j inside the fiber. The effective Raman gain coefficient, that is, the ratio of Raman gain coefficient $g_R(\lambda_i, \lambda_j)$ to the effective area $A_{eff}(\lambda_i, \lambda_j)$, is found for each pump and signal mode pairs as shown by[11]

$$\frac{g_R}{A_{eff}} = \frac{\iint g_R I_p I_s dS}{\iint I_p dS \iint I_s dS} = \frac{\iint g_R(x,y)\left|F_p(x,y)\right|^2 \left|F_s(x,y)\right|^2 dS}{\iint \left|F_p(x,y)\right|^2 dS \iint \left|F_s(x,y)\right|^2 dS}, \qquad (4)$$

where the variable $F_i(x, y)$ is the transverse mode field distribution with subscripts $i = p$, and s denoting the pump and Stokes beams.

The grade-index fiber used in the experiment actually contains about 800 modes. The connections between fibers were all carried out by a low-loss core alignment fusion technology. So the center axes of two circularly symmetric fibers coincide. Because of the symmetry of the system, only modes that have the same azimuthal symmetry will be excited at the splice[12]. In this simulation, there are supposed to be five transverse modes for both the signal light and pump light excited in the GIMF used in the experiment: LP_{01}, LP_{02}, LP_{03}, LP_{04}, and LP_{05}.

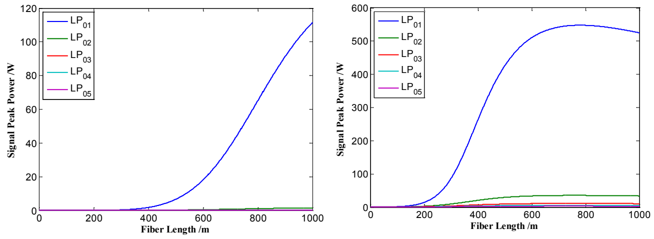
The transverse modes distribution in the GIMF can be obtained by mode theory[13]. Meanwhile, the beam quality (in terms of M^2) of the individual transverse mode of GIMF can be obtained in accordance with the mode distribution[13,14], which is shown in Table 1.

The beam quality of a beam containing multiple fiber modes can be determined by considering the electric field of the beam to be a simple superposition of modes[14]. In the simulation, the pump peak power was 2000 W with a flat pulse profile, whereas the CW seed power was 50 mw in the RFA. Assuming the five proportional modes of the pump light were equally excited at the launching end, the beam quality factor of the pump light was calculated as $M^2 = 6.5$.

The models of unseeded SRS process and Raman amplification were carried out. In the unseeded SRS process, the amplitude of each Stokes mode was taken to be equally as 10^{-3} mW due to approximate seeding via spontaneous Raman scattering[13]. In the seeded RFA, according to the experiment, the 50 mW signal light was equally distributed in the five modes like the pump light. According to the mode evolution simulation in the RFA, the power distributed over the various modes of Stokes along the fiber longitudinal direction in the Raman gain fiber was as shown in Fig. 5. The mode evolution of Stokes in the unseeded SRS process was as shown in Fig. 5(a), while the mode evolution of

Table 1. Beam Quality of the Transverse Modes of the GIMF

Mode	LP_{01}	LP_{02}	LP_{03}	LP_{04}	LP_{05}
M^2	1.0	3.0	5.0	7.0	10.0



(a) (b)

Fig. 5. Mode evolution of Stokes in: (a) unseeded SRS process and (b) Raman amplifier.

signal in the seeded Raman amplifier was as shown in Fig. 5(b).

From the results, the LP_{01} mode dominated in the output light in the above two cases. The M^2 factor of the output Stoke light after unseeded SRS process was calculated as 1.1. The amplified signal in the RFA had an M^2 of 1.6. The results showed that the beam quality of the output light improved significantly than that of the input light, which agreed well with the results of the experiments.

In conclusion, we present experimental results that show significant beam cleanup properties of both the SRS and Raman amplification effect in the GIMF. The phenomenon is explained by the simulation of the mode competition during the SRS process in the RFA. We suggest a feasible method to improve the brightness of the aberrated pulses light through SRS in the multi-mode fiber.

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