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Patrick Roumayah, Joshua Bradford, Justin Cook, Jose Enrique Antonio-Lopez, Rodrigo Amezcua Correa, Martin Richardson, "High average power pulsed multi-mode Raman fiber laser in graded index fiber," Proc. SPIE 10512, Fiber Lasers XV: Technology and Systems, 105121X (26 February 2018); doi: 10.1117/12.2289308

SPIE.

Event: SPIE LASE, 2018, San Francisco, California, United States

# High average power pulsed multi-mode Raman fiber laser in graded index fiber

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## ABSTRACT

Raman fiber lasers have seen increased interest recently, due to their ability to access difficult wavelength ranges without the use of specially doped materials and to avoid some of the obstacles of very high power rare-earth doped fiber lasers, including modal instability and photodarkening. Though most modern works in Raman fiber lasers are based on fiber laser or direct diode pumping, solid state lasers have been developed with extremely high average powers and are readily available commercially.

This work explores a very short fiber length high average power multi-mode Raman laser system. The custom 200um graded index fiber is pumped by 30ns pulses with average powers up to 750W and pulse energies up to 7.5mJ at 1030nm, by a solid state commercial laser system. Pump-only and seeded configurations are examined. In the seeded case, higher order mode activation is demonstrated by detuning the single mode seed to preferentially feed energy to the less confined modes.

5 orders of Stokes are demonstrated, ranging from 1078nm to 1350 nm. Beam enhancement is observed by qualitative measurement of minimum beam waist, and average powers up to 70W are achieved at an energy of 1.4mJ.

**Keywords: Raman Laser, Fiber Laser, Stokes Generation, Raman Fiber Laser, Graded Index Fiber**

## 1. MOTIVATION

Raman fiber lasers are gaining interest in recent years as a potential alternative to rare-earth doped lasers, as they allow for laser generation at a wide variety of wavelengths. The Raman output is not limited to electronic transition wavelengths based on a dopant, but rather is dependent on a specific shift from the pump wavelength based on the host material. In silica glass, this shift is 13.2 THz, so near 1μm, the wavelength shift is ~50nm. As such, the quantum defect is quite low. For a single Stokes shift in a silica glass Raman laser, it is on the order of 5% for 1μm and decreases for shorter wavelengths. Since the gain per unit length and the quantum defect are both quite low, the cooling requirements can be reduced compared to a similar power rare-earth fiber laser. In addition, germanium doped fibers are not subject to photodarkening. This increases the long term usability of the gain medium, avoids inefficiency due to photodarkening absorption, and may increase the threshold for modal instability, a primary obstacle in high power scaling for fiber lasers [1, 2]. Pump wavelength is completely flexible and the output gain is broad, on the order tens of nanometers in amorphous silica, so the potential output wavelength is limited only by the transparency of the fiber.

It is well established that core pumped Raman lasers in graded index fibers (GIF) demonstrate brightness enhancement[3-7]. The higher germanium content of the center of the waveguide exhibits higher nonlinear refractive index (and higher

Fiber Lasers XV: Technology and Systems, edited by Ingmar Hartl, Adrian L. Carter, Proc. of SPIE Vol. 10512, 105121X · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2289308

Raman gain) so the more highly confined modes are preferentially converted[5]. This causes the Raman output to demonstrate better beam quality than the residual pump, making it a desirable fiber geometry for a Raman fiber laser.

# 2. EXPERIMENTAL SETUP

## 2.1 Configuration

The experimental setup is shown in figure 1. The pump laser is coupled into the 200um graded index fiber through a shared coupling lens alongside the seed, after a beam combining optic. The Raman conversion takes place in the GIF, and the output is sent to a 1kW power meter while being observed by an optical spectrum analyzer.

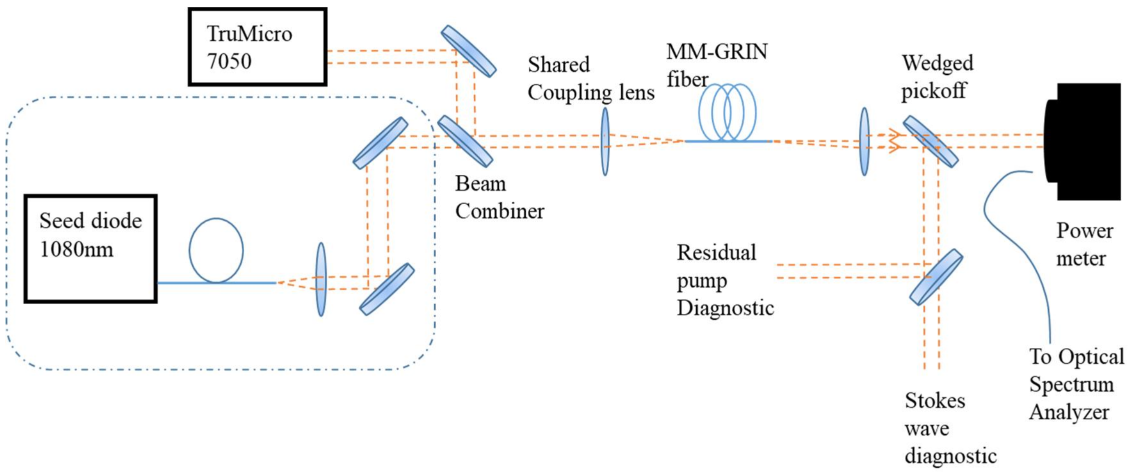


Figure 1. Experimental setup.

## 2.2 Graded index fiber

The graded index fiber used in this report is a custom design manufactured in house at the University of Central Florida by the Microstructured Fibers and Devices group. A microscope image is shown in Fig. 2 and a refractive index profile is shown in Fig. 3. The large area core and high refractive index contrast of .03 are necessary to guide the relatively low beam quality generated by the pump laser used in this experiment. 35 m and 12 m fiber lengths were used in this project.

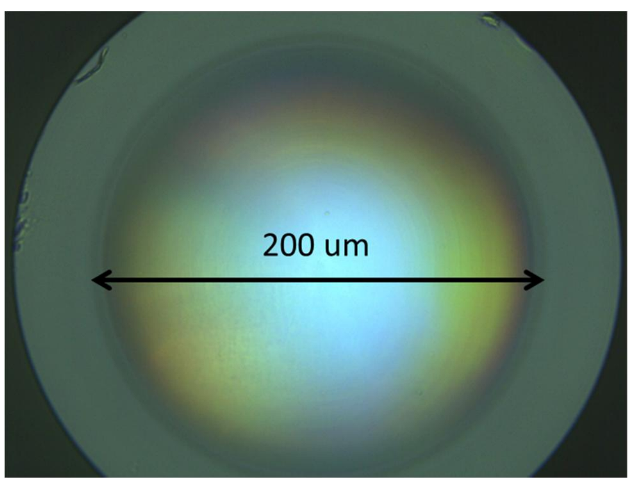


Figure 2. Microscope image of GIF

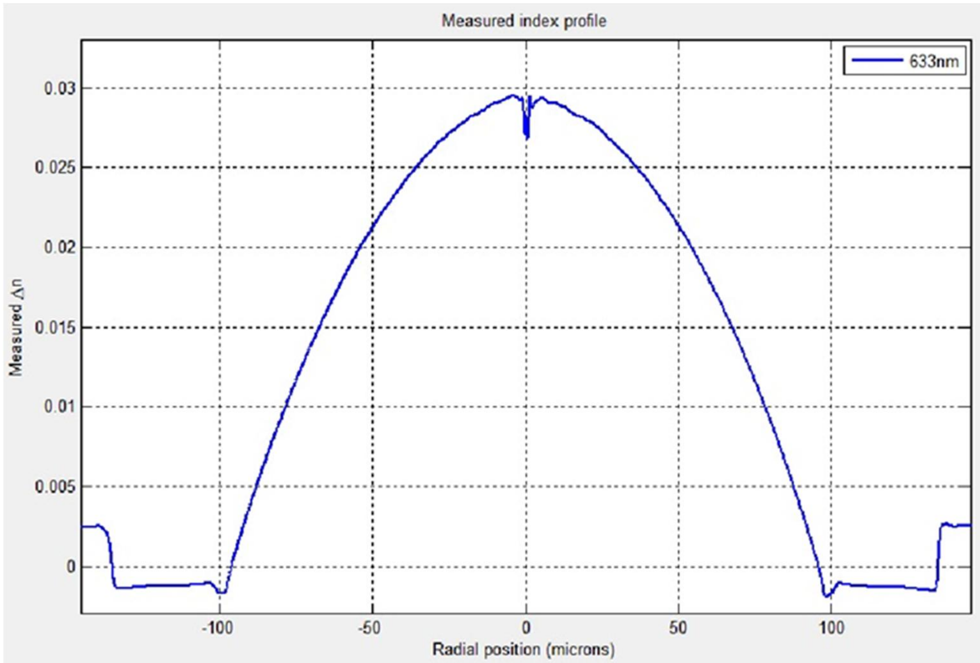


Figure 3. Refractive index profile of GIF.

## 2.3 Pump laser

The Raman laser in these studies is pumped by a commercial off-the-shelf Trumpf TruMicro 7050 pulsed thin disc laser, which is based on the principle of cavity dumping. The beam quality is 22 mm*mrad, but is found to deteriorate slightly with higher average power. The pulse duration is 30ns, with a tunable repetition rate from 5 kHz to 100 kHz and a maximum average power of 750W and pulse energy of 75 mJ. In this configuration, the apparent damage threshold of the GIF is 20mJ, but powers up to 7.5mJ were explored as that is sufficient to investigate the full range of average powers generated by the pump laser. Figure 4 shows what energies are achievable at frequencies 5, 10, 15, 50, and 100 kHz.

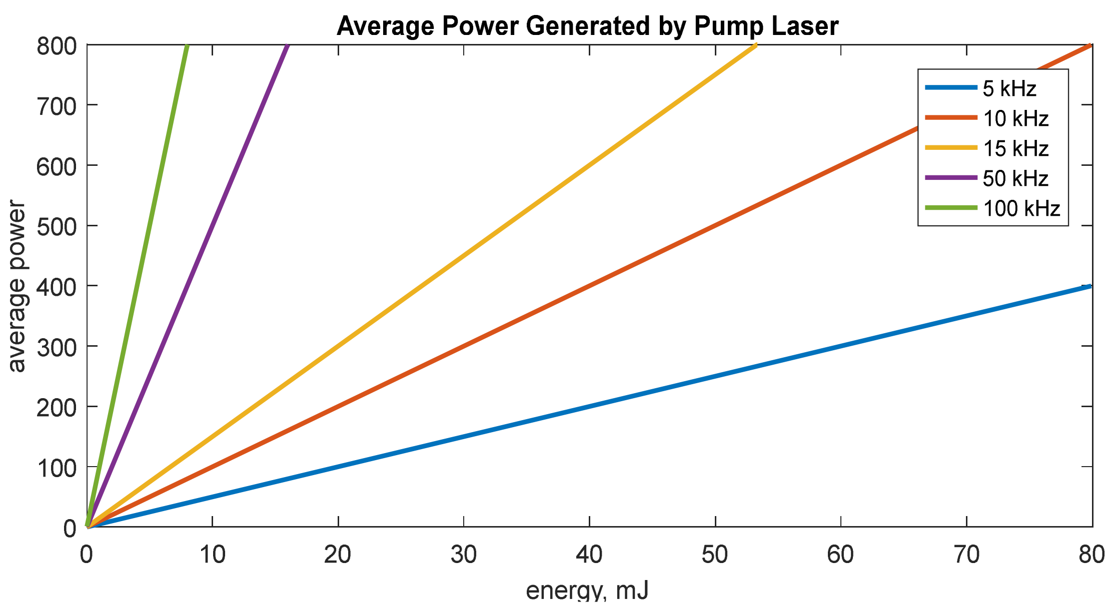


Figure 4. Average power vs energy at several frequencies of operation.

## 2.4 Theory

Raman gain is based on the Raman Effect, a nonlinear wavelength shift toward lower frequency by accessing the vibrational modes of the atoms or molecules in a medium. This effect can be stimulated in a similar fashion to the stimulated emission of an electron transition laser. In silica, the gain bandwidth is broad and follows the curve in Fig. 5, with the peak on the order of $5*10^{-14}$ m/W.

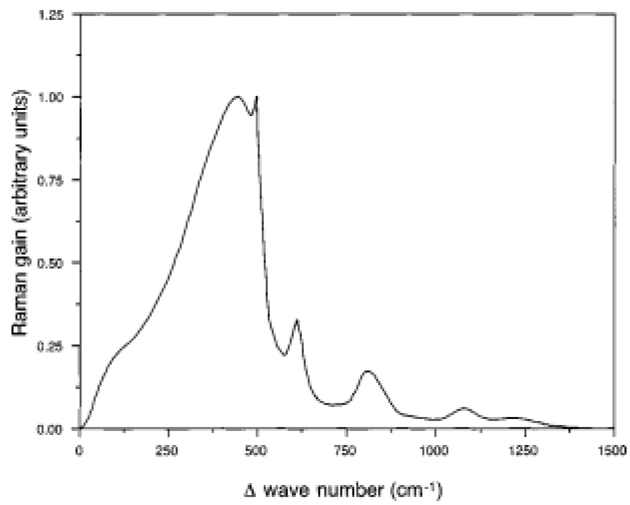


Figure 5. Gain spectrum of Raman Effect in silica fiber [8].

The intensity in the first Stokes follows equation 1:

$$\frac{\partial I_s}{\partial z} = g_r I_s I_p \quad (1)$$

Where $I_S$ is the intensity in the first Stokes, $I_P$ is the intensity in the pump, $g_r$ is the Raman gain, and Z is the propagation distance in meters. In each of the subsequent orders, the previous Stokes order acts as the pump for the next.

This equation leads to one of the important design considerations of Raman fiber lasers: the length of the gain medium has to be optimized to a specific power level. A simulation is shown in Fig. 6 that demonstrates the Raman conversion in a single mode of the multi-mode fiber. The conversion to first Stokes happens over a short length (on the order of 1 m) and may convert to higher order Stokes if the fiber length allows it. In this simulation, a small seed (230mW) at 1st Stokes (labeled R1 in Fig. 6) is propagated alongside the pump. Increasing or decreasing the seed intensity will advance or delay the conversion, and can be used to compensate for fiber length and pump intensity.

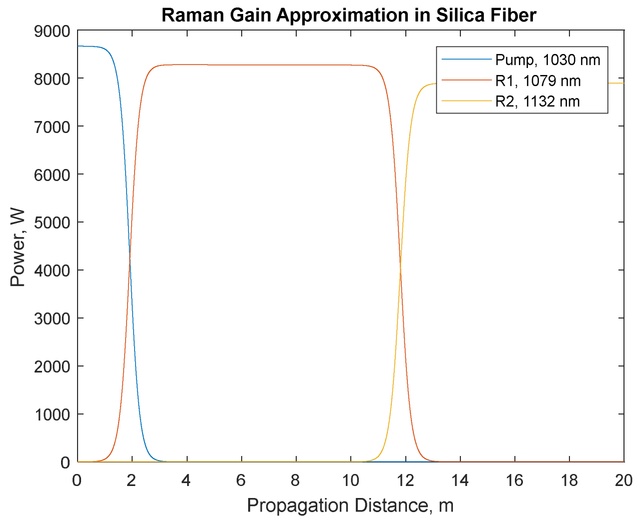


Figure 6. Raman gain approximation of a single mode in 200µm GIF.

In multi-mode fiber, the intensity $I_S$ and $I_p$ may be higher in the more highly confined, lower order modes, depending on coupling. In addition, the higher germanium content of the center of the core has a higher $g_r$. These effects together preferentially transfer energy into the lower order transverse modes of the Stokes signal.

## 3. PUMP-ONLY RESULTS

Figure 7 shows the output spectrum ranging up to 7.5 mJ at 100 kHz. The gain of each Stokes signal is proportional to intensity, so even in the relatively short Raman fiber used in this experiment 5 orders of Stokes shifts are readily apparent. The full power of the pump is utilized, and the fiber was found to be able to handle the 750W of average power only for short periods, as the polymer was undergoing thermal degradation. The cumulative quantum defect of 5 shifts is on the order of 25%, and 213 W of Stokes power is measured between 1050nm and 1400nm. It is found that some of the lower order modes are converted to second Stokes before higher order modes are converted to first Stokes, limiting efficiency to first Stokes to around 8%.

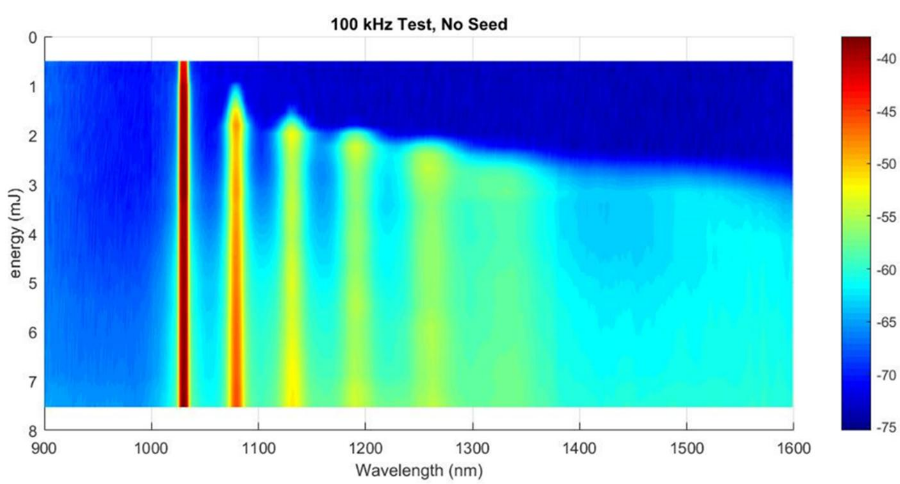


Figure 7. Output spectrum evolution up to 7.5 mJ in the pump-only configuration, 100kHz.

A small power pickoff of the beam is analyzed with a diffraction grating, and the unaltered (transverse) extent of the beam was measured to determine the minimum beam waist after a 40mm optic, in order to get a qualitative idea of beam quality enhancement. Figure 8 shows the pump and Stokes minimum beam waist and how it varies with energy. The beam-waist reduction to first Stokes is consistently around 2.

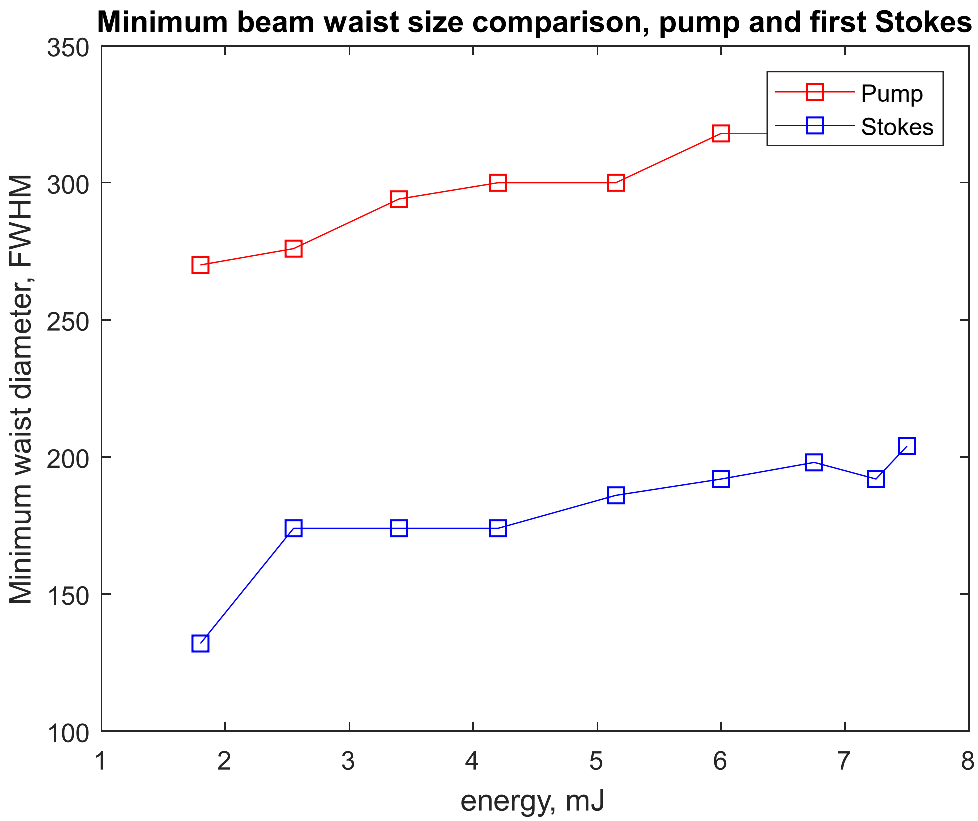


Figure 8. Minimum beam waist for Stokes and Pump output

## 4. SEEDED RESULTS

### 4.1 Lowest order Mode Excitation

In order to improve power efficiency, a low power (230mW CW) seed was constructed and propagated with the pump. Though the seed is 9-10 orders of magnitude lower than the peak power of the pump, there is a significant change in the output characteristics of the laser system. Figure 9 shows the spectral evolution in the seeded and pump-only case. The first Stokes is generated even before 1 mJ of pump, and efficiency to first Stokes peaks at 15%. This work is done at 15 kHz.

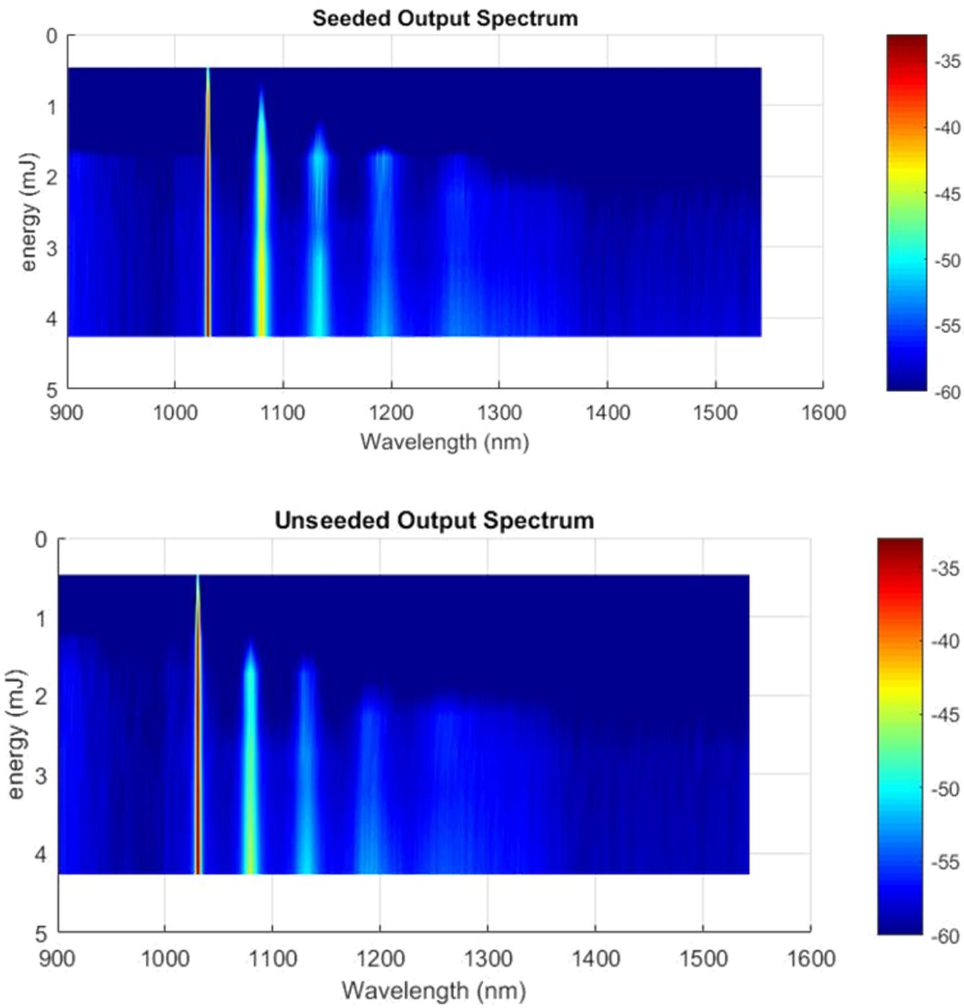


Figure 9. Seeded and Unseeded output spectral evolution.

After this experiment the fiber was reduced to 12m to optimize first Stokes output at higher energy, and the seed was shifted from fundamental coupling to access some of the higher order transverse modes.

### 4.2 Multi-Mode Excitation

As each propagating mode is more or less independent in their conversion to the Stokes wavelengths, some of the less confined modes are converted too late. To mitigate this, the single mode seed is decoupled from the fundamental mode of the graded index and optimized for maximum first Stokes output. By feeding energy to the higher order modes, first Stokes can be generated concurrently across the many modes. Figure 10 shows the best result demonstrated so far: 36% efficiency to first Stokes in a 12m fiber at 4.3 mJ.

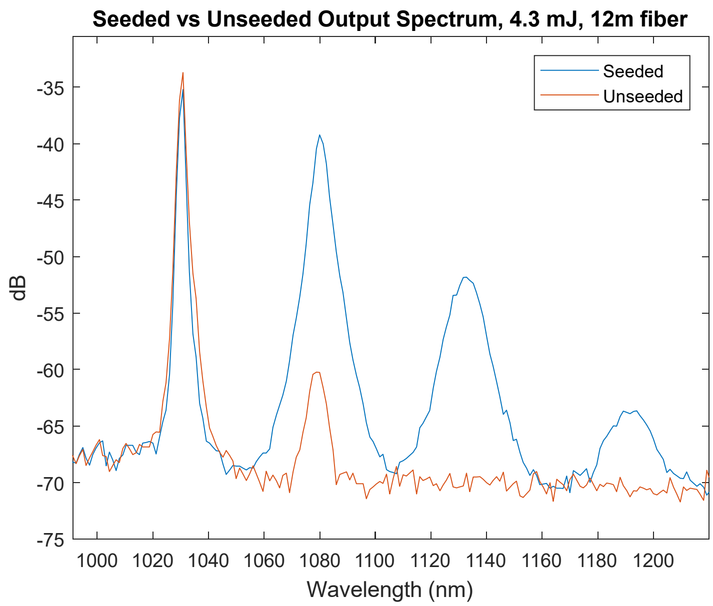


Figure 10. Seeded vs Unseeded Spectrum, 50kHz 4.3mJ, detuned seed

With the detuned seed there is a marked improvement in efficiency and total power to first Stokes. At 4.3 mJ and 50 kHz the maximum power in first Stokes was 70W, corresponding to a conversion efficiency from launched pump of 36%, and an output energy of 1.4mJ.

In order to confirm that the mechanism granting this improved efficiency is higher order transverse mode conversion, the beam waist of the Stokes signal seeded and pump-only is examined in figure 11. It is shown that the seeded case sacrifices some beam quality. The beam waist is larger by approximately 50%, which still demonstrates a reduction from the Pump beam waist of about 40%.

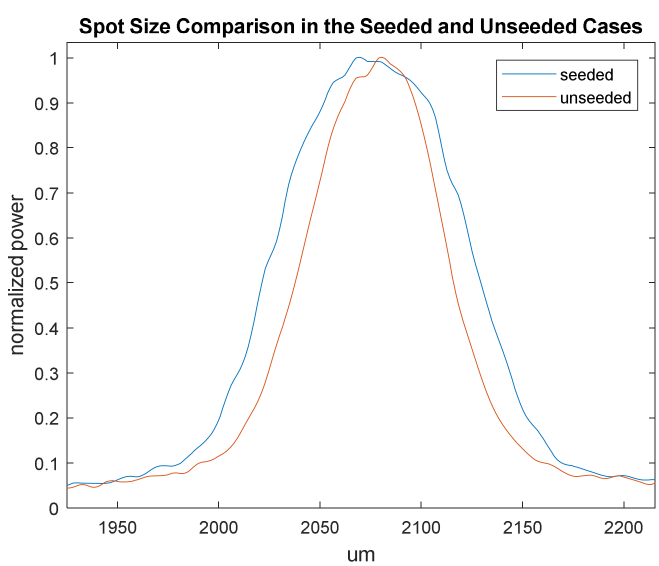


Figure 11. Size comparison of the minimum beam waist diameter in the seeded and pump-only case at 50kHz, 4.3mJ, detuned seed.

## 5. CONCLUSIONS

In this experiment, a high energy and high average power fiber Raman laser was developed. We demonstrated generation of Stokes lines with high peak power and average power over a range of 350nm. A seed on the order of $10^{-10}$ of the power of the pump was demonstrated to have dramatic effects on the efficiency of a multi-mode Raman amplifier. Beam quality improvement compared to the pump was demonstrated qualitatively. Differential mode activation was observed by detuning of a small seed laser, effectively allowing an increase in efficiency at the cost of beam quality. So far, 70W average power first Stokes was produced, with >200W expected.

## 6. ACKNOWLEDGEMENTS

The authors acknowledge funding support from Air Force Office of Scientific Research (Contract FA9550-15-1-0041), the High Energy Laser – Joint Technology Office, (Contract FA9451-15-D-0013 0001), the US Army REDCOM (Contract W911NF1210450), the Army Research Office, (Contract W911NF-11-1-0297), the US Army (Contract W911NF0710159), and the State of Florida.

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