Power scaling of Raman fiber lasers

Yan Feng*, Lei Zhang, and Huawei Jiang
Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences,
and Shanghai Key Laboratory of Solid-state Laser and Application, Shanghai 201800, China
*feng@siom.ac.cn, http://laser.im/english

ABSTRACT

Raman fiber laser is an efficient way to expand the spectral coverage of fiber lasers. In recent years, output power of Raman fiber laser has been scaled quickly. There is a great potential in further power scaling, technical innovations, and scientific applications. An integrated ytterbium-Raman fiber amplifier architecture was proposed, which allows power scaling of Raman fiber laser to over kilowatt and more. Hundred watt level single frequency Raman fiber amplifier was achieved, which allows the generation of high power sodium guide star laser. New scheme of cladding pumped Raman fiber laser is studied in order to improve the brightness enhancement. Furthermore, possible application in spectral beam combing is discussed.

Keywords: Raman fiber laser, Raman fiber amplifier, power scaling, brightness enhancement, beam combination

1. INTRODUCTION

Fiber lasers have drawn extensive attention due to robustness, high efficiency and high power scaling capacity. Yb-doped fiber laser at 1 μm has reached 20 kW in nearly diffraction-limited beam quality. However, the emission bands of rare earth doped fiber lasers with over 100 W output are narrow and isolated at 1, 1.5 and 2 μm, which limits the field of application. For example, there are plenty of demands in scientific research on lasers at special wavelengths which cannot be covered by rare earth doped fiber lasers.

Various nonlinear frequency conversion technologies can be applied to extend the spectral range of fiber lasers. Among them, Raman fiber laser is particularly interesting, because the frequency conversion is achieved inside the fiber, which allows the laser system in a robust all-fiber configuration.

In recent years, Raman fiber lasers scale up sharply due to the development of Yb-doped fiber laser. First 100 W-level Raman fiber laser was reported in 2009, where a core-pumped spectrally asymmetric Raman fiber oscillator was designed to overcome the linewidth broadening effect and an efficiency of 85 % is achieved[1]. Codemard et al. demonstrated a 100 W continuous wave (CW) Raman fiber laser operating at 1120 nm, cladding-pumped with an YDF laser[2]. Supradeepa et al reported a 300 W high-efficiency cascaded Raman fiber laser at 1.5 μm with a novel amplifier architecture, core-pumped by a high power YDF laser[3]. In their experiments, the wavelength division multiplexer (WDM) used to combine the Raman pump and seed lasers needs to handle hundreds to thousands watts laser power. For even higher power, this component could be the bottle neck.

In 2014, we proposed an integrated ytterbium-Raman fiber amplifier architecture and demonstrated a 300 W single-mode linearly-polarized fiber laser at 1120 nm[4]. Later, with the proposed architecture, further power scaling to kilowatt level is reported[5,6]. Raman fiber amplifier has been applied to the development of sodium guide star laser, and achieved over 50 W CW 589 nm laser by frequency doubling of a single frequency Raman fiber amplifier at 1178 nm[7].

Figure 1 summarizes the development of Raman fiber laser in the past decade. One can see that the power of Raman fiber laser or amplifier increases exponentially.

In this talk, we will review the recent developments on power scaling of Raman fiber lasers. Some of our works will be presented in detail, including the integrated Yb-Raman fiber amplifier architecture, the first kilowatt Raman fiber amplifier, the application in sodium guide star laser development, and new scheme of cladding pumped Raman fiber laser. Perspective in further power scaling and possible application in beam combination will be discussed.

Fiber Lasers XII: Technology, Systems, and Applications, edited by L. Brandon Shaw, John Ballato,
Proc. of SPIE Vol. 9344, 93440U · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2086852

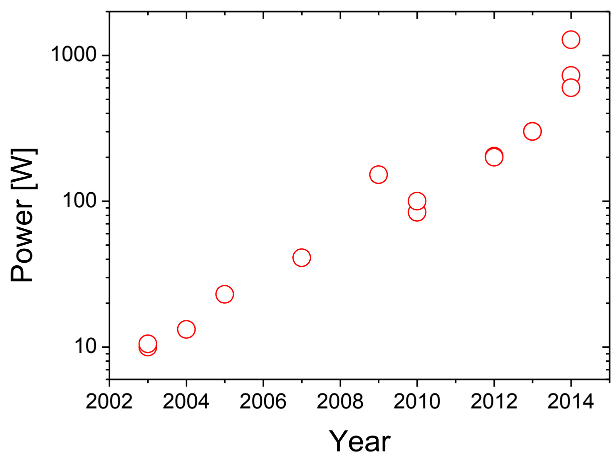

Figure 1. Power evolution of Raman fiber laser and amplifier in the past decade. An exponential increase is seen.

2. INTEGRATED YB-RAMAN FIBER AMPLIFIER

Integrated ytterbium-Raman fiber amplifier architecture was proposed for power scaling of Raman fiber laser[4]. Standard high power Yb-doped fiber amplifiers are seeded with multiple lasers, whose wavelength separations are close to the Raman shift. The seed laser with the shortest wavelength is at the middle of the Yb gain spectrum, which gets amplified efficiently. The laser power is then transferred to the longer wavelengths successively in the following optical fiber by stimulated Raman scattering. The most important improvement in the architecture is the elimination of the wavelength division multiplexer that has been used in almost all high power core-pumped Raman fiber laser. Here the Raman seed lasers and pump laser are propagated and amplified in the core of the same fiber.

In a proof of principle experiment, a 1070 and 1120 nm dual wavelength laser is injected into an polarization maintaining single mode Yb fiber amplifier and a piece of passive fiber is spliced after the amplifier[4]. A 300 W linearly-polarized Raman fiber laser at 1120 nm is demonstrated with gain fiber of 125 µm cladding diameter and 10 µm core diameter, as shown in Figure 2. Shortly after that, using gain fibers of 400 µm cladding and 10 µm core, up to 580 W single-mode linearly-polarized Raman fiber laser at 1120 nm is achieved. Furthermore, a 1.3 kW near-single-mode Raman fiber laser is generated with gain fiber of 400 µm cladding and 20 µm core, as shown in Figure 3, which is the first report of Raman fiber laser with over kilowatt output[6].

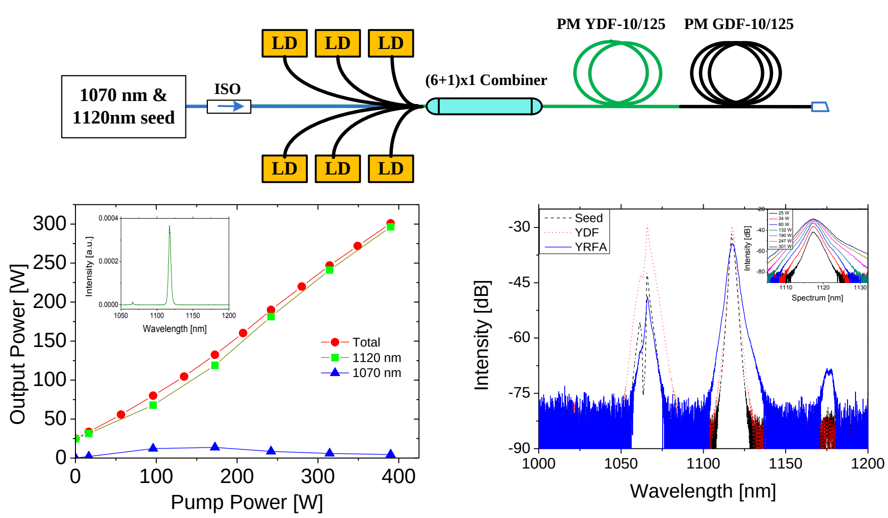

Figure 2. Integrated Yb-Raman fiber amplifier with single-mode polarization maintaining fibers, which generates up to 300 W single-mode linearly polarized fiber laser at 1120 nm[4].

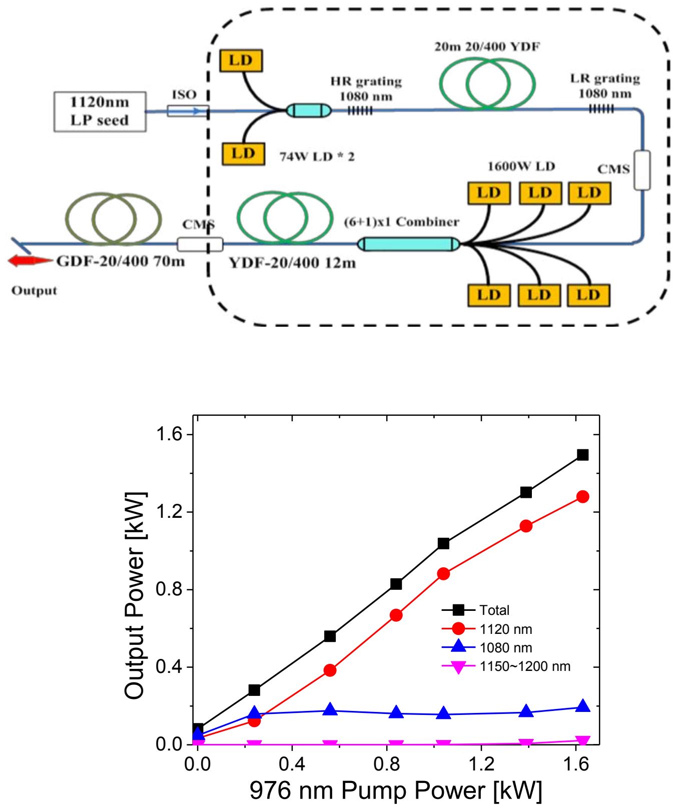

Figure 3. A kilowatt level nearly single mode integrated Yb-Raman fiber amplifier[6].

Since all current high power ytterbium fiber lasers have a master oscillator power amplifier scheme, the proposed architecture can be applied conveniently, and further scales the Raman fiber laser output and extend spectral coverage.

3. APPLICATION IN SODIUM GUIDE STAR LASER

Our works on high power Raman fiber laser are initially motivated by development of sodium guide star laser. Around the world, large aperture telescopes are built to observe our universe more sharply. However, due to atmosphere turbulence, wavefront of the star light is disturbed and the image of stars is blurred. Astronomers use a technology called laser guide star adaptive optics to solve this problem. To do this, they need an artificial star above the atmosphere as a reference. The artificial star can be generated by shining a narrow linewidth laser at 589 nm on the sky to excite a layer of sodium atoms at about 90 km high. We work on a Raman fiber laser based method to generate sodium guide star laser. A 1178 nm laser is produced in optical fiber by stimulated Raman scattering, and then frequency doubled to 589 nm.

To generate the required narrow linewidth high power 1178 nm laser, a master oscillator power amplifier architecture is used. The master oscillator is a DFB diode laser at 1178 nm. The power amplifier is Raman fiber amplifier pumped by a 1120 nm fiber laser, which is with the integrated Yb-Raman fiber amplifier architecture as discussed in previous section. In narrow linewidth fiber amplifiers, the main technical challenge for power scaling is the stimulated Brillouin scattering effect, which generates a down-shifted backward propagating light and limits the amplifier output. SBS is suppressed by applying longitudinally varied strain along the gain fiber. The strain introduces proportional shift of SBS gain spectrum. By this way, SBS light from different portion of the gain fiber is spectrally isolated and could not get amplified efficiently in other portions of the fiber.

The laser can work in both pulsed and continuous-wave format. In the pulsed case, the 1178 nm Raman fiber amplifier produces square-shaped pulses with tunable repetition rate (500 Hz to 10 kHz) and duration (1 ms to 30 μs), while the peak power remain constant with a record peak power of 120 W. The 589 nm laser generated by frequency doubling in a resonant cavity has a peak power as high as 84 W. In the continuous-wave case, the same laser setup generates up to 57 W 589 nm output, which is the highest output ever reported for fiber based yellow laser[7].

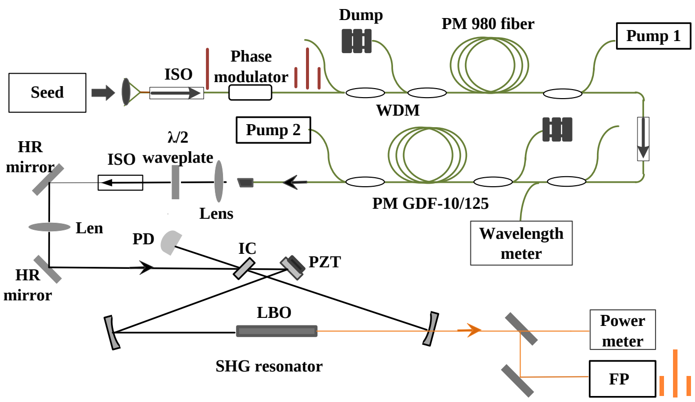

Figure 4. Schematic diagram of the Raman fiber amplifier based sodium guide star laser system, including the seed laser, RFAs, and doubling cavity[7].

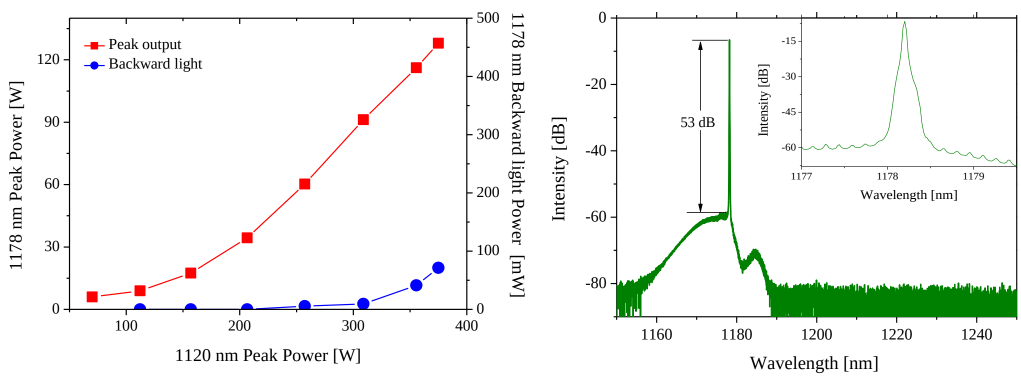

Figure 5. Peak power of single frequency 1178 nm Raman fiber amplifier and backward light as functions of the 1120 nm pump peak power. And the spectrum of the 1178 nm Raman fiber amplifier at full output power[7].

Studies show that re-pumping the sodium atoms at D2b line, which is about 1.71 GHz toward the blue with respect to the D2a line, can increase the return flux from the sodium layer. The 1.71 GHz re-pumping frequency component is generated by modulating the seed laser at 1.71 GHz and designing the doubling cavity with a free spectral range of 1.71 GHz in the laser. The power ratio and exact frequency shift can be easily tuned.

The flexibility of the laser system in both temporal and spectral format offers much design options for laser guide star adaptive optics Further power scaling to 100 W level is feasible with a higher power 1120 nm pump fiber laser, optimized 1178 nm narrow band Raman fiber amplifier, and careful thermal management. The primary challenge is still the mitigation of SBS.

4. CASCADED-CLADDING-PUMPED CASCADED RAMAN FIBER AMPLIFIER

Cladding pumped Raman fiber laser was proposed by Nilsson et al. in 2002[8]. Different from core pumped Raman fiber laser, the cladding pumped Raman fiber laser emits light with higher brightness than the pump laser. However, if the cladding-to-core area ratio is too large, the intensity generated in the core can greatly exceed that in the cladding long before the pump laser is depleted. It leads to the generation of parasitic second-order Stokes light in the core, limiting the conversion from pump light to first Stokes light. To increase the conversion efficiency, the area ratio between the inner cladding and core has to be less than ~ 8, which then limit the actual enhancement of brightness. A specially designed W-type fiber can be used to improve the cladding to core area ratio. However, the improvement is limited, as the area ratio can only be increased to about ~ 40.[9]

We propose a cascaded-cladding-pumped cascaded Raman fiber laser architecture with multiple-clad fiber as gain medium to overcome the inner-cladding-to-core area ratio restriction[10]. The schematic diagram of the multi-cladding fiber is shown in Fig. 6. The low brightness pump light is coupled into the second cladding (first inner cladding) of the fiber, first Raman Stokes light is generated in the third cladding. Similarly, the generated Stokes light will act as pump light and generate the higher-order Stokes light in the fourth cladding. Such processes happen in cascades until the single-mode laser is generated in the fiber core. If one designs the neighboring claddings with small area ratio (for example, less than 8), parasitic second Stokes laser could be suppressed. As a result, by introducing the intermediate claddings, the restriction on the cladding to core area could be released.

We investigated a cascaded-cladding-pumped cascaded Raman fiber amplifier as a typical realization. A theoretical model was developed and the numerical simulation results proved that the new proposed architecture can indeed improve the conversion efficiency and brightness enhancement. For fiber with first inner cladding diameter of 125 μm and core diameter of 10 μm, best Raman conversion happens with four cladding fiber and the conversion efficiency is as high as 55 %.

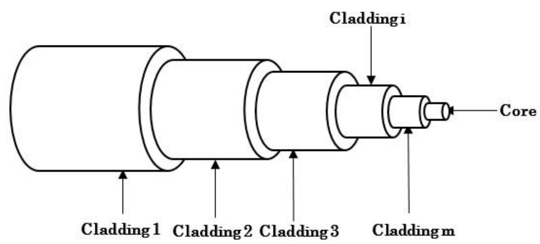

Figure 6. Schematic diagram of the multi-cladding fiber.[10]

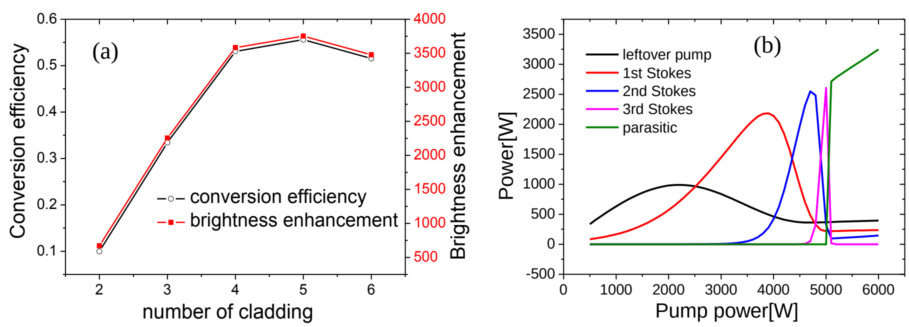

Figure 7. (a) Conversion efficiency and brightness enhancement as functions of the number of cladding. (b) Evolution of residual pump light and all the Stokes components as functions of pump power for RFA with a 400 m-long four cladding fiber.[10]

5. APPLICATION IN SPECTRAL BEAM COMBINATION

Power scaling of fiber lasers are limited by optical nonlinearity, optical damage, and thermal issues. A variety of beam combining technologies have been investigated for further power scaling. Among those technologies, spectral beam combining is rather successful. Due to limited gain bandwidth of rare earth doped fiber, diffraction optics such as gratings is used to combine multiple beams. However, the number of beams that can be combined is limited by the gain bandwidth divided by spectral separation of beams, which is determined by the dispersion capability of the gratings. And the linewidth of individual beams has to be small compared to the spectral separation of beams. Otherwise, the quality of beam after the grating will be a problem. But high power narrow linewidth fiber laser remains a technical challenge.

A major advantage of Raman fiber laser and amplifier is the wavelength flexibility. Fig.8 illustrates the spectral coverage of cascaded Raman scattering pumped by a 1070 nm Yb fiber laser. Within 10 Raman shifts, laser at any wavelength between 1 to 2 μm can be generated in principle. Of course, careful design of the cascaded Raman fiber laser configuration and gain fiber itself will be required to achieve the goal.

The ultra-broadband tunability of Raman fiber laser offers a new way to spectrally combine laser beams: interference based spectral beam combination. For example, ten fiber lasers with spectral separation of 30 nm are generated with cascaded Raman conversion (from 1030 to 1300 nm). Because the spectral separation is 30 nm, dielectric bandpass filters can be used to combine beams sequentially. A schematic diagram of interference based spectral beam combining is illustrated in Fig. 8. Here, the dielectric coated mirrors, which is easy to manufacture, are the combining devices instead of the gratings. Thus, the requirement on the linewidth of individual beams is released, which also decrease the technical difficulty.

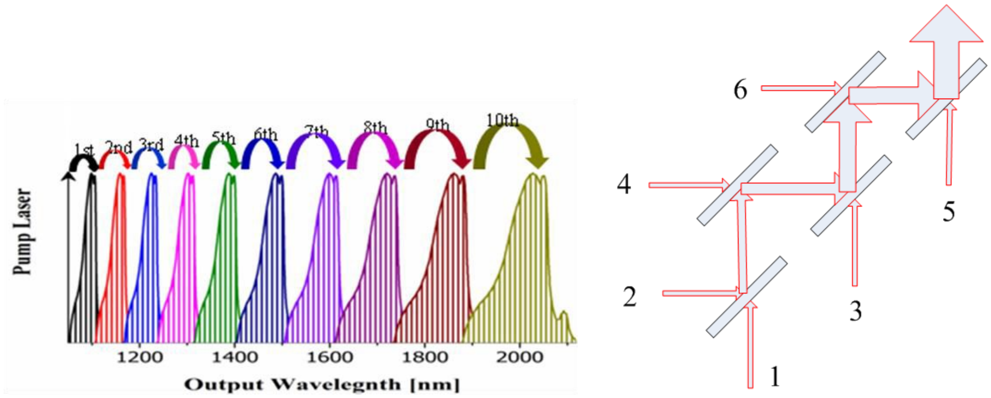

Figure 8. Spectral coverage of cascaded Raman scattering pumped by a 1070 nm Yb fiber laser, and a schematic diagram of interference based spectral beam combining.

SUMMARY

The recent developments on power scaling of Raman fiber lasers is reviewed in the talk. Some of our works will be presented in detail at the conference, including the integrated Yb-Raman fiber amplifier architecture, the first kilowatt Raman fiber amplifier, the application in sodium guide star laser development, and new scheme of cladding pumped Raman fiber laser. Perspective in further power scaling and possible application in spectral beam combination will be discussed.

REFERENCES

[1] Y. Feng, L. R. Taylor, and D. B. Calia, "150 W highly-efficient Raman fiber laser," Opt. Express **17**, 23678–23683 (2009).

[2] C. A. Codemard, J. Ji, J. K. Sahu, and J. Nilsson, "100 W CW Cladding-Pumped Raman Fiber Laser at 1120 nm," Proc. SPIE - Int. Soc. Opt. Eng. **7580**, 75801N (2010).

[3] V. R. Supradeepa and J. W. Nicholson, "Power scaling of high-efficiency 15 μm cascaded Raman fiber lasers," Opt. Lett. **38**, 2538 (2013).

[4] L. Zhang, H. Jiang, S. Cui, and Y. Feng, "Integrated ytterbium-Raman fiber amplifier," Opt. Lett. **39**, 1933 (2014).

[5] H. Zhang, H. Xiao, P. Zhou, X. Wang, and X. Xu, "High power Yb-Raman combined nonlinear fiber amplifier.," Opt. Express **22**, 10248–55 (2014).

[6] L. Zhang, C. Liu, H. Jiang, Y. Qi, B. He, J. Zhou, X. Gu, and Y. Feng, "Kilowatt Ytterbium-Raman fiber laser," Opt. Express **22**, 18483 (2014).

[7] L. Zhang, H. Jiang, S. Cui, J. Hu, and Y. Feng, "Versatile Raman fiber laser for sodium laser guide star," Laser Photon. Rev. **8**, 889–895 (2014).

[8] Nilsson J, Sahu J K, Jang J N, Sahu J K, Jang J N, Selvas R, Hanna D C and Grudinin A B 2002 Proc. Optical Amplifiers and Their Applications 2002 PD2-1/2/3.

[9] J. Ji, C. A. Codemard, M. Ibsen, J. K. Sahu, and J. Nilsson, "Analysis of the conversion to the first Stokes in cladding-pumped fiber Raman amplifiers," IEEE J. Sel. Top. Quantum Electron. 15(1), 129–139 (2009).

[10] 1. H. Jiang, L. Zhang, and Y. Feng, "Multiple-clad Raman fiber laser for brightness enhancement," in Advanced Solid State Lasers (OSA, 2014), p. AM5A.23.