

Received January 9, 2019, accepted February 2, 2019, date of publication February 14, 2019, date of current version March 18, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2899452

Pure Passive Fiber Enabled Highly Efficient Raman Fiber Amplifier With Record Kilowatt Power

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This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 11704409, and in part by the Huo Yingdong Education Foundation of China under Grant 151062.

ABSTRACT Kilowatt-level high-efficiency all-fiberized Raman fiber amplifier based on pure passive fiber is proposed for the first time in this paper. The laser system is established on master oscillator power amplification configuration, while a piece of graded-index passive fiber is utilized as Stokes shifting as well as gain medium, which is entirely irrelevant to the rare-earth-doped gain mechanism. When the pump power is 1368.8 W, we obtained 1002.3-W continuous-wave laser power at 1060 nm with the corresponding optical-to-optical efficiency of 84%. The beam parameter M^2 improves from 9.17 of the pump laser to 5.06 of the signal laser through the amplification process, and the brightness enhancement is about 2.57 at maximum output power as a consequence of the beam clean-up process in the graded-index fiber. To the best of our knowledge, we have demonstrated the first kilowatt-level high-efficiency Raman fiber amplifier based on pure passive fiber with brightness enhancement.

INDEX TERMS Fiber lasers, fiber nonlinear optics, high power amplifiers, Raman scattering.

I. INTRODUCTION

High power fiber lasers (HPFLs) have been the subject of considerable attention over decades of years in commercial and civilian applications covering industrial manufacturing, material processing and medical treatment [1], [2]. Among these fiber lasers, stimulated Raman scattering (SRS) is one of the main physical limits which challenges power scaling, in that at high power level more signal light transfers into Raman light at longer wavelength and the output laser power declines [3]. From another point of view, Raman fiber lasers (RFLs) are wavelength-agile alternative to obtain high power output, which utilize SRS to obtain gain in optical fiber [4]–[9]. The generated wavelength is determined by the provided pump wavelength and Stokes shift, therefore in RFLs there is wide achievable lasing waveband by controlling these parameters. When shorter wavelength shifting range is chosen, the quantum defect is low which can mitigate the heat load [10]. In addition, generally in relatively long passive fibers with common doping concentration of germanium there is no photon darkening (PD) [11].

The associate editor coordinating the review of this manuscript and approving it for publication was Zinan Wang.

In the past decade RFLs with high power level have been demonstrated with potential in power scaling, and the typical structure is core-pumped RFL based on pure Raman gain which can realize several-hundred-watt level laser [6]–[8]. However in these laser systems the Stokes shifting is achieved in fiber core, as a consequence it can hardly enhance the laser brightness through amplification. Then higher power output is acquired through fiber lasers employing integrated Yb-Raman gain [12]–[14], nevertheless the brightness decreases in the Raman shifting process and the issues of PD reappear which will influence the performance of laser system.

Recently the fast development of fiber components and the brightness enhancement of pump lasers make it possible for power scaling in passive fibers that employ pure Raman gain [15]–[21]. Cladding-pumped Raman fiber lasers are common structures, while due to the requirement on cladding-to-core area ratio below ~ 8 to suppress higher Stokes order lasing it is necessary to manufacture custom and costly fibers, even if low-loss fibers are required [21]. Besides, using graded-index (GRIN) fiber in core-pumped structure has a relatively simple construction and enhances the brightness in fiber core. In 2016, Glick *et al.* [18] report

an LD-pumped Raman fiber laser in free space configuration which obtains 80 W Raman laser output, and brightness enhancement is achieved through the beam clean-up procedure of GRIN fiber in the cavity. Then by means of modifying the system and adding up pump energy the lasing power increases to 154 W [19]. In 2017, Zlobina *et al.* [20] propose an all-fiber Raman fiber laser that also utilizes GRIN fiber and acquire power of 50 W at 954 nm, while the FBGs inscribed in GRIN fiber are the key devices which are specially fabricated for efficient reflection and mode selection effect. In 2018, Glick *et al.* [21] report an all-fiber Raman laser based on GRIN fiber and obtain power of 135 W at 1081 nm with brightness enhancement, and these achievements manifest that in pure RFLs the employment of GRIN fiber has potential in power scaling as well as brightness enhancement. It should be noted that the mentioned achievements are realized in oscillator configuration, while the FBGs are pivotal components which are specially inscribed on GRIN fiber with large core diameter. The FBGs are still developing for better performance and the handling and endurance ability of FBGs may be one of the restrictions for power scaling.

Apart from this, master oscillator power amplification (MOPA) configuration is another alternative for HPFLs that can acquire high laser power, and as a matter of fact most several-kilowatt HPFLs utilize this configuration at present time [22]–[27]. This architecture avoids the stability problems of high power oscillators, meanwhile the power scaling will benefit from the higher coupled pump power. Previously, we demonstrate an all-fiberized Raman fiber amplifier (RFA) employing GRIN fiber and obtain several-hundred-watt level high power output as well as brightness enhancement, which validates the feasibility of realizing high power laser in pure passive fiber enabled MOPA configuration [28]. In the present work, we report the first kW-level Raman fiber amplifier based on pure passive fiber. The laser system is established based on MOPA configuration, in which the signal laser is Ytterbium-doped fiber laser (YDFL) lasing at 1060 nm, correspondingly pump lasers at 1018 nm are utilized which match well due to typical Raman gain spectrum in silica fiber. In the amplifier GRIN fiber is employed as Stokes shifting and gain medium. When the pump power reaches 1368.8 W, the total output power is 1268 W at maximum and correspondingly 1060 nm laser power is 1002.3 W with the optical-to-optical efficiency of 84%. The beam parameter M^2 improves from 9.17 of the pump laser to 5.06 of the signal laser through the amplification process, and the brightness enhancement is about 2.57 at maximum output power as a result of the beam clean-up process in GRIN fiber. To the best of our knowledge, we have demonstrated the first kilowatt-level high efficiency RFA based on pure passive fiber.

II. EXPERIMENTAL SETUP

As is illustrated in Fig. 1, the experimental design of the amplifier is based on MOPA mechanism. One single mode

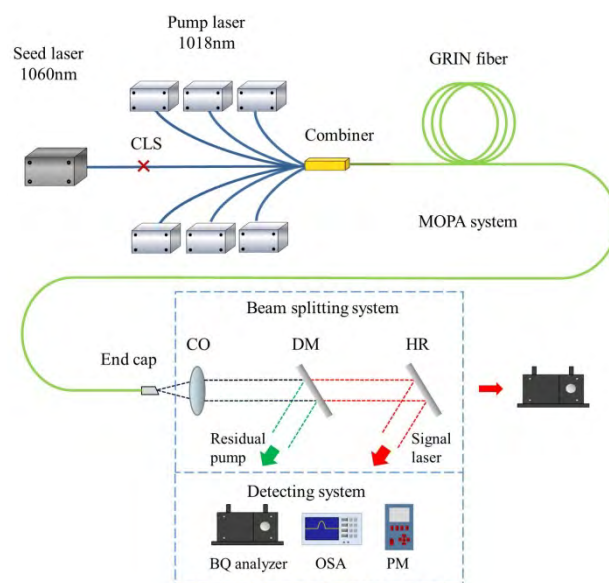


FIGURE 1. Schematic of Raman laser amplifier based on GRIN fiber, the beam splitting system and detecting system.

YDFL operating with central wavelength of 1060 nm serves as the seed laser which emits 75 W signal light, while six home-made high power YDFLs lasing at 1018 nm offer pump energy [29]. The Ytterbium-doped fiber (YDF) of these lasers has the same core/inner-cladding diameter of 15 $\mu\text{m}/130 \mu\text{m}$, and the laser cavity parameters have been optimized for good performance. The available pump energy is 1368 W in the aggregate and all the YDFLs are coupled into a home-manufactured 7×1 combiner [30]. The radial size of input fiber is the same with the pigtail of the YDFLs, while the core and cladding diameter of output fiber are 50 μm and 360 μm , respectively. A piece of double-clad GRIN fiber is spliced to the output fiber of the combiner that serves as Raman convertor and gain medium, which has length of 50 m with core/cladding diameter of 62.5 $\mu\text{m}/125 \mu\text{m}$. The refractive index profile of the GRIN fiber is measured and the core NA is around 0.275. At the end of the GRIN fiber an end cap is employed for high power lasing. To acquire better cooling effect, the GRIN fiber winds around a metal barrel and the whole system is placed on water-cooling plate which maintains at 18°C.

The performance of the fiber amplifier is monitored through the beam splitting system and detecting system as is shown in Fig. 1. The beam splitting system consists of a set of optical lens, including one collimator mirror (CO), one dichroic mirror (DM) and one high reflectivity mirror (HR). The exit laser output from the end cap consists of signal light at 1060 nm and residual pump light at 1018 nm. After the end cap the laser is first collimated by CO, then by utilizing DM the residual pump light is reflected while the signal laser is transmitted. The HR has reflectivity of over 99%, which can split up a fraction of signal laser for beam quality (BQ) measurement. In the detecting system the laser power is recorded by power meter, while the wave spectrum

is measured by optical spectrum analyzer (YOKOGAWA, AQ6370D) through monitoring the scattering light of output laser. The beam quality parameter and beam shape at focal spot are measured by BQ analyzer (Laser Quality Monitor from Prime Company).

III. RESULTS AND DISCUSSIONS

Fig. 2 demonstrates the power scaling characteristics of the Raman fiber amplifier. The amplification process begins when pump light at 1018 nm is injected, and the signal power at 1060 nm starts to increase. In that at the beginning the amplification is not sufficient, the growth of signal power is relatively slower than that of residual pump laser at 1018 nm. Then with the increment of pump power, the growth of signal laser power accelerates and the scaling process is almost linear. When the pump power is 1368.8 W, the total output laser reaches 1268 W at maximum, of which the 1060 nm laser power is 1002.3 W and the optical-to-optical efficiency is 84%. Further increase of signal laser is mainly limited to available pump energy. The residual pump power increases at first, then with the rapid amplification the pump power gradually decreases to 265.7 W.

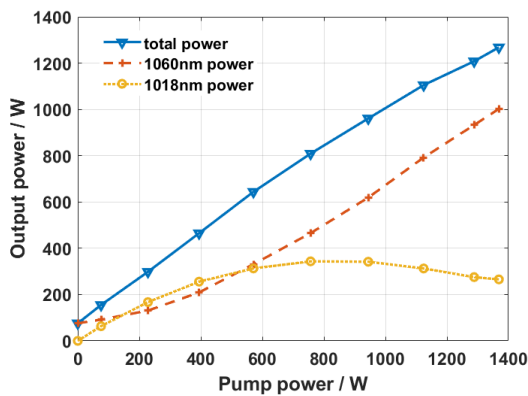


FIGURE 2. The output power characteristics (including total output power, 1060 nm laser power, and residual 1018 nm laser power measured from end cap).

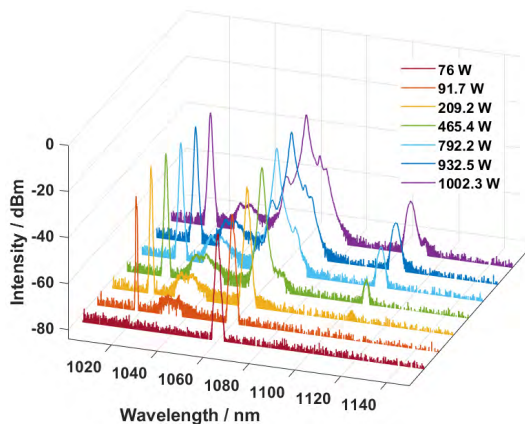


FIGURE 3. Spectrum under different launching pump power levels in logarithmic scale (legend is the corresponding output signal laser power).

The output spectrum of Raman amplifier on logarithmic scale is monitored as is shown in Fig. 3. With the increment

of pump power, the signal laser keeps increasing. On account of the gain competition of amplified spontaneous emission (ASE), there is laser generating at 1025 nm ~ 1045 nm in pump lasers [31], which is also indicated in the spectrum in Fig. 3. Despite of this, the amplifier functions with stable lasing and no self-oscillation appears. High order Raman light at 1113nm arises in the spectrum when the signal laser power reaches 331 W, and at this time the signal wave spectrum strongly broadens and lateral wings are observed on both sides of the signal spectrum which results from four-wave-mixing (FWM) [32]. Then the power of signal and high order Raman wave keep increasing, and the full width at half maximum (FWHM) of signal spectrum increases from 0.66 nm (seed laser) to 1.14 nm (maximum output power). Under maximum output signal power the high order light is about 30 dB lower than signal light of which the power is negligible compared to signal laser.

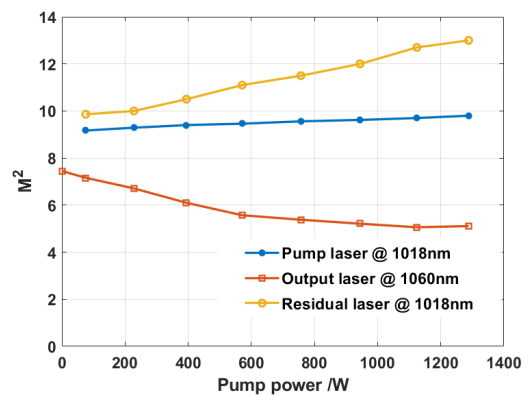


FIGURE 4. M^2 of pump laser, residual pump laser and output signal laser vary with increasing pump power.

Through our detecting system the beam quality parameter M^2 is also monitored, as is illustrated in Fig. 4. The M^2 of pump laser is first measured after the end cap, while the BQ remains stable and M^2 slightly increases from 9.17 (75.7 W) to 9.8 (1288 W). In the amplification the M^2 of signal and residual pump laser are also recorded. During the power scaling procedure, the M^2 of signal laser decreases as a result of beam clean-up scheme in GRIN passive fiber. On the contrary, the M^2 of residual pump laser keeps increasing, which may indicate that in pump laser the proportion of light with good beam quality converts to the signal laser. This outcome can be concluded from the transverse distribution of pump and signal light as well as the overlap integrals of different modes in the GRIN fiber [33], [34].

Fig. 5 shows the beam spot at focal point recorded by the BQ analyzer. The beam quality measurement results of pump light and seed laser after the combiner and the end cap are shown in Fig. 5 (a) - (d), respectively. The M^2 of pump light and seed laser both rise up after transmitting in the GRIN Raman fiber and beam shape of the laser degrade. Then through the amplifying process the M^2 of signal laser decreases from 7.45 to 5.06 gradually, as is demonstrated

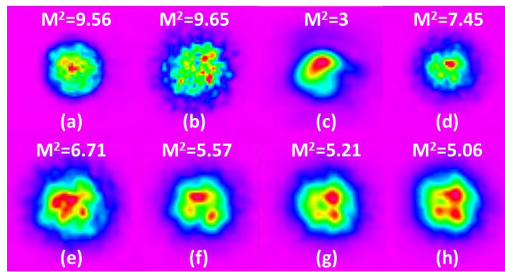


FIGURE 5. Beam shape at focal spot measured by BQ analyzer of pump light from combiner (a) and end cap (b), seed laser from combiner (c) and end cap (d), and amplified signal laser from end cap with power 209.2 W (e), 465.4 W (f), 792.9 W (g), and 1002.3 W (h).

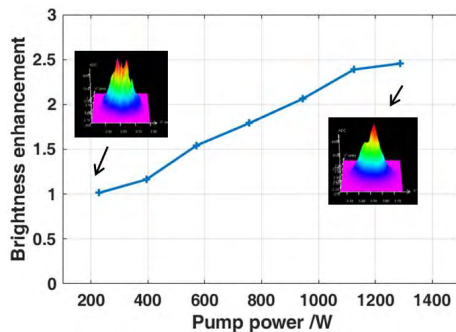


FIGURE 6. The brightness enhancement varies with the increasing pump power (the sub-graph is the 3D isometry of the beam shape at focal spot).

in Fig. 5 (e) - (h). Moreover, although the brightness of master oscillator is higher than that after the combiner, the brightness enhancement of GRIN fiber that we are exploring enlightens us more on the power scaling and brightness enhancement of new wavebands.

We calculate the brightness enhancement factor on the basis of beam quality measurement, which is defined as the output laser brightness divided by pump laser brightness. The brightness (B) can be expressed as below

$$B = \frac{P}{(M^2 \times \lambda)^2} \quad (1)$$

where P represents the laser power, M^2 is the beam quality parameter and λ is the laser wavelength [2]. Fig. 6 plots the brightness enhancement factor with different pump power, which indicates an ascending tendency. At maximum pump power the brightness of signal laser is $3.484 \times 10^9 \text{ W}/(\text{sr}\cdot\text{cm}^2)$ and the brightness enhancement reaches 2.57. The contrast of 3D isometry of the beam shape at focal spot indicates the beam clean-up effect.

Before this experiment GRIN fiber with different fiber length are utilized to test the performance of the Raman amplifier including 400 m, 300 m, 250 m and 100 m. The power scaling of these fiber amplifiers are limited to the high order Raman threshold, and the correspondingly maximum signal output power at 1060 nm is 75.9 W, 121.7 W, 134.5 W and 528.8W. Through optimizing the length of GRIN fiber, the high order Raman threshold is improved and the obtainable maximal signal laser power increases.

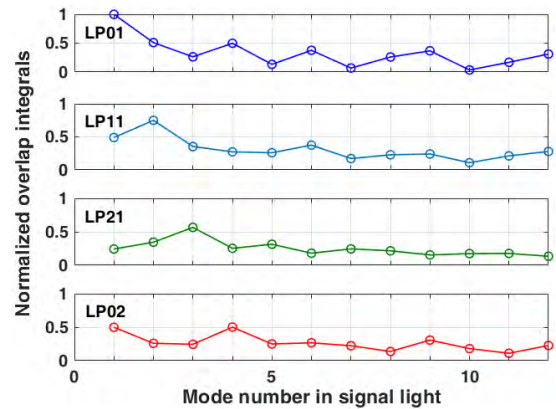


FIGURE 7. Normalized overlap integrals between pump modes (including LP01, LP11, LP21, and LP02 mode) and signal modes.

In order to better illustrate the power evolution in the GRIN fiber, the Raman fiber amplifier is numerically analyzed. The model is established on Raman coupled differential equations, and by calculating the overlap integrals between different pump and signal modes the Raman gain of different modes in the GRIN fiber can be acquired [33]. The transverse mode distribution is calculated by finite element method, and the corresponding normalized overlap integrals between the first four pump modes and different signal modes in the GRIN fiber are illustrated in Fig. 7. Results show that the values of overlap integrals are in close agreement with that in [33] and [34], while for high order transverse modes the overlap integrals are increasingly smaller, which have less influence on the total output power.

The peak Raman gain coefficient of the GRIN fiber is $8.5 \times 10^{-14} \text{ m}/\text{W}$, and the refractive index is

$$n(r) = n_0 \sqrt{1 - 2\Delta r^2} \quad (2)$$

where r is the normalized radius, n_0 is 1.5 and Δ is 0.0168, which represents the relative refractive index difference. Since that the Raman gain coefficients of high order modes are relatively smaller, we suppose that the power is equally divided into the first 12 low order modes in pump and signal light to simplify the calculation. In the simulation the power of pump and signal laser are set to 1200 W and 80 W, respectively, and the output power characteristics of the laser are obtained and illustrated in Fig. 8 (a) - (d). The calculating results indicate that in pump light the low order modes are primarily consumed, while in signal light the LP01 mode possesses the most power increment and reaches the highest output power. With the conversion from 1018 nm light to 1060 nm light, the signal power rises up gradually and the maximum output power is $\sim 1.107 \text{ kW}$, which is close to the experiment result. In the simulation the high order Raman light threshold is not reached and the power is still low. The model has simplified the transmission process of light in the GRIN fiber and the actual mode constitutions in the laser, nevertheless in the numerical simulations the clean-up effect is quite consistent with reality. It can be predicted

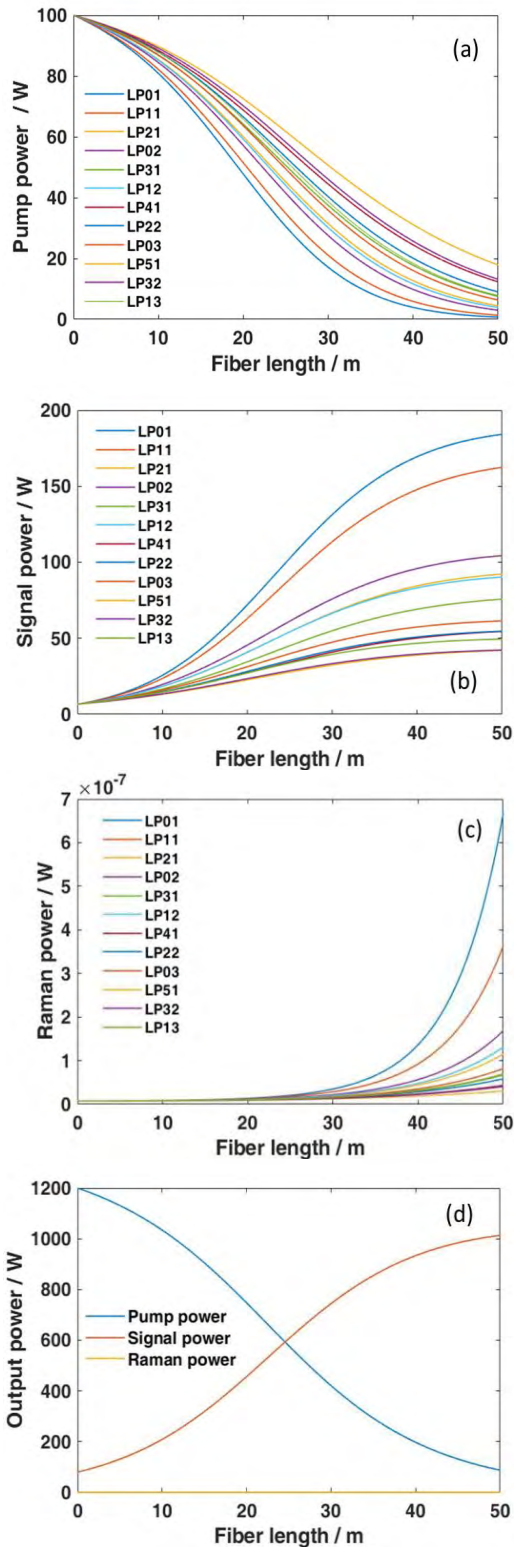


FIGURE 8. The power evolution of different modes of (a) Pump laser, (b) Signal laser, (c) High order Raman laser, and (d) the total output power of the fiber amplifier (including total pump, signal, and high order Raman laser).

that higher lasing power can be achieved if further majorization of other parameters in GRIN fiber is realized in this configuration.

IV. CONCLUSION

In general, we report the first kW-level pure Raman gain enabled fiber amplifier. The laser system is established based on MOPA configuration, in which the signal laser lasing at 1060 nm and pump lasers at 1018 nm are utilized that match well related to typical Raman gain spectrum in silica fiber. A piece of GRIN Raman fiber is utilized as Stokes shifting and gain medium in the amplification. When the pump power is 1368.8 W, the total output power reaches 1268 W at maximum, of which the 1060 nm laser power is 1002.3 W and the corresponding optical conversion efficiency is 84%. The beam parameter M^2 improves from 9.17 of the pump laser to 5.06 of the signal laser through the amplification process, and the brightness enhancement is about 2.57 at maximum output power as a consequence of the beam clean-up process in GRIN passive fiber. To the best of our knowledge, this is the first demonstrated kilowatt level high efficiency Raman fiber amplifier based on pure passive fiber.

REFERENCES

- [1] C. Jauregui, J. Limpert, and A. Tünnermann, "High-power fibre lasers," *Nature Photon.*, vol. 7, no. 11, pp. 861–867, Oct. 2013.
- [2] M. N. Zervas and C. A. Codemard, "High power fiber lasers: A review," *IEEE J. Sel. Topics Quant.*, vol. 20, no. 5, pp. 219–241, Sep. 2014.
- [3] D. J. Richardson, J. Nilsson, and W. A. Clarkson, "High power fiber lasers: Current status and future perspectives," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 27, no. 11, pp. B63–B92, Oct. 2010.
- [4] H. Jiang, L. Zhang, and Y. Feng, "Silica-based fiber Raman laser at >2.4 μm ," *Opt. Lett.*, vol. 40, no. 14, pp. 3249–3252, Jul. 2015.
- [5] V. Fortin, M. Bernier, J. Carrier, and R. Vallée, "Fluoride glass Raman fiber laser at 2185 nm," *Opt. Lett.*, vol. 36, no. 21, pp. 4152–4154, Nov. 2011.
- [6] Y. Feng, L. R. Taylor, and D. B. Calia, "150 W highly-efficient Raman fiber laser," *Opt. Express*, vol. 17, no. 26, pp. 23678–23683, Dec. 2009.
- [7] V. R. Supradeepa and J. W. Nicholson, "Power scaling of high-efficiency 1.5 μm cascaded Raman fiber lasers," *Opt. Lett.*, vol. 38, no. 14, pp. 2538–2541, Jul. 2013.
- [8] J. Song et al., "Investigation on extreme frequency shift in silica fiber-based high-power Raman fiber laser," *High Power Laser Sci. Eng.*, vol. 6, no. 2, pp. 21–28, Mar. 2018.
- [9] Z. Wang et al., "High power random fiber laser with short cavity length: Theoretical and experimental investigations," *IEEE J. Sel. Topics Quantum Electron.*, vol. 21, no. 1, pp. 10–15, Jan. 2015.
- [10] T. Yao and J. Nilsson, "835 nm fiber Raman laser pulse pumped by a multimode laser diode at 806 nm," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 31, no. 4, pp. 882–888, Apr. 2014.
- [11] H. J. Hoffman, J. J. Koponen, M. J. Söderlund, and S. K. T. Tammela, "Measuring photodarkening from single-mode ytterbium doped silica fibers," *Opt. Express*, vol. 14, no. 24, pp. 11539–11544, Nov. 2006.
- [12] L. Zhang et al., "Kilowatt Ytterbium-Raman fiber laser," *Opt. Express*, vol. 22, no. 15, pp. 18483–18489, Jul. 2014.
- [13] H. Zhang, R. Tao, P. Zhou, X. Wang, and X. Xu, "1.5-kW Yb-Raman combined nonlinear fiber amplifier at 1120 nm," *IEEE Photon. Technol. Lett.*, vol. 27, no. 6, pp. 628–630, Mar. 15, 2015.
- [14] Q. Xiao et al., "Bidirectional pumped high power Raman fiber laser," *Opt. Express*, vol. 24, no. 6, pp. 6758–6768, Mar. 2016.
- [15] C. A. Codemard, J. K. Sahu, and J. Nilsson, "100-W CW cladding-pumped Raman fiber laser at 1120 nm," *Proc. SPIE*, vol. 7580, Feb. 2010, Art. no. 75801N.
- [16] J. Ji, C. A. Codemard, and J. Nilsson, "Analysis of spectral bendloss filtering in a cladding-pumped W-type fiber Raman amplifier," *J. Lightw. Technol.*, vol. 28, no. 15, pp. 2179–2186, Aug. 1, 2010.
- [17] H. Jiang, L. Zhang, and Y. Feng, "Cascaded-cladding-pumped cascaded Raman fiber amplifier," *Opt. Express*, vol. 23, no. 11, pp. 13947–13952, May 2015.
- [18] Y. Glick et al., "High power, high efficiency diode pumped Raman fiber laser," *Laser Phys. Lett.*, vol. 13, no. 6, May 2016, Art. no. 065101.

- [19] Y. Glick, V. Fromzel, J. Zhang, N. Ter-Gabrielyan, and M. Dubinskii, "High-efficiency, 154 W CW, diode-pumped Raman fiber laser with brightness enhancement," *Appl. Opt.*, vol. 56, no. 3, pp. B97–B102, Jan. 2017.
- [20] E. A. Zlobina *et al.*, "Generating high-quality beam in a multimode LD-pumped all-fiber Raman laser," *Opt. Express*, vol. 25, no. 11, pp. 12581–12587, May 2017.
- [21] Y. Glick, Y. Shamir, A. A. Wolf, A. V. Dostovalov, S. A. Babin, and S. Pearl, "Highly efficient all-fiber continuous-wave Raman graded-index fiber laser pumped by a fiber laser," *Opt. Lett.*, vol. 43, no. 5, pp. 1027–1030, Jan. 2018.
- [22] V. Gapontsev *et al.*, "2 kW CW ytterbium fiber laser with record diffraction-limited brightness," in *Proc. CLEO/Eur.*, Munich, Germany, Jun. 2005, p. 508.
- [23] E. Stiles, "New developments in IPG fiber laser technology," in *Proc. 5th Int. Workshop Fiber Lasers*, 2009, p. 4.
- [24] P. Yan *et al.*, "3.1 kW monolithic MOPA configuration fibre laser bidirectionally pumped by non-wavelength-stabilized laser diodes," *Laser Phys. Lett.*, vol. 14, no. 8, Jul. 2017, Art. no. 080001.
- [25] P. Zhou *et al.*, "High-power fiber lasers based on tandem pumping," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 34, no. 3, pp. A29–A36, Mar. 2017.
- [26] F. Beier *et al.*, "Single mode 4.3 kW output power from a diode-pumped Yb-doped fiber amplifier," *Opt. Express*, vol. 25, no. 13, pp. 14892–14899, Jun. 2017.
- [27] T. Li *et al.*, "Power scaling of narrow-linewidth fiber amplifier seeded by Yb-doped random fiber laser," *IEEE J. Sel. Topics Quantum Electron.*, vol. 24, no. 5, Sep./Oct. 2018, Art. no. 0903208.
- [28] Y. Chen, J. Leng, H. Xiao, T. Yao, and P. Zhou, "High-efficiency all-fiber Raman fiber amplifier with record output power," *Laser Phys. Lett.*, vol. 15, no. 8, Jun. 2018, Art. no. 085104.
- [29] H. Xiao, P. Zhou, X. L. Wang, X. J. Xu, and Z. J. Liu, "High power 1018 nm ytterbium doped fiber laser with an output power of 309 W," *Laser Phys. Lett.*, vol. 10, no. 6, Jun. 2013, Art. no. 065102.
- [30] H. Zhou, Z. Chen, X. Zhou, J. Hou, and J. Chen, "All-fiber 7×1 signal combiner with high beam quality for high-power fiber lasers," *Chin. Opt. Lett.*, vol. 13, no. 6, Jun. 2015, Art. no. 061406.
- [31] P. Zhou, X. Wang, H. Xiao, Y. Ma, and J. Chen, "Review on recent progress on Yb-doped fiber laser in a variety of oscillation spectral ranges," *Laser Phys.*, vol. 22, no. 5, pp. 823–831, Apr. 2012.
- [32] S. A. Babin, D. V. Churkin, A. E. Ismagulov, S. I. Kablukov, and E. V. Podivilov, "Four-wave-mixing-induced turbulent spectral broadening in a long Raman fiber laser," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 24, no. 8, pp. 1729–1738, Aug. 2007.
- [33] A. Polley and S. E. Ralph, "Raman amplification in multimode fiber," *IEEE Photon. Technol. Lett.*, vol. 19, no. 4, pp. 218–220, Feb. 15, 2007.
- [34] N. B. Terry, T. G. Alley, and T. H. Russell, "An explanation of SRS beam cleanup in graded-index fibers and the absence of SRS beam cleanup in step-index fibers," *Opt. Express*, vol. 15, no. 26, pp. 17509–17519, Dec. 2007.



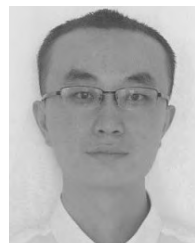
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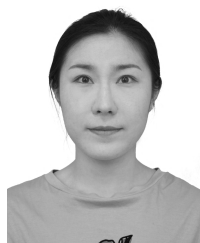
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