Beam cleaning effects in multimode GRIN-fiber Raman lasers and amplifiers

A.G. Kuznetsov, I.N. Nemov, A.A. Wolf, S.I. Kablukov, S.A. Babin, Yizhu Chen, Tianfu Yao, Jinyong Leng, and Pu Zhou

Institute of Automation and Electrometry SB RAS, Novosibirsk, Russia
Novosibirsk State University, Novosibirsk, Russia
College of Optoelectronic Science and Engineering, NUDT, Changsha, China

Corresponding author: babin@iae.nsksu; zhoupulu203@163.com

Abstract. Raman conversion in multimode GRIN fibers is accompanied by sufficient improvement of the output beam quality in comparison with that for pump radiation which is known as Raman beam clean-up effect [1]. This effect offers opportunities to create amplifiers and lasers of new type based on directly 9xx-nm diode pumped passive GRIN fibers, which may operate at almost any wavelength in transmission window (0.95-2 micron) of silica fibers. Here we review experimental results and physical mechanisms leading to the beam quality improvement (beam cleaning) in multimode Raman lasers and amplifiers, including effects of Raman gain, fiber Bragg gratings and Rayleigh backscattering feedback in GRIN fibers.

1. Introduction
Raman conversion in multimode graded-index (GRIN) fibers is accompanied by sufficient improvement of the output beam quality in comparison with that for pump radiation which is known as Raman beam clean-up effect [1]. This effect offers opportunities to create amplifiers and lasers of new type based on directly 9xx-nm diode pumped or tandem pumped passive GRIN fibers with fiber Bragg gratings (FBGs), which may operate at almost any wavelength in transmission window (0.95-2 micron) of silica fibers [2-8].

In Raman fiber lasers in addition to the Raman beam clean-up effect based on specific spatial features of Raman gain in GRIN fibers, mode-selective properties of FBGs inscribed by femtosecond pulses and transverse structure of Rayleigh backscattering both employed for the cavity feedback can further improve the output beam quality, see [6, 9, 10] and citation therein. As a result, high-efficiency CW generation of nearly diffraction limited output beam at 950-1000 nm with power level of ~100 W in such LD-pumped all-fiber GRIN RFL has been demonstrated. In fiber amplifiers, the output power of all-fiberized Raman fiber amplifier based on GRIN fiber has increased to several-hundred-watt with tandem pumping scheme involving combined fiber lasers and then kilo-watt level with high efficiency and significant beam clean-up effect [7, 8]. Recently, 2 kW level CW Raman fiber amplifier based on GRIN fiber with an optical-to-optical efficiency of more than 90% has been achieved [11].

Here we review experimental results and physical mechanisms leading to the beam quality improvement in directly LD-pumped Raman lasers generating around 980 nm and tandem-pumped amplifiers generating near 1120 nm based on GRIN fibers. Output characteristics, scaling capabilities, further development and potential applications of such GRIN-fiber lasers and amplifiers will be also discussed.
2. LD-pumped GRIN-fiber Raman lasers operating near 980 nm

Experimental scheme of the LD-pumped RFL based on the 100-μm core GIF is presented in Fig. 1. Pump radiation from three fiber pigtailed high-power LDs operating at the wavelength of 938 nm or 915 nm is combined together by a 3x1 multimode fiber pump combiner. Core diameter and numerical aperture of the LD pigtail fibers are 105 µm and 0.15–0.22, respectively. The input ports of the fused pump combiner are made of multimode step-index fiber with 105-μm core and output port is made of a 100-μm core GRIN fiber with numerical aperture of 0.29. It is spliced to the same 1.1-km-long 100-μm core GRIN fiber with the Raman gain provided by LD pumping. The linear laser cavity for the 1st Stokes wave at wavelength of 976 nm or 950 nm is formed in the GRIN fiber by a high-reflection UV FBG and an output low-reflective FS FBG (both at the corresponding 1st Stokes wavelength S1). A cavity for the 2nd Stokes order at wavelength of 976 nm is also formed by two FBGs: HR UV FBG(S2) and LR FS FBG(S2). The reflectivity of input and output FBGs is ~90% and ~4%, respectively. It should be noted that the HR FBG is inscribed by CW UV interference pattern formed in the core area, while the LR FBG is inscribed point-by-point by femtosecond pulses tightly focused in the center of the GRIN fiber core thus providing the selection of fundamental transverse mode.

The output fiber end is cleaved with an angle of >10° to eliminate Fresnel reflection. Dichroic mirrors M1, M2, M3 are used to separate pump radiation and Raman generation at 976 nm. Major part of their power (95%) gets on power meters P1 and P2, respectively, while the residual radiation passed through mirrors M2 and M3 is used to measure output spectrum and profile of the generated beam by an optical spectrum analyzer (OSA) and Thorlabs M–measurement system, respectively. A bandpass filter IF is used to measure quality parameter M2 of the 1st or the 2nd Stokes beams.

To analyze the beam cleaning effect in a multimode fiber, we measured the quality parameter of the pump beam M from three diodes at the fiber output with the power not exceeding the SRS threshold. As a first step, we have compared two RFL lasers with two different sets of FBGs (UV FBG(S1) and FS FBG(S1)) that generate 1st Stokes at 976 nm. Reflectivity spectra of the set #1 of FBGs are shown in fig. 2, in which the FWHM of UV FBG spectrum is 1.4 nm. In figure 3, the residual pump and the output Stokes power as a function of the input pump power is shown. With the exceeding SRS threshold, energy transfers from the pump wave to the Stokes one. Thus, the residual pump power stops growing and a linear Stokes power increase is observed. The maximum achieved Stokes power at the wavelength of 976 nm was ~41.6 W when the cavity was pumped at 185.5 W.
Figure 4 shows the measurement of the beam divergence, the beam profile near the waist and the calculated parameter $M^2$ for the pump radiation (938 nm), which was $M^2 \sim 34$. The profile of the output pump beam has a smooth shape due to the mixing of the transverse modes during propagation along the GRIN fiber line. The measured parameter $M^2$ for the Stokes wave at a power of 5 W turns out to be $\sim 2.3$ (figure 5). It is slightly changes with increasing power reaching $M^2 \sim 2.5$.

In order to study the effect of FBG on the laser output characteristics, a second set of FBGs with optimized parameters was manufactured. The reflection spectra of a set of gratings #2 are shown in Fig. 6. In this case, the UV HR FBG has a pronounced maximum and it is precisely coincident with the maximum of LR FS FBG. Because of better optimization of FBGs the efficiency of power conversion to the Stokes wave increased and its maximum output power reached 49.1 W when the cavity was pumped at 185.5 W (Fig. 7). At the same time, the parameter $M^2$ for the Stokes wave (wavelength 976 nm) at a power of 5 W turns out to be 1.86
As the Stokes power increases, the beam quality parameter slowly grows and reaches 2.04 at 44 W. This beam quality is the best result for single-stage Raman lasers with strong multimode fibers having a core diameter of 100 \( \mu \text{m} \). Thus, it was shown that improving the quality of the FBGs, providing better discrimination of higher transverse modes, leads to better output beam quality of the generated Stokes wave. Estimated enhancement of brightness \( P/(M^2\lambda)^2 \) amounts to about 70 in this case.

To obtain second-order Stokes wave generation at 976 nm, the laser scheme was modified by adding two additional gratings with a central reflection wavelength coinciding with the second Stokes wavelength. In this scheme three laser diodes with a wavelength of 915 nm were used. UV and FS FBGs(S1) had central reflection wavelength of 950 nm that is nearly equal to the 1st Stokes band. The second cavity cascade was formed by a pair of UV and FS FBGs(S2) with a maximum of reflection near 976 nm that is ~15 nm off the gain maximum for the 2nd Stokes wave. Figure 9 shows the output spectrum in 2-cascaded RFL configuration at different input pump powers. At input pump power >150 W, generation at 1st and 2nd Stokes wavelengths (950 nm and 976 nm) is observed and a maximum 2nd Stokes (976 nm) output power was 11.2W. The measured parameter \( M^2 \) for the 1st Stokes wave is ~2.3, but at the same time \( M^2 \) of the 2nd Stokes wave is improved to the value of 1.9-2 (fig. 10). For configuration without output FBG for the second Stokes wave, the Raman lasing occurs due to the random
distributed feedback via Rayleigh backscattering. In this random RFL (RRFL) configuration the threshold is higher but slope efficiency is also higher (see Fig.9), whereas beam quality improves to $M^2\sim1.6$ (this value was measured with different UV FBG(S2) at the wavelength of $\sim990$ nm corresponding to the 2nd Stokes gain maximum).

Fig. 9. Measured output power of the random (filled symbols) and conventional (open symbols) RFL at the first Stokes wavelength of 950 nm (circles) and the second Stokes wavelength of 976 or 978 nm for RFL/RRFL respectively (triangles) and transmitted pump power at 915 nm (squares) versus the input pump power.

Fig. 10. Beam quality of the 2nd order Stokes wave at 976 nm in RFL configuration. Inset: intensity profile of the generation in the waist.

3. Tandem-pumped GRIN-fiber Raman amplifiers operating near 1120 nm

Compared with oscillators, the structure of amplifier evades the possible durability limitations of fiber devices such as the FBGs, meanwhile combines more pump laser for power scaling. Therefore, based on master oscillator power amplification (MOPA) scheme a high power Raman fiber amplifier (RFA) is established, which consists of one seed oscillator and the fiber amplifier, as shown in Fig. 11 [7]. The wavelengths of pump and seed laser are 1018 nm and 1060 nm, respectively, and the tail fibers all have core/cladding diameters of 15/130 µm. The combined laser is coupled from a homemade tapered fiber bundle (TFB) into the core of a piece of GRIN passive fiber, which has core diameter of 62.5 µm and length of 100 m.

Fig. 11. Schematic diagram of the RFA based on MOPA configuration with a piece of GRIN fiber.
With the injected pump power rises to 766 W, the signal laser increases from 23.8 W of seed laser to maximum output power of 528.8 W with its ratio to total output power of 80.9%. The conversion efficiency is 78.8% and residual pump power is 125.2 W. As is depicted in Fig. 12, the beam parameter $M_2$ improves from 10.4 of the pump laser to 4.2 of maximum signal laser through the Stokes shifting in GRIN fiber, and the brightness enhancement (BE) is $\sim$3.85. The further power scaling is limited by the 2$^e$-order Raman laser, which is $\sim$21 dB lower than the signal laser at maximum. For power boosting the amplifier is optimized with increment of pump laser and optimization of GRIN fiber, consequently the maximum signal power improves to 1002.3 W with optical-to optical efficiency of 84% [8]. The $M_2$ improves from 9.17 of pump laser to 5.06 of signal laser with BE of 2.57.

It should be noted that in the kilowatt-level RFA system the employed wavelength is not the optimum one, since that the pump lasers are Ytterbium-doped fiber laser emitting at 1018 nm which is threatened by the amplified spontaneous emission (ASE) with higher power level [12]. In order to enhance the robustness of system, in the subsequent study the parameters in the amplifier are further majorized for power scaling, and the schematic of the RFA is demonstrated in Fig. 13. The wavelengths of pump and seed laser are set 1080 nm and 1130 nm, respectively, and the core/cladding diameter of the fibers is 20/400 µm. The maximum output power of seed and pump lasers are 200 W and 3.5 kW, which are combined and injected into the Raman GRIN fiber through a well-matched combiner. The core diameter and length of the GRIN fiber is 100 um and 23 m, respectively [11].

The output power characteristics of the RFA are shown in Fig. 14. When the injected pump power is 3.34 kW, the total output power reaches 3.26 kW at maximum and the power at 1130 nm is 2.087 kW. The 1130 nm laser power increases linearly and the conversion efficiency slightly grows to 90.1% at maximum power. When the 1130 nm power is 0.789 kW, higher order Raman light centered at 1185 nm is captured in the spectrum which increases slowly, and at maximum pump power the power at 1185 nm is 1.45W. The $M_2$ of signal laser raises up from 15 to 8.9 during the power boosting process. To the best of our knowledge, this is the highest power in the field of Raman fiber lasers based merely on Stokes radiation.

**4. Conclusions**

Thus, we have demonstrated capabilities of multimode GRIN fiber Raman lasers and amplifiers. Directly LD-pumped GRIN fiber Raman lasers are shown to offer nearly singlemode Raman lasing with high-quality ($M_2$<2) output beam at 976 nm with brightness enhancement in comparison with combined LD pump beam ($M$~34) of about 70. The beam cleaning effect in this case is mainly defined by the mode-selective properties of FBGs forming the cavity in GRIN fiber. It is shown to be sensitive to the FBG quality and matching between HR UV FBG and LR FS FBG and number of Stokes cascades (for
the 2nd Stokes wave the quality is further improved, especially with Rayleigh backscattering random feedback). In GRIN fiber amplifiers, the beam cleaning effect is mainly defined by the spatial features of Raman gain (well-known Raman beam clean-up effect) resulting in output beam quality of M~5 at 1120 nm. The brightness enhancement amounts to about 2.6 in this case, but output power is much higher (of kW level) provided by tandem pumping scheme with combined LD-pumped 1018-nm Yb-doped fiber lasers. Further scaling to 2 kW level has been demonstrated, which is the highest power in the field of Raman fiber lasers based merely on Stokes radiation.

The study is supported by Russian Foundation for Basic Research (grant 19-52-53021) and National Natural Science Foundation of China (NSFC-RFBR, Grant 61911530134) in frames of Russian-Chinese project.

References
[1] 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 15 (26), 17509 (2007).
[2] S. I. Kablukov, E. I. Dontsova, E. A. Zlobina, I. N. Nemov, A. A. Vlasov, and S. A. Babin, “An LD-pumped Raman fiber laser operating below 1 μm”, Laser Phys. Lett. 10 (8), 085103 (2013).
[3] T. Yao, A. V. Harish, J. K. Sahu, J. Nilsson, “High-power continuous-wave directly-diode-pumped fiber Raman lasers”, Applied Sciences 5, 1323-1336 (2015).
[4] Y. Glick, V. Fromzel, J. Zhang, A. Dahan, N. Ter-Gabrielyan, R. K. Pattnaik, and M. Dubinskii, “High power, high efficiency diode pumped Raman fiber laser”, Laser Phys. Lett. 13, 065101 (2016).
[5] Y. Glick, Y. Shamir, A. A. Wolf, A. V. Dostovalov, S. A. Babin, S. Pearl Highly efficient all-fiber continuous-wave Raman graded-index fiber laser pumped by a fiber laser. Opt. Lett. 43 (5), 1027-1030 (2018).
[6] E. A. Evmenova, A. G. Kuznetsov, I. N. Nemov, A. A. Wolf, A. V. Dostovalov, S. I. Kablukov, S. A. Babin, “Cascaded random lasing in a multimode LD-pumped graded-index fiber,” Sci. Rep. 8 (1), 17495 (2018).
[7] Yizhu Chen, Jinyong Leng, Hu Xiao, Tianfu Yao, Jiangming Xu and Pu Zhou, “High-efficiency all-fiber Raman fiber amplifier with record output power,” Laser Physics Letters 15 (8), 85104 (2018).
[8] Y. Chen, J. Leng, H. Xiao, T. Yao, and P. Zhou, in 8th EPS-QEOD Europhoton Conference (Barcelona, Spain, 2018), paper TuM1.6.
[9] S. A. Babin, “Multimode fiber Raman lasers directly pumped by laser diodes,” IEEE J. Sel. Top. Quantum Electron. 24, 1400310 (2018).
[10] S. A. Babin, “High-brightness all-fiber Raman lasers directly pumped by multimode laser diodes. High Power Laser,” Sci. and Eng. 7, e15 (2019).
[11] Y. Chen, T. Yao, Y. An, J. Song, J. Xu, H. Xiao, J. Leng, and P. Zhou, ”2 kW High-efficiency Raman Fiber Amplifier Based on Graded-index Passive Fiber," in Laser Congress 2019 (ASSL, LAC, LS&C), OSA Technical Digest (Optical Society of America, 2019), paper ATu1A.3.
[12] H. Xiao, J. Leng, H. Zhang, L. Huang, J. Xu, and P. Zhou, “High-power 1018 nm ytterbium-doped fiber laser and its application in tandem pump,” Appl. Opt. 54, 8166–8169 (2015).