Modal Dynamics of Random Raman Lasing in Multimode Graded-Index Fibers

C Fan[1], T Yao[1], J Wu[1], H Xiao[1], J Xu[1], J Leng[1], P Zhou[1], A G Kuznetsov[2], A A Wolf[2], I N Nemov[2], and S A Babin[2]

[1] *College of Advanced Interdisciplinary Studies, National University of Defense Technology, 410073, Changsha, China*

[2] *Fiber optic laboratory, Institute of Automation and Electrometry SB RAS, 630090, Novosibirsk, Russia*

Contact Email: leks.kuznecov@gmail.com

CW Raman fiber laser (RFL) based on multimode graded-index (GRIN) fibers directly pumped by high-power multimode laser diodes (LDs) attracts recently great deal of attention. It has been shown that the beam quality parameter is improved from $M^2\sim30$ for the LD pump to $M^2\sim2$ for the Stokes beam generated in the cavity based on special fs-inscribed fiber Bragg grating (FBG) as output coupler [1]. The pump-to Stokes brightness enhancement (BE) factor reaches 73 for the 976-nm Stokes generation of $\sim$50 W power [2]. It is also possible to obtain sufficient BE in a half-open cavity with random distributed feedback *via* natural Rayleigh scattering in GRIN fiber, but in this case the Raman threshold is high ($\sim$500W) even with $M^2\sim10$ pump laser at 1070 nm enabling $\sim$300 W Stokes generation at 1120 nm with BE=6.1 [3]. Here we study an opportunity to reduce Raman threshold and to obtain random Raman lasing in LD-pumped multimode GRIN fiber with enhanced backscattering on artificial fs-inscribed random structures of Rayleigh type (random points) or an array of short FBGs randomly spaced in longitudinal and transverse directions. Another goal is to test scaling capabilities for output power of random RFL with higher pump powers than that in [3]. In both experiments, 100-um GRIN fibers with UV-inscribed HR FBG (R$\sim$90%) are explored and some kinds of unstable behavior with specific modal dynamics is observed and analyzed.

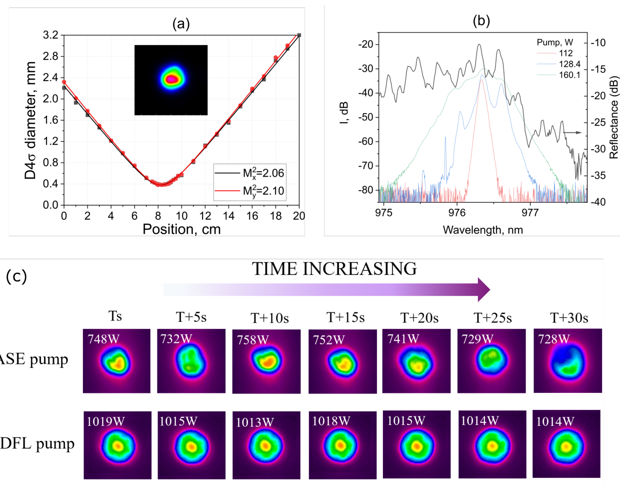

Figure 1: Beam quality (a) and spectrum (b) of MM RFL based on the random 2D FBG array (L=0.5mm, N=14, dL=0.7mm, dx=10um, dy=0). Beam profiles at maximum RRFL power monitored by CCD with a time interval of 5s (c)

In the first experiment, we used 940-nm LD pumped 1-km long GRIN fiber with the HR FBG and artificial Rayleigh reflector (ARR) or random FBG array as an output coupler. With ARR, Raman lasing starts at >140 W pumping and the output Stokes power at 976 nm at $\sim$180W pumping amounts to 6.2W at beam quality $M^2\sim3.2$. At the same time the spectrum is rather noisy in correspondence with irregular mode dynamics. With the random FBG array of short (<0.5 mm) FBGs, the best results were obtained for the 2D structure consisting of 14 FBGs with average longitudinal spacing between FBGs of $\sim$0.7 mm and random variation of their transverse coordinate within 10 µm interval. The random Raman lasing starts at $\sim$105W pumping, the Stokes power reaches $\sim$30W at 174W pumping, whereas the beam quality $M^2\sim2$ and the spectrum become stable at high powers (fig1a,b). The estimated BE value is $\sim$40. At the same time, the generated RFL spectrum "mimics" the irregular peaks of reflection spectrum (black curve) arising from the interference within the random FBG array. As a result, at low powers narrow (0.1 nm) Stokes peak is generated, then it becomes multi-peak and washed out at high powers resulting in $\sim$0.3 nm bandwidth (that is typical value for FBG-based MM FRL [1]).

A kilowatt level random RFL (RRFL) in a half-open cavity structure was built to study scaling capabilities and the effect of pump temporal stability on the dynamics of RRFL in the method of utilizing different pump sources, a high-power 1080-nm incoherent amplified spontaneous emission (ASE) and an ordinary high-power Yb-doped fiber laser (YDFL). Employment of 250-m GRIN fiber as gain medium and half-open cavity based on HR FBG and random distributed feedback *via* Rayleigh backscattering results in a high-power brightness enhanced RRFL. The comparison on output spectra, linewidth, 2nd order Raman and beam quality between different pumped RRFLs has shown that lower coherence source pumped RRFL has a better performance on these output characteristics. When pumped by ASE, a 722 W RRFL with optical-to-optical efficiency of 79.3%, FWHM linewidth of 1.5 nm, M^2 factor of 4.7 was obtained and the peak intensity of 2nd order Raman light at 1188 nm is about 32 dB lower than that of the signal laser which limiting the further power scaling (BE$\sim$9). When pumped by YDFL (with $\sim$1 kW threshold), the output power was improved to 1013 W with the sacrifice of beam quality whose M^2 factor is 12 and the RRFL had a wider linewidth of 3.4 nm, lower optical-to-optical efficiency of 74.2% and a higher threshold of 2nd order Raman light whose peak intensity is about 37 dB lower than that of the signal. At the same time, the ASE-pumped RRFL exhibits specific modal dynamics at maximum power with beam shape variation in 5 second scale, see Fig.1c (as well as the measured spectra). The measurements show that the YDFL-pumped RRFL has a better temporal stability because of its poor beam quality, which corresponds to a low power density in the fiber core.

Thus, we have developed low-threshold ($\sim$100 W) LD-pumped RRFL based on MM GRIN fiber with half-open cavity with random FBG array demonstrating $\sim$30 W generation at 976 nm with BE$\sim$40, stable beam and spectrum (0.1-0.3 nm wide), in contrast to RRFL based on artificial Rayleigh reflector with unstable parameters. With high-power laser-source pumping and natural Rayleigh backscattering, $\sim$1 kW output is obtained for YDFL pumping with BE$\sim$1.5, whereas with ASE source BE grows to $\sim$9 at 722W output, but the beam becomes unstable at maximum power. The observed instability has a significant difference with the modal instability of high-power single mode fiber lasers such as YDFLs.

Acknowledgements: This work was funded by National Natural Science Foundation of China (11704409, 62061136013, 61905284), Russian Science Foundation (21-42-00019).

References

[1] S A Babin, E A Zlobina and S I Kablukov, IEEE J. Sel. Top. Quantum Electron. **24**, 1400310 (2018)

[2] A G Kuznetsov, S I Kablukov, E V Podivilov and S A Babin, OSA Continuum **4**, 1034 (2021)

[3] Y Chen, C Fan, T Yao, H Xiao, J Leng, P Zhou, I N Nemov, A G Kuznetsov and S A Babin, Opt. Lett. **46**, 1185 (2021)