Main results of the RSF project № 21-72-30024 in 2021

The project aims at solving the problem of efficient control by the characteristics of multimode radiation with a help of femtosecond-laser induced 3-dimentional refractive index structures of regular and random character inside the multimode fiber, which allow to filter, modify, convert, couple the modes to each other in a controlled manner. This opens principally new opportunities in controlling multimode beams both in linear and nonlinear (with Raman, Kerr, four-wave mixing effects etc.) regimes and offers development of new technologies and devices on the base of fs-structured multimode (MMF) and multicore (MCF) fibers.

1st year of the project was devoted to the development of methods for characterizing and managing the parameters of multimode radiation with a help of spatial light modulator, development of techniques for forming in MMF 3-dimensional regular structures like 3D FBG with a help of point-by-point fs modification of refractive index, investigation of regimes for selecting fundamental mode or set of modes in Raman laser based on graded-index (GRIN) MMF with diode pumping and in-fiber 3D FBGs and achieving Raman lasing in step-index MMF with diode pumping, experimental and theoretical study of joint action of nonlinear Raman and Kerr effects on the mode dynamics and beam quality at the Raman conversion of multimode radiation in GRIN MMF with in-fiber 3D FBGs, development of technology for 3D interferometric reflectors in MCF based on FBGs inscribed in different cores, and Raman lasing with such structures, study of the effect of Rayleigh scattering by fs-induced random 1D refractive index structures on the characteristics of a DFB fiber laser. At the execution of this plan the following results have been obtained:

1) Methods of characterization and controlling the multimode radiation parameters have been developed based on the mode decomposition (MD) of the beam with a help of spatial light modulator (SLM) and their testing on the task of pulse propagation in GRIN MMF is performed. In particular, software is developed which allows for the measuring mode distribution by phase-only SLM in fully automated regime. The procedure of calibration and analysis of saved data (beam reconstruction) is automated. Optimization of the process of phase mask generation, data acquisition and saving allows us to sufficiently reduce the time of MD procedure. Working abilities of MD method has been tested on the analysis of optical pulses of different nature and duration from sub-nanosecond to picosecond in MMF. In all the cases, an excellent agreement has been demonstrated between the measured and reconstructed (from MD) near-field distributions (speckle structures). The modification of MD method for the analysis of quasi-CW output of multimode Raman laser including highly-multimode pump beam and low-order modes of Stokes beam.

2) Techniques of forming 3-dimensional structures in MMF with a help of point-by-point femtosecond modification of refractive index have been developed. For setting a desired profile of the structure, the development of technique for scanning of focused beam has been performed in frames of two approaches. The first approach uses a shift of laser beam in the focal plane of the objective at changing the input angle into the focusing optics by means of rotated plate before it. The second approach uses a shift of the fiber during the inscription process by means of a 3-dimansional nano-positioner, to which a ferrule with the fiber is fixed. With the developed scanning techniques, we developed and created the inscription devices and modules for scanning the focused laser beam inside MMF with graded- and step-index profiles (and in MCF as well). With their help the samples of regular and random structures have been inscribed.

3) Experiments on fabricating 3D FBGs with various parameters in different fs inscription schemes (point-by-point, astigmatic beam, transverse scanning) in comparison with traditional UV-laser FBG inscription have been performed. 3D FBG spectral characteristics have been studied depending on inscription conditions and optimal ones have been chosen. With the optimal FBGs, a Raman laser based on GRIN MMF selecting fundamental mode LP_{01} (beam quality $M^2<2$ at power >50 W at 976 nm) gives record brightness enhancement (BE=73) of the generated Stokes beam in comparison with highly-multimode laser-diode pump radiation (M^2~34 at 940 nm). An opportunity of higher order transverse mode (LP11) generation is such laser is demonstrated. A cascaded generation of the 2nd Stokes order at 1019 nm with diffraction-limited beam quality (M2~1.3) has been demonstrated. Besides, diode-pumped Raman laser with step-index MMF has been assembled and started, in which high-order modes (set of modes) are generated.

4) Experimental and theoretical study of the joint action of nonlinear and linear effects on the mode dynamics and beam quality at Raman conversion of multimode radiation from laser diodes in graded-index MMF with in-fiber FBGs. The profiles of pump and Stokes beams are measured together with their mode composition with a help of MD method, the effects of interaction between intensive pump and signal waves (burning of the spatial holes) are studied. For the experimental conditions a numerical simulation on the base of coupled-mode model has been performed, which describes well the main effects. A detailed

comparison of the experimental and numerical results has shown that the depleted dip in the pump beam is broadened due to the strong random mode coupling. Herewith, it is converted into the narrow and high-intensity nearly-singlemode Stokes beam, which results in brightness enhancement. In spite of the strong linear random mode coupling, the Stokes beam is not blurred due to the joint action of Kerr self-cleaning and FBG filtering. These effects only weakly influence on the highly-multimode pump laser-diode beam, whose transverse profile is mainly defined by the random mode coupling leading to its parabolic shape at the input and nearly homogeneous depletion at the output. In analogous experiments with step-index MMF, the output pump beam profile becomes nearly-rectangular whereas the Stokes beam becomes multimode and strongly modulated due to interference, with much worse quality parameter (M^2~12) than that in graded-index MMF.
5) The technology of 3D interferometric reflectors is developed based on FBGs inscribed in different cores with regular or random axial shifts. Spectral properties of such structures are studied as dependent of their parameters. A Raman laser based on 7-core MCF with 3D interferometric reflectors formed near fiber ends in peripherical cores, has been created and studied. It is shown that the 3D interferometric reflectors inside MCF with cross-coupling of the cores lead to modulation of the laser spectra near the threshold. As a result, this technique provides multi-peak generation and at special conditions to the selection of a single narrow spectral peak. Besides, a selective inscription of highly reflecting FBGs in chosen cores of MCF allows for the shaping of output beam in MCF laser and thereby provides spatial localization of the Stokes beam e.g. in the central core, whereas the pump and intra-cavity Stokes radiation are homogeneously distributed between all the cores.
6) An influence of Rayleigh scattering in the outer fs-induced random 1D refractive-index structures on the characteristics of Er-doped fiber DFB laser has been studied. In particular, the technology and characterization of the fabricated samples of random structures in SMF has been performed. It is shown that one can obtain Rayleigh scattering (RS) level enhancement by +50 dB/mm over natural RS level in standard SMF-28e+ fiber at the relatively low level of induced losses in the sample (<2 dB). Attachment of the Rayleigh reflector of relatively short length (5 cm) leads to the narrowing of the DFB laser linewidth (~1 kHz) by one order, similarly to the Rayleigh reflection from 25-km spool of SMF-28e+ fiber. Implementation of the 10-cm sample with scattering level of +41 dB/mm and low losses (0.5 dB) instead of one FBG in linear cavity of Er-doped fiber laser leads to single-frequency (<10 kHz) random generation with power up to 2.5 mW, with opportunity of smooth wavelength tuning within the Er gain bandwidth by means of second tunable FBG, while keeping the narrowband generation regime.

As results of the 1st year, 12 WoS/Scopus papers have been published [1-12] ([1-3] of them – in 1st quartile journals), 13 conference presentations have been made (2 of them - invited), International young scientists school has been organized and 1 postdoc from Germany attracted to the project. The project results are shown in Internet on the website of Fiber Optics Laboratory at IA&E:
http://www.iae.nsk.su/index.php/ru/laboratory-sites/l17

Main publications:

1. S. A. Babin, A. G. Kuznetsov, O. S. Sidelnikov, A. A. Wolf, I. N. Nemov, S. I. Kablukov, E. V. Podivilov, M. P. Fedoruk, S. Wabnitz. Spatio‑spectral beam control in multimode diode‑pumped Raman fibre lasers via intracavity filtering and Kerr cleaning. *Sci. Rep*. **11**, 21994 (2021) | https://doi.org/10.1038/s41598-021-01491-0

2. M. I. Skvortsov, A. A. Wolf, A. V. Dostovalov, O. N. Egorova, S. L. Semjonov, and S. A. Babin. Narrow-linewidth Er-doped fiber lasers with random distributed feedback provided by artificial Rayleigh scattering. *J. Lightwave Techn.*, published online DOI:10.1109/JLT.2021.3116758

3. A.G. Kuznetsov, I.N. Nemov, A.A. Wolf, S.I. Kablukov, and S.A. Babin. Multimode LD-pumped all-fiber Raman laser with excellent quality of 2nd-order Stokes output beam at 1019 nm. *Opt. Express* **29** (11) 17573-17580 (2021).

4. A. G. Kuznetsov, I. N. Nemov, A. A. Wolf, E. A. Evmenova, S. I. Kablukov, S. A. Babin. Cascaded generation in multimode diode-pumped graded-index fiber Raman lasers. *Photonics* **8**(10), 447 (2021). https://doi.org/10.3390/photonics8100447

5. M. I. Skvortsov, A. A. Wolf, E. A. Fomiryakov, V. N. Treshchikov, S. P. Nikitin, A. A. Vlasov, A. V. Dostovalov, S. A. Babin. Er-doped fiber laser with regular and random distributed feedback. *J. Phys. Conf. Ser*., (2022) accepted, in print.
6. М. И. Скворцов, С. Р. Абдуллина, А. А. Вольф, А. В. Достовалов, А. Е. Чурин, О. Н. Егорова, С. Л. Семёнов, К. В. Проскурина, С. А. Бабин. Одночастотный эрбиевый лазер со случайной распределенной обратной связью на основе неупорядоченных структур, созданных фемтосекундным лазерным излучением. *Квант. электр.* **51**(12) 1051 – 1055 (2021). https://doi.org/10.1070/QEL17650
7. А.Г. Кузнецов, С.И. Каблуков, Е.В. Подивилов, С.А. Бабин. Исследование пространственных характеристик выходного пучка каскадного ВКР-лазера с многомодовой диодной накачкой. *Квант. электр.* **51** (12) 1090 – 1095 (2021). https://doi.org/10.1070/QEL17657
8. M.I. Skvortsov, V.I. Labuntsov, A.A. Wolf, A.V. Dostovalov, S.A. Babin. Seven-core fiber Raman laser with fs-inscribed random structures. *Proc. SPIE*, vol.11773: Micro-structured and Specialty Optical Fibres VII (Event: SPIE Optics + Optoelectronics, 2021, Online Only), 117730H (2021); doi: 10.1117/12.2592527
9. A. G. Kuznetsov, S. I. Kablukov, S. A. Babin. Multimode diode-pumped graded-index fiber Raman laser with pulsed generation in all-fiber scheme. *Proc. SPIE* vol: 11890: Advanced Lasers, High-Power Lasers, and Applications XII (SPIE/COS Photonics Asia 2021), 118901A (2021); https://doi.org/10.1117/12.2601490
10. V. D. Efremov, A. A. Antropov, E. A. Evmenova, and D. S. Kharenko. Numerical simulation of the picosecond fiber optical parametric oscillator based on PCF.. *Proc. SPIE*, vol. 11905:Quantum and Nonlinear Optics VIII (SPIE/COS Photonics Asia 2021), 119051L (2021); https://doi.org/10.1117/12.2601314
11. K. Bronnikov, A. Dostovalov, A. Wolf, and S. Babin. Influence of parameters of FBG array inscribed in a multicore optical fiber on the accuracy of shape reconstruction of a flexible medical instrument. *OSA Optical Sensors and Sensing Congress 2021* (19 – 23 July, 2021, Virtual Event), OSA Technical Digest (Optical Society of America, 2021), paper SM2A.3 https://doi.org/10.1364/SENSORS.2021.SM2A.3
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