Project RSCF 14-22-00118
Main results 2017

In 2017 the all-fiber scheme of Raman fiber laser (RFL) with direct laser diode (LD) pumping of multimode graded-index (GRIN) fiber has been optimized in concern of higher LD coupling efficiency, better fundamental mode selection by cavity fiber Bragg gratings (FBGs), and sending back to the cavity the transmitted pump radiation. In particular, coupling coefficient of three LD output has been increased up to 75% with the use of specially designed multimode pump combiner and multimode graded-index Raman fiber of large core diameter (100 micron). As a result, slope efficiency of Raman conversion in 1.1 km long fiber has reached 84%, and maximum output power at 954 nm exceeded 62 W at the second Stokes generation threshold. At low output powers (<13 W) an instability of output parameters is observed reasoned by a transverse modes competition being essential near the generation threshold. At increasing power a stable generation of established low-order modes is set with average parameters which are almost independent of power: beam quality factor is M2=2.5-3.3, laser line width is 0.2-0.4 nm. The opportunity to increase fundamental mode selection efficiency by cavity FBGs has been demonstrated. As a result, beam quality of the Raman laser has been improved to 2.2-2.6 at comparable generation threshold, power and efficiency at 954 nm. Further improvement of FBG mode selection properties is shown to be possible by means of optimization of FBG transverse profile shape at different focusing of fs pulses into the GRIN fiber core. Extra-cavity multimode FBGs reflecting transmitted pump radiation are developed and set in the Raman laser exit which are able to reduce the residual pump power by 30-40% thus reducing generation threshold from ~120 to ~90 W. Herewith, the output power well above the threshold has been also increased by 20-40% at the expense of slight slope efficiency reduction.

A technology of long-period grating (LPG) and tilted FBG inscription by means of transverse scanning of GRIN fiber core by fs pulses has been implemented. The grating characteristics and their influence on the 2^{nd} Stokes threshold in the GRIN-fiber Raman laser with direct diode pumping have been studied. A sample of tilted FBG inscribed in the100-micron GRIN-fiber core has the cladding resonance with amplitude of -12 dB and width of 10 nm which is comparable with Raman gain profile width. This makes possible the desired effect of the 2^{nd} Stokes threshold shift, but a parasite influence of Bragg resonances reflecting high order transverse modes back into the core is observed that requires further optimization of the tilted FBG structure.

A generation of the all-fiber Raman laser with direct diode pumping has been obtained at different wavelengths, including cascaded generation of the 1^{st} and 2^{nd} Stokes orders thus demonstrating a possibility to tune the laser wavelength in a broad range from ~950 to ~1080 nm. In particular, a wavelength tuning of the Raman fiber laser with 915 nm LD pumping around 1^{st} Stokes Raman gain maximum in the range of 950-958 nm has been demonstrated with power level 55-65 W, while in the Raman laser with 950 nm FBG cavity an efficient cascaded generation of the 2nd Stokes waves at 990 and 978 nm in open cavity with random distributed feedback for this wavelengths. Output power at 978 nm amounts to 15 W at the beam quality parameter M2=1.7-2 that is sufficiently better than that for the 1^{st} Stokes wave. Besides, generation of multimode GRIN Raman laser in an all-fiber scheme with tandem (cascaded) pumping by multimode LDs at 976 nm and multimode Yb fiber lasers at 1030 nm has been demonstrated which provides output power up to 135 W at 1080 nm with absolute optical efficiency of 68%. The beam quality parameter measured at the maximum power amounts to M2=2.5 that is also achieved by means of special cavity FBGs being fs-inscribed in the central

part of multimode GRIN fiber core. The achieved efficiency and brightness are the record values for Raman lasers based on multimode GRIN fibers.

An opportunity of efficient second harmonic generation (SHG) with the developed directly diode pumped RFL at different wavelengths in PPLN crystals providing output power in blue range (477 and 489 nm) is shown. The SHG power growth is nearly quadratic with increasing RFL power, i.e. the slight reduction of beam quality does not influence significantly on the focusing regime and the laser line width does not exceed the phase matching width of the crystal. At that, the SHG efficiency (~0,0015 1/W) nearly corresponds to the calculated one with an account for the random polarization of the diode-pumped RFL.

A technology of random FBG (array of random FBGs) has been developed and their influence on Raman generation in a singlemode fiber as an example has been studied in comparison with the Raman lasing based on Rayleigh scattering (RS) induced random distributed feedback. An array of 57 FBGs with random phases and amplitudes inscribed in a polarization maintaining fiber with Yb fiber laser pumping (at 1045 nm) provides linearly polarized Raman lasing with power up to 5.7 W at 1092 nm and narrow linewidth of <0.08 nm. At low powers (~10 mW) the regime becomes single-frequency one with linewidth of <100 kHz (0.0004 pm). In comparison with the RS-based random fiber lasers the developed random laser secures single-frequency generation with linear polarization in a relatively short fiber. Besides, it has been shown that simple scheme of RS-based random fiber Raman laser with a broadband Sagnac fiber mirror enables efficient cascaded generation of up to 5 Stokes orders with the wavelength tuning in a broad range. In germanosilicate fiber the range is limited by zero dispersion wavelength (ZDW~1400 nm), whereas phosphosilicate fibers characterized by 3 times larger Stokes shift gives an opportunity to "jump" beyond ZDW: 9 W at 1515 nm has been demonstrated. In addition, new schemes of mode selection based on reflective fiber interferometer (RFI) with thin metal film have been demonstrated. In a short fiber laser with semiconductor optical amplifier and RFI, a single-frequency linearly polarized generation has been obtained with power of 1 mW and linewidth of 217 kHz. As the use of metal film limits the RFI application in high power fiber lasers, a new scheme of completely diffractive RFI has been proposed and realized. The results of this work offer perspectives of RFI applications for mode selection in fiber lasers with high-power diode pumping.

Thus, all the tasks planned for this year have been fulfilled, at that new effects and generation regimes of the CW diode-pumped GRIN-fiber Raman laser have been observed, which will be studied in detail at the next stage together with earlier planned tasks on the pulsed Raman lasing for which preliminary studies have also been performed in the reported period. The obtained results have been presented in 21 conference papers (4 invited, 12 oral, 5 poster) on the leading international conferences in optics and laser physics, and published in 1 book and 22 journal papers, 12 of which in journals from Web of Science and Scopus data bases. 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

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