Project RSCF 14-22-00118
Main results

The goal of the project is to study the processes of nonlinear interaction of multimode radiation with structured multimode fiber waveguides and to develop on this base the Raman fiber lasers with direct pumping by high-power laser diodes providing an efficient generation of high-quality laser radiation (both continuous-wave and pulsed) in the all-fiber scheme without using rare-earth-doped fibers, to achieve new regimes of laser generation and to develop principles of nonlinear conversion of the radiation into new spectral bands in such scheme.

In the first year of the project the following results have been achieved, in accordance with the project plan. The mechanisms of "beam cleaning" effect in a graded-index fiber have been clarified, the scheme of Raman laser based on the 62.5 micron core graded-index fiber with pumping by high-power laser diodes is optimized for generation around 980 nm. Optimal lengths of Raman fiber laser as dependent of the pump power is obtained for gradient-index fiber with core diameters 62.5 and 85 micron. The ultimate efficiency of Raman fiber laser with random distributed feedback has been demonstrated. Relative quantum efficiency defined as the ratio of generated photon and pump photon (in absence of generation) numbers at the laser exit reaches 100% both for the first and the second Stokes waves. It has been shown that the generation spectrum of such random fiber laser has the hyperbolic secant shape, just like in a conventional Raman fiber laser. Principally new schemes of Q-switching and mode locking for Raman fiber lasers have been developed and experimentally tested. New regimes of pulsed operation with duration from microseconds to tens of femtoseconds have been demonstrated. New types of dissipative solitons, so called Raman dissipative solitons, have been obtained and characterized. They are shown to be synchronously generated at propagation of the main solitons in the cavity – thus principally new opportunity to generate femtosecond pulses at new wavelengths has been demonstrated.

In the second year of the project the following results have been achieved, in accordance with the project plan. In the Raman laser based on the gradient-index fiber with 62.5-micron core pumped by a laser diode with power up to 65 W at 915 nm, a CW generation at new wavelength of 954 nm with slope efficiency above 40% and high beam quality has been demonstrated. Femtosecond technology is developed and various refractive index structures are inscribed in different-type fibers, possibilities of their application for management of spectral characteristics in lasers are treated. An opportunity to achieve single-frequency regime has been demonstrated in a fiber laser with distributed feedback based on the Bragg grating with random refractive-index profile. An all-fiber multi-beam interferometer capable to provide a narrowband spectral filtering of laser radiation at reflection, with characteristics analogues to those for Fabry-Perot interferometer in transmission, has been realized. It is show that application of this interferometer as a mirror in fiber lasers offers single-frequency operation with fast and continuous frequency tuning in a broad range.

New efficient schemes of Raman fiber lasers based on polarization maintaining (PM) fibers of Panda type have been demonstrated both in CW and pulsed regimes. In CW regime, a Raman fiber laser with random distributed feedback in PM fiber generates linearly-polarized Stokes wave at 1.11 micron record with absolute optical efficiency of 87% (92% quantum efficiency of conversion) at power of ~10 W. In a longer PM fiber, a cascaded Raman generation of linearly-polarized radiation of higher-order Stokes waves is demonstrated. A cascaded Raman generation of femtosecond pulses has been obtained for the first time in a 40-m PM fiber cavity. It is shown that in this case a regime of Raman dissipative solitons with cascaded synchronous pumping is realized: the main soliton (1020 nm) pumps 1st-order Raman soliton (1065 nm), which in its turn pumps 2nd-order Raman soliton (1115 nm). As a result, the solitons pulses of different orders have similar characteristics: energy of 5-10 nJ, duration of ~40 ps, compressed to <300 fs by an external grating. Herewith they are coherent with each other and their coherent combination results in interference pattern of <38 fs within the pulse envelope.

Opportunities of nonlinear frequency conversion in various schemes of Raman fiber laser are studied. In particular, four wave mixing of the main (1015 nm) and Raman (1055 nm) dissipative solitons of ~40 ps duration, obtained in the process of synchronous Raman generation, in an external PM photonic crystal fiber (PCF) at variable pulse delay results in generation of Stokes pulse with tunable wavelength in 1084-1102 nm range. A second harmonics generation (SHG) with CW Raman fiber laser with regular (in a linear cavity) and random distributed feedback (RDFB) with Sagnac or FBG mirror at one fiber end, has been studied. Their comparison shows that the maximum SHG power is reached in the RDFB Raman fiber laser with FBG due to maximal spectral density in this scheme. The generated red power at 654 nm exceeds 100 mW.

In the 3rd year of the project, the development and optimization of Raman fiber laser with direct diode pumping and various schemes of nonlinear conversion has been continued. In particular, first all-fiber variant of such laser has been realized on the base of graded-index fiber pumped by high-power laser diodes at 915 nm, which generates the Stokes wave at 954 nm with pump-to-Stokes differential conversion efficiency beyond 60%. The single transverse mode output of 10 W level has been obtained in such laser for the first time demonstrating high beam quality (M2~1.2) and narrow spectrum (linewidth <0.5 nm), which are by an order of magnitude better than those for the pump radiation (20 and ~10 nm, respectively). Implementation of specially designed output fiber Bragg grating, inscribed by femtosecond pulses in the central area of the multimode core resulted in single transverse mode selection without any loss in laser efficiency.

In the all-fiber configuration with pump combiner connecting 1-3 laser diodes (LD) to the graded-index (GRIN) fiber, the Raman laser output at 954 nm approaches 50 W at the expense of beam quality reduction to 2.6, whereas further growth is limited by available LD power and relatively high losses at the splice point between the combiner and GRIN fibers. The ways to improve the GRIN-fiber Raman laser efficiency have been proposed.

High beam quality and output power opens the opportunity of efficient frequency doubling of the developed LD-pumped all-fiber Raman laser in the nonlinear crystal (with generation near ~480 nm) using conventional techniques for singlemode beams. Experiments on the second harmonics generation (SHG) in all-fiber configuration with the use of periodically poled fibers have been performed. SHG optimization for multi- and single-frequency radiation has given similar results in single-pass scheme. Besides, a 2-fold enhancement of SHG power has been demonstrated for single-frequency regime at placing poled fiber in the ring fiber cavity.

A simple and reliable picosecond Raman fiber laser based on the polarization maintaining (PM) fiber cavity with active mode locking performed by an acousto-optic modulator and supported by the self-amplitude modulation via nonlinear polarization rotation effect. Output pulses with energy beyond 20 nJ at duration ~50 ps have been obtained at the Stokes wavelength. It has been also shown that the parametric mixing of two chirped picoseconds pulses (conventional and Raman dissipative solitons with wavelengths of 1025 and 1070 nm, respectively) in a photonic-crystal fiber having zero-dispersion wavelength near 1040 nm, enables generation of up to 8 output spectral components (chirped pulses) appeared equidistantly in the spectral range of 900-1250 nm. It has been shown that the pulses at new wavelengths are linearly chirped and can be compressed by gratings to ~300 fs, similar to input pulses. The multiwavelength coherent structure consisting of chirped pulses can be called as “dissipative soliton comb”. Thus, a principally new approach for generating femtosecond pulses at new wavelengths in a broad spectral range being coherent with each other, has been proposed and demonstrated.

In addition, the process of generation and parametric conversion of the Raman laser radiation in fibers with internal structures of various types, have been studied and optimized. In particular, in polarization-maintaining fibers of Panda type, a cascaded Raman lasing from 1st to 5th Stokes order (with wavelength change from ~1.1 to ~1.4 micron) has been realized in the half-open cavity with fiber loop mirror and random distributed feedback via Rayleigh backscattering. In contrast to conventional Raman fiber lasers with cascaded FBG cavities, such scheme is much simpler and more efficient. The record integral optical efficiency of pump conversion to higher Stokes orders (exceeding 87%, 75% and 70% for 1st, 2nd and 3rd order, respectively) has been demonstrated at ~10 W output power of linearly polarized radiation. Herewith, the laser linewidth is only weakly dependent on power (as cubic root) reaching about 1, 2 and 3 nm for the 1st, 2nd and 3rd order respectively, in accordance with the developed kinetic theory of spectral broadening at cascaded Raman lasing. Besides, first demonstration of random lasing in an active Bismuth-doped fiber developed at FORC RAS, has been performed. An all-fiber all-PM variant of optical parametric oscillator based on a highly-nonlinear polarization-maintaining (PM) photonic-crystal fiber has been realized.

In conclusion, unique opportunities for practical applications of the developed variants of Raman fiber lasers have been demonstrated. In particular, the LD-pumped all-fiber Raman lasers generating nearly single-transverse-mode diffraction limited output beam at power levels of tens of Watts, represents a unique high-brightness pump source in the wavelength range 950-1000 nm suitable for various solid state and fiber lasers. Efficient frequency doubling of such Raman fiber lasers offers new type of lasers in blue-green range (470-500 nm) for applications biomedical imaging and laser displays. The developed high-efficiency cascaded Raman lasers with random distributed feedback implemented in polarization-maintaining fibers (as well as Bismuth-doped fibers) with lasing in the range of 1.35-1.45 micron are very interesting for telecom and remote sensing applications as an efficient pump sources of distributed Raman amplifiers and tunable sources for interrogation of FBG sensors. The developed all-fiber all-PM optical parametric oscillator tunable in the 0.9-1 micron range, picosecond Raman fiber laser with active mode locking, and fiber generator of dissipative soliton comb in 0.9-1.3 micron range are perspective in bio-imaging based on optical coherent tomography, CARS and multi-photon spectroscopy techniques, whereas femtosecond one is suitable for micromachining and structuring of various materials including fiber waveguides.

Thus, the project results in development of new laser platform based on structured singlemode and multimode fibers with direct LD pumping, comprising refractive index periodic structures of variable shape, fabricated in the fiber core by femtosecond pulses, which enable efficient control of generated composition of transverse and longitudinal modes and as a result the laser output characteristics (power, spectrum, spatial-temporal dynamics). This platform shown to offer principally new opportunities both in fundamental research and practical applications. The announced tasks of the project have been completely fulfilled.

The obtained results have been presented in 39 papers (11 invited, 23 oral, 5 poster) on the leading international conferences in optics and laser physics, and accepted/published in 3 books and 46 papers, 35 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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