Project RSCF № 14-22-00118

«Generation and nonlinear conversion of radiation in the scheme of Raman fiber laser with direct diode pumping of a high power»

It is known that all-fiber scheme of a laser doesn't need any adjustment and provides high conversion efficiency of incoherent radiation from the high-power multimode laser diodes into the stable singlemode laser beam of a high quality, that is especially important in practical applications. However, even the most efficient Yb-doped fiber lasers have also some drawbacks: relatively narrow range of operating wavelengths (1-1.15 micron), photodarkening of the active fiber (and corresponding decrease in efficiency) with operating time, etc.

Recent developments in the technology of semiconductor light sources with an opportunity to combine their beams in a single fiber have offered new opportunities for power and brightness enhancement of the pump sources that enables developments of new all-fiber laser configurations, in which new regimes of generation and nonlinear conversion may be obtained and studied. In particular, one of the most actual directions is the study of possibilities to develop efficient all-fiber schemes for the generation and conversion of laser radiation in absence of rare-earth (Yb, Er, Tm, etc.) doped active fibers, namely, in passive fibers with Raman gain induced by direct pumping from laser diodes.

In this project it is proposed 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.

Main results (2014)

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 gradient-index fiber have been clarified, the scheme of Raman laser based on the 62.5 micron core gradient-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 combine coherently with basic dissipative solitons thus demonstrating an opportunity of spectral multiplexing for femtosecond pulses.

The obtained results have been presented in 4 oral talks (1 is invited) on the leading international conferences in optics and laser physics, and accepted/published in 11 papers, 9 of which in journals from Web of Science and Scopus data bases.

Publications 2014

1. S. A. Babin, I. D. Vatnik, A. Yu. Laptev, M. M. Bubnov, E. M. Dianov. High-efficiency cascaded Raman fiber laser with random distributed feedback. *Opt. Express* **22** (21) 24929-24934 (2014).
2. Z. Wang, H. Wu, M. Fan, Y. Rao, I. Vatnik, D. Churkin, E. Podivilov, S. Babin, H. Zhang, P. Zhou, H. Xiao, and X. Wang, Random Fiber Laser: Simpler and Brighter, *Optics and Photonics News*, N12: Special Issue "Optics in 2014", p.30 (2014).
3. А. В. Достовалов, А. А. Вольф, С. А. Бабин. Поточечная запись ВБР первого и второго порядка через полиимидное покрытие фемтосекундным излучением с длиной волны 1026 нм. *Прикладная фотоника,* т.1, № 2, 48-61 (2014).
4. S. A. Babin, E. I. Dontsova, I. D. Vatnik, S. I. Kablukov. Second harmonic generation of a random fiber laser with Raman gain. *Proceedings SPIE* , v. 9347, paper 9347-34, p.1-9 (2015).
5. А. Н. Малов, А.М. Оришич, А. В. Достовалов, А.Г. Кузнецов, С.А. Бабин. Сравнительные характеристики применения импульсно-периодического CO_2-, волоконного наносекундного и фемтосекундного лазеров для изготовления микроотверстий. *Прикладная фотоника,* т.2, №2, с.166-182 (2015)
6. А.В. Достовалов, А.А. Вольф, С.А. Бабин. Запись длиннопериодных волоконных решеток ограниченным щелью пучком фемтосекундного излучения (λ = 1026 нм). *Квант. электроника*, **45** (3), 235–239 (2015).
7. A. G. Kuznetsov, E. V. Podivilov, S. A. Babin. Actively Q-switched Raman fiber laser. Laser Phys. Lett. **12** (3) 035102 (2015) [5pp].
8. A. V. Dostovalov, V. P. Korolkov, S. A. Babin. Simultaneous formation of ablative and thermochemical laser-induced periodic surface structures on Ti film at femtosecond irradiation. *Laser Phys. Lett.* **12** (3) 036101 (2015).
9. D. V. Churkin, I. V. Kolokolov, E. V. Podivilov, I. D. Vatnik, M. A. Nikulin, S. S. Vergeles, I. S. Terekhov, V. V. Lebedev, G. Falkovich, S. A. Babin and S. K. Turitsyn. Wave kinetics of random fibre lasers. *Nature Comm.* **6**, 6214 (2015).
10. D. S. Kharenko, A. E. Bednyakova, E. V. Podivilov, M. P. Fedoruk, A. Apolonski, and S. A. Babin. Feedback-controlled Raman dissipative solitons in a fiber laser. *Opt. Express* **23** (2) 1857-1862 (2015).
11. E. A. Zlobina, S. I. Kablukov, and S. A. Babin. High-efficiency CW all-fiber parametric oscillator tunable in 0.92-1 μm range. *Opt. Express* **23** (2) 833-838 (2015).

12. S. A. Babin, E. V. Podivilov, D. S. Kharenko, A. E. Bednyakova, M. P. Fedoruk, O. V. Shtyrina, V. L. Kalashnikov, A. Apolonski. SRS-driven evolution of dissipative solitons in fiber lasers. *Chapter in Book "Nonlinear Optical Cavity Dynamics"*, ed. by Philippe Grelu, Wiley VCH Verlag GmbH *458 pages, 2015* (*ISBN: 978-3-527-41332-4).*

Main results (2015)

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 near-Gaussian output beam quality has been demonstrated. Using femtosecond technology, various refractive index structures are inscribed in different-type fibers, and posssibilities 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 with record absolute optical efficiency of 87% (92% quantum efficiency of conversion) at power of ~10 W. In a longer PM fiber (1000 m), a cascaded Raman generation of linearly-polarized radiation of high-order Stokes waves is obtained with record quantum efficiency: 83% for the 2nd (1.17 micron) and 77% for the 3rd (1.23 micron), respectively. The output spectrum is broadened with increasing order, but almost independent of output power amounting to ~1, ~2, and ~3 nm for the 1st, 2nd and 3rd orders, respectively. A theory is developed, which adequately describes the cascaded Raman generation in PM fibers. A cascaded Raman generation of femtosecond pulses has been obtained fro the first time in a cavity containing 40-m PM fiber. 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 soliton 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, from 1084 to 1102 nm. The duration of the compressed parametric pulse is below 2 ps, and its energy reaches 1 nJ. A second harmonics generation (SHG) of 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 the maximal spectral density in this sheme. The generated red power at 654 nm exceeds 100 mW. Because of low coherence, such fiber source is interesting for bio-imaging applications.

The obtained results have been presented in 14 oral talks (4 invited) on the leading international conferences in optics and laser physics, and published in 16 papers, 11 of which in journals from Web of Science and Scopus data bases.

Publications 2015

1. Е. А. Злобина, Е. И. Донцова, С. И. Каблуков, С. А. Бабин. Моделирование эффекта чистки пучка и оптимизация параметров ВКР-лазера на основе градиентного световода с прямой диодной накачкой. *Прикладная фотоника*, **2** (1), 31-43 (2015).
2. I. A. Lobach, S. I. Kablukov, E. V. Podivilov, A. A. Fotiadi, S. A. Babin. Fourier synthesis with single-mode pulses from a multimode laser. *Opt. Lett.* **40** (15) 3671-3674 (2015).
3. I. A. Lobach, S. I. Kablukov, M. A. Melkumov, V. F. Khopin, S. A. Babin, and E. M. Dianov. Single-frequency Bismuth-doped fiber laser with quasi-continuous self-sweeping. *Opt. Exp.* **23** (19), 24833-24842 (2015).
4. O**.** **A.** Gorbunov, S**.** Sugavanam, D**.** V. Churkin**.** Intensity dynamics and statistical properties of random distributed feedback fiber laser. *Opt. Lett.* **40** (8), 1783-1786 (2015).
5. D. V. Churkin, S. Sugavanam, I. D. Vatnik, Z. Wang, E. V. Podivilov, S. A. Babin, Y. J. Rao, S. K. Turitsyn. Recent advances in fundamentals and applications of random fiber lasers. *Advances in Optics and Photonics* **7** (3), 516-569 (2015).
6. E. A. Zlobina, D. S. Kharenko, S. I. Kablukov, S. A. Babin. Four wave mixing of conventional and Raman dissipative solitons from single fiber laser. *Opt. Exp.* **23** (13), 16589-16594 (2015).
7. E. A. Zlobina, S. I. Kablukov, S. A. Babin. Linearly polarized random fiber laser with ultimate efficiency. *Opt. Lett.* **40**, (17) 4074-4077 (2015).
8. A. A. Wolf, A. V. Dostovalov, I. A. Lobach, S. A. Babin. Femtosecond laser inscription of long-period fiber gratings in a polarization-maintaining fiber. *J. Lightwave Techn.* **33** (24), 5178-5183 (2015).
9. A. V. Dostovalov, A. A. Wolf, V. K. Mezentsev, A. G. Okhrimchuk, S. A. Babin. Quantitative characterization of energy absorption in femtosecond laser micro-modification of fused silica. *Opt. Exp.* **23** (25) 32542-32547 (2015).
10. Лобач И.А., Каблуков С.И., Мелькумов М.А., Хопин В.Ф., Бабин С.А., Дианов Е.М. Одночастотный висмутовый лазер с самосканированием частоты. *Фотон-экспресс*, №6(126), с.87-88 (2015).

11. Харенко Д.С., Беднякова А.Е., Подивилов Е.В., Федорук М.П., Аполонский А.А., Бабин С.А. Генерация мощных фемтосекундных ВКР-импульсов в волоконном лазере. *Фотон-экспресс*, №6(126), с.71-72 (2015).
12. Злобина Е.А, Каблуков С.И, Бабин С.А. Эффективный линейно-поляризованный волоконный ВКР-лазер со случайной обратной связью. *Фотон-экспресс*, №6(126), 74-75 (2015).
13. Злобина Е.А, Харенко Д.С., Каблуков С.И, Бабин С.А. Четырехволновое смешение диссипативных солитонов на основной и стоксовой частотах, генерируемых в одном волоконном лазере. *Фотон-экспресс*, №6(126), 234-235 (2015).
14. В. С. Терентьев, В. А. Симонов. Численное моделирование волоконного отражательного фильтра на основе металло-диэлектрической дифракционной структуры с повышенной лучевой стойкостью. *Квант. электр.* (в печати).
15. E. I. Dontsova, S. I. Kablukov, I. D. Vatnik, S. A. Babin. Frequency doubling of Raman fiber lasers with random distributed feedback. *Opt. Lett.* (in print).
16. D. S. Kharenko, A. E. Bednyakova, E. V. Podivilov, M. P. Fedoruk, A. Apolonski, S. A. Babin. Cascaded generation of coherent Raman dissipative solitons. *Optics Letters* (published on-line: www.osapublishing.org/ol/upcoming.cfm).