ISSN 1054-660X, Laser Physics, 2011, Vol. 21, No. 8, pp. 1525–1529.

Random Distributed Feedback Raman Fiber Laser Operating in a 1.2 μm Wavelength Range[1]

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Received November 1, 2010; in final form November 11, 2010; published online July 4, 2011

Abstract—The random distributed feedback fiber laser operating via the stimulated Raman scattering and random distributed feedback based on the Rayleigh scattering is demonstrated in the 1.2 μm frequency band. The RDFB fiber laser generates at 1174 nm up to 2.4 W of output power with corresponding slope efficiency more than 30%. The output radiation has the spectral shape similar to the conventional Raman fiber lasers and spectral width less than 1.7 nm.

DOI: 10.1134/S1054660X11150047

INTRODUCTION

A conventional laser scheme normally requires two key elements: a gain material that provides amplification and an optical cavity that traps the light creating a positive feedback. Lasing occurs when the total gain in the cavity overcomes the total cavity losses. Operational characteristics of conventional lasers are determined both by the features of the gain medium and by the cavity design that defines the structure of laser modes. On the contrary, in random lasers there is no cavity. The multiple scattering of photons in an amplifying disordered medium increases the effective optical path making possible lasing [1, 2]. The output characteristics of random lasers are determined by the build-up of the radiation at multiple scattering processes resulting in randomly embedded local spatial generation modes [3, 4].

The typical random laser materials are powder of laser crystals, nanoparticles of different materials such as ZnO or TiO_2 which have ultra-high refractive index and, thus, provide strong scattering [1], Random laser generally needs to be pumped by a pulsed source thus generating in the pulsed regime. The optical spectrum of the random lasers has usually a complex shape changing from pulse to pulse. Angular dependence is also irregular revealing the complex spatial mode structure [2]. Low-dimensional random laser systems have more regular behavior. It has been shown that random multi-layers with disorder may provide directional output [5]. Directional pulsed random lasing has been also demonstrated in the photonic crystal fiber with the hollow core filled with a suspension of TiO_2 nanoparticles in a Rhodamin 6G dye solution [6]. In this way, the fiber waveguide properties are combined with traditional bulk random material (amplifying dye with randomly scattering nanoparticles) providing one dimensional random lasing.

An alternative approach has been proposed in the recent paper [7]. The refractive index of standard telecommunication fiber has natural submicron-scale inhomogeneities, which are randomly distributed along the fiber. During propagation, the light is scattered by the inhomogenities obeying the Rayleigh law. Contrary to the conventional random materials providing strong scattering, the Rayleigh backscattering coefficient is extremely small, having a typical value of $\varepsilon = 4.5 \times 10^{-5}$ km^{-1} only [8]. Despite the smallness of random scattering, its influence is crucial for the operation of ultra-long Raman fiber lasers having the fixed cavity length up to 300 km [9]. The unique feature of optical fiber is that the small random feedback can be amplified through the Raman scattering effect if the fiber is properly pumped [8]. As a result, the random generation in 1550 nm spectral band is possible in a standard telecommunication fiber. The random distributed feedback is very weak and provided at very long lengths contrary to the well-known regular distributed feedback being strong and accumulated over short (several cm) fiber length that is used for the single-frequency generation in optical fibers, see, for example, [10–13]. The proposed random distributed feedback fiber laser (RDFB fiber laser) has a number of advantages against the conventional random lasers: directional laser generation, stationary operation, a localized narrow spectrum [7]. Further the lasing based on a random distributed feedback is demonstrated in different types of cavities with and without conventional point-action reflectors [14]. Other investigations in this field include the demonstration of stationary Raman lasing in a hybrid cavity formed

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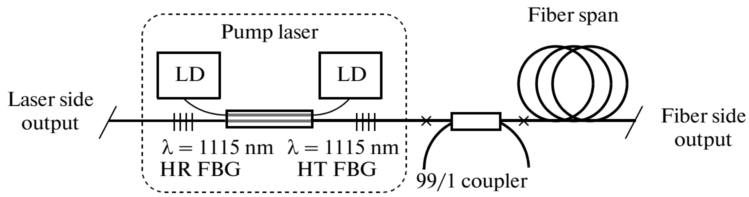

Fig. 1. Experimental scheme.

by a fiber Bragg grating (FBG) and RS-based distributed mirror in an 11-km long fiber [15] providing narrow spectrum following FBG reflection bandwidth as well as Rayleigh scattering based dual-wavelength generation in ultra-long (200 km) Raman fiber laser [16].

In the all cited papers the results are demonstrated in the 1550 nm wavelength range. However, the described principle of the random generation in the optical fiber is valid for any spectral range. Moreover, the lower wavelength is, the higher Rayleigh scattering coefficient is. In this paper we demonstrate the RDFB fiber laser operating in 1.2 μm wavelength range. The laser provides CW generation of a narrow spectrum with total efficiency up to 34%.

EXPERIMENTAL SETUP

To achieve a random generation in the low wavelength range, we have used 980-HP optical fiber being single mode down to the 920 nm. A span of 2 km of such fiber was pumped with the ytterbium doped fiber laser (YDFL), based on the GTWave double-core fiber and two fiber Bragg gratings—a highly reflective (R = 98%) and a highly transmissive (R = 20%), see Fig. 1. The YDFL operates at 1115.6 nm with the bandwidth of ~0.05 nm having the maximum output power up to 7 W. The pump wave provides the Raman amplification in the 1.2 μm wavelength range. Contrary to the scheme proposed in [7], the fiber was pumped from the one end only.

Both ends of the fiber span and the laser output were performed with angle polished ends to prevent Fresnel back reflection which amount of ~4% is critical for the RDFB laser operation. Even dirty spots on the fiber ends could provide an additional parasitic feedback, dramatically changing the laser behavior. Note that in an active fiber the generation is possible in the angled end configuration combined with FBG due to the high gain in the active fiber, see, for example, [17]. A broadband 99 : 1 coupler was used to measure the radiation which is incident to the fiber span and backscattered from that. Optical spectra as well as the total power were measured with an optical spectra analyzer.

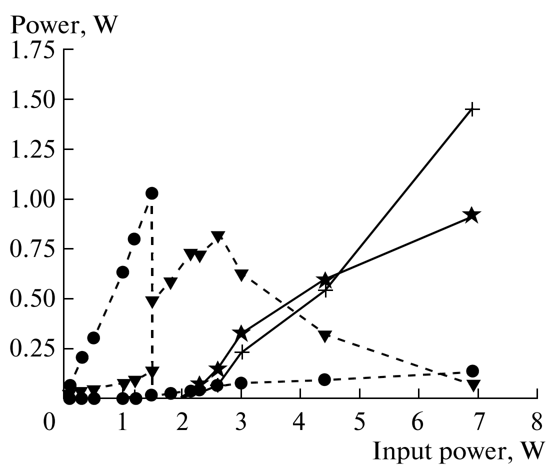

Fig. 2. Output pump power from laser (circles, dashed line) and fiber (triangles, dashed line) sides as well as Stokes wave power of fiber (stars, solid line) and laser (crosses, solid line) outputs versus YDFL power.

RESULTS

At low pump power level, <1.5 W, the system does not provide any generation at the Stokes wavelength because the Raman gain and the random feedback are too small. In this case, only the pump wave is propagating in the fiber in both directions. In the pump wave power range from tens of milliwatts to 1.5 W, most of the radiation is backscattered from the fiber and emits from the laser side output, see Fig. 2 (circles). The typical spectrum of the pump wave observed in this regime is shown at Fig. 3 by a red solid line. A number of Stokes and anti-Stokes Brillouin components, shifted on 15 GHz from the primary wavelength, are generated. As a result, the pump wave is reflected back from the fiber. The time dynamics of the radiation shows quasi-periodical high amplitude spikes, with the duration of spike <70 ms, and repetition rate of hundreds of hertz for the neighbor spikes (Fig. 4a). Correlations in time dynamics are disappeared over several periods, Fig. 4b.

At the higher pump power level, >1.5 W, the reflected from the fiber span pump wave power is dramatically decreased, Fig. 2, circles, at the same time, the residual power from the fiber span is increased, Fig. 2, triangles. The pump wave spectrum is broad and smooth indicating no SBS processes now, Fig. 3, dashed line.

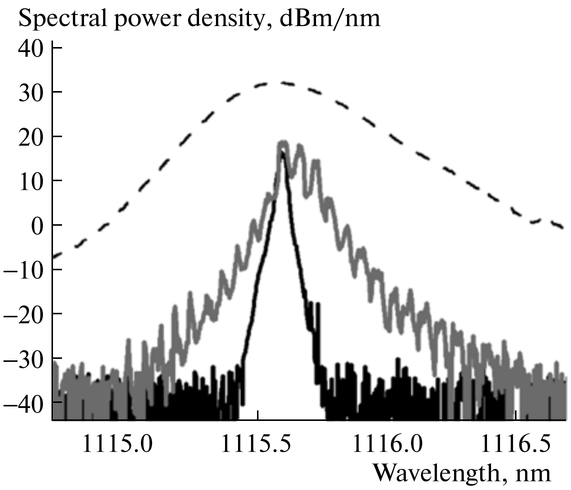

Fig. 3. Pump wave spectra measured after the propagation in a fiber span at different pump power levels: 10 mW—black solid line, 40 mW—grey line, 1.8 W—black dashed line.

The pump radiation provides a distributed Raman amplification near 1175 nm due to the Raman scattering process. While the pump power is under the threshold value, only a small amount of the wideband amplified spontaneous emission (ASE) near the Raman gain maximum is present. But as the pump power overcomes the threshold of ~2.2 W, the generation of the Stokes wave starts owing to the random Rayleigh scattering feedback. The generation slope efficiency is about ~30% for the total output power from both fiber and laser sides, see Fig. 2. The generation efficiency for the fiber side output slightly decreases at high pump powers. At the highest available pump power, the total generation power is as high as 2.4 W.

Near the generation threshold, the ASE spectrum becomes narrower, and a noise of the significant level appears stochastically in different parts of the spectrum, Fig. 5a, that is a typical feature of the random lasing. With the pump power increases, the random noise vanishes, resulting in a stable over the time generation. The spectrum width increases while pump power increasing, and reaches the value of the 1.7 nm for the full width at half maximum (FWHM), Fig. 5b.

The spectrum shape is different at different power levels. At low generation power, the spectrum is modulated with a number of peaks, being ~70 GHz apart, Fig. 6a. While at higher powers, Fig. 6b, the spectrum becomes smooth having the shape similar to the spectral shape of the conventional Raman fiber lasers with point-based reflectors in the cavity [18]. We have carefully checked that the generation spectrum has the same shape at both fiber ends, Fig. 6.

DISCUSSION

The origin of stochastic noise near the generation threshold is the stimulated Brillouin scattering. It is known that distributed Rayleigh scattering together with stimulated Brillouin scattering (SBS) results in the self-*Q*-switched operation of an Ytterbium doped fiber laser [19]. In a Brillouin laser (i.e., laser based on the SBS-induced gain), double distributed RS feedback results in a significant reduction of the laser linewidth [20]. The combined Brillouin–Raman fiber lasers are also demonstrated [21].

A rough estimation of the SBS threshold under the assumption of one pass propagation of the radiation with the bandwidth of 10 GHz results in several watts of the threshold pump power required for the Brillouin waves generation. But, in the experiment the sufficiently lower threshold value of tens of milliwatts was found. We assume that the threshold is sufficiently decreased because of the reflection from the fiber Bragg gratings forming the YDFL cavity, and a double Rayleigh backscattering contribution [20]. At the pump power higher than 1.5 W, the SBS processes are suppressed. The origin of the SBS processes suppression could be strong nonlinear processes. In particular,

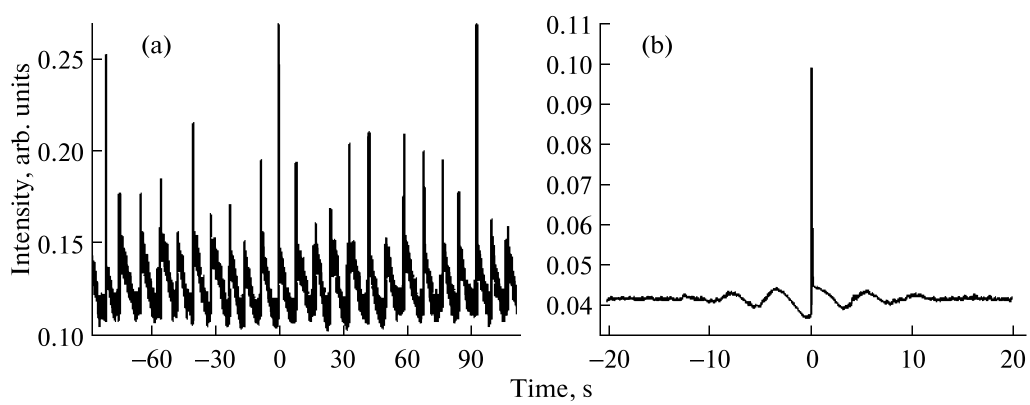

Fig. 4. (a) Time dynamics of output power at 1 W. (b) Correlation function of output intensity at 1.2 W.

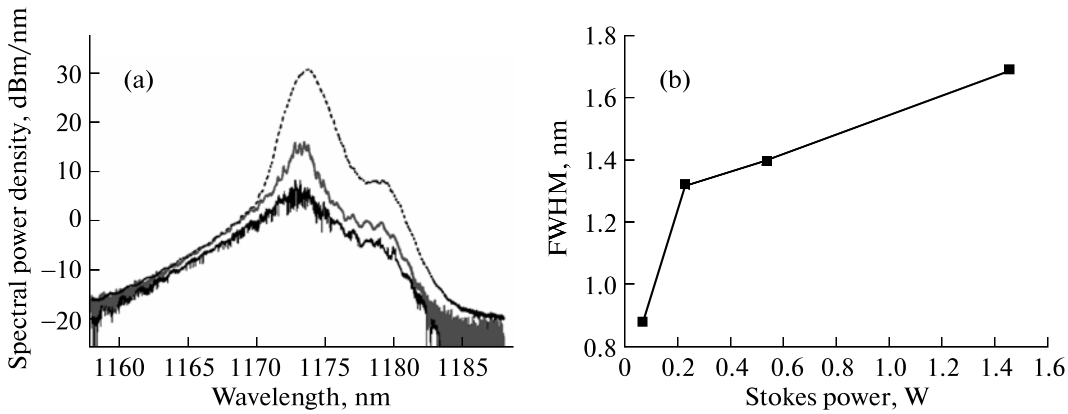

Fig. 5. (a) Laser side Stokes spectra near (2.3 W, black solid line), above (2.6 W, gray solid line), and well above (6.5 W, black dashed line) the threshold. (b) The line width versus the generated power.

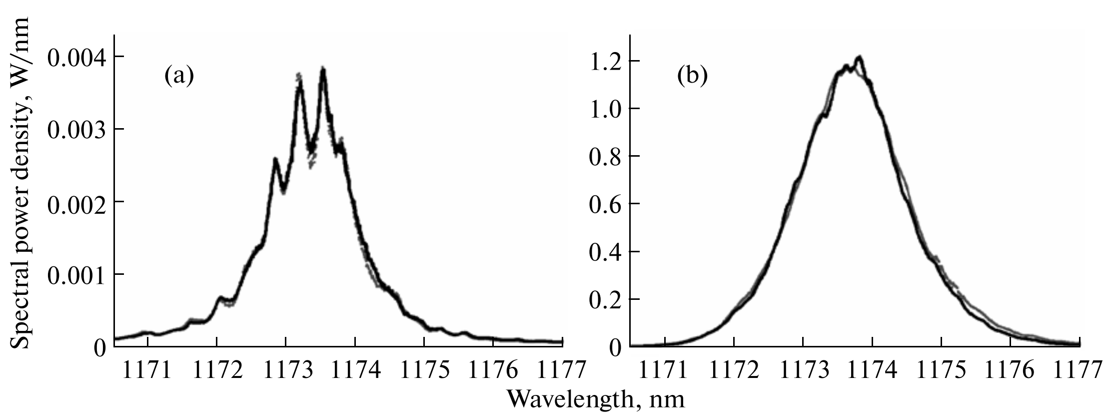

Fig. 6. Stokes component spectra from the fiber side output (black line) and normalized from the laser side (grey squares): (a) above the threshold, 2.3 W of YDFL power; (b) well above the threshold, 7 W of YDFL power.

numerous longitudinal modes of the pump radiation interacts in a long fiber via four-wave mixing processes resulting in a sufficient spectral broadening similar to the observed in the Raman fiber lasers [22]. As a result, the spectrum power density becomes smaller the SBS threshold density, and the SBS is suppressed. Due to it, the most of radiation is not reflected from the fiber span, but propagating along the fiber being just attenuated by the fiber linear losses.

The amplification length, where the generated radiation as well as the backscattered radiation are amplified, can be estimated as $L_{RS} = \ln(g_R P_0/\alpha_s)/\alpha_p$ [7]. Here $g_R = 5.42$ (W km)$^{-1}$ is the Raman gain coefficient, P_0 is the pump power, $\alpha_p = 0.43$ km^{-1} and $\alpha_s =$ 0.37 km^{-1} are losses at the Stokes and the pump wavelength correspondingly [23]. L_{RS} varies in the range of 6–11 km depending on the pump power thus being much bigger than the span length 2 km. So, the whole fiber span acts as a resonator with the rather uniform amplification distribution, so the both laser and fiber side output powers have the similar levels. Fiber span extension can result in efficiency increasing.

An easy model allows us to make an estimation of the random generation threshold power. Let us consider the fiber as a vast set of cavities of various lengths, each forming by mirrors with extremely small reflectivity q, equal to the backscattering factor (that is part of the scattered radiation recaptured by the fiber again). The backscattering factor q was directly measured, $q = 0.002$. The gain/loss balance for one cavity is represented by $q^2\exp(-2\alpha_s l + 2g_R\int_x^{x+l}P_p(\nu)d\nu) = 1$, here x is the left mirror position and l is the cavity length, $P_p(\nu) = P_0 e^{-\alpha_p \nu}$. The generation will start if the total gain of the sum of the cavities overcomes the total losses. So the threshold power P_0 can be derived from $q^2[\int_0^L dx\int_0^{L-x}dl\exp(-2\alpha_s l + 2g_R\int_x^{x+l}P_p(\nu)d\nu)] = 1$.

Solving this equation and counting the losses on splice points (13%), one can get the threshold pump power, value of $P_0 = 1.57$ W that is ~30% under the experimentally observed value. The origin of discrepancy can be in non-perfect fiber parameters estimating.

CONCLUSIONS

We have demonstrated lasing near 1.2 μm wavelength range in a fiber span with the stimulated Raman scattering as amplification mechanism and the Rayleigh backscattering as the random distributed feedback. The setup exhibits the clear generation threshold and provides up to the 2.4 W of the output light at 1174 nm with more than 30% total slope efficiency. The radiation is stable over the time and well-localized over the spectrum having the full width at half maximum less than 1.7 nm. Thus, the generation wavelength range of the random distributed feedback fiber lasers is sufficiently increased.

Note that using of a tunable YDFL fiber laser as a pump source [24] is an easy way to generate widely tunable RDFB generation in the 1.1–1.2 μm wavelength range. The output RDFB fiber laser generation can be also frequency doubled using approaches implemented for frequency doubling of conventional Raman fiber lasers [25] as spectral properties of both lasers are similar. Finally, statistical properties of the RDFB fiber lasers are of great interest as Rayleigh scattering can sufficiently change the laser generation statistics [2]. So the statistical properties of RDFB fiber lasers can differ sufficiently from statistical properties of conventional Raman fiber lasers [26].

REFERENCES

1. H. Cao, J. Phys. A **38**, 10497 (2005).
2. D. S. Wiersma, Nat. Phys. **4**, 359 (2008).
3. J. Fallert, R. Dietz, J. Sartor, D. Schneider, C. Klingshirn, and H. Kalt, Nature Photon. **3**, 279 (2009).
4. D. S. Wiersma, Nature Photon. **3**, 246 (2009).
5. V. Milner and A. Z. Genack, Phys. Rev. Lett. **94**, 073901 (2005).
6. C. J. S. de Matos, L. S. Menezes, A. M. Brito-Silva, M. A. Martinez Gamez, A. S. L. Gomes, and C. B. Araujo, Phys. Rev. Lett. **99**, 153903 (2007).
7. S. K. Turitsyn, S. A. Babin, A. E. El-Taher, P. Harper, D. V. Churkin, S. I. Kablukov, J. D. Ania-Castañón, V. Karalekas, and E. V. Podivilov, Nature Photon. **4**, 231 (2010)
8. G. P. Agrawal, *Fiber-Optic Communication Systems* (Wiley Intersci., Maiden, 2002).
9. S. K. Turitsyn, J. D. Ania-Castañón, S. A. Babin, V. Karalekas, P. Harper, D. V. Churkin, S. I. Kablukov, A. E. El-Taher, E. V. Podivilov, and V. K. Mezentsev, Phys. Rev. Lett. **103**, 133901 (2009).
10. H. Imam, Nature Photon. **2**, 26 (2008).
11. X. H. Li, X. M. Liu, Y. K. Gong, H. B. Sun, L. R. Wang, and K. Q. Lu, Laser Phys. Lett. **7**, 55 (2010).
12. M. Delgado-Pinar, A. Diez, J. L. Cruz, and M. V. Andres, Laser Phys. Lett. **6**, 139 (2009).
13. S. A. Babin, D. V. Churkin, S. I. Kablukov, A. S. Kurkov, and M. A. Nikulin, Laser Phys. **17**, 1292 (2007).
14. D. V. Churkin, S. A. Babin, A. E. El-Taher, P. Harper, S. I. Kablukov, V. Karalekas, J. D. Ania-Castanon, E. V. Podivilov, and S. K. Turitsyn, Phys. Rev. A **82**, 033828 (2010).
15. O. Frazao, C. Correia, J. L. Santos, and J. M. Baptista, Meas. Sci. Technol. **20**, 045203 (2009).
16. A. E. El-Taher, M. Alcon-Camas, S. A. Babin, P. Harper, J. D. Ania-Castañón, and S. K. Turitsyn, Opt. Lett. **35**, 1100 (2010).
17. Y. Zhang, Y. Tian, Ch. Song, W. Wang, B. Yao, and Y. Wang, Laser Phys. Lett. **6**, 590 (2009).
18. S. A. Babin, D. V. Churkin, A. E. Ismagulov, S. I. Kablukov, and E. V. Podivilov, Opt. Lett. **33**, 633 (2008).
19. S. V. Chernikov, Y. Zhu, J. R. Taylor, and V. P. Gapontsev, Opt. Lett. **22**, 298 (1997).
20. A. A. Fotiadi and R. V. Kiyan, Opt. Lett. **23**, 1805 (1998).
21. N. A. M. Ahmad Hambali, M. A. Mahdi, M. H. Al-Mansoori, M. I. Saripan, A. F. Abas, and M. Ajiya, Laser Phys. Lett. **7**, 454 (2010).
22. S. A. Babin, D. V. Churkin, A. E. Ismagulov, S. I. Kablukov, and E. V. Podivilov, J. Opt. Soc. Am. B **24**, 1729 (2007).
23. L. de la Cruz-May and E. B. Mejia, Laser Phys. **19**, 1017 (2009).
24. V. A. Akulov, D. M. Afanasiev, S. A. Babin, D. V. Churkin, S. I. Kablukov, M. A. Rybakov, and A. A. Vlasov, Laser Phys. **17**, 124 (2007).
25. S. I. Kablukov, S. A. Babin, D. V. Churkin, A. V. Denisov, and D. S. Kharenko, Laser Phys. **20**, 365 (2010).
26. D. V. Churkin, S. V. Smirnov, and E. V. Podivilov, Opt. Lett. **35**, 3288 (2010).