High-efficiency generation in a short random fiber laser

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Abstract. We demonstrate a high-efficiency random lasing in a 850-m span of a phosphosilicate fiber. Random distributed feedback owing to the Rayleigh backscattering in the fiber enables narrowband generation with the output power of up to 7.3 W at the Stokes wavelength λ_S=1308 nm from 11 W of the pump power at λ_P =1115 nm. The laser demonstrates unique generation efficiency. Near the generation threshold, more than 2 W of output power is generated from only 0.5W of pump power excess over the generation threshold. At high pump power, the quantum conversion efficiency defined as a ratio of generated and pump photons at the laser output exceeds 100%. It is explained by the fact that every pump photon is converted into the Stokes photon far from the output fiber end, while the Stokes photons have lower attenuation than the pump photons.

Since its first demonstration [1], random fiber lasers based on distributed feedback (DFB) provided by Rayleigh scattering (RS) and distributed gain provided by stimulated Raman scattering (SRS) have demonstrated their great potential due to the opportunity to generate stable narrow-band laser radiation in a simple and reliable configuration without any cavity elements (mirrors or frequency selectors). Random DFB fiber lasers have proven to possess a lot of attractive features. Thus, the lasers could operate with high total efficiency [2,3]. The multiwavelength operation has been demonstrated [4-7]. Due to nonselective type of the feedback together with broad amplification spectrum of SRS, tunable operation of excellent flatness can be obtained [8,9]. All these make it possible to design a fully-switchable tunable multiwavelength random laser [10]. Cascaded operation providing new ranges of the generation wavelength, has been also shown [2,11,12]. It has been noticed recently [8,13], that the total efficiency of a random DFB fiber laser with co-directional pumping has exponential dependence on fiber length that is defined by linear attenuation of pump and laser light in the fiber. So, decreasing of the cavity length may sufficiently enhance the laser efficiency, but the threshold pump power will be increased too. So, finding a balance between these factors will result in maximum efficiency at moderate pumping. Here we extend our preliminary results [14] obtained in a short-fiber (850 m) random DFB laser pumped by a ~10 W Yb-doped fiber laser being focused on the details of pump-to-Stokes conversion and the role of RS-based feedback in such a short fiber.

To design the high-efficiency random DFB fiber laser, we use a forward-pumped random fiber laser configuration [13], Fig. 1. The laser is based on a short span (*L*=850 m) of a phosphosilicate fiber featured by a large Stokes shift (1330 cm^{-1}) of P_2O_5-related Raman gain peak [15,16]. As a pump laser, we use an Yb-doped fiber laser (YDFL) emitting at 1115 nm. The pump light is coupled into the fiber span via a wavelength-division multiplexer (WDM). The output end of the fiber is spliced to an angle-polished connector to avoid Fresnel reflection at the fiber end facet. We have inspected the output connector reflection by means of optical time domain reflectometer and estimated the parasitic reflection to be of 10^{-6} that two order of magnitude lower than the integral Rayleigh backscattering strength $R_{RS} \sim 10^{-4}$. The opposite end (i.e. 1.3 µm port of WDM) was terminated by a Sagnac fiber-loop mirror (FLM) that allows one to reduce the generation threshold by a factor of 2 as compared with the random DFB fiber laser configuration without mirror [13].

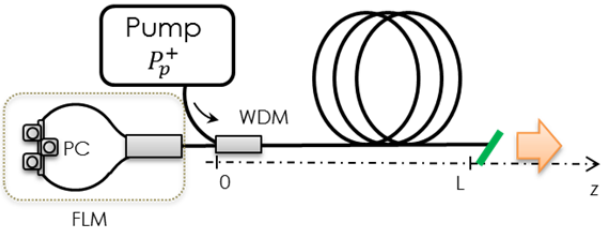

Fig. 1. Experimental setup of the random DFB laser with forward (co-directional) pumping.

The laser has a generation threshold $P_{pump}^{th} = 5.5\,W$, Fig.2a. Above the threshold, the residual pump power at the laser output is decreased down to zero value, whereas the generated Stokes wave power at 1308 nm reaches the value of $P_s^{out} = 7.3$ W at the input pump power $P_p^{in} = 11$ W.

To verify the obtained generation to be owing to Raylegh backscattering but no to parasitic point-action reflections, we performed the numerical simulations of the output power using power balance model [3,13]. The parameters of the fiber were measured to be as follows: Raman gain coefficient $g_R = 1.35\frac{1}{W\cdot km}$, linear losses at pump wavelength $\alpha_p = 0.33\frac{1}{km}$ and at Stokes wavelength $\alpha_s = 0.18\frac{1}{km}$, the Rayleigh backscattering coefficient $\varepsilon = Q\alpha_s$, where factor $Q = 0.0017$. To simulate the scheme under investigation, we set the full reflection condition at the point $z = 0$ and weak reflection of 10^{-6} at the output APC connector ($z = L$). A comparison of the numeric results (red line) with the experimental data (red squares) is shown in Fig. 2b, and good agreement has proved. We checked that the parasitic reflection at the output connector is negligible.

In the short random DFB fiber laser we observe the exceptional dependence of the output power on the pump power. First of all, the generation power increases rapidly above the threshold reaching the output power value of 2 W at only 0.5 W excess of the pump power over the threshold (i.e. at $P_p^{in} = 6$ W), Fig. 2a. The differential generation efficiency defined as dP_s^{out}/dP_p^{in} demonstrates the corresponding behaviour: just above the threshold it amounts to several hundred percent and then gradually falls down being stabilized at the level of ~75% for pump powers of ≥10W, see Fig.3a, Note that in conventional lasers the output power dependence is usually close to linear with a small region of the exponential growth around the generation threshold because of the ASE influence, see e.g. [15,16].Taking that the relative losses of the laser power are defined by its outcoupling and do not change with the increasing input pump power, high differential efficiency near the threshold is defined by rapid decrease of residual (unconverted) pump power. On the contrary, in conventional Raman fiber lasers the residual pump power may even grow, because of increasing spectral losses at reflection from narrowband fiber Bragg gratings (FBGs), which should be compensated by a corresponding increase of integral (over length) Raman gain [17,18]. The losses may not change also in a high-Q cavity with broadband reflectors, or in cavity consisting of a broadband high-reflection mirror (FBG) and narrowband low-reflection output FBG [19] resulting in a similar power dependence to that one in the short random fiber laser with extremely low integral reflection ($R_{RS} \sim 10^{-4}$). In this sense, in random DFB lasers the output power is nearly the same as the intra-cavity one if we measure it near the output fiber end.

The second important fact is the ultimate absolute and quantum generation efficiencies of the demonstrated random DFB fiber laser high above the generation threshold. Indeed, the absolute optical efficiency defined as the ratio of the output generation power to the input pump power, $\eta = P_s^{out}/P_p^{in}$, approaches 66%, see Fig.3b. Here the output power depends linearly on the input pump power with almost the same slope as the output pump in absence of laser generation (compare the dashed curve and dots on Fig. 2a). This, in particular, means that the energy is transferred from one spectral band (1115 nm, pump wave) to the new spectral band (1308 nm, Stokes wave) in the most efficient way. To highlight this fact, we calculate the quantum efficiency by taking into account the linear losses for the pump wave, $P_p^{out}/P_p^{in} = \exp(-\alpha_p L) \approx 0.76$, and the quantum limit of energy conversion, $h\nu_s/h\nu_p = 0.85$. Here ν_s and ν_p are Stokes and pump light frequencies correspondingly, $\alpha_p = 0.33\ \ 1/km$ is linear attenuation at the pump frequency. The short random RDF fiber laser demonstrates efficiency slightly higher than the maximum possible conversion efficiency, $\eta_{max} = \exp(-\alpha_p L)\, h\nu_s/h\nu_p = 64\%$, see Fig. 3b. Note that this formula is obtained analytically under the assumption of equal attenuation for the pump and Stokes waves, $\alpha_p = \alpha_s$, see [8,13] for details.

And what is more important, corresponding quantum conversion efficiency can reach and even exceed 100% in our case. We calculate the number of the photons emitted from the random laser output Stokes as $N_s^{out} = P_s^{out}/h\nu_s$. At the same time, the number of pump photons reaching the far end of the fiber span in a passive regime (if there is no generation of the Stokes wave) is given by $N_p^{out} = P_p^{in} e^{-\alpha_p L}/h\nu_p$. We plot the ratio of the generated Stokes photons to the pump photons at the fiber output (*z*=*L*), and found that the energy transfer to a new spectral band in the short random fiber laser is accompanied with the increase of the photon number by several percent: $N_s^{out}/N_p^{out} = 1.03$, corresponding rise is clearly seen in Fig. 3c. The demonstrated values of absolute and quantum efficiencies are sufficiently higher than the maximum efficiencies demonstrated up to date in random fiber lasers, see review paper [13], and slightly higher than that in very short (50-m) 1.24-µm phosphosilicate Raman fiber laser with the linear cavity formed by fiber Bragg gratings [16].

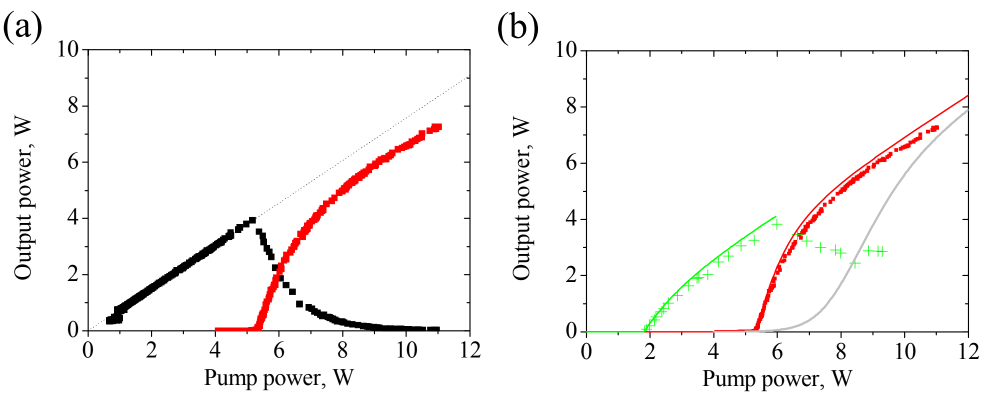

Fig. 2. **The power characteristics of the short random DFB fiber laser**: (a) The output power at 1308 nm (red points) together with the pump power at 1115 nm (black points). The dashed black line is the transmitted output pump power under assumption of gain absence. (b) The comparison of the output power of the short random DFB fiber laser in experiment (red dots) and numerics (red curve) with the output power of the same system without random Rayleigh scattering feedback (grey curve, numerics) and with the output power of the laser with 4% broadband mirror (green crosses, experiment, and green curve, numerics).

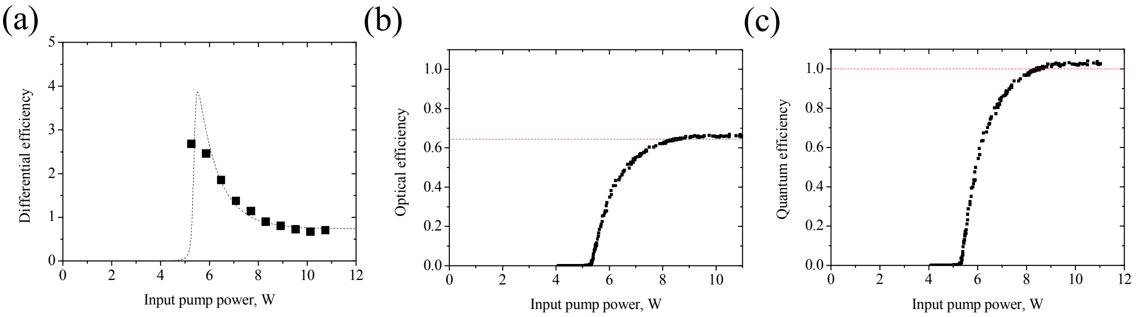

Fig. 3. **The generation efficiency in short random DFB fiber laser.** (a) A differential generation efficiency defined as P_S^{out}/dP_p^{in} . (b) Total optical efficiency as the ratio of the output generation power to the input pump power. The horizontal dashed line is the maximum conversion efficiency $\eta_{max} = \exp(-\alpha_p L)\frac{h\nu_s}{h\nu_p} =$ 64%. (c) The quantum conversion efficiency defined as the ratio of the generated photon number at the laser output to the pump photon number at the system output if the Raman conversion is absent.

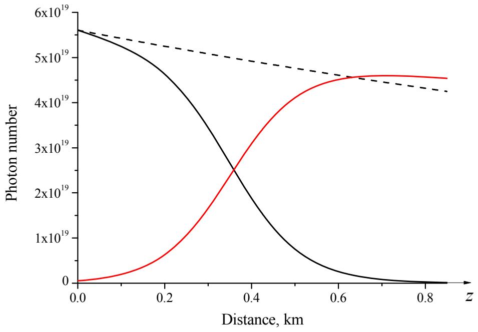

Fig.4. **Number of photons along the fiber in the short random DFB fiber laser** at 1115 nm (pump wave, black curve) and at 1308 nm (generation wave, red curve). The number of photos in the case if the Raman conversion is absent is shown by dashed line. Calculations are made for 10W input pump power.

To clarify the reason of the increase in apparent photon number, we analyse the distribution of the number of photons along the length of the random fiber laser that is effectively the longitudinal power distribution [20]. To do that we use the power balance model [3,13] reduced to photon numbers by normalization on corresponding quantum energy. High above the generation threshold, the pump wave is almost fully converted into the Stokes wave near half-way to the output end, $z = L/2$, see Fig. 4. The generated Stokes wave propagates at the rest part of the fiber with lower attenuation as compared with that for the pump wave since linear losses are defined in this spectrum band mainly by the Rayleigh scattering coefficient inversely proportional to fourth power of wavelength, $\alpha \sim \lambda^{-4}$ [21]. Thus less Stokes photons are lost during the propagation to the fiber end comparing with losses of photons for the pump wave. The effect of propagation with different losses on different wavelengths on the photon number can be estimated as $\exp(-\alpha_s L/2)/\exp(-\alpha_p L/2) = 1.07$ in assumption that all pump photons are converted into Stokes ones exactly at point $z=L/2$. For more precise estimation, one should take into account that the conversion occurs in some interval around $z=L/2$. Thus, the observed effect of the increased number of the generated photons at the laser output, and, correspondingly, of the increased laser`s quantum efficiency comparing with the maximum quantum efficiency is defined by the specific distribution of the generated and pump power over the fiber length and sufficiently different linear losses for different spectral bands.

Despite of extremely small value of the integral Rayleigh backscattering coefficient, $R_{RS} \sim 10^{-4}$, the random distributed feedback has a crucial role on the generation performances of the short random DBF fiber laser. Indeed, if the feedback is organized in conventional way by reflecting sufficient part of the radiation from the point-action mirror, the output efficiency as well as the output power deteriorates. We have performed measurements and calculations in the case of 4% Fresnel reflection from the normally-cleaved fiber end (at $z=L$), Fig. 2b. Despite the lower generation threshold in this case, the maximum output power is much lower compared with the pure random lasing because of the cascaded second Stokes wave generation starting at the pump power levels more than 5.5 W.

Another limiting case is the system without any feedback: neither randomly distributed nor conventional point-action reflection. Indeed, at high powers (~10 W) an efficient pump-to-Stokes conversion may also occur in a single pass without any feedback in the regime of amplified SRS [2]. The random feedback cannot be obviously eliminated in experiments, so we analyse the power performances of the single-pass system numerically under the power balance model. In such one-pass system, the generation threshold is obviously higher than in the random fiber laser. The initial stage of exponential power increase is more pronounced here. At high pump powers, the system almost reaches the power level of the random fiber laser. However, the spectral properties of the radiation are sufficiently different. Indeed, in a random laser, despite the feedback is small, the Rayleigh backscattering plays a crucial role in spectrum formation: the measured generation spectrum experiences narrowing while pump power overpass the generation threshold, Fig.5. In contrary, in the single-pass system, the output spectrum keeps its gain-related shape in logarithmic scale, being proportional to $g(\lambda)$, see lower curve in Fig.5, as only an exponential power increase $\exp(g(\lambda) P_p L)$ (limited by the pump depletion) takes place in this system, see also [2,22].

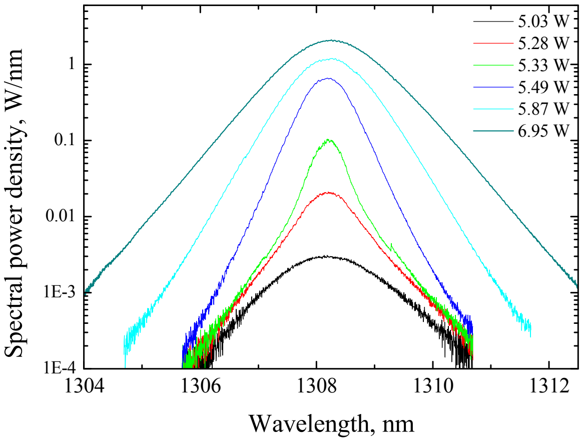

Fig. 5. The output spectra of the short random DFB fiber laser for different pump powers.

To conclude, we design a short random DFB fiber laser of an ultimate power performance. Near the generation threshold, more than 2 W of output power generates from only of 0.5W of pump power excess over the generation. At high power over the generation threshold, the random fiber laser has an ultimate quantum efficiency (~100%) of the photons conversion rate to a different spectral band: each absorbed pump photon is converted to the emitted laser photon. Moreover, the conversion efficiency defined for the output radiation reaches 103%. This effect is attributed to the specific distribution of the number of photons over the random fiber laser's length and sufficiently lower linear losses for the Stokes photons compared to that for the pump photons. At that, the obtained absolute optical efficiency of 66% corresponds to maximum possible value defined by quantum limit and attenuation of pump and laser waves in 850-m long phosphosilicate fiber. Using germanosilicate fibers (with smaller Stokes shift) of shorter length (≤50 m), one can reach absolute efficiency up to 95.5% defined by a quantum limit. Such a short random DFB fiber laser requires hundreds of Watts pumping, but it seems feasible in absence of intracavity elements like FBGs used in conventional Raman fiber lasers [19].

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