

Cascaded random distributed feedback Raman fiber laser operating at 1.2 μm

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Abstract: We demonstrate a CW random distributed feedback Raman fiber laser operating in a 1.2 μm spectral band. The laser generates up to 3.8 W of the quasi-CW radiation at 1175 nm with the narrow spectrum of 1 nm. Conversion efficiency reaches 60%. Up to 1 W is generated at the second Stokes wavelength of 1242 nm. It is shown that the generation spectrum of RDFB Raman fiber laser is much narrower than the spectrum in the system without a weak random feedback.

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1. Introduction

In recent decades there has been a great deal of interest in light generation using irregular feedback. This concept is exploited in random lasers based on active media without any regular optical cavity (see review papers [1,2] and references therein). The output characteristics of random lasers are determined by the build-up of the radiation during multiple scattering processes resulting in randomly embedded local spatial generation modes [3,4].

A number of approaches have been proposed to achieve the random generation in optical fibers. A directional pulsed random lasing has been demonstrated in the short 4 mm photonic crystal fiber with a hollow core filled with a suspension of TiO₂ nanoparticles in a Rhodamin 6G dye solution [5]. 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. Alternatively, the authors of [6] demonstrated the laser generation using the array of randomly spaced identical fiber Bragg gratings (FBGs) written in an Er-doped fiber. Furthermore, the Er-doped fiber random laser based on the continuous grating with randomly distributed phase errors has been reported in [7].

Most recently, a radically different concept was proposed in [8]. It is well-known that light propagating in the fiber core is naturally scattered by randomly distributed fluctuations of refractive index. This is a standard Rayleigh scattering in silica glass that, in particular, defines the fiber loss in a broad spectral interval. A distributed feedback potentially can be provided by a naturally present Rayleigh backscattered radiation which is captured by the fiber waveguide. At first glance, this is rather difficult to implement, because the Rayleigh backscattering coefficient is extremely small having a typical value of only $\epsilon \sim 10^{-4} \text{ km}^{-1}$ [9]. However, in a long optical fiber such very small random distributed feedback can be amplified, for example, by using the Raman gain. As a result, the CW generation of stable narrow spectrum near 1550 nm was demonstrated in the 83-km fiber span with a random

distributed feedback (RDFB) based on Rayleigh scattering only (without any point reflectors) [8].

Despite of its relative weakness, Rayleigh backscattering is an important factor in many other fiber systems from telecommunications to lasers. It is known that cooperative stimulated Brillouin scattering (SBS) and Rayleigh backscattering processes result in the Q-switched regime in ytterbium fiber laser [10]. The presence of Rayleigh feedback suppresses the intensity fluctuations and reduces a linewidth in Brillouin fiber lasers [11]. Rayleigh backscattering, considering as a parasitic effect in the 10-km Raman fiber amplifier, causes an unstable lasing in the amplifier without a signal power with the complex spectral structure [12]. Using Rayleigh backscattering as an effective mirror in a combination with conventional FBG, a stable Raman lasing was obtained in the 11-km fiber span, with the narrow spectrum following the FBG reflection bandwidth [13]. The multi-wavelength generation in fiber lasers based on cooperative influence of Raman gain [14] or Brillouin gain [15] with Rayleigh scattering is also feasible.

Furthermore, the concept proposed in [8] has been implemented in other fiber laser systems. Different hybrid Raman fiber laser (RFL) systems operating via combination of RDFB and a conventional FBG have been demonstrated in [16]. The dual-wavelength [17] and multi-wavelength [18] generation in RDFB based ultra-long RFLs has been achieved. Finally, stimulated Brillouin scattering has been used instead of Raman gain to obtain the random generation via random distributed feedback [19]. The one of qualitative models of the RDFB fiber laser has been suggested in [20]. In general, random lasers in optical fiber present an interesting opportunity to implement in practical devices an original theoretical idea of light generation by an amplifying scattering medium proposed by Letokhov in 1967 [21].

All the demonstrated set-ups generate in 1.5 μm spectral bands. However, it is likely that the same lasing concept could be realized in a broad spectral range. In this paper we demonstrate the Raman fiber laser with random distributed feedback via Rayleigh scattering operating in a 1.2 μm spectral band. We have achieved up to 3.8 W of the quasi-CW radiation near 1175 nm with the narrow spectrum of 1 nm. Conversion efficiency reaches 60% that is alone a rather impressive achievement for random lasers. Moreover, the second Stokes wave with power of more than 1 W is generated near 1242 nm. To the best of our knowledge, the cascaded generation of a CW radiation due to random distributed feedback is observed for the first time. It is shown that the generation spectrum of RDFB Raman fiber laser is much narrower than the spectrum in the system without weak random feedback.

2. Experimental Setup

The experimental setup is shown at Fig. 1. We investigate the generation of Raman Stokes component in a fiber span, which is pumped by the ytterbium fiber laser. As opposed to [8], a one-arm scheme is investigated, in which the pump wave is coupled into the fiber only from one side.

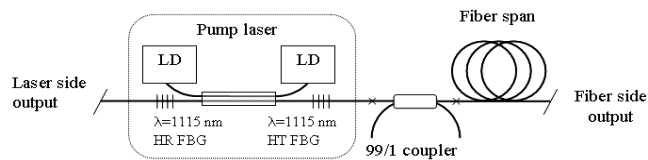


Fig. 1. Experimental setup.

The pump laser was made of a fiber with one single-mode active and one multimode passive core (GTWave), with highly reflective ($R = 98\%$) and low reflection ($R = 20\%$) fiber Bragg gratings acting as cavity mirrors at 1115.6 nm. The pump laser provides up to 7.5 W of depolarized radiation with the spectral width of 0.05 nm.

To generate a Stokes wave near 1175 nm via random distributed feedback, we have tested two different kinds of fiber: 2 km of Nufern 1060-XP and 10.7 km of OFS TrueWave XL. The 1060-XP fiber maintains only LP₀₁ mode, whereas the TrueWave fiber has the cutoff wavelength of 1.3 μm and, therefore, it is formally multimode for the spectral range under study. Both outputs of the laser system – out of the fiber (on the right side of Fig. 1) and out of the pumping laser (on the left side of Fig. 1) – are performed with angle polished connectors to avoid 4% Fresnel reflection that is crucial for the RDFB laser operation. It was observed that even dirty spots on the connector interface might considerably influence the system behavior.

The power and optical spectra of the residual pump and the generated Stokes waves are measured at both forward (fiber side output) and backward (laser side output) directions. We have used 99/1 broadband coupler to prove the radiation propagating in backward direction being the same with the radiation emitted from the laser side output. The impact of the active GTWave fiber on the Stokes generation is negligible. It was also checked that 1115-nm FBGs do not influence RDFB lasing at 1175 nm.

3. Results and discussion

3.1 Power characteristics

At high enough pump power, the system starts to generate the Stokes wave near 1175 nm in a quasi-CW regime. As there are no point reflectors, the generation is possible via random distributed feedback. Figure 2 depicts the output power dependence of the generated Stokes components on the pump power. The threshold pump values are of 1.6 W for 10.7 km TrueWave and 4 W for 2 km 1060-XP.

We have obtained up to 2.5 W of forward and 1.7 W of backward Stokes wave power in 2 km long 1060 XP fiber with slope efficiency of 50% and 80% for backward and forward direction correspondingly. In the 11 km TrueWave fiber span, the backward Stokes wave output power is much higher than the forward output power: For the highest pump power, 3.5 W of backward and 0.3 W of forward Stokes wave is observed. The slope efficiency of about 60% is achieved in the backward direction.

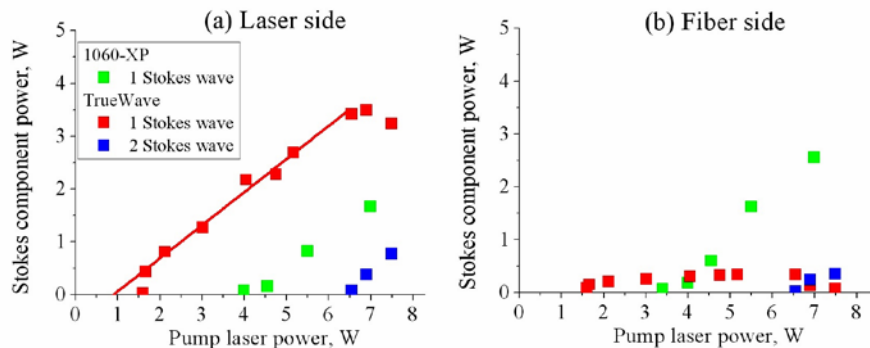


Fig. 2. Random distributed feedback Raman fiber laser output power from different side of the system: (a) pump laser side and (b) fiber side. Green squares – the first Stokes power in 1060-XP, red and blue squares – the first and second Stokes component in TrueWave correspondingly.

Such a difference in the forward/backward intensity ratio is analyzed in terms of amplification length L_{RS} (see [8] for details). Within the length less than L_{RS} from the coupling point of the pump wave ($z = 0$), Raman gain is higher than the optical losses. For the $z > L_{RS}$ Raman gain is lower than the optical losses for the generated wave. Near the threshold, L_{RS} can be found as $L_{RS} = \ln(g_R P_0 / \alpha_S) / \alpha_P$. Here g_R is the Raman gain coefficient, P_0 is pump

power, α_p and α_s are pump and Stokes linear losses, see Table 1. The fiber parameters were estimated from manufacturer specification and from our own measurements.

Table 1. Parameters of Fibers Under Study

Fiber span	Linear losses, km ⁻¹		Raman gain g_R , W ⁻¹ km ⁻¹	Amplification length L_{RS} , km	Kerr coefficient γ , W ⁻¹ ·km ⁻¹	GVD parameter β_2 , nm ⁻² ·km ⁻¹
	α_p @111 6nm	α_s @1173 nm				
2 km 1060-XP 10.7 km TrueWave	0.28	0.23	1.22	11	3.5	26.5
	0.17	0.14	1.86	18	2.4	62

Near the threshold, amplification length presents $L_{RS}^{TW} = 18 \text{ km} > L^{TW}$ for TrueWave and $L_{RS}^{XP} = 11 \text{ km} \gg L^{XP}$ for 1060-XP. This means that 2 km long 1060-XP fiber span is pumped almost uniformly, and roughly the same amplification for both forward and backward waves is provided. In the 11 km long TrueWave fiber at large distance Raman gain can become comparable or, due to pump depletion at high generation power, even lower than the losses. Thus, the forward Stokes wave is just attenuated at large z . However, this region does not influence the backward wave generation that takes place mostly at small z . Additional power discrimination may arise from competition between the two generated waves which utilize the same pump thus emphasizing their difference.

Due to high power of the first Stokes component achieved with 11km long TrueWave fiber, the generation of the second Stokes component appears. The generation threshold of the second Stokes wave was found to be 6.5 W, and up to 1.1 W of radiation at 1240 nm is observed, Fig. 2. To the best of our knowledge, this is the first demonstration of the cascaded generation of the random distributed feedback fiber laser.

As the TrueWave fiber has the cut-off wavelength around 1.3 μm , the pump wave is formally propagates in a multimode transverse regime. Nevertheless, the output Stokes wave beam quality measurements reveal the good M^2 factor of 1.1, i.e. only the fundamental transverse mode is generated. The effect of a beam clean-up in the Raman generation was shown for a graded-index multimode fiber [22], but never has been discussed for the non-zero dispersion shifted fiber like TrueWave which has a special index profile.

We have also checked temporal behavior of the generated radiation: There were no substantial temporal fluctuations at the time scale $> 20 \mu\text{s}$.

3.2. Generation threshold estimations

An estimate of the generation threshold can be made by considering the whole span as a multitude of cavities of various lengths. Mirrors of each such cavity, being actually the fluctuations of reflective index, have reflectivity equal to backscattering coefficient $\varepsilon = \alpha_s \cdot Q$. Here backscattering factor Q is the part of the total Rayleigh scattered radiation (defining loss coefficient α_s that amounts to $\sim 0.2 \text{ km}^{-1}$ at 1.2 micron), which is recaptured by the fiber and propagating in the backward direction. The backscattering factor was measured to be: $Q = 0.002$ for both fibers. The generation starts when total gain for all cavities overcomes the total losses. The gain/losses balance equation is similar to one derived in [8] for symmetric pumping scheme and can be expressed as

$$\varepsilon^2 \left[\int_0^L dx \int_0^{L-x} dl \cdot \exp(-2\alpha_s l + 2g_R \int_x^{x+l} P_p(v) dv) \right] = 1. \quad (1)$$

Here L is the full length of the fiber. Basing on this equation, one can estimate the values of 1.1 W and 5.6 W of the generation threshold in 11 km of TrueWave and 2 km of 1060-XP, respectively.

Draw attention on the step-wise manner of the first Stokes wave power dependence near the threshold in TrueWave fiber (see at Fig. 2). The origin of such behavior is the stimulated

Brillouin scattering (SBS) of the pump wave, observed in the pump laser in the range of pump powers up to 1.6 W. In our case, SBS processes prevent propagation of the pump wave over long distance, thus, making difficult the Raman generation due to random distributed feedback as it requires accumulation of feedback over the long length. Raman generation can start no sooner than SBS processes are terminated. So, the correct threshold in the absence of parasitic SBS should be estimated by linear approximation of output power dependence (Fig. 2), and presents 0.9 W being quite similar to estimated 1.1 W.

For the 2 km of 1060-XP fiber the estimated threshold of 5.6 W is higher than the experimentally measured threshold of 4 W. This difference we attribute to the difference of the estimated fiber coefficients with real ones and to parasitic point feedback on the fiber output facets.

3.3 Spectral characteristics

Below the generation threshold, only a broad spectrum of amplified spontaneous scattering (similar to amplified spontaneous emission in active fibers, ASE) is observed. However, when the pump power approaches the threshold, the impact of Rayleigh feedback grows rapidly. As a result, a narrow line with the full width at half maximum (FWHM) of about 1 nm is generated, Fig. 3a. Some narrow structures are clearly seen on the generation spectrum. The peaks are 40-70 GHz distant from each other. This difference does not coincide with SBS frequency shift. At high pump power, the second line corresponding to the second peak of the Raman gain spectral profile appears in the spectrum of the radiation generated in 11 km long TrueWave fiber span, Fig. 3b. Note that narrow structures observed in the generation spectrum near the threshold are smoothed at powers well above the threshold because of nonlinear interactions of different spectral components [23].

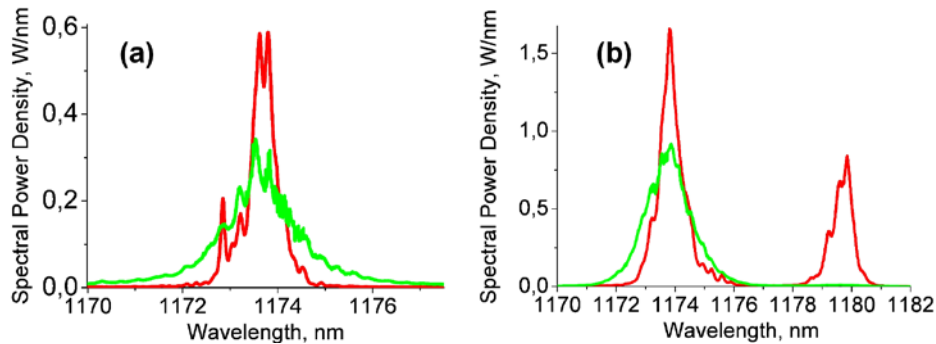


Fig. 3. Random distributed feedback fiber laser spectra generated in 11 km long TrueWave fiber (red) and 2 km long 1060-XP fiber (green): (a) near the threshold and (b) well above the threshold.

The higher are pump and generated powers, the wider and smoother is the generation spectrum. At Fig. 4 the width dependence on the output power is represented for the individual lines generated in the TrueWave (near 1174 nm) and the 1060-XP (near 1174 nm) fiber.

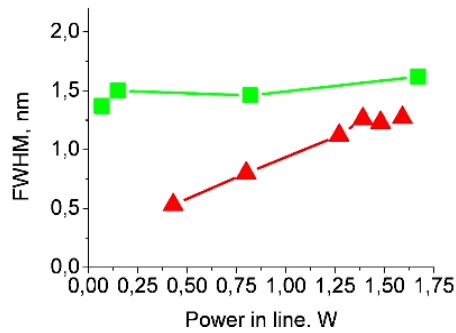


Fig. 4. The line width for 1060-XP peak (green squares), and for left (red triangles) peak in TrueWave.

At low generation power levels, the line width in the 1060-XP is roughly two times larger than the width of corresponding line generated in the TrueWave fiber. Using simple dimensional analysis, the spectral broadening factor of $\Gamma \sim \sqrt{\gamma P_s / \beta_2}$ can be derived, here γ is Kerr nonlinearity coefficient, P_s is the generated power and β_2 is group velocity dispersion parameter, measured in $\text{nm}^{-2} \cdot \text{km}^{-1}$. At $P_s = 0.5$ W, the $\Gamma = 0.35$ value for the 1060-XP fiber is 1.85 time higher than $\Gamma = 0.19$ value for the TrueWave fiber, what is in rough agreement with the experiment, Fig. 4. Note that the spectrum doesn't broaden with generation power increase in 1060-XP fiber. As it has been shown experimentally [24] and theoretically [25] the spectrum of a Stokes radiation can preserve its spectral width during the propagation in a long fiber under some conditions.

It has been also shown previously that in a conventional RFL with point-based highly-reflective mirrors spectrum broadening is caused by turbulent four-wave mixing of different longitudinal modes and can be described by the weak wave turbulence (WWT) approach [24,26]. Note that a spectral broadening factor derived via WWT approach for conventional RFL with high-Q shows the same dependence on parameters like $\Gamma \sim \sqrt{\gamma P_s / \beta_2}$. In the low-Q cavity RFL spectral broadening mechanism is the same [27]. Despite the fact that in the RDFB fiber laser there is no cavity of fixed length, the random refractive index variations could be thought as a multitude of very weak cavities of varying lengths [8] resulting in continuum of spectral components. Therefore, four-wave-mixing caused turbulent-like interactions of the components still can have impact on the spectral performances of RDFB fiber lasers.

The second Stokes wave radiation has two peaks for the whole pump range above the threshold, with the powerful long-wavelength line and the broad low-power short-wavelength one, Fig. 5.

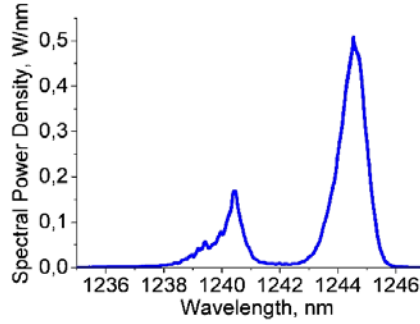


Fig. 5. Second Stokes wave spectrum observed in 10.7 km of TrueWave, at 7.5 W of pump power.

Finally, we have compared the spectral properties of RDFB fiber laser with spectral properties of the system without any feedback. Namely, we have considered the one pass scheme in which the forward propagating Stokes wave is amplified starting from the spontaneous emission level and Rayleigh backscattering is not taken into account. The following set of balance equations describes the process [28]:

$$\begin{cases} [d/dz + \alpha_s]N_s(\nu) = g_R(\nu)P_p(z)(N_s(\nu)+1), \\ [d/dz + \alpha_p]P_p(z) = -g_R(\nu)P_p(z) \int (N_s(\nu)+1) d\nu \cdot h\nu_p. \end{cases} \quad (2)$$

Here $N_s(\nu) = dP_s/d\lambda \cdot \lambda^3/(hc^2)$ is a spectral density of photons at ν frequency, ν_p – pump wave frequency. $g(\nu)$ – frequency-dependent Raman coefficient taken from [29].

The numerically calculated spectrum in this one pass system is shown at Fig. 6. During propagation along the fiber, the ASE spectrum could become narrower [30]. However, for our fiber parameters the resulting spectrum remains too broad comparing to the spectrum of the generation via random distributed feedback, Fig. 6. This is one more confirmation of the fact that we have observed in our system the laser generation in a cavity formed by random distributed feedback via Rayleigh backscattering, but not just spontaneous emission amplification in a one-pass scheme.

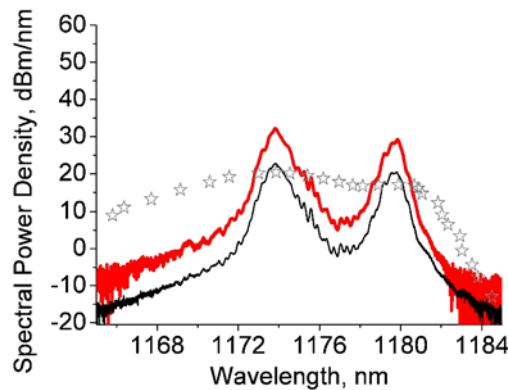


Fig. 6. Spectra of Stokes wave observed in 10.7 km of TrueWave in forward (black line) and backward (red line) directions. Spectrum of ASE calculated for one-pass scheme (gray stars). The logarithmic scale is used. Pump power is equal to 4 W.

Note that the RDFB fiber laser demonstrates practically the identical spectra for the light emitted from two laser outputs (laser side and fiber side), see Fig. 6. This fact might imply efficient mixing of the backward and forward waves, taking place due to Rayleigh feedback.

4. Conclusions

We have demonstrated the random distributed feedback Raman fiber laser operating in 1.2 μm wavelength range. Up to 3.8 W of output power near 1175 nm (first Stokes wave) and up to 1.1 W at 1242 nm (second Stokes wave) was generated. Thus, we have practically demonstrated that random distributed feedback results in efficient generation in other spectral band than initially demonstrated in [8]. The cascaded generation of Stokes components is achieved in RDFB Raman fiber laser for the first time to the best of our knowledge.

The power and spectral properties of the radiation generated in two different types of fibers are investigated. It is shown that Raman generation of single LP_{01} mode can be obtained below the cut-off wavelength of non-zero dispersion shifted fiber. It is shown that the one pass generation without any feedback provides the spectrum much wider than observed. Thus random feedback based on Rayleigh scattering plays a key role in formation of the narrow line-width generation.

It is likely that numerical modeling based on nonlinear Schrödinger equations could describe the generation properties of the random distributed feedback RFL similar how it is demonstrated for the conventional RFLs [24,31,32] and ytterbium doped fiber lasers [33]. This study will be presented elsewhere.

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