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Tunable random fiber laser

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An optical fiber is treated as a natural one-dimensional random system where lasing is possible due to a combination of Rayleigh scattering by refractive index inhomogeneities and distributed amplification through the Raman effect. We present such a random fiber laser that is tunable over a broad wavelength range with uniquely flat output power and high efficiency, which outperforms traditional lasers of the same category. Outstanding characteristics defined by deep underlying physics and the simplicity of the scheme make the demonstrated laser a very attractive light source both for fundamental science and practical applications.

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Random lasers operating without a traditional cavity have been demonstrated in a number of configurations with various materials; see [1–6] for a review of studies based on early ideas [7,8]. In a standard laser scheme, a gain medium is placed in an optical cavity that provides positive feedback and defines the structure of the laser modes. However, in random lasers the multiple scattering of photons in an amplifying disordered medium increases the effective optical path, eventually resulting in lasing. The output characteristics of random lasers are shown to be determined by randomly embedded local spatial modes that may coexist with nonlocalized extended modes [5,6].

Random lasers have clear advantages, such as simple technology without the need to engineer a precise cavity; e.g., just a semiconductor powder may be used in diode lasers; see, e.g., [4]. At the same time, more complicated (not fully understood) physical mechanisms define their output characteristics resulting in their current performance, which typically features pulsed operation with complex emission spectra and accidental direction of the output beam. These features have to be significantly improved to challenge conventional lasers in practical applications. Various schemes are proposed and applied to improve the performance of random lasers with the goal of achieving stationary operation with beam quality comparable to those of conventional lasers. A promising solution is to use low-dimensional random systems [9–12]. It has been shown that a directional output may be provided by random multilayers [9] or by 4-mm long photonic crystal fiber whose central hole is filled with bulk random material: a suspension of TiO_2 particles in a Rhodamine 6G dye solution [10].

A principally different class of one-dimensional weakly scattering random lasers [11] based on a conventional telecommunication fiber was demonstrated recently which exploited the intrinsic disorder of the fiberglass structure [12]. Indeed, the refractive index in the core of a standard telecommunication fiber has submicron-scale inhomogeneities, which are randomly distributed along the fiber. Propagating light experiences Rayleigh scattering on these inhomogeneities [13] resulting in light attenuation. In the random laser considered here we take advantage of both light wave guiding in a fiber and the random Rayleigh scattering (RS) that typically is a nondesirable effect in fiber devices. Only a small fraction of the scattered radiation is reflected back into the fiber waveguide: In a single-mode telecom fiber this part amounts to 1/600 of the total RS intensity that is defined by the waveguide acceptance angle. Hence, the Rayleigh backscattering coefficient is extremely small, having a typical value as low as $\varepsilon = 4.5 \times 10^{-5}$ km^{-1}. This feature makes the laser system considered in [12] rather different from many traditional random lasers [1–10] operating in the diffusive regime based on strong scattering. In spite of its weakness the randomly backscattered radiation amplified through the Raman effect during propagation in a long-fiber waveguide may provide feedback sufficient for lasing. In this paper we demonstrate an important step in moving random lasers to the stage of practical applications. As will be shown in this paper, the characteristics of the proposed tunable random fiber laser outperform conventional Raman fiber lasers.

Figure 1 illustrates the scheme of the proposed tunable random distributed feedback (RDFB) fiber laser. The important difference compared to the basic scheme of the RDFB fiber laser described in [12] is that a fiber-pigtailed tunable filter is introduced in the center of the scheme. The symmetric configuration with two spans of standard single mode optical fiber (SMF-28) of total length $L = 2 \times 21$ km $= 42$ km was used as a random laser medium to provide maximum output power when the Raman gain is equal to the loss at the ends of the fiber [12]. The fiber has a loss coefficient $\alpha \sim 0.045$ km^{-1} (0.2 dB/km) in the transparency window of silica glasses around 1550 nm. Two equal-power 1455-nm pumping waves are coupled at the center through 1450/1550-nm couplers in opposite directions, thus providing distributed Raman gain with coefficient $g_R \sim 0.39$ km^{-1} W^{-1} at ∼1555 nm. The tunable bandpass filter connected between the couplers acts as a wavelength-selective element that can be tuned over the conventional telecom range 1530–1570 nm. The transmission spectrum of the filter (with ∼1.5-nm FWHM and ∼2-dB insertion loss) measured by a supercontinuum source is illustrated in the inset of Fig. 1. Angled cleaves were used at the fiber end facets to eliminate Fresnel reflection and ensure that the feedback was due to the Rayleigh scattering only. The laser output power and spectra are measured from both ends with a high-resolution (∼0.01-nm) optical spectrum analyzer (OSA) connected via an angled-cleaved connector. The radio

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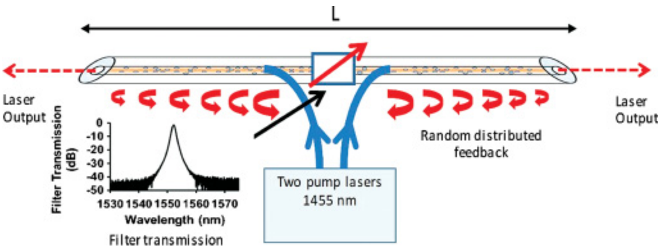

FIG. 1. (Color online) Schematics of the tunable RDFB fiber laser. Photons propagating in both directions are scattered obeying Rayleigh's law. Amplification is achieved by coupling two equal-power, 1455-nm pump waves into the center, while the tunable bandpass filter in the middle sets the wavelength (filter transmission spectrum is in the inset); the fiber length was chosen to give maximum output power.

frequency (rf) spectra characterizing intensity fluctuations were also measured using a photodiode and electric spectrum analyzer (ESA) with a resolution of ∼100 Hz.

Figure 2(a) shows the power measured at the left end while tuning the filter. Such tuning curves were measured at different total pump powers. Note that in the symmetric system with symmetric pumping the measured spectra and output powers are equal at both fiber ends. Near the threshold, the tuning curves closely follow the Raman gain spectral dependence with two maxima at 1555 and 1565 nm. With increasing pump power, the tuning range broadens and the tuning curve becomes flatter. At a total pump power of $\geqslant$6 W, the laser output power becomes almost constant with a variation of only ∼3% in the range 1535–1570 nm. This flatness is much better than that in a conventional linear cavity in the same fiber, or in ring cavities [14,15], where power flatness is around 20% in that range. Figure 2(b) shows the variation of the laser output spectrum for a constant pump power of 6 W. The generated laser spectra are nearly the same, being ∼50 dB above the noise level for all wavelengths except the shortest: When the filter is far away from the Raman gain maximum the system starts to lase near the Raman gain peak around 1555 nm, as is the case of a RDFB laser without any filter [12].

The corresponding power dependence at fixed wavelength is shown in Fig. 3. At the threshold the generation is unstable as a result of cooperative Rayleigh-Brillouin scattering [16]. When the pump power is increased well above the threshold the laser starts to operate in the quasi-continuous regime (constant in the μs scale and with 10% noise in the ns scale) with increasing output power nearly proportional to the pump power. We performed a direct comparison of the tunable RDFB laser with a conventional Raman laser with a linear cavity formed by broadband 4% reflection from the normally cleaved fiber ends, and with a second cavity configuration based on one cleaved fiber end and a highly reflecting fiber loop mirror connected to the other end of the same fiber. For the cavity with 4% reflections the threshold is lower and becomes much lower when the loop mirror is connected, but at high pump power the RDFB fiber laser reaches twice the output power compared to the 4% cavity amounting to $\sim 1.1 \times 2 = 2.2$ W from two ends with ∼30% efficiency (see inset) at >40% slope efficiency and

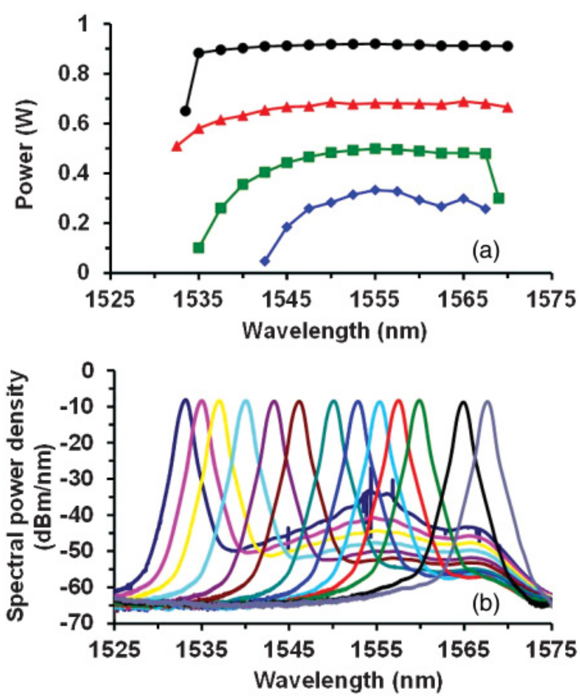

FIG. 2. (Color online) RDFB fiber laser tuning characteristics. (a) Tuning range in linear scale for different total pump power $P = 2P_{\text{in}} = 2.5$ W (diamonds), 3.5 W (squares), 4.5 W (triangles), 6 W (circles); at $P > 5$ W the variation of the laser output power is ∼3% (0.1 dB) for all wavelengths in the range 1535–1570 nm. (b) Spectra at different filter wavelengths are shown at $P = 6$ W. For wavelengths away from the Raman gain maximum (gain spectrum nearly corresponds to amplified background noise with two maxima at 1555 and 1565 nm and 10 dB gain variation), lasing at ∼1555 nm appears [12].

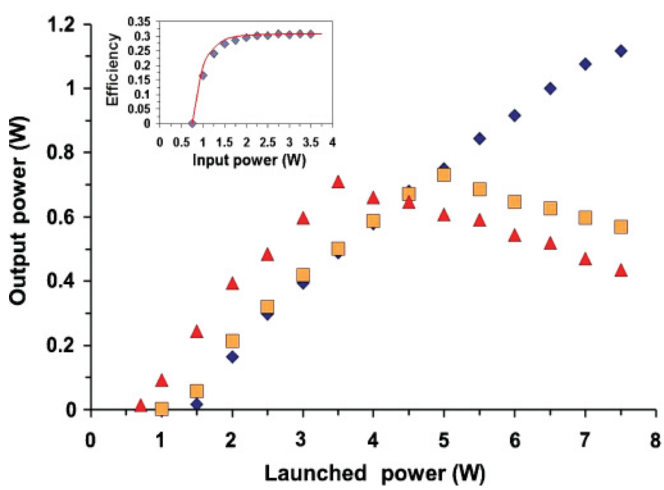

FIG. 3. (Color online) RDFB fiber laser power in comparison. Left output power (at 1560 nm) as a function of the total input pump power $P = 2P_{\text{in}}$ (at 1455 nm). For random fiber laser (diamonds) the output power is >1.1 W, demonstrating efficiency of ∼30% for total power from both ends (see inset). For 4% cavity and loop-mirror cavity (squares and triangles, respectively) the threshold is lower but maximum power is lower as well. The scheme with loop mirror has only one output end so its total power is two times lower than in symmetric schemes. Inset: RDFB laser efficiency in experiment (points) and theory (line).

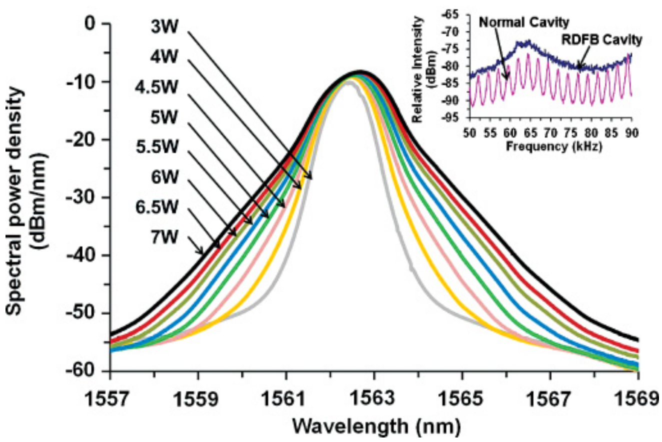

FIG. 4. (Color online) Tunable RDFB laser spectrum. Spectra for wavelength 1562.5 nm at different total pump power. With increasing power, the top part of the spectrum remains almost constant while exponential wings grow. Inset: Radio frequency spectra. For random fiber laser no mode beatings are seen but for a conventional fiber Raman laser a clear mode structure is observed.

approximately four times higher output than the loop mirror cavity which delivers laser power from one fiber end only.

The measured laser output spectrum matches the filter transmission near the threshold, but broadens with power; see Fig. 4. Note that the top part of the spectrum defined by the filter remains almost the same while exponential wings grow with increasing powers, similar to the spectral broadening in a conventional Raman fiber laser defined by turbulencelike nonlinear interactions of multiple cavity modes [17]. The principal difference between the random cavity and a conventional cavity is seen in the radio frequency spectrum; see inset in Fig. 4. For a conventional fiber Raman laser with 4% reflectors, a clear mode structure with spacing $c/2Ln \sim 2.4$ kHz corresponding to the round trip in the cavity with length $L = 42$ km was observed (similar to the Raman laser with highly reflecting mirrors [18]), as opposed to the random fiber laser where no mode beatings are seen. Thus, the developed tunable random fiber laser exhibits high-efficiency generation with a narrow-spectrum, quasi-CW output power with high-frequency intensity fluctuations having Gaussian probability density function, as is seen with a conventional fiber laser. At the same time, it has key distinctions, namely, much higher output power, outstanding flatness of the power tuning curve, and a continuous "modeless" spectrum consisting of random frequency components. A theoretical description of such spectrum and corresponding power fluctuations is a complicated problem that may be solved in terms of a new stochastic approach that is beyond the scope of this short paper. Here we break ground in RDFB fiber laser description providing a balanced approach for its average output characteristics.

The observed efficiency and flatness can be understood considering a simplified analytical model of the random fiber laser based on RS that we only outline here. Solving the balance equation for pump power $P_p(z)$ and generated Stokes wave power $P_{f,b}(z)$ (f: forward, b: backward) in the symmetric fiber system with two pump waves of power $P_{\rm in}$ coupled at the center ($z = 0$) in opposite directions as shown in Fig. 1, one can obtain the generation efficiency in the limit of very low reflection coefficient in the fiber spans (estimating in the first approximation RS as an accumulated reflector with coefficient $R \gg 1$) taking equal losses $\alpha_p \approx \alpha$:

$$\eta = \frac{P_{\rm out}}{P_{\rm in}} = \exp\left(-\delta_1 - \delta_2 - \alpha L/2\right) \frac{g_R}{g_P} \times \left\{1 - \exp\left[g_R\left(P_{\rm in}^{\rm th} - P_{\rm in}\right)\frac{1-\exp(-\alpha L/2)}{\alpha}\right]\right\}, \quad (1)$$

where $P_{\rm in} = P_p(z = 0)$ and $P_{\rm out} = P_{f,b}(z = \pm L/2)$ are input pump and output generated power in each direction, $L/2$ is the length of each arm, δ_1 and δ_2 are the loss coefficients for the input and output coupling, g_P and g_R are the Raman gain coefficients at the pump and laser wavelength, correspondingly. The generation threshold $P_{\rm in}^{\rm th}(\lambda) = \frac{1}{2}\frac{\alpha\ \exp(\delta_1)\ [\ln(1/R)+\alpha L]}{g_R(\lambda)\ [1-\exp(-\alpha L/2)]}$ is wavelength sensitive due to the variation of the Raman gain coefficient $g_R(\lambda)$. Since the factor $g_R(\lambda)/g_P(\lambda)$ is close to unity, the efficiency $\eta(\lambda)$ is almost independent of wavelength, and its deviation from the limiting value $\eta_0 \approx \exp[-\delta_1 - \delta_2 - \alpha L/2]$ becomes exponentially small at high $P_{\rm in}$. As a result, the constant power corresponding to efficiency η_0 is achieved for all wavelengths. It is approached exponentially with increasing power in the experiment, in correspondence with formula (1); see inset in Fig. 3. The formula is valid for extremely low reflection coefficient ($R_{\rm eff} = 1/600 \approx 0.0017$ for RS feedback) and long ($L/2 \geqslant \alpha^{-1}$) fiber pumped by high-power radiation ($g_R P_{\rm in}/\alpha \ll \ln[1/R]/2$), all conditions which are satisfied in our experiment. The maximum possible conversion efficiency is $\eta_{\rm max} \approx \exp(-\alpha L/2)$, estimated as 0.4 in our case ($L/2 = 21$ km), and we are close to this value in the experiment. Note that though the reflection coefficient is very low it is of principal importance for lasing resulting in a specific power dependence [Eq. (1)]. Considering only an amplified spontaneous wave without the feedback, the output power is an exponential function of the wavelength-dependent Raman gain coefficient $g_R(\lambda)$ at the studied pump powers.

Compared to a conventional laser, the studied RDFB fiber laser has higher slope efficiency in spite of a significantly higher threshold (see Fig. 3); therefore its output power surpasses the power of the Raman laser with 4% cavity already at $\sim$4 W pump power. Moreover, the output power for the Stokes wave generated in the normal cavity manifests an abrupt saturation that is defined by generation of the second Stokes wave. In the scheme with RS-based random distributed feedback, the threshold for the second Stokes wave generation becomes much higher due to much lower integral reflection, thus resulting in much higher achievable power for the first Stokes wave. In addition to extremely low reflection the developed random fiber laser is characterized by a very specific longitudinal laser power distribution with maximum at the edge of the gain region similar to diffusive random lasers [11], and very low power in the center [12] where the tuning filter is placed. As a result, the nonlinear loss due to filtering, which is sensitive to the spectral broadening, is lower for the proposed random laser as it has much lower local power at the filter. Another important feature of the RDFB laser is self-adjustment of the effective distributed cavity: High output power depletes the pump wave thus shortening the effective length of the cavity $2L_{RS}(P)$, potentially allowing the use of shorter fibers providing higher efficiency, $\eta_{\max} \approx \exp(-\alpha L/2)$. Competition of random spectral components which utilize the same pump should lead to their self-organization. These new effects are important for description of spectral and noise characteristics which is a challenging goal for the development of random fiber laser theory.

Thus we have demonstrated a tunable random fiber laser with outstanding characteristics and a rather simple design solution, albeit exhibiting rich and complex underlying physical mechanisms. The demonstration of this high-power efficient random fiber laser with broad-range flat tuning and very good spatial and spectral performance performance (high-quality beam with narrow spectrum defined by the tunable filter) represents a significant milestone for random laser science and adds a dimension to the applications of disorder-based light sources. The demonstrated laser presents an interesting object for fundamental research as well as a practical device with high performance and simple design implemented in standard optical fiber by means of standard telecom components, widening a range of applications in optical communication, sensing, and secure transmission.

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