While pump power increases, the amplification length decreases because of the pump power depletion. When $L_{RS} < 1/\alpha$, Eq. (16) can be simplified using Eq. (15):

$$L_{RS} = \frac{1}{g_S P_P(0)} \ln\left(g_S P_P(0) \sqrt{\frac{2}{\alpha\varepsilon}} \Bigg/ \left(1 - \frac{P_{th}}{P_P(0)}\right)\right) \quad (17)$$

L_{RS} depends on pump power inversely, with the logarithmic accuracy. This analytical result is also in good agreement with both experimental data and numerical simulation, see Fig. 6(b).

6. Discussion and conclusions

Summarizing the obtained results, the longitudinal power distributions generated in the random DFB fiber laser in symmetric configuration have been studied both experimentally and theoretically. The simple analytical model describes with high accuracy first Stokes wave characteristics, namely: generation threshold, power dependence at center point ($z = 0$), the position of maximum power ($|z| = L_{RS}$) as well as the spatial longitudinal distribution. The numerical and analytical calculations of the first Stokes wave give very close values which are also in good quantitative agreement with obtained experimental results.

It has been found that the spectral shapes are identical for the opposite waves and do not change during the propagation of the waves along the fiber. That is consistent with the idea of Rayleigh scattering feedback being responsible for the lasing and coupling of the spectral characteristics of both waves.

The specific combination of distributed Raman amplification with maximum gain in the center ($z = 0$) defined by the symmetric pumping scheme and the RS-based random DFB cavity results in a specific distribution of the generated Stokes wave power. The distribution is symmetric both for the forward and backward Stokes waves, which reach maximum power at symmetric points $|z| = L_{RS}$ corresponding to the boundary of the amplification region. At $|z|> L_{RS}$ the generated power attenuates nearly exponentially with a coefficient defined by linear losses.

In previous works, the spatial mode power distribution was measured in conventional DFB fiber lasers with short (cm-long) active media in which strong regular fiber Bragg gratings with π-shift in the center was inscribed [21]. In a conventional DFB laser the generated power has maximum power at the center with exponential attenuation to fiber ends. At the absence of π-shift in a DFB cavity, power distributions for the opposite waves become different and reach their maximum values at the fiber ends corresponding to the boundary of both the active fiber and regular grating. In this sense the random DFB fiber laser has some similarity with a conventional DFB fiber laser based on a grating without phase shifts. Note that introducing irregularities in the fiber Bragg grating by means of inscription in the active fiber either an irregular array of short FBGs [22] or introducing random phase shifts in a relatively long (tens of centimeters) grating of DFB laser [23] leads to a spatial power distribution with maximum in the center of the active fiber similar to the distribution observed in a DFB fiber laser with a π-shifted regular grating [21].

Another important feature of the power distribution in the random DFB fiber laser is its dependence on the pump power. The position of maximum generated power appears to shift to the pump coupling point ($z = 0$) nearly inversely with pump power. Such behavior is defined by pump power depletion, see Fig. 5, leading to corresponding shift of the gain boundary point L_{RS} to the center. The model offers the way of power optimization: the half-length of the random DFB fiber laser L should be close to L_{RS} value to eliminate exponential attenuation of the generated wave thus reaching highest possible conversion efficiency (defined by loss factor $\eta \sim exp(-\alpha L)$ [12]) which could be even higher than that for conventional Raman fiber laser with linear cavity formed in the same fiber. This estimate is in agreement with the measured conversion efficiency in power maxima ($|z| = L_{RS}$), exceeding $\eta \sim 0.6$; see Fig. 3. As we have found here, increasing pump power well above the threshold

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results in reduction of the optimal length nearly inversely with power, down to $L \sim L_{RS} < 5$ km in our case. Relevant shortening of the fiber will lead to higher random lasing threshold, however, the conversion efficiency may be further increased because of the loss reduction.

The next limitation is induced by the second Stokes wave generation after reaching the second threshold. It has been found that the second Stokes wave has quite different longitudinal distribution with maximum shifted to longer distances, $|z| > L_{RS}$. The second Stokes wave distribution is also more uniform compared to the first Stokes wave distribution at the same average generated powers. It is likely that the higher order schemes could provide an even more flat distribution that could be important for possible telecom applications such as quasi-lossless transmission [14]. Optimization of the output power for the second Stokes wave can make the optimal arm length in the symmetric scheme longer than the one for the first Stokes in correspondence with the position of maximum power for the second Stokes wave. Therefore, using the symmetric random DFB scheme one can optimize output power for each Stokes order, thus reaching maximum possible conversion efficiency of the cascaded Raman fiber laser of corresponding length for the chosen order. Note that the specific saturation character demonstrating almost full depletion of the first Stokes wave confirms high-efficiency conversion to higher order Stokes waves. Measured conversion efficiency for power values at the maxima of the distribution is over 60% not only for the first order, but also for the second order Stokes wave. In the framework of the model developed in [15] for a fiber laser with linear cavity formed by point-based mirrors, the strongly decreasing output power of the first Stokes wave at powers higher than the second Stokes wave generation threshold means strongly decreasing losses for the first Stokes wave. Indeed, the ratio of the output power to the average power inside the fiber is decreasing with pump power, Fig. 3. This may be interpreted as an increase of the finesse of the effective cavity of the random DFB fiber laser with increasing power, quite opposite to the case of a laser with a conventional FBG based cavity where a cavity finesse is decreased owing to a spectral broadening of the generated radiation in excess of the FBG bandwidth; see, e.g., [15]. Thus, this important drawback of conventional Raman fiber lasers is eliminated in the random DFB fiber laser because the distributed Rayleigh mirror is naturally broadband and has equal reflection for all frequencies inside the generated spectrum.

Thus, the obtained results have an important impact on the identification of the lasing mechanism in random DFB fiber lasers and the search for new applications.

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