Calculation of output power of random DFB fiber laser

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We present a comprehensive study of power output characteristics of random distributed feedback Raman fiber lasers. The calculated optimal slope efficiency of the backward wave generation in the one-arm configuration is shown to be as high as ~ 90% for 1 W threshold. Nevertheless, in real applications a presence of a small reflection at fiber ends can appreciably deteriorate the power performance. The developed numerical model well describes the experimental data.

Introduction

Random distributed feedback (RDFB) Raman fiber lasers (RFLs) [1] have attracted a great interest for a past couple of years because of specific properties compared to other types of random lasers (see [2] for a review). Up to date, a number of different schemes are proposed [3-10] resulting in cascaded, multi-wavelength, tunable operation making RDFB lasers comparable to conventional RFLs performances [11,12]. Using a balance equation set, the longitudinal power distribution could be calculated numerically [13] and analytically [14]. The balance equation set provides also a possibility to optimize the performance of the laser. It's worth determining the highest possible efficiency of the RDFB laser as it's the crucial issue for the future application. In the present paper we make a power optimization of the random DFB fiber laser, and show that a one-arm configuration with a single pump provides better performances than the symmetrical configuration [1].

Numerical model

We study the single pump configuration where the pump light is coupled into a long fiber span from one side. To model the power performances of a random DFB fiber laser, we use the well-known power balance equation set, dealing with longitudinal power distribution of pump, first and second Stokes wave and taking into account Raman amplification, Rayleigh backscattering and fiber losses. We calculate the power performance of the random DFB lasers which were experimentally studied in [5]. We model the laser operating at 1.2 μm and based on 10.7 km fiber. The balance equation set provides us a good prediction for the first Stokes wave power as well as for the first Stokes wave generation threshold, Fig. 2a. However, big discrepancy turned out in second Stokes wave generation threshold: 12.4 W in numeric, 6.6 W in experiment.

In general, the threshold could become lower if there is an additional feedback in the cavity. To check this, we modify the boundary conditions introducing parasitic point-like reflection due to surface scattering at fiber ends. The parasitic reflection values of only $4\cdot10^{-5}$ give a good agreement for the second Stokes generation threshold keeping an accuracy for prediction of the first Stokes wave power. It is important that in the experimental conditions such a small value of the parasitic reflection is simply achievable because of dust and dirt on the fiber end surface, or physical damage of output connectors, as even low-reflection angle-polished connectors usually reflect no less than 10^{-6}.

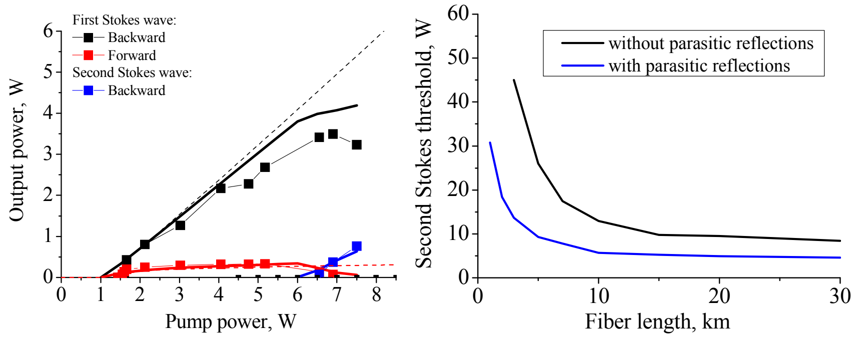

Fig. 1. (a) First Stokes (forward – red, backward - black) and Second Stokes (backward - blue) output powers for the random DFB laser based on 10.7 км TrueWave fiber: experimental data (boxes), numerical calculation without (dash) and with (solid) parasitic reflection. (b) Calculated generation threshold of second Stokes wave with (blue) and without (black) parasitic reflections of $4\cdot10^{-5}$ at the fiber ends.

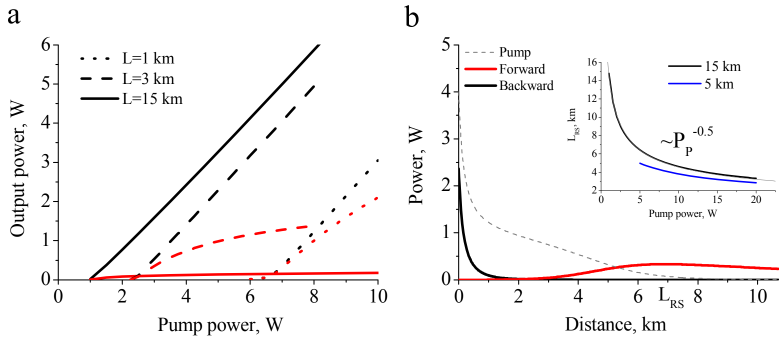

Fig. 2. (a) The forward and backward output powers for different fiber lengths (red – forward waves, black – backward waves). (b) The typical longitudinal power distribution of the pump wave and generated forward and backward wave. Pump power is 4 W. Calculations are made for TrueWave fiber and lasing at 1.2 µm. Inset: L_{RS} dependence on pump power for different fiber lengths.

The integral value of the random distributed feedback is as small as $\alpha_S \cdot Q \cdot L \sim 10^{-3}$-$10^{-4}$, so even a tiny parasitic feedback can sufficiently influence the generation properties.
Parasitic scattering could sufficiently reduce the second Stokes wave generation threshold, Fig. 1b, and thus limit the maximum achievable power in the first Stokes wave. Finally, parasitic reflection affects the generation efficiency also. The differential efficiency in experiment with a parasitic scattering is lower than in numerical simulation with zero point-like scattering, Fig. 1a, and with increasing the parasitic reflection this effect becomes more pronounced. Thus, one needs to carefully manage parasitic reflection in experiments to achieve the desired laser performances.

Power optimization

The balance equation set can be used for power optimization of the random DFB fiber laser. In the following calculations we do not consider parasitic point reflections. It has been found that the forward and backward output powers depend completely differently on pump power. While the pump power increases, the forward output power starts to be saturated, while the backward output power increases linearly, Fig. 2a. It is important that the backward output power is always higher than the forward power.

Saturation of the forward output power is obviously caused by the shifting of the point $z=L_{RS}$, where the saturated Raman gain is equal to losses, $g_S \cdot P_P(L_{RS})=\alpha_S$. While the pump power increases, the value of LRS is reduced due to the pump wave depletion. Thus the forward wave propagates more in a loss region at $z>L_{RS}$, and the forward output power is saturated. From the practical point of view, such saturation could be an important drawback of the laser. However, comparing the single pump one-arm scheme under study with classical symmetrical scheme with two pumps [1] reveals that the single arm scheme is more favorable as L_{RS} decreases as only $1/\sqrt{P_P}$, Fig. 2b, insert, contrary to the law of $1/P_P$ in symmetrical configuration [14]. This means that saturation effects in forward output power are less pronounced in the one-arm single-pump configuration. Decreasing L_{RS} at higher pump power does not affect the backward wave output power, as the typical length of backward wave amplifying is always less than L_{RS}, and backward wave is mainly amplified near the fiber end where the pump wave is undepleted, Fig.4b. As a result, the backward wave output power depends always linearly on pump power without any saturation. In addition, the backward output of the random DFB fiber laser does not include any residual pump, so it is preferably to use a single-pump one-arm configuration with backward output in practical applications.

Finally, we found that the generation efficiency the backward output power is almost constant while varying fiber length for and reaches ~ 90% that is close to the quantum limit of 95%. For the system under study with the threshold of 1 W, total efficiency reaches the value of 70% at pump level of 7 W. For the forward output power the efficiency decreases with exponential law $\exp(-\alpha_S \cdot L)$ similar to the symmetrical random laser configuration [14]. The backward output power efficiency varies only slightly over broad range of Raman gain and loss values.

Conclusion

We have presented the detailed analysis of power performances of the one-arm single-pump random DFB fiber laser. It is found that even tiny parasitic reflection at fiber ends play a key role determining the laser power performance. The laser radiates mainly in the direction backward to the pump power. Single-pump one-arm configuration is more preferable comparing to symmetrical configuration with 2 pumps from the fiber center [1], as saturation effect in forward output wave are less pronounced, and the high efficiency of the backward wave generation almost does not depend on fiber length, losses and Raman gain coefficient. Using the model of NLSE [15,16] one can calculate spectral and statistical properties of RDFB fiber lasers similar to works [17-20]. The calculation of noise performances of RDFB lasers and comparison with noise level of conventional RFLs is also of high importance [21-22], as this lasers should have no resolvable mode structure.

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