NLSE-based modeling of random DFB fiber laser power and spectrum

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For the first time we report full numerical modeling of random distributed feedback fibre laser based on Rayleigh scattering. The model is based on generalized non-linear Schrödinger equation. We compare simulated and experimentally observed spectra, longitudinal power distributions, lasing threshold and dependence of lasing power on pump power.

Introduction

Random DFB fiber lasers has attracted a great attention since first demonstration [1]. Different fiber laser systems based on the random DFB concept were studied in the past year generating in different spectral bands, providing cascaded, tunable, multi-wavelength output [5-12] similar to conventional RFL performances, see, for ex., [13,14], including a potential for efficient frequency doubling [15]. It has been shown that noise level of RDFB fiber lasers could be lower than in conventional RFLs [16,17]. Using a balance equation set, the longitudinal power distribution could be calculated numerically [1] and analytically [11]. However, spectral and statistical properties of RDFB fiber laser can not be calculated within the balance equation model. Here we present first numerical simulations of the RDFB fiber laser using NLSE-based model.

Numerical Model

In order to simulate lasing in random DFB fibre cavity we used a set of non-linear Schrödinger equations similar to used earlier for investigation of conventional RFL, YDFL, Brillouin lasers and supercontinuum sorces [18-22], but with additional terms that describe Rayleigh scattering. Propagation equations can be z-averaged over dispersion walk-off length of the Stokes wave and pumping what results in nulling of phase cross-modulation term:

$$\frac{\partial A_p^{\pm}}{\partial z}-\frac{1}{v_{gs}}\frac{\partial A_p^{\pm}}{\partial t}+\frac{i}{2}\beta_{2p}\frac{\partial^2 A_p^{\pm}}{\partial t^2}+\frac{\alpha_p}{2}A_p^{\pm}=i\gamma_p\left|A_p^{\pm}\right|^2 A_p^{\pm}-\frac{g_p(\omega)}{2}\left(\left\langle\left|A_s^{\pm}\right|^2\right\rangle+\left\langle\left|A_s^{\mp}\right|^2\right\rangle\right)A_p^{\pm} \qquad (1)$$

$$\frac{\partial A_s^{\pm}}{\partial z}+\frac{i}{2}\beta_{2s}\frac{\partial^2 A_s^{\pm}}{\partial t^2}+\frac{\alpha_s}{2}A_s^{\pm}-\frac{\varepsilon(\omega)}{2}A_s^{\pm}=i\gamma_s\left|A_s^{\pm}\right|^2 A_s^{\pm}+\frac{g_s(\omega)}{2}\left(\left\langle\left|A_p^{\pm}\right|^2\right\rangle+\left\langle\left|A_p^{\mp}\right|^2\right\rangle\right)A_s^{\pm}$$

where A is complex field envelope, z is a longitudinal coordinate in the direction of wave vector, t stands for time in a frame of references moving with pump wave, v_{gs} is a difference between pump and Stokes waves inverse group velocities, β_2, α, γ, g are dispersion, linear attenuation, Kerr and Raman coefficients, ε is Rayleigh scattering coefficient, ω stands for frequency, ± denotes counter-propagating waves, “s” and “p” are used for Stokes and pump waves.

In contrast to equation set used earlier for fiber laser modelling [18-20,22], Eqs. (1) contain a small term proportional to $\varepsilon = 2.0\times10^{-4}$ dB/km = 4.5×10^{-5} km^{-1}, Rayleigh scattering coefficient. We consider only energy income into Stokes waves whereas corresponding energy depletion of pump waves are considered with other linear energy losses through the term proportional to α. Energy income to pump waves through Rayleigh scattering is neglected since it's not amplified by stimulated Raman scattering.

We integrated Eqs. (1) along z using iterative approach, i.e. when integrating equations for $A^{+}_{\mathrm{s,p}}$ we used $A^{-}_{\mathrm{s,p}}$ obtained on previous iteration, and vice versa. This approach is quite easy for use due to the fact that counter-propagating waves enter into equations only by means of their intensities which are slowly varying along z. The only exception is the term proportional to ε which describe backward Rayleigh scattering. In order to integrate this term spectra of Stokes waves were saved at N_1 = 50 z-points during each iteration and were used at the next iteration. Rayleigh term was calculated in Fourier domain what makes it easy to make ε frequency-dependent by introducing factor ω^2/ω_0^2 for amplitudes which correspond to ω^4 law for energy. Before being added to Stokes wave, the backward-scattered wave taken from previous iteration is multiplied by a complex factor $e^{i\varphi}$ with random phase φ and time-shifted in a random way, i.e. the following transformation is applied (shown for simplicity for the "+"-wave only):

$$A_s^+(z+\Delta z) = A_s^+(z) + \left(\varepsilon \cdot \int\limits_z^{z+\Delta z} \mathrm{d}z' \int\limits_{-\infty}^{+\infty} \mathrm{d}\omega \left| A_s^-(L-z') \right|^2 \right) \cdot \frac{A_s^-(L - z_{\mathrm{prox}})}{\int \left| A_s^-(L - z_{\mathrm{prox}}) \right|^2 \mathrm{d}\omega} \cdot \frac{\omega^2}{\omega_0^2} \cdot e^{i\varphi_0 + i\omega\tau_0}$$

where φ_0 and τ_0 are random phase and time shifts which are generated independently at each numerical step Δz, z_{prox} stands for z-coordinate of the closest point where spectra of counter-propagating Stokes wave were saved at previous iteration.

Since the laser is symmetrical and can be represented as a half cavity with an ideal mirror the propagation equations (1) were integrated only along right half of the cavity what allowed us to slightly simplify computation scheme.

In contrast to similar simulations of conventional RFLs and YDFLs [18-20s] where lasing spectrum is defined primarily by fiber Bragg gratings (FBG) and non-linear optical interactions, modeling of Rayleigh laser requires taking into account spectral profile of Raman gain. In this work we used Gaussian approximation for Raman gain profile.

Results and discussion

We calculate a dependence of lasing power (i.e. Stokes "+"-wave) as a function of single-side pump power, Fig.1. The oscillator has a lasing threshold close to 0.8 W, which corresponds to experimental observations [1, 2] and analytical calculations [11]. If pump power is well above the threshold the output power grows linearly with pump power what agrees well with previous experimental observations [1,2].

Figure 2b shows longitudinal power distributions of pump (blue lines) and Stokes waves (red lines) obtained in numerical simulations for 2 W of a single-side pump power. The power distributions reproduce qualitatively those observed earlier in experiment and in analytical calculations [11]. The power distribution differs from exponential law at z ~ 3.5 km what is due to z-dependent depletion rate caused by stimulated Raman scattering.

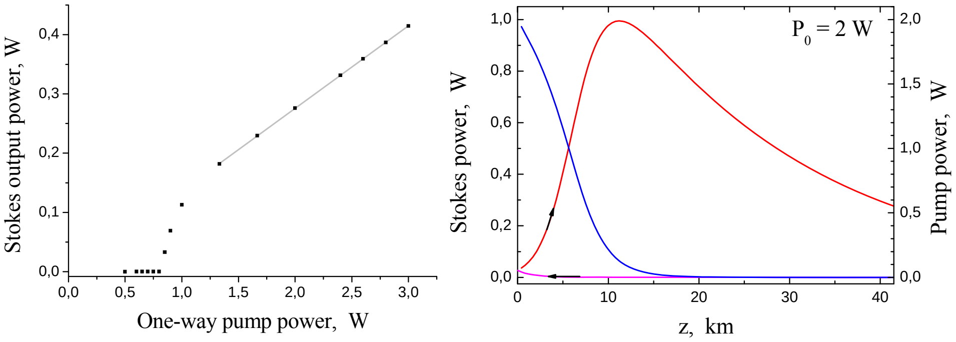

Fig. 1 (a) Output laser power vs. one-side pump power. (b) Longitudinal power distribution for pump (blue line) and Stokes wave (red and magenta lines for "+" and "–" Stokes waves correspondingly).

Typical spectra of generated Stokes waves are shown in Fig. 2a. Probability density functions (PDF) of output power are shown in Fig. 2b. Similar to relatively short Raman fiber lasers with FBG mirrors the intensity PDF of random-feedback laser are not exponential [23-25].

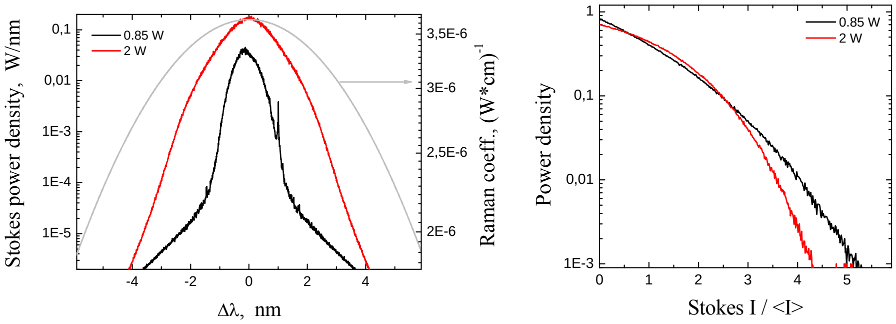

Fig. 2. (a) Spectrum for generated Stokes "+"-wave at cavity exit ($\Delta\lambda = \lambda - 1556$ nm) together with Raman gain profile (grey) and (b) Intensity power density functions for generated Stokes wave intensity I/<I>

Conclusions

For the first time a numerical modeling of random distributed feedback fibre laser based on Rayleigh scattering are performed with the use of generalized non-linear Schrödinger equation. Simulation results are shown to be in good qualitative agreement with previous experimental observations in generation spectrum, longitudinal power distributions and dependence of output power.

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