The counter-propagating traveling-wave technique for optimizing a continuous-wave fiber laser presenting excited state absorption

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***Abstract*—We report results of simulation of a continuous-wave fiber laser with active medium presenting an excited state absorption. The laser was simulated using the counter-propagating traveling-wave technique with taking into account two laser waves propagating along the laser cavity in opposite directions, two waves of amplified spontaneous emission, and exited state absorption observed for both pump and laser wavelength. We show that the optimal reflection of the output selective mirror baser on a fiber Bragg grating depends on pump power and the active fiber length.**

***Index Terms*—Optical fiber lasers, excited state absorption, simulation.**

I. Introduction

Fiber lasers (FLs) are efficient devices with high optical efficiency, excellent power budget, large power scaling, and operation wavelengths from near-infrared to middle-infrared optical range, depending on the optical fiber host and active dopants. The mayor part of the active dopants used for fabrication of optical fibers demonstrate exited state absorption (ESA) which limits FLs' efficiency. Numerical simulation of FLs permits one to optimize parameters of FL cavities at which the maximum of the output FL power may be reached. Usually, the parameters for the FLs optimization is reflection of the output laser power and the active fiber length.

In this work we report the results of modeling of continuous-wave (CW) FL based on the active fiber that presents ESA at both the pump and the laser wavelengths. For simulation we chose the silica fiber doped with erbium as an active medium and the counter-propagating traveling-wave technique for the numerical study.

II. Energy levels and the fiber laser simplified scheme

The simplified energy diagram of the erbium ion is shown in Figure 1, which is limited by fife energy levels. The levels 1 and 2 ($^4\mathbf{I}_{13/2}$) are the ground and the laser (excited) states, respectively. The level 3 ($^4\mathbf{I}_{11/2}$) is the pump level. Other levels correspond to ESA at the pump (3→5) and the laser (2→4) wavelengths.

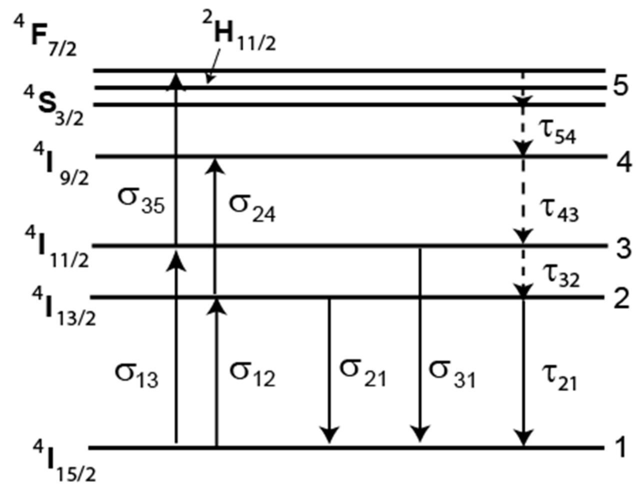

Figure 1. Energy-level diagram used in modeling: photon and phonon transitions are shown by solid and dash lines, respectively; cross-sections σ_{ij} and decay times τ_{ij} for transitions between the levels i and j are marked near the corresponding arrows.

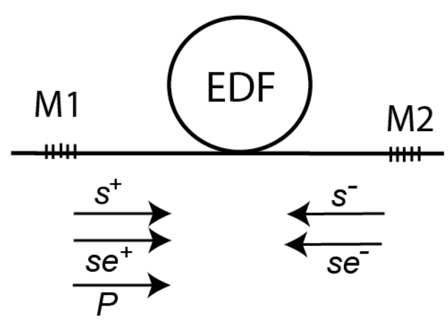

Figure 2. Scheme of FL: EDF is erbium-doped fiber, M1 and M2 are 100%- and variable mirrors, respectively. s^+, s^-, se^+, and se^- are signal (laser) and SE counter-propagating waves, and P is the pump wave.

The sketch of FL is shown in Figure 2. It is seen that there are four waves propagating along the cavity in the opposite directions: two laser waves and two ASE waves, and only one pump wave propagating to the right direction. The boundary conditions for these five waves and the output laser signal s_{out} are as follows:

$$P(0) = P_0 \quad (1)$$
$$s^+(0) = s^-(0) \quad (2)$$
$$s^-(L) = M_2 s^+(L) \quad (3)$$
$$s_{out} = (1 - M_2)s^+(L) \quad (4)$$

where $z = 0$ corresponds to position of the mirror M1, $z = L$ to the mirror M2 (the output mirror), P_0 is the input pump power (this value is given), and L is the cavity length.

III. COUNTER-PROPAGATED TRAVELING-WAVES

The laser model considers fife waves traveling along the cavity: two laser waves, two SE waves and one pump wave. The equations for these waves are as follows:

$$\frac{dP(z)}{dz} = -\alpha_{p0}\left[n_1(z) - \left(\xi_p - \varepsilon_p\right)n_3(z)\right]P(z) \quad (5)$$
$$\frac{ds^{\pm}(z)}{dz} = g_{s0}[(\xi_s - \varepsilon_s)n_2(z) - n_1(z)]s^{\pm}(z) \quad (6)$$
$$\frac{dse^{\pm}(z)}{dz} = g_{se0}[(\xi_{se} - \varepsilon_{se})n_2(z) - n_1(z)]se^{\pm}(z) \quad (7)$$

where $\varepsilon_p = \sigma_{35}/\sigma_{13}$, $\varepsilon_s = \sigma^s_{24}/\sigma^s_{12}$, $\varepsilon_s = \sigma^s_{24}/\sigma^s_{12}$, $\varepsilon_{se} = \sigma^{se}_{24}/\sigma^{se}_{12}$, $\xi_p = \sigma_{31}/\sigma_{13}$, $\xi_p = \sigma_{31}/\sigma_{13}$, $\xi_s = \sigma_{21}/\sigma_{12}$, and $\xi_{se} = \sigma^{se}_{21}/\sigma^{se}_{12}$. Here sub-symbols p and s corresponds to transitions at the pump and the laser wavelengths, whereas se to wavelength at which SE have maximal gain. Parameters α_{p0}, g_{s0} and g_{se0} are the small-signal absorption at the pump wavelength, non-saturated gain at the laser and at the SE wavelengths, respectively, variables n_1, n_2, and n_3 are populations of the correspondent erbium levels normalized to erbium concentration. Populations of the 4th and 5th levels are considered via the balance equations, see ref. [1].

IV. RESULTS AND DISCUSSION

Considering the balance equations and erbium-doped fiber parameters discussed in ref. [1], the counter-propagating traveling waves at the pump, the laser and SE wavelength, and the boundary conditions, we obtained the dependence of the output laser power versus reflection of the output mirror for different pump power (see Figure 3). In these simulations, the laser and the pump wavelengths were considered as 1550 nm and 975 nm, respectively, and the active fiber length was $L = 4$ m. From this figure one can see that the optimal reflection at which the laser demonstrates the maximum power is about 10%. At increasing the M2 reflection above this value, the intra-cavity laser power grows, which leads to increasing a number of the ESA transitions' resulting in additional fiber heating, and the laser efficiency decreases. At decreasing M2 reflection below the optimal value, the laser cavity power drops down because the cavity Q-factor decreases to the small values at which the laser is inefficient.

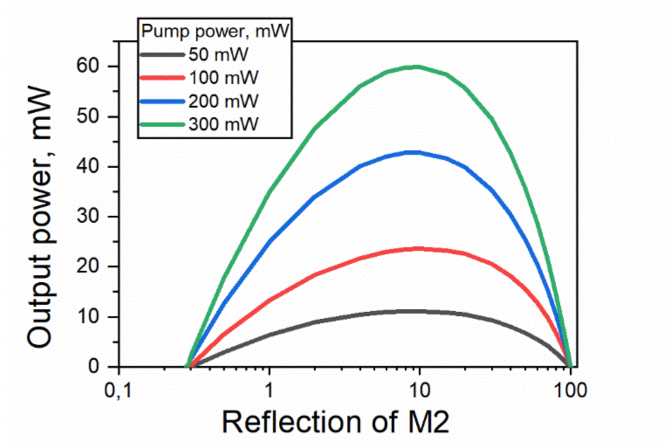

Figure 3. Output laser power as a function of pump power.

REFERENCES

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