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Optimization of strongly pumped Yb-doped double-clad fiber lasers using a wide-scope approximate analytical model

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ABSTRACT

An analytical model based on the rate equations of strongly pumped Yb-doped double-clad fiber laser (DCFLs) is presented. The output power and the distributed laser along the whole fiber have been found. In this paper, most parameters affecting the laser performance have been considered. The influences of scattering losses, pump reflection, output reflectivity, doping concentration and fiber length have been studied. It is shown that for wide ranges of the previous parameters and large variations of the input powers for all types of pumping (forward, backward and two-end), the maximum relative error of the output power would be less than 2.72% when the results are compared with the numerical model. Depending on our analytical model, a simple optimization method has been illustrated for high-power laser oscillators.

1. Introduction

High efficiency, high power, good beam quality and compactness are interesting features of double-clad fiber lasers (DCFLs) over the other lasers. These attractive features led to applications of DCFLs in diverse fields such as industry, military, medicine and telecommunications. In recent years, an output power of 1.36 kW and an efficiency of 83%, was obtained from a single fiber with no amplifying stages [1]. There are some analytical approximations for predicting the output parameters of fiber lasers which have different levels of complexity. In an attempt the scattering losses were considered, but it has a large relative error when compared to numerical results and it increases with the increase of the output reflectivity. The relative error is 6.4% for an output reflectivity of 0.2 [2]. Other approximations showed that the relative error increases with the decrease of the output reflectivity and it is 6% for a typical resonator (high feedback reflectivity of about 0.98 and low output reflectivity of about 0.04) [3].

In a new model, the relative error has been improved to about 2.4%, but this model works only for short fibers (15 m for a typical resonator), also this model has not been tested for a wide range of reflectivities that the mentioned error has been obtained after testing only three reflectivities′ values [4]. Furthermore the mentioned articles [2], [3,4], never consider the pump reflection.

In this paper, the set of rate equations (REs) for linear Yb^{+3}-doped DCFLs are solved analytically using two steps, the first step is done by applying rough approximations to obtain the preliminary values of unknowns. The second step uses only one main approximation regarding the backward signal power, to develop an explicit analytical model whose inputs are the preliminary values calculated in the first step. Our analytical model considers most influencing parameters on the fiber laser performance. The analytical results are in good agreement with the numerical ones that the maximum relative error between both results remains below 2.72%, even though wide ranges of these-parameters values and different pumping types are investigated. Finally, a simple method is presented to optimize high-power fiber lasers. The numerical analysis is based on the fourth-order Runge–Kutta method to solve the fiber′s REs while the binary chopping method is used as a shooting method to correct the successive initial values until reaching the desired precision.

2. Rate equations

Our linear cavity is composed of Yb-doped DCFL of length L and four fiber Bragg gratings (FBGs) with reflectivities of R_{1p}, R_{2p} at the pump wavelength λ_p, and R_{1s}, R_{2s} at laser wavelength λ_s. The back FBGs serve as feedback mirrors for both laser and backward pump radiations in the backward pumping case. The output FBGs have reflectivities of R_{2p} at λ_p and R_{2s} at λ_s. They are used as an output coupler for laser and as a feedback mirror for forward pump radiation in the forward pumping case. Fig. 1. shows schematic illustration of the laser oscillator.

CW operation with the strong pumping case is assumed, therefore the gain is well saturated and the spontaneous emission

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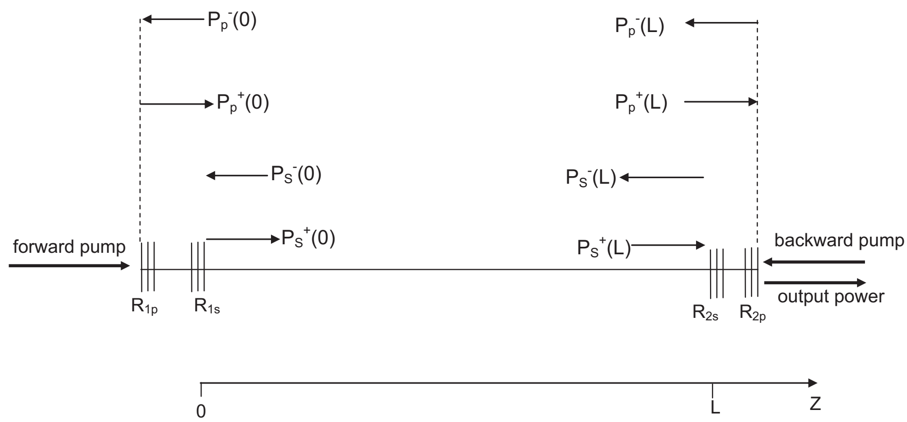

Fig. 1. Schematic illustration of a linear laser cavity. $P_s^{\pm}(z)$ QUOTE and $P_p^{\pm}(z)$ QUOTE are the signal and pump powers respectively propagating in the positive direction (+) and in the negative one (−).

can be neglected. The excited-state absorption (ESA) is eliminated because of the quasi-three-level system of the Ytterbium ion [5]. The laser output and the pump have very narrow spectral widths and they are approximated by their single wavelengths λ_p and λ_s. The rate equations for steady-state operation are as follows [5]:

$$\frac{N_2(z)}{N} = \frac{(P_p\sigma_{ap}\Gamma_p/h\nu_pA)+(P_s\sigma_{as}\Gamma_s/h\nu_sA)}{(P_p\Phi_p\Gamma_p/h\nu_pA)+(1/\tau)+(P_s\Phi_s\Gamma_s/h\nu_sA)} \quad (1)$$

$$\pm\frac{dP_p^{\pm}(z)}{dz} = -\Gamma_p\left[\sigma_{ap}N - pN_2(z)\right]P_p^{\pm}(z) - a_pP_p^{\pm}(z) \quad (2)$$

$$\pm\frac{dP_s^{\pm}(z)}{dz} = \Gamma_s[sN_2(z) - \sigma_{as}N]P_s^{\pm}(z) - \alpha_sP_s^{\pm}(z) \quad (3)$$

where

$$P_p = P_p^+ + P_p^- \; P_s = P_s^+ + P_s^- \quad (4)$$

$$\varnothing_s = \sigma_{as} + \sigma_{es}, \; \varnothing_p = \sigma_{ap} + \sigma_{ep} \quad (5)$$

$P_p^-(z)$ and $P_p^+(z)$ are the backward and forward pump powers at the position z in the fiber, while $P_s^-(z)$ and $P_s^+(z)$ are the backward and forward signal powers. $\sigma_{ap}, \sigma_{ep}, \sigma_{as}$ and σ_{es} are the absorption and stimulated cross sections at λ_p and λ_s respectively. α_p and α_s represent the scattering loss coefficients for the pump and laser. ν_p and ν_s are the pump and laser frequencies. N is the total doping concentration while N_2 is the population of the upper laser level.

Γ_p is the fraction of the pump power coupled into the active core and is given approximately by the ratio between the area of the core (A) and that of the multimode cladding. Γ_s represents the transverse overlap between the laser beam intensity and dopants concentration profiles [6].

3. Analytical solution

Our main objective is to find an accurate expression for $P_s^+(z)$. To accomplish this, at first the preliminary values $P_p^{\pm}(z)$, $P_s^-(z)$ and $P_s^+(0)$ are found by rough approximations, then these values are considered as the inputs values of our analytical model to give, finally, an accurate value for the output power.

3.1. $P_p^{\pm}(z)$ calculation

The population inversion $N_2(z)$, is assumed to be independent of z and equals to its averaged value $\overline{N}_2$. By using Eq. (3), the gain of the fiber can be calculated as follows:

$$G = \int_0^L \frac{dP_s^+(z)}{P_s^+(z)} = \Gamma_s\varnothing_s\int_0^L N_2(z)dz - (\Gamma_s\sigma_{as}N + \alpha_s)L \quad (6)$$

By considering a linear cavity with the threshold condition, $\overline{N}_2$ can be found:

$$\overline{N}_2 = \frac{1}{\Gamma_s\varnothing_s}\left\{\frac{1}{L}\ln\left(\frac{1}{\sqrt{R_{1s}R_{2s}}}\right) + \Gamma_s\sigma_{as}N + \alpha_s\right\} \quad (7)$$

The pump power at any point of the fiber, can be found by using the approximation $N_2(z) = \overline{N}_2$ in Eqs. (2) [7]:

$$P_p^+(z) = P_p^+(0)e^{-\overline{\gamma}_pz} \quad (8-a)$$

$$P_p^-(z) = P_p^-(L)e^{-\overline{\gamma}_p(L-z)} \quad (8-b)$$

where

$$\overline{\gamma}_p = \Gamma_p[\sigma_{ap}N - \varnothing_p\overline{N}_2] + \alpha_p \quad (8-c)$$

As seen from Fig. 1, the following boundary values for the forward and backward pumps $P_p^+(0)$ and $P_p^-(L)$ respectively, are developed as [8]

$$P_p^-(L) = R_{2p}P_p^+(L) + (1-R_{2p})P_{in2} \quad (9)$$

$$P_p^+(0) = R_{1p}P_p^-(0) + (1-R_{1p})P_{in1} \quad (10)$$

P_{in1} and P_{in2} are the forward and backward input pump powers. Following the above relations, $P_p^-(L)$ and $P_p^+(0)$ can be obtained as

$$P_p^+(0) = \frac{R_{1p}(1-R_{2p})P_{in2}e^{-\overline{\gamma}_pL} + (1-R_{1p})P_{in1}}{1-R_{1p}R_{2p}e^{-2\overline{\gamma}_pL}} \quad (11)$$

$$P_p^-(L) = \frac{(1-R_{2p})P_{in2} + R_{2p}(1-R_{1p})e^{-\overline{\gamma}_pL}P_{in1}}{1-R_{1p}R_{2p}e^{-2\overline{\gamma}_pL}} \quad (12)$$

The above relations of $P_p^+(z)$ and $P_p^-(z)$ are in good agreement with the numerical solutions that the maximum relative error is 1.93%, as it can be seen from Fig. 2. Therefore these expressions are used as final results for pump distributions inside the fiber.

3.2. Preliminary calculation of $P_s^-(z)$ and $P_s^+(0)$

The preliminary expressions for signal powers in both directions will be calculated by using the above approximation $N_2(z) = \overline{N}_2$, and by solving Eq. (3), the following expressions are obtained:

$$P_s^+(z) = P_s^+(0)e^{\overline{\gamma}_sz} \quad (13-a)$$