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Optimal cavity design for high-radiance, double-clad, Yb^{3+}-doped fiber lasers

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ABSTRACT

An analytical model for optimal cavity determination in Yb^{3+}-doped double clad fiber lasers (YDFL) in free running configuration is presented. The proposed model is based on laser cavity design parameters such as pump and signal wavelengths, emission and absorption cross sections, core diameter and doping concentration. It derives the optimal cavity for maximum conversion efficiency, considering both counter propagating and co-propagating amplified spontaneous emission in the core, along with boundary conditions at the fiber facets. Results show that the model could determine an optical cavity length for Yb^{3+}-doped fibers 10,000 ppm doping concentrations, 1–100 m fiber length range, core diameters between 1 and 25 μm, for different inner cladding geometries. The aim is to perform exact determination of important cavity parameters for designing efficient, diffraction limited, high-radiance optical fiber laser devices with emphasis on optimal cavity length.

1. Introduction

Cladding pumped fiber lasers offer a combination of relatively high-gain and low threshold powers, high efficiencies, quasi service-free operation, and high reliability. Those characteristics make Ytterbium-doped fiber lasers important devices for many applications such as power amplifiers, medicine, military, industrial processing and Telecommunications [1]. Optical waveguiding in these fiber structures allows management of thermal distortion issues on the lasing field even at very high powers. The geometry and shape of an optical fiber is advantageous as it reduces thermal loading density and is good for heat sinking. Output powers of over 1 kW in nearly diffraction-limited beams have been reported [2,17], and lasers with a few hundred Watts of diffraction-limited and even single frequency beams from Yb^{3+}-doped fibers at wavelengths around 1 μm have been reported [3–5]. Nevertheless, although these interesting devices have been in the market for some years, profound experimental details are still required. For many practical applications it is desirable to design the optimal cavity length to achieve efficient absorption of pump radiation from high power diodes for a given lasing wavelength. Several works have reported the design characteristics of Yb^{3+}-doped fiber laser such as critical power, lasing threshold, cross section, broad-gain bandwidth and high efficiency [6–9]. In all those studies, Yb^{3+}-doped fiber lasers are considered as two-level systems and the rate equations corresponding for populations in the background level ($^2F_{7/2}$) and the excited level ($^2F_{5/2}$) have been considered in steady state conditions, with results that are in good agreement with experimental results.

In this work, the optimal cavity for maximum conversion efficiency is theoretically derived, in Section 2. In Section 3 the results for the simulation based in our model are given. In Section 4 the experimental setup for an Yb^{3+}-doped fiber laser pumped in continuous wave regime for maximum efficiency is presented.

2. Model

Analysis of the rate equations for populations in the background and the excited levels in steady state conditions lead to an equation for the population in the excited and background levels as given by [10]:

$$N_2 = \frac{\gamma_p P_p/P_{\mathrm{Psat}} + \gamma_s(P_s^+ + P_s^-)/P_{\mathrm{Ssat}}}{P_p/P_{\mathrm{Psat}} + (P_s^+ + P_s^-)/P_{\mathrm{Ssat}} + 1} N_t \tag{1}$$

$$N_1 = 1 - N_2 \tag{2}$$

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where $P_{Psat} = A_{inner} h\nu_p/\tau\sigma_p$, $P_{Ssat} = A_{core} h\nu_s/\tau\sigma_s$, $\gamma_p = \sigma_a^p/\sigma_p$, $\gamma_s = \sigma_a^s/\sigma_s$, $\sigma_p = \sigma_a^p + \sigma_e^p$, $\sigma_s = \sigma_e^s + \sigma_a^s$. A_{core} and A_{inner} are the areas of the core and inner cladding respectively, h is Planck's constant, ν_p and ν_s are pump and laser frequencies, τ is the fluorescence lifetime, $\sigma_a^p, \sigma_e^p, \sigma_e^s, \sigma_a^s$ are the absorption and emission cross section for the pump and signal, respectively. And $P_s^+(z)$ represents the signal in co-propagating direction with the pump power (0 to L), and $P_s^-(z)$ is the signal in counter-propagating direction with the pump power (L to 0).

On the other hand, the gain signal and depleting pump along the fiber in the z position are given by the following standard rate equations:

$$\frac{dP_s^{\pm}(z)}{P_s^{\pm}(z)dz} = \pm\Gamma_s\left[\sigma_e^s N_2(z) - \sigma_a^s N_1(z)\right] \tag{3}$$

$$\frac{dP_p(z)}{P_p(z)dz} = \Gamma_p\left[\sigma_e^p N_2(z) - \sigma_a^p N_1(z)\right] \tag{4}$$

where $\Gamma_{p,s}$ represents the overlapping factor for the pump and signal, respectively. They are introduced to account for the fact that some fraction of the pump power propagates into un-doped cladding of the fiber. In this work, these factors were simply calculated by using the area of the core divided by the area of the inner cladding [11]. For simplicity, Eqs. (1)–(4) are used to normalize the pump and signal powers: $P_P/P_{Psat} \to q$, $(P_s^+ + P_s^-)/P_{Ssat} \to \rho_s^+ + \rho_s^-$. Substituting the population in the upper N_2 and lower N_1 levels in Eqs. (3)–(4), it is obtained:

$$\frac{d\rho_s^{\pm}}{\rho^{\pm}dz} = \pm\frac{Cq - D}{q + (\rho_s^{\pm} + \rho_s^-) + 1} \tag{5}$$

$$\frac{dq}{qdz} = \frac{A(\rho_s^+ + \rho_s^-) - B}{q + (\rho_s^+ + \rho_s^-) + 1} \tag{6}$$

where $A = \Gamma_p(\sigma_p\gamma_s - \sigma_a^p)$, $B = \sigma_a^p\Gamma_p N_t$, $C = \Gamma_s N_t(\sigma_s\gamma_p - \sigma_a^s)$ and $D = \sigma_a^s\Gamma_s N_t$. As the signals in co-propagation and counter-propagation have an exponential form, the multiplication of both results as:

$$\rho_s^+(z)\rho_s^-(z) = {\rho_0}^2 \tag{7}$$

and boundary conditions at the fiber facets are:

$$\rho_s^-(L) = R_2\rho_s^+(L) \text{ and } \rho_s^+(0) = R_1\rho_s^-(0) \tag{8}$$

As boundary conditions, it is possible to obtain one expression for the gain g, ρ_0 and the total signal as follows:

$$g = \frac{\rho_s^+(L)}{\rho_s^+(0)} = \frac{1}{\sqrt{R_1R_2}} \text{ and } \rho_0 = \sqrt{R_2}\rho_s^+(L) \tag{9}$$

$$\rho_s^+ + \rho_s^- = \rho_0 R \tag{10}$$

$$R = \left(\frac{1+R_2}{\sqrt{R_2}}\right). \tag{11}$$

Again, Eqs. (5) and (6) for the signal co-propagating and unidirectional pump as a function of the new R parameter can be written as:

$$\frac{d\rho_s^+}{\rho_s^+ dz} = \frac{Cq - D}{q + \rho_0 R + 1} \tag{12}$$

$$\frac{dq}{qdz} = \frac{A\rho_0 R - B}{q + \rho_0 R + 1} \tag{13}$$

Integrating Eq. (13), for q in the interval $[q_0, q]$ and z in the interval $[0, L]$, the expression for cavity length could be given by:

$$L(q) = \frac{(q - q_0)}{A\rho_0 R - B} + \frac{(\rho_0 R + 1)}{A\rho_0 R - B}\ln\left(\frac{q}{q_0}\right) \tag{14}$$

The cavity length is a function of the pump power and the output power signal $\rho_s^+(L) = \rho_0/(R_2)1/2$. Where the parameter ρ_0 is obtained by dividing Eq. (12) by Eq. (13), the resulting differential equation is integrated for q and ρ_s^+ within the intervals $[q_0, q]$ and $[\rho_s^+(0), \rho_s^+(L)]$, respectively. The resulting equation is a function of the input power given by:

$$\rho_0(q) = \frac{B}{AR} + \frac{1}{AR\ \ln\left(1/\sqrt{R_1R_2}\right)} \times \left(C(q - q_0) - D\ \ln\left(\frac{q}{q_0}\right)\right) \tag{15}$$

The signal in the co-propagating direction with the pump grows exponentially and starts decreasing when the pump is depleted by the absorption of the active medium. This implies that the signal reaches a maximum value in $z = L_M$, which is determined when Eq. (12) is equal to zero, i.e., $q = D/C = q_{min}$. Substituting q_{min} in Eqs. (14) and (15) we obtain:

$$L_M = \frac{(D/C - q_0)}{A\rho_0' R - B} + \frac{(\rho_0' R + 1)}{A\rho_0' R - B}\ln\left(\frac{D/C}{q_0}\right) \tag{16}$$

and

$$\rho_0'(q) = \frac{B}{AR} + \frac{1}{AR\ \ln(1/\sqrt{R_1R_2})} \times \left[C((D/C) - q_0) - D\ \ln\left(\frac{D/C}{q_0}\right)\right] \tag{17}$$

where $q_0 = P_{P0}/P_{Psat}$ and P_{P0} is the launched power.

The criteria taken to define the saturation is for when the slope = $1/e$ (this number is commonly used to find a limiting point [15,16]), in this case $q_0 = Q_{OPT}$.

Then, using Eqs. (16) and (17) the mathematical expression of the optimal cavity length L_{OPT} is obtained:

$$L_{OPT} = \frac{1}{A\rho_0' R - B}\left[\frac{D}{C} - Q_{OPT} + (\rho_0' R + 1)\ln\left(\frac{D}{CQ_{OPT}}\right)\right] \tag{18}$$

where the following expression for Q_{OPT} can be found as:

$$\frac{1}{A\rho_0' R - B}\left[-1 + \frac{\rho_0' R + 1}{Q_{OPT}} + R\frac{d\rho_0'}{dQ_{OPT}}\ \ln\left(\frac{D}{CQ_{OPT}}\right)\right] + \left[\frac{D}{C} - Q_{OPT} + (\rho_0' R + 1)\ \ln\left(\frac{D}{CQ_{OPT}}\right)\right]\left(\frac{-AR(d\rho_0'/dQ_{OPT})}{(A\rho_0' R - B)^2}\right) = \frac{1}{e} \tag{19}$$

where:

$$\frac{d\rho_0'}{dQ_{OPT}} = \frac{1}{AR\ \ln(1/\sqrt{R_1R_2})}\left(C - \frac{D}{Q_{OPT}}\right)$$

and

$$Q_{OPT} = \frac{\text{Optimal launched pump power}}{P_{Psat}}$$

3. Experiments and results

Fig. 1 shows a schematic diagram of the experimental setup. The pump source consisted of a diode bar with 27 W output power operating at 915 nm. The pump beam was collimated using a 1-inch anti-reflection coated, aspheric lens with 14.5 mm focal length with 0.4 NA. The collimated beam was then coupled into the YDF by another aspheric 14 mm focal length lens. Between the two aspheric anti-reflection coated lenses there was a dichroic mirror to protect the pump source and extract the signal from the cavity. It