Power distribution in Yb^{3+}-doped double-cladding fiber laser

**Qiang Zhang (张 强)[1], Jianquan Yao (姚建铨)[1], Peng Wang (王 鹏)[1],
Jianing Zhou (周佳凝)[1], Yuanqin Xia (夏元钦)[2], and Baigang Zhang (张百钢)[1]**

[1] *College of Precision Instrument and Opto-Electronics Engineering,
Institute of Laser and Optoelectronics, Tianjin University, Tianjin 300072*
[2] *State Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001*

Received February 19, 2004

The distribution of pump light and signal light in Yb^{3+}-doped double-cladding fiber laser is analyzed based on a rate equation model. Numerical simulation results are obtained. The numerical solution of the rate equation is shown to be in excellent agreement with the experimental data.

OCIS codes: 140.3510, 060.2320.

Rare-earth-doped fiber laser has become popular in recent years[1] due to its outstanding advantages, such as reliable, efficient, compact, and low-cost high power etc.. It was applied in many fields such as measurement, communication, transducer, material processing, medicine, and so on. The main doped ions in double-cladding fiber are Nd^{3+}, Yb^{3+}, Ho^{3+}, Tm^{3+}, Pr^{3+}, and Er^{3+}. Different doped ions make the fiber present different characteristics for the different energy level structures. Yb^{3+} ions have drawn much attention for its simple energy level structure and excellent spectrum characteristics. In this work, we introduce a method to analyze the models of pump light and signal light in Yb^{3+}-doped double-cladding fiber laser. A set of coupled steady-state equations are introduced, along with the definitions of relevant parameters. Exact numerical solution of the rate equation for a certain double-cladding fiber laser is provided. We compare the exact numerical solution and the experimental result.

Figure 1 is the configuration of the double-cladding fiber laser. It consists of a doped fiber section of length L with rare-earth ions at a constant concentration N_0, independent of position z along the fiber. The pump power $P_p^+(z)$ at wavelength λ_p is coupled into the inner cladding of the fiber at $z = 0$ and propagated in the positive z-direction. When $z = L$, the pump light is reflected back into the fiber and the part of the pump power at wavelength λ_p propagates in the negative z-direction is $P_p^-(z)$. $P_s^+(z)$ and $P_s^-(z)$ are the signal powers propagating in the positive and negative z-direction in the core, respectively.

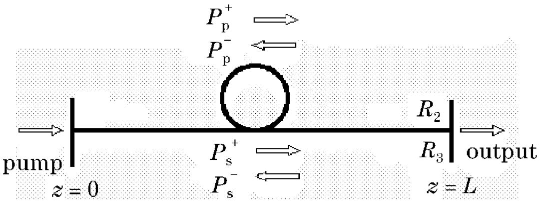

Fig. 1. Schematic illustration of the double-cladding fiber laser.

The reflectivity of cavity mirror for signal light is R_1 at $z = 0$ and R_2 at $z = L$. At $z = L$, the reflectivity of cavity mirror for pump light is R_3.

The fraction of the pump power actually coupled into the active core is represented by the power filling factor Γ_p, approximately given by the ratio between the area of the core and that of the multi-mode inner cladding. The fiber core is single-mode, so, for the signal, we use the power filling factor of the lowest order LP$_{01}$ mode as the power filling factor Γ_s[2]. For convenience, we assume that the spectrum distribution of the laser satisfies function δ[3].

Under pumping condition, particles on the ground state E_1 of Yb^{3+} ions jump to the excited state E_2, the stimulated transition probability is W_{12}. Particles on energy level E_2 jump back to ground level E_1 with spontaneous transition probability A_{21} and radiationless transition probability S_{21}. Under sufficiently strong pumping condition, the pumping rate is high enough to reach population inversion, the main transition is stimulated absorption W_{12} and stimulated emission W_{21}. Particle densities on level E_1 and E_2 are N_1 and N_2, respectively, and the particle density satisfy

$$N_1 + N_2 = N_0, \tag{1}$$

so the rate equation on level E_2 is

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = W_{12}N_1 - N_2(W_{21} + A_{21} + S_{21}). \tag{2}$$

In respect that $W = \sigma v N$ and $N = \frac{P}{vh\nu A}$, the photon density of pump light and signal light are $N_p = \frac{\Gamma_p}{vh\nu_p A}[P_p^+(z)+P_p^-(z)]$ and $N_s = \frac{\Gamma_s}{vh\nu_s A}[P_s^+(z) + P_s^-(z)]$, respectively. Here, σ is the stimulated emission cross section for excited state or absorption cross section for ground state; N and A represent photon density and area of core cross section, respectively.

Because as $S_{21} \ll A_{21}$, $S_{21} \ll W_{21}$, S_{21} could be neglected. Taking account of $A_{21} = \frac{1}{\tau}$, we can get

$$\frac{\mathrm{d}N_2(z)}{\mathrm{d}t} = \left(\frac{\Gamma_\mathrm{p}\sigma_\mathrm{ap}}{h\nu_\mathrm{p}}\right)\frac{[P_\mathrm{p}^+(z)+P_\mathrm{p}^-(z)]}{A}[N_0 - N_2(z)] + \left(\frac{\Gamma_\mathrm{s}\sigma_\mathrm{as}}{h\nu_\mathrm{s}}\right)\frac{[P_\mathrm{s}^+(z)+P_\mathrm{s}^-(z)]}{A}[N_0 - N_2(z)] - \left(\frac{\Gamma_\mathrm{s}\sigma_\mathrm{es}}{h\nu_\mathrm{s}}\right)\frac{[P_\mathrm{s}^+(z)+P_\mathrm{s}^-(z)]}{A}N_2(z) - \frac{N_2(z)}{\tau}. \quad (3)$$

When keeping the pumping for a long period, the particle density maintains dynamic equilibrium, $\frac{\mathrm{d}N_2(z)}{\mathrm{d}t} = 0$, then

$$\frac{N_2(z)}{N_0} = \left\{\frac{[P_\mathrm{p}^+(z)+P_\mathrm{p}^-(z)]\sigma_\mathrm{ap}\Gamma_\mathrm{p}}{h\nu_\mathrm{p}An_1} + \frac{[P_\mathrm{s}^+(z)+P_\mathrm{s}^-(z)]\sigma_\mathrm{as}\Gamma_\mathrm{s}}{h\nu_\mathrm{s}An_0}\right\} \Big/ \left\{\frac{[P_\mathrm{p}^+(z)+P_\mathrm{p}^-(z)]\sigma_\mathrm{ap}\Gamma_\mathrm{p}}{h\nu_\mathrm{p}An_1} + \frac{1}{\tau} + \frac{[P_\mathrm{s}^+(z)+P_\mathrm{s}^-(z)](\sigma_\mathrm{as}+\sigma_\mathrm{es})\Gamma_\mathrm{s}}{h\nu_\mathrm{s}An_0}\right\}, \quad (4)$$

where ν_p and ν_s are frequencies of pump light and signal light, respectively; σ_ap is the absorption cross section of pump light; σ_as and σ_es are absorption cross section and emission cross section of signal light; n_0 and n_1 are the refractive indices of signal and pump light, respectively.

The propagation characteristic of signal power in fiber could be described by[4]

$$\pm\frac{\mathrm{d}P_\mathrm{s}^\pm(z)}{\mathrm{d}z} = g(z)P_\mathrm{s}^\pm(z) - \alpha_\mathrm{s}P_\mathrm{s}^\pm(z), \quad (5)$$

where $P_\mathrm{s}(z)$ is the power of signal light, with the sign presenting the positive or the negative z-direction; α_s and $g(z)$ are loss and gain coefficient of signal light, respectively. Because $g(z) = \Gamma[N_2(z)\sigma_\mathrm{es} - N_1(z)\sigma_\mathrm{as}]$, $N_1 + N_2 = N_0$, we can get

$$\pm\frac{\mathrm{d}P_\mathrm{s}^\pm(z)}{\mathrm{d}z} = -\Gamma_\mathrm{s}\left[\sigma_\mathrm{as}N_0(z) - (\sigma_\mathrm{as}+\sigma_\mathrm{es})N_2(z) + \frac{1}{\tau}\right]P_\mathrm{s}^\pm(z) - \alpha_\mathrm{s}P_\mathrm{s}^\pm(z). \quad (6)$$

For the same argument, we can get the equation of propagation characteristic of pump power as

$$\pm\frac{\mathrm{d}P_\mathrm{p}^\pm(z)}{\mathrm{d}z} = -\Gamma_\mathrm{p}[\sigma_\mathrm{ap}N_0(z) - \sigma_{ap}N_2(z)]P_\mathrm{p}^\pm(z) - \alpha_\mathrm{p}P_\mathrm{p}^\pm(z). \quad (7)$$

Table 1. Parameters Used for the Example of Yb^{3+}

$\lambda_\mathrm{p} = 975$ nm	$\lambda_\mathrm{s} = 1090$ nm
$\sigma_\mathrm{as} = 1.4\times10^{-23}$ cm^2	$\sigma_\mathrm{es} = 2\times10^{-21}$ cm^2
$\sigma_\mathrm{ep} = 2.5\times10^{-20}$ cm^2	$\sigma_\mathrm{ap} = 2.5\times10^{-20}$ cm^2
$A = 8.825\times10^{-7}$ cm^2	$N = 4.33\times10^{19}$ cm^{-3}
$\alpha_\mathrm{s} = 5\times10^{-5}$	$\Gamma_\mathrm{s} = 0.82$
$\Gamma_\mathrm{p} = 7.75\times10^{-4}$	$\alpha_\mathrm{p} = 3\times10^{-5}$
$R_3 = 0.04$	$v = 2\times10^8$ m/s
$R_1 = 0.98$	$\tau = 1\times10^{-3}$ s
$R_2 = 0.04$	$n_1 = 1.45$
$n_0 = 1.452$	

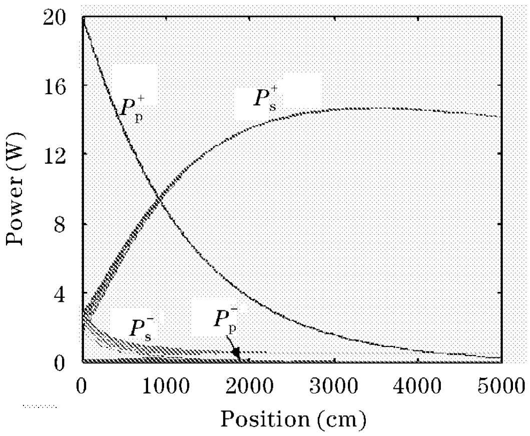

Fig. 2. Pump and signal power as a function of the position along the fiber for different fiber length.

Equations (4), (6), and (7) make up of a differential equations set. The boundary conditions are

$$P_\mathrm{s}^+(0) = R_1P_\mathrm{s}^-(0), \quad P_\mathrm{s}^-(L) = R_2P_\mathrm{s}^+(L), \quad P_\mathrm{p}^-(L) = R_3P_\mathrm{p}^+(L). \quad (8)$$

The parameters we used in the calculation are given in Table 1.

We can get the numerical solution by MATLAB.

Figure 2 describes the variation of the pump and signal power with the fiber length of the Yb^{3+}-doped double-cladding fiber laser. We set the fiber length to the values of 10, 12, 14, 16, 18, 20, 24, 28, 32, 36, 40, 45, and 50 m. The pump power is injected at $z = 0$ and $P_\mathrm{p}^+(0)=20$ W.

From Fig. 2 we can see that the change of fiber length has little influence on $P_\mathrm{p}^+(z)$. As the value of R_3 is very small, the pump power propagates in the negative z-direction is little, so when $L > 30$ m, this part of power could be neglected. To get the maximum output power, there must be an optimum fiber length. When $L > 25$ m, the curves of $P_\mathrm{s}(z)$ for different fiber length are almost of superposition. For the parameter listed in Table 1, we can get the optimum fiber length $L = 35$ m.

Corresponding to different fiber length fiber, at the same point, for example $z = 0$, as shown in Fig. 3, with the increase of fiber length L, the values of $P_\mathrm{s}^+(z)$ and $P_\mathrm{s}^-(z)$ increase slowly. When the fiber length reaches the point about $L = 35$ m, the values get the maxima, then as the fiber length increases more, the values of $P_\mathrm{s}^+(z)$ and $P_\mathrm{s}^+(z)$ decrease slowly.

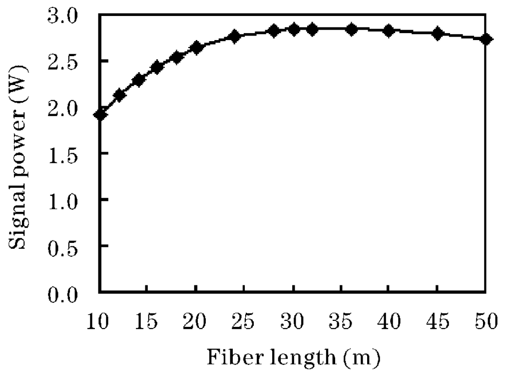

Fig. 3. Signal power at $z = 0$ versus fiber length for different fiber laser.

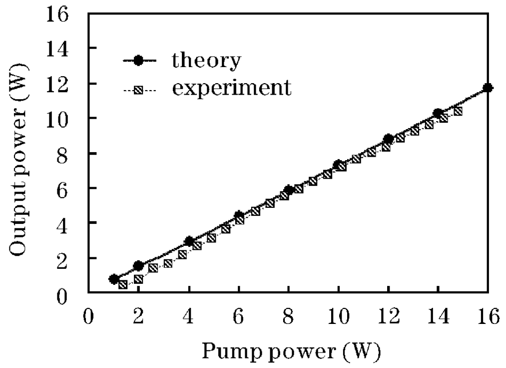

Fig. 4. Output power versus pump power.

In the experiment, the pump power is $P_p = 25$ W, the wavelength of pump light $\lambda_p = 975$ nm. The fiber used in the experiment is Yb^{3+}-doped double-cladding fiber and its inner cladding is D-shape. The length of the fiber is 30 m. The pump power was injected into the fiber at $z = 0$ and the coupling efficiency is 56%. The reflection index of cavity mirror for signal light at $z = 0$ is $R_1 = 0.98$. At $z = L$ the cavity mirror was substituted by the end face of fiber, so the indices of reflection for pump light and signal light are decided by the Fresnel reflection, $R_2 = R_3 = 0.04$. The variation of the output power with pump power is described in Fig. 4. For comparison, we present the output power of the numerical solution and experimental data in the same figure. It can be seen that the two curves are almost of superposition. The output power increases linearly with the pump power, as expected, and the slope efficiency is 73.2%. According to the experiment, with the increase of the pump power, the power density on the cross-section of coupling end increases, and the fiber end is apt to be damaged, which will influence the coupling efficiency. So to achieve high power laser output, damage at the fiber end is an important problem for us to overcome. Changing the value of R_3 could increase the absorption efficiency, it is another guarantee of high power output.

In this paper, a rate equation model was used to study the distribution of pump light and signal light in Yb^{3+}-doped double-cladding fiber laser. Exact numerical solution of the rate equation is shown to be in excellent agreement with the experimental data. The optimum fiber length for maximum output power was obtained.

This project was supported by Tunable Laser State Key Lab on Harbin Institute of Technology under Grant No. 51472030301JW1401. Q. Zhang's e-mail address is zh9660@126.com.

References

1. Q. H. Lou, J. Zhou, J. Q. Zhu, Z. L. Wu, L. F. Kong, J. X. Dong, Z. H. Ye, Y. R. Wei, and Z. J. Wang, Chin. Opt. Lett. **1,** 559 (2003).
2. T. Erdogan, J. Lightwave Technol. **15,** 1277 (1997).
3. Z. L. Wu, G. F. Chen, and X. H. Wang, Acta Photon. Sin. (in Chinese) **31,** 332 (2002).
4. L. Y. Song, Y. B. Guo, and L. J. Wang, Laser Journal (in Chinese) **24,** 8 (2003).