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Optics & Laser Technology 37 (2004) 3–7

Optics & Laser Technology

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Threshold characteristics of linear cavity Yb^{3+}-doped double-clad fiber laser

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Received 21 October 2003; received in revised form 19 December 2003; accepted 4 February 2004

Abstract

The threshold characteristics of linear cavity Yb^{3+}-doped double-clad fiber laser have been studied theoretically and experimentally. By solving rate equations, the expression for threshold pump power is obtained. The effects of fiber length, mirror reflectivity, pump wavelength, laser wavelength and Yb^{3+} concentration on threshold pump power are discussed. Then, the Yb^{3+}-doped double-clad fiber laser with linear cavity is developed. By using various output couplers, threshold pump power has been measured. The experimental results are in accord with theory.

Keywords: Fiber lasers; Linear cavity; Double-clad fiber

1. Introduction

High power fiber lasers have some unique advantages including high conversion efficiency, excellent beam quality, small volume and weight. They will be widely used in medical, military, industrial processing and modern telecommunication. High power fiber lasers usually base on double-clad fiber which consists of three layers, i.e., a single-mode core doped by rare-earth element, an inner silica cladding, and an outer cladding with lower index comparing to that of inner cladding. The inner cladding with large area and numerical aperture (NA) will accept a large amount of pump light from multimode laser diode sources, the coupled pump light is well absorbed in the doped core along the long length of the cavity and thus efficiently utilized. Recent years, with the improvement of high-power multimode diode and the development of double-clad fiber, the output power of high power fiber lasers increases greatly [1–3]. As we know,Yb^{3+} ions have two simple energy levels, and the upper energy level has long fluorescence life. Yb^{3+} ions also have high quantum efficiency and wide absorption spectrum (generally from 900 to 1200 nm), so one of the interests is to develop the high power Yb^{3+}-doped double-clad fiber lasers. In order to optimize fiber laser performances, analytical or numerical analysis is essential. The theoretical and analytical models of Er^{3+}-doped single-clad fiber lasers have been developed very intensively in numerous papers [4–7]; while the reports about the model of Yb^{3+}-doped double-clad fiber laser are less. Basing on propagation equations and overlap factors, Bertoni [8] and Kim et al. [9] introduced the numerical models for double-clad fiber laser. The dependences of output power on output mirror reflectivity, pump power and fiber length, etc., can be obtained by using the model. Patrick Even et al. presented an analytical model for double-clad fiber laser [10,11]. The model was based on the balance photons carried out in the active fiber, and lead to a simple analytical solution. From this model, the expressions for output power and threshold pump power were obtained, the dependences of pump threshold power on fiber length is discussed. In this paper, by solving rate equations, the pump threshold characteristics of line cavity Yb^{3+}-doped double-clad fiber lasers are studied, the effects of fiber length, mirror reflectivity, Yb^{3+} ions concentration, pump wavelength and laser length on pump threshold power are analyzed. The results provide theoretical

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doi:10.1016/j.optlastec.2004.02.002

guidance for design and fabrication of double-clad fibers and high-power fiber lasers.

2. Theory analyses

Under steady state conditions, the populations in upper and lower energy level of Yb^{3+}-doped fiber are described as [12]

$$n_2=\frac{\sigma_{ap}\sigma_s P_s^{sat}P_p+\sigma_{as}\sigma_p P_p^{sat}(P_s^{+}+P_s^{-})}{\sigma_p\sigma_s P_p P_s^{sat}+\sigma_p\sigma_s P_p^{sat}(P_s^{+}+P_s^{-})+\sigma_p\sigma_s P_p^{sat}P_s^{sat}}, \tag{1}$$

$$n_1=1-n_2. \tag{2}$$

P_s^+ and P_s^- are forward and backward laser power along the fiber, respectively, P_p is the input pump light power, their propagation equations are given by

$$\frac{dP_p(z)}{dz}=\Gamma_p N_t(\sigma_{ep}n_2-\sigma_{ap}n_1)P_p(z), \tag{3}$$

$$\frac{dP_s^+(z)}{dz}=\Gamma_s N_t(\sigma_{es}n_2-\sigma_{as}n_1)P_s^+(z), \tag{4}$$

$$\frac{dP_s^-(z)}{dz}=-\Gamma_s N_t(\sigma_{es}n_2-\sigma_{as}n_1)P_s^-(z). \tag{5}$$

P_p^{sat} and P_s^{sat} are the pump and laser saturation power, they are given by

$$P_p^{sat}=\frac{h\upsilon_p A}{\Gamma_p\sigma_p\tau}, \tag{6}$$

$$P_s^{sat}=\frac{h\upsilon_s A}{\Gamma_s\sigma_s\tau}. \tag{7}$$

In Eqs. (1)–(7), τ is fluorescence lifetime, υ_s and υ_p are laser and pump light frequencies, h is Plank's constant, A is effective core area, N_t is the density of Yb^{3+} ions, Γ_s is the overlap factor of laser mode field with the doped area, $\Gamma_p=S_d/S_{ic}$ is the overlap factor of pump mode field with the doped area, S_d and S_{ic} are the core and inner cladding cross-sections of Yb^{3+}-doped double-clad fiber. σ_{es} and σ_{as} are laser emission and absorption cross-sections, σ_{ep} and σ_{ap} are pump light emission and absorption cross-sections, respectively, $\sigma_s=\sigma_{es}+\sigma_{as}$, $\sigma_p=\sigma_{ep}+\sigma_{ap}$.

The gain of the Yb^{3+}-doped double-clad fiber is given by

$$G=\int_0^L g(z)\,dz=\Gamma_s N_t\int_0^L[\sigma_{es}n_2-\sigma_{as}n_1]\,dz, \tag{8}$$

where L is the length of Yb^{3+}-doped double-clad fiber. From Eqs. (1), (2), (4),(5) and (8), we can obtain

$$G=A_s\rho\left[\frac{\sigma_s}{A_p\sigma_p\rho}\ln\frac{P_p(L)}{P_p(0)}+\frac{\sigma_{es}\sigma_{ap}-\sigma_{ep}\sigma_{as}}{\sigma_p}L\right]. \tag{9}$$

For a linear cavity fiber laser, the stationary condition is described as

$$R_1R_2\exp(2G)=1. \tag{10}$$

R_1 and R_2 are input and output cavity mirror reflectivity, respectively. From Eqs. (9) and (10), we can obtain

$$G_p=\ln[P_p(L)/P_p(0)]=\frac{\Gamma_p\sigma_p}{2\Gamma_s\sigma_s}\ln(1/R_1R_2)-\frac{\sigma_{es}\sigma_{ap}-\sigma_{ep}\sigma_{as}}{\sigma_s}\Gamma_p N_t L. \tag{11}$$

The boundary conditions of P_s^+ and P_s^- can be written as

$$P_s^+(0)=R_1P_s^-(0)\quad P_s^-(L)=R_2P_s^+(L). \tag{12}$$

From Eqs. (4) and (5), the following expression can be easily found:

$$P_s^+(0)P_s^-(0)=P_s^+(L)P_s^-(L). \tag{13}$$

From Eqs. (1)–(5), we can obtain

$$\frac{1}{A_p\rho\sigma_p P_p^{sat}}\frac{dP_p(z)}{dz}+\frac{1}{A_s\rho\sigma_s P_s^{sat}}\left(\frac{dP_s^+(z)}{dz}+\frac{dP_s^-(z)}{dz}\right)+\frac{1}{A_p\rho\sigma_p P_p}\frac{dP_p(z)}{dz}+\frac{\sigma_{ap}}{\sigma_p}=0. \tag{14}$$

By combining, Eqs. (11)–(13), we integrate Eq. (14) from 0-L, then the $P_s^+(L)$ can be written as

$$P_s^+(L)=\frac{\upsilon_s}{\upsilon_p}\cdot\frac{P_p^{sat}}{1-R_2-\sqrt{R_1R_2}+\sqrt{R_2/R_1}}\times\left[\frac{P_p(0)}{P_p^{sat}}(1-\exp(G_p))-G_p-\Gamma_p N_t\sigma_{ap}L\right]. \tag{15}$$

The output power of fiber laser can be described as

$$P_{out}=(1-R_2)P_s^+(L). \tag{16}$$

Namely,

$$P_{out}=\frac{\lambda_p}{\lambda_s}\cdot\frac{(1-R_2)P_p^{sat}}{1-R_2-\sqrt{R_1R_2}+\sqrt{R_2/R_1}}\times\left[\frac{P_p(0)}{P_p^{sat}}(1-\exp(G_p))-G_p-A_p\rho\sigma_{ap}L\right]. \tag{17}$$

When $P_{out}=0$, the threshold pump power is obtained

$$P_{th}=P_p^{sat}\frac{G_p+\Gamma_p N_t\sigma_{ap}L}{1-\exp(G_p)}. \tag{18}$$

3. Discussions

At different conditions, the relations between threshold pump power and Yb^{3+} concentration are shown in Fig. 1,

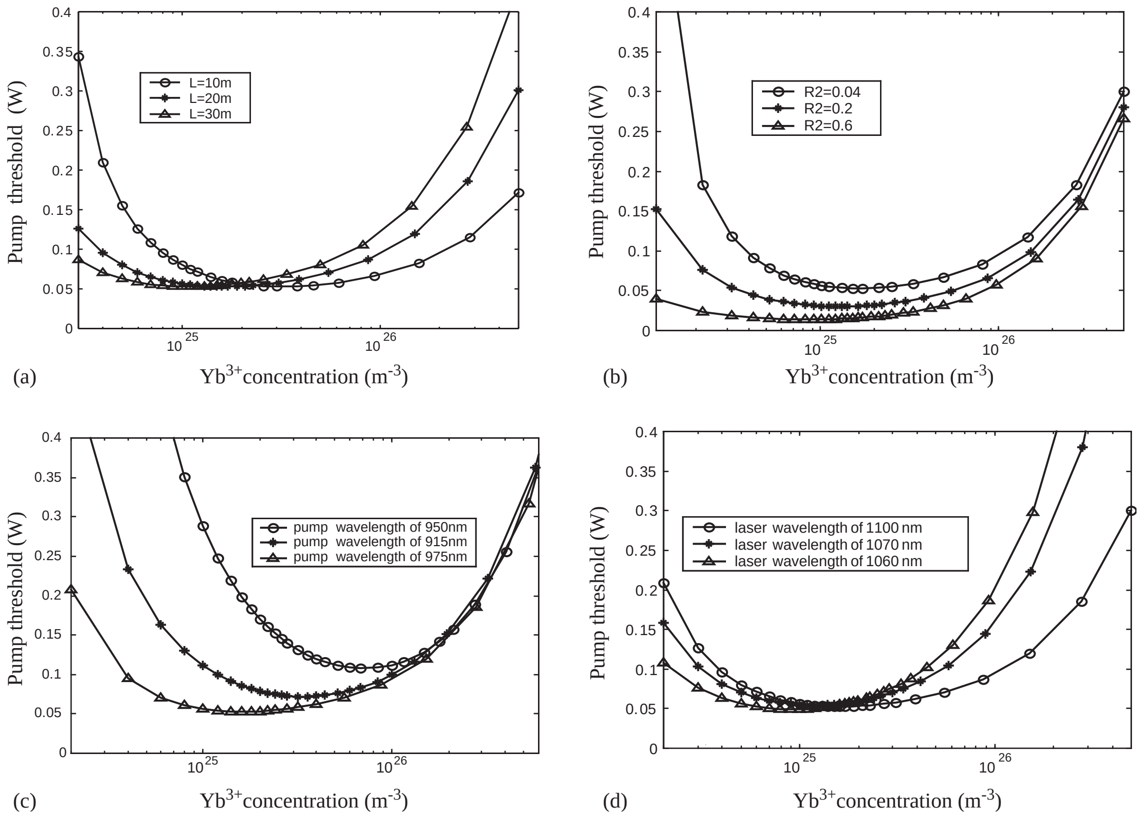

Fig. 1. Threshold pump power as a function of Yb^{3-} concentration at different conditions of (a) fiber length, (b) R_2, (c) pump wavelength, (d) laser wavelength.

where $R_1 = 0.98$, the diameters of double-clad fiber core and inner cladding are 5 and 85 μm, respectively. When $\lambda_p = 975$ nm, $\sigma_{ap} = 2.5 \times 10^{-24}$ m^2, $\sigma_{ep} = 2.5 \times 10^{-24}$ m^2; when $\lambda_p = 915$ nm, $\sigma_{ap} = 0.8 \times 10^{-24}$ m^2, $\sigma_{ep} = 2.5 \times 10^{-26}$ m^2; when λ_p=950 nm, σ_{ap}=0.25×10^{-25} m^2, σ_{ep}=1×10^{-26} m^2; when $\lambda_s = 1100$ nm, $\sigma_{as} = 1.0 \times 10^{-27}$ m^2, $\sigma_{es} = 2.0 \times 10^{-25}$ m^2; when $\lambda_s = 1060$ nm, $\sigma_{as} = 6.0 \times 10^{-27}$ m^2, $\sigma_{es} = 3.5 \times 10^{-25}$ m^2; when $\lambda_s = 1070$ nm, $\sigma_{as} = 3.0 \times 10^{-27}$ m^2, $\sigma_{es} = 2.5 \times 10^{-25}$ m^2 [12]; From Fig. 1, we know that the relations between threshold and Yb^{3+} concentration show bathtub-shape, in a certain concentration range, the thresholds are lower and keep invariable; and beyond this concentration range, the thresholds increase greatly. During designing a double-clad fiber laser, four parameters can be changed, they are fiber length, mirror reflectivity, pump and laser wavelength. Fig. 1 indicates that the dependence of threshold on Yb^{3+} concentration has little relation with above four parameters, and is decided only by the fiber itself. So, when we manufacture double-clad fiber, the Yb^{3+} concentration should be in a certain range to obtain lower threshold.

The curves of threshold versus the radius of inner cladding are shown in Fig. 2. When the radius of inner cladding is smaller, the effect of radius size on threshold is little; but the threshold increases evidently when the radius of inner cladding increase to a certain size. The shorter the fiber is, the faster the change appears. For double clad fiber, the absorption of pump is not only link to the doping concentration and core dimension but also the size of the inner cladding. With the radius of inner cladding increasing, the absorbing efficiency of pump light will decrease [11]. Larger radius of inner cladding can accept a large amount of pump light and improve coupling efficiency of pump light, but larger size of inner cladding will decrease absorption of pump, then cause the threshold increase. So, there should be have an optimal size of inner cladding.

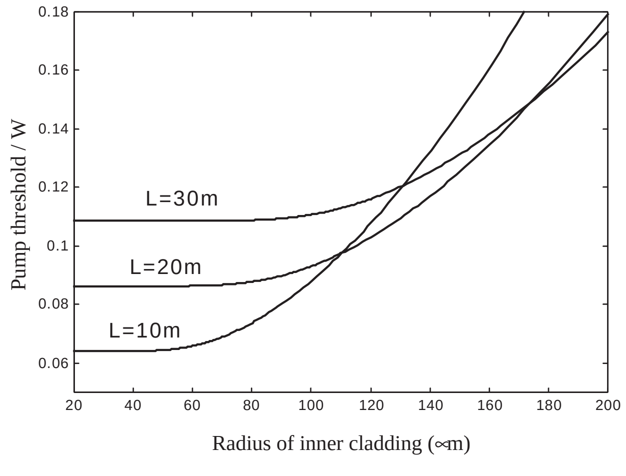

Fig. 2. Threshold pump power as a function of radius of inner cladding.

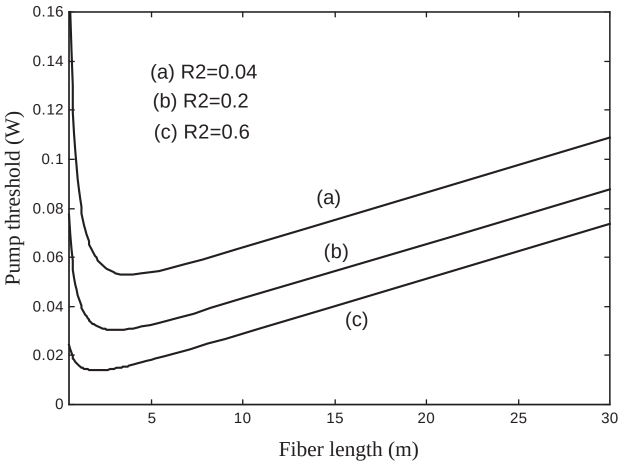

Fig. 3. Threshold pump power as a function of fiber length at different R_2.

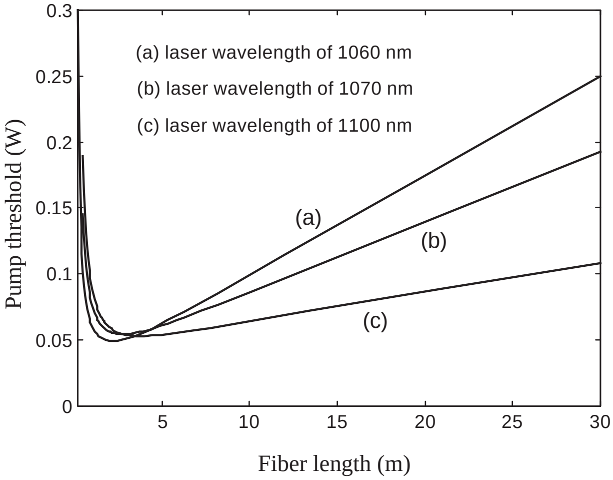

Fig. 4. Threshold pump power as a function of fiber length at different laser wavelength.

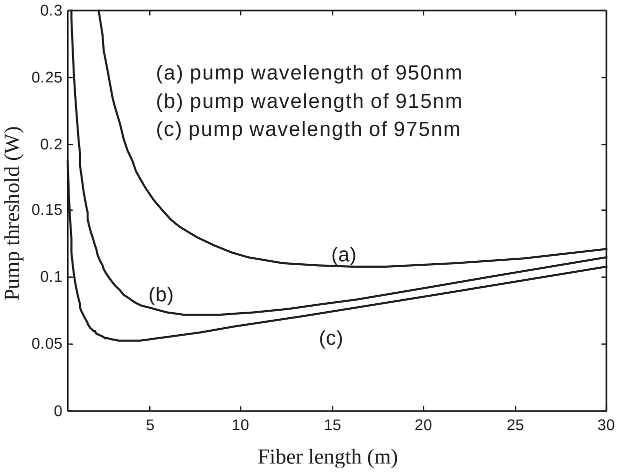

Fig. 5. Threshold pump power as a function of fiber length at different pump wavelength.

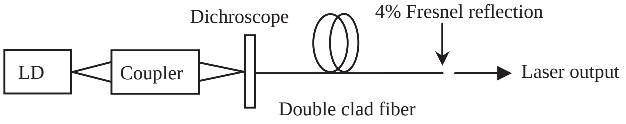

Fig. 6. Experimental setup of Yb^{3+}-doped double-clad fiber laser.

Threshold pump power versus fiber length at different conditions are shown in Figs. 3–5. The effect of fiber length on threshold is evident; there is an optimal length, which makes the threshold of fiber laser lowest. With increasing of R_2, the threshold pump power decreases. For different laser wavelength, the lowest threshold level and optimal fiber length is also different. When the fiber is shorter, the threshold of fiber laser increases with the increasing of laser wavelength; when the fiber is longer, the threshold decreases with the increasing of laser wavelength. With increasing of the fiber length, lowest threshold moves to longer wavelength. The threshold also changed with the pump wavelength variety, the lowest threshold pump power is attained at pump wavelength of 975 nm. From Eq. (18), the threshold has close relation with absorption cross-sections, for Yb^{3+}-doped fiber, the cross-section is maximum when the pump wavelength is 975 nm [12]. The larger cross-section makes the pump light absorbed efficiently, and then lower threshold is obtained. So, when we design fiber laser, one of the methods decreasing threshold is to select the pump source with center wavelength of 975 nm.

4. Experimental

The experiment setup is shown in Fig. 6. The double-clad fiber was CP1100 that was made at Fibercore Ltd. The fiber was composed of a 5 μm-diameter core with a NA of 0.15 and an inner cladding that had a 85 μm quasi-circular-shape cross-section. The inner cladding was surrounded by an outer cladding and provided a NA for the pump light of 0.22. The fiber length is 20 m. The center wavelength of diode laser pump source is 970 nm. In a Fabry–Perot cavity, the input mirror is a dichroic mirror with high transmissivity of 95% at 970 nm and high reflectivity of 99% at 1100 nm. The output end of the double-clad fiber is perpendicularly cleaved, and acts as the cavity output coupler with about 4% Fresnel reflection. Fig. 7 shown the curve of output power depending on pump power, the experimental results of threshold pump power is 102 mW. The output spectrum is shown in Fig. 8, the center wavelength is 1100 nm. Also the output coupler mirrors with reflectivity of 30% and 60% were used, the threshold pump powers are 79 and 68 mW, respectively. Then we use the theoretical mode (from Eq. (18)) to calculate the thresholds, the results are 86.8 ($R_2 = 0.04$), 60.5 ($R_2 = 0.3$) and 51.5 mW ($R_2 = 0.6$). There is a good agreement between theoretical and experimental results.

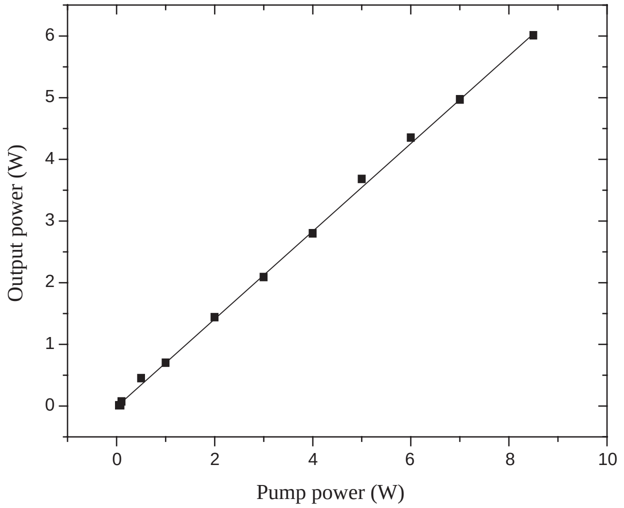

Fig. 7. Output power as a function of pump power.

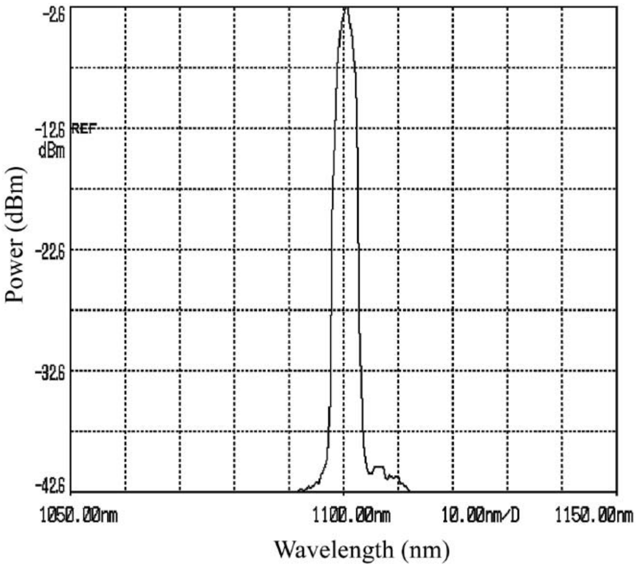

Fig. 8. The spectrum of Yb^{3+}-doped double-clad fiber laser.

5. Conclusions

The threshold characteristics of linear cavity Yb^{3+}-doped double-clad fiber laser have been studied theoretically and experimentally. By solving rate equations, the expression for threshold pump power of linear cavity Yb^{3+}-doped double-clad fiber laser is obtained. The effects of fiber length, mirror reflectivity, pump wavelength, laser wavelength and Yb^{3+} concentration on threshold pump power are discussed. From the discussion, we can draw the following conclusions:

(1) The curves of threshold pump power depending on Yb^{3+} concentration show bathtub-shape, in a certain concentration range, threshold is lowest and keeps invariable; beyond this range, the threshold increases greatly. The dependence of threshold on Yb^{3+} concentration is decided only by fiber itself.

(2) When the radius of inner cladding is smaller, the radius size almost has no effect on threshold level; when the radius of inner cladding increase to a certain size, the threshold increases evidently. In order to obtain lower threshold, the size of inner cladding should be limited in a certain value.

(3) The threshold of double-clad high power fiber laser is related with fiber length, there is an optimal length that makes the threshold lowest. The threshold also changed with the pump wavelength variety, when pump wavelength is 975 nm, the threshold is lowest.

Yb^{3+}-doped double-clad fiber laser with line cavity is developed. When the R_2 are 4%, 30% and 60%, the threshold pump powers are 102, 79 and 68 mW, respectively. The experimental results are in accord with theory.

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