JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 9, No. 8, August 2007, p. 2345 - 2350

Research of Nd^{3+}-doped polarization-maintaining fiber laser

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By means of numerical analysis, the distribution of pump light and the output laser power along the fiber with different fiber length has been researched. The experimental research of Nd^{3+} -doped polarization-maintaining fiber (PMF) laser is reported, which is pumped by 808 nm semiconductor laser. The influence of different fiber winding radius on output power and polarization characteristic of the laser is studied. Double wavelength peak at 1060 nm and 1092 nm are gained. The maximum output power of the laser is 7.35 W at 1060 nm, the slope efficiency is 58.3%.

(Received May 30, 2007; accepted June 27, 2007)

Keywords: Laser technique, Fiber laser, Nd^{3+}-doped polarization-maintaining fiber, Polarization

1. Introduction

The basic mode HE_{11} is double degenerate state because of a good circular symmetry in ideal single mode fiber. The double degenerate state is broken due to the defect in practical fiber, so the modal birefringence are generated. In order to maintain polarization in single mode fiber, the birefringence must be introduced into fiber. So the effective refractive index of HE_{11}^x and HE_{11}^y are different, the difference of transmission constant βx and βy is becoming augmentation, coupling chance of the double mode is minished. The polarized light will maintain their polarization state transmission in fiber if the polarizing direction is parallel to a optic axis direction of fiber, thereout the polarization maintaining optical fiber will be made [1]. The primary structure of double-clad polarization maintaining optical fiber: panda-type PMF, bow tie-type PMF, ellipse clad-type PMF and ellipse core-type PMF etc. Generally , the PMF laser is made by using the coaction of PMF and accessional polarization device, or corrosion bragg grating on fiber, the double-clad adulteration PMF laser was studied only by Upendra H [2~4]. In this paper the PMF laser and output laser polarization characteristic are researched by using panda-type double-cladding Nd^{3+}-doped PMF, and the PMF laser was made.

2. Numerical modeling and analysis of fiber laser

The theoretical model of fiber laser is shown in Fig. 1. We consider a Nd^{3+}-doped PMF of length L, doping content is N。, the pump light is coupled into inner cladding of the fiber at z=0, and along with the forward of inner cladding transmission, the pump light is reflected by output mirror at z=L and inverse transmission. $Pp^+(z)$ and $Pp^-(z)$ are forward and backward powers of the pump light, $Ps^+(z)$ and $Ps^-(z)$ are forward and backward powers of the operation light. R_1 and R_2 are fore stand mirror and end mirror reflectance ratio of the operation light, R_3 is end mirror reflectance ratio of the pump light [5].

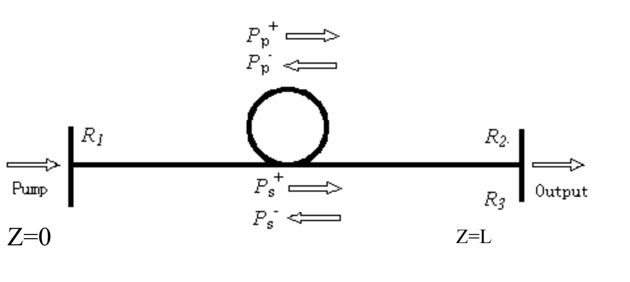


Fig. 1. Diagrammatic sketch of fiber laser.

For the Nd^{3+}-doped double-cladding fiber, the ions of Nd^{3+} basic state E_1 are pumped to energy level E_2, stimulated absorption transition probability is W_{12}, the ions of energy level E_2 return basic state E_1 chiefly by fashion of spontaneous transition A_{21} and non radiative transition S_{21} before the ionic numbers back turn. The pumping speed is rapid enough if pump light is powerful enough, the ionic numbers back turn may be come into being, then stimulated radiation and stimulated transition between energy level E_1 and energy level E_2 are absolute advantage. N_1 and N_2 are ionic numbers density of energy level E_1 and energy level E_2, the equation of every energy level ionic density with time is [6~8]

$$\frac{dN_2}{dt} = W_{12}N_1 - N_2(W_{21} + A_{21} + S_{21})$$

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

due to $S_{21} << A_{21}$, $S_{21} << W_{21}$,so S_{21} can be ignored, $W = \sigma\upsilon N$, where σ is stimulated emission cross section or stimulated absorption cross section, N is photon number density, υ is light velocity in operation material, so $N = \frac{P}{s}$, s is cross section. The photon number density of pump light is $N_p = \frac{\Gamma_p}{h\nu_p A}\left(P_p^+(z) + P_p^-(z)\right)$, the photon number density of operation light is $N_s = \frac{\Gamma_s}{h\nu_s A}\left(P_s^+(z) + P_s^-(z)\right)$, because $A_{21} = \frac{1}{\tau}$, so upper level ion density with time is

$$\frac{dN_2(z)}{dt} = \left(\frac{\Gamma_p\sigma_{ap}\upsilon_p}{h\nu_p}\right)\frac{\left(P_p^+(z) + P_p^-(z)\right)}{A}(N_0 - N_2(z)) + \left(\frac{\Gamma_s\sigma_{as}\upsilon_s}{h\nu_s}\right)\frac{\left(P_s^+(z) + P_s^-(z)\right)}{A}(N_0 - N_2(z)) - \left(\frac{\Gamma_s\sigma_{es}\upsilon_s}{h\nu_s}\right)\frac{\left(P_s^+(z) + P_s^-(z)\right)}{A}N_2(z) - \frac{N_2(z)}{\tau} \tag{2}$$

Where coefficient of coupling *Γ*p is approximate ratio of core area and inner cladding area, power block coefficient *Γ*s is ascertained according to the core of double-clad fiber and operation light wavelength.

when pump excitation maintain long time, $\frac{dN_2(z)}{dt} = 0$, then we can assume $\upsilon_p = \upsilon_s = \upsilon$, thereout

$$\frac{N_2(z)}{N_0} = \frac{\frac{\left(P_p^+(z) + P_p^-(z)\right)\sigma_{ap}\Gamma_p}{h\nu_p A} + \frac{\left(P_s^+(z) + P_s^-(z)\right)\sigma_{as}\Gamma_s}{h\nu_s A}}{\frac{\left(P_p^+(z) + P_p^-(z)\right)\sigma_{ap}\Gamma_p}{h\nu_p A} + \frac{1}{\tau\upsilon} + \frac{\left(P_s^+(z) + P_s^-(z)\right)(\sigma_{as} + \sigma_{es})\Gamma_s}{h\nu_s A}} \tag{3}$$

Here A is core section area, ν_p and ν_s are pump light frequency and operation light frequency, σ_{ap} is absorption cross section of pump light, σ_{as} is absorption cross section of operation light and σ_{es} is emission cross section of operation light.

The transmission characteristic of signal in fiber is described below

$$\pm\frac{dP_s^\pm(z)}{dz} = g(z)P_s^\pm(z) - \alpha_s P_s^\pm(z) \tag{4}$$

α_s is loss coefficient of signal light, $g(z)$ is gain coefficient of the signal light, from $g(z) = \Gamma_s\left[N_2(z)\sigma_{es} - N_1(z)\sigma_{as}\right]$ gain $g(z) = -\Gamma_s\left[\sigma_{as}N_0(z) - (\sigma_{as} + \sigma_{es})N_2(z)\right]$, put into formula (4)

$$\pm\frac{dP_s^\pm(z)}{dz} = -\Gamma_s\left[\sigma_{as}N_0(z) - (\sigma_{as} + \sigma_{es})N_2(z)\right]P_s^\pm(z) - \alpha_s P_s^\pm(z) \tag{5}$$

We can gain the transmission characteristic of pump light in the same manner

$$\pm\frac{dP_p^\pm(z)}{dz} = -\Gamma_p\left[\sigma_{ap}N_0(z) - (\sigma_{ap} + \sigma_{ep})N_2(z)\right]P_p^\pm(z) - \alpha_p P_p^\pm(z) \tag{6}$$

(5) and (6) formula construct a differential equations set, boundary condition are

$$P_s^+(0) = R_1P_s^-(0) \quad , \quad P_s^-(L) = R_2P_s^+(L) \quad ,$$

$$P_p^-(L) = R_3P_p^+(L)$$

The numerical solution of the equations set is obtained by MATLAB software.

Chart 1 Nd^{3+} -doped double-cladding fiber laser parameter list.

λ_p =808 nm	λ_s =1060 nm	σ_{as} =1.4×10^{-23} cm^2	σ_{es} =2.9×10^{-20} cm^2
σ_{ep} =2.5×10^{-23}cm^2	σ_{ap} =2.5×10^{-20}cm^2	A=1.96×10^{-11}cm^2	N=4.33×10^{19}cm^{-3}
α_s =5×10^{-5}	Γ_s =0.82	Γ_p =16×10^{-4}	α_p =3×10^{-5}
R_3=0.04	υ =2×10^{8}m/s	R_1=0.98	τ =0.34×10^{-3}s
R_2=0.04	$n_1 = 1.45$	$n_0 = 1.474$	

The theoretical curve of pump power and output laser power along fiber are shown in Fig. 2 when pump power is 20 W and fiber length is 20 m.

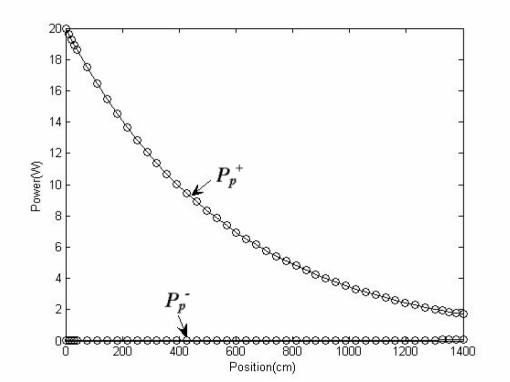


Fig. 2. (a) Distribution curve of pump light.

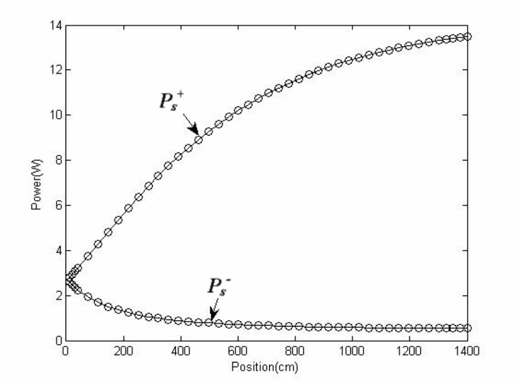


Fig. 2. (b) Distribution curve of signal light.

The theoretical curves of pump power and output laser power along fiber are shown in Fig. 3 when pump power is 20 W and fiber length are 10m, 14 m, 18 m, 20 m, 24 m, 32 m, 40 m and 50 m. From Fig. 3 we can know that the power distribution of forward transmission pump light is almost changeless when fiber length is change, and the power of antipropagation pump light is ignored when the fiber length is long enough. The power distribution curve of forward transmission laser in fiber obviously change along with the L when the fiber length is less than 10 m. The power distribution curve of operation light is almost identical when the fiber length is more than 10 m. The maximum output power has a best fiber length, in this paper the best length of the fiber is 15 m when the power in fiber is 20 W.

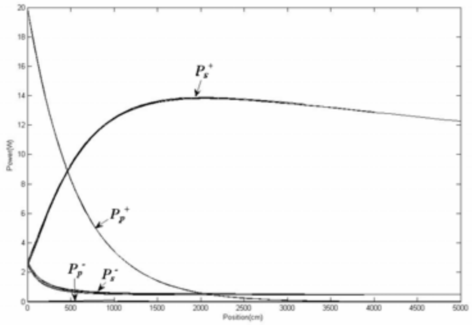


Fig. 3. Distribution curve of pump power and running power with different fiber length.

3. Experimental setup

The setup of PMF laser is shown in Fig. 4. As a active laser medium we used a Nd^{3+}-doped panda-type double-clad fiber with a single-mode core of 5 um diameter and a core cladding diameter of 125 μm, the length of PMF is 14 m, the dichroic mirror (high reflection at 1060 nm and high transmission at 808 nm) and the fiber end face wich is upright chipping (reflection index of 1060 nm is 4%) construct a F-P resonant cavity. A fiber-coupled high-power diode laser at 808 nm was used as pump source. The 86142B-type spectrograph was employed to detect the output laser, the output power was measured by using a power meter.

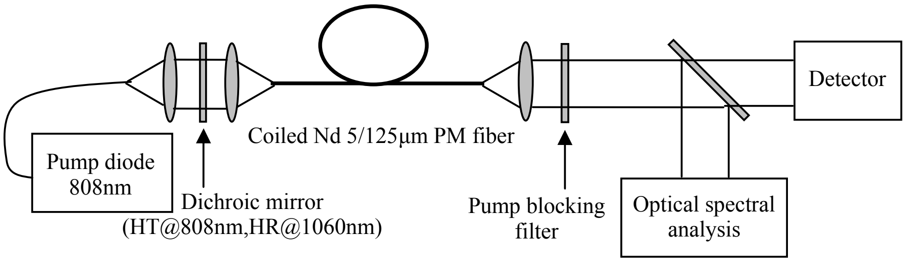


Fig. 4. The experimental setup of double-cladding PMF laser.

4. Experimental results and analysis

The absorption peak of Nd^{3+} is about 808 nm, so the semiconductor laser whose output wavelengh is 808 nm was employed. Threshold current of the pump laser is 6A, and the peak output power is 24W. The curve of power which comes into fiber with pump current is shown in Fig. 5.

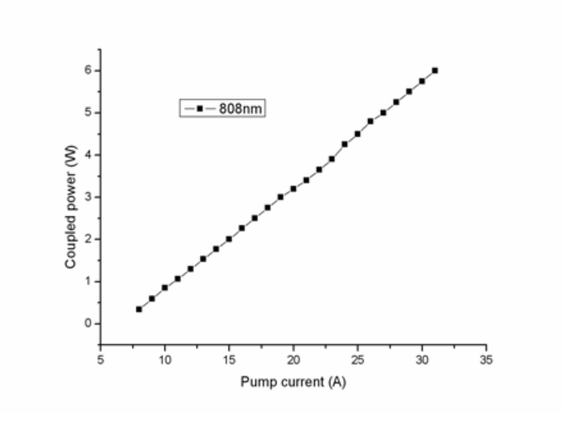


Fig. 5. Power curve of pump laser in fiber.

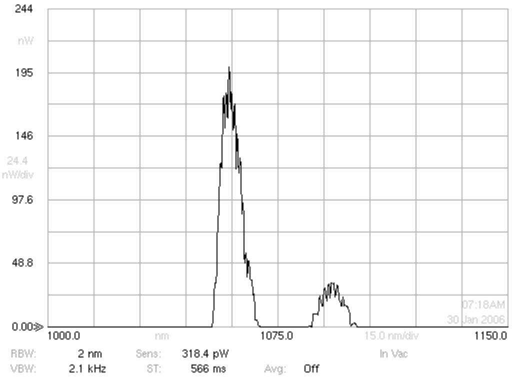
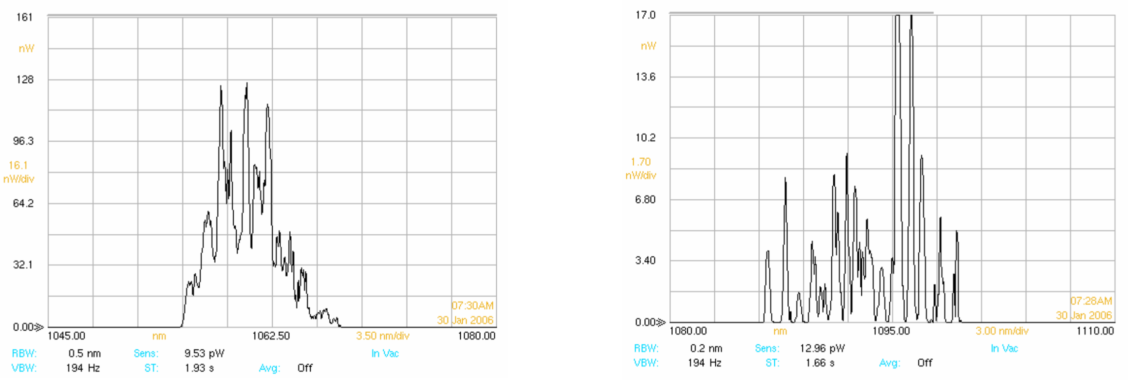


Fig. 6. Spectrum of PMF laser.

The spectrum of output laser is shown in Fig. 6 when fiber absoption pump power is 2.25 W. In Fig. 6 it is shown the second laser peak whose wavelength is 1092 nm. The fine structure of the spectrum is shown in Fig. 7. The multi-peak of fine structure may be the embodiment of various longitudinal mode.

In order to check the influence of fiber flexure type on output laser power, the output laser power of circular shape winding and renal shape winding were compared. The curve chart of output power was shown in Fig. 8. From Fig. 8 we can see that the power index of these two conditions are not obvious, but the difference of output laser polarization degree is big, it was shown in Fig. 9. It is indicate that the influence of PMF flexure type on the polarization state of output laser is more evident, the polarization degree of output laser is big for renal shape winding.



(a) fine structure of spectrum at 1060 nm.

(b) fine structure of spectrum at 1092 nm.

Fig. 7. Fine structure of spectrum of double-cladding PMF laser.

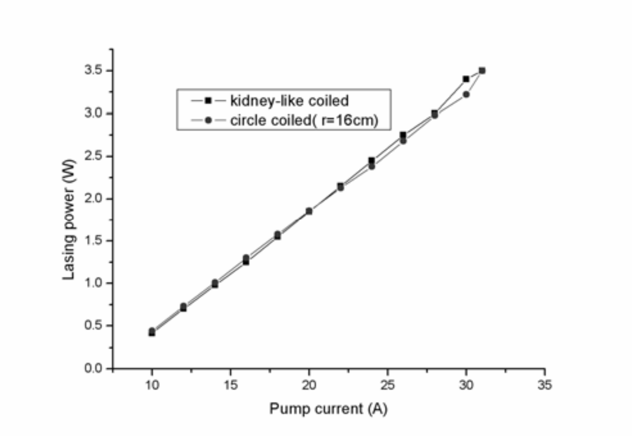


Fig. 8. Output power curve of fiber laser.

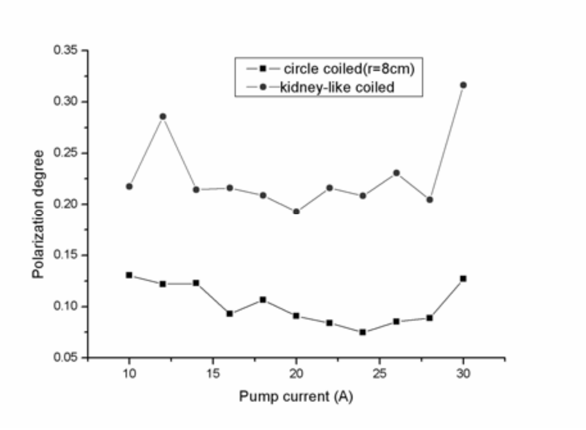


Fig. 9. The comparison of polarization degree in different fiber winding shape.

The maximum output power is 7.35 W when pump current is 38 A and the pump power entering into fiber is 14 W. At the same time, the influence of different fiber winding radius on output laser power in circular shape winding are compared, is shown in Fig. 10. From Fig. 10 one observes that the output power is high when the fiber winding radius is small. It is shown that the absorption of pump light may be improved when the winding radius is changed, and the pump efficiency is increased. The polarization degree of two conditions is shown in Fig. 11, and we can observe that the polarization degree of output laser is high when the fiber winding radius is small.

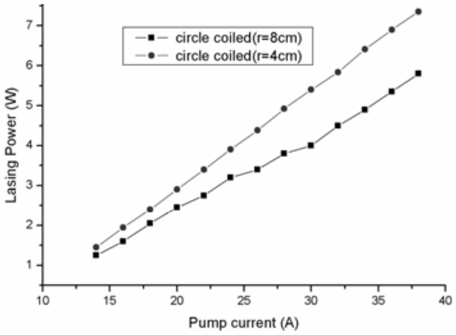


Fig. 10. Power curve of different fiber winding radii.

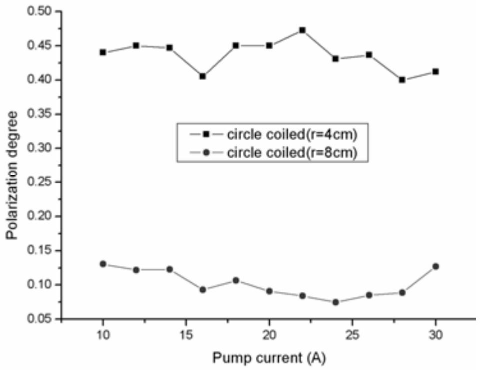


Fig. 11. Laser polarization degree of different fiber winding radii.

5. Conclusion

The coupled wave equations are deduced from energy level transition of Nd^{3+}, the pump and output characteristic of Nd^{3+}-doped laser are numerically modelled by using MATLAB software; The experimental of PMF laser is studied by using F-P cavity. The double wavelength output at 1060 nm and 1092 nm are gained, and we get the conclusion that the output laser polarization degree of the PMF laser is changed along with the winding fashion and winding radii of the fiber. The maximum output power of the PMF laser is 7.35 W at 1060 nm, the slope efficiency is 58.3％.

Acknowledgements

This research was supported in part by the National Natural Science Foundation of China (Grant No. 10474071), the Ph.D. Programs Foundation of Ministry of Education of China(Grant No.20040056010).

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