A 980 nm Yb-doped single-mode fibre laser with 946 nm Nd:YAG laser as pump source

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Based on rate equations, this paper gives expressions of the output power, the pump power threshold, the slope efficiency, the fibre optimal length and the laser gain of a quasi-three-level Yb-doped fibre laser. The gain relationship between quasi-three-level system and four-level system is also given, which provides a theoretical basis for suppressing the four-level transmissions. In the experiment, we adopt the backward pumping configuration and use a linear cavity. The Yb-doped fibre laser has an output power of 372 mW of single-mode laser emission at 980 nm with a slope efficiency of 21.2% when the fibre length is 29.5 cm close to an optimal fibre length in theory. The experimental results accord well with the theoretical analyses.

Keywords: quasi-three-level, Yb-doped fibre, 980 nm laser
PACC: 4255N, 4260D, 4281

1. Introduction

As fibre lasers can easily achieve high photo-electron conversion efficiency, small heat load, single-mode, single-frequency operation and ultra-short pulses (fs) with simple structure and small size, they are widely used in laser processing, laser medical areas, optical communications and national defense applications.[1,2] Moreover, the rapid development of high-power laser diode and the doped fibre design and manufacture improves the competitiveness of fibre lasers with traditional solid-state lasers. For these reasons, fibre lasers become one of the fastest growing laser technologies currently.

Compared with other doped fibre lasers, Yb-doped fibre lasers (YDFL) can obtain high quantum conversion efficiency and suffer neither excited state absorption (ESA) nor concentration quenching effect.[3] Generally, most of the high-power YDFL operate in a four-level system (1030 nm −1200 nm), which have been widely used in laser processing areas.[4,5] However, as the increasing number of channels of dense wavelength division multiplexing demands higher and higher output powers of erbium-doped fibre laser amplifier,[6] the high-power high-quality quasi-three-level YDFL at 980 nm which is an important pump source of erbium-doped fibre amplifier also becomes one of hot research areas in the field of fibre laser. Besides, frequency doubling laser at 980 nm can obtain the blue green laser at 490 nm serving as a window-band of seawater, which has important applications in underwater communication and exploration. At the present time, there are some reports on the research of single-mode YDFL at 980 nm. Single-mode output power 0.65 W at 980 nm from all-fibre laser pumped by a 1.1 W 946 nm Nd:YAG laser was obtained by Zenteno *et al.*[7] A single-mode fibre laser with 2 W continuous wave (CW) output at 978 nm pumped by 914 nm Nd:YVO_4 solid-state laser was produced by Bouchier *et al.* in 2005.[8]

This paper provides the theoretical analysis of the quasi-three-level YDFL and gives expressions of the output power, the laser gain, the pump power threshold, the slope efficiency and the fibre optimal length, which are all deduced from the rate equations and the optical theory of laser light propagation. To suppress the four-level transmissions in the laser, a reasonable fibre length is obtained by solving the gain relationship between quasi-three-level system and four-level system. In the experiment, a quasi-three-level single-mode YDFL emitting 372mW at 980 nm is achieved, which is pumped by a 946 nm Nd:YAG laser.

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2. Theory

The model shown in Fig. 1 is the backward pumping configuration of the fibre laser, where $P_{\rm p}^{\rm in}$ and $P_{\rm las}$ are the input pump power and the output laser power respectively, $P_{\pm}^{\rm in}$ and $P_{\pm}^{\rm out}$ are the laser power of two opposite directions transmitting in Yb-doped fibre respectively, $R_{1\rm s}(R_{1\rm p})$ and $R_{2\rm s}(R_{2\rm p})$ are the reflectivities of two cavity mirrors at the lasing (pump) wavelength ($R_{1\rm p} \doteq 0$), and T_1 and T_2 represent the transmissions of the optics at the both ends of the fibre.

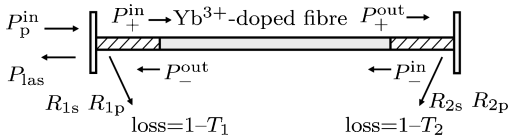


Fig. 1. Schematic diagram of YDFL geometry.

Based on rate equations $P_{-}^{\rm out}$ can be given by[9]

$$\begin{aligned} P_{-}^{\rm out} &= P_{-}^{\rm in}\exp\left(-\alpha_{\rm s}L+\frac{P_{\rm s}^{\rm in}-P_{\rm s}^{\rm out}}{P_{\rm s}^{\rm IS}}+\frac{P_{\rm p}^{\rm in}-P_{\rm p}^{\rm out}}{P_{\rm s}^{\rm CS}}\right) \\ &= T^2R_{\rm s}^2P_{-}^{\rm out}\exp\left(-2\alpha_{\rm s}L+\frac{2P_{\rm p}^{\rm abs}}{P_{\rm s}^{\rm CS}}+\frac{2P_{\rm s}^{\rm abs}}{P_{\rm s}^{\rm IS}}\right), \quad (1) \end{aligned}$$

where $R_{\rm s}^2 = R_{1\rm s}\cdot R_{2\rm s}$, $T = T_1\cdot T_2$, $\alpha_{\rm s}(\alpha_{\rm p})$ is the laser (pump) absorption coefficient, $P_{\rm s}^{\rm IS}(P_{\rm p}^{\rm CS})$ and $P_{\rm s}^{\rm CS}(P_{\rm p}^{\rm IS})$ are laser (pump) intrinsic-saturation power and cross-saturation power respectively, $P_{\rm p}^{\rm abs}$ is the pump power absorbed in its single pass through the fibre, and $P_{\rm s}^{\rm abs}$ is the power absorbed at the lasing wavelength in the fibre. For the quasi-three-level YDFL,

$$P_{\rm p}^{\rm CS} \doteq P_{\rm p}^{\rm IS} = \frac{A_{\rm eff}}{\Gamma_{\rm p}}\frac{1}{\tau_2}\frac{1}{\sigma_{\rm p}^{\rm a}}$$

and

$$P_{\rm s}^{\rm CS} \doteq P_{\rm s}^{\rm IS} = \frac{A_{\rm eff}}{\Gamma_{\rm s}}\frac{1}{\tau_2}\frac{1}{\sigma_{\rm s}^{\rm a}+\sigma_{\rm s}^{\rm e}},$$

where $A_{\rm eff}$ is the effective dopant area, $\Gamma_{\rm s}(\Gamma_{\rm p})$ denotes the transverse overlap of the laser (pump) beam with the dopant ions, τ_2 is the metastable lifetime, $\sigma_{\rm s}^{\rm a}(\sigma_{\rm p}^{\rm a})$ and $\sigma_{\rm s}^{\rm e}(\sigma_{\rm p}^{\rm a})$ are the laser (pump) absorption and emission cross-section. So $P_{\rm s}^{\rm abs}$ can be deduced from Eq. (1) to be

$$\begin{aligned} P_{\rm s}^{\rm abs} &= \left[(T_1^2R_{1\rm s}-1)-(T_2^2R_{2\rm s}-1)\frac{T_1^2R_{1\rm s}}{TR_{\rm s}}\right]\cdot P_{-}^{\rm out} \\ &= -T_{\rm eff}\cdot P_{-}^{\rm out}, \quad (2) \end{aligned}$$

where

$$T_{\rm eff} = (T_2^2R_{2\rm s}-1)\frac{T_1^2R_{1\rm s}}{TR_{\rm s}}-(T_1^2R_{1\rm s}-1).$$

$P_{\rm p}^{\rm abs}$ can be given by

$$\begin{aligned} P_{\rm p}^{\rm abs} &= P_{\rm p}^{\rm in}\left[1-\exp\left(-\alpha_{\rm p}L+\frac{P_{\rm s}^{\rm abs}}{P_{\rm p}^{\rm CS}}+\frac{P_{\rm p}^{\rm abs}}{P_{\rm p}^{\rm IS}}\right)\right] \\ &\quad +T_2^2R_{2\rm p}P_{\rm p}^{\rm in}\cdot\exp\left(-\alpha_{\rm p}L+\frac{P_{\rm s}^{\rm abs}}{P_{\rm p}^{\rm CS}}+\frac{P_{\rm p}^{\rm abs}}{P_{\rm p}^{\rm IS}}\right) \\ &\quad \times\left[1-\exp\left(-\alpha_{\rm p}L+\frac{P_{\rm s}^{\rm abs}}{P_{\rm p}^{\rm CS}}+\frac{P_{\rm p}^{\rm abs}}{P_{\rm p}^{\rm IS}}\right)\right]. \quad (3) \end{aligned}$$

From Eqs. (1)–(3), we obtain

$$\begin{aligned} &P_{\rm s}^{\rm CS}\left[\alpha_{\rm s}L+\frac{T_{\rm eff}P_{-}^{\rm out}}{P_{\rm s}^{\rm IS}}-\ln(TR_{\rm s})\right] \\ &= P_{\rm p}^{\rm in}\left[1-(G_{\max}TR_{\rm s})^{-q}\right] \\ &\quad \times\left\{1+T_2^2R_{2\rm s}(G_{\max}TR_{\rm s})^{-q}\right\}. \quad (4) \end{aligned}$$

Substituting $P_{-}^{\rm out} = P_{\rm las}/(1-R_{1\rm s})T_1$ into Eq. (4), $P_{\rm las}$ ($P_{\rm las} = \eta'\cdot(P_{\rm p}^{\rm in}-P_{\rm p}^{\rm th})$) can be obtained. As a result, slope coefficient $\eta = \eta_q\eta'$ and threshold power $P_{\rm p}^{\rm th}$ of a backward pumping configuration of the fibre laser can be given as follows:

$$\begin{aligned} \eta = \eta_{\rm q}\eta' &= \frac{\eta_{\rm q}(1-R_{1\rm s})T_1}{T_{\rm eff}}\cdot\left[1-(G_{\max}TR_{\rm s})^{-q}\right] \\ &\quad \times\left\{1+T_2^2R_{2\rm p}\cdot(G_{\max}TR_{\rm s})^{-q}\right\}, \quad (5) \end{aligned}$$

$$P_{\rm p}^{\rm th} = \frac{h\gamma_{\rm p}P_{\rm s}^{\rm CS}[\alpha_{\rm s}L-\ln(TR_{\rm s})]}{[1-(G_{\max}TR_{\rm s})^{-q}]\cdot\{1+T_2^2R_{2\rm p}\cdot(G_{\max}TR_{\rm s})^{-q}\}}. \quad (6)$$

where $\gamma_{\rm p}$ is the quantum efficiency, $G_{\max}$ denotes the maximum gain: $G_{\max} = \exp[(\alpha_{\rm p}/q-\alpha_{\rm s})\cdot L]$ with q being the saturation power ratio: $q = P_{\rm s}^{\rm CS}/P_{\rm p}^{\rm IS}$.

As is well known, the output light at 980 nm from the quasi-three-level YDFL is located on the peaks of emission cross-section and absorption cross-section simultaneously, thereby resulting in a serious re-absorption effect. On the other hand, the fibre laser is easy to operate at the four-level transmissions about 1030 nm, owing to little inversion of ions and small absorption cross-section. Therefore, in order to obtain an efficient operation at 980 nm, it is necessary to suppress the emissions around 1030 nm and reduce the re-absorption

loss simultaneously, which can be achieved by choosing the optimal fibre length. The theory of choosing the optimal fibre length in the quasi-three-level YDFL is introduced below

Considering the serious re-absorption effect, the optimal fibre length is obtained by differentiating the laser power with respect to the fibre length: $\mathrm{d}P_{\mathrm{las}}/\mathrm{d}L = 0$, as follows:

$$L_{\mathrm{opt}} = \frac{1}{\alpha_{\mathrm{s}} q - \alpha_{\mathrm{p}}} \ln \left\{ \frac{T_2^2 R_{2\mathrm{p}} - 1 + \left[\left(T_2^2 R_{2\mathrm{p}} - 1 \right)^2 - \dfrac{8 T_2^2 R_{2\mathrm{p}} P_{\mathrm{s}}^{\mathrm{CS}} \alpha_{\mathrm{s}}}{(\alpha_{\mathrm{s}} q - \alpha_{\mathrm{p}}) \cdot P_{\mathrm{p}}^{\mathrm{in}}} \right]^{1/2}}{4 T_2^2 R_{2\mathrm{p}} (T R_{\mathrm{s}})^{-\mathrm{q}}} \right\} \tag{7}$$

At the same time, in order to suppress the emissions at the longer wavelengths (around 1030 nm) and realize the operation at 980 nm in the YDFL, it is necessary to make the unwanted gain at 1030 nm lower than the laser gain at 980 nm which can be obtained by numerically simulating the transcendental equation below:

$$P_{\mathrm{p}}^{\mathrm{in}} - P_{\mathrm{p}}^{\mathrm{in}} \left(\frac{G}{G_{\max}} \right)^{\mathrm{q}} = P_{\mathrm{s}}^{\mathrm{CS}} (\alpha_{\mathrm{s}} L - \ln G) + P_{\mathrm{s}}^{\mathrm{in}} (G - 1). \tag{8}$$

The relationship between the undesired gain at 1030 nm and the laser gain at 980 nm in Yb-doped single-mode fibre ($\beta = 1$) is found to be[10]

$$G_{1030} = 0.14 G_{980} + 1.1 \alpha_{\mathrm{p}}. \tag{9}$$

The range of the fibre length can be obtained by solving Eqs. (8) and (9), that is, the optimal fibre length should be so chosen that these two conditions can be satisfied simultaneously.

3. Theoretical calculation and simulation

According to the theory we have presented the output power, the pump power threshold, the slope efficiency, the fibre optimal length and the laser gain of the YDFL can be calculated after the values of the parameters have been used in the equations. The single-mode Yb-doped fibre used in the experiment had a core diameter of 6 μm and an absorption coefficient of 34 dB/m for pumping at 946 nm. The absorption cross-sections and the emission cross-sections for the pump power and the laser wavelength which were determined by experiment are given as follows: $\sigma_{\mathrm{p}}^{\mathrm{a}} = 7.5 \times 10^{-25}$, $\sigma_{\mathrm{p}}^{\mathrm{e}} = 1 \times 10^{-25}$, $\sigma_{\mathrm{s}}^{\mathrm{a}} = 64 \times 10^{-25}$, and $\sigma_{\mathrm{s}}^{\mathrm{e}} = 66 \times 10^{-25}$. The maximal incident pump power at 946 nm was 2W with a coupling efficiency of 52.3% when the pump power at 946 nm was 3.4W (I=28A). The metastable particle life was τ_2= 0.76 ms. The 0° fibre end was utilized as an output coupler of the laser and a plane mirror coating with high reflection (HR) was used as an other cavity mirror ($R_{1\mathrm{s}} = 0.04$, $R_{1\mathrm{p}} = 0.04$, $R_{2\mathrm{s}} = 0.998$, $R_{2\mathrm{p}} = 0.998$). The reflectivities of the two cavity mirrors around 1030 nm are $R_1 = 0.04$ and $R_2 = 0.002$ respectively. The intra-cavity transmission coefficients are $T_1 = 1$ and $T_2 = 0.05$ respectively. The pump overlap factor and the laser overlap factor are $\Gamma_{\mathrm{s}} = 0.8$ and $\Gamma_{\mathrm{p}} = 0.8$ respectively. The slope efficiency, the pump power threshold, the output power and the laser gain of the YDFL each as a function of fibre length are shown in Fig.2 (a), Fig.2 (b), Fig.2 (c) and Fig.2 (d), respectively.

According to the relationship between the undesired gain around 1030 nm and the laser gain at 980 nm, the gain at 980 nm was numerically obtained to be always higher than the one around 1030 nm when L was less than 61 cm in Yb-doped fibre as shown in Fig. 2(d). From Figs. 2(a) and 2(b), it can be seen that there is an optimal fibre length for this fibre laser. Figure 2(c) shows the laser power of fibre laser as a function of fibre length. From these results, it is indicated that when the fibre length is chosen to be 29.5 cm the output power at 980 nm is highest, at the same time, the four-level transmissions cannot operate. So the fibre length was chosen to be around 29.5 cm in the experiment.

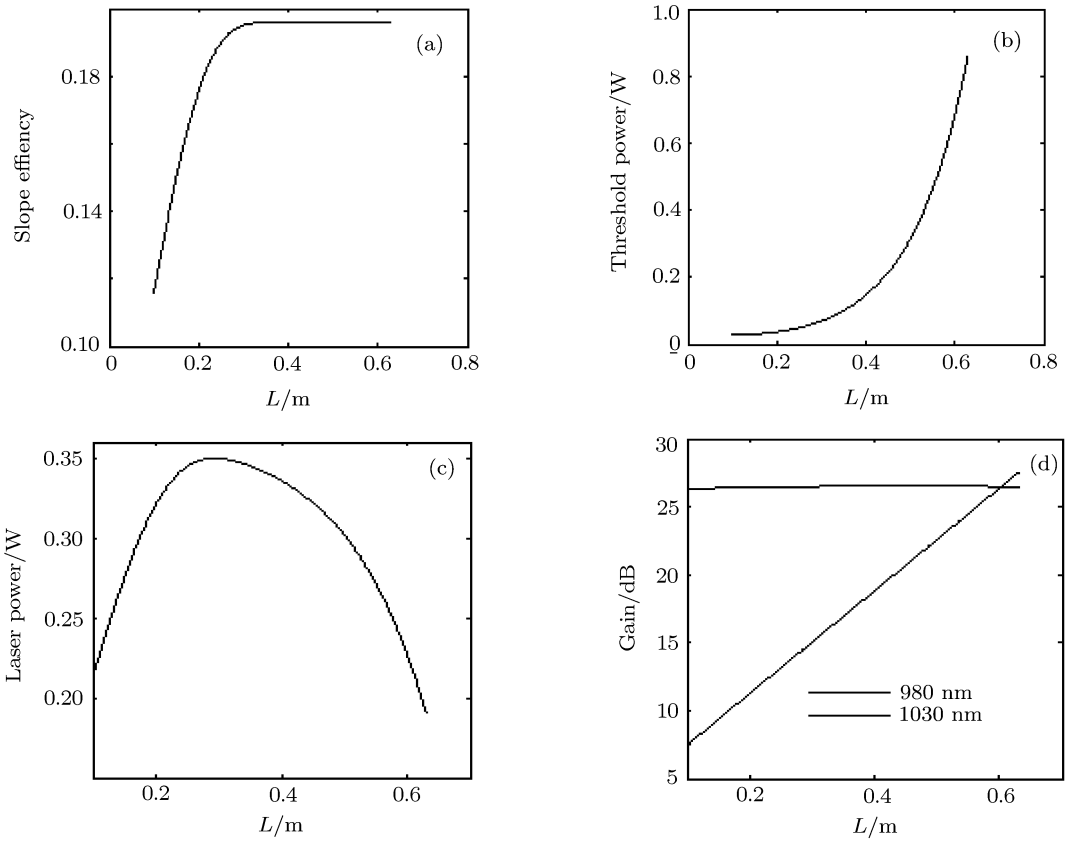


Fig. 2. Slope efficiency (a), threshold power (b), laser power at 980 nm (c), and gains of light at 980 nm and at 1030 nm in Yb-doped fibre (d), each as a function of fibre length.

4. Experiment and results

We adopted the experimental set-up shown in Fig. 3. The pump source of the fibre laser was a home-made 946 nm Nd:YAG laser pumped by a 200 μm-fibre-coupled laser diode at 808 nm. The pump light at 808 nm was coupled via two lenses into the Nd:YAG crystal with a doped level of 1.0 at.%. A plane-concave cavity composed of a face-coating Nd:YAG crystal and a concave output mirror with a curvature radius of 100 mm and transmission of 5% was used in our experiment. Both sides of the crystal were coated with anti-reflections at 1064 nm and 1320 nm to prevent oscillating for the strong four-level transmissions in Nd:YAG. The Nd:YAG laser emitted a maximum CW output power of 4.23 W at 946 nm with a slope efficiency of 18.8% for a 23.4 W incident pump power at 808 nm. The laser emitted nearly TEM_{00} (fundamental transverse mode) radiation with $M^2 \sim 1.4$ (M denotes beam quality factor).[11] The 946 nm light was coupled via mirror M1, dichroic mirror M2 and lens L3 into the Yb-doped fibre.

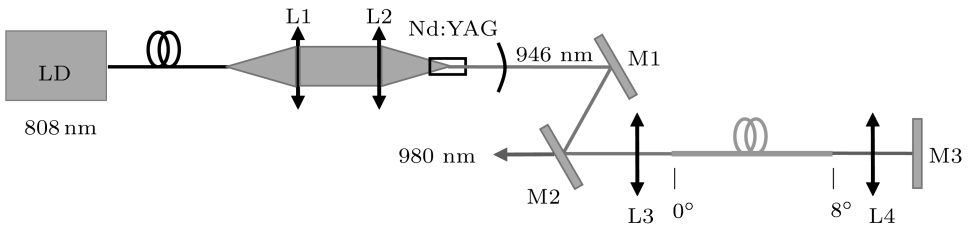


Fig. 3. Experimental set-up of the 980 nm single-mode YDFL.

We utilized a single-mode Yb-doped fibre with a length of 28cm and the fibre ends were ground at angles of 0° and 8° separately. The fibre end at 0° angle was used as an output end with a 4% Fresnel reflection at 980 nm. The other cavity mirror M3 was coated to have a high reflection at 980 nm and high transmission at 1030 nm as shown in Fig. 3. The 980 nm laser beam emitted from the end at 8° was collimated by a lens L4 and then reflected by cavity mirror M3 back into the fibre.

The output power at 980 nm was measured with a power meter. The maximum output power was 372 mW and the threshold pump power was about 75 mW with a slope efficiency of 21.2%. These experimental results accord with the theoretical results that the maximum laser output power is 350 mW with a slope efficiency of 19.4% and the threshold pump power was 60 mW when the fibre length was 28cm. As shown in Fig. 4, the 980 nm laser output rises almost linearly with pump power increasing. When the pump power was 3.4 W, the output laser power reached 372 mW. However, as the power pump continuously increased, the 980 nm output power began to fall quickly, which was most likely because the beam quality of the 946 nm solid-state laser was degraded due to the higher-order mode oscillations as 808 nm pump power increased. Then the 946 nm power coupled into the fibre also began to decline. We also measured the spectrum characteristics of the output laser. The laser wavelength ranged from 977 to 981 nm with a central wavelength of 980 nm and the laser linewidth was about 4 nm just as shown in Fig. 5.

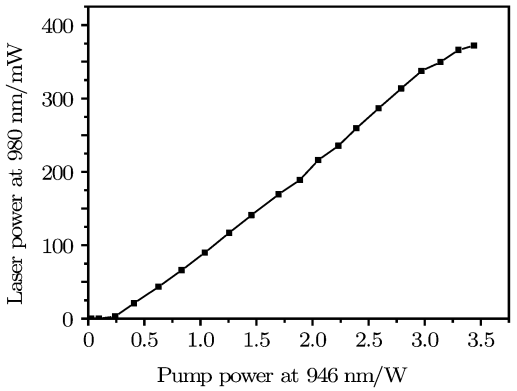


Fig. 4. Output power of 980 nm single-mode YDFL versus 946 nm pump power.

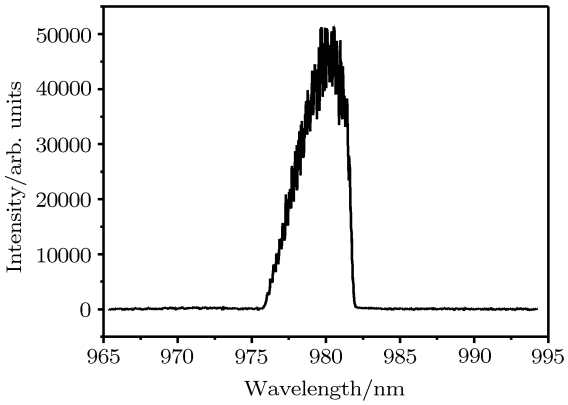


Fig. 5. Spectrum of the 980 nm single-mode Yb-doped fibre laser.

We chose other two fibres with the lengths of 18cm and 36.8cm for the contrastive experiments. The corresponding maximum 980 nm laser output powers were 277mW and 304mW with the slope efficiencies of 15.4% and 15.8% respectively. From the experimental results, we can conclude that when the fibre length was shorter than the optimal length, the pump power could not be fully absorbed by the fibre, which led to a low efficiency as well as a low laser output power. However, when the fibre length was longer than the optimal length, the pump power was insufficient for the fibre and the laser suffered serious re-absorption loss at 980 nm, consequently, the laser efficiency and the laser output power decreased correspondingly.

5. Conclusion

Based on the rate equations of YDFL, we deduce the expressions of its output power, pump power threshold, and slope efficiency. The optimal fibre length is also obtained in view of re-absorption loss and the gain relation between 1030 nm and 980 nm in Yb-doped single-mode fibre. In the experimental study, a single-mode YDFL with an output power of 372 mW is achieved, which is pumped by a home-made 946 nm Nd:YAG laser. The laser slope efficiency is 21.2% and the laser linewidth is about 4 nm ranging from 977 nm to 981 nm. These experimental results accord well with the theoretical analyses.

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