Influence of mode competition on beam quality of fiber amplifier*

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Theoretical and experimental studies of the influence of the mode competition on the output beam quality of fiber amplifiers are presented. Rate equations and modal decomposition method are used in the theoretical model. In the experiment, the output beam-quality factor of a fiber amplifier, which is based on a Yb-doped double-clad large mode area fiber as a function of the seed beam quality and the pump power of the amplifier, is measured. The experimental results are consistent with the theoretical analysis.

Keywords: fiber laser and amplifier, mode competition, beam quality

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1. Introduction

High power continuous-wave fiber lasers and amplifiers are widely used in industrial fields.[1–3] Higher output power means that they can be used to process the larger mechanical bulk, and the laser beam with high beam quality can improve the processing speed and accuracy.[4–7] Therefore, the output power and beam quality are two significant features of fiber lasers and amplifiers. In order to obtain the high power, large mode area (LMA) fibers are adopted in fiber lasers to mitigate the nonlinear impairments and the damage limitations. However, the output light field of LMA fiber is the superposition of multiple modes, and its beam quality is not so high as that of fundamental mode.[8]

The interaction between transverse mode and population inversion can affect the amplifier performance, partially defeating the purpose of using LMA double-clad (DC) Yb-doped fiber. However, few studies are dedicated to the influences of seed beam quality and pump power of the amplifier on the transverse modes competition. Bhutta *et al*. investigated theoretically the effect of the spatial distribution of the active-ion concentration in multimode step-index waveguides on transverse-mode selection for continuous-wave laser operation.[9] Although Jiang and Marciante discussed the effect of transverse spatial-hole burning on the beam-quality factors; they did not mention the function of seed beam quality and pump power in the transverse mode competition.[10] In our previous model,[11,12] the transverse mode competition was studied based on the straight mode and the bent mode distribution, but the beam quality of amplifier influenced by the seed beam quality and the pump power due to the transverse mode competition was not included. Andermahr and Fallnich modeled the transverse mode interaction in an LMA fiber amplifier by solving the Fresnel wave equation including local gain saturation,[13] but they considered only the signal field, in which the pump power was not included.

In this paper, we present both the theoretical and experimental studies of the influence of the mode competition on the beam quality of fiber amplifier. The transversally resolved steady state rate equations for the active fiber are used to assess the transverse mode competition. And the beam quality of fiber amplifier is calculated by a modal decomposition of the output mode field. In the experiment, the beam-quality factor as a function of the seed beam quality and the pump power of the amplifier is measured for a fiber amplifier based on a Yb-doped double-clad LMA fiber. Results of numerical simulations based on the model decomposition method are compared with experimental results. The experimental results are consistent with the theoretical analysis. Experiments and theory verify that seed beam quality and pump power of amplifier have an effect on the output beam quality of amplifier.

2. Modeling of rate equations and beam quality calculation

This model is the result of a combination of the transversally resolved rate equations and a beam quality factor calculation method. In the following, these two simulation methods will be presented separately.

2.1. Transversally-resolved steady state rate equations

The propagation properties of pump light and laser in an end-pumped double-clad fiber amplifier with a linear cavity (as depicted schematically in Fig. 1) are discussed. Due to the fact that laser diodes are usually used as the pump source of fiber lasers and a broadband seed source is used in the experi-

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ment, the phase differences between the transverse modes are not taken into account in the model. Meanwhile, our model is a scalar model. Based on the single mode steady-state rate equations, laser power propagation can be described by the propagation of each mode of fiber. And the pump light is assumed to be homogeneous over the cross section of the inner cladding. So the rate equations of pump light and each laser mode are written as

$$\frac{N_2(x,y,z)}{N(x,y,z)} = \frac{\dfrac{\left[P_{\mathrm{p}}^{+}(z)+P_{\mathrm{p}}^{-}(z)\right]\sigma_{\mathrm{ap}}\Gamma_{\mathrm{p}}(x,y)}{h\nu_{\mathrm{p}}} + \dfrac{\sum_i\left[P_{si}^{+}(z)+P_{si}^{-}(z)\right]\sigma_{\mathrm{as}}\Gamma_{si}(x,y)}{h\nu_{\mathrm{s}}}}{\dfrac{\left[P_{\mathrm{p}}^{+}(z)+P_{\mathrm{p}}^{-}(z)\right]\left(\sigma_{\mathrm{ap}}+\sigma_{\mathrm{ep}}\right)\Gamma_{\mathrm{p}}(x,y)}{h\nu_{\mathrm{p}}} + \dfrac{\sum_i\left[P_{si}^{+}(z)+P_{si}^{-}(z)\right]\left(\sigma_{\mathrm{as}}+\sigma_{\mathrm{es}}\right)\Gamma_{si}(x,y)}{h\nu_{\mathrm{s}}} + \dfrac{1}{\tau}}, \tag{1}$$

$$\frac{\mathrm{d}P_{\mathrm{p}}^{\pm}(z)}{\mathrm{d}z} = \sum_x\sum_y\Gamma_{\mathrm{p}}(x,y)\left[\left(\sigma_{\mathrm{ap}}+\sigma_{\mathrm{ep}}\right)N_2(x,y,z)-\sigma_{\mathrm{ap}}N(x,y,z)\right]P_{\mathrm{p}}^{\pm}(z)-\alpha_{\mathrm{p}}P_{\mathrm{p}}^{\pm}(z), \tag{2}$$

$$\frac{\mathrm{d}P_{si}^{+}(z)}{\mathrm{d}z} = \sum_i\left\{\sum_x\sum_y\Gamma_{si}(x,y)\left[\left(\sigma_{\mathrm{es}}+\sigma_{\mathrm{as}}\right)N_2(x,y,z)-\sigma_{\mathrm{as}}N(x,y,z)\right]P_{si}^{+}(z)-\alpha_{\mathrm{s}}P_{si}^{+}(z)\right\}+2\sigma_{\mathrm{es}}N_2(x,y,z)\cdot\frac{hc^2}{\lambda_{\mathrm{s}}^3}\Delta\lambda_{\mathrm{s}}, \tag{3}$$

where $N_1(x,y,z)$ and $N_2(x,y,z)$ are the population densities of the lower and upper lasing levels at the position (x,y,z) respectively; $N(x,y,z)=N_1(x,y,z)+N_2(x,y,z)$ is the doping concentration distribution; h is the Planck constant; τ is the upper level lifetime; ν_{p} and ν_{s} are the frequencies of pump light and signal light respectively; $P_{\mathrm{p}}^{+}(z)$ and $P_{\mathrm{p}}^{-}(z)$ are the pump powers in the forward and backward directions respectively; $P_{si}^{+}(z)$ is the signal power of the i-th transverse mode in the forward direction for an amplifier; σ_{ap} (σ_{ep}) and σ_{as} (σ_{es}) are the pump absorption (emission) and signal absorption (emission) cross sections at the pump and signal wavelengths respectively; α_{p} and α_{si} are the attenuation factors of the pump and signal of the i-th mode due to the light scattering and light absorption and the fiber bending; $\Delta\lambda_{\mathrm{s}}$ is the spectral width of signal; $2\sigma_{\mathrm{es}}N_2hc^2\cdot\Delta\lambda_{\mathrm{s}}/\lambda_{\mathrm{s}}^3$ denotes the effect of spontaneous emission on the power evolution; $\Gamma_{\mathrm{p}}(x,y)$ and $\Gamma_{si}(x,y)$ are the power filling distributions of pump and signal, which can be expressed as follows:

$$\Gamma_{\mathrm{p}}(x,y)=\frac{1}{A_{\mathrm{clad}}},$$
$$\Gamma_{si}(x,y)=\frac{\varphi_{si}(x,y)}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\varphi_{si}(x,y)\,\mathrm{d}x\mathrm{d}y}. \tag{4}$$

Here, A_{clad} is the area of the inner cladding, and $\varphi_{si}(x,y)$ is the transversal normalized intensity distribution of the signal beam of the i-th mode.

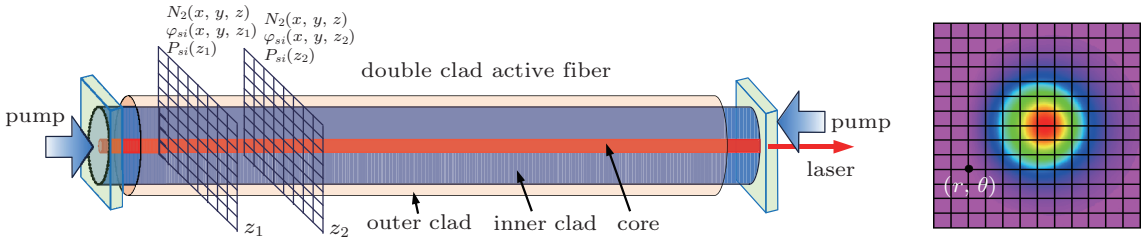


Fig. 1. (color online) Illustration of plane grid difference method.

The partial differential equations (1)–(3) describe the theoretical model of transverse mode competition in the large-mode-area fiber. The population densities of the upper level N_2 (x, y, z) of gain medium at the position of (x, y, z) as a function of the signal powers of $P_{si}^{+}(z)$ and $P_{si}^{-}(z)$ and the pump power of $P_{\mathrm{p}}^{+}(z)$ and $P_{\mathrm{p}}^{-}(z)$ are described in Eqs. (1)–(3) that express the power propagation of pump light and each laser mode along the fiber, respectively. The terms on the right-hand side of Eq. (3) represent the influences of the model gain, model loss, spontaneous emission, and coupling between different modes on the power propagation of each mode.

In the case of fiber amplifier, the partial differential equations (1)–(3) with the given initial conditions (i.e., the initial power of each mode, which is determined by the excitation of the seed) is an initial value problem (IVP), which can be solved by using the fourth-order Runge–Kutta method.

2.2. Beam quality evaluation

Based on transversally-resolved steady state rate equations, output light field composed of fiber eigenmodes is computed. According to Ref. [14], in the case of ignoring the phase difference between different modes, field distribution at the output facet of a fiber can be decomposed into a linear superposition of the eigenmodes

$$E(x,y,z_0)=\sum_i c_i\cdot E_i(x,y), \tag{5}$$

where c_i is the weighting factor; $|c_i|^2$ describes the power content within the i-th laser mode; $E_i(x,y)$ is the normalized field distribution of the i-th laser mode and it is the eigenmode when the gain is ignorable. The center coordinate $x_0(z_0)$ and the variance $\sigma_x^2(z_0)$ of the fiber laser beam at the output facet are given by

$$x_0(z_0)=\iint x\left|\sum_i c_i\cdot E_i(x,y)\right|^2 \mathrm{d}x\mathrm{d}y, \tag{6}$$

$$\sigma_x^2(z_0)=\iint (x-x_0(z_0))^2\left|\sum_i c_i\cdot E_i(x,y)\right|^2 \mathrm{d}x\mathrm{d}y. \tag{7}$$

Based on Kirchhoff's–Fresnel diffraction, the beam center of $x_0(z)$ and the variance $\sigma_x^2(z)$ of the beam at the position of z as a function of the beam center of $x_0(z_0)$ and the variance $\sigma_x^2(z_0)$ at the output facet of z_0, are written as follows:

$$x_0(z) = x_0(z_0)-A_1(z-z_0), \tag{8}$$

$$\sigma_x^2(z) = \sigma_x^2(z_0)-A_2\cdot j\frac{\lambda}{2\pi}(z-z_0) +A_3\cdot\left(\frac{\lambda}{2\pi}\right)^2\cdot(z-z_0)^2. \tag{9}$$

Here,

$$A_1=j\cdot\frac{\lambda}{4\pi}\iint\left[E\cdot\frac{\partial E^*}{\partial x}-E^*\cdot\frac{\partial E}{\partial x}\right]\mathrm{d}x\mathrm{d}y,$$

$$A_2=\iint(x-x_0)\left[E\cdot\frac{\partial E^*}{\partial x}-E^*\cdot\frac{\partial E}{\partial x}\right]\mathrm{d}x\mathrm{d}y,$$

and

$$A_3 = \iint\left|\frac{\partial E}{\partial x}\right|^2\mathrm{d}x\mathrm{d}y +\frac{1}{4}\cdot\left\{\iint(x-x_0)\left[E\cdot\frac{\partial E^*}{\partial x}-E^*\cdot\frac{\partial E}{\partial x}\right]\mathrm{d}x\mathrm{d}y\right\}^2.$$

According to the discussion by Siegman in Ref. [15], the connection between the variance $\sigma_x^2(\tilde{z}_{0x})$ of the beam at the beam waist $\tilde{z}_{0x}$ and the beam quality factor M_x^2 is given by the following expression:

$$\sigma_x^2(z)=\sigma_x^2(\tilde{z}_{0x})+M_x^4\frac{\lambda^2}{16\pi^2\sigma_x^2(\tilde{z}_{0x})}\cdot(z-\tilde{z}_{0x})^2. \tag{10}$$

From Eqs. (8), (9), and (10), the beam quality factor M_x^2 which is defined by output field distribution, can be expressed as follows:

$$M_x^2=\sqrt{4A_3\sigma_x^2(z_0)+A_2^2}. \tag{11}$$

Similarly, the beam quality factor M_y^2 in the y direction can be obtained by replacing x with y in Eq. (11).

Consider the fact that there is no transverse phase difference between the mode fields, A_1 and A_2 and the last term on the right-hand side in expression for A_2 vanishes, namely, $A_1=A_2=0$, then the beam quality factor will be simplified into

$$M_x^2=2\sqrt{\left[\sum_i|c_i|^2\cdot\sigma_{xi}^2(x_0)\right]\cdot\left[\iint\sum_i|c_i|^2\cdot\left|\frac{\partial E_i(x,y)}{\partial x}\right|^2\mathrm{d}x\mathrm{d}y\right]}, \tag{12}$$

$$M_y^2=2\sqrt{\left[\sum_i|c_i|^2\cdot\sigma_{yi}^2(y_0)\right]\cdot\left[\iint\sum_i|c_i|^2\cdot\left|\frac{\partial E_i(x,y)}{\partial y}\right|^2\mathrm{d}x\mathrm{d}y\right]}. \tag{13}$$

Equations (12) and (13) are the expressions for calculating the beam quality factor of LMA fiber laser. The parameters involved in these two expressions are mode field distribution, power content within each mode, second-order intensity moment, mode field gradient, etc. The beam-quality factor of light field can be calculated by Eq. (12) and Eq. (13).

3. Results of numerical simulations and discussion

The fiber laser, which we analyze numerically, is shown in Fig. 2. This fiber laser system consists of a seed source and an amplifier stage. The amplifier stage employs forward-pump scheme. In the calculation, the active fibers, which are used as seed source, and amplifier stage have the core/cladding diameter of 20/400 μm, and the numerical aperture of Yb-doped fiber core is 0.06. As a result, LP_{01} and LP_{11} modes both propagate without loss in the fiber core. However, as LP_{11} mode has two polarized directions LP_{11x} and LP_{11y}, there is not always circular symmetry. So those two directions need to be considered separately. The dependence of the output beam quality of amplifier on seed, and the effects of pump power and signal power on the output beam quality of amplifier are calculated.

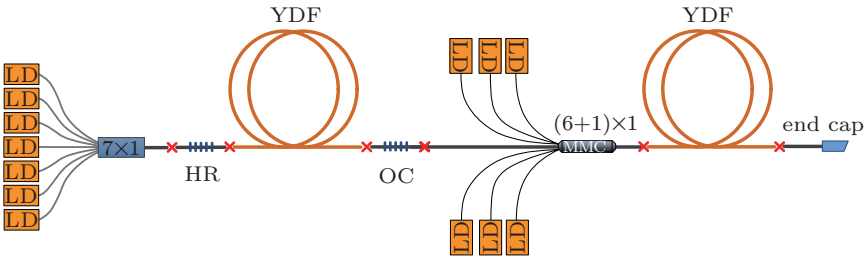


Fig. 2. (color online) Illustration of a fiber laser system.

3.1. Influence of seed on output beam quality of amplifier

The dependence of output beam quality of amplifier on seed with a forward pump power of 500 W is calculated. In the calculation, we study the output beam quality of amplifier stage when the seeds with different beam qualities and different powers (as shown in Table 1) are used. Different modes have different percentages in the seed-beams, corresponding to No. 1–No. 4 in Table 1, the fraction of the fundamental mode decreases, which leads to the poorer beam quality factor of M^2. Under the seed powers of 10 W, 50 W, and 200 W, the output beam quality of amplifier with four different seeds which correspond to No. 1–No. 4 in Table 1 are studied respectively, and the results are shown in Fig. 3.

Table 1. Beam quality of seeds which are used in Fig. 3.

No.	Seed laser mode			Beam quality M^2
	LP_{01}	LP_{11x}	LP_{11y}	
1	90%	5%	5%	1.118
2	80%	10%	10%	1.218
3	70%	15%	15%	1.320
4	60%	20%	20%	1.420

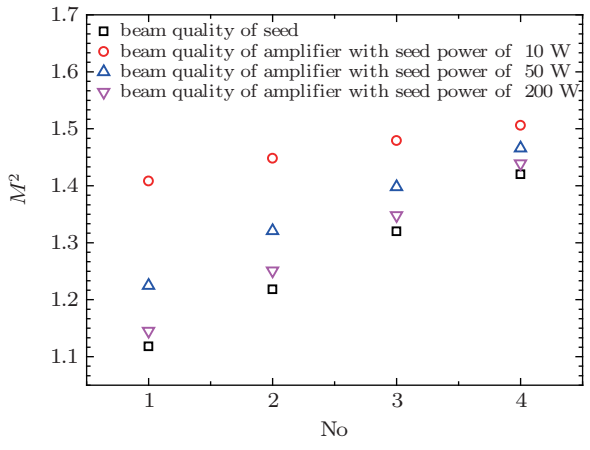


Fig. 3. (color online) Beam quality of amplifiers with different seeds.

We conclude from Table 1 and Fig. 3 that the output beam quality of amplifier stage deteriorates, owing to the degradation of the beam quality of seed. When the fundamental mode has a percentage of 90% in the seed, M^2 of output laser of the amplifier stage is ~ 1.155 when the seed power is 50 W. However, when the seed light degrades to the point that the fundamental mode accounts for 60%, M^2 of the output laser degrades to ~ 1.506 with seed power of 10 W. And, the output beam quality of the amplifier becomes high with the increase of the seed power for the same fraction of each mode in the seed.

3.2. Effects of pump power and seed power on the output beam quality of amplifier

We calculate the effects of pump power and seed power on the output beam quality of amplifier. Two seeds (as shown in Table 2) with a power of 100 W, which have beam quality values of $M_x^2 = M_y^2 = 1.119$ and $M_x^2 = M_y^2 = 1.220$ respectively, are employed in the simulation. The amplifier is forward pumped with different pump powers. The computational results are described in Fig. 4. For the same seed, the output beam quality decreases as the pump power increases. And under the same pump power, the output beam quality is improved when the fundamental mode power has a bigger percentage in the seed. The results indicate that compared to the amplification of high-order mode seeds, the amplification of fundamental mode seed becomes smaller with the increase of pump power, which causes the fraction of fundamental mode in the output laser of amplifier stage to decrease, and then the beam quality of output laser worsens.

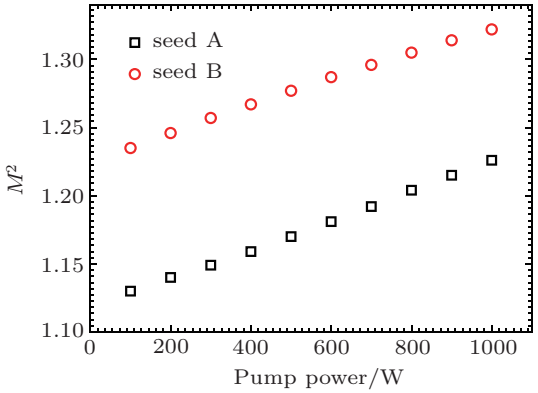


Fig. 4. (color online) Beam quality of output light of amplifiers under different pump powers.

Furthermore, the seeds shown in Table 2 with different powers and the pump light with 1000 W are used, and the am-

plifier is forward pumped. The simulated results are shown in Fig. 5, indicating that under the fixed pump power and the fixed power percentage of each mode in the seed source, the output beam quality of the amplifier stage improves with the increase of seed power. It indicates that the higher seed power, i.e., the higher power of fundamental mode, leads to a bigger fraction of fundamental mode in the output laser of amplifier stage, which means the higher beam quality of output laser.

Table 2. Beam quality of seeds which are used in Fig. 5.

	Seed laser mode		M^2 of seed
	LP_{01}	LP_{11}	
A	90%	10%	1.119
B	80%	20%	1.220

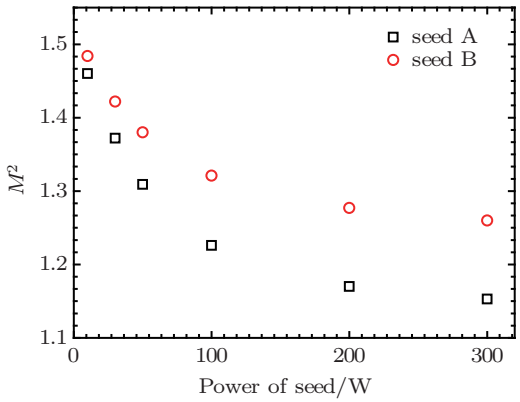


Fig. 5. (color online) Beam quality of amplifiers with different seeds under pump power of 1 kW.

4. Experimental setup and results

4.1. Experimental setup

In the experiment, the developed fiber laser consists of two stages: a laser oscillator stage and a booster amplifier stage. All components are connected by fusion splice. The experimental setup is depicted in Fig. 2. Laser oscillator contains a double-clad ytterbium-doped fiber (YDF), a 7×1 end-pumped combiner, and a pair of FBGs. YDF with core/inner cladding diameter of 20 μm/400 μm (0.06/0.46) was manufactured by Nufern. The absorption of YDF at 975 nm is 1.7 dB/m and the fiber length is 11 m. The laser cavity is formed by a pair of FBGs. One of them is used as the high reflector ($R > 99\%$) and the other one is used as the output coupler ($R = 10\%$). At the output port of oscillator, there is a cladding light stripper (CLS) to absorb unwanted cladding light. The unwanted cladding light is composed of two types: the residual pump light and the signal light leaking into the cladding. The latter is due to the signal loss at the splice point which would impair the output beam quality of the system. The cladding light stripper is made by polishing the fiber cladding directly with a piece of sandpaper with a grit size of 8 μm. The details can be found in Ref. [16].

The power amplifier stage is composed of a gain fiber and a forward end-pumped combiner whose input port is linked to the output port of the oscillator. At the output of the MOPA system, an end-cap with a length of 2 mm and an angle of 8° is employed to minimize back-reflection into the amplifier and avoid the surface damage. The gain fiber used in the amplifier is the same as in the laser oscillator with a length of 15 m, and a coiled diameter of 60 cm which is enough to avoid the influence of curve on the output beam quality. In the end-pumped combiner, the core/cladding diameter of pump fiber is 220 μm/242 μm (NA 0.22). The core/cladding diameter of the active DCF is 20 μm/400 μm (NA 0.06/0.46). The input port of pump fiber of the end-pumped combiner is connected to the output port of a 7×1 end-pumped combiner. Seven pigtail fiber output pump laser diodes (LDs) are combined to one output by using the 7×1 combiner. Each LD through a pigtail fiber of 105 μm/125 μm (NA 0.15) can provide an output power of 25 W. The 7×1 combiner is homemade with an input fiber of 105 μm/125 μm (NA 0.15) and an output fiber of 220 μm/242 μm (NA 0.22).

4.2. Analysis on experimental results

Firstly, the output beam quality of the amplifier with the same pump power but different seeds is studied by using a broadband seed source whose full width at half maximum is 1.5 nm. In the experiment, three different seeds are injected as the input of oscillator, and three output powers of 37.3 W ($M_x^2 = 1.227, M_y^2 = 1.289$), 63.3 W ($M_x^2 = 1.274, M_y^2 = 1.383$), and 91.1 W ($M_x^2 = 1.303$, $M_y^2 = 1.405$) are achieved respectively, which are the inputs of the amplifier stage. Output field patterns of amplifier stage with the pump powers of 138 W and 276 W respectively, are shown in Fig. 6. The seed field patterns of the amplifiers are depicted in Figs. 6(a)–6(c); the output field patterns of the amplifiers with pump powers of 138 W and 276 W are shown in Figs. 6(d)–6(f) and Figs. 6(g)–6(i) respectively.

In order to testify the agreement between the theoretical results and the experimental results, the beam quality of output light, which has the same parameters as the output light attained in the experiment, is calculated by using the theoretical model. In the computation, the seed, which has a similar beam quality to the seed in the experiment, is obtained by adjusting the power percentages of different modes as shown in Table 3. The calculated results are shown in Fig. 7. The comparison between the theoretical results and the experimental results shows that they accord well with one another. Moreover, from Fig. 7, we can see that the worst beam quality of seed leads to the worst output beam quality of amplifier. Results in Fig. 7 are in good agreement with the calculated results in Section 3.

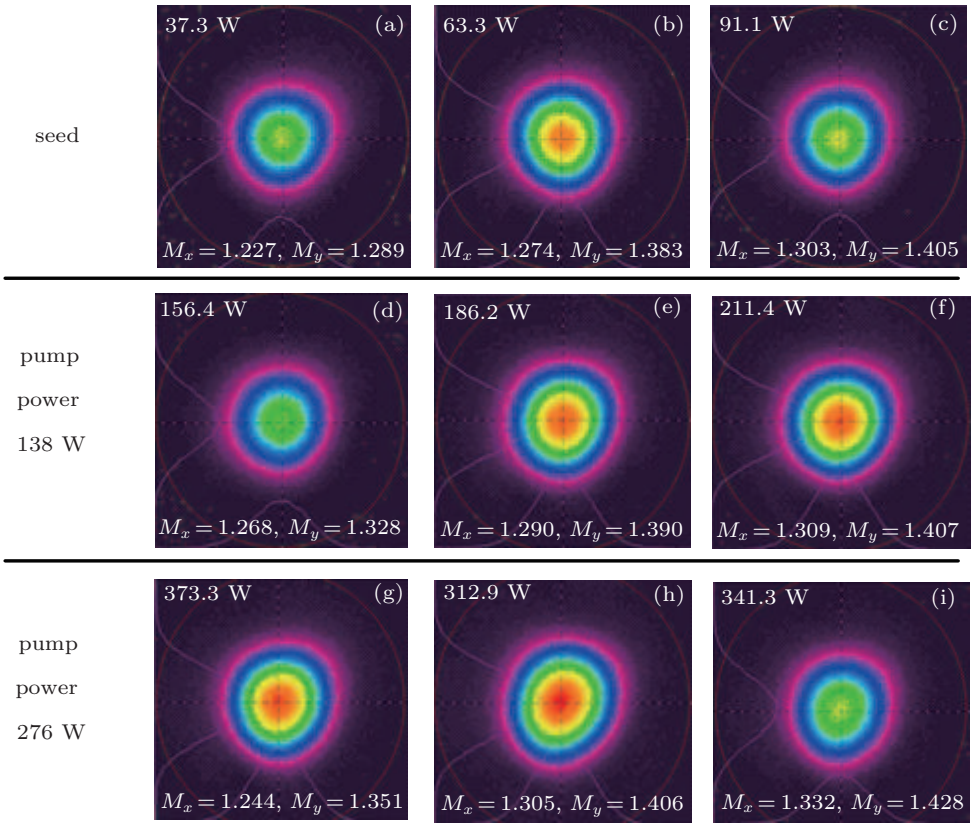


Fig. 6. (color online) Field patterns of seed and amplifier output: (a)–(c) seeds with powers of 37.3 W, 63.3 W, and 91.1 W; (d)–(f) amplifiers with pump power of 138 W; (g)–(i) amplifiers with pump power of 276 W.

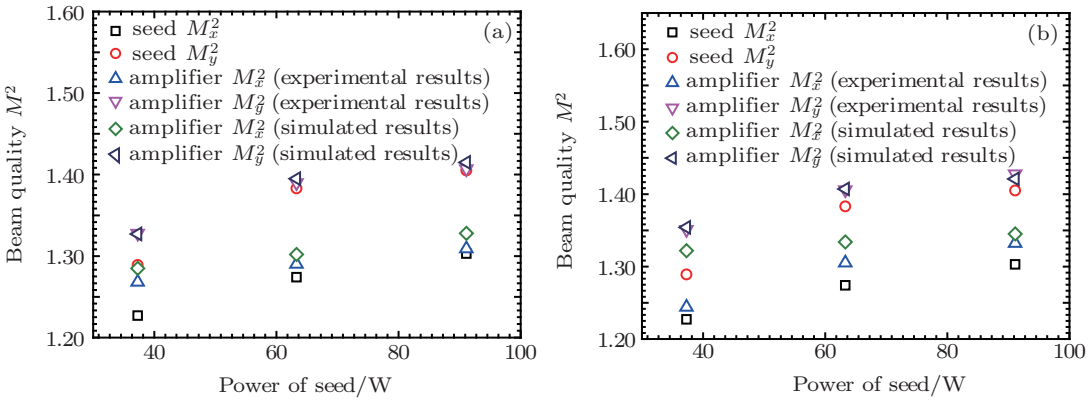


Fig. 7. (color online) Output beam quality of amplifiers with different seeds. (a) pump power of 138 W, (b) pump power of 276 W.

Table 3. Beam quality of seeds which used in Fig. 8.

Seed laser mode			Beam quality factor	
LP_{01}	LP_{11x}	LP_{11y}	M_x^2	M_y^2
75.4%	10.8%	13.9%	1.227	1.289
68.4%	13.1%	18.5%	1.274	1.383
65.8%	14.6%	19.6%	1.303	1.405

We study experimentally the influences of pump power on the output beam quality of amplifier under the same seeds. The seed with a power of 63.3 W and beam quality of $M_x^2 = 1.274$, $M_y^2 = 1.383$ is used. By adjusting the pump power, the field pattern and the beam quality of output light are measured. And the measurement results are shown in Fig. 8. It is seen that for the same seed-sources, the beam quality of output light becomes worse with the increase of pump power.

In addition, the seed has the power percentages of 68.4% of LP_{01}, 13.1% of LP_{11x}, and 18.5% of LP_{11y} with the beam quality of $M_x^2 = 1.274$ and $M_y^2 = 1.383$ which are obtained in theory. Here, we firstly calculate the beam quality factor of each transverse mode, i.e., $M_x^2 = M_y^2 = 1.011$ for LP_{01} mode, $M_x^2 = 3.018$ and $M_y^2 = 1.011$ for LP_{11x} mode, $M_x^2 = 1.011$ and $M_y^2 = 3.018$ for LP_{11y} mode. If the modal content is c_1, c_2, and c_3 for LP_{01}, LP_{11x}, and LP_{11y} in seed respectively, and it is a

broadband seed source, the modal content in this seed can be computed from the equations of $c_1 \times 1.011 + c_2 \times 3.018 + c_3 \times 1.011 = 1.274$, $c_1 \times 1.011 + c_2 \times 1.011 + c_3 \times 3.018 = 1.383$, and $c_1 + c_2 + c_3 = 1$, three equations with three unknowns, so that we can obtain $c_1 = 68.4\%$, $c_2 = 13.1\%$, and $c_3 = 18.5\%$. Under this seed-source and different pump powers, the output beam quality of amplifier is calculated, and the calculated and experimental results are presented in Fig. 9. It is noted that the calculated results and experimental results are in good agreement with each other, particularly when the pump power is lower than 300 W. However, when the pump power is higher than 300 W, the beam quality of calculation is a bit better than the experimental result. It must be mentioned that the calculation model considers only the effect of model competition on the beam quality of amplified laser, ignoring the thermally induced change of refractive index of gain fiber in the case of high pump power.

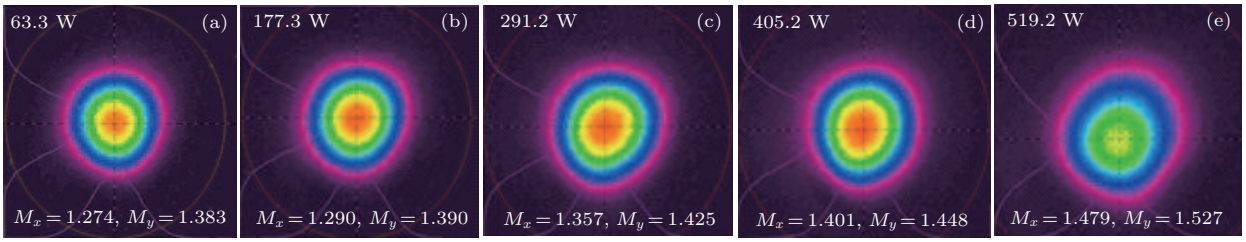


Fig. 8. (color online) Light field patterns and beam quality of the output light of amplifier.

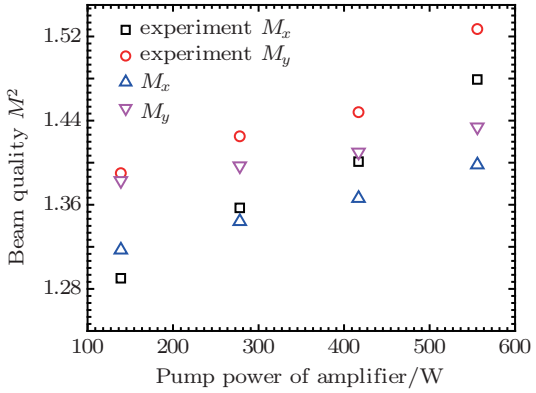


Fig. 9. (color online) Output beam quality of amplifiers under different pump powers.

5. Conclusion

The output beam quality of an MOPA fiber laser is investigated in simulation and experiment. The simulation is based on a combination of the transversally resolved rate equations and the beam quality factor calculation. The theoretical calculation shows the beam quality of the amplifier stage deteriorates, owing to the degradation of the seed beam quality, and the beam quality of output laser decreases with the increase of pump power for the same seed. These are due to the interaction between transverse mode and population inversion. In the experiment, an MOPA fiber laser system is assembled. The output beam quality is measured with different seeds and pump powers of amplifiers. The experimental results show the same properties as the theoretical analysis. In order to testify the agreement between the theoretical results and experimental results, the seeds with the same beam quality in the experiment are used in the calculation. In the result, the calculation results are in good agreement with experimental results.

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