Theoretical analysis of the mode coupling induced by heat of large-pitch micro-structured fibers*

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In this paper, a theoretical model to analyze the mode coupling induced by heat, when the fiber amplifier works at high power configuration, is proposed. The model mainly takes into consideration the mode field change due to the thermally induced refractive index change and the coupling between modes. A method to predict the largest average output power of fiber is also proposed according to the mode coupling theory. The largest average output power of a large pitch fiber with a core diameter of 190 μm and an available pulse energy of 100 mJ is predicted to be 540 W, which is the highest in large mode field fibers.

Keywords: fiber amplifier, large pitch fiber, mode coupling

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1. Introduction

Increasing the fiber core diameter is a prime method to reduce the nonlinear effect of a pulsed fiber amplifier. By employing micro-structured fiber (MSF) with non-continuous interface to increase the difference in loss between modes, the core diameter can be enlarged further to 100 μm. It is demonstrated that near diffraction limited beam quality laser output with a pulse width of 20 ns and pulse energy of 22 mJ is achieved by employing a large pitch fiber (LPF) with 135-μm core diameter.[1] It seems that the LPF is one of the most promising approaches for core diameters beyond 100 μm.[2–4] However, MSFs, including large pitch fibers, suffer from mode instabilities when laser powers exceed a certain value due to losses of confinement compared with that in continuous interface, resulting in a dramatic decrease in beam quality.[5–8]

According to the 135-μm MSF fiber structure, we for the first time fully investigate the output laser beam quality change trend of the discontinuous interface of MSF with core diameter varying from 51 μm to 190 μm in laser amplification. The mode competition caused by the mode gain and loss is considered. What is more, we focus on the influence of average output power on beam quality of the nearly 200-μm fiber. With the increase of the fiber core size, the mode loss difference decreases. Taking the beam quality factor $M^2 < 1.5$ as the upper limit value, the core diameter of MSF can be expanded to nearly 200 μm. This is the biggest fiber core for the high beam quality laser output. Its biggest advantage is to effectively reduce the nonlinear effects in the pulse amplification, increasing the available pulse energy, which can reach 80 mJ/m. When $M^2 < 2$, the average power can reach 540 W. This theoretical laser output power level has broken all of the available work intervals of the pulse fiber laser at mJ level (the pulse energy of more than 20 mJ has an average single pulse power lower than 150 W[2]).

The calculated results in this paper provide the reference for the laser available work interval of currently very large mode area MSFs. For further lowering the pulse nonlinear effect and obtaining MSF with a core diameter of more than 200 μm, and also with a high quality beam output laser average power above 500 W, it must make a bigger breakthrough on the structure. But for pulsed fiber amplifiers requiring high pulse energy, the available pulse energy is as high as 100 mJ. So the situation where high energy and high average power cannot be realized at the same time should be broken.[9]

A super large mode area and large pitch fiber suitable for fiber drawing with diameter as large as 190-μm has been designed, which is, to our knowledge, the largest core-diameter fiber able to maintain near diffraction limit beam quality. In this paper, in order to analyze the average power output ability of the 190-μm Yb-doped large pitch fiber amplifier, we take into consideration the thermally induced mode coupling in mode competition. We arrive at the conclusion that the largest average output power of this amplifier can reach 540 W and its available pulse energy can reach 100 mJ when working in the near diffraction-limited configuration ($M^2 < 2.0$).

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2. Theoretical model

The large pitch fiber used in this paper and the characteristic mode distribution are shown in Fig. 1. The fiber has 18 air-holes that are hexagonally arranged in two circles with the central hole missing: the core diameter ($d_{\rm core}$) is 190 μm, the diameter of air hole cladding (d) is 19 μm, and the air-hole pitch (Γ) is 104.5 μm. The fundamental mode (FM) has a mode diameter of 180 μm, and a propagation loss of 1 dB/m. The first higher order mode (HOM) has a mode diameter of 273 μm and a propagation loss of 19 dB/m, which is 18 dB/m higher than that of the FM. As to this fiber, the available pulse energy, which is defined as $E_{\rm available} = h\nu(n_{\rm trp} - n_{\rm trs})A_{\rm doped}$, with $n_{\rm trp,s} = N_0\sigma_{\rm ap,s}(\sigma_{\rm ap,s} + \sigma_{\rm ep,s})$,[10] can be 80 mJ/m, making it perfectly suitable for applications in high average power, high peak power-pulsed amplifiers.

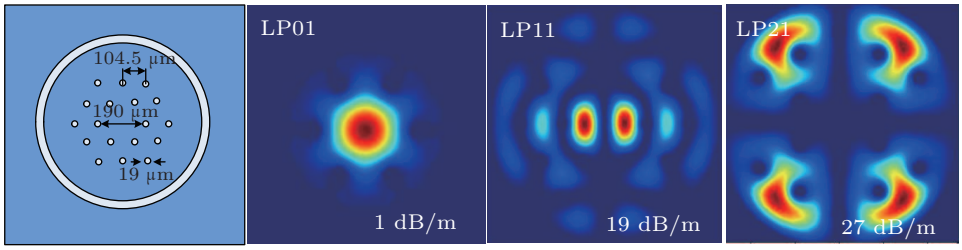


Fig. 1. (color online) End-face of the large pitch fiber used and its several major modes.

A large core-diameter fiber amplifier with no interface can achieve high peak power output but the output beam quality would suffer a decrease when the output average power exceeds a certain value. The physical mechanism behind this is not quite clear, except for the fact that the influence of nonlinear effect is ruled out because the threshold has nothing to do with the peak power and is only influenced by the average power.[5] There are many explanations of this phenomenon.[11–14] One explanation is that it is due to the formation of induced long-period gratings.[12] Here the interference pattern of the FM between an HOM is mapped into the population inversion and, therefore, locally modifies the refractive index of the core, resulting in coupling between FM and HOMs. But due to the short length of MSF in general application, the influence of induced long-period gratings is not significant. According to the power scaling estimation,[15] the thermally induced mode deformation is one of the most important factors to restrict the possible output power of MSF, especially for large mode area (LMA) fibers. The heat produced by the fiber changes the refractive index, causing the fiber modes to shift. Therefore, the newly generated modes couple with the original modes, resulting in the decrease of beam quality.[16] For this reason, the thermal effect introduces an independent limitation to avoid multimode output. Plenty of research has focused on the beam quality deterioration caused by thermally induced mode coupling,[13,16,17] but they have failed to combine thermally induced mode coupling with mode competition.

In this paper, we substitute the thermally induced mode coupling into mode competition for a 190-μm core-diameter fiber amplifier at high power levels, acquiring the relationship between the average output power and the beam quality. The influence of thermally induced mode coupling on laser beam quality is also given. A schematic figure of the laser amplifier using the 190-μm core-diameter fiber is shown in Fig. 2.

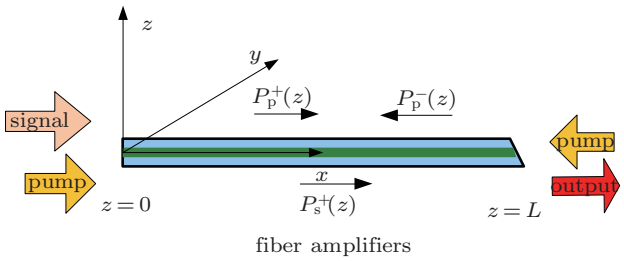


Fig. 2. (color online) Schematic diagram of the fiber amplifier.

Suppose that all of the modes can propagate along the fiber, then the population of the fiber core, the signal power, and the pump power of each mode will be given by the following space and time independent steady-state rate equations:[18]

$$\frac{N_2(x,y,z)}{N_1(x,y,z)} = \frac{\dfrac{[P_{\rm p}^{+}(z)+P_{\rm p}^{-}(z)]\sigma_{\rm ap}\varphi_{\rm p}(x,y)}{h\nu_{\rm p}} + \sum_{i=1}^{M}\dfrac{[P_{si}^{+}(z)+P_{si}^{-}(z)]\sigma_{\rm as}\varphi_{si}(x,y)}{h\nu_{\rm s}}}{\dfrac{[P_{\rm p}^{+}(z)+P_{\rm p}^{-}(z)]\sigma_{\rm ep}\varphi_{\rm p}(x,y)}{h\nu_{\rm p}} + \dfrac{1}{\tau} + \sum_{i=1}^{M}\dfrac{[P_{si}^{+}(z)+P_{si}^{-}(z)]\sigma_{\rm es}\varphi_{si}(x,y)}{h\nu_{\rm s}}}, \tag{1}$$

$$\pm\frac{{\rm d}P_{\rm p}^{\pm}(z)}{{\rm d}z} = \left\{\iint_A \left[\sigma_{\rm ep}N_2(x,y,z) - \sigma_{\rm ap}N_1(x,y,z)\right]\varphi_{\rm p}(x,y)\,{\rm d}x{\rm d}y\right\}P_{\rm p}^{\pm}(z) - \alpha_{\rm p}P_{\rm p}^{\pm}(z), \tag{2}$$

$$\pm\frac{\mathrm{d}P_{si}^{\pm}(z)}{\mathrm{d}z}=\left\{\iint_{A_j}[\sigma_{es}N_2(x,y,z)-\sigma_{as}N_1(x,y,z)]\varphi_{si}(x,y)\,\mathrm{d}x\mathrm{d}y\right\}P_{si}^{\pm}(z)-\alpha_{si}P_{si}^{\pm}(z)-\sum_{j=1}^{M}d_{ij}[p_{si}^{\pm}(z)-p_{si}^{\pm}(z)], \tag{3}$$

where τ is the spontaneous lifetime of the upper lasing level; h is the Planck constant; ν_s and ν_p are the laser and pump frequencies, respectively; N_1 and are N_2 the population densities of the lower and upper lasing levels; N_0 is the doping concentration distribution; $P_p^+(z)$ and $P_p^-(z)$ are the pump powers in the forward and backward directions, respectively; $P_{si}^+(z)$ and $P_{si}^-(z)$ are the signal powers of the i-th transverse mode in the forward and backward directions, respectively; $\sigma_{\alpha p}$ ($\sigma_{\alpha s}$) and σ_{ep} (σ_{es}) are the pump absorption (emission) and signal absorption (emission) cross sections, respectively; α_p and α_{si} are the laser and pump loss factors of the i-th mode, respectively; φ_p and φ_{si} are the normalized intensity distributions of the pump and i-th mode; and, d_{ij} is the power coupling coefficient between the i-th and j-th modes.

The thermal effect appears when the output power is high enough to exceed the threshold, resulting in a change of the refractive index. According to Ref. [16], the thermally induced refractive index change in MSF can be described as

$$\Delta n_{\mathrm{core}}=\frac{Q(z)a^2\beta}{4\rho}\left[1-\left(\frac{r}{a}\right)^2+2\ln\left(\frac{b}{a}\right)+\frac{2\rho}{bH}\right],\quad(0\le r\le a), \tag{4}$$

$$\Delta n_{\mathrm{inner-clad}}=\frac{Q(z)a^2\beta}{4\rho}\left[\frac{2\rho}{bH}-2\ln\left(\frac{r}{b}\right)\right],\quad(a\le r\le b), \tag{5}$$

where a and b are the radii of core and inner-clad, respectively. The heart density $Q(z)$ is expressed as $Q(z)=\eta\cdot\alpha\cdot P_p^+(z)/(\pi a^2)$; η is the quantum defect, which is described as $\eta=1-\lambda_p/\lambda_s$; α is the absorption coefficient of pump light, which is expressed as $\alpha=\sigma_{ap}n_{trp}A_{doped}/A_{pump}$, with $n_{trp}=N_0\sigma_{ap}/(\sigma_{ap}+\sigma_{ep})$, A_{doped} and A_{pump} being the areas of active region and pump cladding; $\beta=\mathrm{d}n/\mathrm{d}T$ is the thermal–optic coefficient; and, H is the convection heat transfer coefficient. In order to investigate the complex thermal mechanics in LPF in a quick and simple way, besides utilizing the simplified average thermally induced index parameters, we replace the thermal conductivity κ by $\kappa=(A_{silica}\kappa_{silica}+A_{air}\kappa_{air})/(A_{silica}+A_{air})$ in the summary form, with A_{silica} and A_{air} being the areas of the silica material and air holes in the inner-cladding, respectively.

The thermally induced index change affects the mode profiles, which would change the final output beam quality of the fiber laser system. In an amplifier, the eigenmodes change along the fiber as the thermal perturbation caused by the residual pump power and the waste heat change. The mode coupling effect is a function of fiber parameters, pump direction, pump power, seed power, etc. The mode coupling coefficient between two modes can be described by the overlap integral of their normalized field distributions, and is defined as[19]

$$d_{ij}=\frac{\left|\int_A E_i(x,y)\cdot E_j^*(x,y)\,\mathrm{d}s\right|^2}{\left[\int_A E_i^*(x,y)\cdot E_i^*(x,y)\,\mathrm{d}s\right]\left[\int_A E_j(x,y)\cdot E_j^*(x,y)\,\mathrm{d}s\right]}, \tag{6}$$

where E_i and E_j are the normalized field distributions of the i-th mode and j-th mode, respectively; and, A denotes the fiber cross section area.

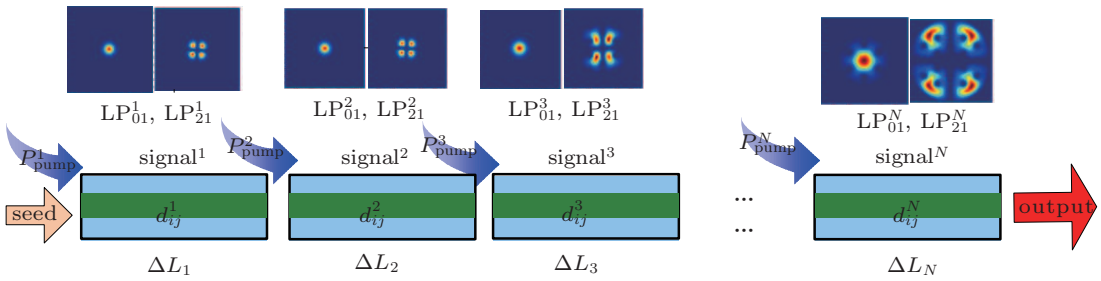


Fig. 3. (color online) Mode coupling in heating process.

The heat-induced index change relates to pump power, while pump laser power differs at different positions of the gain fiber; therefore, the eigenmode distribution and the coupling coefficients change constantly along the fiber length direction. As shown in Fig. 3, taking the coupling between LP_{01} and LP_{21} for example, we describe the mode instability procedure. Dividing the fiber with length L into N segments, each with a length of ΔL, then according to Eqs. (4) and (5) and COMSOL software, we can derive the LP_{01}^1 and LP_{21}^1 of the first segment ΔL_1 after the index change has been induced by initial pump power. The coupling coefficient d_{ij}^1 can be calculated according to Eq. (6) by LP_{01}^1 and LP_{21}^1 and the seed laser modes LP_{01} and LP_{21}. Substituting the obtained values into rate equations (1)–(3), we can then derive the pump power

P^2_{pump} and the signal power signal[1] after propagating a length of ΔL_1. We can then calculate LP^2_{01} and LP^2_{21}, and d^2_{ij} can be calculated by LP^1_{01}, LP^1_{21}, LP^2_{01}, and LP^2_{21}. As the seed laser power of the second segment, signal[1] should be substituted into the second segment ΔL_2 and introduce mode competition. The laser mode and power after mode competition of N segments can be derived this way. The equivalent output mode field diameter (MFD) and beam quality (M^2) can then be calculated. In this paper, we only give the influence of the heat instability on output beam quality by adopting a relatively simple method, the results need to be supported and improved by further theoretical and experimental researches.

3. Results and discussion

The fiber laser's output beam quality and equivalent mode field diameter under a certain pump power can be calculated according to the mode coupling analysis. Then, by the limit of beam quality, we obtain the utmost pump power and the corresponding maximum output laser power. The mode coupling tends to happen between lower order modes, especially with FM. The calculation results show that coupling between LP_{21} and LP_{01} takes place most easily. So only the coupling between these two modes is taken into consideration in the following calculation. The calculation parameters are shown in Table 1. A forward pump is used in mode coupling because the pump light can be absorbed almost completely in this case; therefore, little residual heat is introduced, resulting in FM output without influence of heat.

Table 1. Parameter values used in the calculation of index change.

Parameter	Value	Parameter	Value
d_{core}	190 μm	σ_{ap}	2.34×10^{-24} m^2
d	19 μm	σ_{ep}	2.34×10^{-24} m^2
Γ	104.5 μm	σ_{as}	2.41×10^{-26} m^2
L	1.2 m	σ_{es}	3.82×10^{-25} m^2
N_0	3.68×10^{25} m^{-3}	β	11.8×10^{-6} K^{-1}
λ_{p}	975 nm	ρ_{silica}	1.38 W· m^{-1}·K^{-1}
λ_{s}	1040 nm	ρ_{air}	0.023 W· m^{-1}·K^{-1}
h	6.626×10^{-34}	H	1000 W· m^{-2}·K^{-1}
τ	1.0 ms	δ	0.083
α_{p}	2.0×10^{-3} m^{-1}	α	4.06

Figure 4 shows the LP_{01} and LP_{21} distributions after the heat has induced index change under different pump powers. We can obtain that, as the pump power is higher, the laser modes have a stronger tendency to shrink into the fiber core. This is because higher pump power results in higher residual heat and larger index change. On the other hand, the change in the fiber core is bigger than in cladding, resulting in the enlargement of equivalent numerical aperture (NA).

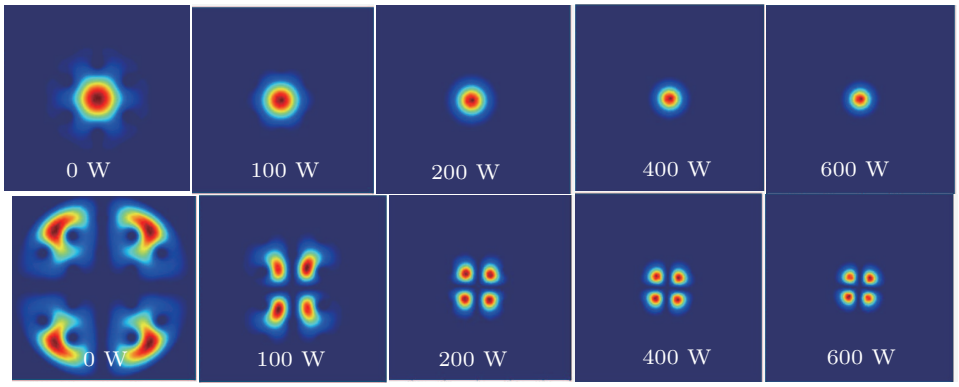


Fig. 4. (color online) Simulated laser modes after index change under different pump powers.

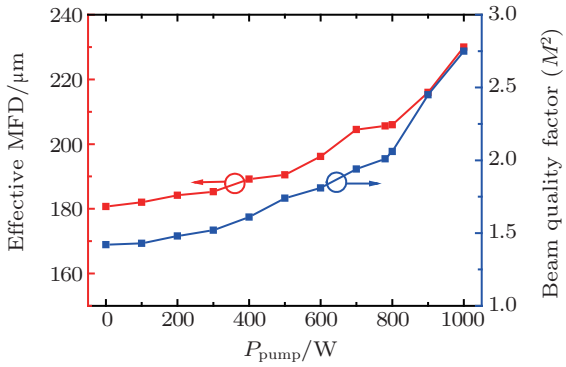


Fig. 5. (color online) Simulated results of the M^2 and MFD of output laser under different pump powers.

Figure 5 gives the simulated results of the M^2 and MFD of output laser under different initial pump powers, from which we can see that the MFD increases and the output beam quality decreases with pump power increasing. The situation deteriorates under the higher power operation. This is due to the mode instability accelerating under the higher pump power, then the mode coupling coefficient is higher under high power operation, resulting in LP_{21} accounting for a higher proportion in the output laser.

Taking $M^2 = 2.0$ as the upper limit of the output beam quality, the threshold pump power is obtained to be 780 W.

The simulated results of M^2 and MFD of the signal at different positions of the fiber when pump power is $P_{\text{pump}} = 780$ W are shown in Fig. 6. The LP_{21} is excited due to mode coupling, which accounts for a higher proportion in the total output power; therefore, the M^2 increases at the beginning. In the middle segments of the fiber we see the decrease of M^2. This is due to the decrease of mode coupling coefficient and the shrink in proportion of LP_{21} in the output power with the decrease of pump power. In the end segment of the fiber the M^2 increases again because the heat decreases with the decrease of pump power and the laser modes tends to spread out to the cladding as heat decreases. In this case, M^2 takes a dominant position in laser modes at different positions of the fiber. The MFD increases along the fiber, also owing to the influence of pump power decreasing on laser mode distribution. The output laser power in fiber end is 540 W, with an available pulse energy of almost 100 mJ, which is suitable for pulse amplifier with a repetition rate of more than 5 kHz.

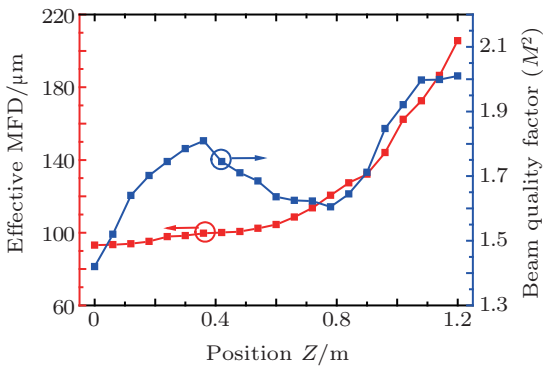


Fig. 6. (color online) Simulated results of M^2 and MFD of the signal laser at different positions under $P_{\text{pump}} = 780$ W.

4. Conclusions

In this paper, we propose a method to analyze the mode coupling due to heat-induced index change. The method is based on the mode competition model, which is similar to the actual functioning mechanism of the gain fiber. We also predict the maximum average output power according to the mode coupling theory. For the large pitch fiber with a core diameter of 190 μm, we analyze the influence of mode coupling on the MFD and beam quality of output laser. The result shows that, with the increase of the initial pump power, the fiber mode instability is enhanced, the MFD of output laser increases, and the beam quality declines. The beam quality is the main factor restricting the promotion of average power for large mode area fiber. In the case of $M^2 \leq 2$, the maximum average power reaches 540 W and the available pulse energy is 80 mJ/m, which is suitable for high energy, high average power pulse amplifier with a repetition rate of more than 5 kHz.

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