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Mode instability in a Yb-doped stretched core fiber

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ABSTRACT

In this work we present the theoretical study of transverse mode instability (TMI) in ytterbium (Yb)-doped rectangular core fibers with different core aspect ratios using the fast Fourier transform (FFT) beam propagation method (BPM). As expected, the rectangular core fiber with larger aspect ratio (AR.) offers more efficient heat dissipation than a circular core fiber. However, it is found that the rectangular core fiber does not benefit from the better heat dissipation to suppress the TMI when compared to the circular core counterpart. The temperature building in the rectangular core fiber decreases by up to 24.6% with a 10:1 aspect ratio core, while threshold pump power drops by up to 38.3% when compared to a circular core fiber with the same core area. Our study reveals that the weaker gain saturation effect compensate the thermal advantage from more efficient heat dissipation.

Keywords: Fiber optics amplifiers and oscillators, thermal effects, fiber properties.

1. INTRODUCTION

High average power fiber lasers with good beam quality are found as an attractive source in many applications for industrial, defense and scientific research [1]. Output powers of fiber lasers surpasses bulk solid-state lasers thanks to its larger surface-to-active-volume ratio which efficiently extracts heat and makes robust single-mode operation [1, 2]. Jay W. Dawson et al. analyzed the scalability of diffraction-limited fiber lasers and amplifiers to high average power in [3], and it shows that the highest output power of fiber laser is determined by a combined effect of thermal lens and nonlinear scatterings such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). However, H. J. Otto et al. found that the transverse mode instability (TMI) can occur before such combined limitation, and set lower power scalability limitation for normal circular core fiber with diameter less than 100 μm [4]. The TMI was firstly reported in large mode area (LMA) fiber amplifier in 2011 [5], and it is recognized as the major limitation for high power scalability in fiber amplifiers and lasers till now. Upon an onset of the TMI, the fundamental mode (FM) power transfers to a higher-order mode (HOM), and consequently the TMI degrades output beam quality as well as limits the FM power scalability. Soon after the observation of TMI phenomenon in high power fiber operation, C. Jauregui et al. suggested that the TMI is caused by the changed refractive index in the core, which is induced by variations in the population of upper level lasing ions [6]. Shortly afterwards, A. Smith et al. considered the temporal evolution of the upper level ions population and temperature-induced index grating [7]. Now it is widely agreed that the TMI is caused by following three conditions [8]: a) FM and HOM interfere each other to produce an irradiance grating that has a period equal to the beat length between the modes; b) Different regions of irradiance grating in the fiber core have different population inversion levels, thus different heat generation through a quantum defect. The generated heat variation leads to the formation of thermal grating via the thermo-optic effect and the grating accounts for the modal power transfer. c) A phase shift between the irradiance grating and the temperature-induced refractive index grating is induced by the thermal diffusion time across the core, frequency offset and different propagation constant among different modes.

A rectangular (or ribbon) core fiber design has been proposed for mode area scaling above 1000 μm^2 [9-11]. The asymmetric core offers bending insensitivity and better heat dissipation as compared to the circular core fiber, suggesting better TMI performance. However, there has been no investigation on TMI in this type of fiber, to the best of our knowledge. In this paper, we use the numerical model to present theoretical investigation of TMI in a rectangular core fiber. Compared to the semi-analytical model, the numerical model offers more flexible platform to adopt the asymmetric fiber geometry. The output HOM power versus frequency offset, TMI threshold pump power and temperature distribution are compared between rectangular core with different aspect ratios (AR.) and circular core fibers.

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2. SHORT DESCRIPTION OF MODEL

The TMI can be modeled via numerical [12-14] or semi-analytical models [15-17]. A. Smith et al. proposed the highly numeric model in [13], and such model can simulate a variety of shapes of the core, refractive index and doping profiles. Additionally, it is simple to add additional physical effects, such as photodarkening effect and bending effect. However, the highly numeric model needs longer computing time compared with other analytical models. K. R. Hansen et al. presented the semi-analytical model in [15, 16]. The advantages of such model are needing shorter running time and easily capturing the essential physics of TMI by equations that describe the power transfer coefficient. However, the semi-analytical model can only handle the circular core fiber and rely on some approximations. In this paper we utilize the fast Fourier transform (FFT) based beam propagation method (BPM) to numerically simulate the TMI in fiber, and it is similar to the highly numeric model in [13]. The big advantage of such model is that it can simulate the rectangular core shape of fiber, not only the circular core shape, and we simply describe the main equations that construct the model in the following. Here we consider the HOM as second order mode LP₁₁, therefore the input signal field is presented by

$$E_s(x, y, t) = \sqrt{P_{01}} E_{01}(x, y) + \sqrt{P_{11}} E_{11}(x, y) e^{-i\Delta\omega t} \quad (1)$$

where P_{01} is the LP₀₁ mode input power and P_{11} is the LP₁₁ mode input power, E_{01} and E_{11} are the normalized LP₀₁ and LP₁₁ mode amplitude, $\Delta\omega$ is the frequency offset between modes. The beam propagation equation is described as follows and we utilize the FFT based method [13, 18] to solve it.

$$\frac{\partial E_s(x, y, z, t)}{\partial z} = -\frac{i}{2k_c} \nabla_{\perp}^2 E_s(x, y, z, t) - \frac{i[k^2(x, y, z, t) - k_c^2]}{2k_c} E_s(x, y, z, t) + g(x, y, z, t) E_s(x, y, z, t) \quad (2)$$

Where k_c is the carrier wave number in the cladding, $\nabla_{\perp}^2$ is the Laplacian operator in the x and y dimensions, $g(x, y, z, t)$ is the laser gain and $k(x, y, z, t)$ is the carrier wave number in the core. The changed refractive index of core $n_{core}(x, y, z, t)$ is expressed as

$$n_{core}(x, y, z, t) = n_{core} + \frac{dn}{dT} T(x, y, z, t) \quad (3)$$

where n_{core} is the refractive index of core, dn/dT is the thermo-optic coefficient. In order to get the changed refractive index $n_{core}(x, y, z, t)$, we need to calculate the temperature distribution $T(x, y, z, t)$ using the following equation and it is solved by using the Green's function method detailed in [13, 19]

$$\rho C \frac{\partial T(x, y, z, t)}{\partial t} = Q(x, y, z, t) + K \left(\frac{\partial^2 T(x, y, z, t)}{\partial x^2} + \frac{\partial^2 T(x, y, z, t)}{\partial y^2} \right) \quad (4)$$

where K is the thermal conductivity, ρ is the density, C is the heat capacity and $Q(x, y, z, t)$ is the thermal load in fiber core.

3. CALCULATION OF FREQUENCY OFFSET FOR MOST POWER TRANSFER

The phase shift between moving temperature grating and moving irradiance grating is essential for the power transfer from fundamental mode (LP₀₁) to higher order mode (LP₁₁). This phase shift is induced by the thermal diffusion time across the core and frequency offset between the modes. The most efficient power transfer occurs at the phase shift where the frequency offset matches to the inversion of thermal diffusion time [8]. In the following, we compute output power of the LP₁₁ mode versus the frequency offset in a circular core fiber and rectangular core fibers with AR of 1:1, 4:1 and 10:1 in order to find out the frequency offset that makes the most efficient power transfer from LP₀₁ to LP₁₁. It is experimentally found that the TMI follows the matched frequency offset [20]. Hence, our simulation results can be served as a good guideline to estimate significance of TMI in different core geometries.

The parameters of circular core and rectangular core fibers used in this paper are listed in Table 1. Type 1 fiber is the conventional circular core fiber, type 2 to type 4 fibers are rectangular core fibers with AR. 1:1, AR. 4:1 and AR. 10:1. It is noted that the core area is nearly the same around 1960 μm^2 for all types of fibers, which promises nearly the same output total signal power, pump power and pump efficiency. Other parameters used in the simulations are as follows, the signal wavelength is assumed at 1064 nm, and the pump wavelength at 976 nm, and the pumping radius is 100 μm for all types of fibers. We use signal emission and absorption cross-section of $3.58 \times 10^{-25} \text{ m}^2$, and $6.00 \times 10^{-27} \text{ m}^2$ [8],

respectively. The pump emission and absorption cross-sections are $1.87 \times 10^{-24} \text{ m}^2$, and $1.53 \times 10^{-24} \text{ m}^2$ [8]. Mass density is 2201 kg/m^3 , heat capacity is $702 \text{ J/(kg} \times \text{K)}$ and thermal conductivity is $1.38 \text{ W/(m} \times \text{K)}$ [8]. We assume the launched signal power at LP_{01} mode is 10 W , and LP_{11} mode has 10^{-3} W at the launched end.

Table 1. Fiber parameters used in the simulation

	Type 1	Type 2	Type 3	Type 4
Core radius	$25 \text{ }\mu\text{m}$			
Core width		$44.3 \text{ }\mu\text{m}$	$88.8 \text{ }\mu\text{m}$	$140 \text{ }\mu\text{m}$
Core height		$44.3 \text{ }\mu\text{m}$	$22.2 \text{ }\mu\text{m}$	$14 \text{ }\mu\text{m}$
Aspect ratio (AR.)		1:1	4:1	10:1
Cladding radius	$200 \text{ }\mu\text{m}$	$200 \text{ }\mu\text{m}$	$200 \text{ }\mu\text{m}$	$200 \text{ }\mu\text{m}$
Core area	$1963 \text{ }\mu\text{m}^2$	$1963 \text{ }\mu\text{m}^2$	$1963 \text{ }\mu\text{m}^2$	$1960 \text{ }\mu\text{m}^2$
Cladding index	1.45	1.45	1.45	1.45
NA	0.06	0.06	0.06	0.06
LP_{01} effective mode area	$1167 \text{ }\mu\text{m}^2$	$1083 \text{ }\mu\text{m}^2$	$1232 \text{ }\mu\text{m}^2$	$1368 \text{ }\mu\text{m}^2$
LP_{11} effective mode area	$1062 \text{ }\mu\text{m}^2$	$1015 \text{ }\mu\text{m}^2$	$1196 \text{ }\mu\text{m}^2$	$1345 \text{ }\mu\text{m}^2$
Signal effective mode area	$1167 \text{ }\mu\text{m}^2$	$1083 \text{ }\mu\text{m}^2$	$1232 \text{ }\mu\text{m}^2$	$1368 \text{ }\mu\text{m}^2$
LP_{01} effective refractive index	1.45117	1.45116	1.45110	1.45099
LP_{11} effective refractive index	1.45105	1.45104	1.45107	1.45097
Ion concentration	$3.5 \times 10^{25} \text{ m}^{-3}$	$3.5 \times 10^{25} \text{ m}^{-3}$	$3.5 \times 10^{25} \text{ m}^{-3}$	$3.5 \times 10^{25} \text{ m}^{-3}$
Doping area	Core doping	Core doping	Core doping	Core doping
Fiber length	2 m	2 m	2 m	2 m
LP_{01} overlap with doping area	0.9826	0.9811	0.9627	0.9229
LP_{11} overlap with doping area	0.9525	0.9508	0.9619	0.9223
LP_{01} overlap with LP_{11}	0.8576	0.8598	0.8645	0.8692

Figure 1 presents the normalized output LP_{11} power content versus the frequency offset between two modes for type 1 to type 4 fibers, and it is clear to see that the frequency offset makes the most power transfer from LP_{01} mode to LP_{11} mode lies at 1160 Hz, 1580 Hz, 520 Hz and 260 Hz, respectively. As such frequency offset equals to the inversion of thermal diffusion time across the core, so it will take longer time to diffuse the heat to core edge in rectangular core AR. 4:1 and AR. 10:1 fibers compared in circular core fiber, which is due to the longer distance between center and edge of the core along core width. Therefore, rectangular core (AR. 10:1) fiber has the smallest frequency offset at 260 Hz that makes the most power transfer from LP_{01} mode to LP_{11} mode compared with other types of fibers. Additionally, as the core to core edge distance along core width is shorter in rectangular core AR. 1:1 fiber compared in the circular core fiber, hence the square core (AR. 1:1) fiber has the largest frequency offset at 1580 Hz among them.

Figure 1. Normalized output LP₁₁ power content versus frequency offset for circular core 25 μm radius fiber, rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1), rectangular core 88.8 $\mu\text{m} \times 22.2 \mu\text{m}$ (AR.4:1) and rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fibers.

4. SIMULATION OF TMI IN RECTANGULAR CORE FIBER

In the previous section, the simulation results show that when frequency offset lies at 1160 Hz, 1580 Hz, 520 Hz and 260 Hz for circular core 25 μm radius fiber, rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1), rectangular core 88.8 $\mu\text{m} \times 22.2 \mu\text{m}$ (AR.4:1) and rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR.10:1) fibers, the most power transfer from LP₀₁ mode to LP₁₁ mode happens. As such frequency offset is usually in agreement with the measured frequency in experiment [20], so we utilize these frequency offset values in the following simulations.

Figure 2 shows the temperature distribution at the launch end at $t=0$ when input pump power is 160 W, and it is clear to see that rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber has the lowest temperature 1.253 K, which is smaller than that in rectangular core 88.8 $\mu\text{m} \times 22.2 \mu\text{m}$ (AR. 4:1) fiber 1.486 K, rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber 1.644 K and circular core 25 μm radius fiber 1.58 K. This means that rectangular core fiber with larger AR. has better thermal dissipation compared with circular core fiber.

Figure 2. Temperature distribution at the launch end within the whole core and cladding region in (a) circular core 25 μm radius fiber, (b) rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR.1:1) fiber, (c) rectangular core 88.8 $\mu\text{m} \times 22.2 \mu\text{m}$ (AR.4:1) fiber and (d) rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR.10:1) fiber.

Figure 3 presents the temperature profile evolution within the fiber core versus the fiber length in x-z plane at $t=0$ when input pump power is 160 W. As only the increased temperature in fiber core can change the refractive index, which in turn causes the power transfer from LP₀₁ mode to LP₁₁ mode, therefore we only calculate the temperature distribution in

fiber core for time saving. It is shown from figure 3 that the maximum increased temperature in rectangular core $44.3\text{ }\mu\text{m} \times 44.3\text{ }\mu\text{m}$ (AR. 1:1) fiber is 4.241 K, which is higher than 4.103 K in circular core $25\text{ }\mu\text{m}$ radius fiber, 3.957 K in rectangular core $88.8\text{ }\mu\text{m} \times 22.2\text{ }\mu\text{m}$ (AR. 4:1) fiber and 3.618 K in rectangular core $140\text{ }\mu\text{m} \times 14\text{ }\mu\text{m}$ (AR. 10:1) fiber. The maximum increased temperature in rectangular core (AR. 10:1) fiber decreases by about 24.6% compared in circular core fiber. It again manifests that rectangular core fiber with larger AR. has better thermal dissipation than circular core fiber. It is mainly because that larger AR. makes the fiber core (acts as heat source) edge gets closer to the cladding, therefore the heat can be more efficiently dissipated and the increased temperature in the core becomes lower.

Figure 3. The temperature profile evolution in the core along fiber length for (a) circular core $25\text{ }\mu\text{m}$ radius fiber, (b) rectangular core $44.3\text{ }\mu\text{m} \times 44.3\text{ }\mu\text{m}$ (AR.1:1) fiber, (c) rectangular core $88.8\text{ }\mu\text{m} \times 22.2\text{ }\mu\text{m}$ (AR.4:1) fiber and (d) rectangular core $140\text{ }\mu\text{m} \times 14\text{ }\mu\text{m}$ (AR.10:1) fiber.

Figure 4 illustrates the time averaged LP_{01} mode power, LP_{11} mode power, total signal power and pump power evolution along the fiber length when input pump power is 160 W, and all the output powers are listed in table 2. It is noted that the output total signal power is nearly the same about 149 W, and pump efficiency are all above 95% for all types of fibers. Rectangular core $140\text{ }\mu\text{m} \times 14\text{ }\mu\text{m}$ (AR. 10:1) fiber has the largest output LP_{11} power content, while rectangular core $44.3\text{ }\mu\text{m} \times 44.3\text{ }\mu\text{m}$ (AR. 1:1) fiber has the least output LP_{11} power content. This means that the TMI effect is stronger in rectangular core fiber with larger AR. than in circular core fiber.

Table 2. Output powers for type 1 to type 4 fibers.

	Type 1	Type 2	Type 3	Type 4
Output LP_{01} power	148.62 W	147.71 W	142.59 W	107.6 W
Output LP_{11} power	1.02 W	0.46 W	7.29 W	39.45 W
Output total signal power	149.71 W	148.51 W	149.34 W	148.6 W
Pump efficiency	> 95%	> 95%	> 95%	> 95%

Figure 4. Time averaged powers versus fiber length for (a) circular core 25 μm radius fiber, (b) rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR.1:1) fiber, (c) rectangular core 88.8 $\mu\text{m} \times 22.2 \mu\text{m}$ (AR.4:1) fiber and (d) rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR.10:1) fiber.

Figure 5 shows the output LP_{11} power content versus the input pump power. It is widely believed that the decreased temperature can suppress the TMI and increase the threshold pump power, however, the threshold pump power (10% output LP_{11} power content in total signal power) in rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber decreases by about 38.3%, from 238 W to 145 W, compared in circular core 25 μm radius fiber. However, it is noted that the rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber increases the threshold pump power by 14.9% in comparison with circular core fiber, from 238 W to 273 W. It is shown from table 1 that the difference of LP_{01} and LP_{11} modes overlap with doping area is nearly the same, which means that they have little influence on the TMI and threshold pump power for these four types of fibers. In the following, we analyze the influence of gain saturation effect and power coupling between LP_{01} and LP_{11} modes on the TMI and threshold pump power for rectangular core (AR. 1:1) and (AR. 10:1) fibers.

Figure 5. The output LP_{11} power content versus the input pump power for circular core 25 μm radius fiber, rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR.1:1) fiber, rectangular core 88.8 $\mu\text{m} \times 22.2 \mu\text{m}$ (AR.4:1) fiber and rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR.10:1) fiber.

5. THEORETICAL ANALYSIS OF TMI IN RECTANGULAR CORE FIBER

It can be seen from table 1 that rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber has the largest effective mode area of 1368 μm^2 , which is larger than 1167 μm^2 in circular core fiber. Among them, rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber has the smallest effective mode area of 1083 μm^2 . A. Smith et al. has analyzed the influence of gain saturation

effect on TMI in [21] that the higher intensity of signal or lower intensity of pump helps to increase the gain saturation effect and suppress the TMI in fiber. For the four types of fibers used in the simulation, when the input signal power is same, the fiber which has larger effective mode area generates relative lower signal intensity and hence weaker gain saturation effect. Figure 6 presents the normalized signal intensity and upper state population (n_2) profiles at the input end for circular core 25 μm radius fiber, rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber and rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber when pump power is 150 W. Here we use the Full width at half maximum (FWHM) ratio of upper state population (n_2) to signal intensity to describe the gain saturation effect in fiber. It is shown from figure 6 that the signal intensity FWHM are 26.2 μm , 73 μm and 25 μm for circular core 25 μm radius fiber, rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber and rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber, the corresponding n_2 FWHM are 29.3 μm , 78.2 μm and 28.6 μm , respectively when pumping radius is 100 μm . Therefore, the rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber has the smallest FWHM ratio of n_2 to signal intensity at 1.0712, which is smaller than 1.1183 in circular core 25 μm radius fiber. Among them, rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber has the largest FWHM ratio of 1.144. It means that rectangular core (AR. 10:1) fiber has the weakest gain saturation effect, while rectangular core (AR. 1:1) fiber has the strongest gain saturation effect. In order to eliminate the gain saturation effect difference on TMI in rectangular core fibers, we increase the pumping radius from 100 μm to 130 μm in rectangular core (AR. 10:1) fiber and decrease the pumping radius from 100 μm to 85 μm in rectangular core (AR. 1:1) fiber, which makes the n_2 FWHM width become 81.64 μm and 27.8 μm , respectively. Under this condition, the FWHM ratio of n_2 to signal intensity is around 1.115 for these three types of fibers, which promises the nearly same gain saturation effect for them.

Figure 6. The normalized signal intensity and upper state population (n_2) profiles at the input end for (a) circular core 25 μm radius fiber, (b) rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber and (c) rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber when pump power is 150 W.

Figure 7 shows the output LP_{11} power content versus the input pump power for circular core 25 μm radius fiber (pumping radius 100 μm), rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR. 10:1) fiber (pumping radius 130 μm) and rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR. 1:1) fiber (pumping radius 85 μm). It is clear to see that when the pumping radius of rectangular core (AR. 1:1) fiber decreases from 100 μm to 85 μm , the threshold pump power drops from 273 W to 245 W, which is quite close to the 238 W in circular core fiber. Therefore, we conclude that the stronger gain saturation effect in rectangular core (AR. 1:1) fiber is the main factor that suppress the TMI and increase the threshold pump power compared with circular core fiber. When we increase the pumping radius of rectangular core (AR. 10:1) fiber from 100 μm to 135 μm , although the threshold pump power increases from 145 W to 182 W, however, it is still much less than the threshold power 238 W in circular core fiber. This verifies that except for weaker gain saturation effect in rectangular core (AR. 10:1) fiber, other factors still play a role in promoting the TMI in comparison with circular core fiber, and it needs further investigation.

Figure 7. The output LP₁₁ power content versus the input pump power for circular core 25 μm radius fiber (pumping radius 100 μm), rectangular core 44.3 $\mu\text{m} \times 44.3 \mu\text{m}$ (AR.1:1) fiber (pumping radius 85 μm) and rectangular core 140 $\mu\text{m} \times 14 \mu\text{m}$ (AR.10:1) fiber (pumping radius 130 μm).

6. CONCLUSIONS

In this paper we numerically simulate the TMI effect in rectangular core fibers with different AR. of 1:1, 4:1 and 10:1. As expected, rectangular core (AR. 10:1) fiber, which decreases the temperature by 24.6% compared with circular core fiber, has the best thermal dissipation among these four types of fibers. However, the threshold pump power in rectangular core (AR. 10:1) fiber drops by 38.3%, from 238 W to 145 W, in comparison with circular core fiber. We conclude that this is attributed to the weaker gain saturation effect in rectangular core (AR. 10:1) fiber. Additionally, the rectangular core (AR. 1:1) fiber increases the threshold pump power by 14.9% compared with circular core fiber, from 238 W to 273 W. We verify that the stronger gain saturation effect in rectangular core (AR. 1:1) fiber helps to suppress the TMI effect and increase the threshold pump power.

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