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Near diffraction-limited laser output from a very large size rectangular core crystalline waveguide

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Near diffraction-limited laser output from a very large size rectangular core crystalline waveguide laser was achieved experimentally. A crystalline waveguide, with a rectangular core size of 320 μm × 400 μm by 1.0 at.% Yb:YAG (core) and 0.5 at.% Er:YAG (cladding), was designed and fabricated. The rectangular core area was approximately 64 times larger than the conventional device core area. Using a continuous diode laser end pumping, an output power of 26 W, with the beam quality of $M_x^2 = 1.22$, $M_y^2 = 1.05$ in the far-field, was obtained in the experiment. The design method that is used to enlarge the crystalline waveguide core size and suppression high-order transverse mode, can be applied for various kinds of crystalline waveguide lasers.

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The crystalline waveguide laser has been recognized to be the promising laser architecture as efficient and power scaling with nearly diffraction-limited beam quality. The lasers have the potential for CW tens of kilowatts of laser output power from only a meter of waveguide length, and for high peak power of a milliwatt pulse, due to their much higher thermal conductivity and lower SBS gain, compared with silica glass fibers [1,2]. However, it also faces a number of challenges, such as waveguide core size enlargement and high-order transverse mode suppression, to guarantee the beam quality of the output light field. Usually, the rectangular core waveguide is designed using single-mode cutoff condition, namely, $B < 1.37$ [3,4], where the $B = (2a/\lambda) \times \mathrm{NA}$ number is normalized frequency, similar to $V = (2\pi a/\lambda) \times \mathrm{NA}$ number for a round waveguide (a is the core size). A series of experimental results have been reported with a crystalline waveguide that is highly efficient and has an output of nearly diffraction-limited beam quality, while the rectangular waveguide core size is about 40 μm, as the inner cladding is undoped YAG material [5,6]. However, it is still a problem as waveguide core size enlargement for high-power applications. As reported, waveguide lasers with the core size of 300 and 500 μm, respectively, which are larger than the single-mode cutoff condition, resulted in poor beam quality output, where the inner cladding is also undoped YAG material [7,8]. In order to achieve single-mode operation of large core size waveguides, there are several known methods, for example, deep etching in semiconductor waveguides [9] and using small index contrast in polymer waveguides [10]. These waveguides have the disadvantage of being sensitive to severe corner losses, crosstalk, and background scattering [11]. The multi-trench channel waveguide structure is also a method to enlarge the core size for single-mode operation[12]. However, this method is difficult for the preparation of crystalline waveguides. Thus, we need to adopt methods which are suitable for a crystalline waveguide. In order to solve this problem, the inner cladding refractive index match with the core and the mode competition are employed to increase the crystalline waveguide core size, producing near diffraction-limited laser output in the far-field with a very large size rectangular core.

In this Letter, we introduce the method of design and the principle verification of the crystalline waveguide laser. A very large core size Yb:YAG crystalline rectangular waveguide with a dimension of 320 μm × 400 μm was used. The near diffraction-limited laser output was obtained, as the beam quality of the crystalline waveguide was $M_x^2 = 1.22$, $M_y^2 = 1.05$, by laser output measurement. The high-order transverse mode suppression in the enlarged rectangular waveguide core was also verified.

Considering the crystalline waveguide core as a mode transmission device, the rectangular waveguide core size of a single mode can be enlarged by reduction the numerical aperture (NA) number between the core and inner cladding. First, we have to choose the core material as the gain medium. The Yb:YAG, with a doping concentration of 1.0 at.%, is an ideal material to achieve high energy output. Thus, the refractive index of the crystalline waveguide core is determined as the selected core material. Secondly, in order to match the refractive index with the crystalline waveguide core material, we need to choose a crystal as the inner cladding material. Er:YAG is chosen to replace the conventional undoped YAG material, due to the Er:YAG absorption wavelength being different from the Yb^{3+} ion absorption wavelength of 940 nm and emission center wavelength of 1030 nm. Thus, the inner cladding refractive index can be easily selected by adjustment doping concentration of Er:YAG [13]. Thirdly, due to a crystalline waveguide optical system with a small NA, the refractive index of the inner cladding material should be considered. A 0.5 at.% Er:YAG is the design for the refractive index match with 1.0 at.% Yb:YAG. The refractive index difference, between the 1.0 at.% Yb:YAG and 0.5 at.% Er:YAG, is measured at only 4×10^{-6}, by the interferometric measurement method (the accuracy of $\sim 10^{-7}$) with specially prepared diffusion bonded crystal [14]. The small refractive index difference of Δn, between the Yb-doped YAG core and Er-doped YAG cladding, provides a sufficiently low NA of the designed waveguide, which is derived to be ~0.0038. Fourthly, using the cutoff condition of a single mode, $B = (2a/\lambda) \times \mathrm{NA}$, as $B = 1.37$, we calculate that the rectangular waveguide core size as 185.1 μm. Such a large waveguide core size can be expected to conduct a single-transverse-mode transmission. It can be seen that the core size is about 4.4 times larger than the core size of a conventional waveguide, which uses undoped YAG material as the inner clad [5,6]. Further enlargement of the core size of the waveguide by a refractive index match method is difficult, because the NA cannot be further reduced by the limitation of the material characteristics of the existed and the waveguide mode selection ability. Therefore, we choose a mode competition method to further enlarge the core size of a waveguide as single-mode transmission.

Considering the crystalline waveguide core as an active device, the core size of a single-mode rectangular waveguide can be further enlarged by the mode competition. It is well known that the mode competition is a normal method for large-mode-area glass fiber selection of the fundamental mode by many experimental techniques, for example, coiling fiber [15,16]. For a crystalline waveguide, it cannot be coiled. The core size, as the value of the upper limit, is necessary to exactly determine, while the mode competition method is used to suppress the higher-order mode in the case of gain saturation. For exactly calculating the core size of allowing upper limit value, the power constraint factor Γ is used as follows:

$$\Gamma = \frac{\int_{-\frac{d}{2}}^{\frac{d}{2}} \int_{-\frac{w}{2}}^{\frac{w}{2}} |U(x,y)|^2 \mathrm{d}x\mathrm{d}y}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |U(x,y)|^2 \mathrm{d}x\mathrm{d}y}, \tag{1}$$

where $U(x,y)$ is the electric field distribution of the waveguide section and can be expressed by the electric field solution in different regions of the waveguide cross section [17], and d and w are the width and thickness of the core layer, respectively. For simplified calculation, let $d = w$; the expression of the power constraint factor is obtained by calculating the electric field solution of the crystal rectangular waveguide:

$$\Gamma = \frac{\left(\frac{d}{2} + \frac{1}{2k_x} \sin k_x d\right)^2}{\left(\frac{d}{2} + \frac{1}{2k_x} \sin k_x d\right)^2 + 2\cos^2 \frac{k_x d}{2} \cdot \frac{1}{\gamma_x}\left(\frac{d}{2} + \frac{1}{2k_x} \sin k_x d\right) + \frac{1}{\gamma_x^2} \cos^4 \frac{k_x d}{2}}, \tag{2}$$

where k_x are the beam vectors in the core, and γ_x are the attenuation coefficients in the inner cladding.

To solve the core size d in a two-dimensional waveguide, it is necessary to get the value of Γ that satisfies single-mode output condition. In the case of a one-dimensional planar waveguide, the single-mode condition is that the size ratio of core-to-cladding be less than 0.6 [18]. Similarly, in a two-dimensional waveguide, the single-mode condition is also that the size ratio of core-to-cladding be less than 0.6 [19]. Therefore, the power constraint factor of the first-order mode, as a single-mode output condition for a two-dimensional rectangular waveguide, is less than 0.64 [20]; namely $\Gamma_{m=1} < 0.64$. Using the characteristic equations of the first-order mode [21], and letting Eq. (2) equal 0.64. According to the two expressions, the upper limit of the core size can be solved, that is 332 μm, while the core layer is 1.0 at.% Yb:YAG, and the inner cladding layer is 0.5 at.% Er:YAG. The final core size is increased approximately eight times, corresponding to the core area increased 64 times, compared with the conventional design using the same core layer material [6,7]. The solution result is a favor for laser oscillation or an amplifier achieving both high beam quality and high output power.

In order to insight understanding of the mode competition, we use the rate-equation approach to simulate and calculate the gain of different modes [18], and derive the ratio of each higher-order mode gain to the fundamental mode gain at different core sizes, namely relative gain (Fig. 1), where I is the laser intensity, and $I_{\mathrm{sat}} = h\nu/\sigma\tau$ is the saturation intensity. There are three conditions in the calculation:, the refractive index difference between the core (1.0 at.% Yb:YAG) and inner clad (0.5 at.% Er:YAG) is 4×10^{-6}, the laser intensity is different in the core, and the electric field of modes is an evanescent field in the cladding. It is different from the Refs. [18,19], in which the electric field of modes is no exponential decay in cladding. While the relative gain of all high-order modes is less than 1, the waveguide can achieve single-mode output. It can be seen that the upper limit of the core size determined by the mode competition is 360 μm in Fig. 1(a), as the laser intensity is equal to the saturation intensity. In addition, in Fig. 1(b), the value is 200 μm, as the laser intensity is equal to 10 times the saturation intensity. Heavy saturation can lead to the upper limit of core size reduction. Therefore, the upper limit of the core size varies with the actual laser intensity as single-mode operation. The simulation and calculation of the relative gain for different modes show that the previous calculation result, 332 μm, has an applicable condition, which is the laser intensity near the saturation intensity.

To verify the calculation results, a very large core size crystalline waveguide is prepared by a diffusion bonding technique for experimental investigation (Fig. 2). The bonding process between crystals includes precision polishing, assembly by optical contacting, and heat treatment. The core material is 1 at.% Yb:YAG, and the size is 320 μm × 400 μm. The cladding material is 0.5 at.% Er:YAG, and the size is 7 mm × 30 mm; the length is 77 mm. In addition, the 914 and 1030 nm antireflection coatings are plated at both ends. Using the crystalline

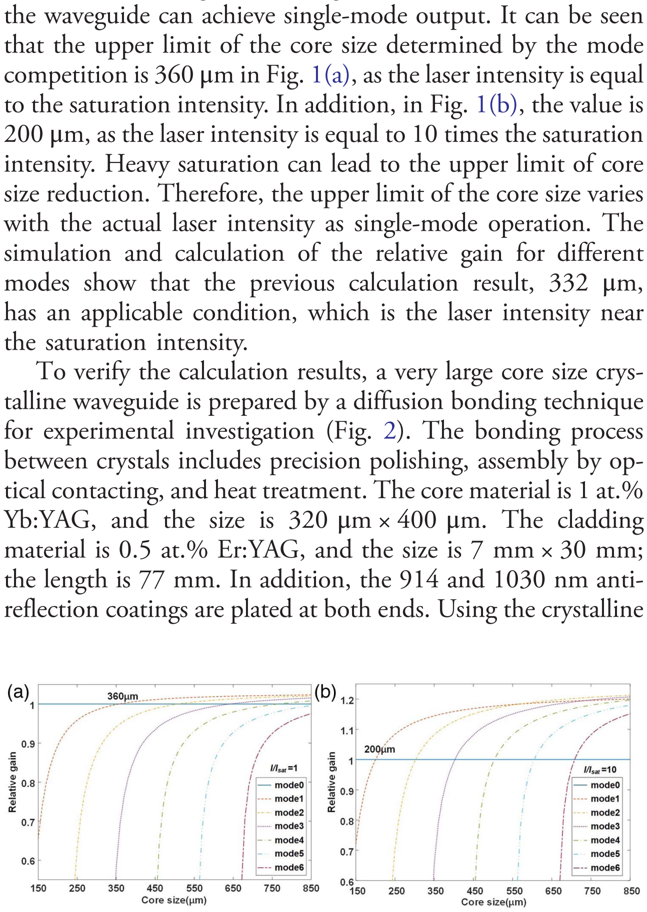

Fig. 1. Relation of the relative gain versus core size of each mode as (a) $I/I_{\mathrm{sat}} = 1$ and (b) $I/I_{\mathrm{sat}} = 10$, where I is the laser intensity, and $I_{\mathrm{sat}} = h\nu/\sigma\tau$ is the saturation intensity.

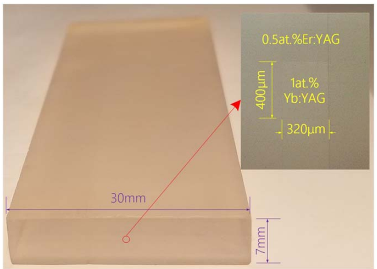

Fig. 2. Crystalline waveguide photo and micrograph.

waveguide to build a laser (Fig. 3), the pump source is a fiber-coupled diode laser with a center wavelength of 914 nm. (The fiber core size is 105 μm). L1 and L2 are convex lenses with focal lengths of 20 and 50 mm, respectively, which constitute a beam expanding collimation system and focus the pump beam into the waveguide core with the waist spot diameter of 260 μm. M1 and M2 are the laser cavity mirrors, and both mirrors close the waveguide ends, in which M1 is high transmission at 914 nm, high reflection at 1030 nm, and M2 is an output coupler with a 50% transmission rate at 1030 nm. The experimental setup photo is shown in Fig. 4. For this cavity configuration, due to the high diffraction loss, an analysis of an open cavity mode shows that excitation of the TEM00 laser mode in such a cavity is impossible, and only a waveguide mode can be supported by the open cavity modes [22]. The temperature of the heat sink is 20°C. The beam splitter reflects the 914 nm surplus pump beam, which is not fully absorbed, and transmits the 1030 nm output beam.

Although the cross section of the crystalline waveguide is rectangular, the far-field spot of the output laser is nearly circular (Fig. 5). The output beam quality is measured by the knife edge method. A convex lens with a focal length of $f = 130$ mm is used to focus the output beam, and the focus beam spot diameter at different positions was measured by using a beam measuring instrument. The beam quality and power of the output beam at different pump powers were measured as shown in the Fig. 5. When the pump power is 102.8 W, the beam quality M^2 of the x and y directions of the output beam measured by this method were 1.22 and 1.05, respectively. The fitting curve of the output beam is shown in Fig. 6. At this point, the waveguide core absorbed pump power reaches 53.6 W, the pump absorption efficiency is 52%, the output power is 26 W, and the light-to-light conversion efficiency is 48.5%. The reason for the low pump absorption efficiency is that the waveguide has only a single-clad structure and has no outer cladding to limit pump light. The absorption efficiency can be improved by the reduction of the inner cladding size of the crystalline waveguide and fabrication of the outer cladding.

Although the crystalline waveguide core size used in this experiment is larger than the size of the fundamental core of the traditional calculation method, the main component of the output beam belongs to the single-transverse mode. It is verified that a very large rectangular core size crystalline waveguide laser can generate near diffraction-limited output. Our design of crystalline rectangular waveguide core size is reliable by using refractive index matching and the mode competition.

It can be seen that the output beam quality in the x-direction is relevantly worse than the y-direction; even the core size of the x-direction is smaller than the y-direction. This result is due to the thermal effect, because the x-direction

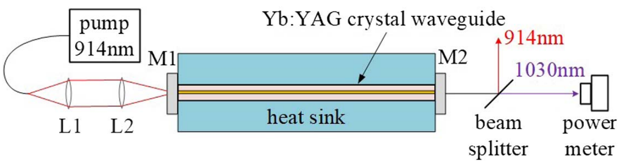

Fig. 3. Experimental setup for a crystalline waveguide laser.

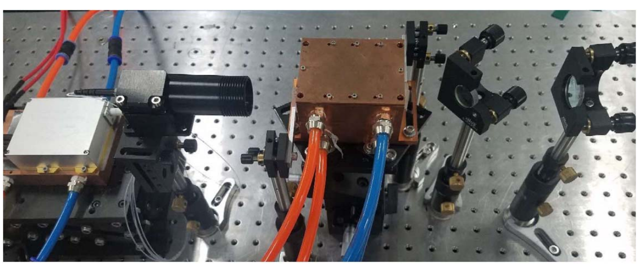

Fig. 4. Experimental setup for a crystalline waveguide laser.

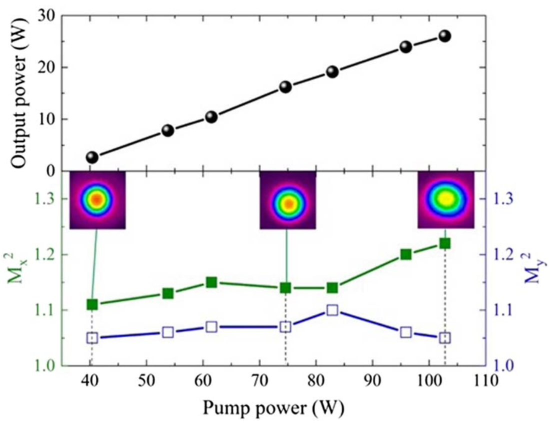

Fig. 5. Output power, beam quality, and spot image of the output beam at different pump powers.

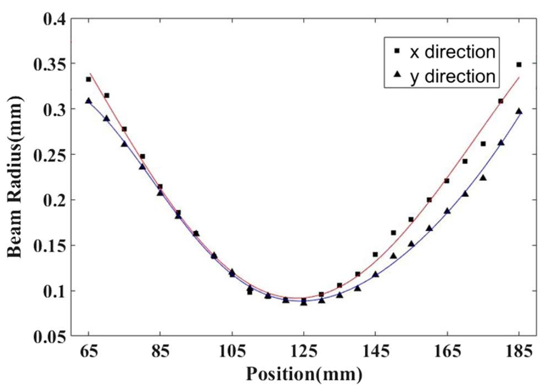

Fig. 6. Beam quality fitting curve with a pump power 102.8 W.

dimension of the crystalline waveguide is 30 mm, which is larger than the y-direction size of 7 mm. The crystalline waveguide has poor heat dissipation in the x-direction, resulting in uneven temperature distribution in the x-direction, generating large thermal stress. In addition, with a core size with 400 μm in the y-direction, which exceeds the upper limit of the core size under the mode competition condition, the output still has a good beam quality that is more obvious than the effect of mode competition due to multiple oscillations. In addition, the core size of the crystalline waveguide for laser oscillator has further increased potential.

In conclusion, we have verified an effective method in which a very large rectangular core size crystalline waveguide laser can generate a near diffraction-limited output, based on the inner cladding refractive index match with the core and mode competition. As the core material is 1.0 at.% Yb:YAG and the inner cladding is 0.5 at.% Er:YAG, the core size of the single-transverse-mode crystalline waveguide can be up to 332 μm, which is approximately eight times larger than the conventional design [6,7]. We also simulate and calculate the relative gain for different modes, to make sure that the previous calculation result is applicable to the case of the laser intensity near the saturation intensity.

Using a fabricated Yb:YAG (core)/Er:YAG (cladding) crystalline rectangular waveguide as the core size of 400 μm × 320 μm, the near diffraction-limited laser output is achieved, with corresponding beam quality $M_x^2 = 1.22$, $M_y^2 = 1.05$ in the far-field, output power of 26 W, and light-to-light conversion efficiency 48.5%. It shows that enlarged core size is reliable for a crystalline waveguide promising a power scaling laser with nearly diffraction-limited beam quality. In order to improve the pump absorption efficiency and output power, the next step is to reduce the inner cladding size of the crystalline waveguide and diffusion bond the outer cladding. This will provide an ideal compact laser source for applications in material processing and radar surveying.

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