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LD End-Pumped Nd:YAG InnoSlab Laser at 1319 nm

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Abstract

The 1319 nm lasers have important research value and application prospects in optical communications, biomedicine and nonlinear frequency conversion. Currently, there are few reports of high power 1319 nm continuous lasers with high beam quality. We have demonstrated a high output power, high beam quality 1319 nm continuous-wave laser by laser diode end-pumped Nd:YAG slab with a stable-unstable hybrid resonator. With a pumping power of 477 W, an output of 96.8 W was obtained with a slope efficiency of 26.5% and stability of 0.27%. A single wavelength laser operation at 1318.7 nm was demonstrated. At an output of 91.1 W, the beam quality factors M^2 in stable and unstable directions were 2.95 and 1.88, respectively.

Keywords

InnoSlab, 1319 nm, Nd:YAG, Hybrid Resonator

1. Introduction

Laser emission around 1319 nm plays an important role in optical communications, biomedical diagnostics, laser displays, beacon light sources, and so on. In addition, high power 1.3 μm lasers can be converted to other wavelengths through nonlinear frequency conversion or used as pump sources for other gain medium lasers. Nd^{3+} doped YAG crystals have proven to be very effective and excellent gain materials for generating 1319 nm lasers and have excellent performance in 1.3 μm dual-wavelength laser output [1] [2] [3], 1319 nm single-wavelength output [4] [5] [6], and laser frequency doubling output [7] [8] [9].

In 2007, Wang *et al.* [10] obtained 192 W continuous laser output of 1319 nm with an optical-optical conversion efficiency of 15.7% using 808 nm laser diode bars side-pumped Nd:YAG rods. End-pumping is generally difficult to produce high power laser output, but it is easy to obtain high conversion efficiency. In 2009, Lü, *et al.* [9] used fiber-coupled 885 nm laser diode end-side pumping Nd:YAG crystal bar to obtain 9.1 W of continuous 1319 nm laser output with 50% optical-to-optical conversion efficiency. It can be seen that few of the reported 1319 nm lasers are able to combine high beam quality and high power output.

In this letter, we achieved a high output power, high beam quality 1319 nm continuous-wave laser using a hybrid resonator with laser diode stacks end-pumped Nd:YAG slab. Finally, A 96.8 W continuous laser output was obtained at a pumping power of 477 W. The fitted slope efficiency and the optical-to-optical efficiency were 26.5% and 20.3%, respectively. Reliable laser output with a time stability of 0.27% of power was measured. The beam quality factor M^2 were 2.95 and 1.88 in the stable and unstable directions respectively, measured at an output power of 91.1 W.

2. Experimental Setup

The schematic diagram of the experimental setup in this letter was represented in Figure 1. The laser diode stacks consisted of 2 × 4 bars with their center wavelengths at 808 nm. The pump light was emitted from the laser diode, shaped by micro-lens on its surface, and injected into the beam coupling system. The pump coupling system consisted of two cylindrical lens groups and a planar optical waveguide. The pump light was finally injected into the Nd:YAG crystal to form a rectangular area with a size of 14 mm × 0.3 mm. The geometric parameters of the Nd:YAG slab were 14 mm × 12 mm × 1 mm, and the doping level was limited to 1 at.%. Each end face (14 mm × 1 mm) was polished and coated with antireflection (AR) coating for 808 nm and 1319 nm. The Nd:YAG slab crystal was encapsulated between two water-cooled copper heat sinks using large surfaces (14 mm × 12 mm) contact method. Indium foil was used to make the thermal contact between crystal and copper heat sink more efficient. Both the

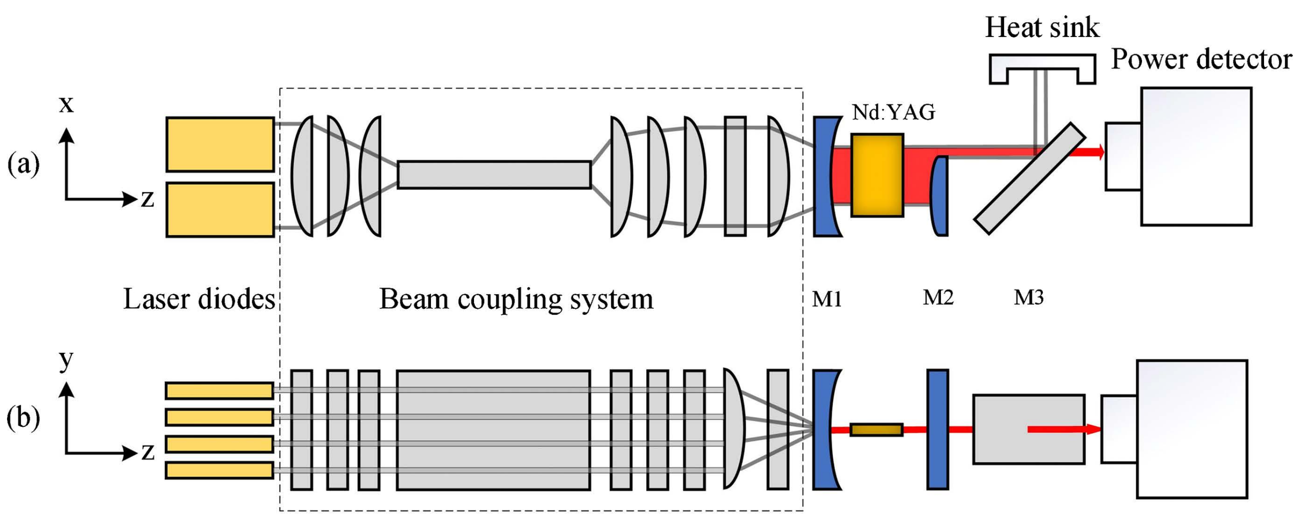

Figure 1. Schematic of experimental setup. (a) In the horizontal direction; (b) In the vertical direction.

laser diode stacks and laser crystal were maintained at a stable temperature, by setting the temperature of the circulating water to 21.5˚C. The hybrid resonator consisted of a concave spherical input mirror (M1) and a cylindrical output mirror (M2). The radius of curvature of above two cavity mirrors was 500 mm (M1) and 450 mm (M2), respectively. Both of them were coated with high reflection (HR) at 1319 nm and high transmission (HT) at 808 nm and 1064 nm. The reflectivity of the input mirror M1 for 1338 nm light was less than 60%, which led to the result that the 1319 nm laser won the mode competition with the 1338 nm laser. Continuous laser output emitted from the polished edge of cylindrical mirror M2. In the vertical direction, the two mirrors formed a concave-flat stable resonator, whereas in the horizontal direction, they constructed an off-axis positive-branch confocal unstable resonator. Amplification of the resonant cavity in the unstable direction was $M = R_1/|R_2| = 1.11$ and the equivalent output transmission was $T = 1 - |R_2/R_1| = 10\%$. Theoretically, the length of the cavity should to be $L = (R_1 + R_2)/2 = 25$ mm. However, taken into consideration the refractive index of the laser crystal, the actual length of the resonant cavity was set to about 30 mm. The parameters for the positive-branch off-axis confocal hybrid resonator are given in **Table 1**.

For Nd:YAG crystals, the emission at 1319 nm is strongly competitive with other emission lines. Therefore, there are many difficulties to overcome to achieve single-wavelength operation at 1319 nm. In particular, the 1319 nm and 1338 nm lasers are very close to each other in spectrum, and effective stimulated emission cross sections of both are very close [11], 8.7×10^{-20} cm^2 and 9.2×10^{-20} cm^2, respectively. Therefore, we must take some measures to suppress the 1338 nm wavelength oscillation. Commonly used methods include inserting an etalon in the cavity [5] and designing the cavity mirror film layer precisely [4] [6]. In order to avoid excess insertion loss, this letter used suitable cavity coating to increase the loss of 1338 nm wavelength. M1 has a transmission higher than 60% at 1338 nm, which makes the oscillation threshold of 1338 nm laser much higher. Eventually, the laser emitted from the coupled output mirror contained only the components of 1318.7 nm laser from the examination results of the spectrometer.

3. Results and Discussion

Figure 2 plotted the functional relationship between laser output power and pump power. The maximum output power of 96.8 W was obtained at a pump power of 477 W. The fitted slope efficiency and corresponding optical-to-optical efficiency were 26.5% and 20.3%, respectively.

Table 1. Parameters for positive-branch off-axis confocal hybrid resonator.

Parameter	Cavity length	Magnification	Equivalent transmission	Spot size
Formula	$L = (R_1 + R_2)/2 + (1 - 1/n)l$	$M = \|R_1/R_2\|$	$T = 1 - \|R_2/R_1\|$	$D = T \times 14$ mm
Value	30 mm	1.11	10%	1.4 mm

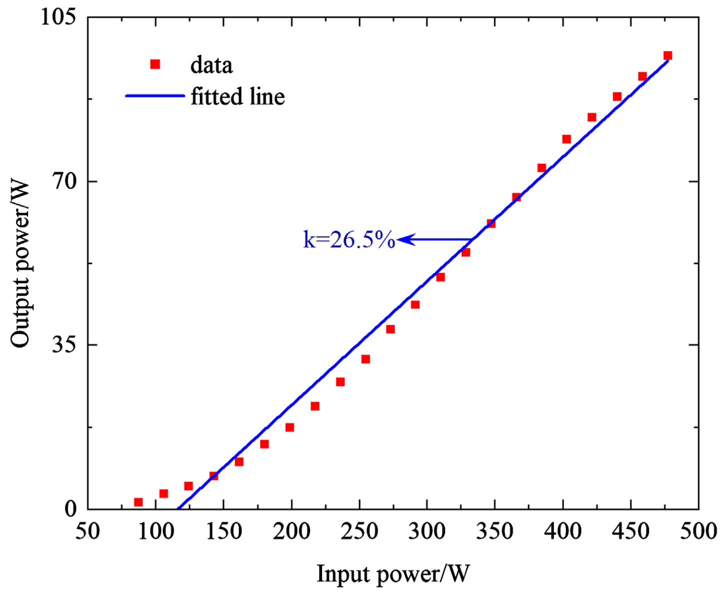

Figure 2. Laser output power versus pump power.

The focal length of thermal lens of the crystal is influenced by three main factors: the refractive index change due to the crystal temperature distribution, the refractive index change due to the crystal thermal stress distribution and the radius of curvature introduced by the crystal deformation. According to the structural characteristics of InnoSlab, the thermal distribution of the slab crystal in the horizontal direction was approximately uniform, and the thermal lens was generated only in the vertical direction. The focal length of the thermal lens in the direction of the stable cavity [12] is:

$$f_t = \frac{SK_c}{P_{ab}\left(\mathrm{d}n/\mathrm{d}T\right)}\left(\frac{1}{1-\exp\left(-\alpha l\right)}\right) \tag{1}$$

where S is the area of the pump region, K_c is the thermal conductivity of the crystal, P_{ab} is the absorbed pump power, $\mathrm{d}n/\mathrm{d}T$ is the thermo-optical coefficient of the crystal, α is the absorption coefficient of the crystal.

By Equation (1), the focal length of the thermal lens is about 51 mm at a pump power of 477 W. As can be seen from **Figure 2**, the output power increased linearly with pumping power and did not show a slope decrease, this cavity structure can still operate stably at a pump power of 1000 W.

We measured the beam quality factors M^2 in vertical and horizontal direction of the output laser using a measuring device composed of a cylindrical lens group and a CCD camera. The spot diameter of the higher order Gaussian beam as a function of distance can be expressed as [13]:

$$d^2\left(z\right) = d_0^2\left(1+\left(\frac{4M^2\lambda z}{\pi d_0^2}\right)^2\right) \tag{2}$$

where λ is the wavelength of the output laser, d_0 is the spot diameter at the beam waist, z is the distance to the beam waist and $d\left(z\right)$ is the spot diameter of the beam at position z. The beam quality factor M^2 can be acquired by fitting the spot radius and position of the collected data. At an output power of 91.1 W, the beam diameters in both directions were measured with the CCD camera. The fitted curves were shown in Figure 3. The beam quality factors M^2 in the stable and unstable direction were 2.95 and 1.88, respectively

The emission spectrum of the output laser was captured with a spectrometer. It confirmed that the laser operation at 1318.7 nm. As can be seen by Figure 4,

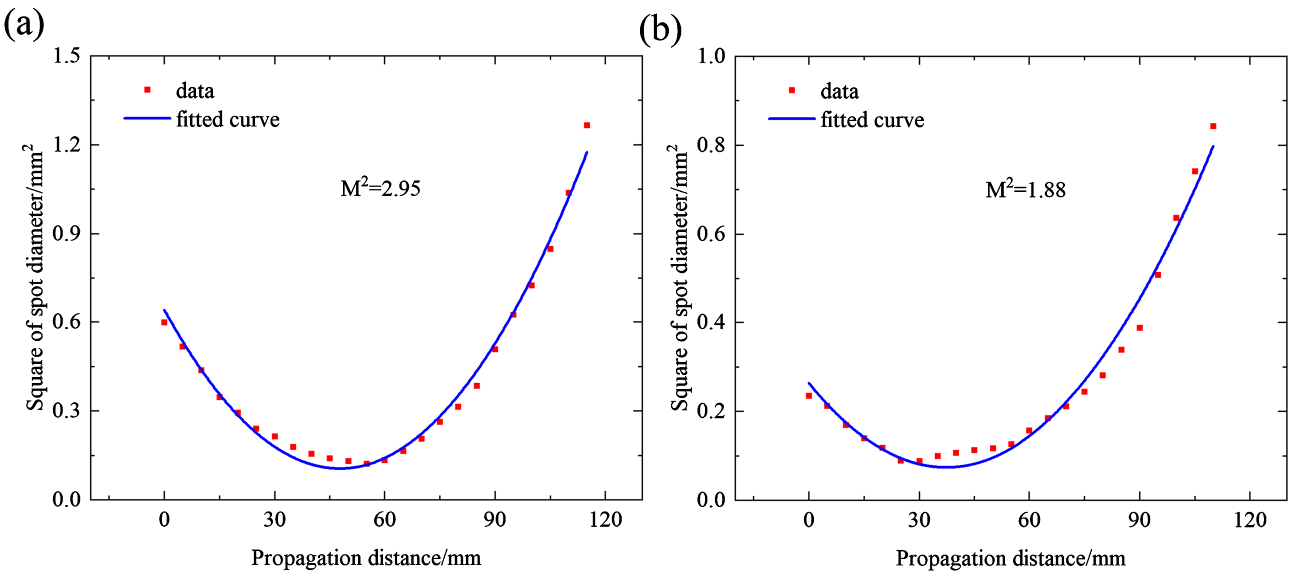

Figure 3. Laser beam quality factors. (a) In the stable direction; (b) In the unstable direction.

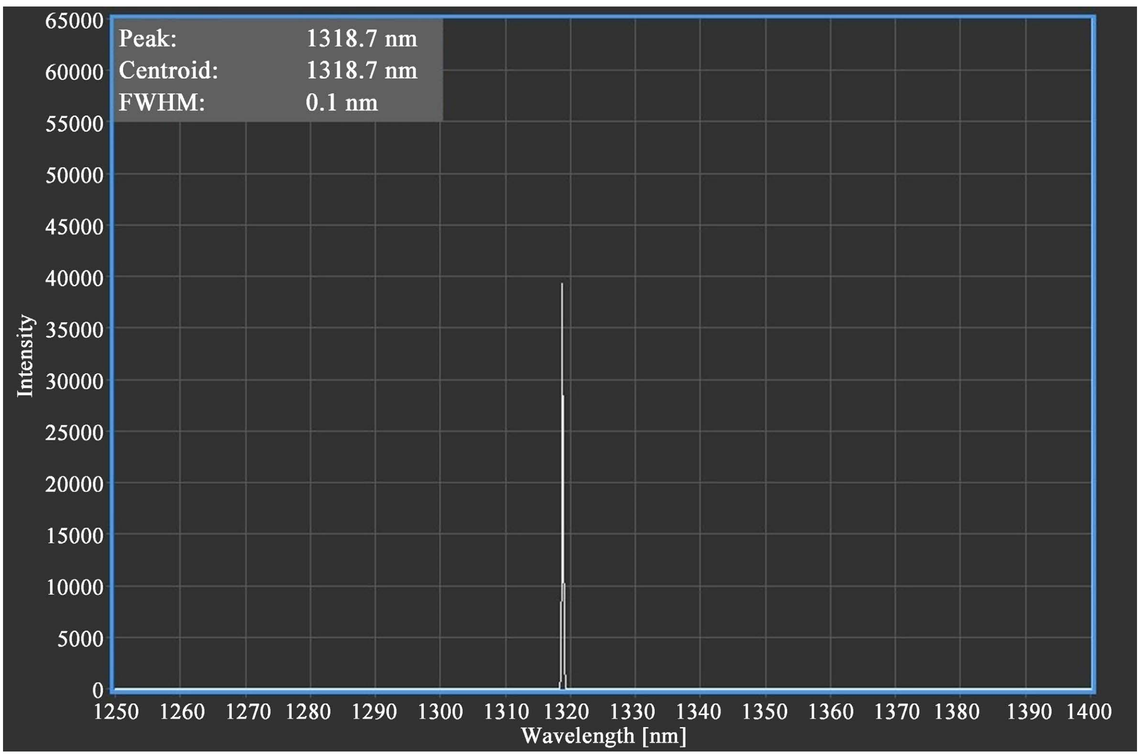

Figure 4. Laser spectrum when output power is 91.1 W.

no other emission was detected in the corresponding wavelength range. We have measured the root-mean-square error of the laser diode end-pumped Nd:YAG InnoSlab laser at the output power of 96.8 W. The time stability was approximately 0.27% for 10 min.

4. Conclusions

In this letter, we reported a high output power, high beam quality 1319 nm continuous wave laser. Under the 477 W of LD end pumping, a continuous laser output of 96.8 W which fitted slope efficiency and optical-to-optical efficiency was 26.5% and 20.3% was obtained with a hybrid resonator. Reliable laser output with power stability of 0.27% was obtained by setting the operating temperature of the laser and pumping system to the optimum temperature. The beam quality factor M^2 were 2.95 and 1.88 in the stable and unstable directions respectively, measured at an output power of 91.1 W.

Due to the thermal lens effect of the end-pumping method, the beam quality in the stable direction was not so good. This may be improved to some extent by inserting a negative cylindrical lens in the cavity.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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