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4350 W quasi-continuous-wave operation of a diode face-pumped ceramic Nd:YAG slab laser

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ABSTRACT

A high efficiency and high power laser diode (LD) face-pumped quasi-continuous-wave (QCW) ceramic Nd:YAG zigzag slab laser is demonstrated. The shape of the LD pump beam is optimized to ensure that the pump size is well matched with the ceramic slab and to improve the uniformity of the intensity distribution along the length and width direction of the ceramic slab. Meanwhile, an efficient cooling technique is adopted to obtain the uniform temperature distribution inside the ceramic slab. Under the LD pump power of 9.98 kW, a maximum average output power of 4.35 kW at 1064 nm is demonstrated at a pulse repetition frequency of 400 Hz, corresponding to an optical to optical conversion efficiency of 43.6%. To the best of our knowledge, this is the highest output power as well as the highest conversion efficiency reported for face-pumped QCW ceramic Nd:YAG single slab laser.

1. Introduction

Since 1995, Ikesue et al. fabricated high-transparency Nd:YAG ceramics with low scattering loss permitting the laser output for the first time [1], ceramics laser has drawn much attention and the progress in fabrication of ceramic has prompted it to be a potential substitute for the traditional single crystal because of significant advantages of ceramic in large size, high doping concentration, low cost and short fabricated period [2]. Ceramic solid state laser can be well matched with the traditional crystal laser in output power and optical to optical conversion efficiency. In 2004, Lu et al. investigated the laser diode (LD) end-pumped ceramic Nd:YAG rod laser with 0.6% Nd^{3+} doped and achieved continue wave (CW) 110 W output power [3]. In 2006, a CW output power of 143 W was demonstrated by Kracht et al. using core-dope ceramic Nd:YAG rod laser [4]. Because of the limited power scaling of rod laser caused by thermal lens effect, the slab configuration using zigzag optical path is proposed as an effective way to improve thermal effect [5], and it has been proven that it is a feasible way to achieve high output power and high optical to optical efficiency. In Ref. [6], a CW output power of 230 W was demonstrated using LD pumped ceramics Nd:YAG slab laser, corresponding to an optical to optical efficiency of 43%. Based on ceramic Nd:YAG multi-slab laser, Mandl et al. obtained CW output power of 100 kW, however, the optical to optical efficiency is only ~25% [7,8]. As well known, compared with the CW operation of the LD pump system, the quasi-continuous-wave (QCW) operation of LD could contribute less to the temperature gradient and thermal effect which have an influence on the output power and optical to optical conversion efficiency [9]. In 2004, QCW face-pumped ceramic slab Nd:YAG laser with output power of more than 160 W was demonstrated by Ciofini et al. [10]. Later, the output power was raised to 350 W corresponding to the optical to optical efficiency of 30% demonstrated by the same group [11]. In 2012, Chen et al. reported a 2.44 kW QCW face-pumped ceramic Nd:YAG slab laser with an output power of 2.44 kW, corresponding to an optical to optical efficiency of 36.5% [12].However, as far as we know, there is no report on the output power over 4 kW for a QCW face-pumped ceramic Nd:YAG single slab laser.

In this paper, we report a high efficiency and high power QCW LD face-pumped ceramic Nd:YAG zigzag slab laser system. By shaping the LD pump beam and adopting efficient cooling technique, the

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average output power of the ceramic slab laser is up to 4.35 kW at LD pump power of 9.98 kW, and the corresponding optical to optical efficiency is 43.6%. This is, to the best of our knowledge, the highest output power and the highest optical to optical efficiency for a ceramic Nd:YAG single slab laser.

2. Slab laser design

The schematic diagram of LD face-pumped zigzag ceramic slab oscillator is sketched in Fig. 1. The selected ceramic Nd:YAG doped with Nd^{3+} ion concentration of 1% is cut into trapezoidal slab in 3 mm thickness, and the pumping face coated with antireflection (AR) at 808 nm is in the size of 116 mm × 50 mm, and the size of the opposite face coated with high-reflectivity (HR) at 808 nm is 120 mm × 50 mm for the double pass face-pumped configuration. The two cut edge facets, which are polished and coated with antireflection at 1064 nm, form an angle of 55° with the larger bottom face, which provides total internal reflections. The laser cavity is composed of a HR plane-concave mirror M1 with radius of 750 mm and a plane–plane output coupler (OC) M2 with transmission $T=60\%$. The M1 mirror is placed 80 mm away from the edge facet of the ceramic slab, and the distance between M2 and the edge facet of the ceramic slab is 60 mm. The 1064 nm laser beam propagates into one edge facet at small incident angle and travels in zigzag path along the length direction inside the ceramic slab. A thermopile power meter (PM) (NOVAII Ophir) is placed behind the M2 to measure the laser power at 1064 nm.

The QCW pumped source for the ceramic slab laser composed of pulsed 808 nm LD arrays (DILAS) is capable to achieve a total average output power of above 10 kW at a pulse repetition frequency (PRF) of 400 Hz. During the experiment, the temperature of the cooling water for pump source is optimized to tune the wavelength of the LD arrays to match the absorb spectrum of Nd:YAG ceramic slab, which was measured in previous work [12]. Due to the importance of uniformity and size of the LD pump beam for the high output power, the shaping optical elements are key to obtain the uniformity and promising size of the LD beam. Here, the shaping optical elements are mainly composed of two parts, including micro-lens and shaping cylinder lens. Each LD stack is collimated with micro-lens arrays in the fast axis and the divergence angle can be significantly decreased from 40° to 0.5°. The overlap among the LD beams in the far field is favorable for achieving uniformity of LD intensity. The cylinder lens with focal length of 150 mm is adopted to compress the LD beam to ensure that the size of the pump beam is approximately equal to the size of that of the pumped face of the ceramic slab. After propagating through these shaping optical elements, the shaped LD beam is radiated onto the top surface (i.e., the pumping face) of the ceramic slab in quasi-rectangle shape in size of 48.5 mm × 97 mm. The intensity distribution of the LD pump beam is investigated by measuring a series of continuous sequence data along the two directions on the pumping face of the ceramic slab. The normalization intensity along the width and length direction of the slab is

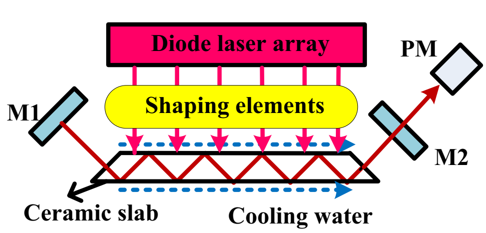

Fig. 1. Schematic diagram of the face-pumped zigzag Nd:YAG ceramic slab laser.

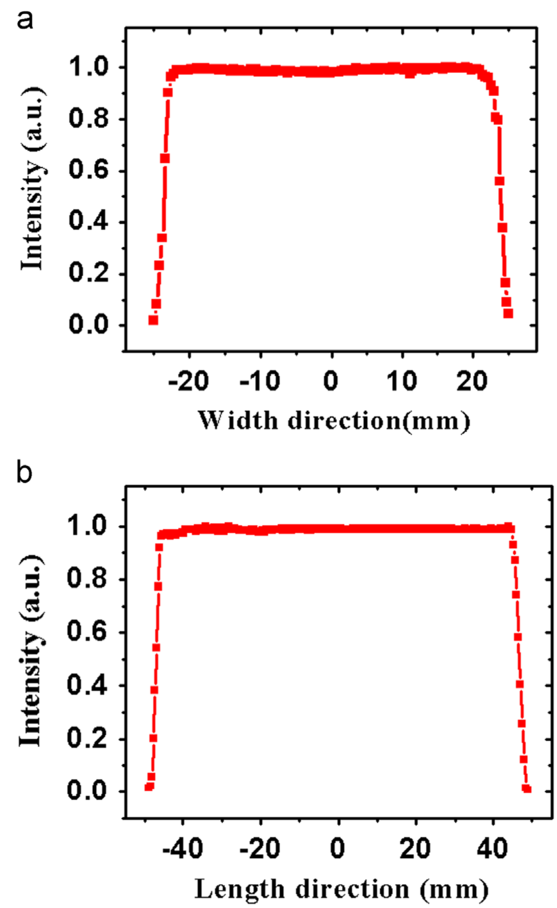

Fig. 2. Measured LD normalization intensity distribution on the pumping face of ceramic slab: (a) along the width direction and (b) length direction.

shown in Fig. 2(a) and (b), respectively. As seen in Fig. 2, in the uniform pumping area of 45 mm × 92 mm, the root means square (RMS) of the normalization intensity fluctuation is ±0.5%.

In order to reduce the influence of the thermal effect to obtain the maximum power extraction, a thin layer of cooling water (about 1 mm thick) is allowed to flow over the two faces along the length direction as depicted in Fig. 1, and the temperature of the cooling water is reduced to 18 °C. This provides an efficient cooling technique. The temperature distribution inside the ceramic slab satisfies the heat conduction equation as reported in literatures [13,14], here, finite elements method (FEM) is used to carry out the numerical simulation of the thermodynamics on the ceramic slab. In our simulation model, it is assumed that the 10 kW LD pump beam is incident on the top surface of the ceramic slab, the pumping length and width are equal to 97 mm and 48.5 mm respectively, exactly just as our experiment adopted. The two faces of the ceramic slab are cooled by the distilled water, the temperature of which rigidly maintained at 18 °C. Fig. 3 shows the simulated two dimensional (2D) temperature distribution over the middle cross section between the faces the ceramic slab. In the pumping region with size of 45 mm × 94 mm, the average temperature is the about 72 °C and the RMS of temperature fluctuation is approximately ±0.6%. It indicates that the temperature distribution is almost uniform except in the edge region. Meanwhile, in the thickness direction, the maximum temperature difference between the centre and the surface of the ceramic slab is only 25 °C. The uniformity of the thermal load over the larger area can contribute to the higher optical to optical conversion efficiency as well as the higher output power.