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RESEARCH ARTICLE

Diode-pumped single-frequency Tm:YAG NPRO laser by using different pumping spot sizes

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Abstract This paper presents the experimental results of the monolithic Tm:YAG nonplanar ring oscillator (NPRO) pumped by two kinds of laser diodes with different pumping spot sizes. By longitudinal pumping in continuous-wave operation, a single-frequency output power of 404 mW was obtained at room temperature, with a slope efficiency of 48.2%. The influences of the pumping spot sizes on the beam properties were also discussed.

Keywords nonplanar ring oscillator (NPRO), Tm:YAG laser, laser diode, pumping spot size

1 Introduction

Diode-pumped 2 μm lasers have applications in laser medicine, high-resolution spectroscopy, and remote sensing, etc., [1–4]. For the coherent lidar applications, 2 μm single-frequency lasers are required. We have generated 2 μm single-frequency laser output from diode pumped microchip CTH:YAG lasers [5]. Up to 31 mW single-frequency laser was obtained from the microchip laser. However, due to the short cavity length, the single-frequency output power was very limited. Multimode oscillation begins when we increase the pumping power. In this paper, we investigated to generate the 2 μm single-frequency laser from diode pumped nonplanar ring resonator Tm:YAG lasers.

The first Tm:YAG nonplanar ring oscillator (NPRO) laser was reported by Kubo and Kane in 1992 [6]. The 2 μm single-frequency output power was 27 mW when the crystal was cooled to a temperature of −23°C. For reducing the thermal influences, the crystal dimensions had to be chosen to be similar to the pump absorption length. The cavity dimensions of a few millimeters lead to a small diameter of the laser mode that is not compatible with the beam quality of high power pump diodes, thus limiting the power scaling possibilities. In addition, the small crystal surfaces significantly increase the requirements for manufacturing. A composite Tm:YAG NPRO reported by Freitag et al. prevented these drawbacks [7]. This laser composite cavity consists of a 3 mm×8 mm×3 mm Tm:YAG active platelet followed by a 9 mm long pure YAG retro-reflector that provides for closure of the nonplanar ring path by means of three total internal reflections. Both the Tm:YAG and the pure YAG crystals were mounted on a Peltier cooler to achieve active temperature control. This NPRO was demonstrated to operate with a single-frequency output power of 150 mW at room temperature. However, it increases the requirements of the parallelism and verticality of crystal for manufacturing this kind of NPRO cavity. In addition, huge thermal lens was induced when pumped by high diode power, which makes higher power single-frequency operation impossible.

In this paper, we report on a diode-pumped miniaturized Tm:YAG NPRO lasers using double diffusion-bonded ring structure. Pumped by two polarization-coupled laser diodes, 404 mW single-frequency output power was obtained from the Tm:YAG NPRO laser. The dependence of the frequency properties of the Tm:YAG NPRO laser on the pumping source was also investigated.

2 Experimental setup

The Tm:YAG NPRO lasers used in our experiment is based on a double diffusion-bonded monolithic crystal. This laser consists of a 4 mm×12 mm×1.5 mm pure YAG,

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a 4 mm×12 mm×4 mm Tm:YAG doped with 6% Tm and a 8.5 mm long pure YAG, as shown in Fig. 1. The 1.5 mm pure YAG was used to decrease the thermal effect generated by pump power. The long pure YAG was used as total internal reflector to realize the nonplanar beam path similar to original NPROs. We have chosen pure YAG to significantly reduce reabsorption losses. The input surfaces of the crystal was multidielectric coated for a high transmission at 785 nm ($T > 99\%$) and for a 1.5% output coupling at 2 μm. In our experiments, the NPRO crystal was attached to a heat sink, which was cooled by a thermal energy converter. The temperature of the heat sink was controlled at 20°C.

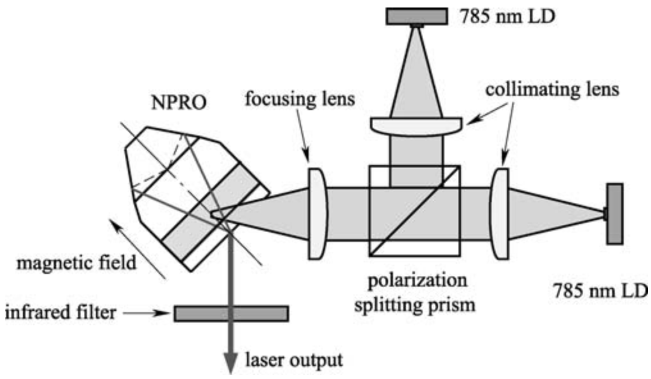


Fig. 1 Composite cavity Tm:YAG NPRO laser end-pumped by two polarization-coupled continuous-wave laser diode (LD: laser diode)

There are two sets of pump system at 785 nm. One is single laser diodes with an emitting area of 180 μm×1 μm and an output power of 3.5 W. The other one consists of two laser diodes (each emitting 2 W) with an emitting area of 100 μm×1 μm. All the diodes were fast axis collimated by using the microcylindrical lens. The area of the beam was collimated to be square, and the divergence of diodes was less than 10° in the fast-axis and the slow-axis. The pump beam from the single laser diode was focused onto the Tm:YAG platelet directly by means of 1:1 imaging optics. When taking a 100 μm diode for use, the two diodes were polarization coupled by a polarization splitting prism, as shown in Fig. 1. The focal length of the collimating lens and focusing lens were all 32 mm. The maximum pump power available at the focus for the two sets of pump system was 2.92 and 2.96 W, respectively. To achieve the single direction oscillating, a permanent magnetic field was applied along the crystal. When the laser output from the NPRO was measured, an infrared filter was used to block the nonabsorbed pumping beam. The filter has a high absorption below 1 μm ($T < 1\%$) and a transmission of $T \approx 90\%$ at 2 μm. The 2 μm output beam, filtered by the infrared filter, was sent to an optical power meter, to a lambda meter or to a scanning confocal Fabry-Perot interferometer for detecting.

3 Results and discussion

First, the output power of the 2 μm single-frequency laser was investigated. The pump spot sizes were 100 and 180 μm introduced above. Figure 2 shows the output powers as a function of the pump powers for the two pumping spot sizes. When pumped by the 100 μm diode, the laser had a maximum single-frequency power of 404 mW with a threshold of 2.16 W. A slope efficiency of 48.2% and a maximum optical to optical efficiency of 13.6% were calculated. When the laser was pumped by the 180 μm diode, the threshold pump power and the maximum single-frequency power changed to 2.34 and 336 mW, respectively. The wavelength of laser was measured to be 2012.982 nm by a laser wavelength meter, as shown in Fig. 3.

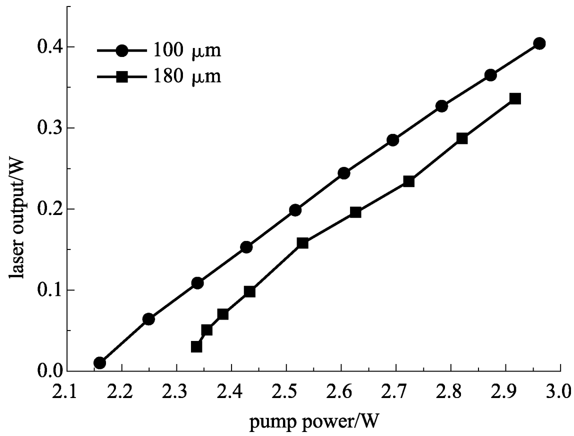


Fig. 2 Output powers of Tm:YAG NPRO laser as a function of pump power

In the quasi-three level laser operation, the TEM_{00} beam size was deliberately chosen to be small to get the high laser efficiency. With this NPRO resonator and the pumping power 2–3 W, the thermal lens lengths were calculated to be about 90–135 mm and 300–450 mm when crystal pumped by the 100 and 180 μm diodes, respectively. When pumped by the 100 μm diode, the TEM_{00} beam radius in the doping Tm:YAG crystal was also calculated to be 182 μm at a 2 W pump power, increasing to 197 μm at a 3 W pump power. When pumped by the 180 μm diode, the TEM_{00} beam radius was calculated to be between 235 and 258 μm. The different thermal lens and TEM_{00} beam radii were caused by the different pump power densities. They bring on the high laser threshold and low laser efficiency and also lead to the unstableness of laser frequency.

The character of the output beams was checked by a scanning confocal Fabry-Perot interferometer (FPI) with a free spectral range of 3.75 GHz and finesse of about 150. Figure 4(a) shows typical plots of the transmitted signal though the FPI in single-frequency operation. When

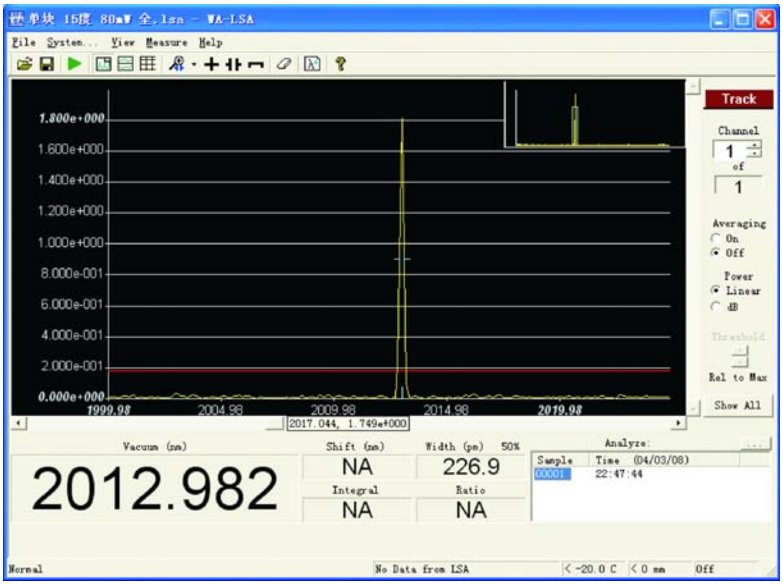
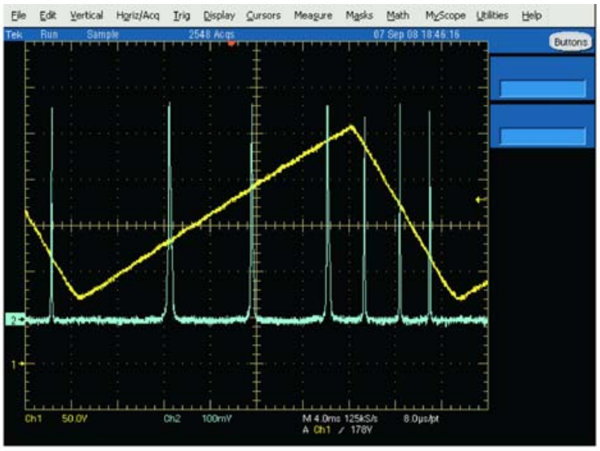
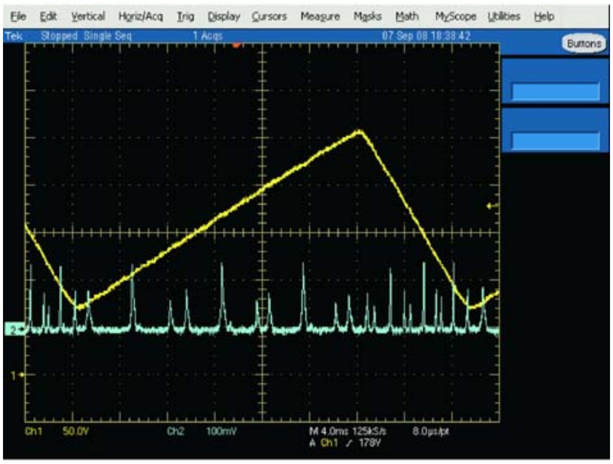


Fig. 3 Wavelength of Tm:YAG NPRO laser



(a)



(b)

Fig. 4 Transmitted signal from scanning FPI showing single-frequency operation (a) and multimode operation (b) in different laser powers pumped by the 100 μm diode, the NRPO laser operated in single frequency all the time except on some mode-hopping point. When pumped by the 180 μm diode, the NPRO laser operated in single frequency in some limited pumping powers. It operated in multimode in some power point, such as 180 mW, which was shown in Fig. 4(b). This difference of frequency character was conducted by the different thermal lens and pump power density, which had been discussed.

4 Conclusion

Single-frequency operation in diode pumped Tm:YAG NPRO lasers by using different pumping spot sizes was reported. The single-frequency output power of 404 mW was obtained with a slope efficiency of 48.2% when the laser was pumped by two polarization coupled laser diodes. The laser threshold, output power, and single-frequency output power are influenced by the pumping spot area.

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