Characteristics of a High-Power Diode-Directly-Pumped Yb:YAG Laser with High Beam Quality

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We have demonstrated and analyzed a high-power continuous-wave (cw) Yb:YAG laser directly pumped into the upper lasing level by a fiber-coupled laser diode with a center wavelength of 969 nm. The output power and the beam quality were compared by changing laser-medium length and the focal length of pump-focusing lens. From a cw Yb:YAG laser a 5-mm-long crystal and a pump-focusing lens with a focal length of 60 mm, an output power 18.1 W has been obtained at center wavelength of 1031 nm. The $M^2$ factors of the laser beam are 1.71 in the horizontal direction and 1.47 in the vertical direction.

**Key Words:** Diode-pumped, Yb:YAG, Continuous wave, Beam quality, $M^2$ factor.

1. Introduction

The availability of high-power InGaAs laser diodes (LD) has now engendered the power scaling of Ytterbium (Yb$^{3+}$) doped lasers. The Yb$^{3+}$ ion has a simple energy-level scheme, which minimizes undesirable effects such as up-conversion, excited-state absorption, and concentration quenching. The small quantum defect reduces the thermal load. Although there are many other Yb$^{3+}$-doped systems with hosts including YSO,$^{3}$ KGW,$^{3}$ CaF$_2$,$^{7}$ GVO,$^{8}$ and so on, Yb:YAG is regarded as one of potential laser media for efficient high-power lasers because of its excellent thermo-mechanical properties and ease of growth of high-quality crystal.

Lasers with high beam quality have a widespread application range, especially some regions that need tight focusing such as laser material processing and medical uses. The large Rayleigh length for a given spot size reduces the requirement for longitudinal alignment and increases the working distance between the objective lens and the focal point, making it possible to protect the optics against debris and fumes in operation.

However, high beam quality is not easy to achieve, especially in high-power operation. One of the main problems in high-power end-pumped lasers is the laser beam distortion due to the highly aberrated thermal lens, making it extremely difficult to simultaneously achieve high efficiency and high beam quality. To overcome this problem, several studies were reported for Yb:YAG lasers. For example, nearly diffraction-limited beam quality was obtained from a cryogenic Yb:YAG laser,$^{3}$ but the laser medium needs to be contained in a cryostat and cooled with liquid nitrogen. Thin-disc lasers also generated almost diffraction-limited Gaussian beams because thermal lens effect can be suppressed due to the heat flow almost parallel to the laser beam.$^{3}$ Unfortunately, in this case the pump beam must be folded many times with mirrors into the laser medium to ensure that most of the pump power is absorbed, which makes the laser setup extremely complex.

We recently developed a laser scheme to obtain high beam quality, which is applicable to quasi-three-level laser media.$^{7}$ There we demonstrated a continuous-wave (cw) diode-pumped Yb:YAG laser oscillated at a center wavelength of 1050 nm with a diffraction-limited Gaussian beam. The laser only employed a highly doped Yb:YAG crystal which pumped directly into the upper lasing level. However, it is not always necessary to use a highly Yb$^{3+}$-doped laser medium. We can also improve the beam quality for various Yb$^{3+}$ concentrations by changing the laser-medium length. In this paper, we describe cw high-power and high-beam-quality operations of Yb:YAG lasers. We reduced Yb$^{3+}$ concentration to avoid thermal fracture, which enabled us to generate higher output power with strong pumping. With the thermal lens at high pump power taken into account, the optimized laser operations were demonstrated by choosing the lengths of the crystals and the focal length of pump-focusing lens.

2. Experimental set-up

Figure 1 is a schematic diagram showing how the pump laser is absorbed in a quasi-three-level laser medium, where the laser medium is longitudinally irradiated by a pump laser. Here we assume that the pump beam transversely has a single center peak like a Gaussian beam. The portions of the laser medium that are not pumped strongly enough to obtain gains can reversely have some losses for the intracavity laser mode, because the lower lasing level of quasi-three-level system is thermally populated at room temperature. The loss regions work like an aperture for the intracavity laser mode, which enables us to improve the beam quality. Changing the Yb$^{3+}$ concentration and length of the laser medium can control the condition of the aperture. The aperture effect is greatly dependent on the position of the intracavity-laser-mode waist and becomes more effective when the intracavity-laser-mode waist position is shifted either rightward or leftward from the center of the laser medium. In this report, we demonstrated the case that the waist of the intracavity laser mode was positioned outside of the laser medium toward the pumping LD as shown in Fig. 1.
Figure 2 shows the schematic diagram of the cw diode-directly-pumped Yb:YAG laser. Throughout this work, a typical V-fold cavity was employed which included a flat dichroic mirror (DM), a concave mirror with a 100-mm radius of curvature and a 20%-transmission output coupler (OC). One of the intracavity-laser-mode waists is situated at the surface of the DM to obtain high beam quality. The coating on the DM surface was higher-than-99% reflective from 1020 nm to 1100 nm, and approximately 96% transmissive at 970 nm. The coating on the curved surface of the concave mirror was the same as the DM, so that the pump beam passed through the laser medium only one time.

The pump source was a fiber-coupled LD (Germany, LIMO50-100-DL970), with an available maximum output power of 45 W. The core diameter of the fiber was 100 μm and the numerical aperture (N.A.) was 0.22. The LD was mounted on a thermoelectric cooler for temperature control, maintaining the center wavelength of the LD at 969 nm with a width of 3 nm for directly-pumping into the upper lasing level, since the Yb:YAG crystal has a strong absorption line at 969 nm with a full width at half maximum (FWHM) of 4 nm. Hereby, the heat and its effects generated by quantum-defect can be minimized in this system. The pump beam was aligned by a collimating lens with a N.A. of 0.25 and a clear aperture of 2.3 mm. Then the collimated pump beam was focused by a pump-focusing lens with a 35-mm focal length into the Yb:YAG crystal through the DM.

First, the output powers and the beam profiles of the lasers were measured for the crystal length of 3, 4 and 5 mm. The Yb:YAG crystals were all 5 at.% Yb3+-doped, and cut at Brewster’s angle with two polished sections, whose dimensions were 3×3 mm2. The crystal was wrapped in a copper holder. An indium foil was used to provide good thermal contact between the crystal and the holder. The temperature of the copper holder was controlled by a Peltier-cooled heat sink.

In order to determine the pumping efficiency of the Yb:YAG crystal, we measured the absorbed powers under lasing condition of the three crystals. The average absorption efficiency of the three crystals under lasing condition was 78.3%, 79.9% and 81.9%, respectively. Obviously, when we used a 5-mm-long Yb:YAG crystal, the pump power was absorbed most efficiently in our experiment.

3. Results and discussion

The results of the laser output power versus the absorbed power for the three Yb:YAG crystals are shown in Fig. 3. We use the absorbed power under lasing condition instead of the incident power for comparison of laser behaviour among three crystals, which is needed to evaluate the optical-to-optical conversion efficiency in practical systems. The lowest threshold pump power of 5.20 W was obtained with a 3.0-mm-long Yb:YAG crystal, although which was slightly smaller than the threshold for the other crystals. However, using this crystal, the maximum slope efficiency of 55.1% was the lowest, while the maximum slope efficiencies of 58.7% for a 4-mm-long crystal and 61.0% for a 5-mm-long crystal were obtained.

The highest output power was obtained with the longest crystal at the maximum pump power, as shown in Fig. 3, since the longest crystal absorbed the highest pump power. Using a 5.0-mm-long Yb:YAG crystal, a cw laser with an output power of 13.7 W was achieved at the center wavelength of 1031 nm. The blue solid line in Fig. 3 was the best fit for the output power of the 5-mm-long crystal. The corresponding optical-to-optical efficiency was 39.9%, which was higher than the optical-to-optical efficiency of 37.9% for a 4-mm-long crystal and the optical-to-optical efficiency of
37.1% for a 3-mm-long crystal.

We measured the transverse laser profiles of the laser beam with a CCD Laser Beam Profiler (OPHIR, PCI-AAL-221). As shown in Fig. 4, the calculated M2 factors of the laser-beam profiles at the maximum output power gradually decrease as the length of the Yb:YAG crystal increases. A fundamental transverse mode of TEM00 was observed by adjusting the concave mirror and the focusing lens carefully with a 5-mm-long crystal. The M2 factors in the horizontal and vertical directions of the laser-beam profile were 1.92 and 1.17, respectively.

For a quasi-three-level laser, the waist radius of the pump beam should be larger than the radius of a laser-cavity mode in the laser medium, 8) as shown in Fig. 5, because the lower lasing level of quasi-three-level system is thermally excited at room temperature. Strong pumping with a high-intensity would exacerbate thermal effects such as thermal lens and thermally induced birefringence, which are particularly pronounced in end-pumped lasers owing to the high thermal density and heat flow mechanism. The focal length of the thermal lens is proportional to the square of pump-beam waist radius. 9) If the pump-beam waist radius, \( \omega \), is large, the thermal lens is not so strong. However, if \( \omega \) becomes smaller, the thermal effect grows and worsens the mode matching between the pump beam and the laser mode. Some optimal point can be expected to exist for the pump-beam waist radius.

We compared the results for various pump-focusing lenses with different focal length of 35, 45, 60 and 75.6 mm keeping the crystal 5.0-mm long. The calculated pump-beam waist radii in the crystal were approximately 67, 92, 138, and 148 \( \mu \)m, respectively, while the average radius of the laser mode in the crystal was calculated to be approximately 76 \( \mu \)m in our experiment without considering the thermal effect. The output power as a function of absorbed pump power for different pump-beam waist radii was shown in Fig. 6.

The lowest threshold of 4.34 W was obtained for \( \omega = 92 \mu \)m. In the case of \( \omega = 67 \mu \)m, since the radius of the pump beam was smaller than that of laser mode at waist, the part of the laser mode outside of the pump beam had loss instead of gain. Furthermore, the pump beam diverged much rapidly at the tail of laser medium and thus the gain also reduced rapidly. So the threshold in this case increased. On the other hand, when the pump-beam waist radius was large, the pump intensity became too low to oscillate. That is why the lowest threshold was obtained for \( \omega = 92 \mu \)m.

At high pump power, the thermal effects increase and result in the mismatching between the pump beam and the intracavity laser mode. Since the thermal effects decrease with the increase of pump-beam waist radius, the maximum output power was obtained in the case of a slightly larger pump-beam waist radius, \( \omega = 138 \mu \)m. The blue solid line in Fig. 6 was the best fit for \( \omega = 138 \mu \)m. The maximum output power was 18.1 W, and the corresponding maximum slope efficiency and optical-to-optical conversion efficiency were 77.5% and 52.4%, respectively. A practically diffraction-limited Gaussian beam was observed simultaneously. Figure 7 showed the corresponding transverse intensity profile of the laser beam.
The $M^2$ factors in horizontal and vertical directions were 1.71 and 1.47, respectively.

For the pump-beam waist radius of 148 $\mu$m, we obtained a little better laser-beam quality whose $M^2$ factors in the horizontal and vertical directions were 1.71 and 1.44, respectively, but a slightly lower optical-to-optical conversion efficiency of 49.8%. There might be two reasons that result in this phenomenon. First, the pump-beam waist radius in the laser medium was so large that the laser medium could not be excited strongly. Second, the strength of thermal lens reduced because of a large pump-beam waist radius, and then the mode matching between the pump beam and laser mode became worse.

4. Conclusion

High output power and high-beam-quality operations of the Yb:YAG lasers were demonstrated systematically based on an approach that the laser medium directly-pumped into the upper lasing level. The aperture effect of the pumped laser medium greatly depends on the position of the intracavity-laser-mode waist. The aperture becomes more effective when the intracavity-laser-mode waist position is shifted to the outside of the laser medium. The laser design for high beam quality is also applicable to high-power lasers even if the thermal lens exists. We obtained the maximum output power of 18.1 W, where the corresponding maximum slope efficiency and optical-to-optical conversion efficiency were 77.5% and 52.4%, respectively. A practically diffraction-limited Gaussian beam was observed simultaneously.

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