Journal of the Optical Society of Korea, Vol. 2, No. 1, March 1998, pp. 5-8

Intracavity frequency doubling of a slab Nd:YAG laser pumped by high power diode laser array

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(Received: December 22, 1997)

A high power diode-array-pumped slab Nd:YAG laser is described. The resonator consists of three mirrors in folded geometry. The laser is operated in acousto-optic Q-switching mode and intracavity frequency doubling is tried. We demonstrate that the laser exhibits frequency doubling efficiency of ~ 60 % with a type I LBO crystal.

I. INTRODUCTION

Recently high-repetition rate Q-switched diode-pumped solid state lasers and their frequency doubling find many applications in micromachining, ranging, remote sensing, space communication and microsurgery [1,2] due to their high conversion efficiency of electricity into laser light, long lifetime, smaller thermal effect, and compactness [3,4]. Usually diode lasers have an emission wavelength matched with one of the absorption peaks of the lasing medium, which is 808 nm for the case of a Nd:YAG laser. Although the rod shape of a Nd:YAG crystal was more popular for a lasing medium, slab geometry was later introduced to solve the high thermal lensing problem in rod crystal cases [5]. The flat surface of a slab laser is more convenient for pumping as a multi-stacked bar shape diode array can be easily matched with the slab surface [6]. In this work, we describe a diode-array-pumped slab-crystal Nd:YAG laser. The resonator consists of three mirrors and it has a folded configuration. The lasing characteristics are measured for the continuous wave (CW) laser as well as an acousto-optically (AO) Q-switched laser. Enhancing the conversion efficiency by intracavity frequency doubling is tried. Although a KTP crystal is usually used in most frequency doubling studies [7,8], we used a type I LiB_3O_5 (LBO) crystal [9] as a nonlinear material for the doubling. It is demonstrated that this laser has a remarkable frequency doubling efficiency of ~ 60% even though the frequency doubled laser has M^2 of ~ 50, which indicates large beam divergence. The laser pulse energy and pulsewidth are also measured as functions of diode output power and Q-switching frequency.

II. EXPERIMENT AND RESULTS

Fig. 1 shows the experimental layout and configuration of the folded resonator used in this experiment. The slab Nd:YAG crystal was located in the center of the pumping chamber (Cutting Edge Optronics, MS508) and one of the slab surfaces was pumped by 24 bars of a CW diode laser (AlGaAs). Maximum total output power of the diode laser was 336 W at an operating current of 24 ampere. Both surfaces of the slab crystal were cooled by water. The window located at the opposite side of the diode bar was high reflection coated. The wavelength of a diode laser depends on the temperature of the cooling water and on the driving current [10,11]. The variation of the diode laser spectrum was measured with a monochrometer and a CCD array (Princeton). Fig. 2 shows the result of the wavelength change measurement. As the current and temperature were increased, the lasing wavelength shifted to the red. When we pumped the slab laser, the temperature was set at 25 °C. At this temperature, the wavelength of the diode laser was 805.8 nm at maximum diode current of 24 ampere. To induce uniform

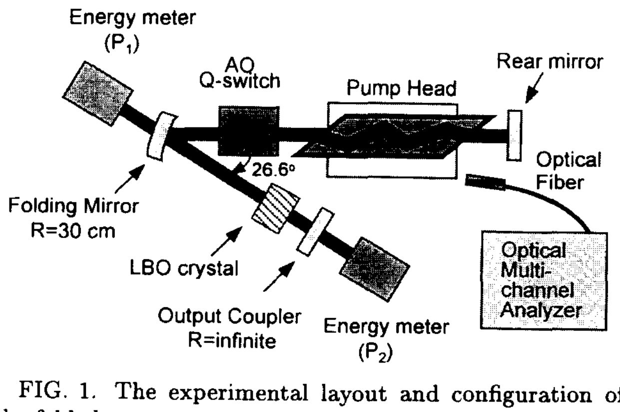

FIG. 1. The experimental layout and configuration of the folded resonator.

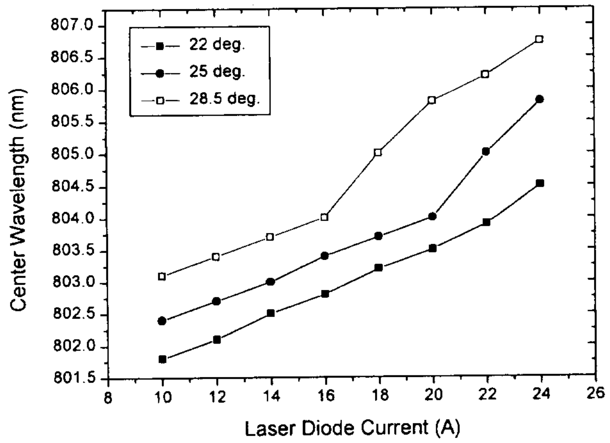

FIG. 2. The change of center wavelength of the diode laser versus driving current and cooling water temperature.

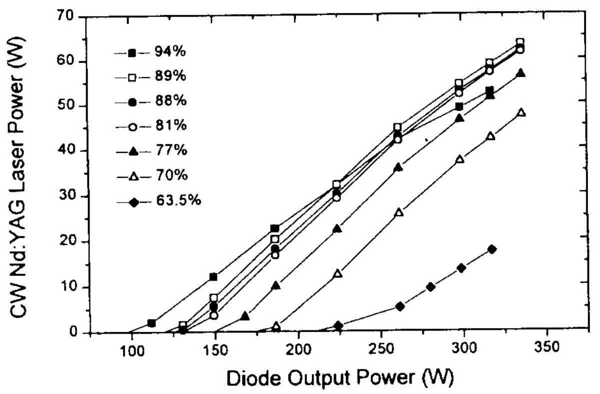

FIG. 3. The variation of CW laser power versus a diode output power and output coupler reflectivity.

pumping distribution in the cross-section of the slab, slightly off-resonant wavelength was used [12].

The end surface of the slab was Brewster angled. The size of the crystal was 5 × 5 × 115 mm^3. The resonator used three mirrors to fold the beam path, as shown in Fig. 1. Total cavity length was about 66 cm. The curvature of the folding mirror was 30 cm, while the output coupler and rear mirror had flat surfaces. With this configuration, the change of the CW output power versus diode output power was measured for various values of the output coupler reflectivity ranging from 64% to 94% at 1064 nm. Fig. 3 shows the measured result of CW output power versus diode output power for a given reflectivity. When the reflectivity was less than 90%, the maximum power increased with the increase of the reflectivity. When the reflectivity became 94%, the maximum power decreased. This result indicates that there exists an optimal reflectivity range for efficient output coupling [13]. If the reflectivity of output coupler is too low, the oscillating laser does not build up high enough to extract all stored energy in the gain medium. If the reflectivity is too high, photon lifetime increases and the laser loses energy due

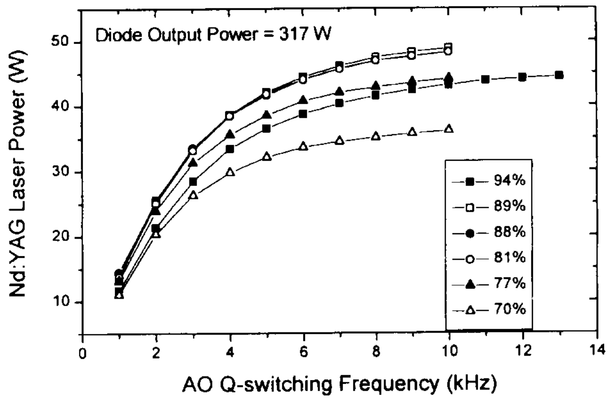

FIG. 4. The variation of laser power versus the AO Q-switching frequency and output coupler reflectivity.

to scattering while oscillating in the cavity. Although the slope efficiency (SE) reached 30.3 % for 89 % reflectivity output coupler case, the high threshold of lasing lowered the pumping efficiency to 18.8 %.

Q-switching of the laser was tried with an acousto-optic modulator (Goosh-Housego, QS-27-5S), which was placed in the vicinity of the pump head. The laser power was measured as functions of the reflectivity and the Q-switching frequency, as shown in Fig. 4. Similar to the CW laser case, the maximum power also decreased when the reflectivity was increased to 94%. The laser power saturated when the Q-switching frequency was increased more than 10 kHz, while the laser pulse energy fluctuated considerably as the Q-switching frequency increased. With the increase of Q-switching frequency, the average power becomes close to CW output power as the total stored energy in the gain medium is extracted at very high frequency [10]. When the frequency increased more than 10 kHz, high energy pulses and small energy pulses appeared in turn in the train of Q-switched pulses and the energy difference between the two kinds of pulses increased with increase of the Q-switching frequency. When the Q-switching frequency increased even more than this, each laser pulse was generated per two Q-switching trigger pulses because threshold population inversion was not built up during the single period of Q-switching pulses. For a laser with low output coupler reflectivity, the maximum frequency below which the laser output power showed stable operation also became lower due to high loss. Both the laser pulsewidth and the pulse buildup time, which is defined as the delay time between the Q-switching trigger pulse and actual lasing output, tended to increase with the increase of the Q-switching frequency. When we set the Q-switching frequency at 5 kHz and increased the diode output power, the laser with high reflectivity output coupler showed an increase of laser power, as shown in Fig. 5. Since the loss in the cavity became smaller for lasers with a higher reflectivity output coupler, the population built up easily even at low pumping power.

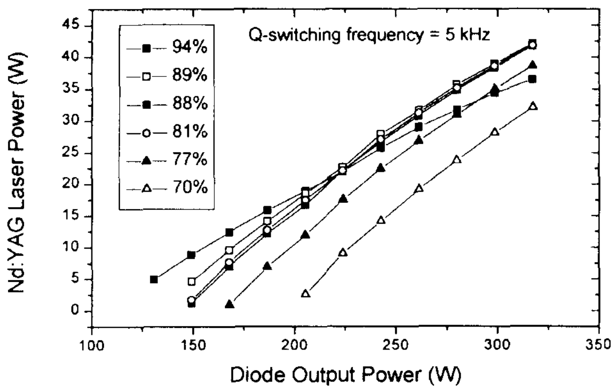

FIG. 5. The variation of AO Q-switched laser power versus diode output power and output coupler reflectivity at fixed frequency of 5 kHz.

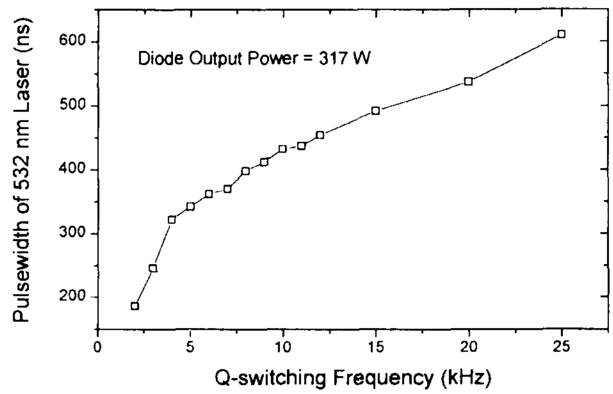

FIG. 7. The frequency doubled laser pulsewidth versus AO Q-switching frequency at fixed diode output power of 317 W.

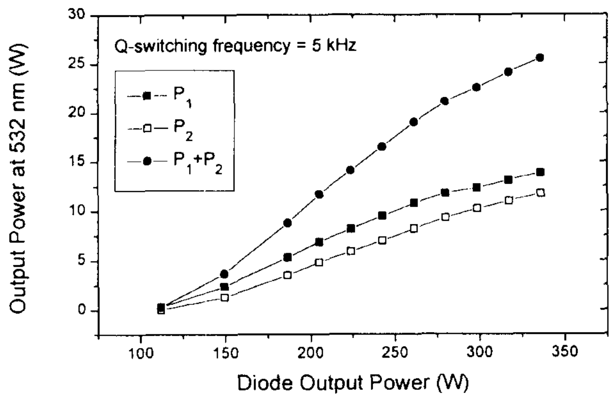

FIG. 6. The frequency doubled output power versus diode output power. P_1 and P_2 represent the points where the power is measured, as depicted in Fig. 1.

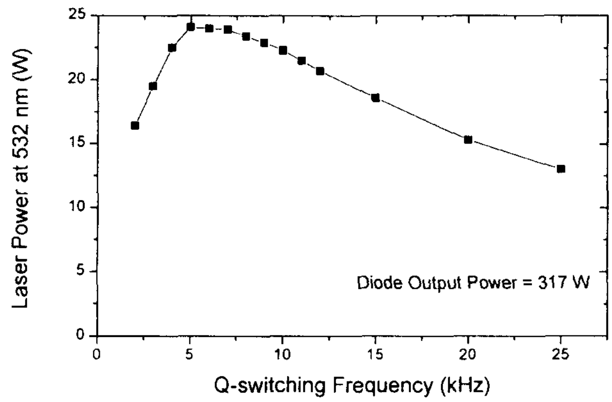

FIG. 8. The frequency doubled laser power versus AO Q-switching laser frequency at fixed diode output power of 317 W.

Therefore lasing started at a lower diode output power. Even in this case, as can be seen in the figure, when the reflectivity became 94%, the maximum power decreased compared with the laser with lower reflectivity. Optimization of the output coupler's reflectivity was also crucial to obtaining high power in Q-switching of the laser as in the CW laser case.

The intracavity frequency doubling was tried to enhance the efficiency [14,15] with three kinds of crystals, KTP, $KNbO_3$, and LBO. A mirror with 99.9% reflectivity at 1064 nm and 90 % reflectivity at 532 nm was used instead of an output coupler when frequency doubling was tried. Frequency doubled light was transmitted through both mirrors of the cavity, as shown in Fig. 1, and the measured output power is shown in Fig. 6. In the figure, P_1 and P_2 represent the place where the power is measured. When non-critically phase matched type I LBO crystal ($5\times5\times18\,mm^3$) was used for intracavity doubling, the laser showed the highest power of 25 W, corresponding to a $\sim$ 50% conversion efficiency of the maximum power in AO Q-switched laser. The efficiency sensitively depended on the crystal oven temperature and slight re-adjustment of the temperature was needed to get the maximum power when we changed the diode output power. Considering the transmission efficiency of the folding mirror at 532 nm is 90%, actual frequency doubling efficiency is estimated to be $\sim$ 60%. When a KTP was used, the power became very unstable at high diode output power and the efficiency was lower than 30% possibly caused by the birefringence and temperature increase of the crystal [16]. The $KNbO_3$ was easily damaged due to high power of the laser beam.

The M^2 of the 532 nm laser beam was measured to be $\sim$ 50, which is similar to the fundamental beam measurement. M^2 values were similar for both the horizontal and vertical direction and nearly independent of the diode output power. The frequency doubled laser beam, 532 nm, showed a wide change of pulsewidth ranging from 180 ns to 410 ns when the Q-switching frequency is increased from 2 kHz to 10 kHz. The frequency range in which the laser power was stable extended to 25 kHz, as shown in Fig. 7, far exceeding the stability range of the fundamental laser with an output coupler, while the pulsewidth became much more dependent on the frequency. Fig. 8 shows that the power of frequency doubled laser is maximum when the frequency is near 5 kHz. At higher Q-switching frequency, the fundamental laser power was increased while the pulsewidth lengthened, and thus the frequency conversion efficiency was decreased owing to low peak power of the fundamental laser pulse. At low Q-switching frequency, the peak power of the fundamental laser pulse was increased although average laser power decreased. Therefore the frequency doubling efficiency also decreased at low Q-switching frequency according to the decrease of fundamental power. Comparing with the laser with an output coupler, frequency doubling plays a role of cavity loss and a detailed analysis for optimal frequency doubling conditions is required in future work.

III. CONCLUSION

The characteristics of an intracavity frequency doubled laser were measured for a folded resonator configuration. The frequency doubling efficiency reached $\sim$ 60% with a non-critically phase matched type I LBO crystal. The laser pulsewidth was increased considerably with the increase of Q-switching frequency. The increase of fundamental laser output power was saturated when the Q-switching frequency increased more than 10 kHz while the frequency doubling efficiency was maximum at lower frequency of 5 kHz.

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