OUTPUT LASER CHARACTERISTICS OF DIODE-PUMPED a-CUT Nd:YVO_4 AND Nd:YAG CRYSTAL LASERS IN CONTINUOUS WAVE AND PASSIVE Q-SWITCHING OPERATIONS: COMPARATIVE ANALYSIS

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ABSTRACT

The experimental results in research and development of laser diode-pumped a-cut Nd:YVO_4 and Nd:YAG lasers at 1064 nm in continuous-wave and passive Q-switching laser operations are presented. The laser characteristics and properties are investigated with a three-mirror folded resonator using different output couplers. In continuous-wave operation, the a-cut Nd:YVO_4 lasers provide optical conversion efficiency larger than that of Nd:YAG ones. In passively Q-switched laser operation with the Cr^{4+}:YAG crystal of 90 % initial transmission, the a-cut Nd:YVO_4 lasers have lower threshold and higher pulse repetition rate than that of Nd:YAG ones, however, the Nd:YAG lasers produce considerably shorter pulse width and higher peak power than that of Nd:YVO_4 ones.

Keywords: diode-pumping, CW and passive Q-switching laser, a-cut Nd:YVO_4 and Nd:YAG crystal.

I. INTRODUCTION

Pulsed lasers in the near infrared region have a wide range of applications and scientific researches. In recent years, Nd^{3+}-doped crystals such as Nd^{3+}:YVO_4 and Nd^{3+}: YAG have been strongly researched as gain media at 1064 nm for all solid-state laser pumped by diode lasers [1-7]. Fortunately, Cr^{4+}:YAG crystal has a saturable absorption band from 900 nm to 1200 nm which makes it a suitable saturable absorber to obtain passively Q-switched laser operation of Nd-doped crystals. This allows one to composes all-solid-state compact, simple and low-cost pulsed lasers passively Q-switched with Cr^{4+}:YAG crystal, providing laser pulses ranging from several to tens of nanoseconds without the need of high voltage or RF drivers as conventional actively Q-switched lasers. Among the laser media at 1064 nm, the Nd^{3+}:YVO_4 crystal has its large stimulated emission cross-section and broad absorption bandwidth. The a-cut Nd^{3+}:YVO_4 crystal has the stimulated emission cross sections at 1064 nm (25 x 10^{-19} cm^2) about 5 times higher than that of Nd^{3+}:YAG. These spectroscopic features are expected to improve diode-pumped a-cut Nd:YVO_4 laser operations.

In this paper, we report the experimental results in research and development of diode-pumped a-cut Nd:YVO_4 and Nd:YAG lasers at 1064 nm in continuous wave (CW) and passive Q-switching laser operations. A Cr^{4+}:YAG crystal of an initial small-signal transmission T_0 = 90 % at 1064 nm was used as an intra-cavity saturable absorber for passively Q-switched laser operations. The laser characteristics of a-cut Nd:YVO_4 and Nd:YAG crystals are investigated with a three-mirror folded resonator using different output couplers. The obtained results allow one to compare the operational characteristics of the diode-pumped CW and Q-switched lasers using a-cut Nd:YVO_4 and Nd:YAG crystals.

II. EXPERIMENT

The criterions for a passively Q-switched laser operation were analyzed with the coupled rate equations [3,4]. One of these criterions requires the saturation of the absorber before the gain saturation in the laser crystal. For the laser and absorber crystals used in our experiments, the a-cut Nd^{3+}:YVO_4 crystal has the stimulated emission cross sections at 1064 nm (25 x 10^{-19} cm^2) about 5 times higher than that of Nd^{3+}:YAG, meanwhile, the stimulated emission cross-section of the Nd^{3+}:YAG crystal is comparable to the ground-state absorption cross-section of Cr^{4+}:YAG crystal absorber (8.3 x 10^{-19} cm^2) [7]. As a result, the parameter A/A_s (the ratio of the effective area in the gain medium to that in the saturable absorber) becomes important for passive Q-switching. The Q-switched laser resonator must shape a beam waist at the absorber smaller than that at the laser medium.

We consider the stable three-mirror cavity configuration (Fig.1) consisting of two flat mirrors G_1, G (output coupler) and a concave mirror, G_2. As previously discussed [8], it is a semi concentric laser resonator, the position of one beam waist is located on the output mirror plane (G) and its diameter is smallest approximately some tens micrometer. The Cr^{4+}:YAG crystal used as an intra-cavity saturable absorber is put as adjacent as possible to the output coupler plane.

The quasi-longitudinal end-pumping configuration was used (as shown in Fig.1). The pump source was the CW diode laser (ATC- Semiconductor Device, Russia) emitted at the wavelength of around 808 nm with a maximal CW laser power of 2 W. Its active cooling and temperature stabilization at 22 ^{0}C were provided by a built-in Peltier cooling device (ATC-LDD-10) maintaining its output laser wavelength matched the absorption peak of the a-cut Nd:YVO_4 or Nd:YAG crystals. The polarization of the diode laser emission is horizontal. The diode has a built-in cylindrical micro-lens for its fast axis collimation. This allows us to use simple pump optics to be a single lens of 35 mm focus length to couple and focus the laser diode light into the laser crystal. The three-mirror laser folded resonator consisted of the flat mirror, G_1 with high reflection coating at 1064 nm and anti-reflection coating at 808 nm at both sides, the concave mirror, G_2 (HR@1064 nm and AR@808 nm, its' focal length is 15 cm) and the output flat mirror of 6 % transmission, G. The two laser materials were used: a-cut, 1% doped Nd:YVO_4 crystal (3 x 3 x 3 mm) and a 1% doped Nd:YAG crystal (3 mm diameter and 3 mm long) that were AR coated on both sides at 808 nm and 1064 nm and mounted on suitable passive copper heat sinks. The Nd: doped crystal were oriented for the maximum absorption at 808 nm. The Cr^{4+}:YAG crystals having the initial small-signal transmissions of 90 % at 1064 nm was used as an intra-cavity saturable absorber. All optical components and crystals were supplied from

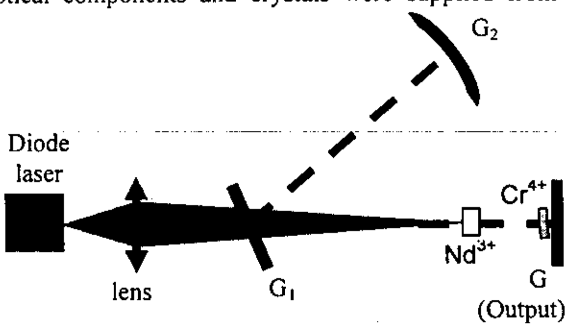

Fig. 1: Experimental setup for three-mirror cavity passively Q-switched Nd^{3+} laser.

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A fast photodiode (rise time <0.3 ns) connected with a digital oscilloscope (500 MHz, LeCroy, USA) was used to record the pulse widths of Q-switched laser pulses. The laser energy was measured by the Joule meter (13PME001, Melles Griot, USA). The laser wavelength and spectra were measured with a grating spectrometer (DFS-8, 3 A°/mm, Russia) equipped with a linear diode array (BP-2048, USA).

CW laser operation:

Firstly we have investigated the output laser characteristics of the diode-pumped a-cut Nd:YVO_4 and Nd:YAG laser in continuous-wave (CW) operation (without Cr^{4+}:YAG) using the output coupling of 6 %. The output average powers of these a-cut Nd:YVO_4 and Nd:YAG lasers versus the incident pump power are presented in Fig. 2.

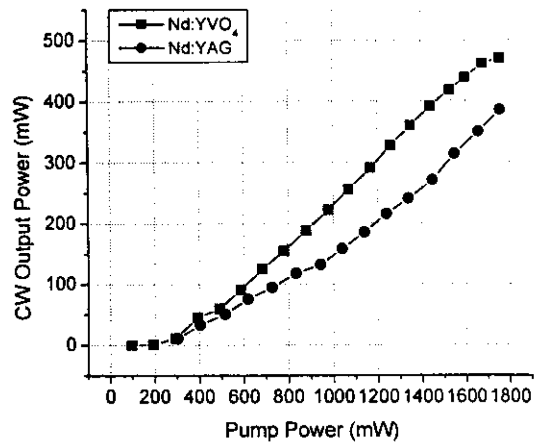


Fig. 2: The CW output power of a-cut Nd:YVO_4 and Nd:YAG lasers as a function of the incident pump power using the output couplings of 6%

The CW laser operation could be easily achieved in both laser materials, however, as is well known that a smaller stimulated emission cross-section of the Nd:YAG crystal normally causes a larger pumping threshold. The minimum pumping threshold of the Nd:YAG lasers is nearly 300 mW, this value is about 2 times larger than that of a-cut Nd:YVO_4 ones.

The a-cut Nd:YVO_4 lasers with the output coupling of 6 % have the maximum output power of 470 mW at the incident pump power of 1760 mW, corresponding to an optical conversion efficiency of 26 % and a slope efficiency of 32 %. Meanwhile, the Nd:YAG lasers only attained the maximum output power of 380 mW at the same incident pump power and output coupling, corresponding to an optical conversion efficiency of 21.6 % and a slope efficiency of 25.5 %. The output powers and optical conversion efficiencies of these two laser crystals are quite different, the a-cut Nd:YVO_4 lasers provided output power and optical conversion efficiency higher than those of Nd:YAG ones. These differences were resulted from the different emission cross-section, i.e., the a-cut Nd^{3+}:YVO_4 crystal has the emission cross-sections at 1064 nm about 5 times higher than that of Nd^{3+}:YAG.

Passively Q -switched laser operation:

Fig. 3 shows the average output powers of passively Q-switched laser operations (with the Cr^{4+}:YAG of T_0 = 90 %) of a-cut Nd:YVO_4 and Nd:YAG versus the incident pump power. There was considerable diversity of pumping thresholds between a-cut Nd:YVO_4 and Nd:YAG Q-switched laser operations, however, their optical conversion and slope efficiencies are not quite different. The maximum average output power of the a-cut Nd:YVO_4 lasers is

230 mW at the incident pump power of 1760 mW for the output coupling of 6 % transmission, corresponding to an optical conversion efficiency of 13 % and a slop efficiency of 20 %. Meanwhile, the Nd:YAG laser attained the average output power of 200 mW at the same incident pump power, corresponding to an optical conversion efficiency of 11.3 % and a slope efficiency of 21.6 %.

As shown in Fig.2 and Fig.3, it is obvious that the pumping thresholds of Q-switched performance are quite higher than those of CW performance due to the intra-cavity saturable absorber induced additional loss in the laser resonator. The pumping threshold of the passively Q-switched Nd:YAG lasers is distinctly larger than that of the a-cut $Nd:YVO_4$ ones. They were nearly 780 mW and 1025 mW for the Q-switched a-cut $Nd:YVO_4$ and Nd:YAG lasers, respectively.

Fig. 4 represents the pump power dependencies of pulse width of the passively Q-switched a-cut $Nd:YVO_4$ and Nd:YAG lasers. Obviously, the Nd:YAG lasers produced pulse width shorter than that of the $Nd:YVO_4$ ones. The pulse widths of the Nd:YAG laser pulses remained around 45 ns, but they decreased rather rapidly from 63 ns to 53 ns for the a-cut $Nd:YVO_4$ lasers increasing of the pump power. When the pump power is larger than 1450 mW, the passively Q-switched a-cut $Nd:YVO_4$ laser operation was sometimes observed to be less stable than that of the Nd:YAG one due to the higher thermal effect of the $Nd:YVO_4$ crystal.

Fig. 5 presents the pulse repetition rate of the Q-switched a-cut $Nd:YVO_4$ and Nd:YAG lasers versus the incident pump power. Increasing the pump power from 600 mW to 1800 mW, the repetition rates of the a-cut $Nd:YVO_4$ lasers increase from 5.4 KHz up to 42 KHz, meanwhile, the repetition pulse rate of Nd:YAG laser only increases from 1.7 KHz to 11.5 KHz.

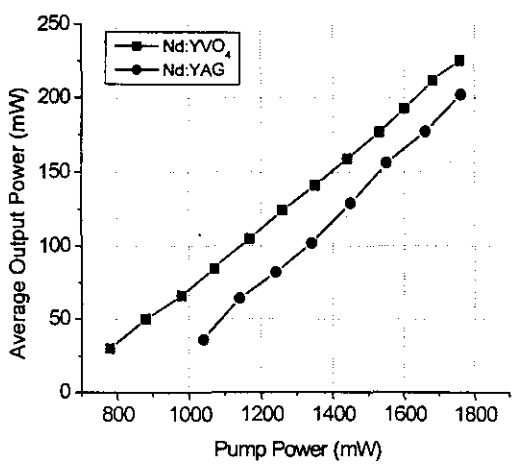


Fig. 3: The average laser output powers of a-cut $Nd:YVO_4$ and Nd:YAG lasers passively Q-switched with a Cr^{4+}:YAG (T_0 = 90 %) as a function of the incident pump power

Fig. 6 represents the pulse width of 53 ns at the pulse repetition rate of 37 kHz of the a-cut $Nd:YVO_4$ Q-switched laser at the pump power of 1500 mW.

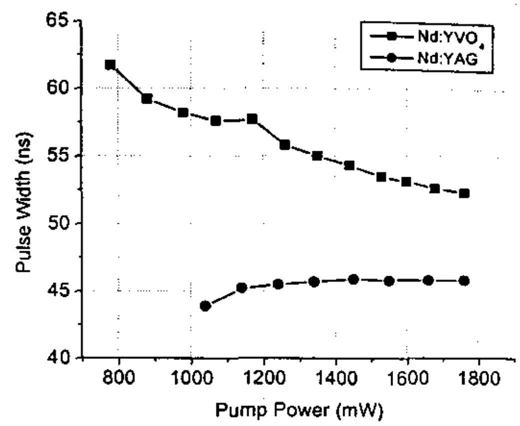


Fig. 4: The pulse widths of the a-cut $Nd:YVO_4$ and Nd:YAG passively Q-switched lasers as a function of the incident pump power

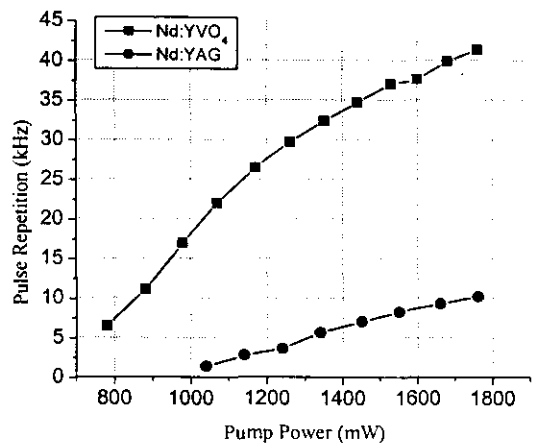
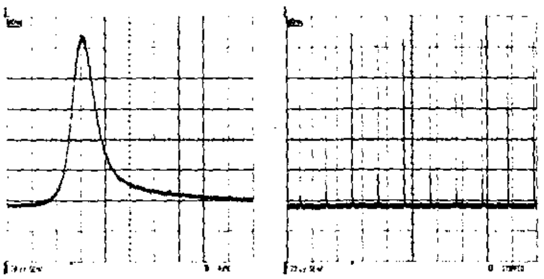


Fig. 5: The pulse repetition rates varied with the incident pump power for the a-cut $Nd:YVO_4$ and Nd:YAG passively Q-switched lasers.

Obviously, the pulse repetition rate of the $Nd:YVO_4$ laser was nearly four times higher than that of the Nd:YAG ones. This indicates that the passively Q-switched Nd:YAG lasers could provide peak powers much higher than that of a-cut $Nd:YVO_4$ ones. In the experimental observations, the pulse repetition rates of both a-cut $Nd:YVO_4$ and Nd:YAG lasers were not stable. This was usually observed in passively Q-switched Nd:doped lasers [3-7].

As shown in Fig. 7, the output peak powers of the passively Q-switched a-cut $Nd:YVO_4$ and Nd:YAG lasers are quite different. Obviously, the Nd:YAG lasers provided pulse width much shorter than that of the Nd:YVO_4 ones (Fig. 4), therefore, the peak power of the Nd:YAG laser was several times larger than that of the a-cut Nd:YVO_4 ones.

For the a-cut Nd:YVO_4 lasers, the peak power increased very slowly when the incident pump power increased and the maximum peak power of about 100 mW was achieved, the increase of pump power mainly increases its pulse repetition rate, meanwhile, the Nd:YAG lasers attain the maximum peak power of 600 W with a lower pulse repetition rate. It should be good to promise small pumping threshold and high peak output power in a passively Q-switched laser operation.



a) b)

Fig. 6 a-b: a) The pulse width of 53 ns Nd:YVO_4 laser passively Q-switched with a Cr^{4+}:YAG (T_0 = 90 %) and the output coupling of 6%; b) the pulse repetition rate of 37 kHz.

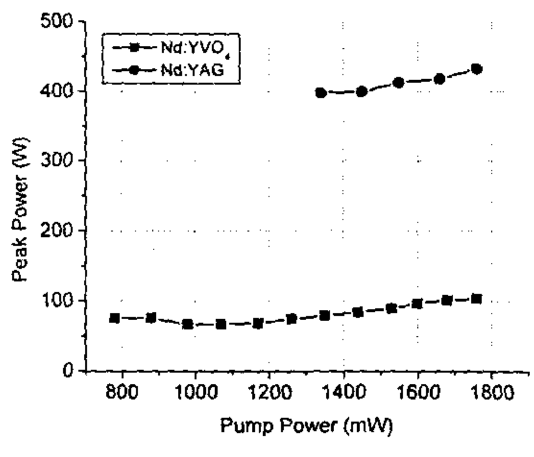


Fig.7: The laser peak power of a-cut Nd:YVO_4 and Nd:YAG lasers passively Q-switched with a Cr^{4+}:YAG (T_0 = 90 %) as a function of the incident pump power.

III. CONCLUSION

In conclusion, we have investigated the output laser characteristics at 1064 nm of CW diode-pumped a-cut Nd:YVO_4 and Nd:YAG lasers in CW and passively Q-switched operations with the Cr^{4+}:YAG crystal saturable absorber. These results allow one to compare the laser characteristics between the a-cut Nd:YVO_4 and Nd:YAG. Due to the larger stimulated emission cross-section, the diode-pumped CW *a*-cut Nd:YVO_4 lasers provide output power and optical conversion efficiency larger than those of the Nd:YAG ones. In passively Q-switched operation, the *a*-cut Nd:YVO_4 lasers have lower threshold and higher repetition rate, however, the Nd:YAG lasers provide considerably shorter pulse width with higher peak powers.

Acknowledgment
The authors would like to thank for the financial supports from Fundamental Research Program (Physics, N.4 033 06), the Laser Program of Vietnamese Academy of Science and Technology and Third World Academy of Science (02-548RG/PHYS/AS).

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