RESEARCH AND DEVELOPMENT OF DIODE-PUMPED PASSIVELY Q-SWITCHED Nd: YVO_4 LASERS USING Cr^{4+}: YAG CRYSTAL AS SATURABLE ABSORBER

Nguyen Trong Nghia*, Do Quoc Khanh, Trinh Dinh Huy, Le Thi Thanh Nga

Centre for Quantum Electronics, Institute of Physics and Electronics, VAST,
10 Dao Tan Str., Ba Dinh Dist., Hanoi, Vietnam

Nguyen Dai Hung

Faculty of Engineering Physics and Nanotechnology,
College of Technology, VNUH, 144 Xuan Thuy Rd., Cau Giay Dist., Hanoi, Vietnam

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ABSTRACT

The results in research and development of diode-pumped passively Q-switched Nd:YVO_4 lasers are presented with Cr^{4+}:YAG crystal used as an intra-cavity saturable absorber. Using *a*-cut Nd:YVO_4 laser crystals, the passively Q-switched lasers have been successfully developed and provided stable single shortest pulses of 40 ns at the repetition rate of 18.5 kHz, the maximal average output power of 180 mW was achieved corresponding to the optical efficiency of 9% and the slope efficiency of 16%. The dependences of average output power, repetition rate, pulse width and peak power on pump diode power for different transmissions of output mirror are also investigated.

Keywords: diode-pumped, passively Q-switched laser, Nd:YVO_4, Cr^{4+}:YAG

1. INTRODUCTION

Diode-pumped passively Q-switched solid-state lasers that are capable of delivering optical pulses of nanosecond duration and high repetition rates (kHz) in the near infrared region have a wide range of applications such as micro-surgeon, laser ranging, injection seeds for amplifiers and remote sensing. In recent years, passive Q-switching of diode-pumped Nd-doped crystal lasers, especially Nd^{3+}:YVO_4 crystals, has been widely considered with Cr^{4+}: YAG crystal used as a saturable absorber, provided laser pulses ranging from several to tens of nanoseconds [1 - 5]. Nd^{3+}:YVO_4 crystal has higher stimulated emission cross sections than that of Nd^{3+}:YAG. Therefore, Nd^{3+}:YVO_4 crystals are usually used as active media in high efficiency diode-pumped lasers. However, the large stimulated emission cross section is not preferable for passive Q-switch. The criterion for a good passive Q-switch can be deduced by the analysis of the coupled rate equations [3]:

$$\frac{\ln(1/T_0^2)}{\ln(1/T_0^2)+\ln(1/R)+L}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s} >> \frac{\gamma}{1-\beta} \qquad (1)$$

* Corresponding author e-mail: ntnghia3n3@yahoo.com

where R is the reflectivity of output mirror, σ is the stimulated emission cross section of the active medium, T_0 and σ_{gs} is the initial transmission and the ground-state absorption cross section of the saturable absorber respectively, L is the non-saturable intracavity round-trip dissipative optical loss, A/A_s is the ratio of the effective area of laser beam in the active medium to that in the saturable absorber, γ is the inversion reduction factor (γ = 1 correspond to four-level system), β is the ratio of the excited-state absorption cross section to that of the ground-state absorption in the saturable absorber. If $\gamma = 1$, $\sigma = 25 \times 10^{-19}$ cm^2, $\sigma_{gs} = 4.3 \times 10^{-18}$ cm^2, β = 0.19 that correspond to the couple a-cut Nd^{3+}:YVO_4/Cr^{4+}:YAG crystals, it is clearly to find that the high A/A_s is easier for obtaining a stable Q-switching. In the other saying, a stable laser resonator configuration providing a beam waist at the absorber much smaller than that at the laser medium must be used.

In this paper, we have used the Gaussian beam model to research the stable linear and folded resonators for the Nd:YVO_4 lasers passively Q-switched with an intra-cavity Cr^{4+}:YAG saturable absorber. The dependence of average output power, repetition rate, pulse width and peak power on incident diode power for different output mirrors are investigated. As a result, the diode-end-pumped passively Q-switched Nd:YVO_4 lasers have been successful developed using *a*-cut Nd:YVO_4 laser crystals. The laser provides single pulses of 40 ns at the repetition rate of 18.5 kHz, the maximal average output power reaches to 180 mW corresponding to the laser efficiency of 9% and the slope efficiency of 16%.

2. Q-SWITCHING LASER RESONATORS

The Gaussian beam model is usually applied to estimate the important parameters of a laser beam inside a stable cavity such as the beam radius $\rho(z)$ and curvature radius of a constant-phase surface R(z).

We consider the fundamental transverse mode of a laser beam in the stable cavity possibly consisting of many mirrors. The transformation of the beam through optical elements is described by ABCD-law. As the Gaussian beam in a stable cavity reproduces itself after reflections from the end cavity mirrors. It means that an absolute curvature radius of the constant-phase surface R(z) at a surface of the end mirrors is equal to its curvature radius. We get the formulas:

$$\tilde{\rho}_1 = \sqrt{\frac{BR_1^2\left(B - DR_2\right)}{\left(AR_1 + B\right)\left[R_2\left(CR_1 + D\right) - \left(AR_1 + B\right)\right]}} \quad ; \qquad R_1 = -R_{M1} \tag{2a}$$

$$\tilde{\rho}_2 = \frac{\left(AR_1 + B\right)^2\tilde{\rho}_1^2 + B^2R_1^2}{R_1^2\tilde{\rho}_1}; \qquad R_2 = R_{M2} \tag{2b}$$

here $\tilde{\rho}_i = \frac{\pi\rho_i^2}{\lambda}$; ρ_1, ρ_2 are the beam radii; R_1, R_2 are the curvature radii of the constant-phase surface at the end mirrors; λ is the laser wavelength; A, B, C, D are the elements of transformation matrix; R_{M1}, R_{M2} are the curvature radii of the end mirrors. From (2a) we get the condition for the stability of a cavity:

$$\frac{BR_1^2\left(B - DR_2\right)}{\left(AR_1 + B\right)\left[R_2\left(CR_1 + D\right) - \left(AR_1 + B\right)\right]} \geq 0 \tag{3}$$

In fact, the equality is not possible because of the aberration and the finitude of the concave mirrors.

The above obtained results are applied to the two cavity configurations: FC (Fig. 1) and FCF (Fig. 2). G_1, G_1' are the flat mirrors; G_2 is the concave mirror with a focal length of f = 150 mm; L, L_1 and L_2 are distances between two adjacent mirrors, as shown in Fig. 1 and Fig. 2.

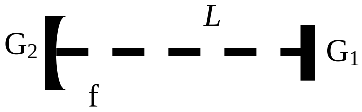

Fig. 1: *Flat - concave mirror cavity (FC cavity)*

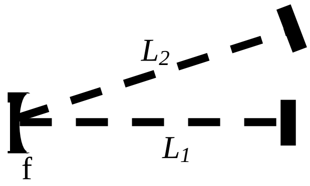

Fig. 2: *Flat-Concave-Flat mirror cavity (FCF cavity)*

2.1 FC cavity

From (2), the condition for the cavity stability is:

$$2f \geq L \geq 0 \tag{4}$$

In this cavity configuration, the position of the unique beam waist coincides with that of the flat mirror G_1. Figure 3 shows the variation of beam waist diameter when the cavity length changes. Clearly, the beam waist diameter is smallest approximately some tens micrometer, when L reaches close to 2f.

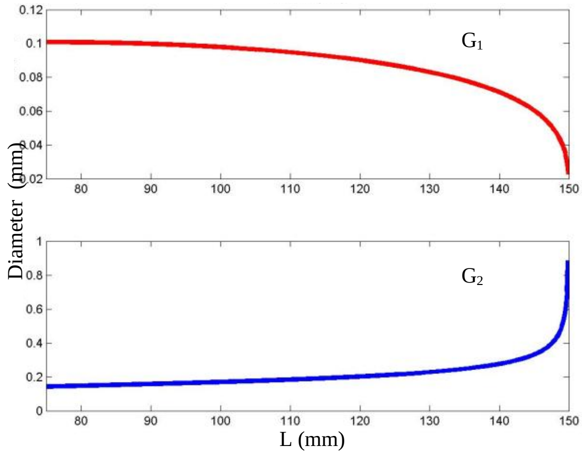

Fig. 3: *The dependence of beam diameters at the surface of flat (G_1) and concave (G_2) mirror on the FC length cavity*

2.2 FCF cavity

From (2), the condition for the stability of FCF cavities is:

$$\left(1-\frac{L_1}{f}\right)\left(1-\frac{L_2}{f}\right)\left(L_1+L_2-\frac{L_1L_2}{f}\right) \geq 0 \tag{5}$$

According to (5), both values of L_1 and L_2 are either larger or smaller f and they must satisfy the conditions: $(L_1 + L_2 - L_1L_2/f) \geq 0$. This cavity configuration creates two beam waists at the surfaces of two flat mirrors. Figure 4 shows the variation of both beam waist diameters when changing distances L_1 and L_2. In order to get small beam waist, the cavity length must be approximate 2f or longer.

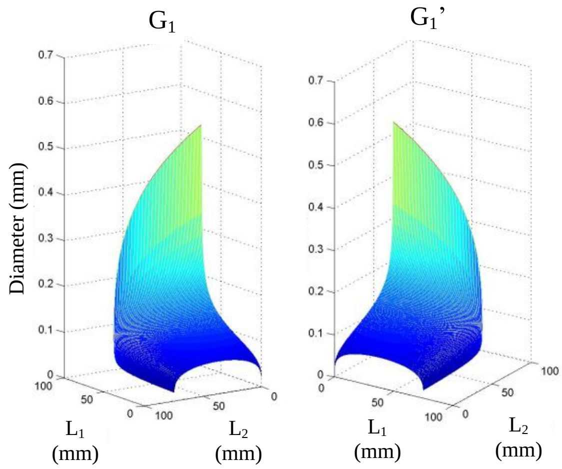

Fig. 4: *The change of waist beam diameter (The values of L_1 and L_2 are both smaller than f)*

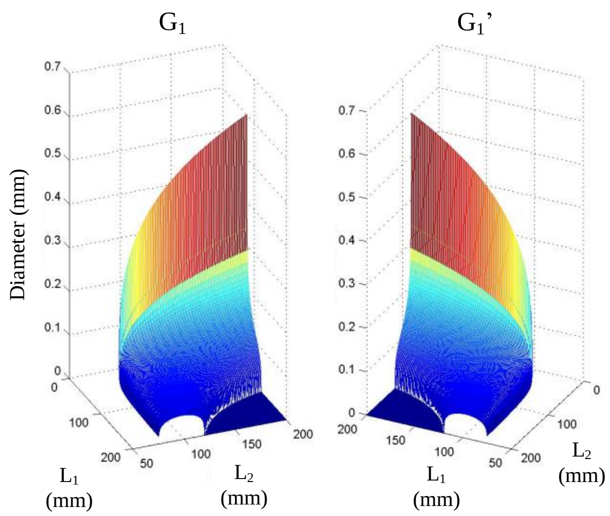

Fig. 5: *The change of waist beam diameter (The values of L_1 and L_2 are both larger than f)*

In comparison of the FC cavity with FCF cavity, it should be observed that the FC cavity is less affected by the aberrations than the FCF cavity, because the beam direction coincides with the main axis of the concave mirror and, therefore, it can create the smaller beam waist. In addition, the length of the FC cavity is approximate or shorter than the FCF cavity. For the reasons, the FC cavity configuration was chosen to build the passively Q-switched solid state lasers in our works.

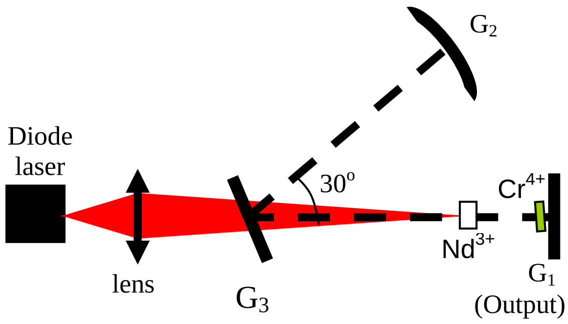

Fig. 6: *Experimental setup for passively Q-switched $Nd^{3+}:YVO_4$ laser*

3. EXPERIMENTS

The schematic of our experimental setup that is based on the FC configuration folded with a flat mirror, as shown in Fig. 6. Note that this cavity configuration has the advantages offering simple and easy optical arrangements. The pump source is a CW diode laser (ATC) emitted at the wavelength of around 808 nm with a maximal laser power of 2W. Its active cooling and temperature stabilization at 22°C is provided by a built-in Peltier cooling device in order to maintain its output wavelength near the absorption peak of $Nd:YVO_4$. The polarization of the diode laser light is horizontal. The diode has a built-in cylindrical micro-lens for its fast axis collimation. This allows us to use simple pump optics, consisting of a single lens of 35 mm focus length. The laser cavity consisted of three mirrors: the flat (G_3) and concave (G_2) mirror of high transmission at 808 nm and high reflection at 1064 nm, the different output flat mirrors (G_1) of 70, 80 and 94% were used. The a-cut, 1% doped $Nd:YVO_4$ crystal (3 × 3 × 3 mm) that was AR coated on both sides for 808 nm and 1064 nm, is mounted on a passive copper heat sink and oriented for the maximum absorption at 808 nm. The saturable absorber $Cr^{4+}:YAG$ with AR coatings at 1064 nm has the initial small-signal transmission of 85% at 1064 nm.

A fast photodiode (rise time < 0.5 ns) connected with a digital oscilloscope (500 MHz, LeCroy, USA) was used to record the duration of output Q-switched laser pulses. The laser pulse energy was measured by the Joule meter (13PME001, Melles Griot, USA). Noted that the Q-switched lasers were operated at single pulse generation during all the experimental measurements.

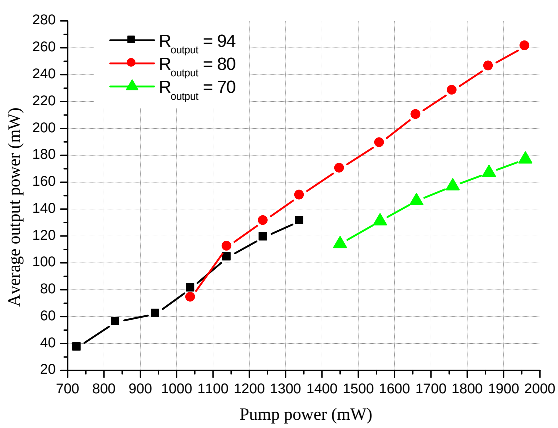

Fig. 7: *The averaged output power of the Q-switched laser versus the pump power*

Figure 7 shows the dependence of the average output power of the passive Q-switched $Nd:YVO_4$ laser on diode pump power for different transmissions of output mirror. The maximal optical efficiency was 13% with the transmission of 80% corresponding to the slope efficiency of 16%.

The laser pulse width almost remained unchanged when the pump power increased from 720 to 1350 mW corresponding to the increase of the repetition rates from 18 KHz up to 57 kHz (R_{output} = 94%). When the pump power is larger than 1350 mW, the Q-switched pulse intensity was observed to be less stable. The peak power was low and about 30 W and almost remained unchanged (Fig. 8), the pulse width has a small change (approximately 2.5%). Therefore, the increase of pump power increased mainly the pulse repetition rates.

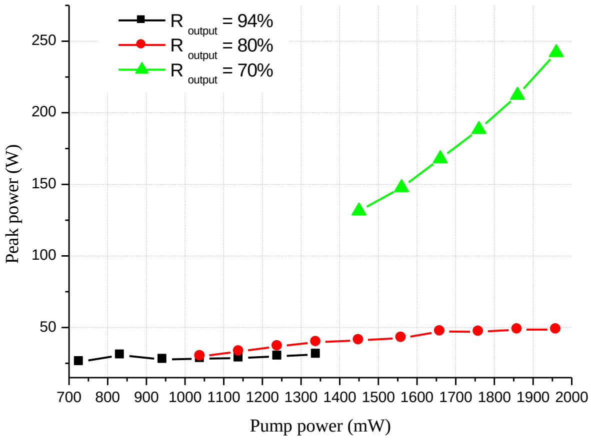

Fig. 8: *The peak power of the Q-switched laser as a function of the pump power*

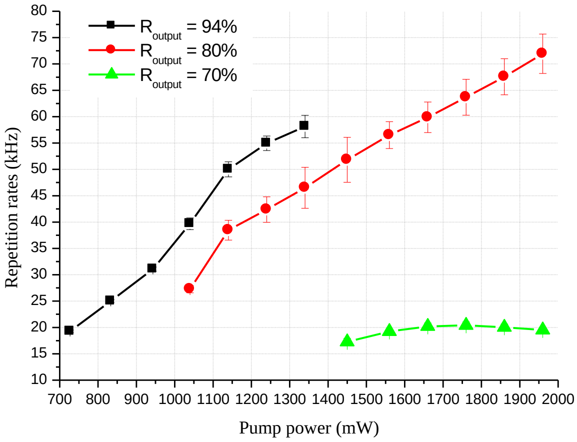

Fig. 9: *The Q-switched pulse repetition rate as a function of the pump power*

Figure 9 and Fig. 10 illustrate the variation of the Q-switched pulse width and pulse repetition rate when increasing the diode pump power.

The shortest pulse width of 40 ns (Fig. 11) was measured when the output mirror of 70% and the power pump of 1960 mW were used. Increasing the pump power increased from 1340 to 1960 mW, the peak power grows from 120 to 240 mW (Fig. 8) and at the same time, the Q-switched laser pulse width decreased from 47 ns to 40 ns (approximately 15%).

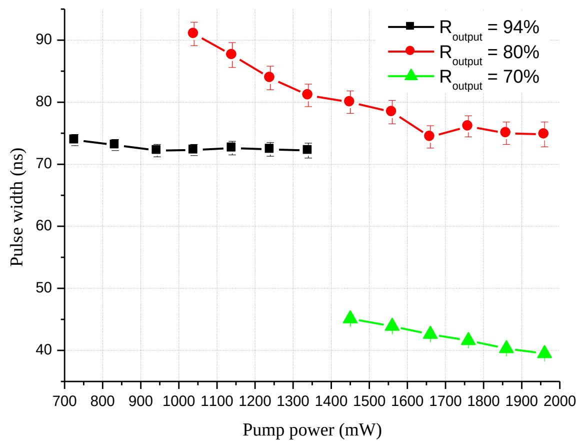

Fig. 10: *The Q-switched pulse width as a function of the pump power*

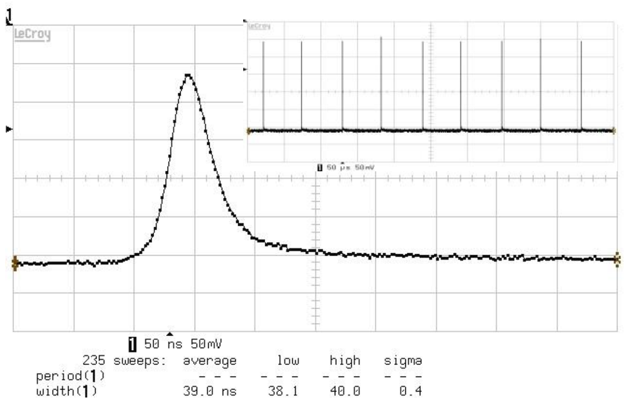

Fig. 11: *Passively Q-switched $Nd^{3+}:YVO_4$ laser pulse profile. Pulse width of 40 ns at 18 KHz; output mirror of 70%; pump power of 1900 mW*

4. CONCLUSION

The diode-pumped passively Q-switched $Nd^{3+}:YVO_4$ lasers have been successfully developed with the $Cr^{4+}:YAG$ crystal used as intra-cavity saturable absorber. The Q-switched lasers have provided the laser shortest pulses of 40 ns with the peak power of 240 W at the repetition rate of 18.5 kHz using the pump power of 1960 mW and the slope efficiency of 16%. In order to get shorter Q-switched laser pulses, the concave mirrors of shorter focal lengths should be used to reduce cavity length and beam waist diameter. Furthermore, the use of c-cut $Nd^{3+}:YVO_4$ or Nd:YAG to replace of a-cut $Nd^{3+}:YVO_4$ crystals [5] to hit the same mark. The obtained results of the pump and laser resonator schemes are still applied for different materials of passively Q-switched solid- state lasers.

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