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Efficient diode-pumped passively Q-switched laser with Nd:YAG/Cr:YAG composite crystal

Jieguang Miao[a,b,*], Baoshan Wang[a,b], Jiying Peng[a,b], Huiming Tan[a], Huikun Bian[a,b]

[a] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun Jilin 130033, China*
[b] *Graduate School of Chinese Academy of Sciences, Beijing 100039, China*

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Abstract

Diffusion bonded Nd:YAG/Cr:YAG composite laser crystal has been employed to perform a compact diode-pumped passively Q-switched laser. At the incident pump power of 3.3 W and pulse repetition rate of 16.3 kHz, the maximum average output of 592 mW has been obtained, corresponding to an optical-to-optical conversion efficiency of 18%. Stable passively Q-switched operation with peak power of 6.5 kW and pulse duration of 6 ns was also achieved. It has been experimentally revealed that Nd:host/Cr:YAG composite structure is a promising material for compact cost-effective Q-switched laser sources with high-peak power and short pulse duration. In addition, thermal lens effect (TLE) in the active medium and its impact on the Q-switched laser performance have been analyzed.
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1. Introduction

In recent years, composite laser materials have exhibited a growing significance in the development of high-power diode-pumped solid-state lasers. Compared with conventional laser crystals, composite ones can efficiently decrease the thermal effects (e.g., thermal lens effect, thermal-induced stress and birefringence, etc.) of the active medium, which consequently improves the output beam quality and increases the overall conversion efficiency. In fact, the undoped segment(s) bonded to the pump faces of the active materials serves as a quality heat sink which can effectively modulate the thermal uniformity and reduce internal temperature rise [1]. Therefore, composite laser materials, other than thermal lens compensation techniques and water or TEC cooling mechanism, provide another promising means to improve the performance of diode-pumped solid-state lasers by reducing thermal effects.

The most widely used simple and cost-effective way to fabricate composite materials is thermal bonding or diffusion bonding which was first accomplished by OnyxOptics, Inc., in 1991 [2]. Diffusion-bonded composite crystals were first used to eliminate radiation trapping effect in Yb:YAG crystal—a quasi-three level active medium [3]. Soon, with the assumption of efficiently decreasing thermal effects with undoped end(s), diffusion-bonded materials were successfully applied to reduce the thermal-induced ground-state absorption loss in the quasi-three level operation of Nd:YAG to generate 946 nm or frequency doubled 473 nm wavelengths [4,5]. More recently, another important application of diffusion bonding technique is Nd:host/Cr:YAG composite structure for compact efficient passively Q-switched lasers.

Diode-pumped Cr:YAG passively Q-switched solid-state lasers, with the merits of low cost, high efficiency, compactness and simplicity [6,7], have become an attractive substitute for electro- and acousto-optically Q-switched lasers. In addition to the Nd:host/Cr:YAG diffusion-bonded crystals, there is another such kind of material

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[*] Corresponding author. Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun Jilin 130033, China. Tel.: +86 431 85696132; fax: +86 431 85604748.
E-mail address: mjgbhk@yahoo.com (J. Miao).

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that could serve as both the active medium and the saturable absorber, namely the Cr,Nd:YAG co-doped crystals which unfortunately have two specific intrinsic defects. On the one hand, the thermal lens effect (TLE) in the Cr,Nd:YAG co-doped material is very serious [8], which inevitably restricts its application in high output level. On the other hand, under the same experimental conditions, the overall conversion efficiency and output pulse energy and peak power of the Cr,Nd:YAG self-Q-switched lasers are relatively low associated with those of the composite Nd:YAG/Cr:YAG crystal passively Q-switched lasers [9]. Therefore, studies on pulsed lasers with Nd:host/Cr:YAG composite structure have become a new inviting branch in the field of solid-state lasers. However, up to now, only a few reports on the lasing characteristics of such kind of materials have been published, which were focused on passively Q-switched microchip lasers [10,11].

In this letter, we report the lasing performance of a compact diode-pumped passively Q-switched laser with Nd:YAG/Cr:YAG composite structure. The maximum average output of 592 mW and peak power of 6.5 kW were obtained, with 3.3 W absorbed diode pump power. Besides, single pulse energy of 38.5 μJ and pulse duration of 6 ns were also achieved.

2. Experimental setup

The active medium used in this setup is an Nd:YAG/Cr:YAG composite structure (Crystech, Inc.) which was fabricated by diffusion bonding technique. Generally, the main composite process comprises three steps. Firstly, the end faces of both the Nd:YAG and Cr:YAG crystals were optically polished to keep exact flatness and parallelism. Secondly, under the room temperature, the two segments were put together, and were integrated by the molecular inter attraction, which is called optical contacting. At last, the integrity was thermally disposed to boost the diffusing actions of ions and holes, and consequently the combination was consolidated and the Nd:YAG/Cr:YAG composite structure was ultimately formed through diffusion bonding. Note that, to keep the end faces used for bonding clean, every step mentioned above should be operated in the environment filled with inert gases.

Fig. 1(a) shows the configuration of the composite crystal. The left part is a 1.0 at.% doped Nd:YAG crystal with the dimensions of $\phi 3\times 7\,\mathrm{mm}^3$, and the other part is a $\phi 3\times 1\,\mathrm{mm}^3$ Cr:YAG saturable absorber with an initial transmission of 70%. Serving as one of the cavity mirrors, the end face on the Nd:YAG segment was anti-reflection (AR) coated at 808 nm and high reflection (HR) coated at 1064 nm, and the other side was AR coated at 1064 nm. The experimental setup is schematically depicted in Fig. 1(b). As it shows, a plane-concave cavity configuration was employed to set the mode waist into the active medium and close to the saturable absorber for good passive Q-switching. The pump source is a 5 W cw diode laser (Lasertel LT-1030) with a center wavelength of 806.5 nm at the room temperature. For the divergent and unsymmetrical emitting property of the diode, a well-designed coupling optics was used here with a coupling efficiency of 93%. The output coupler, with a radius curvature of 50 mm, was partly reflection coated at 1064 nm ($R = 90\%$) on the concave side and AR coated at this wavelength on the other side. Besides, several thermo-electric coolers were used in the experiment to thermally stabilize the diode laser and the composite active medium.

3. Experimental results and discussion

The overall physical cavity length of the passively Q-switched laser is approximately 32 mm. In order to improve the thermal conduction, the composite laser rod was wrapped with indium foil and mounted in a copper block. Moreover, the pump beam was focused into the active medium with an average spot radius of about 100 μm. The

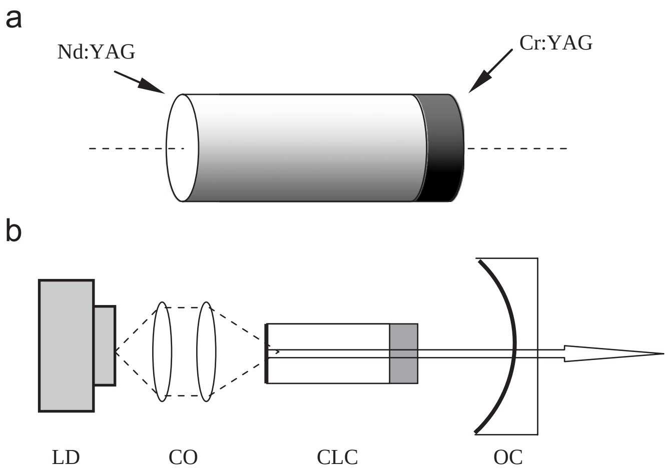

Fig. 1. (a) Configuration of the diffusion-bonded composite Nd:YAG/Cr:YAG crystal. (b) Schematic experimental setup for Cr:YAG passively Q-switched laser with composite crystal. LD, laser diode; CO, coupling optics; CLC, composite laser crystal; OC, output coupler.

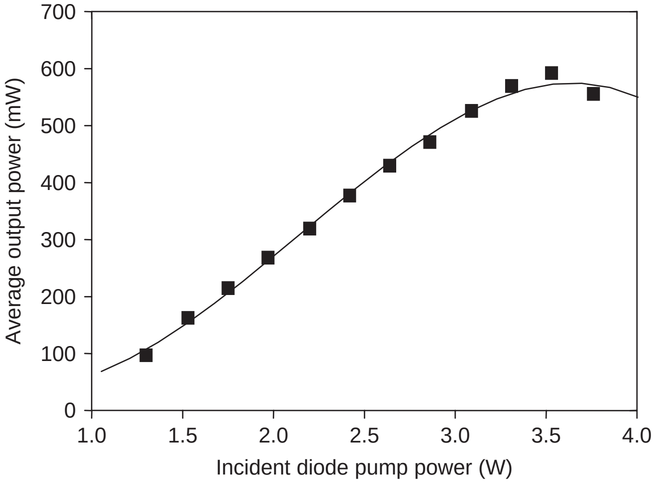

Fig. 2. Average output power of the passively Q-switched laser, with respect to the absorbed diode pump power.

average output power at 1064 nm detected by a LabMaster LM-3 power meter (Coherent, Inc.) is depicted in Fig. 2, in function of the incident diode pump power. As it shows, the average power increases linearly until the diode pump power goes beyond 3.3 W where the fundamental output begins to fall off, owing to the influence of the TLE, and the maximum average power is around 592 mW at this point. For one end face of the composite laser rod HR coated, the thermal focal length describing the TLE can be written as [12]

$$\frac{1}{f} = \frac{\xi P_{\mathrm{abs}}}{2\pi K_{\mathrm{c}}\omega_{\mathrm{p}}^{2}}\left[\mathrm{d}n/\mathrm{d}T + n(1+v)\alpha_{\mathrm{T}}\right]. \tag{1}$$

where K_{c} is the thermal conductivity, α_{T} and $\mathrm{d}n/\mathrm{d}T$ are the thermal expansion and thermal-optic coefficient, respectively, ξ is the fractional thermal load, l is the crystal length, P_{abs} is the absorbed pump power, ω_{p} is the average pump beam waist, n is the refractive index of the active medium, and v is the Poisson's ratio. For the 1.0 at.% doped Nd:YAG, $K_{\mathrm{c}} = 14\,\mathrm{W/(mK)}$, $\alpha_{\mathrm{T}} = 7.5\times10^{-6}\,\mathrm{K}^{-1}$, $\mathrm{d}n/\mathrm{d}T = 7.3\times10^{-6}\,\mathrm{K}^{-1}$, $n = 1.823$, $v = 0.28$, $\xi = 0.3$. Based on Eq. (1) and the parameters mentioned above, at the incident pump power of 3.3 W, we finally obtained the thermal focal length $f = 35.8\,\mathrm{mm}$ which was in good agreement with the experimental value of 32 mm.

Fig. 3 shows the pulse duration and repetition rate of the passively Q-switched laser with respect to the incident diode pump power. It can be seen that at the first stage, the pulse repetition rate increases as the pump power goes higher, which is just corresponding to one of the typical characteristics of passively Q-switched lasers. When the pump power is higher than 3.3 W, under the impact of the TLE, the pulse repetition rate begins to degrade from the peak value of 16.3 kHz. The phenomenon mentioned above could be interpreted as follows. Generally, for an ideal saturable absorber, the intensity-dependent transmission is defined by [13]

$$T = \frac{I_{\mathrm{s}}}{I}\ln\left[1 + (\mathrm{e}^{I_{\mathrm{s}}/I} - 1)T_0\right], \tag{2}$$

where I_{s} and T_0 are the saturation intensity and initial transmission of the saturable absorber, respectively, I is the intracavity fundamental intensity. From Eq. (2) one can get that the transmission T is proportional to the intracavity fundamental intensity I. In the experiment, as the TLE became serious, the fundamental output began to degrade, resulting in the fall-off of the laser intensity at 1064 nm, and consequently led to the further decrease of the transmission T. As a result, the intracavity loss was enhanced, which means that after one pulse was formed, it would take more time for another pulse began to establish. Hence, owing to the TLE in the laser rod, the pulse repetition rate was inevitably reduced. Concerning the pulse duration, as Fig. 3 illustrates, fluctuation within 8% was observed on the whole pump range, and it could therefore be regarded as a constant. The minimum pulse duration as short as 6 ns was obtained. Short pulse performance is a fascinating property of the passively Q-switched lasers with Nd:host/Cr:YAG composite crystals.

The pulse energy and output peak power are shown in Fig. 4. Note that, taking advantages of relatively small stimulated emission cross-section, long upper-state lifetime and fine capacity of energy depositing, Nd:YAG crystals have been proved to be extremely appropriate for Q-switched lasers with high energy and peak power output. During the experiment at the incident pump power of 3.3 W, as Fig. 4 shows, the maximum pulse energy and peak power were obtained as 38.5 μJ and 6.5 kW, respectively. However, it is seen that both the parameters, just as we expected, do not have obvious increase as the pump power goes higher. We attributed it to another characteristic of passively Q-switched lasers. That is, above the oscillation threshold, increasing the pump level only increases the average output power and the pulse repetition rate, but does not lead to significant enhancement of the output energy per pulse [14]. To increase the output pulse energy and peak power, one should optimize the reflectivity of the output coupler and the initial transmission of the saturable absorber. However, just as Fig. 4 indicated, the

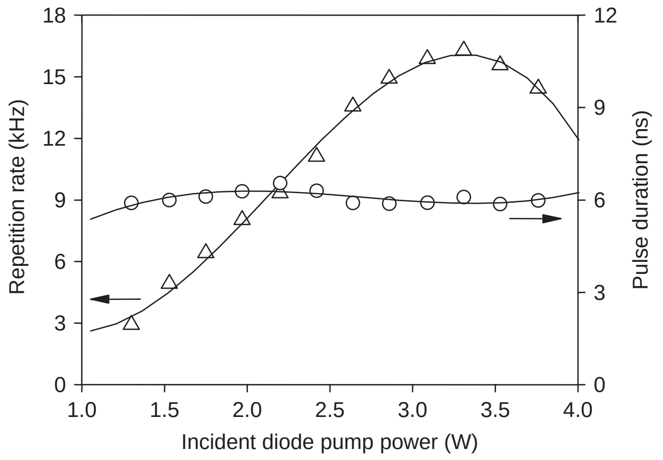

Fig. 3. Pulse duration and repetition rate in function of the incident diode pump power.

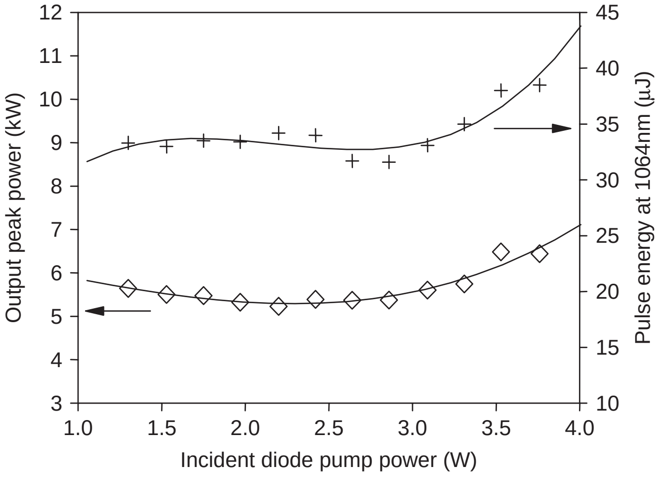

Fig. 4. Pulse energy and output peak power at 1064 nm, with respect to the incident diode pump power.

pulse energy and peak power seem to go up with further increase of the pump power. This phenomenon was caused by the thermally induced fast fall off of the pulse repetition rate (see Fig. 3), since the pulse energy and peak power are inversely proportional to this parameter.

The typical pulse shape and a train of the fundamental pulses detected by a fast InGaAs photodiode and recorded by a LeCroy 9361C Dual 300 MHz oscilloscope are depicted in Fig. 5. According to the theory of passively Q-switched lasers, pulse duration mainly depends on the property of the active medium, the initial transmission of the saturable absorber and the round-trip time of the optical cavity. Given the laser crystal and Q-switcher, the shorter the round-trip time is, the narrower the pulse width becomes. And the round-trip time can be simply calculated as

$$t = \frac{2L}{c}, \tag{3}$$

where c is the speed of the light and L is the optical cavity length defined by [15]

$$L = L^* + l(1/n - 1) + l_s(1/n_s - 1), \tag{4}$$

here L^* is the physical cavity length, l_s and n_s are the length and refractive index of the saturable absorber, respectively. As for this experiment, $L^* = 32\,\text{mm}$, $n_s = n = 1.82$, $l_s = 1\,\text{mm}$, $l = 7\,\text{mm}$. Based on the parameters mentioned above we get $L = 28.4\,\text{mm}$ and $t = 0.19\,\text{ns}$. Considering the round-trip time of 0.19 ns and pulse duration of 6 ns, we are suggested that the deposited energy in the active medium is dumped in about 32 round-trips. As a result, taking advantage of more compact cavity configuration, passively Q-switched lasers with Nd:YAG/Cr:YAG composite structure are perfectly suitable for short pulse and high-peak power performance. In addition, it is seen in Fig. 5(a) that there is a small valley at the tail of the pulse, which was caused by the unoptimized resistance element used in the measuring equipment. And the pulse amplitude and repetition rate fluctuations, as Fig. 5(b) indicated, are well within 10%, exhibiting a very stable passively Q-switched operation.

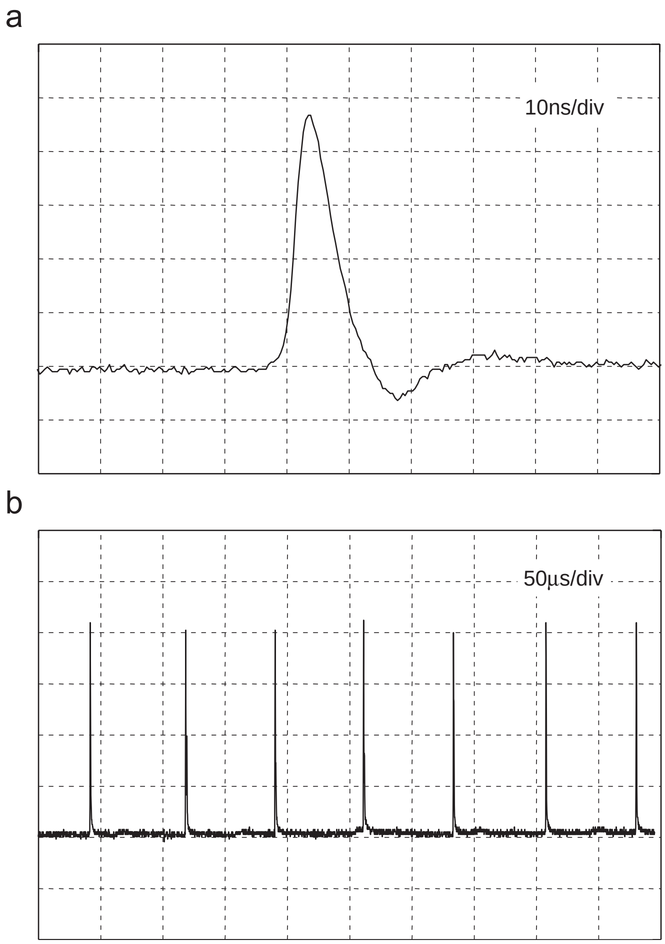

Fig. 5. (a) Temporal profile of the typical fundamental pulses with pulse duration of around 6 ns; (b) a train of the laser pulses, exhibiting stable Q-switched performance.

4. Conclusions

In summary, the lasing performance of a diode-pumped passively Q-switched laser with the relatively new composite material of Nd:YAG/Cr:YAG diffusion bonded structure has been experimentally presented. At the incident pump power of 3.3 W, we obtained 592 mW average output at 1064 nm with an optical-to-optical conversion efficiency of 18%. Efficient passively Q-switched performance with single-pulse energy of 38.5 μJ and pulse duration of 6 ns was also achieved. Experimental results show that Nd:host/Cr:YAG composite structure is a promising material for compact cost-effective Q-switched laser sources with high-peak power and short pulse duration. Moreover, TLE and its impact on the laser performance have been analyzed.

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