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A diode-pumped Cr^{4+}:YAG passively Q-switched Nd:$GdTaO_4$ laser

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ABSTRACT

A diode-pumped Cr^{4+}:YAG passively Q-switched 1066 nm Nd:$GdTaO_4$ laser was demonstrated for the first time to the best of our knowledge. The crystal characteristics of Nd:$GdTaO_4$ was presented. A maximum output power of 3.03 W was obtained at an absorbed pump power of 12.6 W in the continuous-wave (CW) operation, corresponding to a slope efficiency of 28%. The pulsed Nd:$GdTaO_4$ laser performance was investigated theoretically and experimentally. After optimization selection of Cr^{4+}:YAG saturable absorbers, at an absorbed pump power of 12.6 W, the obtained minimum pulse width was ~22 ns with the pulse repetition frequency of 65 kHz, and the single pulse energy and peak power were estimated to be 18.1 μJ and 0.79 kW, respectively. The laser performance can be further improved when a Nd:$GdTaO_4$ crystal with better quality is used.

1. Introduction

Diode-pumped all-solid-state 1.06 μm lasers with high repetition rate and high pulse energy are widely used in many applications such as laser remote sensing, laser processing, laser-induced plasma ignition (LIPI) and laser diagnostics [1–4]. For example, in LIPI, the energy of plasma produced by laser breakdown can be accumulated when a high repetition rate laser is used, and high energy laser pulse can produce high energy plasma. Therefore, a laser with high repetition rate and high pulse energy is beneficial to increase the success probability and reliability of LIPI. Nd^{3+} ion has a typical four energy level structure and emits at 1.06 μm usually. Nd-doped crystals such as Nd:YAG and Nd-doped vanadates (Nd:$GdVO_4$, Nd:YVO_4, and Nd:$LuVO_4$) are adopted as the laser media to produce 1.06 μm laser extensively due to their excellent thermal, mechanical and spectral properties [5–11]. In the periodic table of elements, tantalum (Ta) belongs to of VB group as well as vanadium (V), therefore the characteristics of tantalates are expected. Recently, in the year of 2015, Nd^{3+} doped tantalates of Nd:$GdTaO_4$ single crystal was grown by Czochralski method successfully, and the spectroscopic properties was investigated [12].

Passive Q-switching techniques have the advantages of obviously lower cost, compactness, simplicity in set-up and operation since they do not require external control. Various saturable absorbers such as black phosphorus (BP) and molybdenum disulfide (MoS_2) covering wavelengths from near-infrared to mid-infrared bands have been developed [13–16]. A passively Q-switched mode locking Nd:$GdTaO_4$ laser by MoS_2 saturable absorber was reported in Ref. [17]. Some elementary results were presented in this publication. Cr^{4+}:YAG as one of saturable absorbers has advantages of improved thermo-mechanical properties, large absorption cross section, low saturable intensity and high damage threshold [18–22].

In this paper, a Cr^{4+}:YAG passively Q-switched 1066 nm Nd:$GdTaO_4$ laser was demonstrated for the first time to the best of our knowledge. The crystal characteristics of Nd:$GdTaO_4$ was presented and the continuous-wave (CW) output characteristics with different output couplers were studied. Cr^{4+}:YAG crystal with initial transmission of 90% and 95% were adopted as saturable absorbers. The pulsed Cr^{4+}:YAG/Nd:$GdTaO_4$ laser performance was investigated theoretically and experimentally.

2. Crystal characteristics

Nd:$GdTaO_4$ single crystal was grown by Czochralski method. Raw materials were Nd_2O_3 (6N), Gd_2O_3 (5N), and Ta_2O_5 (4N) powders. The starting materials were weighed with stoichiometric ratio and fully mixed. The initial ratio of Nd^{3+} ion in the raw materials was 2 at%. The mixtures were pressed into pieces, calcined at 1250 °C for 24 h in air and then loaded into iridium (Ir) crucible. The crystal was grown in Nitrogen (N2) atmosphere with a pulling rate of 0.5–1 mm/h and a rotation speed of 5.0–8.0 rpm. There was no volatilization in the process of growth of Nd:$GdTaO_4$. Therefore,

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Table 1
The comparison of spectroscopic properties of $Nd:GdTaO_4$ and Nd:YAG.

Crystals	FWHM (at 808 nm)	σ_a (10^{-20} cm^2) (at 808 nm)	σ_{em} (10^{-19} cm^2) (at 1.06 μm)	τ (μs)	Ref.
$Nd:GdTaO_4$ (a-axe)	6	5.1	3.9	178	[12]
Nd:YAG	1.5	8.3	2.8	230	[23]

compared with other crystals, such as vanadates ($Nd:GdVO_4$, $Nd:YVO_4$, and $Nd:LuVO_4$), it was more easily to control the growth process and obtain a large size $Nd:GdTaO_4$ crystal. The $Nd:GdTaO_4$ samples were cut from transparent part of the as-grown crystal and polished on both sides for measurements. The comparison of spectroscopic properties between $Nd:GdTaO_4$ and Nd:YAG laser crystal is listed in Table 1. It can be seen that the stimulated emission cross section (σ_{em}) of $Nd:GdTaO_4$ is larger than that of Nd:YAG. Compared with the absorption bandwidth (FWHM) of 1.5 nm for Nd:YAG crystal at 808 nm [23], the absorption bandwidth for $Nd:GdTaO_4$ was 6 nm. Therefore, $Nd:GdTaO_4$ is favorable for reducing the demands of pumping source and improving laser efficiency. Furthermore, the upper-level lifetime of 178 μs of $Nd:GdTaO_4$ was smaller than that of 230 μs of Nd:YAG, which is beneficial to produce the high repetition rates lasers. Hence, $Nd:GdTaO_4$ laser has the potential of application in many fields, such as LIPI. Besides, the thermal expansion coefficient of $6.17 \times 10^{-6}\,K^{-1}$ for pure $GdTaO_4$ was lower than that of $7 \times 10^{-6}\,K^{-1}$ for YAG [24,25].

3. Theory analysis

In passively Q-switched laser operation, it is crucial to match the "Q-switched criterion" (the second threshold condition) in order to obtain giant pulses. From analysis of the coupled rate equation, the criterion for a good passive Q-switch was given by [26]:

$$\frac{\ln\left(\frac{1}{T_0^2}\right)}{\ln\left(\frac{1}{T_0^2}\right)+\ln\left(\frac{1}{1-T}\right)+L}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s} > \frac{\gamma}{1-\beta} \tag{1}$$

Table 2
Main parameters used in Eqs. (1) and (2).

Parameter		Value
σ_{em}	Stimulated emission cross section of $Nd:GdTaO_4$ at 1.06 μm	3.9×10^{-19} cm^2 [12]
σ_{gs}	Ground state absorption cross section of Cr^{4+}:YAG at 1.06 μm	8.7×10^{-18} cm^2 [27]
σ_{es}	Excited state absorption cross section of Cr^{4+}:YAG at 1.06 μm	2.2×10^{-18} cm^2 [27]
T_0	Initial transmission of Cr^{4+}:YAG at 1.06 μm	90%, 95%
T	Transmission of the output coupling mirror at 1.06 μm	5%, 10%, 15%
τ	Fluorescence lifetime	178 μs [12]
l	Length of the cavity	40 mm
α	Absorption coefficient	0.56 mm^{-1}

where T_0 is the initial transmission of the saturable absorber, T is the transmission of the output coupling mirror, L is the nonsaturable intracavity round-trip dissipative optical loss, σ_{em} is the stimulated emission cross section of the gain medium, σ_{gs} is the ground state absorption cross section of the saturable absorber, A/A_s is the ratio of the effective area in the gain medium and in the saturable absorber, γ is the inversion reduction factor ($\gamma = 1$ and $\gamma = 2$ correspond to four level and three-level systems, respectively), and β is the ratio of the excited state absorption cross section and the ground state absorption cross section of Cr^{4+}:YAG. In our experiments, no matter which output coupling mirrors with transmission of 5%, 10% and 15% are used, the calculated results for Cr^{4+}:YAG crystals with the initial transmission of $T_0 = 90\%$ and $T_0 = 95\%$ all satisfy the criterion in Eq. (1). The main parameters used in the calculation are listed in Table 2.

The repetition rate in a passively Q-switched laser can be derived from the rate equations. The expression of repetition rate was provided by [28]:

$$f = \frac{1}{-\tau \cdot \ln\left(1 + \frac{\ln\left(T_0^2 R_1 R_2\right)}{2\sigma l \eta \tau \alpha I_p}\right)} \tag{2}$$

where τ is the fluorescence lifetime, l is the length of the cavity, α is the absorption coefficient, I_p is the incident pump intensity (in number of photons per second and per surface unit), R_1, R_2 are the reflection coefficients of the two cavity mirrors respectively, and η is an overlap efficiency factor between the pump beam and the cavity beam which is defined as:

$$\eta = \frac{\left[\iiint_{active} \varepsilon(x,y,z) r(x,y,z) dv\right]^2}{\iiint_{active} \varepsilon(x,y,z)^2 r(x,y,z) dv} \tag{3}$$

where $r(x, y, z)$ and $\varepsilon(x, y, z)$ are the normalized intensity distribution of pump beam and cavity beam, respectively.

4. Experimental setup

The experimental configuration of passively Q-switched Nd:$GdTaO_4$ laser under 808 nm laser-diode end-pumping is shown in Fig. 1. The grown crystal is also shown in the insert of Fig. 1.

The 808 nm diode laser source output was fiber-coupled, and diameter of the fiber was 400 μm and numerical aperture (NA) was 0.22. The maximum output power of the diode laser was

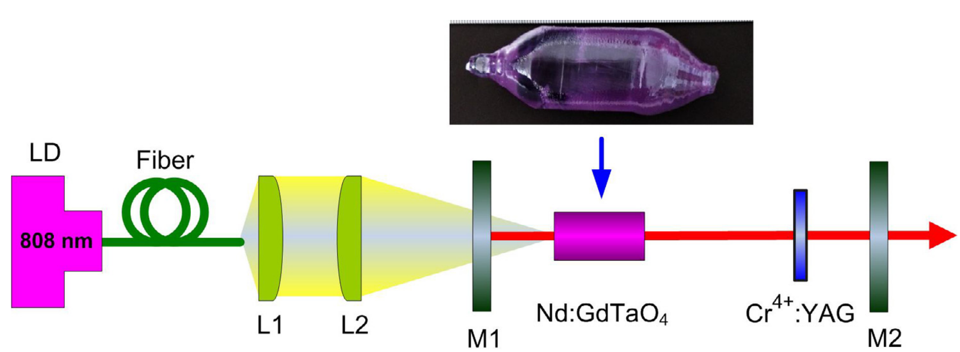

Fig. 1. Experimental setup of the passively Q-switched $Nd:GdTaO_4$ laser.