Analysis of a Laser-Diode End-Pumped Passively Q-Switched Nd:GdVO₄ Laser with V⁢³⁺:YAG Saturable Absorber

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Received September 4, 2008; in final form, September 10, 2008

Abstract—By considering both the transversal and longitudinal Gaussian spatial distribution of the intracavity photon density, a couple of rate equations describing a laser-diode end-pumped passively Q-switched Nd:GdVO₄ laser with V³⁺:YAG saturable absorber have been proposed. Solving these space-dependent rate equations numerically, we obtain the dependences of pulse width, pulse repetition rate, single-pulse energy and peak power on pump power. In the experiment, a laser-diode end-pumped Nd:GdVO₄ laser passively Q-switched by a V³⁺:YAG saturable absorber has been realized, and the experimental results are consistent with the theoretical calculations.

PACS numbers: 42.55.Xi, 42.55.Rz, 42.55.Ah, 42.60.Gd, 42.70.Hj

DOI: 10.1134/S1054660X09030037

1. INTRODUCTION

Laser-diode(LD)-pumped all-solid-state passively Q-switched lasers, due to the advantages of nanosecond order, high repetition rate and visible pulses have wide applications for laser ranging, micro-machining, information storage and remote-sensing, etc. Nd:GdVO₄ crystal is very efficient laser material for diode pumping and it has been shown that it has essential advantages in comparison with Nd:YVO₄ and Nd:YAG [1]. Compared with Nd:YAG crystal, Nd:GdVO₄ has a 7-times higher absorption cross section at 808 nm (σₐ = 5.2 × 10⁻¹⁹ cm²) and a 3-times larger emission cross section at 1.06 μm (σₑ = 7.6 × 10⁻¹⁹ cm²) [2]. Compared with Nd:YVO₄ crystals, Nd:GdVO₄ has a much larger thermal conductivity along the ⟨110⟩ direction at 300 K (about 11.7 W m⁻¹ K⁻¹), which is more than a factor of two higher than that of Nd:YVO₄ and is even higher than that of Nd:YAG crystal [3]. So far, many research has been performed on the diode-pumped CW, Q-switched [4] and mode-locked Nd:GdVO₄ lasers [5].

As for the saturable absorbers, vanadium-doped yttrium aluminium garnet V³⁺:YAG [6, 7] which can work in the range from 1.05 to 1.45 μm [8] has been successfully employed. V³⁺:YAG crystal has different peaks observed in the absorption spectrum, which are attributed to two possible co-ordination sites of the V³⁺ ions: tetrahedral and octahedral. The former one is corresponding to the absorption peak at 1320 nm due to the transition ⁵A₂ → ³T₂(⁵F), which also makes it possible for the passive Q-switching at 1342 nm. The lifetime of the ³T₂(⁵F) level is found to be 22 ± 6 ns [6]. The ground- and excited-state absorption cross sections were calculated to be σₚₐ = (7.2 ± 2.6) × 10⁻¹⁸ cm² and σₑₐ = (7.4 ± 2.8) × 10⁻¹⁹ cm² at 1342 nm, respectively [8]. Up to now, V³⁺:YAG saturable absorber has been successfully employed in many lasers at 1.34 μm, and shown excellent passive Q-switching performance [6–8].

Rate equations are efficient tools for analyzing the performance of a Q-switched laser. But as far as we know, the rate equations obtained under the plane-wave approximation for LD-pumped Q-switched lasers have still been used [9–11]. The plane-wave approximation assumes that the population inversion density and the intracavity photon density within the beam cross section only depend on time. For LD-pumped Q-switched laser, this assumption is not properly satisfied because the fundamental wave is a Gaussian transversal distribution for the TEM₀₀ mode. This assumption leads to large discrepancy in the theoretical calculation of pulse width [12]. When the Gaussian distribution by the spatial variation of the intracavity photon density and initial population within the beam cross section are taken into account in the rate equations, the theoretical results obtained by numerically solving these rate equations are more close to the experimental results than those obtained under the plane-wave approximation [13, 14].

In this paper, we introduce the rate equations of a LD-end-pumped passively Q-switched Nd:GdVO₄ laser with V³⁺:YAG saturable absorber, in which the intracavity photon density is assumed to be Gaussian spatial distribution and the longitudinal variation of the intracavity photon density is also considered. These space-dependent rate equations are solved numerically on a computer. From the numerical solutions, we obtain the dependences of pulse width, pulse repetition rate, single-pulse energy and peak power on pump power. The numerical solutions are consistent with the experi-
mental results obtained from the LD-end-pumped passively Q-switched Nd:GdVO₄ laser with V³⁺:YAG saturable absorber.

2. THEORETICAL CALCULATIONS

We consider the laser depicted in Fig. 1, in which Nd:GdVO₄ works as the gain medium and V³⁺:YAG works as the passive Q-switch. It is longitudinally pumped by a CW laser diode. If the laser runs at TEM₀₀ mode state and the intracavity photon density is assumed to be a Gaussian spatial distribution during the entire formatting process of the LD-pumped actively Q-switched laser pulse, the intracavity photon density \( \phi(r, t) \) for the TEM₀₀ mode can be expressed as

\[
\phi(r, t) = \phi(0, t) \exp \left( \frac{2r^2}{w_f^2} \right),
\]

where \( r \) is the radial coordinate, and \( w_f \) is the average radius of the TEM₀₀ mode, which is mainly determined by the geometry of the resonator; and \( \phi(r, t) \) is the photon density in the laser axis. The photon densities \( \phi_g(r, t) \) at the positions of Nd:GdVO₄ crystal and saturable absorber can be expressed as \[15\], where \( w_g \) and \( w_s \) are the radii of the TEM₀₀ mode at the above-mentioned two positions, respectively. So for this laser, if ignoring the spontaneous radiation during the pulse formation and the V³⁺:YAG saturable absorber is near the output mirror, we can obtain the coupled rate equation.

\[
\int_0^{\infty} \frac{d\phi(r, t)}{dt} 2\pi r dr = \int_0^{\infty} \frac{1}{l_r} 2\sigma n(r, t) l_f \phi_g(r, t) \nonumber - 2\sigma_g n_s(r, t) l_f \phi_s(r, t) - 2\sigma_e [n_{s0} - n_s(t, r)] l_f \phi_s(r, t) \nonumber
\]

\[
- \ln \left( \frac{1}{R} \right) \phi_s(r, t) - L \phi(r, t) \right] 2\pi r dr,
\]

\[
\frac{dn(r, t)}{dt} = R_m(r) - \sigma c n(r, t) \phi_g(r, t) - \frac{n(r, t)}{\tau}, \tag{3}
\]

\[
\frac{dn_s(r, t)}{dt} = \frac{n_{s0} - n_s(r, t)}{\tau_s} - \sigma_g n_s(r, t) \phi_g(r, t), \tag{4}
\]

where \( n(r, t) \) is the average population-inversion density; \( n_s(r, t) \) and \( n_{s0} \) are the ground-state and total population densities of V³⁺:YAG saturable absorber; \( \sigma \) is the stimulated-emission cross section of Nd:GdVO₄ gain medium; \( \sigma_g \) and \( \sigma_e \) are the ground-state and excited-state absorption cross sections of the saturable absorber, respectively; \( l \) and \( l_s \) are the lengths of Nd:GdVO₄ and V³⁺:YAG, respectively; \( t \) is the round-trip time of light in the resonator \( \{ t \} = \{ 2n_{s0} + n_s \} + 2(L - l - l_s)\} / c \); \( n_1 \) and \( n_2 \) are the refractive indices of Nd:GdVO₄ gain medium and V³⁺:YAG saturable absorber, respectively; \( L_s \) is the cavity length; \( c \) is the velocity of light in vacuum; \( R \) is the reflectivity of the output mirror; \( L \) is the intrinsic loss; \( \tau \) is the stimulated-radiation lifetime of the gain medium; \( \tau_s \) is the excited-state lifetime of the saturable absorber; \( R_m = P_m[1 - \exp(-\alpha l)] \exp(-2r^2/w_p^2) \) is the pump rate, where \( P_m \) is the pump power, \( h\nu_p \) is the single-photon energy of the pump light, \( w_p \) is the radius of the pump beam in the gain medium, and \( \alpha \) is the absorption coefficient of the gain medium.

Because the pump light can be approximated by a Gaussian profile, the pumped population density can also be considered to be a Gaussian distribution. For a single pulse of an LD-end-pumped repetitively actively Q-switched laser, the initial population density \( n(r, 0) \) can be assumed to be a Gaussian spatial distribution \[16\]. Thus the initial conditions of Eqs. (3) and (4) can be written as \( n(r, 0) = n(0, 0) \exp \left( \frac{2r^2}{w_p^2} \right) \) and \( n_s(r, 0) = n_{s0} \) \[15\], where \( n(0, 0) = \frac{\ln \left( \frac{1}{R} \right) + \ln \left( \frac{1}{R} \right)}{2\sigma l} \left( 1 + \frac{w_s^2}{w_p^2} \right) \) is the initial population-inversion density in the laser axis, i.e., and where \( T_0 = \exp(-\sigma n_{s0} l_s) \) is the small-signal transmission of the saturable absorber.

Substituting \( \phi_g(r, t), \phi_s(r, t), n(r, 0), \) and \( n_s(r, 0) \) into Eqs. (3) and (4) and integrating the results over time, we obtain

\[
n(r, t) = \exp \left[ -\sigma c \frac{w_p^2}{w_s^2} \exp \left( \frac{2r^2}{w_p^2} \right) \phi(0, t) dt - \frac{t}{\tau} \right]
\]