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Control of the pulse width in a diode-pumped passively Q-switched Nd:GdVO$_4$ laser with GaAs saturable absorber

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Abstract

Different techniques to control the pulse width of a diode-pumped passively Q-switched Nd:GdVO$_4$ laser with GaAs saturable absorber have been studied. It is shown that varying the positions of the saturable absorber in the laser axis and the pump beam waist in the gain medium provides an efficient means to control the pulse width. A rate equation model is introduced to theoretically analyze the results obtained in the experiment, in which the Gaussian spatial distribution of the intracavity photon density, the longitudinal variation of the photon density and the pump beam spatial distribution are taken into account. The numerical calculations of the rate equations are consistent with the experimental results.

Keywords: Pulse width; Passively Q-switched; GaAs; Rate equations; Gaussian spatial distribution

1. Introduction

Diode-pumped solid-state Q-switched lasers have attracted a great deal of attention in recent years [1–5], and have wide applications in the fields of remote sensing, information storage, coherent telecommunications, medicine, etc. Compared with actively Q-switched lasers, the passively Q-switched ones have the advantages of simplicity, compactness, high efficiency and low cost. The main characteristics of the emitted pulses are their width, peak power, and repetition rate. The pulse width and peak power are known to be ruled by the parameters of the gain medium, the saturable absorber, and the cavity. They are thus essentially fixed by laser construction. But applications request the control and adjustment of the pulse width. Theoretical descriptions of passively Q-switched lasers show that the pulse width relies on the pump and laser mode sizes [6]. By varying the laser beam radius in the saturable absorber and the pump beam radius in the gain medium, Lai et al. have studied to control the pulses emitted by passively Q-switched Nd:YAG solid-state lasers with Cr^{4+}:YAG saturable absorber [7]. By varying the pump spot size, changing the cavity length and the pump power in passively Q-switched Nd:YVO$_4$ microchip lasers with semiconductor saturable-absorber mirrors (SESAMs), the pulse width as a function of the effective laser mode area, cavity length and pump power has been discussed, respectively [8].

As a new host material for Nd^{3+} ion, the GdVO$_4$ crystal has been developed by Zagumennyi et al. [9], and Nd:GdVO$_4$ has been experimentally confirmed to be a promising laser medium for diode pumping [10]. It has been shown that Nd:GdVO$_4$ crystals have essential advantages in comparison with Nd:YAG. Nd:GdVO$_4$ has a seven-times higher absorption cross section at 808 nm ($\sigma_a = 5.2 \times 10^{-19}$ cm^2, $E \| c$) and a three-times larger emission cross section at 1.06 μm ($\sigma_e = 7.6 \times 10^{-19}$ cm^2, $E \| c$) [10]. Nd:GdVO$_4$ also has a larger thermal conductivity along the $\langle 110 \rangle$ direction at 300 K (about 11.7 W m^{-1} K^{-1}). During the past few years, diode-pumped Q-switched Nd:GdVO$_4$ lasers have been studied [11–13].

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Semiconductor saturable absorber GaAs has become an attractive candidate for passive Q-switch in diode-pumped solid-state lasers [1–5]. The Q-switching dynamics of GaAs is believed to the result of the photoionization of deep levels, which is about 0.82 eV below the band gap and can arise from the stoichiometric defects in undoped samples [1]. The saturable absorptions of a GaAs wafer include the single-photon absorption (SPA) and two-photon absorption (TPA) as well as free-carrier absorption (FCA). The energy level responsible for absorption around 1 μm is believed to be the EL2 defect (including $EL2^0$ and $EL2^+$) level between conduction and valence bands. EL2 is a defect energy level, i.e., the deep donor level, that exists in undoped GaAs to compensate the shallow acceptors caused by the chemical stain of carbon during the growth of GaAs. Under laser illumination, transitions from EL2 donor to conduction band and from valence band to ionized $EL2^+$ traps take place. The absorption cross sections of $EL2^0$ and $EL2^+$ are $1.0 \times 10^{-16}\,\text{cm}^2$ and $2.3 \times 10^{-17}\,\text{cm}^2$, respectively, which result in a saturation fluence of $1.87\,\text{mJ/cm}^2$ ($EL2^0$) and $8.1\,\text{mJ/cm}^2$ ($EL2^+$) [4]. This is in agreement with other measurements on similar EL2-type defects which also occur in low-temperature (LT) grown GaAs with neutral As antisite, where a saturation fluence of $1.7\,\text{mJ/cm}^2$ was measured [14].

The use of a semiconductor saturable-absorber mirror as a passive Q-switch in a microchip laser is advantageous for several reasons: first, the SESAM is used as an end mirror and has an effective penetration depth of only a few micrometers. Thus we can add a saturable absorber to the microchip laser with only a negligible increase in the cavity length. Therefore we maintain a shorter cavity length and obtain shorter Q-switched pulse widths because the pulse width is directly proportional to the cavity round-trip time. Using the SESAM for Q-switching, pulses as short as 530 ps, 180 ps, and 56 ps in a Yb:YAG, Nd:$LaSc_3(BO_3)_4$ (Nd:LSB), and Nd:YVO_4 microchip laser have been achieved, respectively [15–17]. Indeed, 37-ps pulses have been obtained with a Nd:YVO_4 microchip laser with a SESAM [8]. Second, the band gap of the absorber layer can be adapted to the laser wavelength. It is therefore possible to adapt the system of the absorber to other laser materials at different lasing wavelengths, e.g., at ≈1 μm [16,17], ≈1.3 μm [18], and ≈1.5 μm [19]. Finally, there is enough design freedom to adjust the saturation intensity and the maximum modulation depth independently. Integrating the absorber into a mirror design results in different SESAM designs for which the saturation fluence can be varied between a few $\mu\text{J/cm}^2$ and mJ/cm^2 [19]. These are the absorber parameters that determine pulse width and repetition rate. Thus the pulse width as well as the repetition rate can be designed in a deterministic way over several orders of magnitude. The main disadvantage of the SESAM is that the absorber is grown either by metal-organic chemical-vapor deposition (MOCVD) at normal growth temperature or by molecular beam epitaxy (MBE) at a below-normal growth temperature of 480 °C while in principle the GaAs absorber is much simpler and requires no MOCVD or MBE machines.

In this paper, by translating the saturable absorber along the propagation axis of the laser cavity and varying the position of the pump beam waist in the gain medium, we realize controlling the pulse width in a passively Q-switched Nd:$GdVO_4$ laser with GaAs saturable absorber. To understand the results obtained in the experiment, we introduce a rate equation model in which the Gaussian spatial distribution of the intracavity photon density, the longitudinal variation of the photon density and the pump beam spatial distribution are taken into account. These rate equations are solved numerically and the theoretical calculations agree with the experimental results.

2. Experimental setup and results

The experimental setup is shown in Fig. 1. The pump source is a fiber-coupled laser-diode (made by Semiconductor Institute, Chinese Academic, maximum output power 5 W) which works at the maximum absorption wavelength (808 nm) of the Nd:$GdVO_4$ crystal. The output pump beam from the fiber bundle end, which is 800 μm in diameter, is focused into the laser crystal with a spot size of about 440 μm at the focal plane and far-field half-angle of 18° by a focusing optics. The mirror M_1 with 150-mm curvature radius is high antireflection coated at 808 nm and high reflection coated at 1064 nm. The Nd:$GdVO_4$ crystal doped with 1.0 at.% Nd^{3+} ions is $4 \times 4 \times 5\,\text{mm}^3$. Its front surface is antireflection coated at 808 nm and its rear surface is high antireflection coated at 1064 nm. It is near M_1. The temperature of the Nd:$GdVO_4$ crystal is controlled at 20 °C by means of a temperature controller. The output mirror M_2 is a plane mirror. The distance between M_1 and M_2 is about 12 cm. A TED620B digital oscilloscope (Tektronix Inc., USA) is used to measure the pulse width.

First, by translating the focusing optics at a certain pump power, we obtain the maximum output power when the focal plane of the pump beam in the laser crystal is about 0.8 mm from the pumped end of the gain medium. Keeping this pump position and translating the saturable absorber along the propagation axis of the laser cavity, the dependences of the pulse width on L_0 at different pump

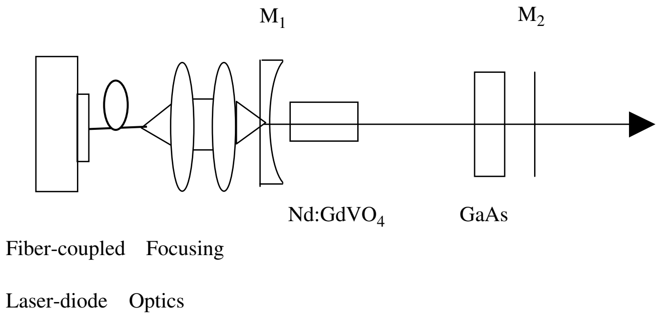

Fig. 1. Schematic of the experimental setup.