Optics and Laser Technology 107 (2018) 424–427

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

# High energy and stable polarized passively Q-switched $Nd^{3+}$:YAG/$V^{3+}$:YAG laser emission at 1444 nm and 722 nm

Hee Chul Lee

*Lutronic Center, 219, Sowon-ro, Deogyang-gu, Goyang-si, Gyeonggi-do, South Korea*

ARTICLE INFO

*Article history:*
Received 3 April 2018
Received in revised form 16 May 2018
Accepted 14 June 2018

*Keywords:*
Lasers
Diode-pumped
Q-switched
$V^{3+}$:YAG

ABSTRACT

A QCW LD pumped linearly polarized Nd3+:YAG/V3+:YAG laser operating at 1444 nm with high peak power of 62 kW is demonstated for the first time. The polarization extinction ratio of the 1444 nm output beam was higher than 1000:1 and the highest second-harmonic generation efficiency at 722 nm was 62.8%. A compact high-peak-power polarized Nd:YAG laser can be used as the master oscillator for a high energy system. In particular, a 722 nm laser is a viable source for biomedical applications such as photoacoustic imaging, oximetry, and tattoo removal.



## 1. Introduction

Passive Q-switching is an important method for short pulse and high-peak-power microchip laser systems, since it does not require additional complicated controllers. It can also shorten pulse duration and enhance pulse energy by a short cavity configuration. However, compared with an actively Q-switched laser, the polarization of a passively Q-switched $Nd^{3+}$:YAG/$Cr^{4+}$:YAG microchip laser output is unstable and uncontrollable. Therefore, it is not suitable for some applications, such as microprocessing, remote sensing, ranging, and efficient wavelength conversion [1–5].

The use of a V:YAG saturable absorber as a Q-switch for diode-pumped lasers with various laser active medium has been reported [6–10]. However, $Nd^{3+}$:YAG laser operation in the 1400 nm region has been reported by only two groups previously [11,12]. Q-switched output pulses of 50 ns pulse width and pulse energy of 24 μJ at a repetition rate of 60 kHz were reported in [11]. Pulse width and pulse energy of 4.2 ns and 34 μJ, respectively, under a pulse repetition rate of 1.5 kHz were reported in [12] based on a composite crystal, which consists of a 4-mm-long $Nd^{3+}$:YAG active medium and a 1-mm-long $V^{3+}$:YAG saturable absorber.

Lasers have a wide range of applications in medicine, both in surgery and diagnostics. In the spectral range with wavelengths larger than 1400 nm, cornea and water have high absorption coefficients; thus, minimal energy is transmitted to the retina. Therefore, wavelengths larger than 1400 nm are called the eye-safe region. Laser operation at approximately 1450 nm can be used for surgery and blood coagulation because water and collagen absorption strongly increase at 1450 nm. Moreover, it can also be used for remote sensing of water vapor [13–15]. In addition, 722-nm lasers have important applications in the biomedical field, such as photoacoustic imaging. Photoacoustic imaging, also called optoacoustic imaging, is a diagnostic technique based on the detection of acoustic waves induced in tissue by the absorption of electromagnetic radiation, usually from pulsed sources on a nanosecond timescale. Experimental results show that approximately 710 nm is an optimal wavelength to construct photoacoustic images of microcalcifications in breast tissue [16–19].

In our experiment, highly stable polarized output was obtained by using [1 0 0] cut $V^{3+}$:YAG and Brewster angle cut $Nd^{3+}$:YAG and YAG. The maximum output energy at 1444 nm and 722 nm were as high as 636 μJ and 383 μJ, respectively, corresponding to a conversion efficiency of IR to deep red of 62.8%. The minimum pulse width of the 722 nm was 8.3 ns. To the best of our knowledge, this is the first report of pulse generation with a few tens of kilowatt level peak output power at the 1444 nm and the deep red spectral region of 722 nm from a compact microchip laser.

## 2. Experimental setup

A fiber-coupled LD with a core diameter of 600 μm, a 120-W quasi-continuous wave (QCW), and a center wavelength of 808 nm was used as the end-pump source. The temperature of the LD was maintained at 25 °C ± 0.01 °C by using a temperature controller [Thorlabs TED4015]. Two lens pairs were used for collimation of the pump beam emitted from the optical fiber and the

*E-mail address:* hclee@lutronic.com

https://doi.org/10.1016/j.optlastec.2018.06.031
0030-3992/

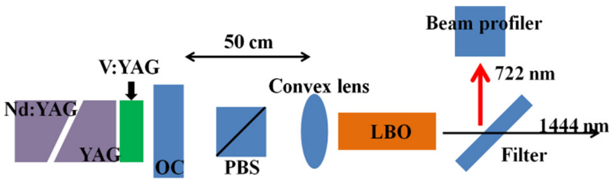


**Fig. 1.** Experimental setup. PBS : Polarization Beam Splitter.

collimated pump beam was focused by an f = 50 mm convex lens, producing a focused spot size of 900 μm (the lens pairs were not shown in Fig. 1). The pumping pulse width was fixed at 200 μs. The flat side of the Brewster angle cut $Nd^{3+}$:YAG laser crystal was coated to achieve a reflectivity (R) of 99.5% at 1444 nm, 30% at 1064 nm, and 50% at 1319 nm. The flat side of the Brewster angle cut YAG was coated to obtain R = 0.5% at 1064–1444 nm [20]. An output coupler (OC) with R value of 80% at 1444 nm and R value of 5% at 1064 nm and a radius of curvature of −3 m was used in the experiments. Both sides of the $V^{3+}$:YAG [Lasertec Inc] were coated for R value of 0.5% at 1444 nm. The center thicknesses of the $Nd^{3+}$:YAG (1% doped) and YAG crystals were 8 mm and 5 mm, respectively. The absorption coefficient of the $Nd^{3+}$:YAG at 808 nm is 4.3 $cm^{-1}$ [21]. Therefore, it is obvious that the pump power can be fully absorbed in our work. Initial transmissions (T) of 74.8%, 81.1%, and 85.6% [1 0 0] cut $V^{3+}$:YAG were employed as a passive Q-switcher to investigate Q-switching characteristics and their lengths were 5.4 mm, 4 mm, and 3 mm, respectively. All crystals were mounted in a copper block and their temperatures were not controlled. The cavity length was 20.5 mm. However, the optical cavity length was changed due to the difference in the thickness of the $V^{3+}$:YAG at T, which can affect the output pulse width and output energy. A cube PBS (polarization extinction ratio >1000:1) was installed in front of the OC to check the polarization state stability and the polarization extinction ratio. An $LiB_3O_5$ crystal (lithium triborate, LBO, θ = 90°, Φ=2.2° at a temperature of 310 K, dual-band anti-reflection coating at 722 nm and 1444 nm) with dimensions of 3 mm × 3 mm × 10 mm was used as a frequency doubler. To avoid measuring the unconverted fundamental energy of the 1444 nm, a 45° filter (R = 95%@722 nm, T = 99%@1444 nm) was placed after the LBO. The measured energy in this study was not compensated for filter loss.

## 3. Results

The emission spectrum of the $Nd^{3+}$:YAG/$V^{3+}$:YAG laser presented in Fig. 2 clearly shows a single wavelength output at 1444 nm.

The [1 0 0] axis cut $V^{3+}$:YAG has a high capability to generate a linearly polarized output beam [12]. However, due to its weak natural birefringence, it is not suitable for a commercial laser system, which requires polarization direction maintenance. A linearly polarized output was reported using a wedged diffusion-bonded Nd:YAG/$Cr4^{+}$:YAG laser that was realized through the small index difference of 0.05 between Nd:YAG and Cr:YAG [22]; however, the index difference was not enough to make a high polarization extinction ratio. Therefore, the direction of the [1 0 0] axis of the $V^{3+}$:YAG was designed parallel to the horizontal polarization. The two Brewster-angle-cut crystals and the crystal axis of the $V^{3+}$:YAG facilitate highly stable polarization outputs [23]. During a 60-min operation with 50-Hz repetition rate, a measured polarization extinction ratio greater than 1000:1 and energy instability (=(max − min)/average) less than 7% were obtained when a T value of 74.8% V:YAG was used. The instability was less than 3% if we ignore the first 10 s of the operation. Since we did not have a beam profiler for the 1444-nm wavelength, the beam quality of the

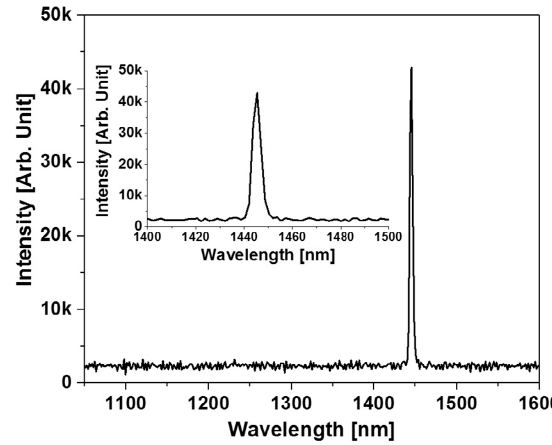


**Fig. 2.** Output spectrum of 1444 nm laser.

1444-nm output was evaluated by its SHG beam. This will be discussed in the next section.

The output energy, average power, and pulse width for three types of $V^{3+}$:YAG with various repetition rates are shown in Fig. 3. The pulse width was measured using a high-speed InGaAs PD (rise time <30 ps). The required pumping energy values to obtain Q-switched pulses were 22.1 mJ, 25.1 mJ, and 31.1 mJ for T values of 85.6%, 81.1%, and 74.8% $V^{3+}$:YAG, respectively. A maximum output energy of 633 μJ with 10 Hz operation was obtained when a T value of 74.8% $V^{3+}$:YAG was used. The rate of decrease of the output energy for each repetition rate was highest when the other two $V^{3+}$:YAG crystals were used. The output energy difference between the 10 Hz and 50 Hz operations for T values of 85.6%, 81.1%, and 74.8% $V^{3+}$:YAG were 6%, 14.2%, and 19.8%,

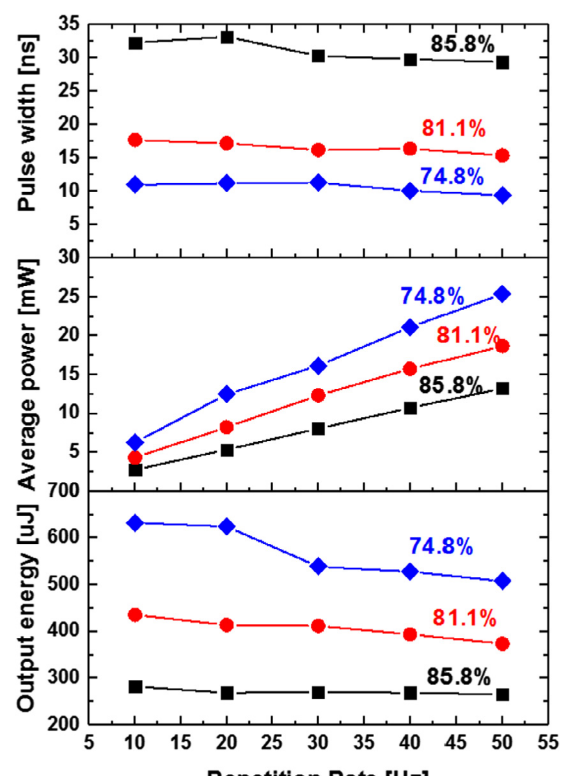


**Fig. 3.** Q-switched output energy, average power and pulse width of three types of $V^{3+}$:YAG with various repetition rates.