E. Räikkönen, O. Kimmelma, M. Kaivola, and S. C. Buchter. 2008. Passively Q-switched Nd:YAG/KTA laser at 561 nm. Optics Communications, volume 281, numbers 15-16, pages 4088-4091.

Optics Communications 281 (2008) 4088–4091

Contents lists available at ScienceDirect

Optics Communications

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

Passively Q-switched Nd:YAG/KTA laser at 561 nm

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ARTICLE INFO

Article history:
Received 30 January 2008
Received in revised form 7 April 2008
Accepted 7 April 2008

PACS:
42.55.Xi
42.60.Gd

Keywords:
Lasers solid-state
Lasers Q-switched
Cr:YAG

ABSTRACT

We demonstrate a compact diode-pumped passively Q-switched Nd:YAG laser operating at the wavelength of 1123 nm, and its frequency-doubling into 561 nm by using a KTA crystal. The laser makes use of a single emitter 2.5 W laser diode, and at 561 nm puts out a 12 kHz pulse train of 4 ns, 5 μJ pulses with an average power of 55 mW. The high pulse energy of the 1123 nm laser allows us to study the saturation of 1123 nm absorption in the Cr^{4+}:YAG Q-switch crystal. The ratio of the ground-state and excited-state absorption cross-sections is found to be $\sigma_{GSA}/\sigma_{ESA} = 5.5 \pm 0.9$.

1. Introduction

Neodymium-doped aluminium yttrium garnet (Nd:YAG) is one of the most widely applied laser crystals due to its favourable combination of mechanical and thermo-optical properties. The laser transitions of Nd:YAG occur in three groups, taking place between the Stark levels of the upper laser state $^4F_{3/2}$ and the lower laser states $^3I_{13/2}$, $^3I_{11/2}$, and $^3I_{9/2}$. The main laser lines are at 1318 nm, 1064 nm, and 946 nm, respectively [1]. The weaker transitions have recently become accessible in practical lasers thanks to the development of high-brightness laser diodes for pumping and advances in thin film fabrication for the cavity mirrors. The least energetic transition in the manifold $^4F_{3/2} \rightarrow {}^3I_{11/2}$ corresponds to the wavelength of 1123 nm, allowing second-harmonic to be generated into the yellow-green region of the visible spectrum at 561 nm. Yellow laser light has important applications, e.g., in medical technology [2,3]. Furthermore, the wavelength of 561 nm is very close to the sensitivity peak of the human eye, so that highly visible, yet low power laser beams can be achieved.

Lasers utilizing the 1123 nm transition in Nd:YAG have been demonstrated in CW-operation [4], and in pulsed mode using both active and passive Q-switching [5–7]. The two main choices for passive Q-switches at around 1 μm are Cr^{4+}-doped crystals such as Cr^{4+}:YAG and semiconductor saturable absorption mirrors (SESAM). The main benefit of Cr^{4+}:YAG is its simplicity as bulk crystal with broadband absorption. However, it has some wavelength dependent nonsaturable loss that can be detrimental for a low gain laser [8]. SESAMs can have smaller nonsaturable loss [7], but in turn they are more elaborate to fabricate since they have to be customized for the specific wavelength.

The Q-switching efficiency of Cr^{4+}:YAG at 1123 nm has been reported to be poor [5,7], but the reason for that remained unexplained. In this article we show that Cr^{4+}:YAG is indeed well suited for passive Q-switching at 1123 nm. We demonstrate a compact, multiple kilowatt peak-power, diode-pumped passively Q-switched Nd:YAG laser operating at the wavelength of 1123 nm, and double its frequency into 561 nm with 23% efficiency using a single-pass KTA crystal. The saturation properties of the Cr^{4+}:YAG crystal at 1123 nm are studied using the Z-scan method, and the ratio of the ground and excited-state absorption cross-sections, $\sigma_{GSA}/\sigma_{ESA}$, is found to be 50% larger than at 1064 nm.

2. Guidelines of laser design

The main design objective of a pulsed, single-pass frequency-doubled laser is the peak power of the pulse at the fundamental wavelength, on which the efficiency of the second-harmonic generation (SHG) strongly depends. In a passively Q-switched laser, high peak power is most efficiently produced by extracting the pulse from a resonator with a short length and hence a small mode volume. This requires the use of a high-brightness laser diode in

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0030-4018/$ - see front matter
doi:10.1016/j.optcom.2008.04.016

the end-pumping configuration. The gain at 1123 nm in Nd:YAG is rather low, the stimulated emission cross-section being only one 15th of the value at 1064 nm [1]. Passively Q-switching a low-gain laser requires a careful balance between the output coupling and the Q-switching modulation in order to keep the intracavity intensity below the damage threshold of the mirror coatings. At the same time, the laser should be able to reach threshold with the available pump power. The value for the output coupling was calculated by assuming an output pulse of 5 kW peak power, an $1/e^2$-mode waist of 100 μm, and a damage threshold of 300 MW/cm^2. With some safety margin, a value of $T_{OC} = 10\%$ was chosen. In order to reach to the design peak power, the unsaturated transmission of the Cr^{4+}:YAG Q-switch was chosen to be $T_0 = 96\%$ based on our experiments with a similar low-gain Q-switched laser operating at the 946 nm transition in Nd:YAG [9].

The low gain of Nd:YAG at 1123 nm also requires suppression of the competing laser transitions at 1064 nm, 1112 nm, 1116 nm, and 1318 nm [1]. The gain at 1318 nm is even lower than at 1123 nm, but that transition must be taken into account because of the low absorption of the Cr^{4+}:YAG saturable absorber at around 1.3 μm [10]. The 1064 nm and 1318 nm transitions can easily be suppressed by using multi-layered high-transmission coatings in the cavity mirrors. However, it can be problematic to use the same principle for the 1112 nm and 1116 nm transitions, because they are so close to 1123 nm in wavelength [1]. Fortunately, the 1123 nm transition is preferred in Q-switched operation due to the local maximum of absorption in Cr^{4+}:YAG at 1114 nm [10].

The nonlinear crystal for SHG at 1123 nm was chosen to be $KTiOAsO_4$ (KTA). A more familiar example of the same crystal family is $KTiOPO_4$ (KTP) that is widely applied to frequency-doubling of Nd-lasers emitting at above 1 μm. The properties of KTA for SHG at 1123 nm are similar to those of KTP at 1064 nm, i.e. it has a very small walk-off angle (3 mrad) and a high effective nonlinearity (3.2 pm/V). Moreover, KTA has a higher damage threshold than KTP, and it does not suffer from the gray-tracking damage [11–13]. KTP can also be phase-matched for SHG at 1123 nm, but it has a larger walk-off angle (25 mrad) between the ordinary and extra-ordinary rays, resulting in a reduced conversion efficiency and in an elliptical beam at the second-harmonic wavelength.

The SHG in KTA is based on type-II birefringent phase-matching. The process is thus most efficient for linearly polarized light at the fundamental wavelength. However, the crystal structure of Nd:YAG is isotropic, so that it emits unpolarized light if no anisotropy is introduced in the laser. Polarized laser output can be most easily obtained by using a bare laser diode as the pump source. A single-emitter laser diode puts out polarized light in a rectangular beam, both of which induce anisotropy in the laser crystal and thereby favour polarized laser output [14,15]. Alternatively, a Brewster plate could be used in the laser cavity, but it would be an extra component just increasing the cavity length.

3. Experimental setup

The laser crystal is 1%-doped Nd:YAG with dimensions of $3 \times 3 \times 3$ mm^3. The first surface has a multi-layer dielectric coating with high-reflection at 1123 nm, anti-reflection at 808 nm, and high-transmission ($T > 80\%$) at the wavelengths of 1064 nm and 1318 nm. The second surface is anti-reflection coated for 1123 nm. The Q-switch is an anti-reflection coated piece of Cr^{4+}:YAG with an initial transmission of 96% at 1123 nm and dimensions of $3 \times 3 \times 0.35$ mm^3. The output coupling mirror has a radius of curvature of 15 cm. The first surface is coated for a reflectivity of 90% at 1123 nm and for high-transmission ($T > 90\%$) at 1064 nm and 1318 nm. The second surface is anti-reflection coated for 1123 nm. The cavity length is 5 mm. The laser crystal is pumped using a single-emitter laser diode with a maximum output power of 2.5 W and an operating wavelength of 808 nm. The emitter size is 1×100 μm^2. The pump light is collimated and imaged into the laser crystal by a pair of high numerical aperture (NA = 0.55) aspheric lenses with focal lengths of 8 mm and 10 mm, respectively. The pump spot is thus highly asymmetric. Cooling of the laser crystal is achieved by wrapping the crystal in indium foil, and mounting it in a thermo-electrically cooled copper block kept at the temperature of 10 °C. The single-pass second-harmonic generation takes place in a 5 mm long KTA crystal that is anti-reflection coated for 1123 nm on the first surface and for 561 nm on the second surface. Measured in free space, the size of the focal spot (FWHM) for SHG is 28 μm. The laser setup is shown in Fig. 1.

The average power of the laser is measured using an Ophir Optronics 3A low power thermal head. A filter made of Schott RG850 glass is used to block the unabsorbed 808 nm pump light, when measurements at 1123 nm are made. The SHG power at 561 nm is measured through a Schott BG40 glass filter. The time characteristics of the laser output are analyzed using a 1 GHz oscilloscope (Tektronix TDS 5104) connected to a photo detector with a rise time of 1 ns (Thorlabs DET-100). The beam quality measurements are done using an Ophir Beamstar FX-50 beam profiler camera equipped with a 4X beam expander.

4. Experimental results

The average power of the laser was measured as a function of the absorbed pump power for both CW (1123 nm) and Q-switched modes (561 nm and 1123 nm) of operation. The results are shown in Fig. 2. The slope efficiency in the infrared is 39% in the CW-mode and 27% in the Q-switched mode when the Cr^{4+}:YAG saturable absorber is inserted into the cavity. At 561 nm, the slope efficiency is 6.5%, corresponding to a conversion efficiency of 23% from the

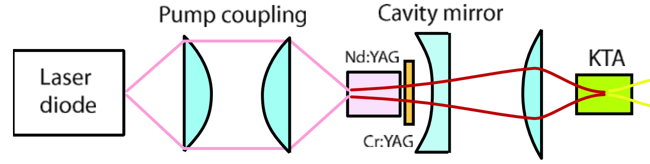

Fig. 1. Schematic figure of the diode-pumped passively Q-switched Nd:YAG/KTA laser.

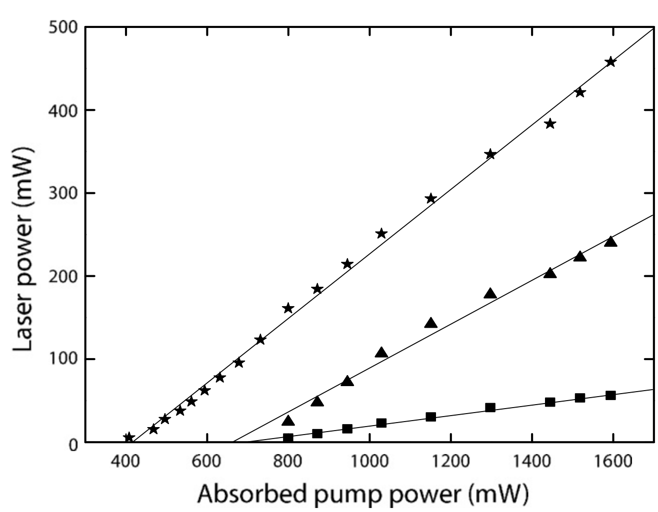

Fig. 2. Laser average power as a function of absorbed pump power for 561 nm Q-switched (■), 1123-nm Q switched (▲), and 1123 nm CW (★) lasers.

fundamental into the second harmonic. The polarization ratio at the fundamental wavelength was measured using a linear polarizer, and it was found to be 0.8. The SHG efficiency could thus be further increased by improving the polarization ratio closer to one. The beam quality factor at 561 nm was determined to be $M^2 = 1.1$ by using the second moment method [16].

The repetition rate of the laser is shown as a function of the absorbed pump power in Fig. 3, together with the pulse energy calculated from the average power. The pulse energy stays fairly constant as a function of the pump power, as expected for a passively Q-switched laser, and it is 5 μJ at 561 nm and 20 μJ at 1123 nm. The oscilloscope trails of the pulses at 561 nm and 1123 nm are shown in Fig. 4. The pulses are almost symmetrical in shape, indicating that the output coupling of the laser is high enough. The pulse length is 4.3 ns at 561 nm and 5.5 ns at 1123 nm. Taking into account the pulse energy, the peak power of the pulse is 1 kW at 561 nm and 3.5 kW at 1123 nm. The stability of the pulse train was typical to a passively Q-switched laser. The amplitude fluctuations were negligible at the lasing threshold and increased as a function of the pump power. At 40 mW of output power in the yellow we measured a pulse-to-pulse amplitude fluctuation of ±5%.

In order to make sure that 1123 nm is the only wavelength lasing in the infrared, the output spectrum of the Q-switched and frequency-doubled laser was measured with an ANDO AQ-6315E optical spectrum analyzer. Lines at only 561 nm and 1123 nm could be observed, as shown in the spectrum in Fig. 5. Unexpectedly, running the laser without the Q-switch did not excite the

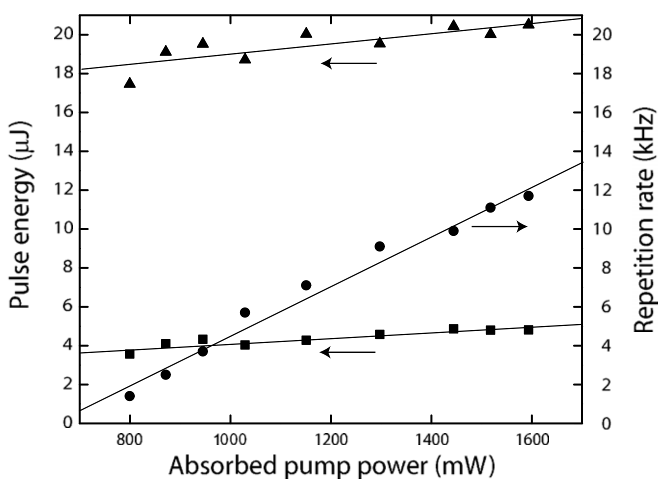

Fig. 3. Repetition rate (●) and pulse energy at 561 nm (■) and 1123 nm (▲) as a function of the absorbed pump power.

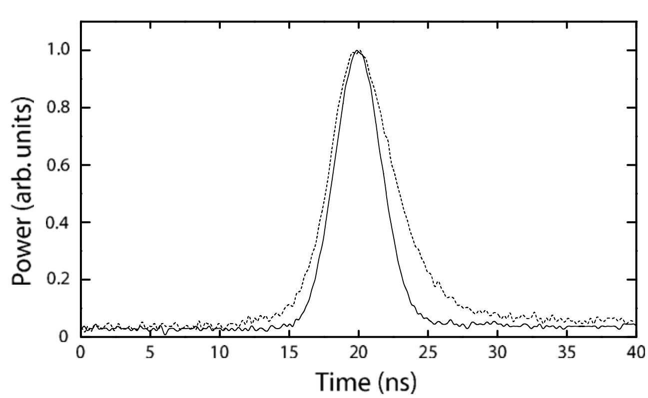

Fig. 4. Oscilloscope traces of pulses at 561 nm (solid) and 1123 nm (dashed).

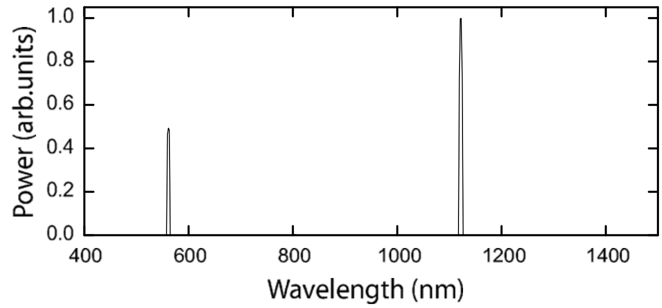

Fig. 5. Measured spectrum of the Nd:YAG/KTA laser.

competing laser lines at 1112 nm and 1116 nm. The result is accounted for the higher loss (∼2%) at 1112 nm and 1116 nm due to the high-transmission coatings of the cavity mirrors designed for 1064 nm.

5. Saturation of Cr^{4+}:YAG at 1123 nm

Saturable absorbers always have some nonsaturable loss that decreases the laser efficiency. In terms of laser operation, the figure of merit is the ratio of the saturable loss to the nonsaturable loss [17]. The major part of the nonsaturable loss in Cr^{4+}:YAG crystal is caused by excited-state absorption that takes place at the same wavelength as the saturable ground-state absorption. The ratio of the ground-state absorption cross-section σ_{GSA} to the excited-state absorption cross-section σ_{ESA} is given by

$$\frac{\sigma_{GSA}}{\sigma_{ESA}} = \frac{\ln T_0}{\ln T_{sat}}, \tag{1}$$

where T_0 and T_{sat} are the unsaturated and (ground-state) saturated transmission of the Cr^{4+}:YAG, respectively [8]. A sample of Cr^{4+}:YAG crystal manufactured by Dayoptics Inc. was measured in the through-the-focus Z-scan configuration. The laser beam was divided into two arms to allow for a reference measurement of the power incident on the crystal. The measurement setup in illustrated in Fig. 6. As the source we used the 1123 nm laser reported in this article. The same sample was also measured using a 1064 nm laser with identical pulse characteristics, so that a comparison to previously published results could be made.

The initial and saturated transmission were measured in the focal plane of the lens (L) with CW and pulsed beams, respectively. Sufficient saturation of the sample was ensured by selecting the spot size so that the saturated transmission was constant for a focal depth of several times the length of the sample. This could be done because the saturated transmission of Cr^{4+}:YAG is constant for an intensity range of two orders of magnitude if nanosecond pulses are used [8].

The measured initial and saturated transmissions, and the calculated ratios of the cross-sections are given in Table 1. At 1123 nm, the ratio was found to be $\sigma_{GSA}/\sigma_{ESA} = 5.5 \pm 0.9$. For the reference measurement at 1064 nm we got the value

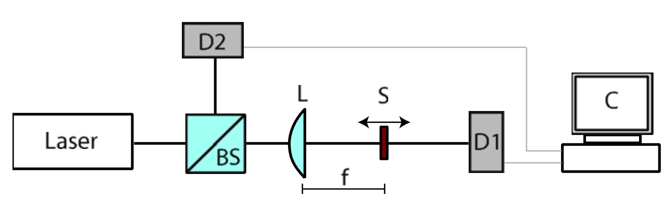

Fig. 6. Setup for measuring the saturation of Cr^{4+}:YAG. D1 = power meter for transmitted light, D2 = reference power meter, BS = beam splitter, L = focusing lens, S = Cr^{4+}:YAG sample, and C = computer for data logging.

Table 1
Initial transmission T_0 and ground-state saturated transmission T_{sat} in the Cr^{4+}:YAG sample at 1123 nm and 1064 nm

Wavelength (nm)	T_0	T_{sat}	$\sigma_{GSA}/\sigma_{ESA}$
1123	0.962 ± 0.001	0.993 ± 0.001	5.5 ± 0.9
1064	0.939 ± 0.002	0.983 ± 0.001	3.7 ± 0.3

$\sigma_{GSA}/\sigma_{ESA} = 3.7 \pm 0.3$, which is in very good agreement with the result reported by Ridderbusch et al. [8]. The nonsaturable loss of the Cr^{4+}:YAG Q-switch at 1123 nm is thus significantly lower than at 1064 nm.

6. Summary

We have demonstrated a compact diode-pumped 1123 nm Nd:YAG laser, that is passively Q-switched using a Cr^{4+}:YAG saturable absorber and single-pass frequency-doubled into 561 nm by using a KTA crystal. The laser is pumped with a single-emitter 2.5 W laser diode, and at 561 nm it puts out a 12 kHz pulse train with an average power of 55 mW, a pulse length of 4 ns, and a pulse peak power of 1 kW. The peak power of the laser is high enough for future applications in nonlinear optics.

The saturation of the 1123 nm absorption in Cr^{4+}:YAG crystal was studied, and the ratio of the ground-state absorption cross-section to the excited-state absorption cross-section was found to be $\sigma_{GSA}/\sigma_{ESA} = 5.5 \pm 0.9$. This ratio is 50% larger than at 1064 nm, increasing the efficiency of the 1123 nm laser due to the smaller amount of nonsaturable loss in the Q-switch. The result is also supported by the high Q-switching efficiency of the laser demonstrated in this paper.

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