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Tunable, passively Q-switched single-longitudinal-mode Nd:YVO_4 laser using a chirped volume Bragg grating

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Abstract A Nd:YVO_4 laser was locked with a chirped volume Bragg grating to achieve single-longitudinal-mode output. Tuning was performed from 1,063 to 1,065 nm by translating the grating and a maximum output power of 4 W was obtained. With a Cr^{4+}:YAG saturable absorber, Q-switched pulses with 4 ns and a pulse energy of 5.7 μJ were achieved which could be frequency doubled in PPKTP with a conversion efficiency exceeding 50 %.

1 Introduction

Passively Q-switched solid-state lasers running on a single-longitudinal mode (SLM) around 1.06 μm have applications in spectroscopy, material characterization and frequency conversion, as they provide high peak power with a well-defined laser spectrum. Nd:YVO_4 is an attractive laser medium with favorable properties like high absorption and emission cross-sections and wide absorption bandwidth, which allows for efficient pumping by laser diodes. Moreover, the-emission is polarized, which facilitates efficient frequency conversion. The most common ways to obtain SLM output from solid-state lasers are using unidirectional ring cavities [1, 2], microchip lasers [3, 4] or the twisted-mode technique [5, 6]. SLM output can also be achieved in other laser types such as VECSEL [7] or fiber lasers using fiber-Bragg grating feed-back [8], but in those cases the laser is not Q-switched. All these lasers use multiple intra-cavity elements to achieve SLM operation (e.g. ring cavities) or have a monolithic design (e.g. microchip lasers), which limits the addition of further features such as tuning.

Volume Bragg gratings (VBG) written in photo-thermo-refractive (PTR) glass [9] have lately been used to provide compact and simple solutions for spectral control and tuning of solid-state lasers [10], optical parametrical oscillators [11] and fiber lasers [12]. Depending on the VBG spectral response, the lasers can run on single frequency or on several modes. In the first case, fine tuning of the wavelength can be obtained by tuning the cavity length with a piezo-element [13] or by temperature tuning of the VBG [14]. Wide tuning was demonstrated by placing the VBG in a retro-reflector configuration, while still maintaining narrow linewidth operation [15]. Recently it has been shown by Pavel et al. [16] that VBGs can be used to enhance the performance of Q-switched lasers, as well as to tune the laser wavelength by temperature adjusting the VBG.Transversely chirped gratings (CVBG) can also be used for wavelength tuning. For these the Bragg condition changes over the aperture, because of the fan structure of the Bragg-planes, and the tuning is obtained by lateral translation of the grating. This has been demonstrated for a distributed feedback dye laser [17], a semiconductor laser [18], an optical parametric oscillator [19] and in our recent work with a diode-pumped Yb:KGW laser [20].

In this work we utilize a CVBG to tune a diode pumped Nd:YVO_4 laser in a simple, linear and compact plane–plane cavity using only two, or three, elements to form the laser. In the latter case a Cr^{4+}:YAG saturable absorber was used to obtain passive Q-switching. Up to 4 W of output power was obtained with a tuning range of 2 nm for continuous wave (cw) operation and 1.08 W of average power in the Q-switched regime with a pulse length of 3.9 ns and a repetition rate of 150 kHz 1064.1 nm. When Q-switched

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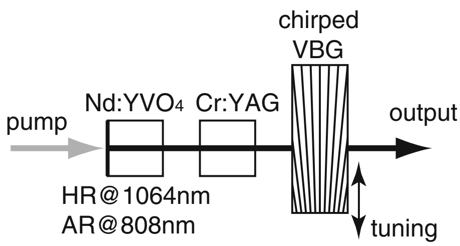

Fig. 1 Experimental setup

the laser runs SLM and frequency doubling using a 1-cm-long PPKTP crystal with a grating period of 9.01 µm resulted in an average power of 547 mW at 532 nm.

2 Experiment and discussion

The laser crystal used was an a-cut 1 at% Nd:YVO_4 with the dimensions 3 × 3 × 3 mm^3. On the pump side it was HR coated for the lasing wavelength at 1,064 nm and anti-reflection (AR) coated for the pump wavelength at 808 nm, while the opposite side was AR coated for both the pump and the lasing wavelengths. A fiber coupled diode laser at 808 nm with a 100-µm core diameter and a numerical aperture of 0.22 was used as the pump and it was focused into the crystal with a beam waist of ~130 µm $1/e^{-2}$ radius. The laser cavity was formed by the HR-coated input surface of the laser crystal and the chirped VBG, see Fig. 1. The total cavity length was 8 mm, hence a 3 × 3 × 3 mm^3 Cr^{4+}:YAG saturable absorber with an initial transmission of 65 % could easily be inserted into the cavity for the Q-switching experiments. The saturable absorber was AR coated on both sides for the lasing wavelength. The chirped VBG (CVBG) had a tuning range from 1,054 to 1,065 nm with a chirp-rate of 0.81 nm/mm. The reflectivity was reduced from approximately 75 % at the shortest wavelength to 20 % at the longest wavelength, see Fig. 5. With a beam size of 100 µm in the cavity the linewidth was below 0.1 nm.

Tuning was obtained by translating the CVBG orthogonally to the optical axis of the cavity and the output power was optimized by slight realignment in every point. The laser emission was linearly polarized and the wavelength could be continuously tuned between 1,063 and 1,065 nm with a maximum power of 4 W at 1064.5 nm using the available pump power of 15 W, see Fig. 2. At this wavelength the threshold was 2.3 W and the slope efficiency 31 %.

For pulsed operation the Cr^{4+}:YAG was inserted to obtain passive Q-switching. The performance depended on the transverse position of the VBG, i.e. the operating laser wavelength. The key parameters for the Q-switched laser

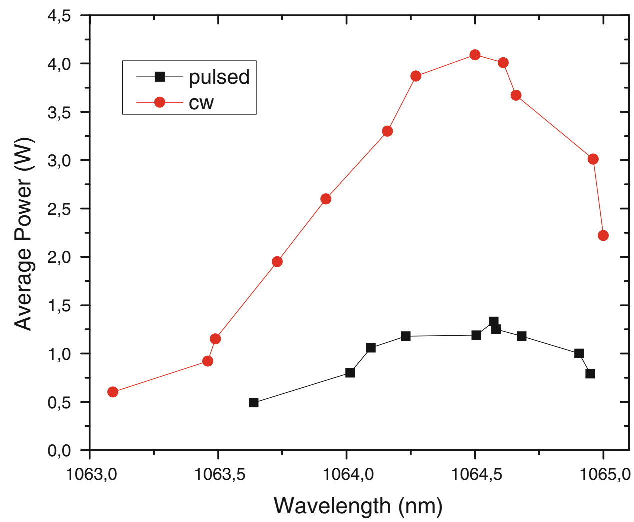

Fig. 2 Laser output power versus operating wavelength in the CW and pulsed regime, at 15 W of pump power, when the VBG is translated

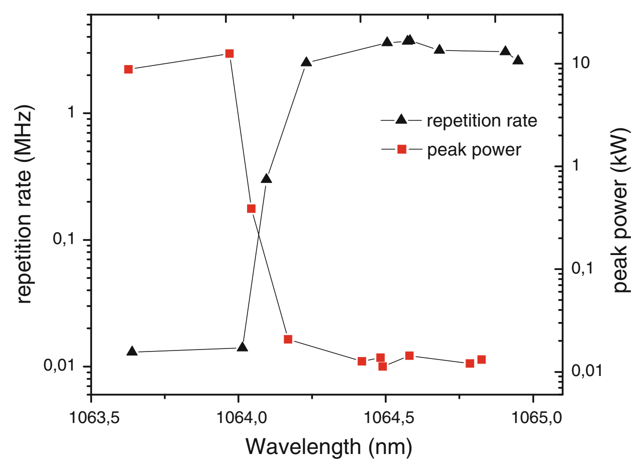

Fig. 3 The repetition rate and peak power as a function of wavelength for the Q-switched laser

are shown in Fig. 3. One can see that the repetition rate and average power vary largely over the tuning range. The average power is somewhat lower than 50 % of what is obtained when the laser is running cw. The repetition rate varies from ten to a few hundred kHz in the shorter wavelength region, to a few MHz at longer wavelengths. Correspondingly the peak power changes from several kW to Watt. The highest peak power, 12.6 kW, was achieved at 1064.14 nm with a pulse duration of 4 ns, a repetition rate of 140 kHz and an average power of 0.8 W, corresponding to 5.7 µJ of pulse energy. The beam propagation factor, M^2, was then 1.3.

The spectral bandwidth of the Q-switched laser was measured with an optical spectrum analyzer and always found to be narrower than 40 pm, limited by the resolution of the optical spectrum analyzer. To get further information on the spectral content a Fizeau interferometer [21] was used. From looking at the interference pattern it is possible to determine the number of longitudinal modes the laser is operating in. In this case, the symmetric interference pattern and the Free-spectral range (FSR) confirm that the laser is running on a single-longitudinal mode, see Fig. 4. A comparison with a Nd:YVO_4 laser with the same cavity length and the CVBG replaced by a plane dielectric mirror with a similar reflectivity of 60 % shows that the Fizeau interferometer can easily resolve multiple longitudinal modes, see Fig. 4.

That the laser was oscillating on a single-longitudinal mode is not intuitive, as the longitudinal mode separation of the cold cavity is roughly 50 pm, so more than one longitudinal mode should be able to oscillate, if the bandwidth of the CVBG is 0.4 nm. To further investigate, why the laser is running on a single-longitudinal mode we simulated the transmission of the CVBG at the center wavelength $\lambda_c = 1064.2$ nm together with the transmission of the Fabry–Perot formed by the Nd:YVO_4 laser crystal (3 mm) and by the air gap between the Nd:YVO_4 laser crystal and the Cr^{4+}:YAG saturable absorber (0.1 mm). From this we found that every second longitudinal mode suffers losses from the Fabry–Perot formed by the end surfaces of the laser crystal. Longitudinal modes, which are even more separated from the main peak, suffer additional losses from the increasing transmission of the CVBG and from the Fabry–Perot, which is resulting from the small air-gap between the laser crystal and saturable absorber. This results in the laser oscillating only at a single longitudinal mode, even at higher output powers.

The tuning and pulsing performance is determined by the reflectivity of the chirped VBG and by gain and loss in the cavity. At shorter wavelengths the tuning range was limited by the gain spectrum and towards longer wavelength by the decreasing reflection of the CVBG. As the initial transmission of the Cr^{4+}:YAG saturable absorber was more or less constant over the tuning range, the relation between the gain and the additional loss from the outcoupling through the CVBG determined the pulsing behavior.

In Fig. 5 the pulse repetition frequency and the emission cross section [22] are plotted versus wavelength. It is clear that the repetition frequency is directly related to the gain and hence to the inversion population build up and, as can be seen in the figure, it changes by several orders of magnitude when the laser was tuned over the gain peak. For regions of low gain, i.e. wavelengths below 1063.7 nm, it takes a comparably longer time to reach threshold and the repetition rate will be low, in this case around 100 kHz. At the same time the inversion becomes high and a large energy can be extracted. When the CVBG was translated and the laser tuned to longer wavelengths, the gain will increase and the threshold is reached much faster, resulting in a much higher repetition rate, up to a few MHz, with corresponding low pulse energy. The small difference, <0.3 nm, between the emission cross section, as measured by Czeranowsky [22], and our measurement of the repetition rate, can very well be explained by the lower

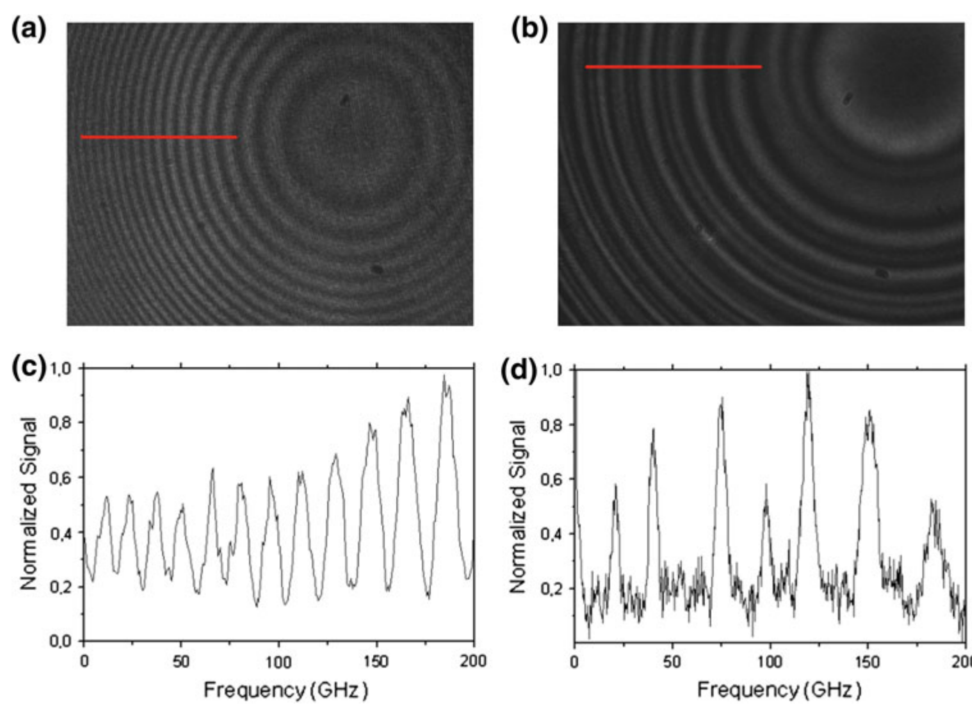

Fig. 4 Longitudinal mode spectrum as determined using a Fizeau interferometer with a free spectral range of 21 GHz. The symmetric pattern in **a** shows that the laser is operating single-mode. The picture **b** shows the multi-mode pattern obtained when the laser was operating using a dielectric output coupler with the same reflectivity. The graphs **c** and **d** show a cross-section (marked with a *red line*) of the intensity distribution in **a** and **b** to visualize single-mode and multi-mode operation, respectively

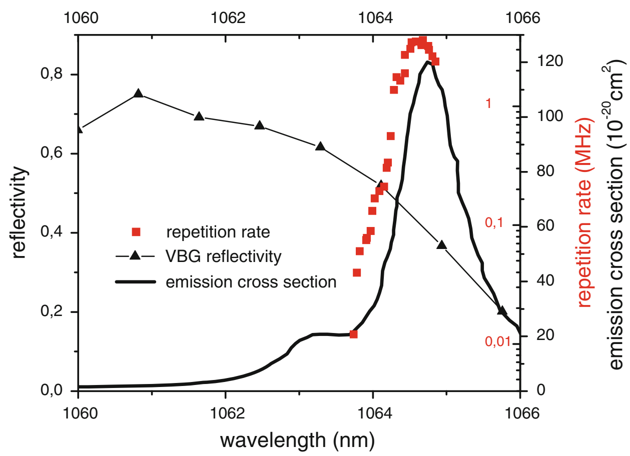

Fig. 5 Dependence of the repetition rate (logarithmic scale) on the emission cross section (linear scale) [21] and reflectivity of the CVBG

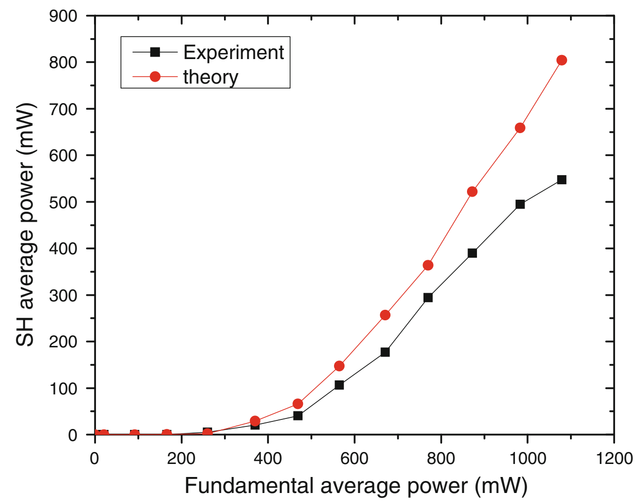

Fig. 6 Measured second harmonic average power at 532.1 nm compared with the expected theoretical second harmonic average power. The theoretical curve uses measured laser parameters (pulse duration and repetition rate)

reflectivity of the CVBG at longer wavelengths. A minor contribution to the discrepancy can also be the absolute calibration of the two spectrometers used in the two laboratories. An important finding in this experiment was that the VBG can force the laser to oscillate in a regime with a low emission cross section around 1,063.8 nm, which allows extraction of high pulse energies from a laser material that otherwise would give low pulse energies.

In a final experiment the pulsed laser was frequency doubled by focusing the beam close to confocal condition (60 µm $1/e^2$ radius), in a 12-mm-long PPKTP sample designed for phase-matching at 1064.1 nm ($\Lambda = 9.01$ µm) and temperature controlled to 20 °C. The PPKTP crystal had an effective length of 10.4 mm and an effective nonlinearity of $d_{\mathrm{eff}} = 10.3$ pm/V. This was measured in the low conversion efficiency regime with a cw Ti:-Sapphire laser by temperature tuning the PPKTP. At 1,064.1 nm the laser was running in the low repetition rate regime (150 kHz, 3.9 ns pulses) with high peak power which guarantees high conversion efficiency. 547 mW of green light was obtained with 1.08 W of input power, i.e. a conversion efficiency of 50.7 %. In Fig. 6 the measured SHG power is plotted against fundamental power. To compare this to theory we assumed a Gaussian-shaped input pulse and pump depletion [23]:

$$\overline{P}_{\mathrm{SHG}} = \overline{P}_F \tanh^2\left[\left(\gamma'_{\mathrm{SHG}}\overline{P}_F\right)^{1/2}\right] \tag{1}$$

where $\bar{P}_{\mathrm{SHG}}$ and $\bar{P}_F$ are the average power of the fundamental and second harmonic, and γ'_{SHG} the nonlinear coefficient for short pulses. In our case of second harmonic generation of a Q-switched laser with ns-pulses, we can neglect group-velocity dispersion and self-phase modulation. γ'_{SHG} is then defined as [24]:

$$\gamma'_{\mathrm{SHG}} = \gamma_{\mathrm{SHG}}\left[\left(\frac{2\ln 2}{\pi}\right)^{1/2}\right]\frac{1}{\tau f} \tag{2}$$

where the input pulse is characterized by its full width at half maximum pulse duration τ and the pulse train has a repetition rate of f. The conversion efficiency without pump depletion with a continuous wave fundamental is defined as [25]:

$$\gamma_{\mathrm{SHG}} = \frac{2\omega^2 d_{\mathrm{eff}} k_\omega}{\pi n^3 \varepsilon_0 c^3} l_c h(B,\xi) \tag{3}$$

As can be seen in Fig. 6 the measured SHG power graph is deviating from the theoretical one at higher fundamental powers. This is primarily due to a temperature-induced phase mismatch introduced in the comparatively long PPKTP by slight absorption of the green light in the rear part of the crystal, reducing its effective length. Similar deviations have previously been observed, for example by Wang et al. [26]. The theoretical curve was calculated using the parameters (repetition rate, pulse length and average power) measured in the experimental curve, point for point, thus making the two curves more directly comparable.

3 Conclusions

In conclusion we have constructed a simple tunable single longitudinal mode diode pumped Nd:YVO_4 laser using a chirped volume Bragg grating. The laser could be tuned from 1,063 nm to 1,065 nm, with a maximum power of

4 W and a slope efficiency of 31 % at 1,064.5 nm. Passive Q-switching using a Cr^{4+}:YAG saturable absorber was obtained both in a low (<20 kHz) and a high repletion rate (>2 MHz) regime, depending on the operation wavelength chosen with the CVBG. The tuning behavior in the Q-switched mode was analyzed and found critically dependent on the gain of the laser crystal, the reflectivity of the output coupler and the initial transmission and recovery time of the saturable absorber. The highest pulse energy obtained was 5.7 μJ, with a pulse length of 4 ns, corresponding to a peak power of 12.6 kW. When frequency doubled in the Q-switched regime, using PPKTP, 547 mW of green light was generated corresponding to a conversion efficiency higher than 50 %.

The use of a CVBG makes it possible to tune a laser to a wavelength where it is possible to achieve high pulse energy in materials with a high-emission cross section such as Nd:YVO_4. As the saturation intensity will be higher in that case, it will then also be easier to maintain single longitudinal mode operation.

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