Single-longitudinal-mode, tunable dual-wavelength, CW Nd:YVO_4 laser

Y. Y. Lin, S. Y. Chen, A. C. Chiang, R. Y. Tu, and Y. C. Huang

Institute of Photonics Technologies, Department of Electrical Engineering, National Tsinghua University, Hsinchu 300, Taiwan
ychuang@ee.nthu.edu.tw

Y. F. Chen

Department of Electrophysics, National Chiao Tung University, Hsinchu 30050, Taiwan

Y. H. Chen

Institute of Optical Sciences, National Central University, Jhongli 320, Taiwan

Abstract: We report a single-longitudinal-mode CW diode-pumped Nd:YVO_4 laser emitting at both 1064 and 1342 nm with 10% optical efficiency at 20-W pump power. The measured spectral widths at 1064 and 1342 nm were less than 450 MHz and 400 MHz, respectively. The two emission wavelengths can be independently tuned over the lasing bandwidths of the dual-wavelength laser.

OCIS codes: (140.3580) Lasers, solid-state; (140.3530) Lasers, neodymium; (140.3480) Lasers, diode-pumped.

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1. Introduction

Diode-pumped solid-state lasers are known to be efficient and compact. Neodymium-ion (Nd-ion) doped laser crystals such as Nd:YVO$_4$, Nd:YAG, Nd:YLF etc. are among the most popular laser host materials. Most laser sources using Nd-doped crystals only emit at a wavelength at a time, despite that several laser transitions are present in those crystals. Among all possible emission lines, the $^4F_{3/2}$ – $^4I_{11/2}$ and $^4F_{3/2}$ – $^4I_{13/2}$ transitions of an Nd-ion have relatively large emission cross sections. Neodymium lasers simultaneously emitting at two lines have recently attracted considerable attention, because the sum frequency of the two transitions results in yellow-orange laser radiation that is useful for fluorescence-excitation or spectroscopic applications. For example, the sum frequency of the two emission lines from a Nd:YAG crystal can be tuned to match the sodium D$_2$ line near 589 nm [1], and the sum frequency of the two emission lines from a Nd:YVO$_4$ crystal at 593 nm is useful for fluorescent bio-imaging.

To have stable dual-wavelength emission from a single laser gain medium, a careful balance between the net laser gains at the two wavelengths is necessary [2,3]. This balance usually results in a much larger output coupling loss at one wavelength than that at the other so that the gain-cross-section difference of the two emission lines can be compensated. Due to the large output coupling at one wavelength, a Q-switched dual-wavelength Nd laser is technically easier than a continuous-wave (CW) one [1-4]. To achieve a narrow laser linewidth, CW emission is the preferred mode of operation for a laser. Recently, CW dual-wavelength laser emission at 1064 nm and 1342 nm from a single Nd:YVO$_4$ crystal has been successfully demonstrated by prudently adjusting the output couplings and laser spot sizes at the two wavelengths [2]. However, the demonstrated linewidths of the CW dual-wavelength lasers were still on the order of 0.4 nm, comprising several longitudinal laser modes [5]. It is therefore the intention of this work to achieve single-longitudinal-mode emissions from a CW dual-wavelength laser. In practice, one can employ an intra-cavity etalon to narrow down a laser's linewidth. Although a dual-wavelength etalon with suitable coating parameters could be obtained from a delicate optical coating process, a single etalon does not have the flexibility of independent wavelength tuning to the two emission lines. Using the dispersion of an optical grating is also a possible approach for reducing laser's linewidth. For example, the external-cavity diode laser adopting a Littrow grating has been a popular laser source that generates wavelength-tunable, single-longitudinal-mode laser radiation. In most cases, a Littrow grating does not have sufficient dispersion for realizing a single-frequency solid-state laser, because the longitudinal mode spacing of a solid-state laser is usually much smaller than that of a diode laser. Fortunately the dispersion of a grating can be greatly enhanced by using a grazing-incidence configuration. This so-called Littman-Metcalf grating was proven useful in achieving single-frequency emissions from a diode laser [6] and an optical parametric oscillator [7] in the past. In this work, we employed a single Littman-Metcalf grating in a CW dual-wavelength Nd:YVO$_4$ laser and demonstrated single-longitudinal-mode emissions at both 1064 nm and 1342 nm with independent wavelength tuning over the lasing bandwidth.

2. Experimental setup

Figure 1 shows the experimental setup of the narrow-line, dual-wavelength Nd:YVO$_4$ laser oscillating at both 1064 and 1342 nm. A 9-mm-long a-cut Nd:YVO$_4$ laser crystal is the laser gain medium whose end faces were antireflection coated at 1064 and 1342 nm. The neodymium concentration of this Nd:YVO$_4$ crystal was 0.3 at.%. The crystal was mounted in a water-cooled copper housing and was in contact with an indium foil to dissipate excess heat. The pump source was a diode laser at 808 nm pigtailed through a multi-mode silica fiber with an 800-μm core diameter and a 0.18 numerical aperture. The pump laser was coupled into the Nd:YVO$_4$ crystal through a lens set with a one-to-one imaging ratio. The coating specifications of mirrors M1-5 are listed in Table 1. In Table 1, the location of each mirror surface was measured from the upstream surface of M1, labeled as S1 in Fig. 1. The input mirror M1 is a planar-concave mirror with a 1-m radius of curvature on the concave side. M1

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and M3 form a resonator for the 1064-nm laser. M1 and M2 form the 1342-nm laser resonator. The smaller coupling loss (8%) at 1342 nm in M2, compared with the higher one (30%) at 1064 nm in M3, is designed to account for the smaller emission cross section at 1342 nm in a Nd:YVO$_4$ crystal. The laser outputs from M2 and M3 are incident on a gold coated grating G (1200 grooves/mm) at 85° from the grating normal. High reflectors M4 and M5 reflect the -1^{st}-order diffraction of the 1064-nm and 1342-nm lasers, respectively, back to the Nd:YVO$_4$ crystal to limit the laser linewidths. At 85° incident angle, the grating feedback to the Nd:YVO$_4$ crystal are only about 33 % and 21% for the 1064 and 1342-nm lasers, respectively. As a result the primary resonator for the 1064-nm laser is still formed by mirrors M1 and M3, and that for the 1342-nm laser is still formed by mirrors M1 and M2. The free-spectral ranges of the two primary resonators are 2.3 GHz and 2.5 GHz at 1064 and 1342 nm, respectively. The useful laser power is coupled out through the 0^{th}-order diffraction of the grating G. Varying the angles of M4 and M5 can independently tune the two output wavelengths near 1064 and 1343 nm, respectively. According to Ref. [2], if the laser waist ratio of the 1064 and 1342-nm lasers is slightly larger than unity, the optimal reflectance at the 1064-nm output coupler M3 can become fairly independent of the waist ratio for a given output coupling at the 1342-nm mirror M2. By adjusting the distance between M2 and M3, we set the waist ratio to be 1.1 and achieved stable CW lasing at the two wavelengths. The laser operated with TEM$_{00}$ modes for both emission lines. The measured polarization directions of the two lines were both along the crystal axis of the Nd:YVO$_4$ crystal.

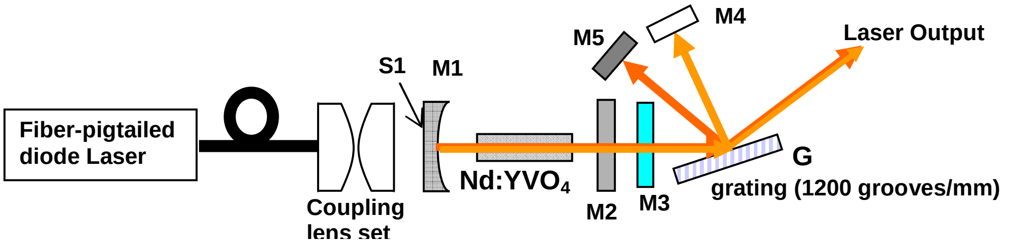

Fig. 1. Schematic of the single-longitudinal-mode tunable dual-wavelength CW Nd:YVO$_4$ laser. Mirrors M1 and M2 form the 1342-nm laser resonator, and mirrors M1 and M3 form the 1064-nm laser resonator. Narrow-line optical feedback at 1064 and 1342 nm are provided by M4 and M5, respectively, through a grazing-incident grating G. Rotating the angles of M4 and M5 independently tunes the 1064 and 1342 nm wavelengths, respectively.

Table 1. Specifications and locations of the mirrors in Fig. 1

Mirror	Upstream surface		Down-stream surface	
	Coating reflectance	distance from S1 (mm)	Coating reflectance	distance from S1 (mm)
M1 (planar/concave)	AR <0.2% @ 808 nm	0	HR >99.8% @ 1064 nm, HR >99.8% @ 1342 nm, HT >90% @ 808 nm.	3
M2 (planar/planar)	PR 92% @ 1342 nm, AR <0.2% @ 1064 nm.	54	AR <0.2% @ 1064 nm, AR <0.2% @ 1342 nm.	57
M3 (planar/planar)	PR 70% @ 1064 nm.	59	AR <1% @ 1064 nm, AR <1% @ 1342 nm.	65
M4 (planar/planar)	HR > 99% @ 1064 nm.	145	uncoated	151
M5 (planar/planar)	HR >99.8% @ 1342 nm.	145	uncoated	151

AR: anti-reflectance, HR: high reflectance, PR: partial reflectance, HT: high transmittance

3. Experimental results

In the following, we first show the measured 1064-nm and 1342-nm spectra of the dual-wavelength laser with and without the grating feedback, and then report the laser output powers at the two wavelengths under single-longitudinal-mode operation.

Figures 2(a) and 2(b) are the measured laser spectra for the 1064 and 1342 nm lasers, respectively, at 20-W pump power. In Fig. 2, all the spectral curves, except those in the insets, were measured by grating monochromators with 0.03- and 0.05-nm resolutions at 1064 and 1342 nm, respectively. In Fig. 2(a), the dashed curve is the 1064-nm spectrum without grating feedback. It is seen that the full spectral width is about 0.4 nm, which is consistent with the previously published results for a dual-wavelength Nd:YVO_4 laser [5]. We then aligned the grating feedback into the laser cavity and scanned the 1064-nm laser spectra using the same monochromator at four arbitrary M4 angles. The results are displayed with open dots in Fig. 2(a), illustrating wavelength tuning over the whole 0.42-nm lasing bandwidth. During the wavelength tuning, mirror M4 was rotated over a 0.5-mrad angle. With the grating feedback the measured spectral linewidths in Fig. 2(a) are narrowed down to the resolution of the monochromator. It is seen that the wavelength-tuned spectral power at 1064 nm was fairly constant over the 1064-nm emission bandwidth. To find out the actual laser linewidth, we further measured the output laser spectrum by using a scanning Fabry-Perot spectrometer with a free-spectral range of 6.8 GHz and finesse of about 210 at 1064 nm. The inset of Fig. 2(a) shows the result of the measurement, indicating a 450-MHz full width at half maximum (FWHM) for the 1064-nm radiation. Although some fine structures in the 1064-nm mode spectrum could suggest some transverse-mode power close to the noise level, we still observed a good TEM_{00} mode profile at the output. The existence of only a single peak within the 2.3-GHz free spectral range of the 1064-nm cavity between M1 and M3 confirms single-longitudinal-mode operation of the 1064-nm laser.

Figure 2(b) shows the spectra of the 1342-nm emission from the dual-wavelength laser. The dashed curve in the plot is the 1342-nm spectrum without grating feedback, consisting of 4 spectral peaks centered at 1342.07 nm, 1342.27 nm, 1342.46 nm and 1342.63 nm. The spectral peaks can not be the longitudinal modes of the 1342-nm laser cavity, because the 30-GHz frequency spacing between adjacent peaks is much wider than the free-spectral range of the cavity. We found in the experiment that the four spectral peaks were not sensitive to the 1342-nm resonator length neither to the presence of the 1064-nm laser. In the setup, mirror M2 has a 2^o wedge angle on the down-stream surface, so the etalon effect from mirror M2 is ruled out. To investigate the etalon effect of M1, we replaced the 3-mm-thick M1 with a 6-mm-thick high reflector at 1342 nm and found no change to the 30-GHz spectral spacing. We have also tried to replace the 9-mm-long Nd:YVO_4 laser crystal with a 12-mm-long one from a different vendor, the fine structure still persisted in the measured spectrum. The spiky spectrum cannot be explained by the Stark splitting in a Nd:YVO_4 crystal either, because the spacing between Stark levels near the 1342-nm transition is much wider than 30 GHz [8]. With the grating feedback, we can tune the 1342-nm wavelength across the 0.62-nm lasing bandwidth by rotating mirror M5 over a 0.9-mrad angle. As shown in Fig. 2(b), the four spectral curves connecting open dots correspond to the emission spectra at four M5 angles that match the four emission peaks in the spiky 1342-nm spectrum without grating feedback. Unlike the smooth tuning curves obtained for the 1064-nm laser, the peak level of each 1342-nm tuning curve strongly depends on the output wavelength relative to the peak locations of the dashed curve. In the past, a three-peak spectrum between 1341.97 and 1342.65 nm was also reported without explanations for a Nd:YVO_4 laser [10]. Thus, it might suggest a need for further spectroscopic study for a Nd:YVO_4 crystal. To find out the actual linewidth of the narrow-line emission at 1342 nm, we separated the 1342-nm laser from the output and scanned it with a Fabry-Perot spectrometer. The spectrometer has a free-spectral range of 11.5 GHz and finesse of about 150 at 1342 nm. The measured 1342-nm line is shown in the inset of Fig. 2(b), indicating a 400-MHz full width at half maximum. The existence of only a single peak within the 2.5-GHz free spectral range of the 1342-nm cavity between M1 and M2 confirms single-longitudinal-mode operation of the 1342-nm laser.

The reported stimulated emission cross section of the 1064-nm line is about 2–3.3 times that of the 1342-nm line [2, 9]. In our experiment, the reflectances of M2 and M3 were carefully selected so that the lasing threshold of the 1342nm line is lower than that of the 1064nm line. Figure 3 shows the measured 1064-nm (filled circles) and 1342-nm (open

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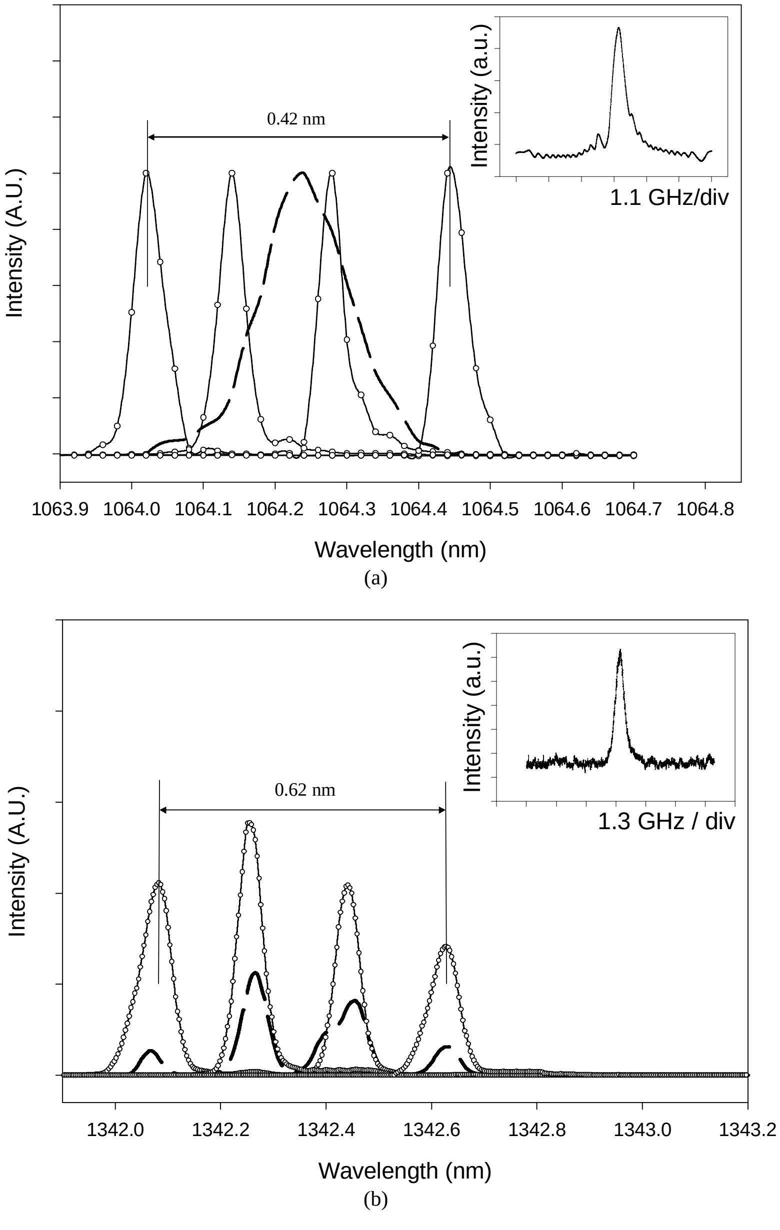
circles) output powers versus pump power under single-longitudinal-mode emission. The triangles are the measured total laser output power. Indeed, the 1342-nm line reaches the lasing threshold first at 4.3-W pump power, and the 1064-nm line has a higher pump threshold near 12 W. As the 1064-nm power builds up, the 1064-nm output power quickly exceeds the 1342-nm power due to the relatively larger output coupling at 1064 nm. At 20-W pump power, the 1064-nm and 1342-nm lasers reach 1.2 W and 0.9 W, respectively. The power stability was better than 3 % and 5 % at 1064 and 1342 nm, respectively, over a 1-hour period at 20-W pump power.



(a)

(b)

Fig. 2. (a) 1064-nm and (b) 1342-nm emission spectra of the dual-wavelength laser. Dashed lines are the laser spectra without grating feedback. Open dots are the spectral power with grating feedback, tuned at four mirror angles at M4 (a) or M5 (b). The inset shows the actual laser linewidth scanned by a Fabry-Perot spectrometer. The measured FWHM linewidths of the 1064-nm and 1342-nm lasers are 400 and 450 MHz, respectively.

As can be calculated from Fig. 3, the optical efficiency at 20-W pump power is about 10.2 %, which is lower than that for a dual-wavelength multi-mode Nd:YVO_4 laser [2]. The degradation of the optical efficiency is due to the optical loss at the grating. However, if a future goal is to generate narrow-line yellow-orange laser through intracavity sum frequency generation, the infrared power and efficiency external to the laser cavity are preferred to be kept low by using high reflection mirrors for M2 and M3. In that case, the optical loss at the grating G can become small.

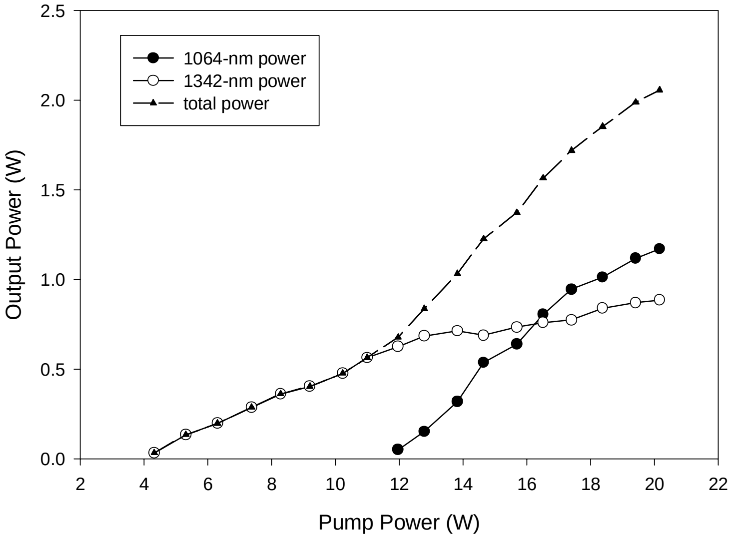


Fig. 3. The output powers of the 1064-nm and 1342-nm lasers versus the diode pump power. The filled and open circles are the measured laser powers at 1064 and 1342 nm, respectively. The triangles are the total output power summed from the two curves. Ten-percent optical efficiency is achieved at 20-W pump power.

4. Summary

We have demonstrated, to the best of our knowledge, the first CW single-longitudinal-mode tunable dual-wavelength Nd:YVO_4 laser emitting at 1064 and 1342 nm. The measured spectral widths of the 1064 and 1342 nm lasers were 450 MHz and 400 MHz, respectively. The grazing-incidence grating adopted in the laser cavity not only effectively narrowed down the laser linewidths, but also allowed for independent wavelength tuning to the two emission lines over the lasing bandwidths. At 20-W pump power, the total laser output power was 2.1 W, which is equivalent to 10.2% optical efficiency.

An extension of this work could be a compact, narrow-line source at the sodium D_2 line or at 589 nm, generated by intracavity summing the emission frequencies of a dual-wavelength Nd:YAG laser at 1064 and 1319 nm. Although the larger gain-cross-section difference of the two emission lines in a Nd:YAG crystal could make CW lasing more difficult at both wavelengths, Q-switched operation in the proposed configuration appears to be a feasible and easier alternative. The narrow-line emission and independent wavelength tuning from the dual-wavelength laser will also benefit to application such as exciting a mesospheric sodium guide star. The sub-GHz linewidth reported in this work is well within the 3-GHz Doppler-broadened sodium linewidth in the mesospheric layer [11].

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