IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 2, April 2018

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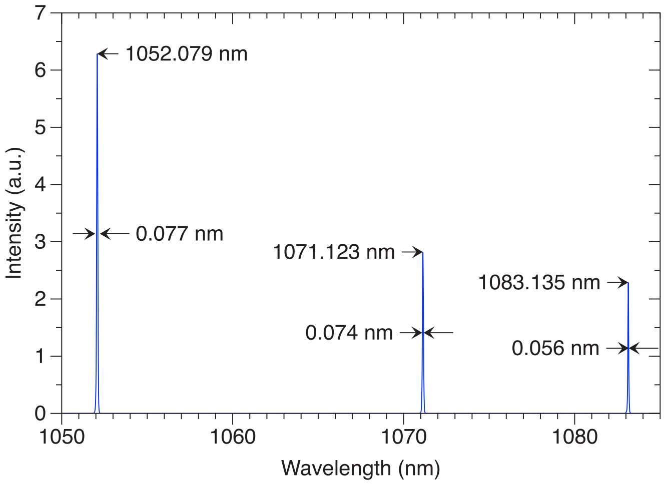

DOI: 10.1109/JPHOT.2018.2809783

Stable Simultaneous CW 1052, 1071, and 1083 nm Narrow Spectral Width Nd-Based Laser Output Using Precise Gain Control With VBGs

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DOI:10.1109/JPHOT.2018.2809783

Manuscript received November 2, 2017; revised January 24, 2018; accepted February 20, 2018. Date of publication February 27, 2018; date of current version March 19, 2018. This work was supported by the Ministry of Science and Technology of Taiwan under Contract 105-2221-E-008-075-MY3. Corresponding author: Te-yuan Chung (e-mail: teyuan@gmail.com).

Abstract: A continuous wave Nd-based laser with simultaneous narrow spectral 1052, 1071, and 1083 nm output was achieved by using temperature-controlled volume Bragg gratings to balance the gain competition between each wavelength and stabilize the laser output. Each output wavelength was characterized thoroughly and showed good stability in both frequency and power.

Index Terms: Bragg grating, diode-pumped laser, multi-wavelength, solid-state laser.

1. Introduction

Lasers with dual-wavelength outputs have been studied for their diverse potential applications such as holographic microscopy [1], phase-shifting interferometry [2], and THz generation [3]. However, Nd-based lasers with multi-wavelength output usually encounter strong gain competition, which results in unstable laser output. In 2000, Chen reported on two setups for dual-wavelength Nd:YVO$_4$ lasers with outputs of 1064 and 1342 nm. A custom designed output coupler with different reflectivities at the two wavelengths was used to achieve dual-wavelength emission [4]. In 2009, Wu *et al*. reported an orthogonally linear polarized Nd:GdVO$_4$ laser operating at 1063 and 1065 nm [5]. In 2010, Chen *et al*. obtained outputs of 1064, 1319, and 1338 nm by using a Nd:YAG ceramic as the gain medium and a hybrid cavity setup [6]. However, the 1319 and 1338 nm output behaviors were not separately measured. In 2013, Lü *et al*. developed a CW Nd:YAG laser that operated at 946, 1319, and 1064 nm by using three custom designed output couplers [7]. In 2014, Wang *et al*. reported using a specially crafted Fabry-Perot band pass filter as the output coupler for a Nd:YAG laser to achieve outputs of 1064 and 1074 nm [8]. However, none of the above studies provided detailed information about the stability of the frequency and power of the laser, which is critical for strongly coupled setups. The multi-wavelength laser that will be demonstrated in this paper will have three output wavelengths due to its potential of performing a real-time surface measurement [9] with a single laser source. The output wavelength selection is achieved by using PTR

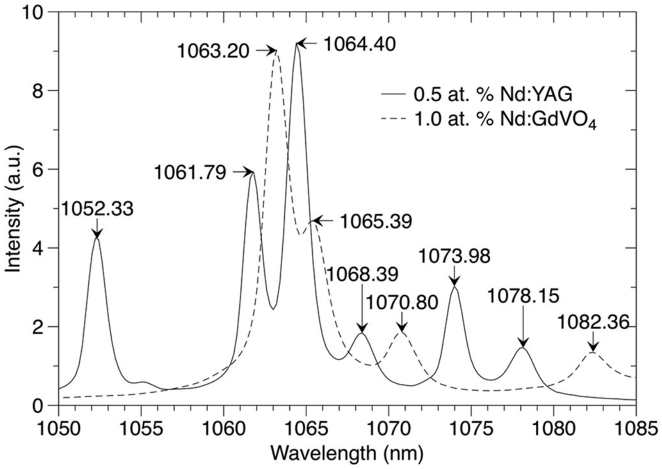


Fig. 1. Fluorescence spectra of the 0.5 at. % Nd:YAG and the 1.0 at. % Nd:GdVO$_4$.

VBGs (photo-thermo-refractive volume Bragg grating) [10]. These gratings can have very narrow diffraction spectra [11] and temperature-tunable Bragg wavelengths of about 10 pm/°C [12].

2. Experiment Setup

The measured fluorescent spectra of the gain media used in this three-wavelength laser are shown in Fig. 1. The measurement was carried out with a spectrometer (StellarNet Inc., EPP2000-NIR2b) with a resolution limit of 0.5 nm. The emission lines in this range belong to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions and are strongly coupled. The line shape of each emission line is roughly proportional to the emission cross section spectrum. Therefore, by precisely selecting the laser wavelength, the corresponding emission cross section and the gain of the laser can be controlled. In this work, the 1052, 1071, and 1083 nm emission lines were chosen. These wavelengths are unique in this laser system and exists only in either one of the gain media for avoiding gain competition between the two crystals.

The laser configuration and the measurement setup are shown in Fig. 2. The laser was pumped by a pigtailed 7 W 808 nm laser made by Lumics GmbH. The pump laser (LD) was set to output 3.4 W of power in the experiments.

The pump laser was collimated by an aspherical lens (Thorlabs CFC-2X-B) and then focused by another aspherical lens (L1, Thorlabs A220TM-B). A plano-concave mirror (M1) with a radius of curvature of 25 cm and a diameter of 12.7 mm was used as the cavity mirror. The concave side of M1 was coated with 1064HR/808AR. The gain media, 0.5 at. % Nd:YAG and 1.0 at. % Nd:GdVO$_4$, were 2 mm and 3.5 mm thick, respectively. Both crystals had clear apertures of 4×4 mm^2 and 1064HR/808AR coatings. The crystals were individually wrapped with indium foil and placed in the same water-cooled aluminum holder with the temperature maintained at 22 °C. The other side of the cavity was composed of three PTR VBGs (Optigrate Inc.). In the paragraphs below, the VBGs are referred to by their Bragg wavelengths, for example, 1052 VBG indicates a VBG with a Bragg wavelength of around 1052 nm. Diffraction efficiencies of 99%, 95%, and 97% were obtained at the Bragg wavelengths for the 1052 VBG, 1071 VBG, and 1083 VBGs, respectively. The facets of all the VBGs were coated with 1064AR. The diffraction spectral widths of all VBGs were less than 0.3 nm. The Bragg wavelengths were individually controlled by placing the 1052 and 1083 VBGs in two separate heated aluminum holders. The 1071 VBG was not placed in a heated holder and was operated at near room temperature. Temperature measurements of the VBGs were performed using an Arduino (Atmel ATmega2560) and a 16-bit A/D Converter (TI ADS1115) with thermistors (SEMITEC 104JT-025) in a voltage divider circuit. This Arduino based

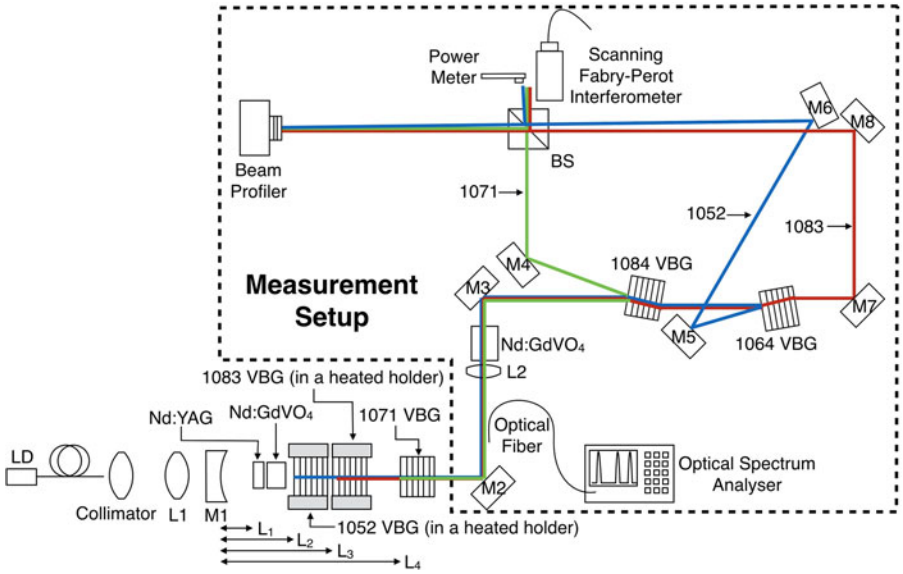
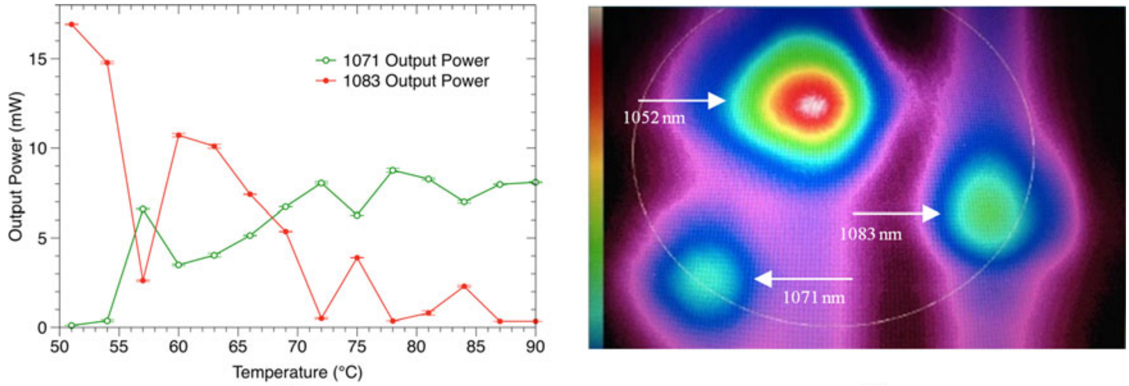


Fig. 2. The laser configuration and the measurement setup.



(a)

(b)

Fig. 3. (a) The laser output power versus the temperature of the 1083 VBG and (b) beam profiles of the three-wavelength laser.

temperature controller provided resolutions better than 0.005 °C within the operating temperature range of the VBG. The distances from M1 to the Nd:YAG, 1052 VBG, 1083 VBG, and 1071 VBG were 3 mm, 12 mm, 19 mm, and 33 mm, respectively. The thicknesses of the 1052 VBG, 1083 VBG, and 1071 VBG were 5.5 mm, 3.76 mm, and 5.5 mm, respectively. In the measurement setup, the laser output was first reflected by a plane mirror (M2) and then collimated by L2 (f = 25 cm). After this, the output was passed through a $3 \times 3 \times 5\ \text{mm}^3$ 1 at. % Nd:GdVO$_4$ to absorb the residual light from the pump laser without attenuating the laser output. The 1084 and 1064 VBGs were used to separate the three laser wavelengths to allow measurements of each laser wavelength. A scanning Fabry-Perot interferometer (Thorlabs SA200-9A) with an FSR of 1.5 GHz was used to identify the details of the spectral behavior of the laser output. The laser output was monitored by a power meter (Ophir LaserStar and Ophir PD300-TP) and a beam profiler (Ophir Beamstar FX 50).

The 1071 and 1083 nm emissions are strongly coupled Nd:GdVO$_4$ transitions. Therefore, precise control over the gain of these two wavelengths is required in order to achieve dual-wavelength output with a single gain medium. By carefully controlling the temperature of the 1083 VBG, the corresponding emission cross section and gain of the 1083 nm laser output can be tuned to

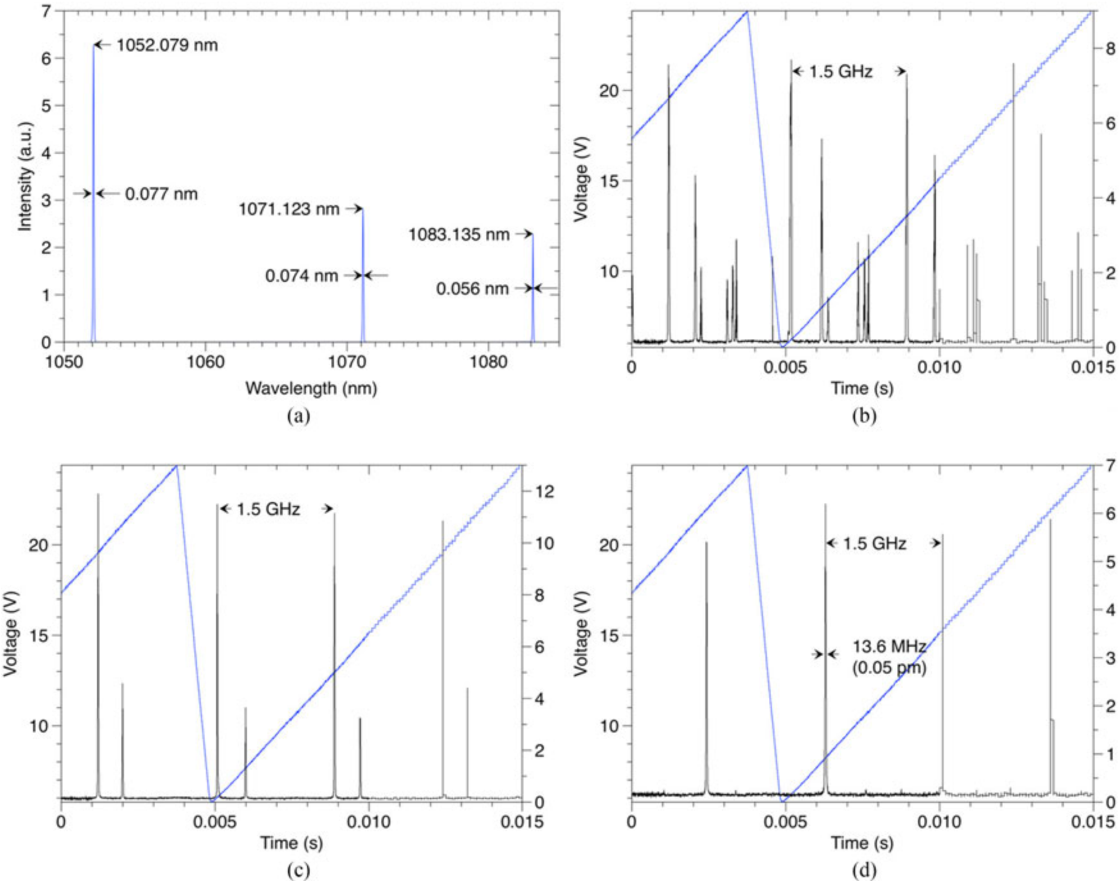


Fig. 4. (a) The laser output spectrum as measured by the OSA and the scanning Fabry-Perot traces for outputs of (b) 1052.079 nm, (c) 1071.123 nm, and (d) 1083.135 nm.

balance the 1071 nm and 1083 nm outputs. Without controlling the temperatures of the VBGs, dual-wavelength output cannot be achieved due to gain competition between the two wavelengths. The 1052 nm emission belongs to the Nd:YAG transition and does not couple with the 1071 nm and 1083 nm outputs.

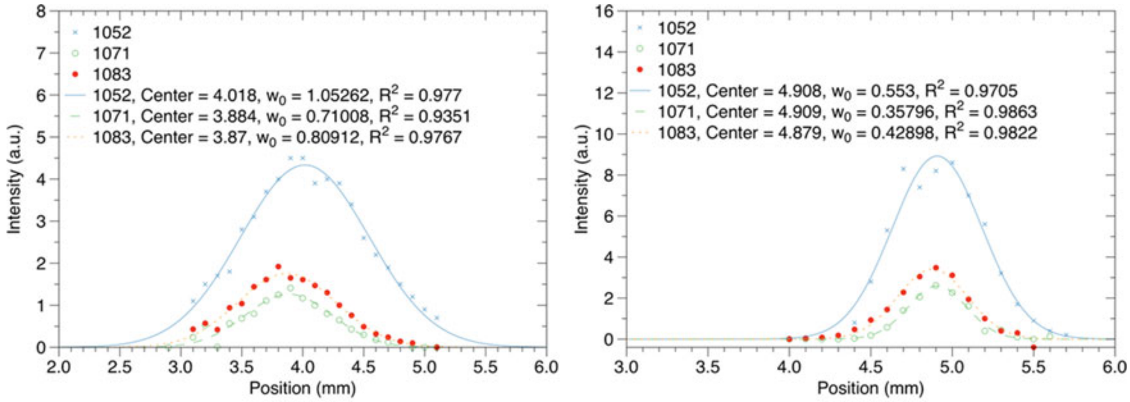
3. Experiment Results

Fig. 3(a) shows the 1071 nm and 1083 nm output power versus the temperature of the 1083 VBG. The output is reasonable for both wavelengths when the temperature of the 1083 VBG is between 56 °C and 70 °C. The properties of the three-wavelength laser were measured with the temperature of the 1083 VBG kept at 64 °C and the temperature of the 1052 VBG kept at 35 °C. If the sequence of the 1071 and 1083 VBG was changed, the required temperature to maintain dual-wavelength output would also be changed. The temperatures of both the 1052 VBG and 1083 VBG were controlled within a margin of error of 0.01 °C, which corresponds to 0.1 pm uncertainty of their Bragg wavelengths. Fig. 3(b) shows the beam profiles of the three-wavelength laser, where the beam profiles were separated intentionally by rotating mirrors in the measurement setup.

Fig. 4(a) is the laser output spectrum measured with an optical spectrum analyzer (OSA, Agilent 86142B) with a resolution limit of 0.06 nm, and shows that the laser wavelengths are 1052.079 nm, 1071.122 nm, and 1083.135 nm. The corresponding Fabry-Perot scanning traces are shown in Fig. 4(b)–(d), respectively. The spectral measurements indicate that these three laser

Table 1
The Laser Output Properties for Different Wavelengths

Wavelength (nm)	1052.079	1071.123	1083.135
Linewidth (pm)	~77	~74	<0.05
Power (mW)	33.9 ± 0.2	14.6 ± 0.2	6.43 ± 0.30
Frequency Jitter (MHz)	30	10	10
Frequency Drift (MHz/min)	8	7	8
M_x^2	1.50	1.16	1.95
M_y^2	1.48	1.21	1.52



(a) (b)

Fig. 5. (a) Horizontal and (b) vertical beam profile measured at 12.0 cm behind the 1071 VBG.

output linewidths are narrow and the 1083.135 nm output even achieved single longitudinal mode output.

The properties of the laser output are shown in detail in Table 1. The laser remained stable for more than 30 minutes. The power and frequency stabilities were good for such an open-loop controlled yet strongly coupled laser system. The beam qualities were measured using a beam profiler. The outputs had an M^2 of less than 1.6 except for the 1083 VBG output in the horizontal direction (x-direction), which was about 1.9. The collinearity of the three wavelengths was also measured by using the knife-edge method in between M2 and L2 and by measuring the individual output powers after the wavelengths were split apart. No obvious angular deviation was found, the 1071 and 1083 nm outputs were matched well in space, as shown in Fig. 5. However, there was a horizontal shift in the optical axis of the 1052 nm by about 100 μm with respect to the other two outputs. This shift might have been caused by a slight misalignment of the 1052 VBG together with the lateral shift induced by the 1071 VBG and the 1083 VBG in the laser configuration.

4. Conclusion

A compact CW laser achieved stable and simultaneous 1052 nm, 1071 nm, and 1083 nm output using Nd:YAG and Nd:GdVO$_4$ as the gain media and temperature-controlled VBGs for precise gain control to balance the gain competition. Since the laser uses VBGs as end mirrors, all three laser wavelength outputs achieved narrow spectral widths, good power stability, good frequency stability, and good beam quality.

Acknowledgment

The authors would like to thank their colleagues for their valuable suggestions.

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