Single frequency 1070 nm Nd:GdVO$_4$ laser using a volume Bragg grating

Nang-Chian Shie,[1,*] Wen-Feng Hsieh,[1,2] and Jow-Tsong Shy[3]

[1] *Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, 30050 Hsinchu, Taiwan*
[2] *Institute of Electro-Optical Science and Engineering, National Cheng Kung University, 701 Tainan, Taiwan*
[3] *Department of Physics, National Tsing Hua University, 30013 Hsinchu, Taiwan*
[*] *ncshie.eo93g@nctu.edu.tw*

Abstract: We demonstrate a single frequency diode-pumped Nd:GdVO$_4$ laser at 1070 nm using a volume Bragg grating as the output coupler of a short plano-concave cavity. The TEM$_{00}$ output had a maximum power of 300 mW and a linewidth less than 23 MHz. The beam propagation parameter M^2 and the divergence angle at 200 mW were 1.2 and 0.37°, respectively. The single frequency tuning range was 5.1 GHz at 100 mW. Upon locking the laser frequency to a confocal reference cavity, a relative stability of 7.58 kHz was achieved. If frequency doubled, such as using a periodically-poled lithium niobate (PPLN) crystal, this laser offers an excellent light source for parity non-conservation experiments of atomic thallium.

OCIS Codes: (050.7330) Volume gratings; (140.3580) Lasers, solid-state; (140.3530) Lasers, neodymium; (140.3570) Lasers, single-mode; (140.3600) Lasers, tunable.

References and links

1. N. H. Edwards, S. J. Phipp, P. E. G. Baird, and S. Nakayama, "Precise measurement of parity nonconserving optical rotation in atomic thallium," Phys. Rev. Lett. **74**(14), 2654–2657 (1995).
2. P. A. Vetter, D. M. Meekhof, P. K. Majumder, S. K. Lamoreaux, and E. N. Fortson, "Precise test of electroweak theory from a new measurement of parity nonconservation in atomic thallium," Phys. Rev. Lett. **74**(14), 2658–2661 (1995).
3. A. D. Cronin, R. B. Warrington, S. K. Lamoreaux, and E. N. Fortson, "Studies of electromagnetically induced transparency in thallium vapor and possible utility for measuring atomic parity nonconservation," Phys. Rev. Lett. **80**(17), 3719–3722 (1998).
4. A. I. Zagumennyĭ, V. G. Ostroumov, I. A. Shcherbarkov, T. Jensen, J. P. Meyn, and G. Huber, "The Nd:GdVO$_4$ crystal: a new material for diode-pumped lasers," Sov. J. Quantum Electron. **22**(12), 1071–1072 (1992).
5. H. D. Jiang, H. J. Zhang, J. Y. Wang, H. R. Xia, X. B. Hu, B. Teng, and C. Q. Zhang, "Optical and laser properties of Nd:GdVO$_4$ crystal," Opt. Commun. **198**(4-6), 447–452 (2001).
6. M. Liao, R. Lan, Z. Wang, H. Zhang, J. Wang, X. Hou, and X. Xu, "10 W continuous-wave Nd:GdVO$_4$ microchip laser," Laser Phys. Lett. **5**(7), 503–505 (2008).
7. T.-Y. Chung, C.-J. Liao, Y.-H. Lien, S. S. Yang, and J.-T. Shy, "Special laser wavelength generation using a volume Bragg grating as Nd:GdVO$_4$ laser mirror," Jpn. J. Appl. Phys. **49**(6), 062503 (2010).
8. Y. F. Chen, M. L. Ku, and K. W. Su, "High-power efficient tunable Nd:GdVO$_4$ laser at 1083 nm," Opt. Lett. **30**(16), 2107–2109 (2005).
9. T. Y. Chung, A. Rapaport, V. Smirnov, L. B. Glebov, M. C. Richardson, and M. Bass, "Solid-state laser spectral narrowing using a volumetric photothermal refractive Bragg grating cavity mirror," Opt. Lett. **31**(2), 229–231 (2006).
10. L. B. Glebov, "Volume Bragg Gratings in PTR glass—New optical elements for laser design," in *Advanced Solid State Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2008), paper MD1.
11. B. L. Volodin, S. V. Dolgy, E. D. Melnik, E. Downs, J. Shaw, and V. S. Ban, "Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings," Opt. Lett. **29**(16), 1891–1893 (2004).
12. G. Venus, L. Glebov, V. Rotar, V. Smirnov, P. Crump, and J. Farmer, "Volume Bragg semiconductor lasers with near diffraction limited divergence," Proc. SPIE **6216**, 621602 (2006).
13. B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Tunable single-longitudinal-mode ErYb:glass laser locked by a bulk glass Bragg grating," Opt. Lett. **31**(11), 1663–1665 (2006).
14. B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Single-longitudinal-mode Nd-laser with a Bragg-grating Fabry-Perot cavity," Opt. Express **14**(20), 9284–9292 (2006).

#153198 - $15.00 USD Received 22 Aug 2011; revised 15 Sep 2011; accepted 27 Sep 2011; published 10 Oct 2011

15. I. Häggström, B. Jacobsson, and F. Laurell, “Monolithic Bragg-locked Nd:GdVO$_4$ laser,” Opt. Express **15**(18), 11589–11594 (2007).
16. B. Jacobsson, J. E. Hellström, V. Pasiskevicius, and F. Laurell, “Widely tunable Yb:KYW laser with a volume Bragg grating,” Opt. Express **15**(3), 1003–1010 (2007).
17. J. E. Hellström, B. Jacobsson, V. Pasiskevicius, and F. Laurell, “Quasi-two-level Yb:KYW laser with a volume Bragg grating,” Opt. Express **15**(21), 13930–13935 (2007).
18. T.-Y. Chung, S. S. Yang, C.-W. Chen, H.-C. Yang, C.-R. Liao, Y.-H. Lien, and J.-T. Shy, “Wavelength tunable single mode Nd:GdVO$_4$ laser using a volume Bragg grating fold mirror,” in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper CThE4.
19. B. Jacobsson, J. E. Hellström, V. Pasiskevicius, and F. Laurell, “Tunable Yb:KYW laser using volume Bragg grating in s-polarization,” Appl. Phys. B **91**(1), 85–88 (2008).
20. T. H. Wang, Y. L. Ju, X. M. Duan, B. Q. Yao, X. T. Yang, and Y. Z. Wang, “Narrow linewidth continuous wave diode-pumped Tm:YLF laser with a volume Bragg grating,” Laser Phys. Lett. **6**(2), 117–120 (2009).
21. N. Vorobiev, L. Glebov, and V. Smirnov, “Single-frequency-mode Q-switched Nd:YAG and Er:glass lasers controlled by volume Bragg gratings,” Opt. Express **16**(12), 9199–9204 (2008).
22. M. Hemmer, Y. Joly, L. B. Glebov, M. Bass, and M. C. Richardson, “Volume Bragg Grating assisted broadband tunability and spectral narrowing of Ti:sapphire oscillators,” Opt. Express **17**(10), 8212–8219 (2009).
23. M. Henriksson, M. Tiihonen, V. Pasiskevicius, and F. Laurell, “ZnGeP$_2$ parametric oscillator pumped by a linewidth-narrowed parametric 2 μm source,” Opt. Lett. **31**(12), 1878–1880 (2006).
24. J. Saikawa, M. Fujii, H. Ishizuki, and T. Taira, “52 mJ narrow-bandwidth degenerated optical parametric system with a large-aperture periodically poled MgO:LiNbO$_3$ device,” Opt. Lett. **31**(21), 3149–3151 (2006).
25. J. Saikawa, M. Fujii, H. Ishizuki, and T. Taira, “High-energy, narrow-bandwidth periodically poled Mg-doped LiNbO$_3$ optical parametric oscillator with a volume Bragg grating,” Opt. Lett. **32**(20), 2996–2998 (2007).
26. B. Jacobsson, C. Canalias, V. Pasiskevicius, and F. Laurell, “Narrowband and tunable ring optical parametric oscillator with a volume Bragg grating,” Opt. Lett. **32**(22), 3278–3280 (2007).
27. P. Jelger and F. Laurell, “Efficient narrow-linewidth volume-Bragg grating-locked Nd:fiber laser,” Opt. Express **15**(18), 11336–11340 (2007).
28. P. Jelger and F. Laurell, “Efficient skew-angle cladding-pumped tunable narrow-linewidth Yb-doped fiber laser,” Opt. Lett. **32**(24), 3501–3503 (2007).
29. T. McComb, V. Sudesh, and M. Richardson, “Volume Bragg grating stabilized spectrally narrow Tm fiber laser,” Opt. Lett. **33**(8), 881–883 (2008).
30. J. W. Kim, P. Jelger, J. K. Sahu, F. Laurell, and W. A. Clarkson, “High-power and wavelength-tunable operation of an Er,Yb fiber laser using a volume Bragg grating,” Opt. Lett. **33**(11), 1204–1206 (2008).
31. K. Seger, B. Jacobsson, V. Pasiskevicius, and F. Laurell, “Tunable Yb:KYW laser using a transversely chirped volume Bragg grating,” Opt. Express **17**(4), 2341–2347 (2009).
32. B. Jacobsson, V. Pasiskevicius, F. Laurell, E. Rotari, V. Smirnov, and L. Glebov, “Tunable narrowband optical parametric oscillator using a transversely chirped Bragg grating,” Opt. Lett. **34**(4), 449–451 (2009).

1. Introduction

Performing high resolution spectroscopy in atomic thallium (Tl) to search for new physics beyond the standard model (SM) requires many single frequency lasers. SM predicts an atomic parity non-conservation (PNC) arising from the exchange of Z_0-Bosons between atomic electrons and nucleons. Atomic thallium ($Z = 81$) is an ideal candidate to search for such a PNC effect because it is heavy (strength of PNC grows as Z^3). The most precision measurements of PNC optical rotation in the $6P_{1/2} \rightarrow 6P_{3/2}$ magnetic dipole transition (1283 nm) in Tl were reported in 1995 [1,2]. More recently, the electromagnetically induced transparency (EIT) was proposed to improve the PNC measurement [3] in which the EIT spectrum of the $6P_{1/2} \rightarrow 6P_{3/2}$ absorption line at 1283 nm is observed when a 535 nm light acts on the $6P_{3/2} \rightarrow 7S_{1/2}$ transition as the “pump”.

Diode pumped solid-state (DPSS) lasers are of high compactness, high efficiency and long lifetime. DPSS have been found to be outstanding light sources for spectroscopy due to their good stability, narrow linewidth, and good beam quality. Neodymium-doped gadolinium orthovanadate (Nd:GdVO$_4$) is an ideal laser crystal for the DPSS lasers for its high pump absorption coefficient and large thermal conductivity [4,5]. Most of the work involving Nd:GdVO$_4$ crystal to date focuses on the high power output at wavelength 1064 nm, which is the main gain peak [6]. However, the fluorescence spectrum of a 0.5 at.% Nd:GdVO$_4$ crystal [7] reveals that there are some weaker emission bands around the main peak. One of the weak emission bands is located at 1070.8 nm, which is only 6 nm away from the main peak. Lasing at

#153198 - $15.00 USD Received 22 Aug 2011; revised 15 Sep 2011; accepted 27 Sep 2011; published 10 Oct 2011

this 1070 nm weak emission, in principle, could be used to generate a 535 nm light needed for the PNC measurement in Tl by frequency doubling in PPLN.

To achieve single frequency operation for DPSS, wavelength selection elements are required. From the fluorescence spectrum of a 0.5% at. Nd:GdVO4 crystal presented in Ref. 7, the emission cross section at 1070.8 nm is about 20% of that at 1063.2 nm. Therefore, to obtain a 1070 nm laser operation with Nd:GdVO4 crystal one must suppress the laser action at 1063.2 nm. A 1083 nm Nd:GdVO4 laser has been demonstrated using a specially coated dielectric mirror with high reflectivity at 1082.6 nm and lower reflectivity around 1060 nm to suppress the lasing at 1064 nm [8]. However, the 1070 nm band is too close to be separated from the 1064 nm band by a dielectric coated mirror. Other methods for the wavelength selection are achieved by inserting an intra-cavity dispersive element, e.g. etalon, which introduces additional loss in the laser resonators resulting in raising the lasing threshold.

Volume Bragg gratings (VBG) offer an alternative approach for the wavelength selection and line narrowing in solid state lasers [9]. VBG is a periodic phase grating recorded in the photo-thermo-refractive (PTR) glass by the thermal development after a holographic exposure to the UV radiation. The PTR glass possesses a large transparent range with low induced losses, high laser damage threshold and a good thermal stability. The PTR VBG has an extremely narrow spectral width (below 1 nm), good angular selectivity (below 10 mrad), and high relative diffractive efficiency (above 99.9%) [10]. Both reflecting and transmitting Bragg grating can be developed in the PTR glass. These unique features make VBG ideal for working as intracavity wavelength selectors or resonator couplers in various types of lasers, depending on designed properties. Its excellent wavelength selectivity has been demonstrated with laser diodes [11,12], solid state lasers [9,13–22], optical parametric oscillators [23–26] and fiber lasers [27–30]. Transversely chirped VBG has also been used for the wavelength tuning to obtain tunable solid-state laser [31] and OPO [32].

CW single-longitudinal-mode Nd:GdVO$_4$ laser operation has been achieved with a short VBG Fabry-Perot cavity [14] or a monolithic VBG cavity [15]. The monolithic VBG cavity provides over 80 GHz single frequency tuning range. However, the power is limited to 30 mW for single frequency operation by the high intracavity loss (~10%). In addition, it is not easy to perform a fast frequency modulation which is often needed in laser spectroscopy.

Recently our group has achieved a 100 mW single frequency end-pumped Nd:GdVO$_4$ laser at 1070 nm with a VBG Fabry-Perot resonator [7]. In this work, we report a 1070 nm single frequency diode-pumped Nd:GdVO$_4$ laser using a short plano-concave resonator in which a VBG serves the purpose of both the output coupler and the wavelength selector. A maximum output power of 300 mW was achieved for the single frequency operation. The single frequency tuning range was about 5.1 GHz at output power of 100 mW. Its output also showed a good beam quality. To demonstrate its stability, the laser frequency was locked to the resonance peak of a confocal optical cavity and a stability of 7.58 kHz relative to the reference cavity was achieved.

2. Experiments and results

2.1 Single frequency Nd:GdVO$_4$ laser

The schematic diagram of the single frequency Nd:GdVO$_4$ laser is shown in Fig. 1. A short plano-concave cavity was employed in our work. An 808-nm fiber-coupled diode laser with a core-diameter of 800 μm and a numerical aperture of 0.12 served as the pump source. The pump beam from the fiber end was focused into the laser crystal with a diameter of about 300 μm through the focusing optics formed by a pair of lenses. The cavity mirror M1 was a concave mirror with a radius of curvature of 300 mm. It had an anti-reflection (AR) coating at 808 nm (R < 0.5%) and 1064 nm (R < 0.2%) on the flat face, as well as an AR coating at 808 nm (R < 5%) and a high-reflection (HR) coating at 1064 nm (R > 99.8%) on the curved face. It is mounted on a piezoelectric transducer (PZT) for fine tuning the laser cavity length. An a-cut 0.5% at.

$Nd:GdVO_4$ crystal with a dimension of 3 × 3 × 4 mm^3 was used as the laser gain medium. The crystal was AR coated at 808 nm ($R < 2\%$) and 1064 nm ($R < 0.2\%$) on the side near M1 and AR ($R < 0.2\%$) coated at 1064 nm and 532 nm on the other side. It was wrapped with an indium foil and mounted in a copper heat sink plate without temperature control and placed closely to M1. A PTR VBG (Optigrate Inc.) having peak reflectivity > 99% at the center wavelength 1069.8 nm with full width at half maximum (FWHM) of 0.356 nm and a dimension of 5 × 5 × 4 mm^3 worked as the output coupler of the laser cavity. The VBG was AR coated at 1064 nm on both facets. It was wrapped with an indium foil and mounted in a copper heat sink and its temperature could be controlled from 15 to 60 °C by a thermoelectric cooler underneath. The distance between M1 and VBG was 10 mm. The laser output power of the laser was measured by a power meter (Scientech 362) at a distance of 100 mm from the VBG output coupler. The output spectrum was monitored by a home-made scanning confocal Fabry-Perot interferometer (FPI) with a free spectral range of 1.5 GHz. An InGaAs detector (Thorlabs DET410) connected to an oscilloscope (Tektronix TDS 2024) was used to detect the spectrum signal after FPI. A wavemeter (Burleigh WA1000) and a beam analyzer (DataRay WinCamD) were used to verify the output wavelength and to monitor the output transverse beam profile respectively.

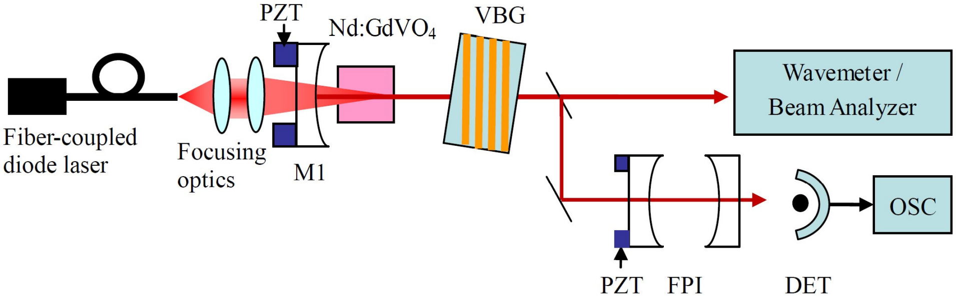

Fig. 1. Schematic diagram of the single frequency laser. Here, VBG: volume Bragg grating; PZT: piezoelectric transducer; FPI: Fabry-Perot Interferometer; DET: detector; OSC: oscilloscope.

The single frequency operation of this plano-concave cavity laser was achieved by the VBG which acted as an output coupler and a wavelength selector. It should be mentioned that there were four weak beams surrounding the main laser output beam. These beams were the reflections of the VBG surfaces since the VBG grating planes are not parallel to the VBG surfaces. They can be used to monitor the single frequency operation with the FPI. The output spectrum (shown in Fig. 2) monitored by the FPI indicates that the laser was operated at single frequency. The non-smooth FPI trace was due to discrete sampling of the digital oscilloscope we used. The detailed spectral profile (shown in the inset of Fig. 2) of the FPI at the output power 200 mW showed a linewdith of 23 MHz which was limited by the instrument resolution of our FPI. The wavelength of the laser output could be tuned by the VBG temperature at a tuning coefficient of ~10 pm/K (or ~-2.6 GHz/K). The vacuum wavelength of the laser was 1070.205 nm (280126.5 GHz) when the VBG was kept at 26 °C. From the Fabry-Perot traces we found that the single frequency tuning range by the PZT tuning was about 5.1 GHz at output power 100 mW. The far-field spatial distribution of the beam at output power 200 mW measured by a beam analyzer is shown in Fig. 3. A nearly Gaussian intensity profile with good circularity was observed at a distance 45 cm from the output coupler. The far field divergence angle of the laser output was around 0.37°. To check the beam quality of this laser, we measured the beam radius for the output beam at the 200 mW power level at different distances from a lens with focal length of 100 mm. The measured beam propagation parameter M^2 was 1.16.

#153198 - $15.00 USD Received 22 Aug 2011; revised 15 Sep 2011; accepted 27 Sep 2011; published 10 Oct 2011

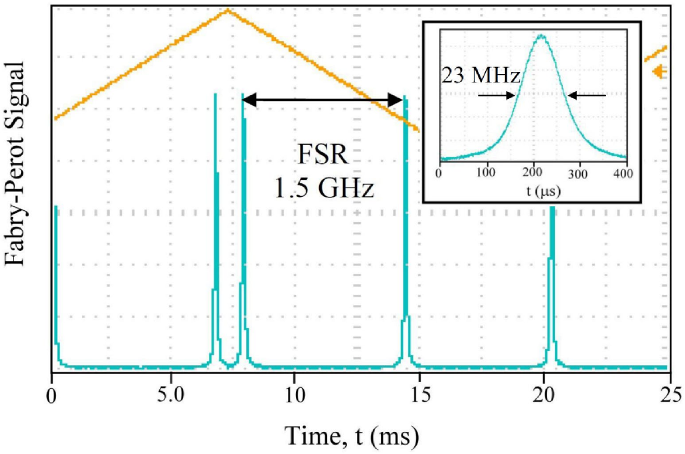

Fig. 2. Transmission curve of FPI of the single frequency Nd:GdVO$_4$ laser (lower trace). Upper trace was the scanning triangle voltage to the FPI. The inset shows the detail of the transmission peak.

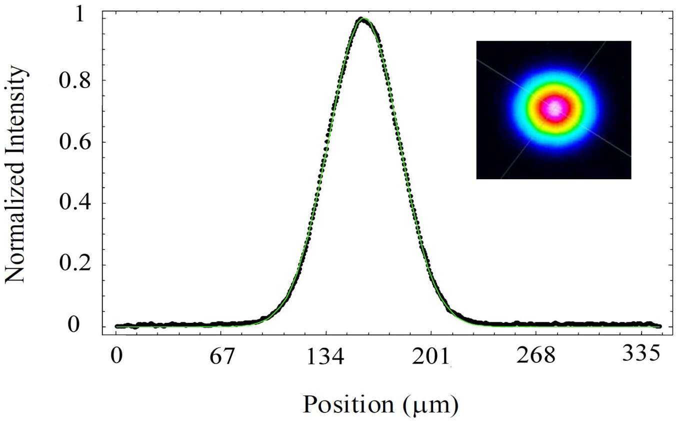

Fig. 3. The far-field intensity distribution of the 1070 nm laser at 200 mW output power. The solid curve is the fitted Gaussian distribution.

However, the optimal position of focusing optics depended on the pump power as a result of thermal lens effect of the laser crystal under pumping. We needed to fine-tune both the focusing optics position and the VBG angle to acquire a single mode laser with a maximum output power at different pump powers. Figure 4 shows the experimental results for the optimal output power for single frequency operation as a function of the pump power. Since the current of 808 nm pump laser could be adjusted by an increment of 1 Amp only, the slope efficiency of 14.5% and threshold pump power of 720 mW were obtained by a linear fitting. A single frequency laser output power of 300 mW had been obtained, limited by the reflectivity of the VBG, and it was difficult to obtain single frequency for higher output power. This fine-tuning procedure makes this laser inappropriate for applications where varying laser power is of prime important.

2.2 Frequency stabilization

To demonstrate the application of this laser to spectroscopy, the resonance peak of the FPI cavity was used as a reference for locking the laser frequency. The experimental arrangement is shown in Fig. 5. A sinusoidal signal with a modulation frequency of 20 kHz was sent to the

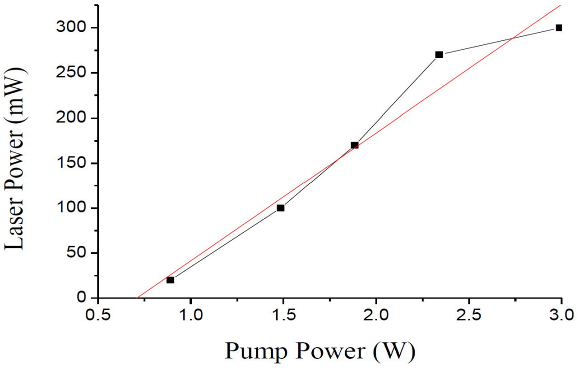

Fig. 4. 1070 nm laser single frequency output power as a function of the incident pump power. The red line is the linear fitting.

input channel 1 of a piezo amplifier (Physik Instrument E663). The piezoelectric actuator (PZT) attached on one of the FPI cavity mirrors was driven by the output 1 of E663 to dither the FPI cavity. To get a proper error signal for frequency locking, the transmitted light after the FPI was demodulated by a lock-in amplifier (Stanford Research SR844). The error signal from the lock-in amplifier was further sent to a PI (proportional and integral) servo controller (Precision Photonics LB1005). The output from LB1005 was amplified by the channel 2 of E663 to drive a piezoelectric actuator attached on the input mirror of the laser cavity for adjusting the cavity length to stabilize the laser frequency.

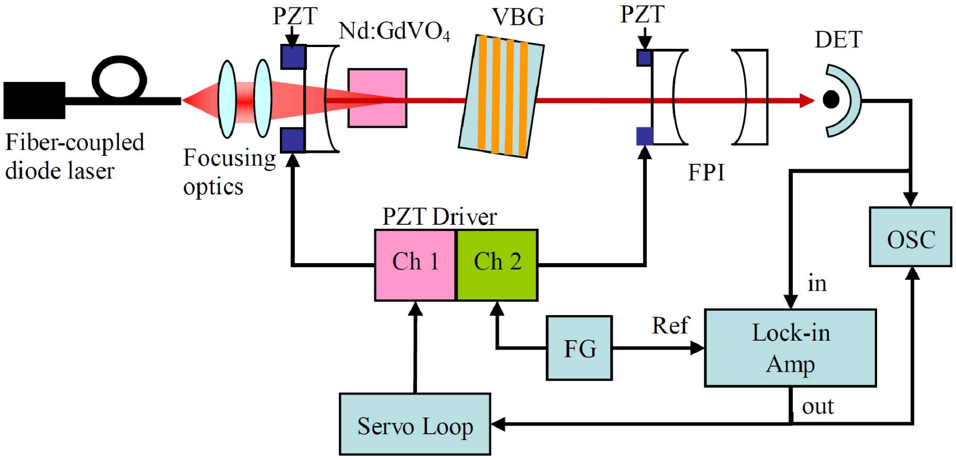

Fig. 5. Schematic diagram of the frequency stabilization setup. Here, VBG: volume Bragg grating; PZT: piezoelectric transducer; FPI: Fabry-Perot Interferometer; DET: detector; OSC: oscilloscope; FG: function generator.

The first-derivative resonance signal obtained by the lock-in amplifier at 3 sec time constant while scanning the laser frequency is shown in Fig. 6(a). This first-derivative signal is proportional to the difference between the laser frequency and the cavity resonance near the resonance center and it was served as the error signal for frequency locking. The error signal was sent to a servo controller and amplified by a piezo controller to to stabilize laser frequency. The slope of this frequency discriminator is 0.77 V/MHz. Figure 6(b) shows the error signal after the laser frequency was locked, which is proportional to the fluctuation of the laser frequency. From the error signal fluctuation we estimate that the peak-to-peak frequency fluctuation is 7.58 kHz (or 2.5×10^{-11}).

#153198 - $15.00 USD Received 22 Aug 2011; revised 15 Sep 2011; accepted 27 Sep 2011; published 10 Oct 2011

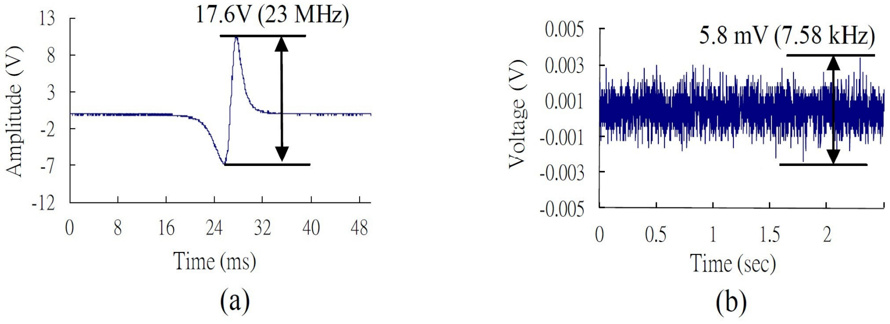

Fig. 6. (a) Error signal obtained by scanning laser frequency across the resonance peak. (b) Error signal after laser was locked.

3. Summary

A single frequency 1070 nm Nd:$GdVO_4$ laser has been demonstrated using a VBG as an output coupler in a plano-concave cavity. The VBG provides efficient mode selection to achieve single frequency operation. In comparison with our previous Fabry-Perot cavity laser [18], better output power and stability were obtained by using a plano-concave cavity to adapt the thermal focal length of the laser crystal. An output power of 300 mW was achieved with a pump power of 3 W, and the slope efficiency was 14.5%. The beam propagation parameter M^2 of this laser at 200 mW output power was ~1.2, indicating a good beam quality. The single frequency tuning range by changing cavity length was about 5.1 GHz at output power 100 mW. The tuning range can be greatly increased by simultaneously tuning the VBG temperature while scanning the PZT such that the reflection peak of VBG is coincide with the laser frequency as shown in Ref. 15. Using a laser crystal with a spherical end surface to replace the concave cavity mirror and the flat crystal can further improve the output power and frequency tuning range. Progress in this direction is currently underway.

To demonstrate its application to spectroscopy, the laser was frequency locked to a confocal Fabry-Perot cavity and a relative stability of 7.58 kHz was obtained. After frequency doubling using PPLN, this laser is an excellent light source for thallium spectroscopy at 535 nm. We plan to use this laser to investigate the EIT spectrum of thallium atom in the near future. Finally, similar laser configuration can be applied to other diode pumped solid-state lasers.

Acknowledgments

We thank Mr. Chien-Jung Liao for help at the early stage of this work and Prof. Te-Yuan Chung for useful discussions. This work was supported from the National Science Council of Taiwan by NSC 96-2112-M-007-014-MY3.