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Sub-5-pm linewidth, 130-nm-tuning of a coupled-cavity Ti:sapphire oscillator via volume Bragg grating-based feedback

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Abstract A novel coupled-cavity Ti:sapphire oscillator architecture featuring a volume Bragg grating as a feedback element is presented. The oscillator provides continuous wave lasing within a spectral linewidth as narrow as 5 pm. The output can be wavelength-tuned over an ultrabroad spectral range of 130 nm, extending from 714 to 842 nm. This unique combination of narrow spectral linewidth and wide tuning range makes the laser suitable for applications such as sensing and Raman and absorption spectroscopy. The laser also displays ideal TEM_{00} mode operation throughout its tuning range with output powers beyond 300 mW. Detailed studies of the cw lasing dynamics across the wide tuning range are described. The general architecture of this design can be implemented for high resolution tuning across the broad spectral emission bands of other solid state lasers with single mode operation.

1 Introduction

Widely tunable lasers with narrow spectral linewidth are used for absorption [1] and Raman spectroscopy [2] and other applications. Coupled-cavity resonators have been used to achieve narrow linewidth tunable laser outputs [3–5] but at the expense of increased resonator complexity featuring intra-cavity prism pairs and gratings [6]. The insertion of volume Bragg gratings (VBG) in solid-state laser or optical parametric oscillator (OPO) cavities [7, 8] has recently proved to be an alternative and elegant approach to achieving wide tunability and narrow spectral linewidth operation. Volume Bragg gratings have been successfully used to dramatically narrow the spectrum of solid-state lasers to spectral width less than 2.5 pm [9–11] and even single mode operation with powers beyond 10 W [12, 13]. Previous works have shown that when used as an intra-cavity turning mirror VBGs act as both a narrowing and a wavelength tuning element. Tuning ranges as wide as 50 nm have been reported for a Yb:KYW oscillator [14] and up to 65 nm for a Ti:sapphire oscillator while keeping a spectral linewidths less than 10 pm [15].

Volume Bragg gratings are holographic gratings recorded by interfering UV light in photo-thermo refractive (PTR) glass where the refractive index of the exposed areas is different from that of the unexposed area. The PTR glasses are typically transparent from 350 nm to 2700 nm which makes them suitable for wavelength tuning applications for many laser systems. Depending on the conditions of exposure, development and design of the holographic grating, diffraction efficiencies greater than 99% can be obtained and the reflectivity bandwidth can be tuned from 30 pm to 1 nm [16].

The tunability of lasers using VBGs relies on the Bragg condition [17]

$$2nd\cos\theta = \lambda,$$

where n is the average refractive index of the glass, d is the spacing between the constant refractive index planes, θ is the angle between the wave vector of the incident beam and the grating vector inside the medium and λ is the wavelength in the VBG. If the VBG is operated in the retroreflecting mode at normal incidence ($\theta = 0°$), the Bragg condition reduces to $2nd = \lambda_0$, where λ_0 is the Bragg wavelength and is set by the VBG design. Therefore, the spectral tuning of a laser utilizing a VBG having grating vector normal to the

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surface of PTR glass is simply determined by the incident angle with respect to the VBG normal since the Bragg condition reduces to $\lambda = \lambda_0 \cos\theta$.

In this paper, we present for the first time the combination of an ultrabroad solid-state laser with spectral selectivity introduced by a coupled-cavity VBG-based external feedback. In particular, the VBG is utilized to provide external feedback to tune and stabilize the center lasing wavelength of a Ti:sapphire oscillator while narrowing the spectral width is ensured by the coupled-cavity architecture. Using such technique, we present a tuning range spanning from 714 to 842 nm, representing a two-fold improvement from previously reported work involving an intracavity VBG [15, 18]. In our approach, the spectral linewidth is kept below 5 pm over the entire tuning range with an output power reaching several hundred milliwatts. Under all conditions, the beam profile remains that of a TEM_{00} mode. In contrast to earlier intracavity spectral narrowing schemes, the feedback technique used in this paper is easy to implement, even in low-gain oscillators. In addition, it enables tuning of the spectral properties without influencing the typically critical alignment of the main oscillator. The current limitation of the setup is set by the reflectivity of the mirrors and the clear aperture of the VBG. Both parameters can readily be upgraded and the ability to tune across a bandwidth as wide as 300 nm with single longitudinal mode operation is within reach.

2 Laser design

The oscillator was a 1.4 m long X-cavity as shown in Fig. 1. The gain medium was a 7.5 mm long, water-cooled Ti:sapphire crystal pumped by a frequency doubled thin-disk Yb:YAG laser (ELS Gemini) providing up to 7 W of pump power at 515 nm. The crystal was placed at the focus of two 5-cm-focal-length curved mirrors to ensure good overlap of the mode volume with the focused pump beam. A fused silica dispersive prism was inserted in one of the arms of the X-cavity for wavelength tuning purposes allowing coarse-tuning of the output wavelength. When tuned only by prism alignment, the center lasing wavelengths of the oscillator could be tuned from 700 nm to 900 nm with output powers in excess of 300 mW. In this case, the reflectivity bandwidth of the cavity mirrors limited the tuning range. The measured spectral linewidth obtained by prism tuning was ~1 nm with spectral jitter up to 300 pm. In order to control and fine-tune the spectral properties of the laser output, a feedback mechanism featuring a VBG was added. In this design, both flat end mirrors of the X-cavity were output couplers with transmissivity of 12% and 1%, respectively. The 1% output coupler provided the main output of the oscillator while the 12% coupler was used as the entry port for the coupled-cavity. The low 1% transmissivity

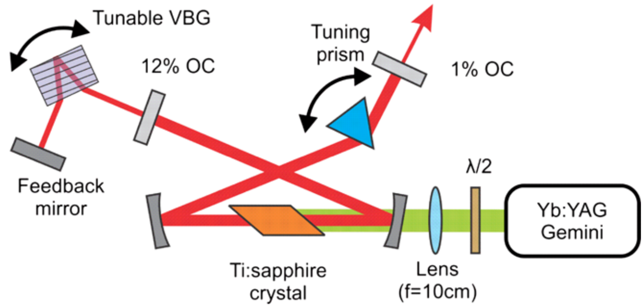

Fig. 1 Sketch of the experimental oscillator layout showing the X-cavity scheme. Spectral selectivity is accomplished by an intra-cavity tuning prism and VBG-based feedback. Fine-tuning of the output spectrum is achieved by rotating the VBG, as indicated on the sketch

of the main output coupler was chosen to limit output coupling losses and devote a greater fraction of the intracavity power for the VBG feedback while limiting the pump requirements. For the feedback, we used a $5 \times 5 \times 5\ mm^3$ VBG (Optigrate Corp.) with a normal incidence Bragg wavelength of $\lambda_0 = 852.16$ nm and a reflectivity linewidth of $\Delta\lambda = 180$ pm (FWHM). Both front and back facets of the VBG were broadband anti-reflection-coated and the holographic grating was recorded at a slant angle with respect to the glass facets to prevent instabilities in oscillator performance caused by residual Fresnel reflections. The feedback mechanism was completed by a high reflectivity (HR) mirror feeding the selected wavelength back into the oscillator.

Typically, the alignment of a free-space cavity with solid-state gain medium and an intra-cavity VBG is rather challenging. In the present scheme these problems were significantly simplified and tuning readily achieved without misalignment of the main oscillator. The desired operating wavelength range was coarsely selected by tuning the intracavity prism—operated with the 12% and 1% output couplers at that point of the alignment procedure. The Bragg condition could be readily found by rotating the VBG outside the cavity. Once the VBG was at the desired Bragg condition, the feedback mirror was aligned to send the beam back onto the VBG in order to be re-injected into the oscillator and the 12% output coupler could eventually be removed. In our proof-of-concept implementation, the VBG and feedback mirror had to be moved simultaneously to wavelength tune the cavity but further engineering—by implementing a true retro-reflector—would readily alleviate this complication.

3 Investigations of the spectral tunability with VBG-based feedback

Spectral tuning was obtained over a ~130 nm range, extending from 714 nm to 842 nm. Rollover in the reflectivity

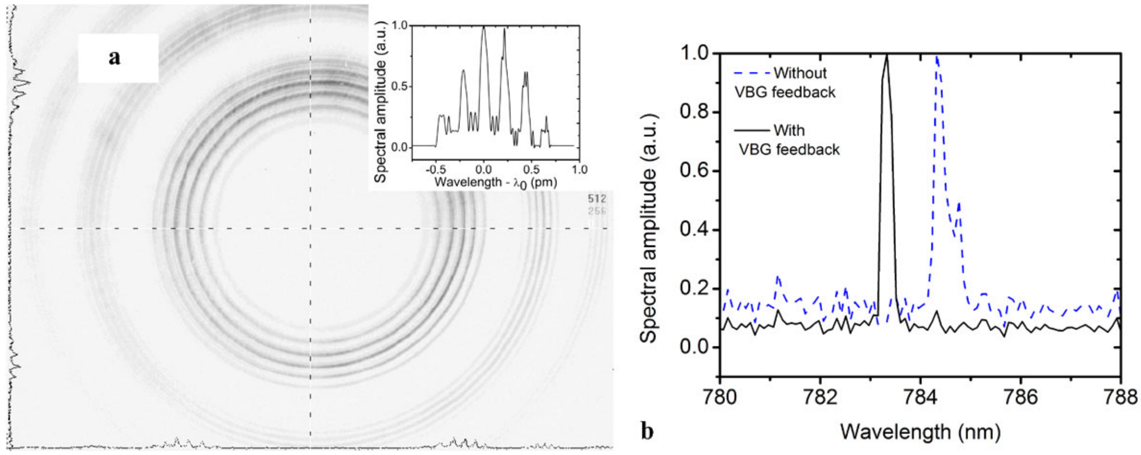

Fig. 2 (**a**) Fabry–Perot interferogram recorded at 788 nm showing six longitudinal modes and view of a section of the first set of rings (*inset*) on a scale normalized to the center wavelength; (**b**) Dynamic spectral behavior of the oscillator: the recorded spectrum (5 s integration time) with feedback indicates a smaller linewidth than without feedback. The spectral widening is attributed to the integration of the jitter

of the mirrors and increased output coupling losses resulting from the finite size of the VBG clipping the beam for wide incident angles were the primary limiting factors to the tuning range. The quasi-Gaussian reflectivity profile of the VBG had a 180 pm FWHM spectral width. Nonetheless spectral linewidths as narrow as 1 pm were measured from the oscillator. This dramatic improvement comes from the interplay between the cavity dynamics and the VBG. Due to the limited single pass gain in the Ti:sapphire crystal and the large cavity output coupling,, only a small amount of the additional intra-cavity losses can be compensated by the gain. Thus, only those longitudinal modes lasing at the peak of the VBG reflectivity profile oscillated, resulting in dramatic spectral narrowing beyond the FWHM of the VBG reflectivity linewidth itself. The output spectral width was measured using a Fabry–Perot interferometer with free spectral range of 1.9 GHz and a finesse $F = 155$. Figure 2(a) shows an interferogram obtained at 788 nm where six longitudinal modes lased under a Gaussian-like envelope. The spectral linewidth is simply retrieved by estimating the interlongitudinal-mode spacing:

$$\Delta\lambda_{\mathrm{mode}} = \lambda^2/2L_{\mathrm{eff}} = 0.22\ \mathrm{pm},$$

where $L_{\mathrm{eff}} = (L - L_{\mathrm{Ti:sapph}}) + n_{\mathrm{Ti:sapph}} L_{\mathrm{Ti:sapph}} \approx 1.4$ m is the cavity length. The measured spectral width at $\lambda = 788$ nm is therefore $\Delta\lambda = 1.3$ pm. Similar measurements and computations performed over the whole tuning range resulted in a measured spectral width consistently below 5 pm (FWHM).

To investigate the efficiency of the feedback system to lock the wavelength, and estimate its effect on jitter reduction, the main cavity was prism-tuned to operate at ~784.3 nm while the VBG was set to provide feedback at ~783.2 nm. A commercial spectrometer (HR2000, Ocean Optics) with 300 pm resolution was used to monitor the output spectrum through the 1% output coupler. The integration time was set to 5 s on the spectrometer to record the apparent broadening due to jitter. The spectra obtained with feedback (783.2 nm line) and without feedback (784.3 nm line) are compared in Fig. 2b. The peak at 783.2 nm is sharp and narrow—limited by the resolution of the spectrometer—and showed no sign of jitter. On the other hand, the peak at 784.3 nm is clearly broader and shows two distinct peaks indicating the presence of jitter. Thus, the VBG not only provides dramatic spectral narrowing but also contributes to locking the wavelength to a fixed value, a desirable feature for many spectroscopic applications.

As the incident angle on the VBG is detuned from normal incidence, the narrower becomes the reflected linewidth and the narrower the acceptance angle for a set input wavelength [19–21]. Thus, as the VBG was detuned from its designed wavelength, the spectral narrowing was enhanced and the angular acceptance of the VBG was reduced. As a consequence, the overall filtering capabilities of the VBG were enhanced.

The performance of the coupled-cavity Ti:sapphire laser was investigated by measuring both the slope efficiency and the output power for a constant pump power of 4 W over the entire tuning range (Fig. 3). In addition, the lasing threshold as a function of wavelength was measured. It ranged from 1.4 W at 845 nm to 1 W at 750 nm and 2.4 W at 720 nm. Based on Fig. 3 and the lasing threshold measurements, three regimes of operation can be identified across the 130 nm tuning range.

- For longer wavelengths from 820 to 845 nm, the relatively low emission cross-section of Ti:sapphire results in limited gain and increased lasing threshold while the VBG, operated close to normal incidence, retains a limited fil-

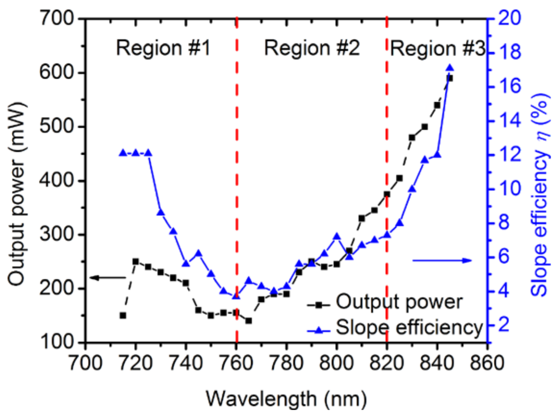

Fig. 3 Evolution of the slope efficiency (*blue triangles*) and the output power (*black squares*) as a function of wavelength for a constant pump power of 4 W. Region #1 (output coupling > 1%, limited emission cross-section, high threshold) is characterized with increased slope efficiency and output power, region #2, (output coupling = 1%, peak emission cross-section, lowest threshold) is characterized by limited slope efficiency and output power and region #3 (output coupling = 1%, limited emission cross-section, low threshold) is characterized by high slope efficiency and output power

tering power. This allows for efficient lasing with large slope efficiency.

- For wavelengths in the mid-spectral range (760–820 nm), the emission cross-section of the Ti:sapphire medium is at its peak, resulting in higher gain and a lower lasing threshold. On the other hand, the spectral selectivity of the VBG narrows resulting in reduced output power and reduced slope efficiency.
- For shorter wavelengths ranging from 715 to 760 nm, the large increase in lasing threshold, slope efficiency and output power is attributed to a larger output coupling from the 1% coupler, designed for operation at 800 nm. This is correlated with the reduced emission cross-section from the Ti:sapphire crystal is consistent with the dramatic increase in lasing threshold. Correspondingly, the increase in output coupling allows for better extraction of the intracavity power resulting in an increase in slope efficiency and output power but eventually preventing lasing for wavelengths shorter than 714 nm.

4 Laser performance at a fixed wavelength

The effect of the VBG feedback on the oscillator performance was investigated at a fixed wavelength of 781 nm. This spectral region is particularly useful for Raman spectroscopy. Figure 4 shows the output power as a function of pump power. For the 1% output coupler without VBG feedback, the slope efficiency was $\eta = 2\%$. To evaluate the fraction of the total output power devoted to the feedback loop (the ratio of the power coupled through the 12% output coupler to the sum of the power coupled through the 1% and

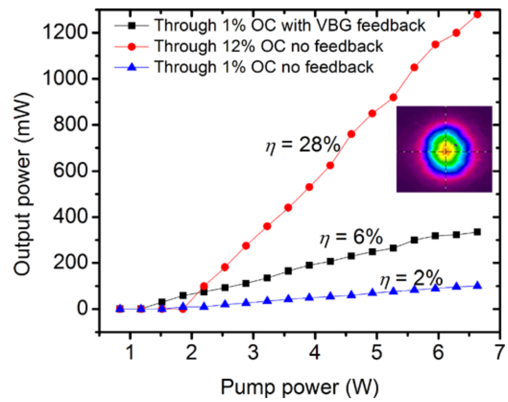

Fig. 4 Characteristic output power versus input power for output measured through the 1% OC without VBG feedback (*upward blue triangle*), through the 12% output coupler without feedback (*red circles*), through the 1% OC with VBG feedback (*black squares*)

the 12% couplers), similar characteristics were measured through the 12% output coupler. In this case, a slope efficiency of $\eta = 28\%$ was observed. Finally, the dependence of output power on input power to the laser when operated with VBG feedback was recorded at the 1% output coupler giving a slope efficiency, $\eta = 6\%$.

Over 90% of the total power output coupled from the cavity is directed onto the VBG to ensure optimum feedback (Fig. 4). At all output powers and all center wavelengths, the spatial profile was close to that of a TEM_{00} mode (inset).

5 Conclusion

A novel cw laser is reported having a tuning range of ∼130 nm while maintaining a linewidth less than 5 pm and exhibiting TEM_{00} mode beam profile. These unique features are achieved by utilizing a VBG in a coupled-cavity arrangement with Ti:sapphire as a gain medium.

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References

1. F. Markert, M. Scheid, D. Kolbe, J. Walz, Opt. Express **15**, 14476 (2007)
2. M. Ramme, J. Cox, M. Hemmer, T. Anderson, M. Richardson, in *LEOS*, Orlando, FL (IEEE Press, New York, 2007)
3. R.J. Lang, A. Yariv, IEEE J. Quantum Electron. **24**, 66 (1988)
4. F.H. Heine, G. Huber, Appl. Opt. **37**, 3268 (1998)
5. P.L. Hansen, C. Pedersen, P. Buchhave, T. Skettrup, Opt. Commun. **127**, 353 (1996)
6. A.J. Tiffany, I.T. McKinnie, D.M. Warington, Appl. Opt. **36**, 4989 (1997)
7. B. Jacobsson, M. Tiihonen, V. Pasiskevicius, F. Laurell, Opt. Lett. **20**, 2281 (2005)
8. M. Henriksson, L. Sjöqvist, V. Pasiskevicius, F. Laurell, Appl. Phys. B **86**, 497 (2007)

9. M. Hemmer, T. Chung, Y. Chen, V. Smirnov, L. Glebov, M. Richardson, M. Bass, in *Conference on Lasers and Electro-Optics (CLEO)*, Baltimore, MD (2007), p. CThE5
10. T. Chung, A. Rapaport, V. Smirnov, L. Glebov, M. Richardson, M. Bass, Opt. Lett. **31**, 229 (2006)
11. B. Jacobsson, V. Pasiskevicius, F. Laurell, Opt. Lett. **31**, 1663 (2006)
12. M. Hemmer, M. Richardson, in *Advanced Solid-State Photonics (ASSP)* (OSA, San Diego, 2010), p. AMB12
13. I. Häggström, B. Jacobsson, F. Laurell, Opt. Express **15**, 11589 (2007)
14. B. Jacobsson, J.E. Hellström, V. Pasiskevicius, F. Laurell, Opt. Express **15**, 1003 (2007)
15. M. Hemmer, Y. Joly, L. Glebov, M. Bass, M. Richardson, Opt. Express **17**, 8212 (2009)
16. L.B. Glebov, Phys. Chem. Glasses, Eur. J. Glass Sci. Technol. B **48**, 123 (2007)
17. I.V. Ciapurin, L.B. Glebov, V.I. Smirnov, Opt. Eng. **45**, 1 (2006)
18. M. Hemmer, Y. Joly, L. Glebov, M. Bass, M. Richardson, in *Laser and Electro-Optics Society (LEOS) Meeting*, Orlando, FL (IEEE Press, New York, 2007)
19. H.T. Hsieh, W. Liu, F. Havermeyer, C. Moser, D. Psaltis, Appl. Opt. **45**, 3774 (2006)
20. J.E. Hellström, B. Jacobsson, V. Pasiskevicius, F. Laurell, IEEE J. Quantum Electron. **44**, 81 (2008)
21. H. Kogelnik, Bell Syst. Tech. J. **48**, 2909 (1969)