# Volume Bragg Grating assisted broadband tunability and spectral narrowing of Ti:Sapphire oscillators

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**Abstract:** A widely tunable, narrow band Ti:Sapphire oscillator is reported. Tunability and spectral narrowing were achieved by use of a volume Bragg grating in the cavity. Tunability was observed from 785 nm to 852 nm while maintaining a spectral linewidth less than 10 pm with essentially no spectral jitter. Oscillation on only 2 longitudinal modes is also reported at 852 nm with the grating at normal incidence providing ~200 mW output power.

**OCIS Codes:** (050.7330) Volume holographic gratings; (140.3580) Lasers, solid-state; (140.3600) Lasers, tunable; (140.4780) Optical resonators; (230.1480) Bragg reflectors

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## References and links

1. B. Jacobsson, J. E. Hellström, V. Pasiskevicius, and F. Laurell, "Widely tunable Yb:KYW laser with a volume Bragg grating," Opt. Express **15**, 1003-1010 (2007).
2. 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:GdVO4 laser using a volume Bragg grating fold mirror," in Conference on Lasers and Electro-Optics (Optical Society of America, 2007), paper CThE4.
3. C.-J. Liao, Y.-H. Lien, T.-y. Chung, S. S. Yangl, and J.-T. Shy, "Lasing action of Nd:GdVO4 at 1070 nm by Volumetric Bragg Grating," in Conference on Lasers and Electro-Optics (Optical Society of America, 2007), paper CThE3.
4. L. B. Glebov, "Volume Bragg Gratings in PTR glass – New optical elements for laser design," in Advanced Solid State Photonics (Optical Society of America, 2008), paper MD1
5. L. B. Glebov, "High brightness laser design based on volume Bragg gratings," in Laser Source and System Technology for Defense and Security II, edited by Gary L. Wood, Mark A. Dubinskii, Proc. of SPIE **6216** (2006) 621601.
6. G. G. Venus, V. Smirnov, and L. Glebov, "Efficient pumping of Rb vapor by high-power volume Bragg diode laser," Opt. Lett. **32**, 2611-2613 (2007).
7. 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**, 229-231 (2006).
8. W. Koechner, *Solid-State Laser Engineering* (Springer), Chapter 3.
9. M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, seventh edition, 1999).
10. J. E. Hellström, B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Finite Beams in Reflective Volume Bragg Gratings: Theory and Experiments," IEEE J. of Quantum Electron. **44**, 81-89 (2008).

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## 1. Introduction

Widely tunable and narrow linewidth lasers have many spectroscopic applications. Usually achieved with the insertion in laser cavities of Lyot filters and etalons respectively both these techniques introduce additional losses in the cavity resulting in a need for increased pump powers. Volume Bragg Gratings (VBG) offer an alternative approach for tuning and line narrowing at low cost and with reduced losses. This has recently been demonstrated with both a cw Yb:KYW laser from 997 to 1050 nm [1] and a Nd:GdVO$_4$ laser tuned from 1062 to 1064 nm [2,3]. Ti:Sapphire is an obvious candidate for a broadly tunable laser since it has an emission spectrum ranging from 700 to 1100 nm. The high stimulated emission cross-section,

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short fluorescence lifetime and homogeneous broadening of this material enable output powers of ~500 mW with only a few Watts of pump power. Here we demonstrate the use of VBG's to both narrow the linewidth of a cw Ti:Sapphire laser to less than 4 pm, and to tune the wavelength over a range of 67 nm.

Volume Bragg gratings are holographic gratings recorded in photo-thermo-refractive (PTR) glass with high. diffraction efficiencies (~99%). PTR glasses are transparent from 350 to 2700 nm permitting wide tenability [4]. With a damage threshold of ~40 $J/cm^2$ (for 8 ns pulses), a nonlinear refractive index similar to fused silica, and multi-kW cw power loading capability VBG are ideal for high intra-cavity powers [4]. The reflectivity bandwith can be designed from 40 to 1000 pm. Spectral tuning as a cavity reflector requires satisfying the Bragg condtion $2nd\cos\theta = m\lambda$ for angles close to normal incidence [5] where $n$ is the index of refraction of the glass, $d$ is the spacing of the grating planes, $\theta$ is the angle of incidence on the grating, $m$ is the diffraction order and $\lambda$ is the wavelength. Limited spectral tuning can also be obtained by temperature tuning, where the diffraction efficiency changes by 7 pm/K [7].

In this paper we describe the performance characteristics of two configurations of Ti:Sapphire lasers using VBG's as resonator mirrors. The first demonstrates near-single frequency operation of a short cavity laser. The second laser uses angular tuning of a longer resonator to exhibit narrow line emission (67 nm) over a broad spectral range.

## 2. Narrow linewidth operation

Although single longitudinal mode operation of a $Nd:GdVO_4$ laser with a VBG has been demonstrated [5], it is much more difficult to produce single mode operation of Ti:Sapphire laser because of its extremely broad gain bandwidth. Here we investigated several cavity configurations for narrow linewidth operation, using either one or two VBG's. The laser comprised a standard X-cavity configuration with a water cooled 2 x 1 mm cross section, 7.5 mm long, 0.1% doped Ti:Sapphire crystal. Two 5 cm focal length dichroic mirrors focused the resonating beam into the crystal. All the optics had broadband antireflection coatings from 700 to 900 nm. The oscillator was pumped either by a 5 W frequency doubled (515 nm) CW thin disk Yb:YAG laser or a multi line 5 W Argon ion laser. The VBG's (5 x 5 x 5 mm, fabricated by Optigrate) used were anti-reflection coated and designed for maximum (99%) reflectivity at $\lambda_0$ = 852.8 nm with a spectral bandwidth of 180 pm. The grating vector was tilted at 0.2° with respect to the faces of the VBG. The cavity length was kept as short as possible to limit the number of modes falling within the reflectivity linewidth of the VBG. The impact of shortening the cavity from 80 cm, used for our earlier studies [6], to 25 cm used in the present investigations is shown in Fig.1. Figure 1 also shows the effects of intra cavity losses: the dashed line represents the lasing threshold, all modes below this line will not have an amplitude high enough to resonate. Whereas many lasing modes were possible with the longer cavity, the shorter one limited oscillation to one or two modes.

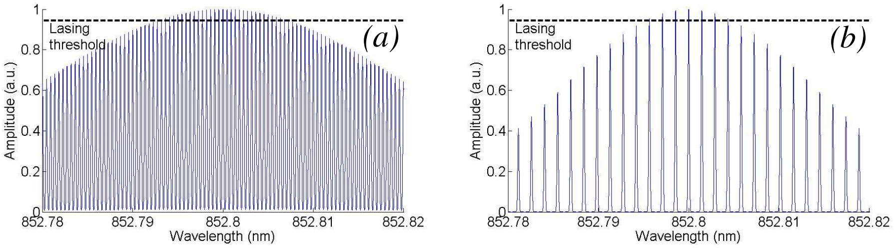

Fig. 1. (a) Theoretical representation of longitudinal modes for an (a) 80 cm and a (b) 25 cm long-cavity

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Three cavities were compared in performance, (i) one with a T = 4% or 12% output coupler M1 at 850 nm and a high reflectivity dielectric mirror as an end mirror M2 (Fig. 2), (ii) a second comprising a VBG replacing the end mirror M2 and the same dielectric output coupler M1 and (iii) a third with VBG's both as an end mirror and as an output coupler.

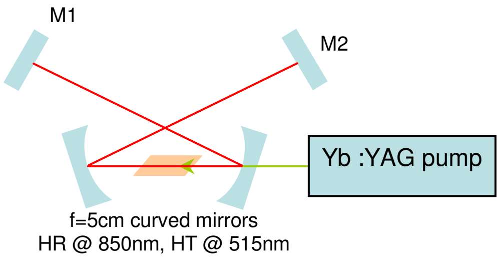

Fig. 2. Cavity configuration

The output power performance of the three configurations are summarized in Fig.3. The low slope efficiency and low output power in the dual VBG configuration (Fig. 3(c)) shows that the output coupling is not optimum. To achieve higher output power with better slope efficiency, one of the VBGs was replaced by a 4% output coupler (Fig. 3(b)) even further improvement of the slope efficiency and output power were achieved with a 12% output coupler (Fig. 3(d)).

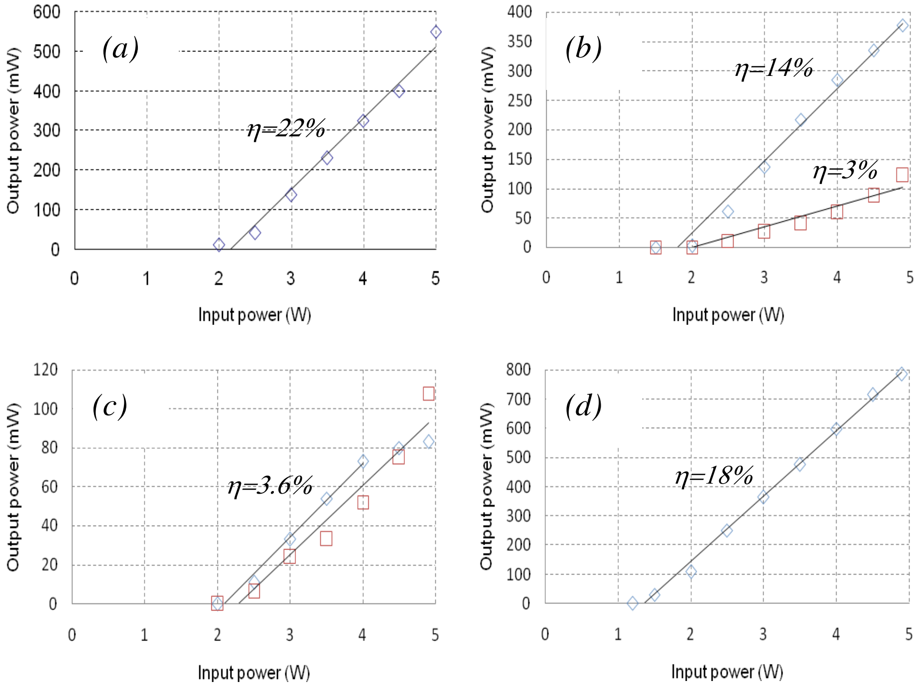

Fig. 3. Characteristics of the oscillator with (a) configuration (i) with M1 = 4% OC and M2 = HR mirror, (b) configuration (ii) with M1 = 4% OC and M2 = VBG, (c) configuration (iii) with M1 = VBG and M2 = VBG, (d) configuration (i) with M1 = 12% OC and M2 = VBG

Using the data from Fig. 3(a) and 3(b) the losses induced by insertion of the VBG in the cavity can be evaluated using the expression [7].

$$P_t = \frac{hc}{2\lambda\sigma\tau}\left[\frac{g_0 L}{a+t} - 1\right] t\pi w^2 \quad (1)$$

where $h$ is Planck constant, $c$ is the speed of light, $\sigma = 3.4\times10^{-23}\mathrm{m}^2$ and $\tau = 3.8\mu\mathrm{s}$ are the stimulated emission cross section and upper level lifetime of the Ti:Sapphire laser transition respectively, $g_0 \sim \sigma\Delta N$ (where $\Delta N$ was estimated based on the dopant concentration) the small signal gain, $L$ the length of the gain medium, $t$ the overall output coupling of the cavity, $w$ the size of the beam at the output coupler and $a$ the losses other than output coupling. From Eq. (1) the losses, $a$, are

$$a = g_0 \frac{L}{2\frac{P_t \lambda\sigma\tau}{hct\pi w^2} + 1} - t \quad (2)$$

For a given pump power, the resulting output power was inserted into Eq. (2) for both the configuration with and without the single VBG (configuration (i) and (ii)), and the two values of $a$ obtained. Since the cavities were identical, the extra losses calculated for the cavity containing a VBG were attributed to its insertion. The procedure was repeated for several pairs of input and output power values, and the differences in $a$ obtained with and without VBG were averaged. Through this approach the loss introduced by insertion of the VBG in the cavity were calculated to be ~3%. These losses result from the interaction of the VBG within the laser cavity since the VBG acts as an intracavity spatial and spectral filter. The losses intrinsically due to VBG itself – measured by passing an 800 nm beam through the VBG off resonance outside the cavity – are negligible.

The spectral properties of the three configurations were also investigated. The effect of adding the VBG to the resonator is shown in Fig. 4 showing the spectrum of configuration (i) (Fig. 4(a)) of the laser measured with a spectrometer having a 0.1 nm spectral resolution and configuration (ii), with the VBG showing a spectrum limited by the resolution (Δλ ~ 0.2 nm), of the spectrometer.

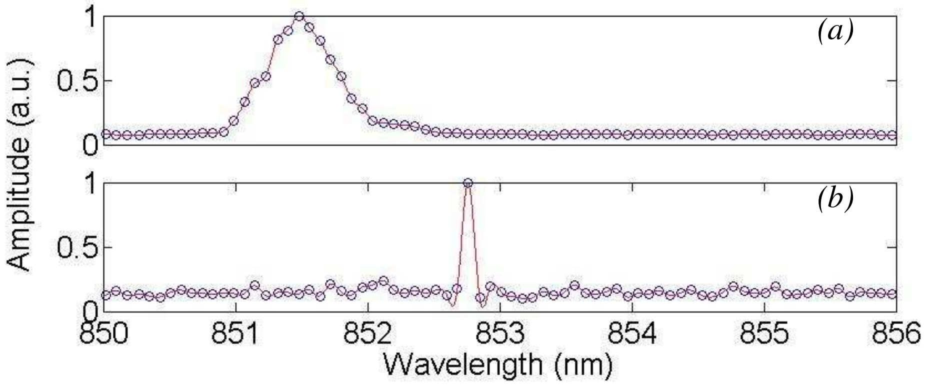

Fig. 4. Effected of adding the VBG to the resonator showing (a) the spectrum of configuration (i) and (b) configuration (ii) with the VBG.

A Fabry-Perot interferometer with a finesse F = 155 and a free spectral range FSR = 3.85 pm was used to analyse the spectrum of the laser with the VBG as an end reflector (Fig. 5). Two longitudinal modes separated by 1.45 pm are visible. The measured spectral width estimated from linewidth retrieval calculations [8] resulted in a spectral width Δλ = 1.35 pm locked at a wavelength λ=852.8 nm.

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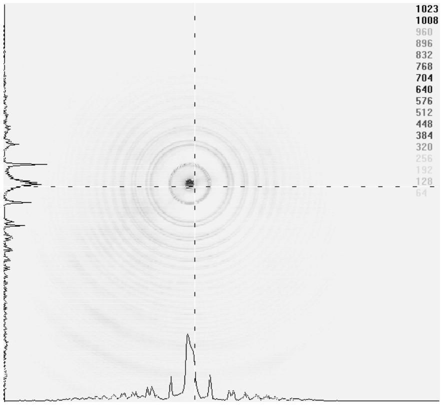

Fig. 5. Interferogram showing two longitudinal modes obtained from Fabry Perot interferometer.

Increasing the cavity length resulted in more modes appearing in the interferogram but the spectral width remained constant. Since the mode spacing was reduced, more modes could fit under the reflectivity curve of the VBG. Introducing the second VBG (configuration (iii)) did not lead to any further narrowing. For stability reasons, the cavity could not be shortened further, but a V cavity should allow for stable operation with a shorter cavity, leading to single mode operation and to a significant step in spectral narrowing.

## 3. Widely tunable narrow linewidth operation

The tunability of the Ti:Sapphire laser was demonstrated using the same VBG, but now as a turning mirror located in one arm of a cavity of length *L* ~ 80 cm (Fig. 6). The laser wavelength would be tunable by simply changing the angle of incidence on the grating. The layout of this resonator is sketched in Fig. 6. All components in this setup were identical to those in the normal configuration experiment.

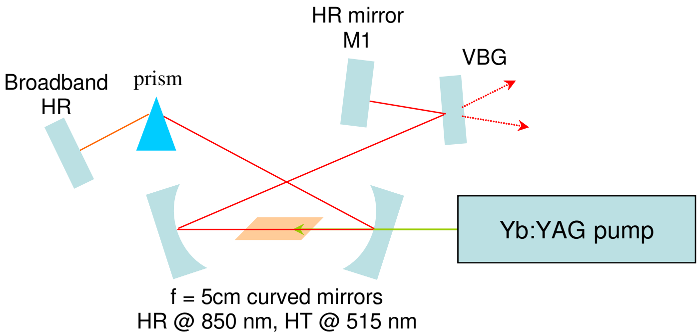

Fig. 6. Ti:Sapphire X-cavity including a tuning prism and a VBG to achieve both tuning and spectral narrowing.

In order to initially select the wavelength, a prism was introduced in the cavity and lasing was obtained without a VBG in the cavity. Once the right wavelength was obtained by prism tuning, the VBG was inserted in the cavity at the Bragg condition for the chosen wavelength and lasing was readily achieved. The prism could then be removed from the cavity and lasing could be obtained easily again after re-aligning the HR mirror. Once the wavelength of choice was selected, rotating the VBG and correcting for alignment on M1 allowed for wide tuning. A different scheme involving a wide angle mirror has been proposed by Jacobsson et al. [1] and could be incorporated into this setup.

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The nominal reflectivity of the VBG, neglecting losses, is defined as the ratio of the reflected power to the sum of the reflected and transmitted powers according to Eq. 3:

$$\eta = \frac{I_{reflected}}{I_{reflected} + I_{transmitted}} \times 100 \tag{3}$$

The effective reflectivity of the VBG, accounting for the increased angular and spectral selectivity as the incident angle on the VBG is increased was measured as a function of wavelength (Fig. 7). A separate tunable laser source was used and the beam was reflected from the VBG. The incident angle on the VBG was changed for each wavelength so that the grating meets Bragg condition. The nominal reflectivity linearly decays with decreasing wavelength for horizontally polarized light.

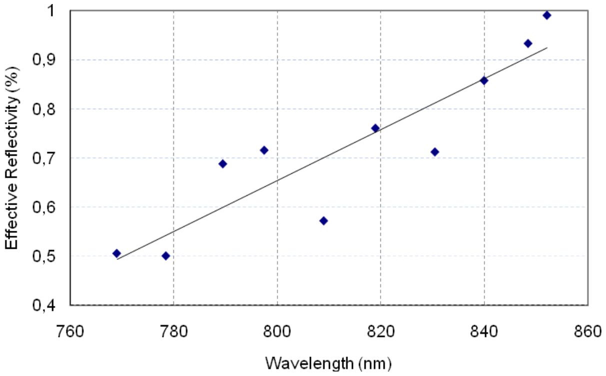

Fig. 7. Wavelength dependence of the effective reflectivity of the VBG used in the oblique incidence configuration.

Tuning of the laser shown in Fig. 6 was achieved from 852 to 785 nm by rotating the VBG. Variations of both the slope efficiency and the lasing threshold were observed (Figs. 8 and 9)

The output power was measured as a function of wavelength for a constant input power (Fig. 8(a)). The output power could be kept essentially constant over more than 30 nm with minor adjustments of the cavity. For the shortest wavelengths in the tuning range, the output coupling was too high to maintain a constant power. The combined effects of the increase of the cross section of Ti:Sapphire when the wavelength is tuned from 852 to 785 nm and the reduction of the effective reflectivity of the VBG, led to an increase of lasing threshold (Fig. 8 (b)). These same combined effects explain the variations of the slope efficiency in Fig. 8(a).

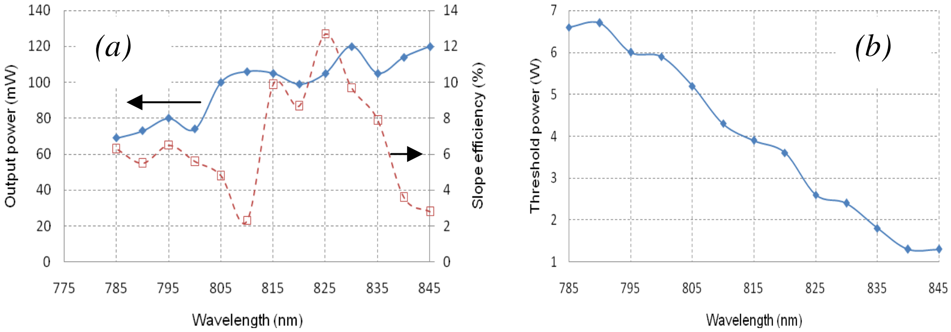

Fig. 8. (a) Output power (solid line) and slope efficiency (dashed line) for a constant pump power P = 4 W, (b) Threshold power as a function of wavelength.

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The slope efficiency was characterized for two wavelengths (785 nm and 845 nm) by measuring the output power through the VBG (Fig. 9). In both cases no other output coupler other than the VBG were in the cavity. Two beams exited through the VBG and the data in Fig. 9 shows the sum of the two. The beam exiting the cavity coming from the curved mirror typically contains more power than the one reflected from the end mirror. The VBG acts as a spatial and spectral filter and the beam coming from the curved mirror is not spectrally and spatially perfect. Even though the diffraction efficiency of the grating is much higher at 845 than 785 nm (Fig. 7), the slope efficiency at 845 nm is much smaller than at 785 nm (Fig. 9). This is expected since the only output coupler being used in the cavity is the VBG itself. Higher diffraction efficiency translates to lower output coupling and, as a result, most of the power at 845 nm is stored in the cavity instead of being coupled out.

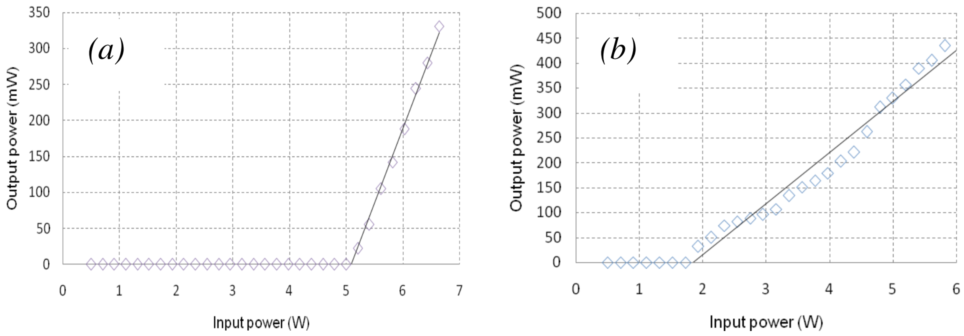

Fig. 9. (a) Characteristics output power versus input power at 785 nm – slope efficiency ~14%, threshold power 5 W (b) Characteristics output power versus input power at 845 nm – slope efficiency ~11%, threshold power 1.7 W.

The beam profile exiting through the VBG is not $TEM_{00}$. However if the end mirror M1 (Fig. 6) was replaced by a 1% output coupler, the beam quality through this mirror was perfectly Gaussian with powers ~100 mW, but the tuning range was reduced to 10-15 nm. As is observed, spectral tuning over over 67 nm from 852.8 to 785 nm is obtained.

Figure 10 shows the spectrum at the lower end of the spectral range. Both the VBG size and its reduced reflectivity with decreasing wavelength limit the short wavelength tuning range

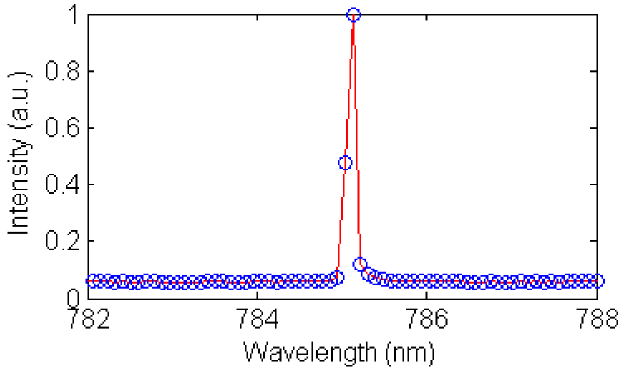

Fig. 10. Normalized spectrum at the lower end of the tuning range (785 nm).

Fabrey-Perot spectrometric measurements (Fig. 11) show the linewidth to be $\Delta\lambda = 1.5$ pm. Over the entire tuning range.

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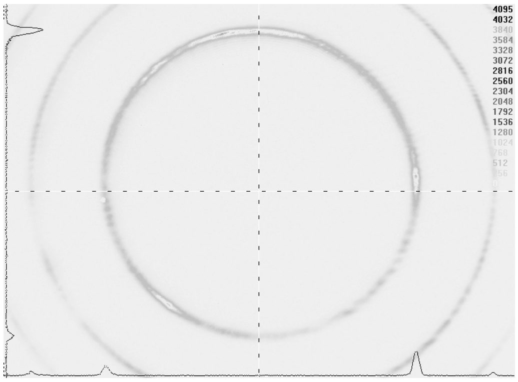

Fig. 11. Fabry-Perot fringes at 834 nm.

Because the cavity length of the resonator is longer in this case (80 cm), the separation of the individual longitudinal modes is no longer resolved.

## 4. Summary

Narrow linewidths (1.35 pm) and broad spectral tenability over 67 nm was achieved in a Ti:Sapphire oscillator using a Volume Bragg Grating as an output coupler. Stability of the spectrum over time was observed which makes this configuration particularly suitable for spectroscopy applications.. Further improvements would include the use of a thicker VBG to permit single mode operation from the Ti:Sapphire laser.

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