A self-tunable Titanium Sapphire laser by rotating a set of parallel plates of active material

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Abstract: In a recent work, the authors reported the experimental demonstration of wavelength tuning in a single birefringent plate of Ti:sapphire crystal based on its own birefringence properties. In that device, the thickness of the active plate, limited by the width of the single order tuning spectral region, imposed a strong constraint in the power performance of the laser. The aim of this work is to overcome this limitation by using a set of several identical birefringent plates so that the wavelength tuning of the laser is obtained by synchronously rotating the plates in their own plane. A discussion about the laser performance is presented.

OCIS codes: (140.3590) Lasers, Titanium; (160.1190) Anisotropic optical materials

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1. Introduction

The development of precise and reliable wide band tunable lasers emitting in both continuous or pulsed ways is important in many fields of science and technology. The tuning mechanism in most of these devices is based on intracavity frequency tuning by using tilted birefringent plates or diffraction gratings [see 1-5 as example], but these elements increase both complexity and cost, and decrease laser efficiency. Moreover, these devices are somewhat limited by the output energy due to optical damage. Recently the authors have reported a simple and powerful method for wavelength-selective tuning in different broad band emitting laser materials based on the crystal own birefringence [6-8]. Among these examples we have shown wavelength self-tuning of a pulsed Ti:sapphire laser, made of a single a-cut crystal plate, throughout half of its full spectral range [8].Unfortunately, the thickness of the

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Ti:sapphire plate is fully limited by the optical passive properties of the material (ordinary and extraordinary refraction indices) and the broadness of the desired tuning band, since the use of a plate thicker than a certain value entails the presence of more than one interference order inside the tuning band. The problem with thickness implies a severe limitation in the power performance of the laser which, however, could be overcome by using several identical plates in series.

In this work we report, for the first time to our knowledge, an experimental demonstration of broadband wavelength self-tuning in a Titanium Sapphire laser based on a series of three active birefringent crystal plates. A 750-1000 nm wavelength tuning range has been attained by using two different sets of IR mirrors in the full spectral range spanned by the fluorescence of the Ti:Sapphire crystal. The measured slope efficiency of the laser is higher than 60%.

2. Theoretical grounds

The wavelength selection can be reached by the combined effect of the plate surfaces and the crystal anisotropy because those surfaces act as partial polarizers. For an angle of incidence close to the Brewster's angle, polarization in the plane of incidence is favored (pi polarization). On the other hand, the crystal anisotropy produces different retardations (δ_1 and δ_2) of the laser field components along the two principal directions, which changes the polarization of the wave inside the crystal. The relative retardation between the components $\Gamma=\delta_1-\delta_2$ depends on the plate thickness, the wavelength, and the tuning angle φ (see Fig. 1). As the second plate surface favors the same polarization as the first one, for a given tuning angle φ, the maximum transmittance of the system will correspond to that wavelength for which the polarization of the wave inside the crystal does not change, that is to say, the wavelength λ_{max} for which the retardation in the plate is a multiple of 2π: $\Gamma(\lambda_{max},\varphi,..)=2m\pi$ $(m\in Z)$.

The expression for the tuning curves can be straightforwardly obtained [9-10]:

$$\lambda_{\max}(\varphi)=\frac{e}{m}\left[n_e\sqrt{1-\sin^2\theta_i\left(\frac{\sin^2\varphi}{n_e^2}+\frac{\cos^2\varphi}{n_o^2}\right)}-n_o\sqrt{1-\frac{\sin^2\theta_i}{n_o^2}}\right] \tag{1}$$

where λ_{max} represents the maximal transmittance wavelength, e the plate thickness, θ_i the incidence angle, and n_o and n_e the ordinary and the extraordinary principal refractive indices respectively.

In the case of an a-cut Ti:sapphire laser plate, n_o and n_e are 1.762 and 1.770 respectively, the incidence angle θ_i is 60^o, so the maximum thickness of the plate to achieve single order tuning in a broad band of about 150 nm must be 500 micron approximately [8]. In this case, the interference order is m =5.

As the thickness of the birefringent crystal limits the gain attainable by the laser, a longer active medium is needed to improve the gain. Keeping in mind that no more than a 500 μm crystal plate can be used to cover a single tuning order in this material, we have chosen an amplifying medium made up of three identical crystal plates of 500 micron oriented with their optical axes parallel to each other. This device avoids the presence of three interference orders inside the gain band, and at the same time allows a significant gain increase. However, an increment of the spectral filter efficiency is not expected, because the effect of the adding several filter plates is counteracted by the lower number of round-trips needed for lasing, just a consequence of the higher gain of the laser.

3. Experimental results and discussion

The laser experiments were performed with a 0.1% Ti^{3+} doped, a-cut $Ti^{3+}:Al_2O_3$ set of three crystal plates. The thickness and diameter of plates were 0.476 mm and 15 mm respectively. Each one of them was put up and glued within a one mm thick steel ring with a central aperture diameter close to 15mm and external diameter of 50mm, so that the distance between consecutive plate faces was 0.5mm approximately. The parallelism between the optical axes was ensured with the aid of a polarization microscope. The achieved tolerances between different plates have been 1 micron for thickness and 1^{o} for the relative orientation of the direction of the optical axes. The combined effect of these tolerances is to lower the transmittance by a few percent.

The set of three disks was placed in a holder which allowed the simultaneous rotation of the three plates in their own respective planes (angle φ in Fig. 1), with a fixed incidence angle $\theta_i = 60^{o}$.

The set was pumped by using a quasi-longitudinal scheme, shown in Fig. 1, with a frequency-doubled Nd:YAG laser (9 ns pulse width). The pumping beam was compressed by means of a telescopic system to a diameter of 3 mm, and its incidence slightly oblique to avoid damaging the mirrors. To prevent potential dependence of the tuned wavelength on the pumping energy, owing to nonlinear effects on refraction index caused by high internal emission intensity in the resonator [8], we strived to extend the size of the spatial mode by increasing the length of the resonator and using mirrors with radius of curvature longer than those of a confocal resonator. In our setup, the resonator was 45 cm long, with a concave rear mirror of 3 m radius of curvature and a flat output coupler with 90% reflectivity, aimed to obtain an acceptable mode and output energy.

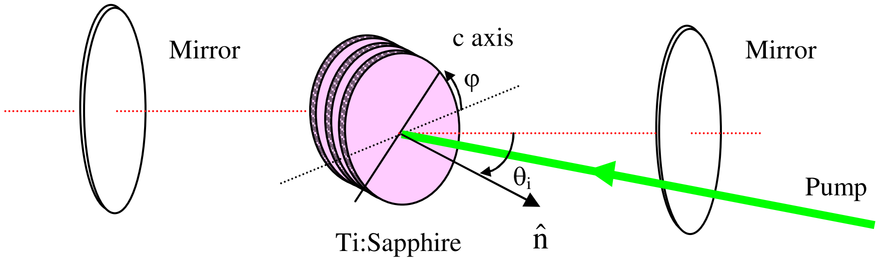

Fig. 1. Experimental set-up for the self-tuned $Al_2O_3:Ti^{3+}$ laser.

Spectral detection of the laser output pulse was performed by using a Jobin Ivon TRIAX 190 monochromator with a Hamamatsu InGaAs array, providing a resolution of 0.2 nm.

Varying the φ angle, the laser emission can be spectrally tuned in a range from about 760 nm to 890 nm, closely corresponding to the high reflectivity region of the mirrors. In Fig. 2 we present the experimental tuning curves obtained with our setup for an absorbed pumping energy of 20 mJ. Two different tuning orders are present with m=4 for low φ angles and m=5 for higher φ angles. It is noticeable that for φ angles around 30^{o}, the tuning wavelengths of both orders m=4 and m=5 lie near the border of the reflecting band of the mirrors, implying that there is no laser emission around that orientation angle. This results from the use of plates some thinner than intended, which increases the spectral broadness of each order.

On the other hand, and independently of plate thickness, for angles very close to 0 or 90^{o} the interference contrast of the two polarization components is too low, and the system is not able to tune, giving rise to an invariant laser spectrum under changes in the φ rotation angle; these emission spectra are centered around 805 nm for $\varphi=0^{o}$ and 820 nm for $\varphi=90^{o}$, (polarizations parallel and perpendicular to the optical axis respectively), and are spectrally much broader than the tuned radiation (30 nm FWHM against 3 nm FWHM of tuned radiation).

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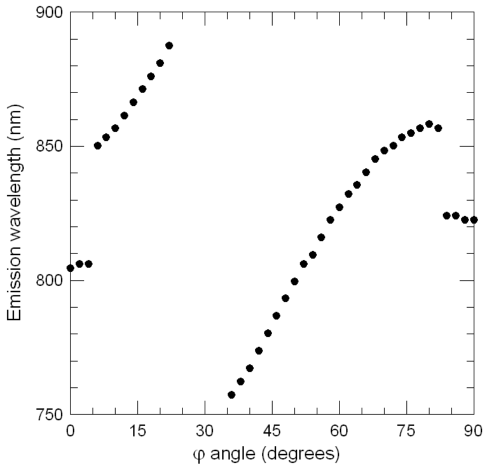

Fig. 2. Tuning range of Ti:sapphire laser as a function of the orientation angle φ between the optical axis and the polarization plane. The plates thickness was 476 microns.

Figure 3 shows the measured intensity of laser emission versus tuned wavelength. The intensity is clearly greater for low φ angles. This is a consequence of the greater cross-section of both absorption and emission for polarization parallel to the optical axis [5].

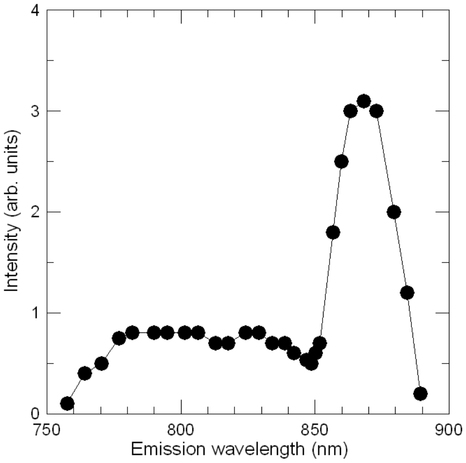

Fig. 3. Relative intensity of the laser emission as a function of the tuned wavelength.

With the aim of investigating the laser energy performance, we measured the output energy for different values of input energy at a fixed orientation of the plates $\varphi = 15^{\circ}$. The outcome is presented in Fig. 4, showing a threshold of 9 mJ and a slope greater than 60% in terms of the absorbed input energy. The laser beam remains transverse monomode up to an input energy of about twice the threshold. As an example Fig. 5 shows a picture of the mode profile for an absorbed pump energy of 15 mJ. Under these conditions, the typical delay respect to the pumping pulse was about 100 ns, and the FWHM of laser pulses about 30 ns.

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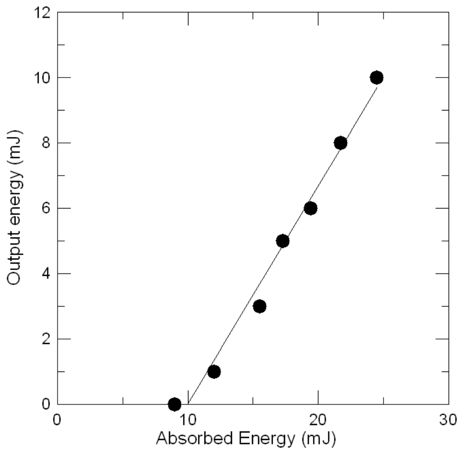

Fig. 4. Laser output energy as a function of the absorbed pumping energy. The orientation angle φ between the optical axis and the polarization plane was fixed at 15° ($\lambda_{max} = 860$ nm).

Finally, we tested tuning in the longer wavelengths region of the emission band, by using HR mirrors in the 850-1050 nm band. Tuned laser emission was obtained between 860 and 1000 nm, as shown in Fig. 6. These results demonstrate that in spite of the quick fall of gain towards longer wavelengths, our method allows tuning over most of the spectral range of the Ti:sapphire crystal.

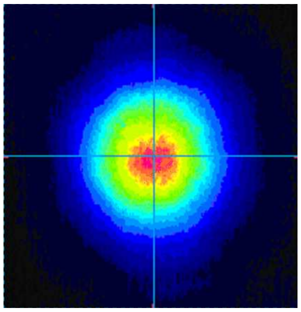

Fig. 5. Spatial mode of the laser output beam.

A fundamental question that remains to be addressed is the effect on laser operation of the actual tolerances in the relative orientation between the optical axes of the plates, the incidence angles and above all, the thickness of the plates. We have confirmed that the threshold pumping energy of the laser with our set of three plates, with 1 micron of width tolerance, is about 0.4 times the single plate threshold, and higher than the ideal factor of one third. Another effect of tolerances is the broadening of the tuned emission spectra. In our case, the measured spectral FWHM of the output laser pulses with an input energy twice the threshold was close to 3 nm, whereas with a single plate in equivalent conditions [8] it was close to 2 nm, which shows a spectral broadening effect, surely due to these tolerances.

With the aim of setting the limits of the tuning system, we have tested a set of two plates with a thickness difference of 3 microns. This value of the tolerance is high enough to give rise to differences in λ_{max} in expression (1) which are comparable to the spectral width of the output laser pulses in some zones of the tuning band. The experimental results when using this set show a very low quality tuning, only achieved over a very narrow band (less than 50 nm) and with no laser emission outside, due to high transmission losses. As expected, laser

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operation was normal for φ angles close to 0 and 90^{o} (untuned emission), since for those orientations there is no tuning effect and the sample thickness is irrelevant.

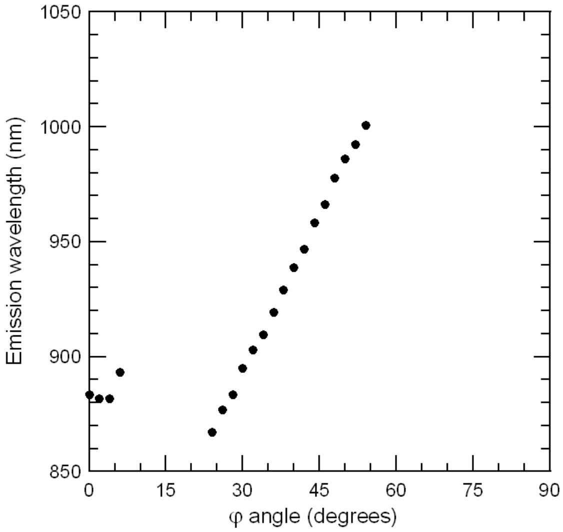

Fig. 6. Tuned wavelength of Ti:sapphire laser as function of the orientation angle φ between the optical axis and the polarization plane in the extended IR zone. The thickness of the plates was 476 microns.

4. Conclusions

Tuning based on its own birefringent properties, has been demonstrate in a Ti:sapphire pulsed laser by rotation of a set of three identical crystal plates. The use of a multi-plate set allows for a higher output energy while preserving a good quality tuning performance all over the spectral emission band. From a practical point of view this is an important approach since it allows the design of Ti:sapphire lasers with no additional intracavity tuning elements, while increasing laser efficiency and reducing complexity and cost. A full characterization of the multi-plate laser system performances was carried out. Firstly, the tuning operation and tuned wavelength as a function of the crystal axis orientation (Figs. 2 and 6), and secondly, the output energy as a function of both the emission wavelength (Fig. 3) and the input energy (Fig. 4) were investigated. The effect of thickness tolerance has been studied, and the importance of its minimization in order to increase the system efficiency has been shown. Although there is a slight decrease in the filter spectral resolution, the laser threshold of the device is about 0.4 times the mono-plate threshold in equivalent conditions.

This compact setup can be easily used for injection-locking in more complex Ti:sapphire lasers and it can be very useful for CW lasers, where the tuning function is usually implemented by means of birefringent intracavity filters.

This device has been patented: patent application number 20080271.

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