Dual wavelength Titanium:Sapphire Laser

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ABSTRACT

On this work we present a Titanium:Sapphire laser with simultaneous dual wavelength operation in the 890 nm region. Dual wavelength operation is obtained using a novel four stage birefringent filter in which we can control wavelength separation by tilting one of the filter elements. The laser operates in continuous wave pumped by a 5.5 Watts 532 nm source producing 100 mW at both wavelengths. We obtained wavelength operation with separation of 2.0 nm to 3.0, corresponding to frequency separation between 0.8 THz to 1.2 THz. The ultimate goal is the development of a source in the terahertz (THz) region of the electromagnetic spectrum for medical applications

Keywords: Laser, birefringent filter, dual frequency operation**.**

1. INTRODUCTION

The dual wavelength laser system that we describe in this manuscript is based on a birefringent filter. An optical filter is a device which selectively transmits light in a particular range of wavelengths while blocking the remainder. This can be achieved using selective absortance in the material. When the desired outcome is the observation on a range of wavelengths, instead of using a set of absorbing filters a wave scanner system is needed. A wave scanner system normally comprises a dispersive element which separates the wavelengths and parts of them are blocked. For most systems the wavelength separation in the spectrum is accomplished by dispersive elements such as diffraction grating or prisms, interference filters, acoustical-optical filters, liquid crystal tunable filters, Michelson interferometers, Fourier Transform interferometers, and multi-order etalons. A type of tunable filtering widely used in lasers and solar spectroscopy is the Birefringent filter (BRF). On the other hand, the use of multiple wavelength sources opens new perspectives in relatively new fields. For example the exploring of dual wavelength sources has been used for optical coherence tomography (OCT) [1] or used as intermediate process for millimeter-terahertz sources (30 µm – 3mm range) [2]. The double source for the OCT is based on two independent low coherence sources, while the intermediate source for a THz laser was done by the use of a grating in a Littrow configuration using two reflective wavelengths.

In particular we are interested on the generation of novel terahertz sources. The generation of pulsed or coherent radiation in the THz-regime has been an active area of research activity in the last years. Now several systems are commercially available, which are complex and therefore expensive in price. The lack of a compact, cheap CW THz laser source with acceptable power output make researches all over the world investigate on the optimization of existing methods or the development of new methods to generate CW THz-radiation.

2. TWO COLOR BIREFRINGENT FILTER

The combination of a birefringent filter consisting of several plates was first introduced by Lyot in 1933. In this proposal the plates oriented normal to the incident light, have cascaded lengths of a factor of two and include perfect entrance and exit polarizers for each element. The optical axis is located at the plates surface and at 45° to the orientation of the polarizer, in order to generate two equal strong polarizing components. The free spectral range (FSR) of the plates is repeatedly cut in half. The convolution of the single transfer functions leads to the transmission of the overall filtering system that consists typically of 3-4 plates. This is known to be the filter with the highest rejection.

As a laser tuning element, the BRF is used as a intracavity tuning element as a cascaded set of filters oriented at Brewster angle, acting as partial polarizers, which lengths keep an integer length relation in the form $1:2:4:...:2^n$. The optical path length behave as a full wavelength phase filter, also known as zero-order retardation plate [3]. The wavelength tuning is achieved by rotating the filter as a unit in such a way that the relative retardation keeps a constant value.

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2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.901690

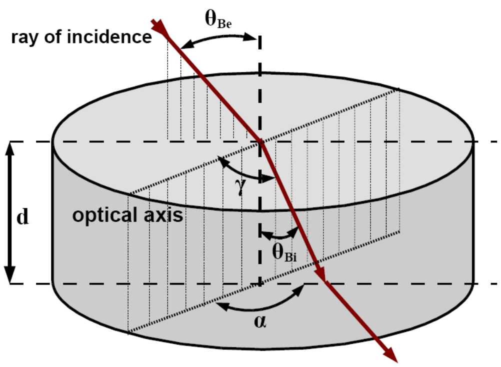


Figure 1: Angle definition of a birefringent element with its optical axis on the surface and a thickness *d*. The angles θ_{Be} and θ_{Bi} are the external and internal Brewster angle respectively. The angle between the optical axis and the normal to the extraordinary wave component is defined as γ and α is the rotation angle of the phaseplate.

To understand the effect of the rotation and/or tilt of the thickest waveplate in the filter resulting in a double peak of the transfer function, we analyze the by the formulas of the induced phaseshift δ of a single waveplate at an angle θ_{Be} for the polarization component parallel to the plane of incidence [4]:

$$\delta = \frac{2\pi}{\lambda} \cdot \frac{d}{\cos(\theta_{Bi})} \cdot \Delta n \cdot \sin^2(\gamma) = 2 \cdot \pi \cdot m \tag{1}$$

where λ is the central wavelength, d is the thickness of the plate, θ_{Bi} is the internal transmission, γ is the angle between the optical axis and the propagating ray and Δn the birefringence of the plate. The thickness of the plate d is chosen in a way to achieve a λ-plate with an integer number m as its order. With a λ-plate the spectral transfer function has its maximum directly at the central wavelength. Considering the optical axis on the plane of incidence of the plate, the graphic definitions of the angles γ and is shown in figure 1. The internal angle θ_{Bi} is calculated by the Snell law knowing the external incident angle θ_{Be}; usually for laser tuning elements θ_{Be} is chosen at Brewster angle.

If the optical axis is placed on the surface of the plate, the angle γ is defined by the following angle combination [5,6]:

$$\cos(\gamma) = \cos(\theta_{Be}) \cdot \cos(\alpha) \tag{2}$$

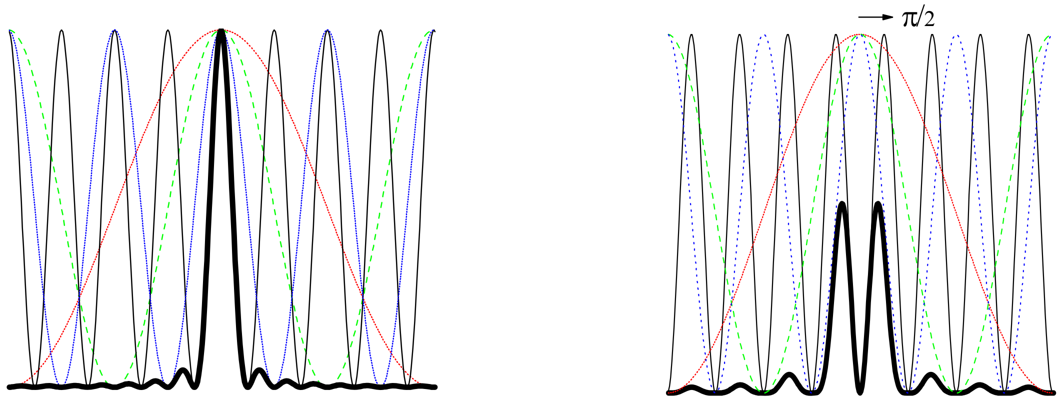
where the angle α describes the rotation of the birefringent plate in azimuthal direction. Moreover the free spectral range (FSR) for the polarization parallel to the plane of incidence of such a birefringent plate at the light incident is defined with consideration of the just introduced projection angles [5]:

$$FSR = \frac{\lambda_o^2}{d \cdot \Delta n} \frac{\cos(\theta_{Bi})}{\sin^2(\gamma)} \tag{3}$$

Therefore, the resulting FSR and the introduced phaseshift of the ordinary and extraordinary polarization component of each birefringent element depend on the rotation angle α in azimuthal direction and on the angle of incidence. Typically the plates of a birefringent filter are designed in a way that at Brewster angle incidence allow 2π phaseshift (λ-plate).

If the thickest plate of the birefringent filter, which has the fastest oscillating response, is rotated and/or tilted in such a way that the resulting phase shift is $\boldsymbol{\pi/2}$ out of all the other plates, the transfer function of this plate has its minimum exactly at the wavelength where the shorter plates of the filter show a maximum. The convolution of the single transfer functions is now resulting in two peaks instead of one as before (Figure 2).

This effect can be achieved for many combinations of tilt and rotation angles by choosing different orders of the phaseshift. For these different combinations also the FSR is varied as a consequence of a larger/shorter optical length inside the birefringent material. Although the inclusion of a tilt departs from the Brewster angle condition, the results is that different separations of the two filtered peaks further tuning in a dual laser frequency operation. As in a standard BRF the bandwidth of the transmitted peak is determined by the number of passes through the filter, which can be selected in a laser cavity depending on the photon lifetime defined by the cavity mirrors reflectivity. As a consequence of this deviation there is a reduction in the overall transmission of the BRF at the two selected wavelengths, which is an undesired, but tolerable effect [7,8].



(a) (b)

Figure 2. Birefingent plates combination for with polarizers between them. Plate thicknesses have a 1:2:4:8 ratio. The single plate response is shown as dash-dotted: dashed:dotted:solid, respectively. The black thick line shows the overall response when (a) the plates are aligned and (b) the thickest plate is rotated by $\pi/2$ with respect to the others.

3. EXPERIMENTAL SETUP

In order to demonstrate a laser in dual wavelength operation we build a Titanium:Sapphire laser using a BRF as described. Titanium Sapphire was chosen for its nonhomogenous broadening [9]. We used a 5 mm long Ti:Sapphire crystal with Brewster windows on the standard Z-cavity configuration to correct for astigmatism (figure 3). We extend the cavity to form a W-configuration. The cavity is stable using an intracavity 50 mm focal length AR coated lens (L2). The system is pumped using an intracavity doubled Coherent® Verdi V5 laser (Nd^{3+}:YVO4 laser doubled with a LBO nonlinear crystal) producing up to 5.5 Watts of 532 nm emission.

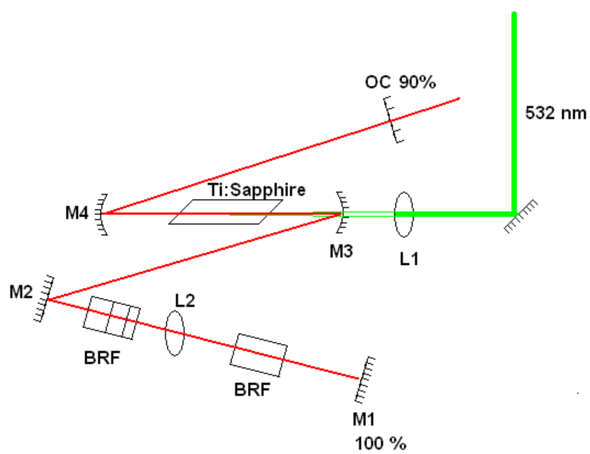
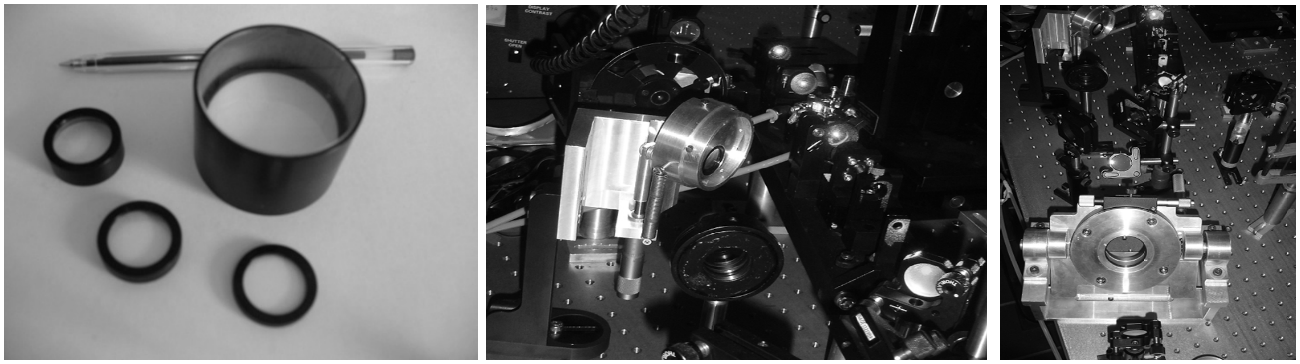


Figure 3. W-shape laser setup configuration. The BRF is place in two independent mounts as described on the text. M1-M4 are 100% mirrors. L1 is the mode matching lens. L2 is a intracavity stability lens. OC is the output coupler.

In order to obtain dual wavelength operation we used a BRF consisting on a set of four independent crystals. Three of the crystals operate as a standard BRF tuning filter [6] mounted at Brewster angle. These first three crystals, named plates 1 2 and 3, are c-cut quartz pieces of 2.0822 mm, 4.164 mm and 8.3288 mm thickness with 1 inch clear aperture (figure 4a). They have a thickness in a sequence 1:2:4 with respect to the thinnest crystal, operating at the 21th, 43th and 86th retarding order at 860 nm, respectively. The fourth element, named plate 4, is a c-cut 33.3154 mm thick crystal with a 2 inch clear aperture, operating on the 344 retarding order at 860 nm, operating close to Brewster angle (figure 4a). This is a crystal 16 times thicker than the thinnest crystal. These crystals were manufactured from a single quartz crystal at High Plain Optics Inc. in Longmont, Colorado, USA.

Plates 1, 2 and 3 were mounted on a rotating controlled mount placed inside the cavity at Brewster angle. Caution was taken to align the slow optical axis of the quartz plates using cross polarizers (figure 4b). Plate 4 was mounted on a specially design mount which can controlled independently the tilt and rotating angles, placed close to Brewster angle with respect to the lasing axis of the cavity (figure 4c)



(a) (b) (c)

Figure 4. (a) BRF filter crystals, (b) plates 1-3 mounted in the laser cavity at Brewster angle on a rotation controlled mount and (c) plate 4 mounted in the laser cavity close to Brewster angle on a tilt and rotation controlled mount.

4. RESULTS

Using the aforementioned laser configuration the system operates as a double wavelength laser. We first align the laser in the a Z-shape free-running configuration without the BRF filter, using M2 as the end cavity mirror. Having this free-running stable cavity it has a 1.4 W pump threshold. We turn M2 to form the W-shape configuration and use L2 as relay lens to have a stable cavity with the four plates BRF on the cavity and achieved a lasing pumping threshold of 3.8 W from the Coherent® V5 laser.

By rotating the plates 1-3 and adjusting plate 4 we achieve double wavelength operation at several rotation and tilt positions on plate 4 (figure 5). Plates 1-3 were placed at Brewster angle and at an angle close to 45° condition. We used Ocean Optics USB 2000 fiber couple spectrometer to obtain the laser spectra. This operation is independent of the mode hoping obtained in a linear cavity. Such effect was observed, but was not relevant for the dual wavelength operation.

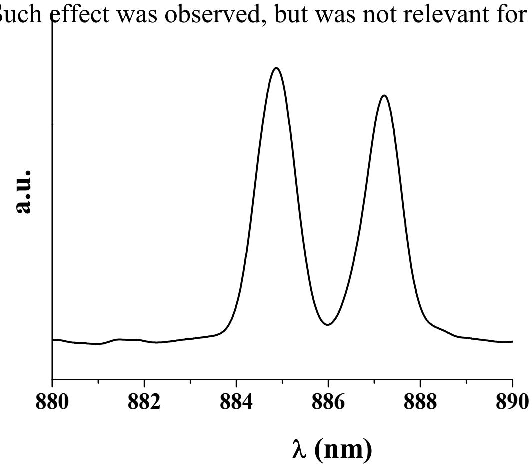


Figure 5. Spectra of double wavelength laser operation using a Ti:Saphire crystal and the design BRF filter. Both wavelengths depart from each other in 2.46 nm, corresponding to 0.917 THz.

By rotating the plates 1-3 close to the 45° condition we can tune the laser, as expected from a BRF. We control the operating central wavelength by rotating the 1-3 plates mount by a small amount. For example, on figure 6 we observe a similar dual operation at different wavelengths rotating the 1-3 plate mount 5° ahead (white) or behind (dark gray) the 45° condition (light gray). Because of the product of filtering properties of the BRF and the gain curve of the laser there is a small variation on the wavelength separation which was not corrected by plate 4.

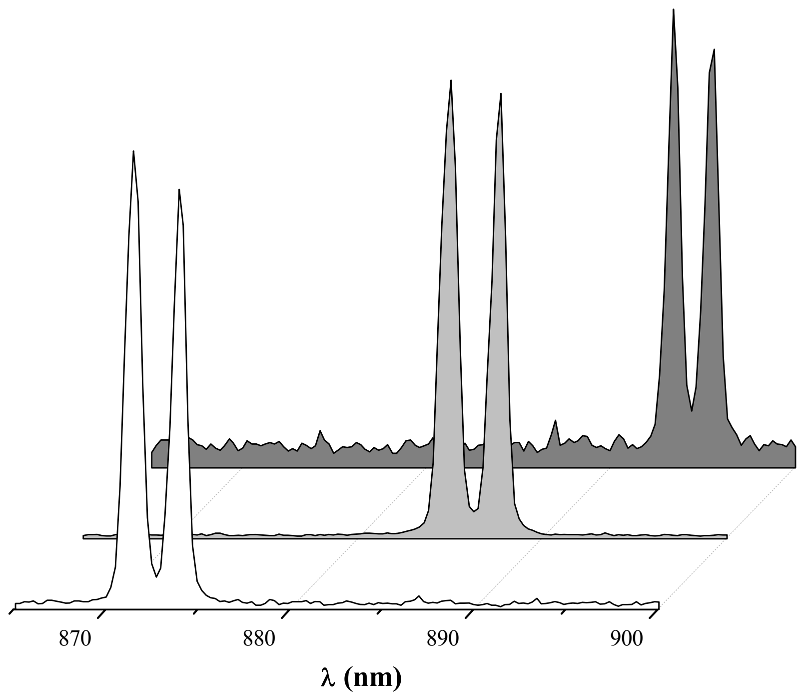


Figure 6. Dual wavelength operation of the Ti:sapphire laser using the design BRF filter. We obtained different central operating wavelengths by rotating the plates 1-3 independent of plate 4. The wavelength separations of the dual wavelength operation on the graph are 2.48 nm (white), 2.71 nm (light gray) and 2.21 nm (dark gray)

On a given central operating wavelength we can fine tune the system by rotating and/or tilting the thickest plate (plate 4) close to the Brewster angle. For example, by tilting the mount by a small amount (less than 1°) we obtain different operating conditions (figure 7). It is difficult to determine the exact angles because of the commonly observed unstable dual wavelength operation.

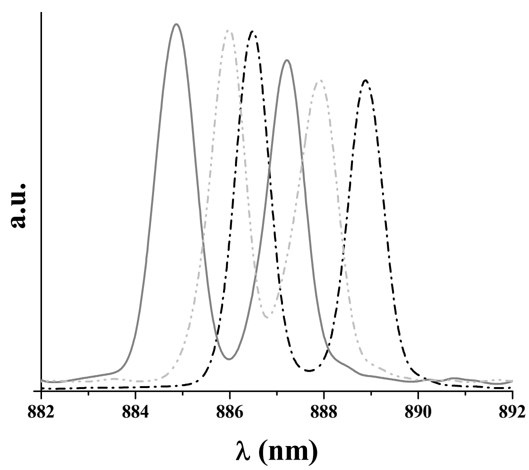


Figure 7. Dual wavelength operation of the laser using the design BRF filter tilting plate 4. The wavelength separations of the dual wavelength operation on the graph are 2.37 nm (solid), 1.91 nm (dash dash dot) and 2.40 nm (dash dot)

Using the complete system we obtain up to 100 mW with the laser operating simultaneously at two wavelengths with our 5.5 W maximum pump power. The dual wavelength operation, in spite of the theoretical analysis presented in section 2, is far of being stable at this point. It is relatively easy to obtain the dual wavelength operation once the laser is aligned, but because gain mode competition and thermal index of refraction variations in the BRF plates, specially the thickest plate, the desired dual wavelength operation is stable up to 15 min and falls out of the stable condition afterwards.

We are working on making the laser stable for longer periods of time by temperature controlling the setup. Also, at this moment in time we cannot be completely sure of simultaneous dual wavelength operation, as we have observed in a different dual wavelength laser operation using a dye laser [10], although due to the reported inhomogeneous broadening of the Ti:sapphire we expect to operate both wavelength simultaneously.

5. CONCLUSIONS

We have presented a Ti:sapphire laser operating in two wavelengths using a novel BRF. The double emission is obtained by means of a thick quartz plate which is tilted and/or rotated independent of a 3-plates standard BRF. Rotating the BRF filter we can select the central operating wavelength, whereas rotating/tilting the thickest plate we control the wavelengths separation. We observed wavelength separations between 1.5 and 2.9 nm on a tuning range of 20 nm on the 860 nm vicinity with 100 mW output at both wavelength pumping with 5.5 W of 532 nm radiation. We are working on stabilizing the dual wavelength emission and verify simultaneous operation to obtain as ultimate goal CW THz emission.

ACKNOWLEDGMENTS

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REFERENCES

[1] Felix Spöler, Stefan Kray, Patrik Grychtol, Barbara Hermes, Jörg Bornemann, Michael Först, and Heinrich Kurz, “Simultaneous dual-band ultra-high resolution optical coherence tomography,”, Opt. Exp 15 (17) 10832 (2007).

[2] S. Hoffmann, M. Hofmann, E. Bründermann, M. Havenith, M. Matus, J.V. Moloney, A.S. Moskalenko, M. Kira, S.W. Koch, S. Saito and K. Sakai, “Four-wave mixing and direct terahertz emission with two-color semiconductor lasers,” Appl. Phys. Lett. **84**, 3585 (2004).

[3] M. Title, “Tunable birefringent filters,” Opt. Eng. 20 (6) 815-823 (1981).

[4] M. Born and E. Wolf, [Principles of Optics] Pergamon Press Inc, 699 (1980).

[5] S.M.Kobtsev and N.A.Sventsitskay, “Application of Birefringent Filters in Continuous-Wave Tunable Lasers: a Review,” Opt. Spectroscopy 73 (1) 114-123 (1992).

[6] Corinna Wetzel, “Design of a novel birefringent filter for a terahertz laser source,” Master Thesis, University of Applied Sciences, Aalen, Germany (2007).

[7] Carlos Gerardo TREVIÑO PALACIOS and Corinna WETZEL “Filtro birrefringente en dos longitudes de onda” Patent MX 280131 B (2010).

[8] M. Naftaly, M.R. Stone, A. Malconi and I. Camara Mayorga, “Generation of CW terahertz radiation using two-color laser with Fabry-Perot,” Elect. Lett. 41 (3) 128-129 (2005).

[9] O.J. Zapata-Nava, C.G. Treviño-Palacios, M.D. Iturbe-Castillo and P. Rodriguez-Montero “Grating cavity dual wavelength dye laser,” Opt. Express.19 (4) 3483-3493 (2011).