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Dual wavelength continuous wave laser using a birefringent filter

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We report simultaneous dual wavelength continuous laser emission with minimum cavity elements. Tunable dual wavelength emission between 805 nm and 840 nm was observed with controlled peak separation around two nanometers, which corresponds to approximately one terahertz. Dual wavelength laser operation is possible using a novel intracavity two plate birefringent filtering element.
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1 INTRODUCTION

Laser source emission is determined by the gain medium and resonator characteristics in which single or multiple wavelengths have been obtained. Multiple wavelengths can produce wavelength beating and extends the capabilities of a laser source by multiple wavelength engineered emission in which the minimum independent obtainable wavelengths are two. Two independent engineered wavelengths, either laser has been used in optical coherence tomography (OCT) [1, 2], optical shop testing [3], commercial fiber communication systems [4], atom interferometry [5], spectroscopy and even to detect parasites in water [7]. Double wavelength emission has been obtained using diode lasers, fiber lasers and dye lasers [9]–[14]. Sources with emission in two wavelengths using titanium sapphire lasers have also been explored using coupled cavities, double-prism dispersion cavities, acousto-optic tunable filters, and with two independent seed injection lasers [15]–[22]. The use of a birefringent filter (BRF) element for dual wavelength (DW) pulsed operation with peak separation larger than 100 nm has also been reported [23].

In this paper we present a tunable continuous wave (CW) dual wavelength configuration with minimum cavity elements realized on a Ti:Sapphire laser. The DW operation is based on a novel BRF designed for dual wavelength transmission. The peak separation observed is close to two nanometers, corresponding approximately to one terahertz in separation between the two emission peaks.

2 BIREFRINGENT FILTER

The combination of several birefringent plates in a filtering system was first introduced by Lyot in 1933. In his design the plates with optical axes aligned have lengths cascaded by a factor of two, with perfect entrance and exit polarizers on each element. Therefore the free spectral range (FSR) of the plates is thus repeatedly cut in half. The product of their single transfer functions can be used to determine the transmission of the overall filtering system.

As a laser tuning filter the elements of a BRF are oriented at the Brewster angle (θ_B). Such BRFs are used intracavity for laser frequency tuning in the form of a cascaded set of filters whose lengths have an integer length relation in the form 1:2:...:2n, where the partial polarizing effect of the system reaches high efficiency due to the oscillation of the radiation in the laser cavity [24]. The thickness of the plates in a BRF, known as λ-

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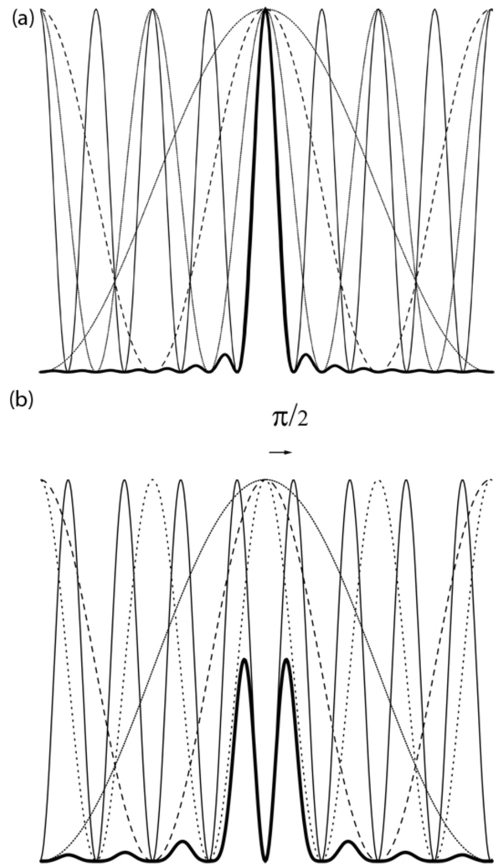

FIG. 1 Transmission of BRF plates between polarizers. The thicknesses are in ratios 1:2:4:8 with individual response in dash-dotted:dashed:dotted:solid respectively. The overall transmission (thick line) is observed when (a) the plates' optical axes are aligned and (b) the thickest plate's optical axis is rotated by $\pi/2$ with respect to the other optical axes.

plates, is designed to allow for a retardation of multiples of 2π at a given wavelength (Figure 1(a)).

If the thickest plate of a BRF, which has the fastest oscillating response, is rotated and/or tilted in such a way that its phase-shift is $\pi/2$ out of phase with respect to the other plates, the transfer function of this plate has its minimum exactly at the wavelength where the other plates of the filter show a maximum. The convolution of the transfer functions then results in two peaks instead of one (Figure 1(b)). This effect can be achieved for various combinations of tilt and rotation angles by choosing different plate orders. For these different combinations the FSR also changes as a consequence of a larger or shorter optical length inside the birefringent material. Although the system departs from the unit transmission condition, the result is that the separation of the two filtered peaks can be controlled and a dual frequency filtered spectrum is obtained. As a consequence of this deviation there is a reduction in the overall transmission of the BRF and an increase in induced losses. The filter induced loss is a tolerable effect, which is diminished using large thicknesses ratios. As in a standard laser tuning BRF, the bandwidth of the transmitted peaks is determined by the number of passes through the filter which is controlled in a laser by the cavity mirrors' reflectivity. A detailed explanation of this dual wavelength filter is given elsewhere, including the body of a patent [25, 26].

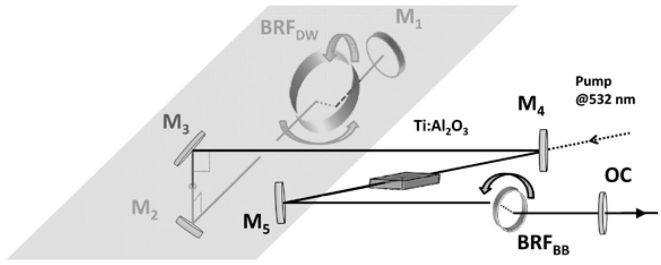

FIG. 2 Dual wavelength laser setup based on a $Ti:Al_2O_3$ crystal. M_1 to M_5 are dielectric IR mirrors, M_4 is a dichroic mirror. OC: Output Coupler. M_2 and M_3 form a 90° periscope. BRF_{BB} is the narrow broadband filter and BRF_{DW} is the thick filter as described in the text.

3 EXPERIMENTAL SETUP

In order to realize dual wavelength emission we used a Ti:Sapphire crystal (Ti:Al2O3) which is a known inhomogeneous laser gain medium capable of dual wavelength operation [22]. We have designed a DW-BRF for operation at 810 nm with a 1 THz frequency separation between the two peaks. This BRF consists of two quartz plates ($n_o = 1.5426$, $n_e = 1.5517$) with a 1:16 thickness ratio at θ_B ($\approx 57°$). The thicknesses of the birefringent plates at normal incidence are 2.082 mm for the thin broadband plate (BRF_{BB}) and 33.315 mm for the thick plate (BRF_{DW}) to produce the double wavelength filtering. The birefringent plates were cut from the same quartz crystal and placed on a 1 inch mount for the BRF_{BB} plate and a 2 inch mount for the BRF_{DW} plate to allow for a clear aperture at θ_B.

We used the Z-fold cavity depicted in Figure 2. The gain medium is a 7 mm long $Ti:Al_2O_3$ crystal with Brewster windows from Del Mar Photonics. A mirror with linear transmission between 3% at 800 nm and 5% at 850 nm was used as output coupler (OC). The cavity was completed with dielectric mirrors: M_1, M_2 and M_3 are flat mirrors, M_4 and M_5 are 100 mm curved mirrors to form a stable cavity. The cavity was pumped through the dichroic mirror M_4.

The two BRF plates were placed on opposite sides of the gain medium with independent tilt and rotation. The thin broadband BRF_{BB} was placed vertically close to θ_B operating on horizontal polarization and rotated perpendicular to the path for coarse tuning of the laser. The large BRF_{DW} was placed horizontally, due to its weight, with fine tilt and rotation capability close to θ_B, thus operating with vertical polarization. A 90°periscope formed with M_2 and M_3 was used to change the polarization accordingly. The laser was pumped with a CW doubled Nd3+:YVO4 laser (Coherent Verdi V5) capable of producing up to 5.5 W at 532 nm. This setup is simple to align and has minimum cavity elements. It avoids the use of multiple trajectories or external active elements as reported in other dual wavelength systems [10]–[17].

3.1 Laser performance

With the cavity fully aligned and only the BRF_{BB} plate in the cavity, the laser has tunability between 805 nm and 840 nm. The spectrum was monitored using a fast monochroma-

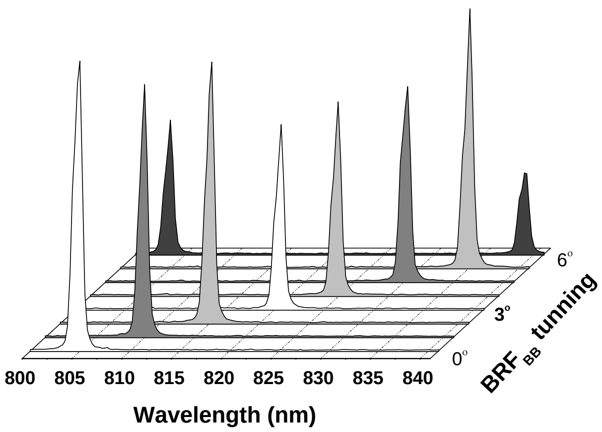

FIG. 3 Laser tuning with only the BRF_{BB} plate in the cavity. Notice the dual wavelength operation at the edge of the tuning range (black spectra).

	P_{Th} (W)	η (%)	I_{max} (mW)
Free run	1.79 ±0.06	3.50 ±0.04	132 ±1
BRF_{BB}	2.04 ±0.05	3.47 ±0.04	120 ±1
$BRF_{DW}+BRF_{BB}$ ($1\,\lambda$)	2.52 ±0.04	2.76 ±0.03	80 ±1
$BRF_{DW}+BRF_{BB}$ ($2\,\lambda$)	3.14 ±0.05	2.59 ±0.05	64 ±1

TABLE 1 Pump threshold (P_{Th}), extraction efficiency (η) and maximum output (I_{max}) for different laser configurations.

tor (Ocean Optics HR4000). This tuning range corresponds to one FSR of the plate. It was obtained by rotating the plate close to 6°(Figure 3).

With only the BRF_{BB} plate in the cavity the system is a standard tunable CW Ti:Sapphire laser. Except that if we play close attention to the extent of the tuning range, when the laser is close to the edge of the tuning range, on occasion there was double wavelength emission with peaks approximately 40 nm apart due to the balance between gain and cavity losses.

4 DUAL WAVELENGTH OPERATION

With both birefringent plates (BRF_{BB} and BRF_{DW}) placed in the cavity close to θ_B, with high pump power we can observe DW emission with different spectral separations ($\Delta\nu$) for various angle combinations of the birefringent plates. For example, in Figures 4 we observe a spectra with double wavelength taken with a high resolution monochromator (Princenton Instruments Acton SP2300 with R955 Hamamatsu Photomultiplier). Within the envelope (dotted line) there are intensity fluctuations due to gain competition and etalon effects from the BRF_{BB}.

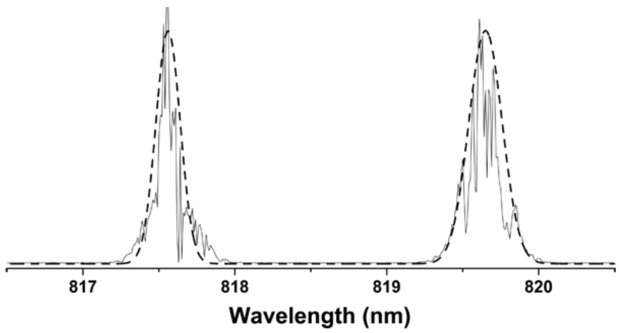

FIG. 4 Ti:Sapphire laser dual wavelength emission (817.57 nm and 819.63 nm) with spectral separation $\Delta\nu$ = 0.953 THz.

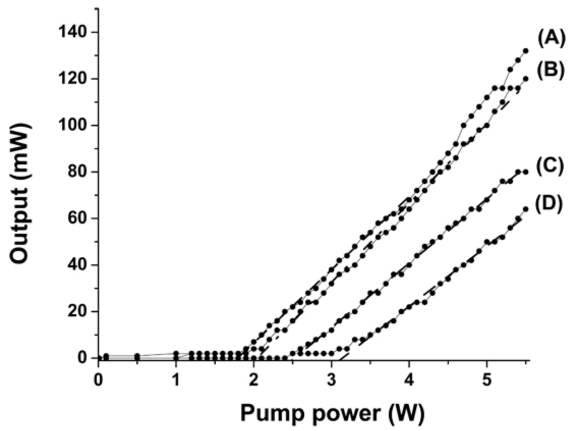

FIG. 5 Laser emission characteristic at 814.6 nm for (A) cavity without BRF, (B) with only BRFBB in the cavity; (C) with BRF_{BB} and BRF_{DW} in the cavity in single wavelength operation and (D) BRF_{BB} and BRF_{DW} in the cavity in dual wavelength operation.

The conditions for DW operation were obtained by analyzing the laser in different configurations. Without the BRF, or free run configuration, the laser operates at 814.6 nm. We obtained the laser characteristic curve (laser output as function of pump power) at this wavelength for: (A) free run; (B) with only the BRF_{BB} in the cavity; with both BRF_{BB} and BRF_{DW} in (C) single wavelength and (D) DW operation (Figure 5).

From these curves we obtained (Table 1) the laser pump threshold (P_{th}), extraction efficiency (η), and maximum output (I_{max}) for the configurations studied. For single wavelength operation we observe a threshold increase and extraction efficiency decrease when the birefringent plates are inserted due to internal losses of the quartz plates and filter strengthening, respectively.

When the system operates in double wavelength emission the BRF no longer exhibits unit transmission and additional losses are induced from the convolution among the birefringent plates (Figure 1(b)) increasing further the laser threshold. But the inhomogeneous gain of the Ti:Sapphire is large enough to sustain DW lasing. We determined the double wavelength tuning capabilities of the system with the complete BRF in the cavity and the BRF_{DW} plate at fixed angle. We fine tuned the system by rotating the BRF_{BB} plate close to 6°by an entire FSR cycle (Figure 6). We observe that the system switches between single (white spectra) and double (grey spectra) wavelength emission while turning the plate. Within a complete BRF_{BB} FSR cycle (dark spectra) we observe 16 positions where there is a double wavelength emission due to the spectral response of the BRF_{DW} plate, in accordance with the BRF design.

Double wavelength laser emission second harmonic generation (SHG) and sum frequency generation (SFG) using a 7 mm

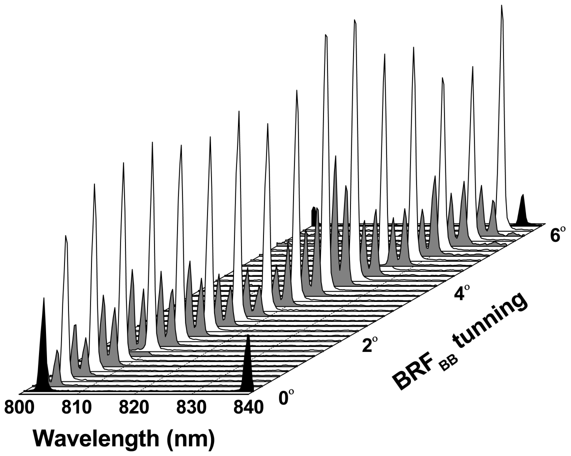

FIG. 6 Laser tuning as function of BRF_{BB} rotation with both BRF_{BB} and BRF_{DW} in the cavity. The laser switches between single wavelength operation (white spectra) and double wavelength operation (grey spectra) within the FSR range of the BRF_{BB} (black spectra).

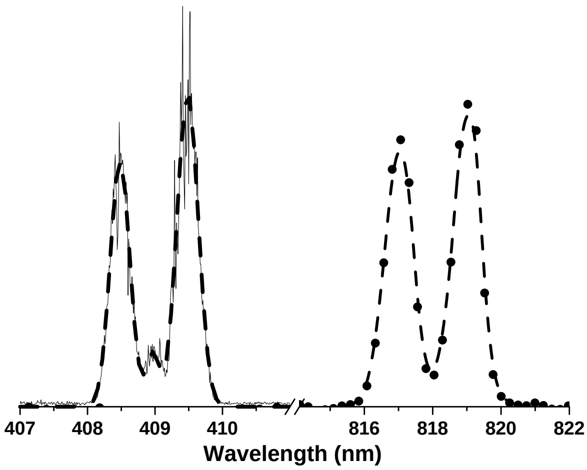

FIG. 7 (Right) Dual wavelength lasing (816.96 and 818.97 nm, $\Delta\nu = 0.901$ THz) and (Left) signal through a BBO crystal producing SHG (408.48 and 409.48 nm) and SFG (408.96 nm). The relative height of the converted peaks are: 1.00 (408.48 nm), 0.28 (408.96 nm), and 1.25 (409.48 nm).

BBO (BaB_2O_4) crystal was observed (Figure 7). SFG is only observed when both signals are present at the same time confirming simultaneous double wavelength operation, in spite of laser fluctuations. The double wavelength emission is unstable and will require feedback to improve the stability of the system. This laser system emitting in two wavelengths simultaneously could potentially be used to generate new wavelengths by nonlinear mixing, in particular due to the wavelength design a source in the millimeter-Terahertz wavelength range.

5 CONCLUSIONS

In conclusion we have demonstrated an all optical simultaneous continuous wave dual wavelength titanium sapphire laser with minimal cavity elements and easy alignment. The dual wavelength is achieved using a two-plate BRF with dual wavelength filtering with design tunable spectral separation around one terahertz.

6 ACKNOWLEDGEMENTS

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