Polarizing Gires-Tournois interferometer as intra-cavity frequency-selective element in high-power lasers

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ABSTRACT

We present a frequency selective optical setup based on a Gires-Tournois interferometer suitable to enforce single-frequency operation of high power lasers. It is based on a birefringent Gires-Tournois interferometer combined with a $\lambda/4$ plate and a polarizer. The high-reflective part of the Gires-Tournois interferometer can be contacted to a heat sink to obtain efficient cooling (similar cooling principle as for the active medium in thin-disk lasers) enabling power scaling up to output powers in the kW range.

Keywords: Frequency-selective element, Single-frequency laser, Power scaling, Spatial hole burning, Gires-Tournois

1. INTRODUCTION

Several applications require single-frequency lasers with high output power. Examples are LIGO¹ and LIDAR.² However, to date single-frequency operation of high power lasers is limited to oscillator-amplifier designs, where the frequency stability is ensured by a master oscillator and the power is delivered by an amplifier. Yet, these oscillator-amplifier systems are complex and limited in tuning range and quality when the amplifier does not contain additional frequency-selective elements.³

Frequency selection in laser oscillators is commonly achieved via a cascade of elements with reduced free spectral ranges and bandwidths. Common elements include optical gratings, birefringent filters and Fabry-Perot interferometers (FPI).⁴ As the FPI is closely related to the here proposed polarizing Gires-Tournois interferometer (PGTI), we summarize some of its basic properties. The FPI free spectral range reads

$$\Delta f_{\text{FPI}} = \frac{c}{2nL}, \quad (1)$$

where c is the speed of light, n refractive index n and L the thickness as depicted in Fig. 1 (a). The finesse $\mathcal{F}$ of a FPI is defined as the free spectral range Δf_{FPI} divided by the bandwidth of its resonances δf_{FPI} (full width at half-maximum)

$$\mathcal{F} = \frac{\Delta f_{\text{FPI}}}{\delta f_{\text{FPI}}} \approx \frac{\pi\sqrt{R}}{1-R}, \quad (2)$$

where R is the common reflectivity of front and back surfaces.

Within a laser cavity, FPIs are usually implemented as bulk optical components (etalons) used in transmission. Power scaling of these etalons is limited by the heat generated in the bulk material related to spurious absorption of the passing beam. The generated heat changes the optical length (nL) of the etalon over the surface exposed to the laser beam (inhomogeneous optical length experienced by the laser beam $nL = n(x, y)L(x, y)$, where x, y are the transverse dimensions), disrupting its functionality. Increasing the transverse sizes of the etalon and the passing laser beam in order to decrease the generated heat density does not mitigate the problem, as it increases the thermal resistivity experienced by the heat flowing from the central region in radial direction. A similar cooling problem occurs in rod lasers. This problem has been solved by the invention of the thin-disk laser.^{5,6}

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Figure 1: (a) Schematic of a Fabry-Perot interferometer with corresponding beam propagation. Front and back side are partially reflective (PR) with reflectivity R . (b) Schematic of a Gires-Tournois interferometer with the front side being partially reflective (PR) and the back side being a high-reflector (HR).

In this publication, we present a narrow-band frequency-selective element, more specifically a polarizing Gires-Tournois interferometer that shows an improved thermal management and is thus apt for high power lasers. In terms of thermal management, by going from a Fabry-Perot interferometer to a polarizing Gires-Tournois interferometer we are taking a similar step as was done from rod- to disk-lasers.

2. GIRES-TOURNOIS INTERFEROMETER

A Gires-Tournois interferometer (GTI) is an optical standing-wave resonator similar to a FPI, but with a partially reflective (PR) front surface and a high reflective (HR) backside (see Fig. 1 (b)). Similarly to the thin-disk, efficient cooling can be realized by contacting the GTI backside to a heat sink.

Because of the HR on the backside, the reflectivity of a sole GTI is unity at all wavelengths, requiring more optical elements in order to use it as frequency-selective element. Alike a FPI, the reflected light of a GTI shows nearly no phase shift out of resonance and a fast change of phase with a total phase shift of 2π when crossing the resonance. The amplitude of the reflected light is given by

$$E = E_0 \frac{\exp(4\pi i L n f c^{-1}) - \sqrt{R}}{1 - \sqrt{R} \cdot \exp(4\pi i L n f c^{-1})}, \quad (3)$$

where E_0 is the electric field amplitude of the in-going beam, R is the (intensity) reflectivity of the PR surface, f the laser frequency and c the speed of light. As practically all power is reflected ($|E| = |E_0|$), it is possible to describe the behavior of the GTI just by the phase delay ϕ of the reflected beam relative to the input beam $E = E_0 e^{i\phi}$. This phase delay reads

$$\phi = 2 \arctan \left(\frac{1 + \sqrt{R}}{1 - \sqrt{R}} \cdot \tan \left(\frac{2\pi i L n f}{c} \right) \right). \quad (4)$$

A plot of ϕ versus f is given in Fig. 2 for two different refractive indices.

If a GTI was used in an interferometer arm, the interference of the two beams (one reflected at the GTI, the other at the reference mirror) would show strong intensity modulations for variations of the laser frequency f . In principle, such a setup might be used as a selective element, but it is impractical given its sensitivity to vibrations. In the next section, we present a device that acts as a GTI and a reference at the same time.

3. BIREFRINGENT GIRES-TOURNOIS INTERFEROMETER

In case the bulk material of the GTI is birefringent, the two polarizations of the injected light experience a different phase delay. As a result, the birefringent Gires-Tournois interferometer (BGTI) shows two phase shift curves corresponding to the ordinary n_o and the extraordinary n_e refractive indices (see Fig. 2).

Figure 2: Phase delay occurring in a Gires-Tournois interferometer with a front side reflectivity of $R = 90\%$ versus the frequency f as given in Eq. (4) for two different refractive indices $n = n_e = 1.5433$ (red) and $n = n_o = 1.5346$ (blue) for $\lambda = 1030$ nm.⁷ The thickness of the substrate is $L = 147$ μm ($\lambda/4$ plate for 1030 nm).

The two phase delays can be combined to form a Jones matrix describing the birefringent Gires-Tournois interferometer

$$M_{\text{BGTI}} = \begin{bmatrix} \frac{\exp(4\pi i L n_o f c^{-1}) - \sqrt{R}}{1 - \sqrt{R} \cdot \exp(4\pi i L n_o f c^{-1})} & 0 \\ 0 & \frac{\exp(4\pi i L n_e f c^{-1}) - \sqrt{R}}{1 - \sqrt{R} \cdot \exp(4\pi i L n_e f c^{-1})} \end{bmatrix}. \quad (5)$$

The resulting phase shifts in the BGTI for the two polarizations are given in Fig. 2. For one polarization on resonance and the other not, the reflected beam experiences a phase shift corresponding to a $\lambda/2$ plate. The relative difference of phase delay (retardation) $\Delta\phi = \phi_e - \phi_o$ occurring in the BGTI can be simplified to

$$\Delta\phi = \phi_e - \phi_o = 2 \arctan \left(\frac{1 - R}{2\sqrt{R} \cdot \sin(4\pi i L \bar{n} f c^{-1})} \right), \quad (6)$$

where $\bar{n} = (n_o + n_e)/2$, assuming the substrate parameters were chosen so that one pass through the bare substrate causes a retardation of $\lambda/4$, i.e., when the condition $(n_e - n_o)L = (k \pm 1/4)\lambda$ holds (with $k \in \mathbb{Z}$).

These BGTIs are known and have been used as frequency filters for laser multiplexing,⁸ but not for high power lasers.

4. POLARIZING GIRES-TOURNOIS

Taken alone the BGTI does not provide any frequency selectivity. However, when combining it with a $\lambda/4$ plate and a thin-film polarizer (TFP) as shown in Fig. 3 a frequency selective setup is obtained. In this a way, the frequency-dependent retardation occurring in the BGTI is converted by the TFP into a frequency-dependent transmission curve.

We name this combination of a TFP, a $\lambda/4$ plate and a BGTI a polarizing Gires-Tournois interferometer (PGTI). The axes of the $\lambda/4$ plate and the BGTI are tilted by 45° with respect to the polarization axis (vertical-horizontal) of the TFP. Because of this rotation (and because the TFP reflects only light which is vertically polarized), in both the $\lambda/4$ plate and the BGTI the radiation has equal parts of ordinary and extraordinary components. On the way back, after propagating back and forth as ordinary and extraordinary beams in the $\lambda/4$ plate and the BGTI, the beams interfere. In the case of vanishing retardation between the ordinary and extraordinary components $\Delta\phi + 2 \cdot 2\pi/4 = 2\pi k$ (with $k \in \mathbb{Z}$), the resulting beam has identical polarization to the incoming beam and thus gets fully reflected on the TFP. This situation occurs when the retardation at the BGTI is $\lambda/4$. In the case of a non-vanishing phase difference $\Delta\phi + 2 \cdot 2\pi/4 \neq 2\pi k$ (with $k \in \mathbb{Z}$), the polarization of the resulting beam is rotated and the TFP introduces losses (see Fig. 3).

The mathematical description of the propagation presented in Fig. 5 (a) in the Jones-matrix formalism takes the form

$$M_{\text{PGTI}} = M_{\text{TFP}} \cdot M_{-45^\circ} \cdot M_{\lambda/4} \cdot M_{\text{BGTI}} \cdot M_{\lambda/4} \cdot M_{45^\circ} \cdot M_{\text{TFP}} . \quad (7)$$

The Jones matrix M_{TFP} describes the TFP, which reflects vertically polarized light. The rotation matrices M_{45° and M_{-45° take into account that the ordinary and extraordinary axis of the $\lambda/4$ plate and the BGTI are rotated by 45° with respect to the horizontal-vertical axes system. The amplitude of the output beam $\vec{E}_{\text{out}}$ can be simply computed by

$$\vec{E}_{\text{out}} = M_{\text{PGTI}} \cdot \vec{E}_{\text{in}} , \quad (8)$$

where $\vec{E}_{\text{in}}$ is the input beam. Assuming a vertically polarized input beam ($\vec{E}_{\text{in}} = (E_{\text{in}}, 0)^T$) and looking at the reflection, the transmission curve $T(f)$ of the PGTI is thus given by

$$T(f) = \left(\frac{E_{\text{out}}}{E_{\text{in}}} \right)^2 = \frac{(R - 1)^2}{(R + 1)^2 - 4 R \cos^2(4\pi i L \bar{n} f c^{-1})} , \quad (9)$$

where E_{out} is the vertical component (which is 100% reflected at the TFP) of the output beam. A plot of the obtained transmission curve $T(f)$ for $R = 50\%$ is shown by the red curve in Fig. 4 (a) and compared with the transmission curve of a Fabry-Perot of identical length and same mirror reflectivities $R = R_1 = R_2 = 50\%$ (black curve). Both curves have the same functionality beside the fact that the free spectral range of the PGTI is half the value of the FPI:

$$\Delta f_{\text{PGTI}} = \frac{c}{4nL} , \quad (10)$$

and its resonances bandwidth δf_{PGTI} is smaller given the fact that one side of the BGTI has a reflectivity R and the other has a reflectivity of 100%.

We want to stress that the choice of a reflectivity $R = 50\%$ is high for a FPI. Normally, a lower R value is utilized to reduce the heat load caused by the laser intensity within the etalon. For this reason in high-power lasers uncoated etalons are often used because of their low reflectivity R ($R = 3.4\%$ for fused silica⁹ and $R = 8.4\%$ for YAG¹⁰). Low R values lead to a low finesse of the FPI which results in broad resonance lines. This can diminish single-mode operation capability of the laser.

On the contrary, the PGTI can sustain higher heat loads given its efficient cooling. This allows the usage of much higher reflectivities R , resulting in higher finesse and thus smaller resonance bandwidths δf_{PGTI} . A plot of the transmission curve for various reflectivities R is given in Fig. 4 (b). Combining the doubled free spectral range relative to a FPI (compare Eq. (1) with Eq. (10)) and the small bandwidth that can be sustained by the PGTI, stringent wavelength selection for high power lasers can be achieved.

Quantitatively, a BGTI made of crystalline quartz of thickness $L = 147\mu\text{m}$ (standard thickness of commercial $\lambda/4$ plates for $\lambda = 1030\text{ nm}$ ¹¹) has a free spectral range of $\Delta f_{\text{PGTI}} = 334.5\text{ GHz}$. A front side-reflectivity of $R = 30\%$ leads to a finesse of $\mathcal{F} = 2.46$ and a bandwidth of $\delta f = 136\text{ GHz}$. Further combinations are: $R = 50\%$, $\mathcal{F} = 4.44$, $\delta f = 75\text{ GHz}$ and $R = 90\%$, $\mathcal{F} = 29.8$, $\delta f = 11\text{ GHz}$ and $R = 99\%$, $\mathcal{F} = 312.6$, $\delta f = 1.07\text{ GHz}$.

Figure 3: Schematic of a polarizing Gires-Tournois interferometer composed of a thin-film polarizer (TFP), a $\lambda/4$ plate and a birefringent Gires-Tournois interferometer (BGTI). The beam propagation is indicated in red.

Figure 4: (a) Transmission $T(f)$ of a polarizing Gires-Tournois (red) and a Fabry-Perot etalon (black) interferometer as a function of the laser frequency. In both cases we assumed a thickness of $L = 147\mu\text{m}$ and a reflectivity $R = 50\%$. Fused silica was assumed for the FPI and crystalline quartz for the PGTI. The PGTI is acting similarly to an etalon of twice the thickness. (b) Transmission $T(f)$ of a PGTI made of crystalline quartz for various front-side reflectivities R : $R = 30\%$ (black), $R = 50\%$ (red), $R = 70\%$ (green), $R = 80\%$ (blue) and $R = 90\%$ (magenta).

5. IMPLEMENTATION IN A LASER RESONATOR

The PGTI can be implemented as a frequency-selective element into a laser resonator. Two possible implementations are shown in Fig. 5. Cooling of the BGTI can be realized in axial direction (along the laser beam axis) by contacting the high-reflective side of the BGTI to the heat sink. In this way a large cooling area and a small path for the heat transport in the GTI allow efficient cooling. This cooling technique has proven itself in thin disk lasers.

The active medium can be inserted between the $\lambda/4$ plate and the BGTI to realize a so-called “twisted-mode” scheme, as the BGTI on resonance acts as a $\lambda/4$ plate.¹² In this way, the PGTI leads to the complete suppression (for linear cavities as in Fig. 5 (a)) or to the reduction (for V-shaped cavities as in Fig. 5(b)) of the spatial hole burning in the active medium^{12, 13} which could prevent single-frequency operation. Therefore this implementation of the PGTI offers a double advantage in the pursue of single-frequency operation: it acts as a frequency-selective element while at the same time suppressing spatial hole burning.

Figure 5: (a) Scheme of a laser resonator that includes a polarizing Gires-Tournois interferometer as a frequency-selective element. The backside of the BGTI is thermally contacted to a heat sink. (b) Similar to (a) for a thin-disk with V-shaped layout.¹²

6. CONCLUSION

We have presented the working principle of an optical system composed of a birefringent Gires-Tournois interferometer (BGTI), a $\lambda/4$ plate, and a TFP that acts as an intra-cavity frequency selective element with narrow bandwidth apt for high power lasers. We called it the polarizing Gires-Tournois interferometer (PGTI).

Its selection curve is identical to the one of a Fabry-Perot interferometer of two times the thickness. The PGTI can be operated at higher finesse and thus narrower resonance bandwidth. Indeed, the efficient cooling that is realized by contacting the backside of the BGTI to the heat sink, allows for high circulating intensities within the BGTI.

Possible resonator layouts implementing the proposed frequency selective system have been shown in Figs. 5 (a) and (b). This frequency-selective element can be implemented in a resonator to also attain “twisted-mode” operation mitigating spatial hole burning effects. The combination of high power handling capability, high frequency selectivity and low loss inherent to this scheme pave the way for single-frequency operation of a thin-disk laser with kW output power.

Funding Information

We acknowledge the support from the Swiss National Science Foundation Project SNF 200021.165854, the European Research Council ERC CoG. #725039 and the ETH Research Grant ETH-35 14-1. K.S. has been supported by the ETH Femtosecond and Attosecond Science and Technology (ETH-FAST) initiative as part of the NCCR MUST program.

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