ANALYZING NUMERICALLY STUDY THE EFFECT OF ADD A SPACER LAYER IN GIRES-TOURNOIS INTERFEROMETER DESIGN

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ABSTRACT

We demonstrated Gires-Tournoise interferometer (GTI) design as an optical standing-wave cavity to generate chromatic dispersion. In this research we design three structures with different spacers to study the impact on the pulse width and reflectivity using two types of dielectric materials TiO$_2$/SiO$_2$ as the high and low refractive index.

Keywords: Gires-Tournoise, Group Delay Dispersion, Optical Filter, Round Trip.

I. INTRODUCTION

Optical filters have been widely applied to optical communication systems and fiber sensing fields. With the rapid development of optical communication, many techniques have been proposed for optical filters, such as birefringence, optical-electric thin-films, array waveguide gratings, ring resonators, fiber gratings, Michelson and Mach-Zehnder interferometers, and Gires-Tournois interferometer (GTI) [1].

Gires-Tournois interferometers are generally used to compensate highly chirped picosecond or femtosecond pulses the way they exist, especially in narrow gain band-width lasers like Nd: YAG. Large amounts of intracavity negative GDD are essential in ultrashort pulse lasers, in order to compensate for the gain bandwidth and self-phase modulation (SPM) due to nonlinear elements [2]. In comparison to a prism pair sequence, the GTI is easily three orders of magnitude more dispersive but also linear over a much smaller bandwidth. The amount of available group delay dispersion can be further increased by reflecting the intracavity pulse several times of the surface of the GTI, because the introduced dispersion is proportional to the number of bounces from the surface. Several schemes of GTI have been proposed introducing these large amounts of group delay dispersion (GDD) [3]. In large gain
bandwidth lasers like Ti:sapphire and Cr:LiSAF the GTI are used to tune the laser in the picosecond regime. This is done by changing the pulse angle of incidence upon the GTI, which thereby correctly compensates a narrow bandwidth of intracavity dispersion [4]. So far, these devices have been used in a much experimental manner, by simply maintaining the round trip time inside the GTI much below the pulse duration and adjusting the number of reactions from its surface in order to minimize the pulse duration. Here we calculate the bandwidth over which the dispersion of a GTI is linear. We are therefore capable of designing a GTI, which introduces constant GDD over the whole gain bandwidth (FWHM), meanwhile keeping the losses low by minimizing the number of reactions needed [4,5].

II. GTI THEORY AND PRINCIPLE OF OPERATION

A Gires-Tournois interferometer consists of two parallel surfaces, the second of which is 100% reflective as show in Figure 1. Therefore, the two quantities which characterize the GTI are the reflection coefficient $r$ of the first surface and the distance $d$ between them [6].

![Schematic setup of a gires–tournois interferometer](image)

**Figure 1:** Schematic setup of a gires–tournois interferometer [7]

The round trip time inside the GTI for an angle of incidence $\theta$ is then given by [4]:

$$t_0 = \frac{2nd}{c} \sqrt{1 - \sin^2\theta}$$  \hspace{1cm} (1)

Where $c$ is the speed of light and $n$ the refractive index of the medium between the mirrors. If the pulse duration is longer than $t_0$, the fields of successive reflections of the same pulse do temporally overlap and the pulse envelope may be reshaped. This puts an upper limit to the distance between the reflecting surfaces. But, as the distance $d$ becomes shorter, the GDD becomes smaller too, as can be seen from the equation below [4]:

$$GDD = 2\pi \frac{dT}{d\omega} = -2\pi \frac{d^2\phi}{d\omega^2} = 2\pi t_0^2 \frac{(r^2 - 1)2r \sin \omega t_0}{(1 + r^2 - 2r \cos \omega t_0)^2}$$  \hspace{1cm} (2)

where, $T$ = group delay, $\omega$=angular frequency, $\phi$ = phase and $r$= reflectivity.

In order to obtain constant negative GDD over finite bandwidth, $\Delta \omega > 0$, the phase has to be adjusted such that the GDD is a minimum. This phase is a function of $r$, as seen in above equation. In order to obtain high values of negative dispersion and large bandwidth
(for short pulse duration), one has to increase the reflectivity of the intermediate mirror in a controlled manner. The commonly used round trip time (1) shows no dependency with the intermediate surface reflectivity. We know, that the higher the reflectivity, the longer the delay time within the GTI. Therefore, as the reflectivity increases, the pulse, coming out of the GTI, gets stretched in time. Taking into account the reflectivity we derive an expression for the decay time of a pulse in a passive resonator, \( \tau \) [4]:

\[
\tau = t_0 \cdot \left[ 1 + \frac{1}{\ln(1/\tau^2)} \right] \quad (3)
\]

Where \( t_0 \) is given by (1). By analyzing numerically various GTI's we found that this expression gives a very good estimate in the case of Fourier transform limited pulse width. A more useful approximation is obtained by calculating the bandwidth, \( \Delta v_{GTI} \), over which the group delay is linear. We therefore expand the group delay as a function of frequency about the points of maximum \( GDD \). At these points the second derivative of the group delay is zero and we obtain [8]:

\[
T(\omega) = T(\omega_0) + \frac{dT(\omega_0)}{d\omega} \Delta \omega + \frac{d^2T(\omega_0)}{6d\omega^3} \Delta \omega^3 \quad (4)
\]

Linearity of the group delay is guaranteed as long as the third term in above equation is smaller than the second term [8]:

\[
\frac{dT(\omega_0)}{d\omega^3} = \frac{dT(\omega_0)}{d\omega} \Delta \omega \quad (5)
\]

Where we have dropped the factor (6) in the denominator of the third term. Using the above criteria for linearity we obtain:

\[
\Delta v_{GTI} = 2 \frac{\Delta \omega}{2\pi} = \frac{1}{\pi} \sqrt{\frac{dT(\omega_0)}{d\omega} \left( \frac{d^2T(\omega_0)}{d\omega^3} \right)^{-1}} \quad (6)
\]

### III. DESIGN AND DISCUSSION

Since in 1984–1987, whereas standard quarter-wave dielectric mirrors were shown to introduce negligible dispersion at the center of their reflectivity bands [9-11], various specific high-reflectivity coatings (GTI, double-stack mirrors, etc.) with adjustable GDD (through angle tuning) were devised and used for the precise control of intra-cavity dispersion in femtosecond dye lasers. The material used in all design is TiO\(_2\)/SiO\(_2\) as the high and low refractive index. The design wavelength is 600nm and the spectral range 450–800nm. Figure 2 and Figure 3 show the reflectance and reflectance GDD, where H and L are quarter wave layers at 800nm with indices 2.35 and 1.45 which correspond to TiO\(_2\) and SiO\(_2\), respectively, and the refractive index of Glass is 1.51. The bandwidth of high reflectance (>70%) is 520–710 nm, and the reflectance GDD value is near zero. Table 1 shows the layer structure for the first design.
Figure 2: Reflections vs. wavelength for the first design

Figure 3: Group delay dispersion vs. wavelength for the first design

Table 1: Layer structure of the first design

<table>
<thead>
<tr>
<th>No.</th>
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Then we add a spacer 2H and a low reflectance stack (LH) to the above design, the reflectance and reflectance GDD of the stack are showing in Figure 4 and Figure 5. Table 2 shows Layer structure of the second design.

Figure 4: Reflection vs. wavelength for the second design

Table 2: Layer structure of the second design
Figure 5: Group delay dispersion vs. wavelength for the second design

Table 2: Layer structure for the second design

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The reflectance is broadening from 190nm to 230 nm (510~740nm), but the reflectance GDD has a high non-linear value in the bandwidth of 570~620nm.

Finally, if the spacer 2H in Figure 4 changed to 10H, then the Layer structure of the third design shows in Table 3.

Figure 6: Reflection vs. wavelength for third design

Figure 7: Group delay dispersion vs. wavelength for the third design
Table 3: Layer structure of the third design

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From Figure 6 and Figure 7, it is clearly seen that the values of the reflectance and reflectance GDD is becoming higher than the one in Figure 4. But the bandwidth of high reflectance is narrow and the non-linear reflectance GDD is worse than the one in Figure 5.

IV. CONCLUSION

A Gires–Tournois interferometer is an optical standing-wave resonator designed for generating chromatic dispersion. The front mirror is partially reflective, whereas the back mirror has a high reflectivity. If no losses occur in the resonator, the power reflectivity is unity at all wavelengths, but the phase of the reflected light is frequency-dependent due to the resonance effect, causing chromatic dispersion. The phase change of reflected light and the dispersion (including group delay dispersion and higher-order dispersion) change periodically with optical frequency, if material dispersion is negligible. There is no second-order dispersion exactly on-resonance or anti-resonance, and positive or negative dispersion between these points.

Ideally, the GTI is operated near a maximum or minimum of the GDD, and the usable bandwidth is some fraction (e.g. one-tenth) of the free spectral range, which is inversely proportional to the resonator length. In the time domain, this means that the pulse duration needs to be well above the round-trip time of the GTI. The maximum magnitude of GDD scales with the square of the resonator length.

From the above result, we can see that the layer structure can be easily adapted for any other wavelength regime. We believe that this compensator of thin-film has more potential to be deployed in ultrafast optics and optical communication.

REFERENCES


