Calculations for Broadband Intracavity Chirp Compensation with Thin-Film Gires-Tournois Interferometers

Niklaus U. Wetter, Edison P. Maldonado and Nilson D. Vieira Jr.
*IPEN-CNEN/SP, Divisão de Materiais Optoeletrônicos, P.O. Box 11049, CEP 05422-970, S. Paulo, SP, Brazil, nuwetter@net.ipen

Recebido em 20 de Agosto 1998

The effectiveness of the Gires-Tournois interferometers (GTI), introduced into femtosecond and picosecond lasers in order to compensate the group delay dispersion (GDD), depends on pulse duration and therefore on the bandwidth over which the GTI dispersion is linear. Thus, by calculating this bandwidth, one can optimize the scheme, employing the GTI, in terms of minimum loss and maximum GDD.

Introduction

Gires-Tournois interferometers are generally used to compensate highly chirped picosecond or femtosecond pulses the way they exist, specially in narrow gain bandwidth 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 [1]. 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) [2]. 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 [3].

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 reflections 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 reflections needed.

Theory

A Gires-Tournois interferometer consists of two parallel surfaces, the second of which is 100 % reflective. Therefore, the two quantities which characterize the GTI are the reflection coefficient r of the first surface and the distance d between them. The round trip time inside the GTI for an angle of incidence θ is then given by [2]

$$t_0 = \frac{2nd}{c}\sqrt{1 - \frac{\sin^2\theta}{n^2}} \tag{1}$$

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 [2]

$$GDD = 2\pi\frac{dT}{d\omega} = -2\pi\frac{d^2\Phi}{d\omega^2} = 2\pi t_2^2\frac{(r^2-1)2r\sin\omega t_0)}{(1+r^2-2r\cos\omega t_0)^2} \tag{2}$$

Where T is the group delay.

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 (eq.(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, τ:

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

Where t_0 is given by equation (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, $\Delta\nu_{GTI}$, 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:

$$T(\omega) = T(\omega_0) + \frac{dT(\omega_0)}{d\omega}\Delta\omega + \frac{d^3T(\omega_0)}{6d\omega^3}\Delta\omega^3 \tag{4}$$

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

$$\frac{dT(\omega_0)}{d\omega^3}\Delta\omega^3 = \frac{dT(\omega_0)}{d\omega}\Delta\omega \tag{5}$$

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

$$\Delta\nu_{GTI} = 2\frac{\Delta\omega}{2\pi} = \frac{1}{\pi}\sqrt{\frac{dT(\omega_0)}{d\omega}\left(\frac{d^3T(\omega_0)}{d\omega^3}\right)^{-1}} \tag{6}$$

In Fig. 1 we calculate the group delay, $T = -d\Phi/d\omega$, of a GTI with 150 micron spacing for two different reflectivities of 4 % and 50 %. Using formula (6) to calculate the bandwidth of the negative slope we obtain 227 GHz and 53 GHz, respectively. When using formula (3) to calculated the bandwidth of a transform limited sech-pulse supported by the same GTI's, we obtain 240 GHz and 128 GHz, respectively. Comparing the two results in Fig. 1 we notice that expression (6) represents the linearity of the slope with better fidelity than equation (3). This behavior becomes more important for higher reflectivities.

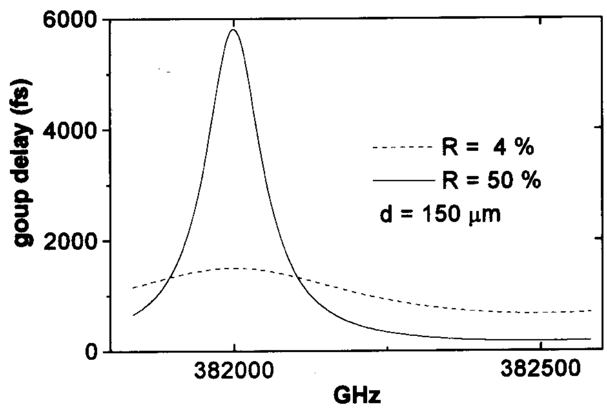

Figure 1. Group delay as a function of frequency calculated for two GTI's with 150 micron distance between the two mirrors. The back mirror is always 100% reflective and the front mirrors are R = 4% and R = 50%, respectively.

In Fig. 2 we use equations (1), (3) and (6) to calculate the minimum pulse duration, for a bandwidth limited sech-pulse, which can be sustained by a GTI used at normal incidence, regardless of the GDD needed for the compensation of the non-linear effects (note that the value of negative GDD is not fixed in Fig. 2). The values are calculated for two different reflectivities, R = 4 % and R = 50 %, the latter being an appropriate reflectivity for large GDD.

From Fig. 2 it becomes clear that approximation (1) gives reliable information about the necessary cavity spacing only if the reflectivity is small, thereby underestimating the minimum pulse duration sustained. By using equation (3), which already considers the effect of the reflectivity and by assuming that the pulse duration must be longer than the photon lifetime of the GTI, the obtained pulse duration are closer to those obtained by using the expression of the bandwidth (6), but still underestimate the minimum pulse duration.

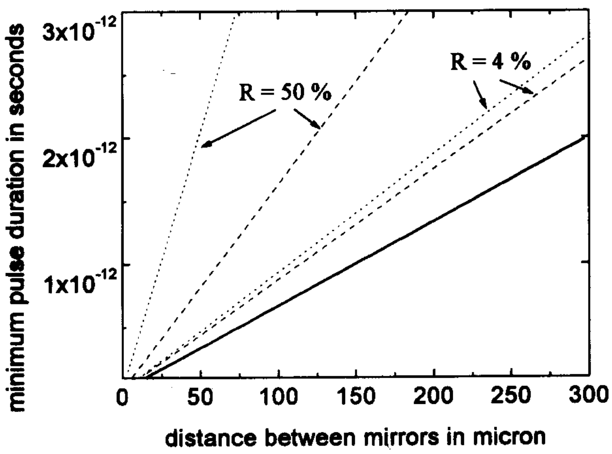

Figure 2. Minimum pulse duration as a function of the GTI cavity spacing and the reflectivity of the first surface. The result obtained with equation one (solid line) always underestimates the minimum pulse width whereas equation three (dashed line) already introduces a correction for the reflectivity. Equation six (dotted line) accounts better for the linearity of the GTI's dispersion at high intermediate mirror reflectivities.

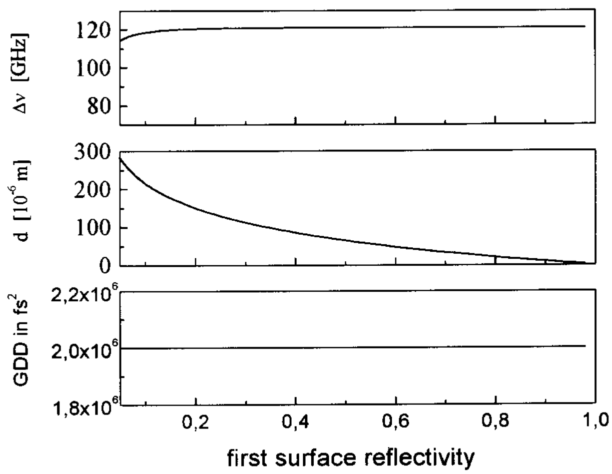

Figure 3. From top to bottom: bandwidth of linear dispersion in GHz, distance between reflective surfaces and GDD as a function of first surface reflectivity. The GDD was held constant in order to obtain a comparison of the maximum bandwidth as a function of first surface reflectivity.

Thus, with the help of (6) we may now design a GTI for a given group delay dispersion and first surface reflectivity while maintaining the linearity of the dispersion over the pulse bandwidth. In Fig. 3 we calculate the values of cavity spacing as a function of the first surface reflectivity for a GTI, which is used at normal incidence (a single bounce of its surface) and shall compensate a GDD of 2×10^6 fs^2. The necessary amount of GDD depends strongly on the balance between SAM (self amplitude modulation) and SPM (self phase modulation) of the particular application.

From Fig. 3, we note that the maximum bandwidth of the pulse, which receives the same GDD, is 120 GHz. This corresponds to a pulse duration (sech-pulse, transform-limited) of 2.6 ps. These values are well in agreement with the in reference [4] cited results for a GTI with 4% reflectivity, 350 micron spacing and $2 * 10^6$ fs^2 GDD.

Broader bandwidths can be obtained from GTI designed for lower values of GDD. For example, a Nd:YAG laser has an active bandwidth of 220 GHz and therefore a GTI with a larger bandwidth could provide the shortest pulse duration. This can be realized for a Nd:YAG system with high SAM to SPM ratios, which requires lower GDD values, [1] or by using a setup with several reflections from the GTI.

Conclusion

We have shown how to introduce maximum negative GDD and maximum dispersion bandwidth from a GTI, by introducing a quantitative calculus for the linearity of the group velocity dispersion.

Acknowledgements

Niklaus U. Wetter and Edison P. Maldonado would like to thank FAPESP for research grants no 93/4999-7, 95/9503-5 and 96/7934-1.

References

1. E.P. Ippen, "Principles of Passive mode Locking", Appl. Phys B **58**, 159 (1994).
2. J. Kuhl, J. Heppner, "Compression of Femtosecond Optical Pulses with Dielectric Multilayer Interferometers", IEEE J. Quant. Electron. **QE-22**, 182 (1986).
3. J. D. Kafka, M. L. Watts, J-W. J. Pieterse, "Picosecond and Femtosecond Pulse Generation in a Regeneratively Mode-Locked Ti:Sapphire Laser", IEEE J. Quant. Electron. **QE-28**, 2151 (1992).
4. M. Ramaswamy, A.S. Gouveia-Neto, D.K. Negus, J.A. Izatt and J.G. Fujimoto, "2.3- ps pulses from a Kerr-lens mode-locked lamp-pumped Nd-YLF laser with a microdot mirror", Optics Letters **18**, 1825 (1993).