Optica Applicata, Vol. XXXIV, No. 1, 2004

Second and third order dispersion of broadband thin-film antireflection coatings for ultrafast lasers

E. COJOCARU

Department of Lasers, National Institute of Laser, Plasma and Radiation Physics,
P.O. Box MG-36, Bucharest-Magurele, R-76900 Romania, e-mail: cojo@ifin.nipne.ro

Ultrashort pulse generation relies on a high quality of the laser cavity dispersion control. Common dielectric thin-film coatings, the broadband antireflection (AR) coatings being included, may introduce great fluctuations on the group delay dispersion (GDD) and the third order dispersion (TOD) of the reflected pulse. By accumulation in time, these fluctuations may contribute to the alteration or the cease of the ultrafast regime, especially in ring laser resonators. With an insignificant computational effort, optimized broadband AR coatings may be designed to provide near-zero values of the GDD and the TOD at the expense of poor AR quality.

Keywords: thin films, antireflection coatings, dispersion control, ultrafast optics.

1. Introduction

Remarkable progress has recently been achieved in the development of ultrafast lasers. The evolution of femtosecond technology relies, among other things, on the quality of the laser cavity dispersion control [1]. In solid-state lasers femtosecond pulse generation needs a net negative group delay dispersion (GDD) that is obviously controlled by crossed prism pairs [2]–[7]. More recently, chirped dispersive mirrors were engineered to produce a broadband negative GDD [8]–[11]. Since for the higher -order dispersion control more than one dispersive system is required, both the crossed prisms and the chirped mirrors could be used at once.

Generally, a major limitation of common multilayer dielectric thin-film coatings is the existence of large fluctuations [12] in their GDD and third order dispersion (TOD). The fewer the common coatings inside the laser cavity, the better the dispersion control. Besides the designed chirped dispersive mirrors, standard laser cavities may contain other common dielectric thin-film coatings on the components, *e.g.*, on the output couplers, the wedged glass plates compensating for the angular wavelength spread, or the beam splitters.

In this note, we show that common broadband antireflection (AR) coatings may also present great dispersion fluctuations. These fluctuations accumulated in time as increased losses (*e.g.*, after one hour of laser function), may contribute to the alteration or the cease of the ultrafast regime, especially in the ring laser cavities. We also show that by using a common least-squares refinement algorithm one may get near-zero GDD and TOD at the expense of poor AR quality, that is at the expense of an increased reflectance value. A review of the computer refinement algorithms for multilayer thin-film coatings may be found, *e.g.*, in [13].

2. Dispersion of broadband antireflection coatings

Generally, the phase ϕ accumulated by a pulse on reflection from a thin-film coating can be represented by Taylor's series expansion [1],

$$\phi(\omega) = \phi(\omega_0) + \left.\frac{\partial\phi}{\partial\omega}\right|_{\omega_0}(\omega-\omega_0) + \frac{1}{2!}\left.\frac{\partial^2\phi}{\partial\omega^2}\right|_{\omega_0}(\omega-\omega_0)^2$$

$$+ \frac{1}{3!}\left.\frac{\partial^3\phi}{\partial\omega^3}\right|_{\omega_0}(\omega-\omega_0)^3 + O(\Delta\omega^4).$$

Here, ω is the angular frequency and ω_0 – the center frequency of the expansion. The first term is a constant, the second represents an overall time shift of the pulse, and the remaining terms represent distortions to the pulse shape. The coefficient of the third term ($\partial^2\phi/\partial\omega^2\left.\right|_{\omega_0}$) is the GDD, whereas the coefficient of the fourth term ($\partial^3\phi/\partial\omega^3\left.\right|_{\omega_0}$) is the TOD. A basic assumption is that Taylor's expansion is well behaved, that is, the effect of each term in expansion produces an alteration of the pulse shape that is significantly smaller than the effect of the previous term.

Now, let us consider a broadband AR coating, as shown in Fig. 1, consisting of nine alternating layers of constant refractive indices 1.45 and 2.3 on a glass substrate

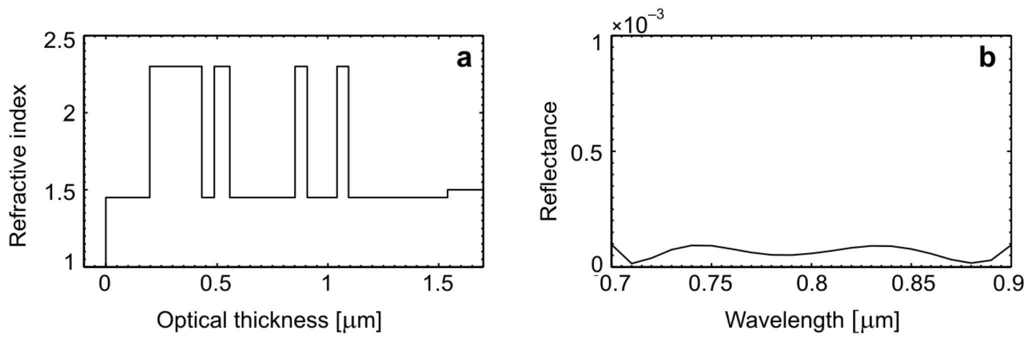

Fig. 1. Relation of optical thickness and refractive index (**a**), and the reflectance spectrum of a broadband antireflection coating (**b**).

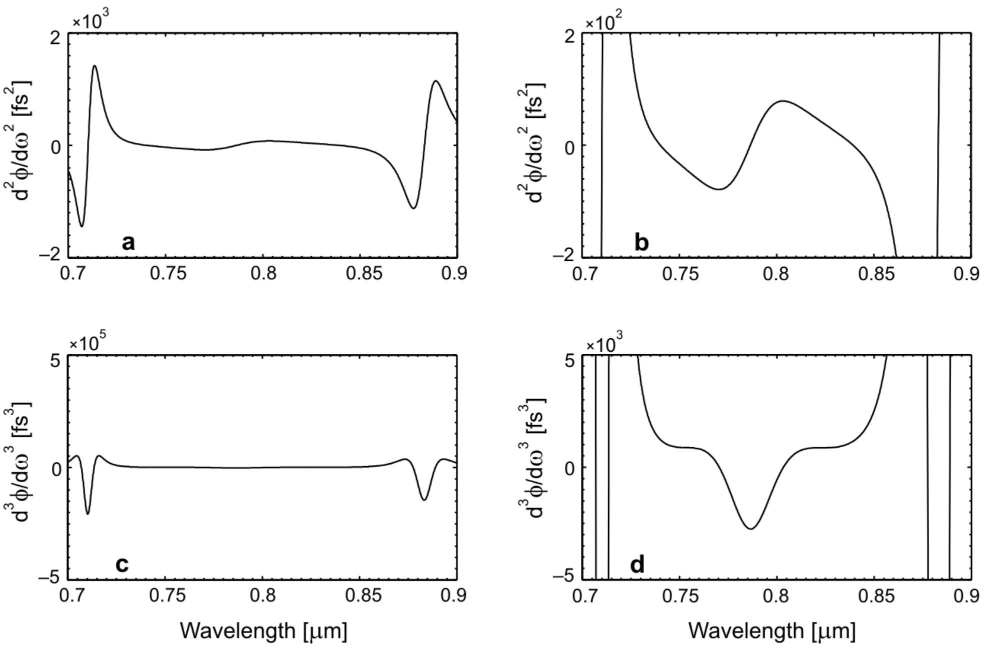

Fig. 2. Group delay dispersion determined by the second derivative of the phase ϕ, expressed in squared femtoseconds (**a**, **b**); the third order dispersion expressed in cubic femtoseconds (**c**, **d**). Two ordinate scales are chosen.

($n_s = 1.5$) in air ($n_0 = 1$). The coating produces a reflectance smaller than 9.7×10^{-5} on the wavelength interval 0.7–0.9 μm. Starting from the substrate, the layers have the following optical thicknesses expressed in micrometers: 0.1975, 0.2342, 0.0564, 0.0698, 0.2936, 0.0554, 0.1346, 0.0523, and 0.4463. The second and the third order derivatives of the phase ϕ produced by reflection on that coating are plotted in Fig. 2. Both the GDD and the TOD have great fluctuations especially towards the borders of the wavelength interval. Thus, the GDD has a maximum absolute value of 1.44×10^3 fs^2 on the borders (Fig. 2**a**) and 79 fs^2 near the center (Fig. 2**b**). The TOD has a maximum absolute value of 2×10^5 fs^3 on the borders (Fig. 2**c**) and 2.7 $\times10^3$ fs^3 near the center (Fig. 2**d**).

3. Optimized design

A common least-squares refinement algorithm [14] was used to minimize the fluctuations of the GDD and the TOD. The GDD was required to exhibit a slight linear variation with a slope suitable for compensating the TOD. Only several iterations were needed. Results are shown in Fig. 3. Starting from the substrate, the layers have the following optical thicknesses: 0.1019, 0.0153, 0.0850, 0.2366, 0.0676, 0.0583, 0.3128, 0.0424, 0.1469, 0.0391, and 0.4537. Small values of the GDD and the TOD are obtained. Thus, in Fig. 3**c**, the GDD varies from 0 to –9 fs^2 on the overall interval, but

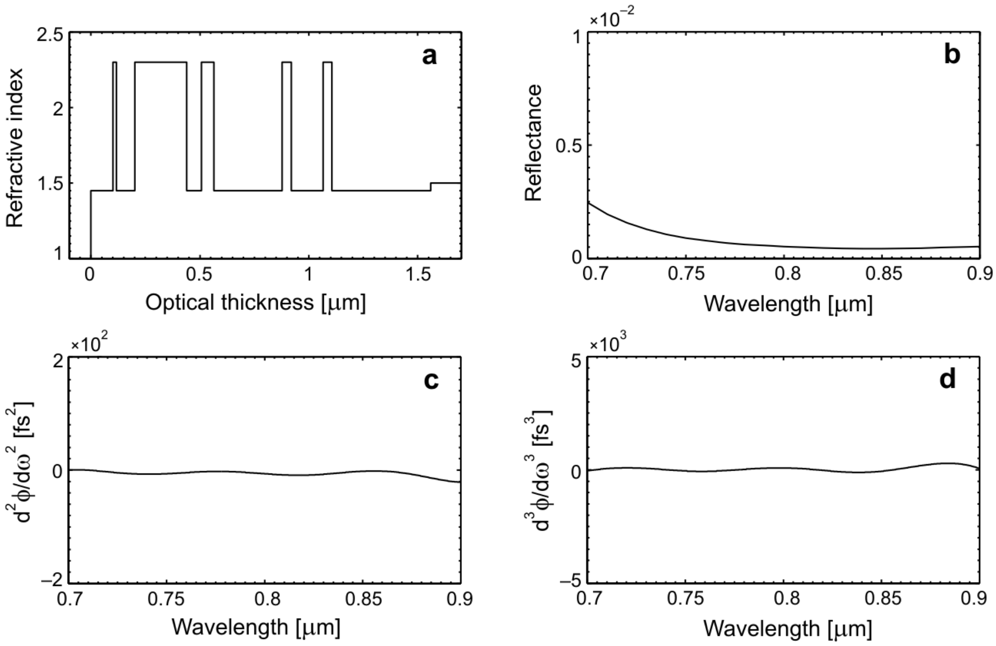

Fig. 3. Relation of optical thickness and refractive index (**a**), and the reflectance spectrum of the dispersion-optimized broadband antireflection coating (**b**); the second order dispersion (**c**) and the third order dispersion (**d**) of the optimized design.

it is –21 fs^2 at 0.9 μm. The TOD fluctuations in Fig. 3**d** are ±50 fs^3 on the overall interval, but with a maximum of 100 fs^3 at 0.88 μm. The minimization of the GDD and the TOD fluctuations is accomplished at the expense of poor AR quality, as shown in Fig. 3**b** – a maximum reflectance value of 2.5×10^{-3} is at 0.7 μm.

Numerical examples given in this note show that the great fluctuations of the GDD and the TOD produced by the common broadband thin-film coatings could be minimized with an insignificant computational effort.

References

[1] Fittinghoff D.N., Walker B.C., Squier J.A., Toth C.S., Rose-Petruck C., Barty C.P.J., IEEE J. Select. Topics Quantum Electron. **4** (1998), 430.
[2] Spence D.E., Kean P.N., Sibbett W., Opt. Lett. **16** (1991), 42.
[3] Krausz F., Spielmann C., Brabec T., Wintner E., Schmidt A.J., Opt. Lett. **17** (1992), 204.
[4] Ober M. H., Sorokin E., Sorokina I., Krausz F., Wintner E., Opt. Lett. **17** (1992), 1364.
[5] LiKamWa P., Chai B.H.T., Miller A., Opt. Lett. **17** (1992), 1438.
[6] Rizvi N.H., French P.M.W., Taylor J.R., Delfyett P.J., Florez L.T., Opt. Lett. **18** (1993), 983.
[7] Piche M., Salin F., Opt. Lett. **18** (1993), 1041.
[8] Szipocs R., Ferencz K., Spielmann C., Krausz F., Opt. Lett. **19** (1994), 201.

[9] STINGL A., LENZNER M., SPIELMANN C., KRAUSZ F., SZIPOCS R., Opt. Lett. **20** (1995), 602.
[10] HEBLING J., MAYER E.J., KUHL J., SZIPOCS R., Opt. Lett. **20** (1995), 919.
[11] XU L., SPIELMANN C., KRAUSZ F., SZIPOCS R., Opt. Lett. **21** (1996), 1259.
[12] LAPORTA P., MAGNI V., Appl. Opt. **24** (1985), 2014.
[13] DOBROWOLSKI J.A., KEMP R.A., Appl. Opt. **29** (1990), 2879.
[14] MATLAB [High-performance numeric computation software v6.5, 2002, Toolbox Optimization], MathWorks Inc. (http://www.mathworks.com/).

Received June 13, 2003
in revised form November 27, 2003