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Double-angle multilayer mirrors with smooth dispersion characteristics

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Abstract: We report the feasibility of precision broadband dispersion control with multilayer mirrors produced in a single coating run. Inherent fluctuations of the group-delay dispersion (GDD) are suppressed by using the mirrors at two different angles of incidence. With a specialized version of the needle optimization algorithm, we have designed the multilayer structure to yield a complementary pair with a resultant GDD substantially free from spectral oscillations characteristic of broadband chirped multilayers. Since the mirrors employed at two different incidence angles are produced in a single deposition run, their overall dispersion is more robust to errors in layer thicknesses than that of previous complementary mirror pairs manufactured in two different steps. This offers the potential for improving production yield and quality of femtosecond dispersion control. We have successfully used the first "double-angle" mirrors for compressing pulses to a duration of 4.3 fs.

OCIS codes: (320.5520) Pulse compression; (310.1620) Interference coatings; (310.4165) Multilayer design; (310.5696) Refinement and synthesis methods.

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1. Introduction

Advancing femtosecond technology to its ultimate limit, to a pulse duration comparable to the optical cycle, is instrumental in developing several novel laser-based technologies, such as attosecond metrology [1-3], compact laboratory sources of coherent X-rays [4, 5], or laser-driven electron accelerators [6]. Near-single-cycle pulses [7] require GDD control over a bandwidth of several hundred terahertz with a precision of better than one femtosecond. Chirped multilayer mirrors (CMs) [8] constitute thus far the only tools capable of meeting these stringent demands as well as coping with the high pulse energies required by the above applications.

CMs rely on a multilayer structure with a gradual change in the optical thickness across the structure, resulting in a wavelength-dependent penetration depth of incident radiation [8]. Alternatively, group delay variation may be introduced with resonant structures implying a wavelength-dependent storage time of incident radiation [9, 10]. Both effects may co-exist [11] to improve the performance of dispersive mirrors (DM). Whilst being able to provide control of GDD, the second derivative of the optical phase shift upon reflection with respect to the angular frequency, over unprecedented bandwidth, broadband DM technology suffers

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from unavoidable spectral oscillations of the GDD: These oscillations may adversely affect the quality of the femtosecond laser pulses being controlled with the DMs. Several approaches have been devised for suppressing these undesirable oscillations: double-chirped mirrors [12-14], “Brewster-angle” DMs [15, 16], back-side-coated DMs [17], tilted-front-interface DMs [18], and complementary pairs of DMs [19-23]. Recently, a time-domain approach based on the direct optimization of the parameters of the compressed optical pulse was also reported [24-26].

In this paper we propose a novel concept for suppressing GDD oscillations. It is based on identical DMs used at two different angles of incidence in combination. The “double-angle” DMs offer: i) better manufacturing stability in comparison to conventional complementary pair approach [19-23]; ii) precision GDD control permitting Fourier-limited pulse generation in the few-cycle regime, iii) reduced manufacturing cost as compared to the complementary-pair approach which requires two perfectly-matched coating runs. By proper selection of incidence angles and application of specialized version of the needle-optimization technique we designed, manufactured, and characterized a double-angle DM with very low overall GDD oscillations. To demonstrate the utility of the new approach, we have used the mirrors for compressing pulses spectrally broadened in a hollow-fiber to a duration of 4.3 fs, very close to their Fourier limit of 4.2 fs.

2. Double-angle dispersive mirror – the basic concept

Among the many approaches developed to suppress inherent spectral oscillations of the GDD of broadband DMs or to minimize their negative effect on pulse quality, the complementary-pair approach has proven most powerful and proliferated in hundreds of laboratories. The complementary-pair design usually consists of two different multilayer dielectric mirrors that are designed so that GDD oscillations of these DMs are in antiphase and hence mutually cancel each other when the same number of mirrors are used for dispersion control.

The double-angle DM approach is based on the same concept. By striking contrast to previous implementations, it draws on identical mirrors used at two different angles of incidence (Fig. 1). Antiphase oscillations of GDD are achieved due to a well-known property of multilayers: their reflectance and GDD versus wavelength shift to shorter wavelengths with increasing angle of incidence [27].

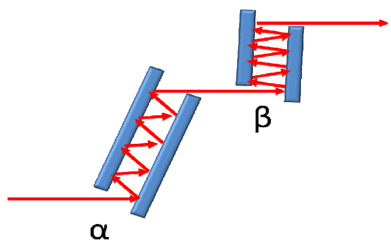

Fig. 1. Schematic of a double-angle DM compressor. The four mirrors employed have been produced in the same coating run with their multilayer structure optimized for mutual cancellations of GDD oscillations at the two different angles of incidence chosen: α=20° and β=5°.

We developed a special synthesis algorithm to design a double-angle DM pair, implemented as a plug-in module to our commercially available software [28]. Our synthesis algorithm uses needle optimization and gradual evolution techniques that are well-proven for the solution of the most complicated thin film design problems [29, 30].

In our proof-of-concept study, we considered the simplest case of two different angles of incidence. The effective reflectance of the double-angle DM is the geometric mean of reflectances for these incident angles and its effective GDD is the arithmetic mean of GDDs for these incident angles. Our synthesis aimed at minimizing the deviation of the effective reflectance from 100% in the spectral region of 550 – 1050 nm and to minimize the deviation of the effective GDD from its target value shown by the dashed line in Fig. 2 over the same

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spectral region. The optimum effective GDD (green curve in Fig. 2) exhibits residual oscillations by an order of magnitude reduced as compared to those of the GDD of the individual mirrors for each incidence angle.

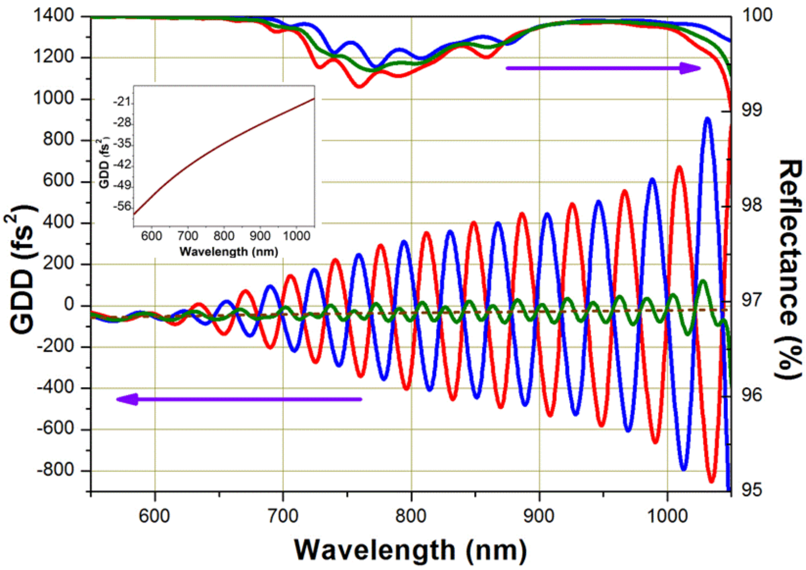

Fig. 2. Characteristics of a DM designed with the double angle approach. Red and blue curves correspond to angles of incidence of 5 and 20 degrees, respectively. Green curves show the effective GDD and reflectance, see definitions in text. Dashed curve and curve in the inset of the figure is the target GDD.

The designed double-angle DM consists of 80 alternating Nb_2O_5/SiO_2 layers, with a multilayer structure shown in Fig. 3.

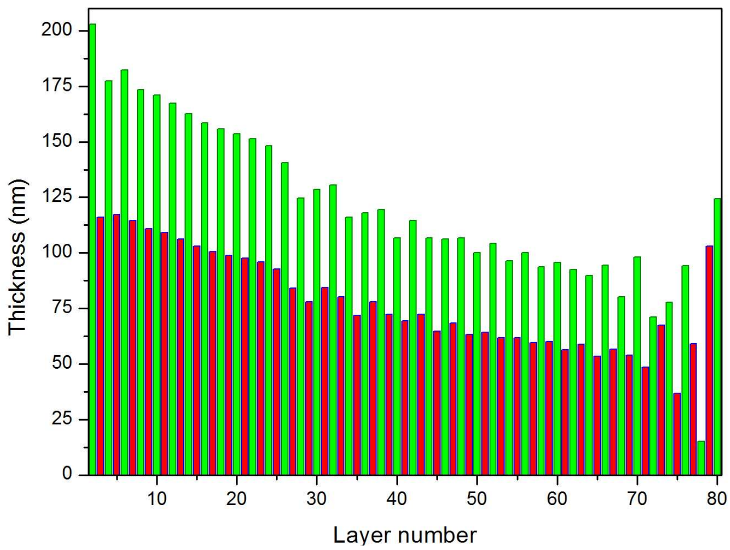

Fig. 3. Physical thicknesses of layers in our prototypical double-angle DM design. Layers are numbered starting from the substrate. Green and red bars correspond to low and high refractive index materials, SiO_2 and Nb_2O_5, respectively.

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The thickness of both types of layers tends to decrease with increasing distance from the substrate, reminding of the design of "classical" chirped mirrors [8]. The physical thicknesses of the layers range from 13 nm to 210 nm.

To check the implications of the residual oscillations of the effective GDD of the double-angle mirror, we simulated the propagation of an ideal transform-limited pulse having the frequency spectrum originating from our hollow fiber (see Fig. 4) through our simple optical system following the fiber. It incorporates a 3-mm path through fused silica, a 5-m path through air and 4 bounces of our double-angle DMs at each of the two selected angles of incidence given in Fig. 1. As revealed by the blue line in Fig. 5, the Fourier-limited input pulse of a duration of 4.2 fs (full width at half maximum, FWHM, of the intensity profile), red line in Fig. 5, suffers virtually no broadening, merely a small fraction (~5%) of its energy is scattered into a satellite pulse.

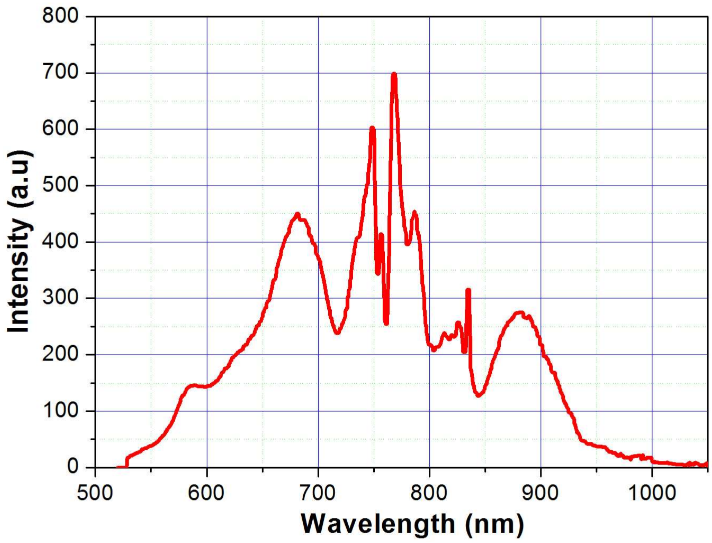

Fig. 4. Spectrum of femtosecond pulses originating from our gas-filled hollow fiber. With constant or linearly-varying spectral phase, it allows the generation of 4.2-fs transform-limited pulses.

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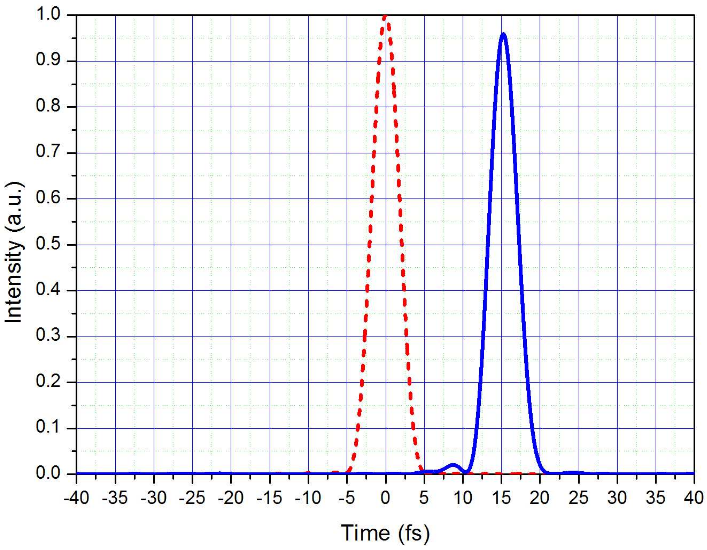

Fig. 5. 4.2-fs Fourier-limited pulse before (dashed line) and after (full line) propagation through dispersive material and our double-angle DM compressor sketched in Fig. 1.

3. Manufacturing of the double angle DM

Successful fabrication of DMs can be as challenging as their design. The main problem is connected with high sensitivity of GDD to even small errors in layer thicknesses. Therefore a high precision of the deposition process is mandatory for successful DM production. We scrutinized our double-angle DM design by means of standard computational error analysis. Layer thicknesses of the design were subjected to independent random variations with normal distribution. Standard deviation of normal distribution was taken as 1 nm for all layers. For each perturbed design we computed GDD and performed statistical analysis of obtained GDD dependencies. Theoretical GDD of initial DM design is shown in Fig. 6 by blue curves for comparison. The green area is represents a band enclosing the GDD with a probability of 68.3%.

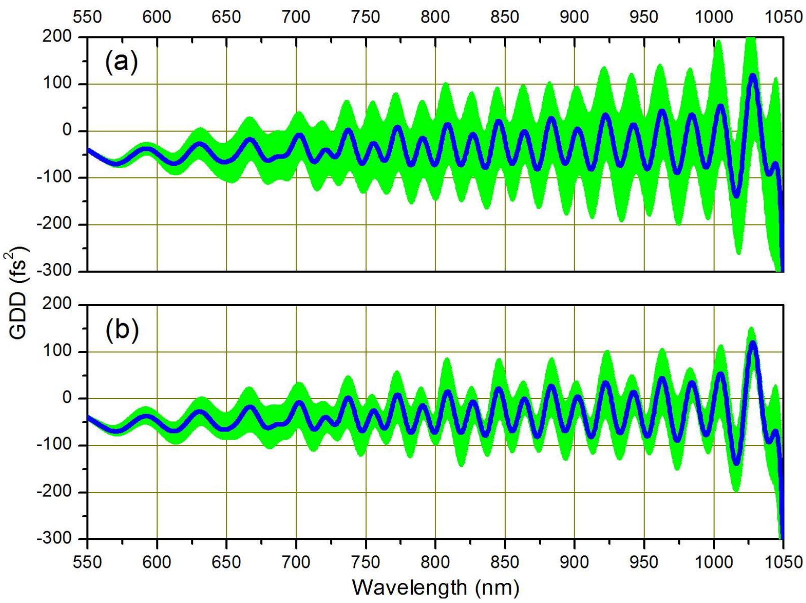

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Fig. 6. Error analysis of our prototypical double-angle DM. Top panel (a) represents the hypothetical case of independent thickness errors in the two complementary DMs. Bottom panel (b) shows the case of identical thickness errors in the both DMs of the pair. Blue curves represent theoretical spectral dependence of GDD, green areas represent the probable range of GDD values, for details, see text.

In an attempt to compare the error sensitivity of the new concept with the conventional complementary-pair approach, we performed this error analysis under two different conditions. First, we subjected the layer thicknesses of each of the mirrors to be used at different angles of incidence to independent random variations (160 in total), simulating the conventional approach relying on complementary mirrors manufactured separately. The results are shown in Fig. 6(a). Subsequently, we subjected layer thicknesses in both mirrors to the same thickness variations (80 independent random variations), corresponding to both mirrors being manufactured in the same deposition run and hence being identical, see Fig. 6(b). It is conspicuous that in the latter case variations of GDD are significantly smaller for the same level of thickness errors. Enhanced robustness of the double-angle DM approach relates to the fact that – for small perturbations – GDD oscillations of identical mirrors used at different incidence angles are affected in the same way and hence remain in antiphase.

For decades, the magnetron sputtering and ion-beam sputtering have been the most reliable techniques for depositing thin dielectric films. Both of these technologies have been widely used for manufacturing DMs [19, 23]. Our double-angle DMs were fabricated with by magnetron sputtering endowed with a time-control thickness monitoring (Helios, Leybold Optics GmbH, Alzenau, Germany). Further details about this technology can be found in [19, 23, 31, 32].

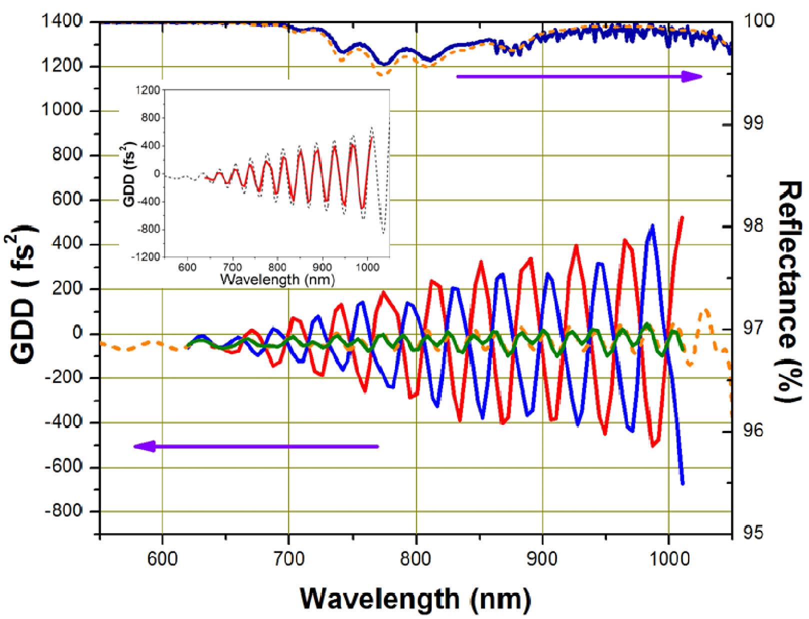

Fig. 7. Measured GDD and reflectance of our prototypical double-angle DM for an angle of incidence of 5 and 20 degrees (full lines). GDD and reflectance of the theoretical design are shown by dashed lines. Red and blue curves correspond to angles of incidence of 5 and 20 degrees, respectively. Dark green and dark blue curves show the effective measured GDD and reflectance, see definitions in text.

After fabrication, the GDD of the DMs was measured with a white-light interferometer [33]. The result is summarized in Fig.7. In the inset of Fig. 7 are shown comparison of measured and theoretical GDD of our prototypical double-angle DM for an angle of incidence

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of 5 degree. We observe a good agreement between the calculated and measured reflectance as well as GDD values.

4. Laboratory compression experiments and discussion

The prototypical double-angle DMs were tested in a hollow-core-fiber/dispersive-mirror compressor seeded by millijoule-scale, sub-25-fs pulses from a kilohertz-rate femtosecond Ti:sapphire laser. The hollow fiber with a length of ~ 1 m and a core diameter of 0.3 mm was filled with neon at a pressure of 2.2 bar and resulted in the output spectrum shown in Fig. 4. The pulses exiting the fiber traveled a distance of 1.7 m in air and 1.5 mm in fused silica and were passed through the double-angle DM compressor sketched in Fig. 1. The duration of the compressed pulse was measured by second-harmonic generation interferometric autocorrelation, utilizing a 5-μm thick, type-1 phase-matched BBO crystal. The measured autocorrelation function is shown in Fig. 8 (full line) along with the one calculated from the measured spectrum (Fig. 4) under the assumption of the absence of spectral phase modulation (dashed line).

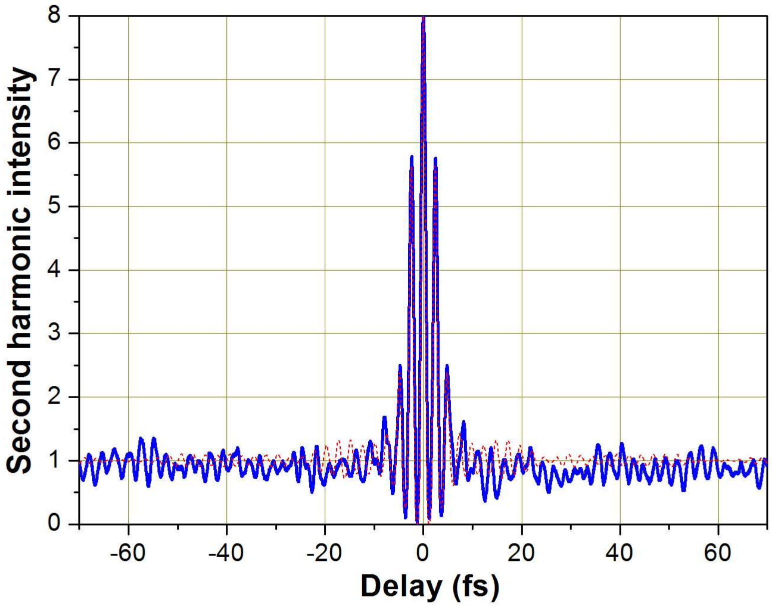

Fig. 8. Dashed line: theoretical interferometric autocorrelation of a pulse with the frequency spectrum shown in Fig. 4 in the absence of spectral phase modulation. This Fourier-limited pulse has a duration (FWHM) of 4.2 fs. Full line: measured interferometric autocorrelation function of the pulses compressed with our prototypical double-angle DM compressor, indicating a pulse duration of ~ 4.3 fs.

Our interferometric autocorrelation measurement yields a near-bandwidth-limited pulse from our double-angle DM compressor with a duration of 4.3 fs. The autocorrelation trace exhibits small oscillations over a delay range of several 10 femtoseconds, indicative of small pre/post-pulsing as a consequence of the residual GDD oscillations in the compressor and incomplete high-order dispersion compensation.

5. Conclusions and outlook

We have demonstrated pulse compression down to the 4-fs regime with dispersive mirrors used at two different angles of incident for suppressing undesirable spectral oscillations of their group delay dispersion. The main advantage of this approach is an increased stability against deposition errors as compared to the conventional complementary-pair approach. In addition, the new concept requires only one coating run for producing all DMs in contrast to the conventional route relying on two perfectly-matched coating runs, thus dramatically reducing deposition cost and deposition time.

In this proof-of-concept study we resorted to designing the DMs for use at only two different angles of incidence. For further suppression of residual GDD oscillations or keeping them at the same level for increasing bandwidth, the number of different angles of incidence can be increased, without compromising complexity and cost of manufacture. Yet another alternative for bettering performance may be a combination of the double-angle DM approach with the time-domain optimization [25]. We are hopeful that the concept presented here will be instrumental in advancing optical pulse compression to its ultimate limit with a simple, cost-effective apparatus.

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