High-dispersive mirrors for femtosecond lasers

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Abstract: We report on the development of highly dispersive mirrors for chirped-pulse oscillators (CPO) and amplifiers (CPA). In this proof-of-concept study, we demonstrate the usability of highly dispersive multilayer mirrors for high-energy femtosecond oscillators, namely for i) a chirped-pulse Ti:Sa oscillator and ii) an Yb:YAG disk oscillator. In both cases a group delay dispersion (GDD) of the order of 2×10^4 fs^2 was introduced, accompanied with an overall transmission loss as low as ~ 2 per cent. This unprecedented combination of high dispersion and low loss over a sizeable bandwidth with multilayer structures opens the prospects for femtosecond CPA systems equipped with a compact, alignment-insensitive all-mirror compressors providing compensation of GDD as well as higher-order dispersion.

OCIS codes: (320.5520) Pulse compression; (310.1620) Interference coatings.

References and Links

1. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**, 219 (1985).
2. R. Szipöcs, K. Ferencz, C. Spielmann, and F. Krausz, “Chirped multilayer coatings for broadband dispersion control in femtosecond lasers,” Opt. Lett. **19**, 201–203 (1994).
3. F. X. Kärtner, N. Matuschek, T. Schibli, U. Keller, H. A. Haus, C. Heine, R. Morf, V. Scheuer, M. Tilsch, and T. Tschudi, “Design and fabrication of double-chirped mirrors,” Opt. Lett. **22,** 831–833 (1997).
4. N. Matuschek, L. Gallmann, D. H. Sutter, G. Steinmeyer, and U. Keller, “Back-side-coated chirped mirrors with ultra-smooth broadband dispersion characteristics,” Appl. Phys. B **71**, 509-522 (2000).
5. V. Pervak, S. Naumov, G. Tempea, V. Yakovlev, F. Krausz, and A. Apolonski, “Synthesis and manufacturing the mirrors for ultrafast optics,” Proc. SPIE **5963**, 490-499 (2005).
6. G. Steinmeyer, “Femtosecond dispersion compensation with multiplayer coatings: toward the optical octave,” Appl. Opt. **45**, 1484–1490 (2006).
7. G. Steinmeyer and G. Stibenz, “Generation of sub-4-fs pulses via compression of a white-light continuum using only chirped mirrors,” Appl. Phys. B **82**, 175-181 (2006).
8. V. Pervak, A. V. Tikhonravov, M. K. Trubetskov, S. Naumov, F. Krausz, and A. Apolonski, “1.5-octave chirped mirror for pulse compression down to sub-3 fs, ”Appl. Phys. B. **87**, 5-12 (2007).
9. A. Fernandez, A. Verhoef, V. Pervak, G. Lermann, F. Krausz, and A. Apolonski. “Generation of 60-nJ sub-40-fs pulses at 70 MHz repetition rate from a Ti:sapphire chirped pulse-oscillator,” Appl.Phys. B **87** 395-398 (2007).
10. S. Naumov, A. Fernandez, R. Graf, P. Dombi, F.Krausz, and A. Apolonski, “Approaching the microjoule frontier with femtosecond laser oscillators,” New J. Phys. **7**, 216 (2005).
11. S. V. Marchese, T. Südmeyer, M. Golling, R. Grange, and U. Keller, "Pulse energy scaling to 5 μJ from a femtosecond thin disk laser," Opt. Lett. **31**, 2728-2730 (2006).
12. S. Dewald, T. Lang, C. D. Schröter, R. Moshammer, J. Ulrich, M. Siegel, and U. Morgner, “Ionization of noble gases with pulses directly from laser oscilator,” Opt. Lett. **31**, 2072-2074 (2006).
13. G. Palmer, M. Siegel, A. Steinmann, and U. Morgner, „Microjoule pulses from a passively mode-locked Yb: $KY(WO_4)_2$ thin-disk oscillator with cavity dumping,“ Opt. Lett. **32**, 1593-1595 (2007).
14. S. V. Marchese, C. R. E. Baer, R. Peters, C. Kränkel, A. G. Engqvist, M. Golling, D. J. H. C. Maas, K. Petermann, T. Südmeyer, G. Huber, and U. Keller, “Efficient femtosecond high power Yb:Lu2O3 thin disk laser,” Opt. Express **15**, 16966-16971 (2007).
15. OptiLayer software: http://www.optilayer.com.
16. A. N. Tikhonov, A. V. Tikhonravov, and M. K. Trubetskov, “Second order optimization methods in the synthesis of multilayer coatings,” Comp. Maths. Math. Phys. **33**, 1339-1352, (1993).
17. A. V. Tikhonravov, M. K. Trubetskov, and G. W. DeBell, “Application of the needle optimization technique to the design of optical coatings,” Appl. Opt. **35**, 5493-5508 (1996).

#93501 - \$15.00 USD Received 6 Mar 2008; revised 10 Apr 2008; accepted 16 May 2008; published 24 Jun 2008

18. V. Laude and P. Tournois, "Chirped-mirror pairs for ultra-broadband dispersion control," in Conference on Lasers and Electro-Optics, 1999 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1999), paper CTuR.
19. V. Pervak, F. Krausz, and A. Apolonski, "Dispersion control over the UV-VIS-NIR spectral range with HfO2/SiO2 chirped dielectric multilayers," Opt. Lett. **32**, 1183-1185 (2007).
20. V. Pervak, S. Naumov, F. Krausz, and A. Apolonski, "Chirped mirrors with low dispersion ripple," Opt. Express **15**, 13768-13772 (2007).
21. R. Szipocs, A. Koházi-Kis, S. Lako, P. Apai, A. P. Kovács, G. DeBell, L. Mott, A. W. Louderback, A.V. Tikhonravov, M. K. Trubetskov: "Negative Dispersion Mirrors for Dispersion Control in Femtosecond Lasers: Chirped Dielectric Mirrors and Multi-cavity Gires-Tournois Interferometers," Appl. Phys. B **70**, S51-S57 (2000).
22. B. Golubovic, R. R. Austin, M. K. Steiner-Shepard, M. K. Reed, S. A. Diddams, D. J. Jones, and A. G. Van Engen, "Double Gires—Tournois interferometer negative-dispersion mirrors for use in tunable mode-locked lasers," Opt. Lett. **25**, 275-277 (2000).
23. A. Fernandez, T. Fuji, A. Poppe, A. Fürbach, F. Krausz, and A. Apolonski, "Chirped-pulse oscillators: a route to high-power femtosecond pulses without external amplification," Opt. Lett. **29**, 1366-1368 (2004).
24. H. A. Haus, J. G. Fujimoto, and E. P. Ippen. "Structures for additive pulse mode-locking," J. Opt. Soc. Am B **8**, 2068-2076 (1991).
25. F.Krausz, M. E. Fermann, Th. Brabec, P. F. Curley, M. Hofer, M. H. Ober, Ch. Spielmann, E. Wintner, and A. J. Schmidt, "Femtosecond solid-state lasers," IEEE J. Quantum Electron. **28**, 2097-2122 (1992).
26. E. Innerhofer, T. Südmeyer, F. Brunner, R. Häring, A. Aschwanden, R. Paschotta, C. Hönninger, M. Kumkar, and U. Keller, "60-W average power in 810-fs pulses from a thin-disk Yb:YAG laser," Opt. Lett. **28**, 367-369 (2003).
27. G. Tempea, B. Považay, A. Assion, A. Isemann, W. Pervak, M. Kempe, A. Stingl, and W. Drexler, " All-Chirped-Mirror Pulse Compressor for Nonlinear Microscopy," in *Biomedical Optics*, Technical Digest (CD) (Optical Society of America, 2006), paper WF2.

1. Introduction

Chirped-pulse amplifiers (CPA) [1] delivering millijoule-energy femtosecond laser pulses at kHz repetition rates constitute major workhorses for nonlinear optics and ultrafast science. These systems rely on rather complex, lossy, and alignment-sensitive stretchers and/or compressors for implementing CPA. As a culmination of the evolution of chirped multilayer mirror technology [2-9], here we demonstrate the feasibility of low-loss, high-dispersion mirrors (HDM) taking over the role of prisms and possibly gratings in conventional CPA systems with the added benefit of providing high-order dispersion control.

Large amount of dispersion, comparable to those applied in CPA systems, is also required in high-energy femtosecond laser oscillators operating at the microjoule level [10-14]. They are either operated in the regime of positive or negative intracavity GDD, requiring large amounts of negative GDD for extracavity compression or stable intracavity solitary pulse formation, respectively. As a first application of HDMs, we utilize them for near-bandwidth-limited pulse generation in both types of high-energy femtosecond oscillators, based on an Yb:YAG disk laser with a spectrum of up to 1.5 nm (FWHM) centered at 1030 nm and a Ti:Sa CPO [10] with a spectrum of 40 nm centered at 800 nm. The overall GDD realized in both cases represent the highest values achieved with the CM technology so far.

2. Theory, design and analysis of HDMs

By definition, a HDM is characterized by a high group delay difference between different spectral components. Because the delay scales with the penetration depth of radiation, a HDM must have a large overall thickness of total multilayer structure. This implies that manufacturing HDM calls for a well-controlled, extended-period (~ 10 hours) deposition process allowing one to deposit a thick multilayer structure with high accuracy.

In a first approximation, a narrowband HDM can be described as a sequence of wavelength-shifted quarter-wave deposited stacks (Bragg reflectors). Each stack in the structure is responsible for reflection of radiation within its respective spectral band, therefore it has to have steep spectral shoulders to avoid undesirable overlap with spectral bands of adjacent stacks.

We have used the commercial OptiLayer software [15], drawing on the needle optimization [16] and the gradual evolution [17] algorithms, for designing our prototypical

HDMs for the 780-820 nm and the 1020-1040 nm spectral ranges. In what follows, we shall discuss the former design in detail, with the design approach and problems to be solved being the same for the longer wavelength range. The complementary CM approach, usually used for providing a smooth GDD in broadband mirrors [18], is difficult to implement for realizing HDMs because of the high sensitivity of the GDD to manufacturing errors. For the time being, we have therefore opted for meeting the dispersion requirements with multiple reflections off one single type of a HDM only. In our one-mirror approach, which tends to suffer from enhanced spectral ripples of the GDD curve, the amplitude of the ripples could be sufficiently suppressed by a specific design procedure that makes upper layers function as an efficient antireflection coating over the relevant spectral band of moderate width. Producing efficient antireflection coatings for a broad spectral range is more difficult, therefore the complementary mirror approach is more efficient in smoothing the ripples. Because of a high number of reflections that is usually needed to introduce the necessary amount of dispersion, the relative magnitude of the GDD ripple should not exceed 10%.

The multilayer structure of the 800-nm HDM design is shown in Fig. 1. The layer thicknesses range between 25 nm and 400 nm, resulting in a total physical thickness of the structure as large as ~ 10 μm. The mirror provides a GDD of about –1300 fs^2 @ 800 nm together with an average reflectivity of 0.9995 in the wavelength range of 780–820 nm (in the absence of scattering losses), see Fig. 2(a). The HDM designed for the spectral range around 1030 nm has a nominal GDD of about –2500 fs^2 and average reflectivity of 0.9999.

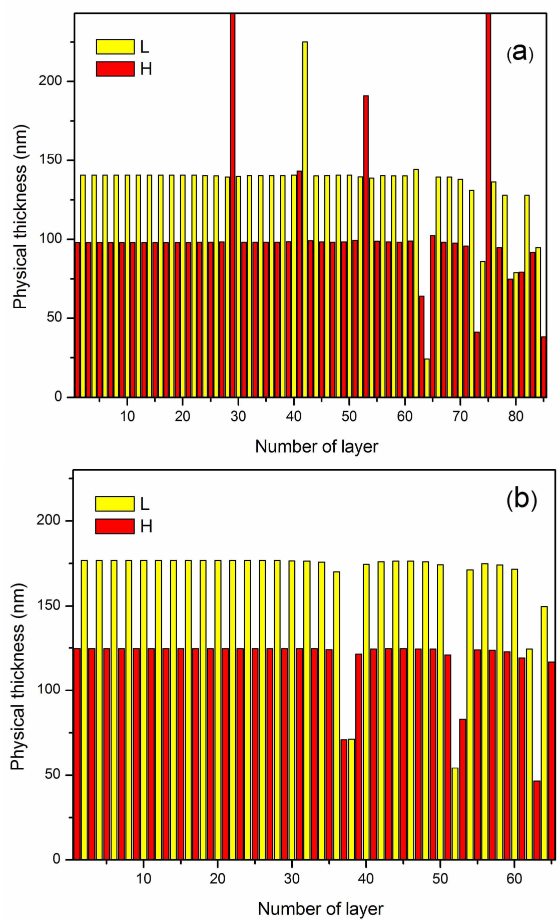

Fig. 1. The refractive index profile of HDMs. (a): HDM for Ti:Sa CPO, (b): for Yb:YAG oscillator.

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These mirrors substantially outperform previously demonstrated high-dispersion CMs in terms of both nominal GDD and bandwidth [10-14].

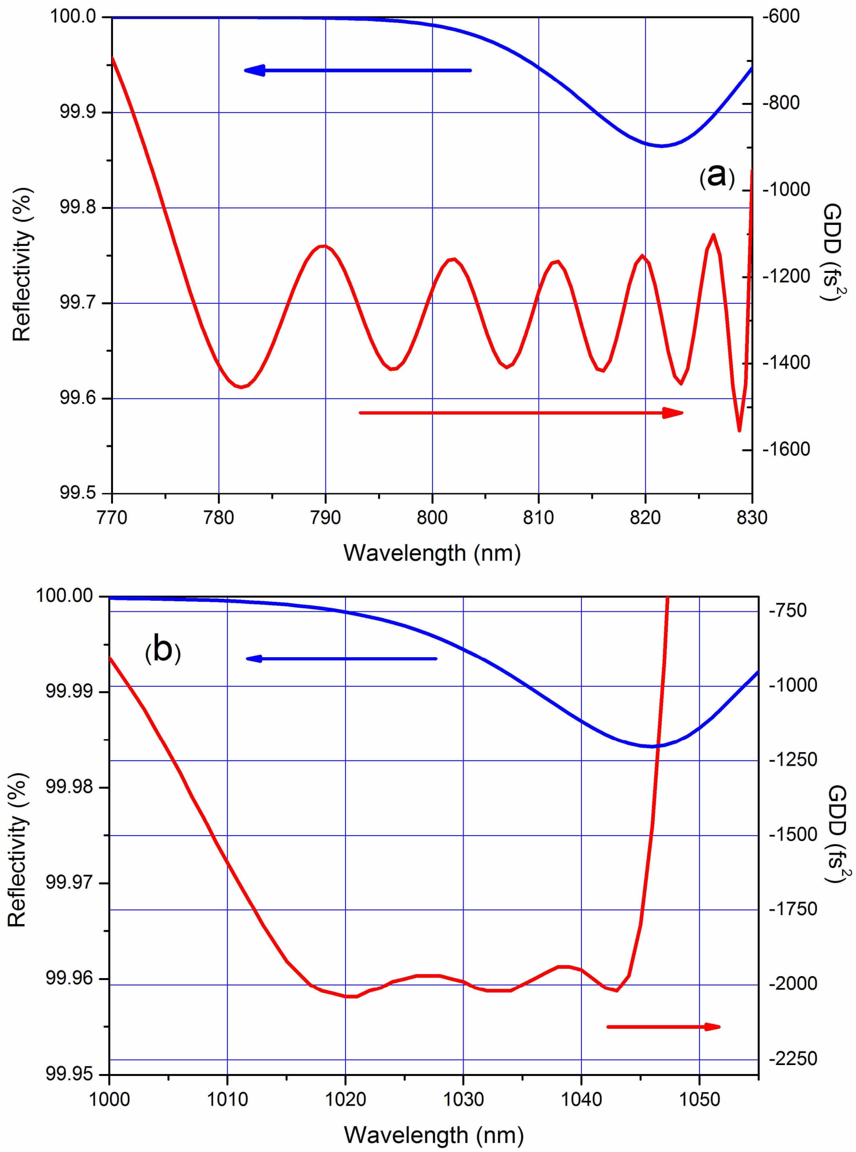

Fig. 2. The calculated GDD and reflectivity of HDMs. (a): HDM for Ti:sapphire CPO, (b): for Yb:YAG oscillator.

The GDD needed to compress the pulses delivered by our Ti:Sa CPO is of the order of 2.5×10^4 fs^2 [10], requiring some 20 bounces off our 800-nm HDM. Fig. 3 reveals that the spectral ripples of the GDD accumulated in 20 bounces deteriorate a 60-fs pulse to a negligible extent: the exiting pulse preserves its incident duration and >95% of the input energy within its main feature.

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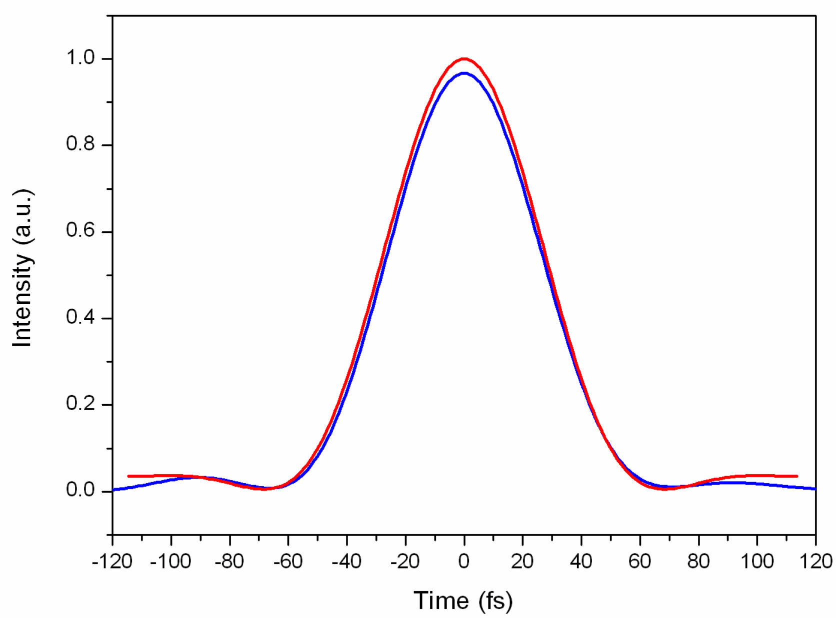

Fig. 3. Change in the temporal profile of a 60-fs pulse by bouncing 20 times off the 800-nm HDM design shown in Fig. 2 (simulation). The red and the blue curves show the temporal intensity profile before and after the bounces, respectively. In the analysis, the nominal (average) value of the mirror GDD was disregarded with only the spectral ripples affecting propagation.

Whether this favourable performance can indeed be put into practice depends on the accuracy of the manufacturing process and the sensitivity of the HDM design to (unavoidable) manufacturing errors. This sensitivity is summarized in Fig. 4 for the two prototypical designs presented above. The extraordinary sensitivity of the HDM design to manufacturing errors suggests that it may be difficult to manufacture a HDM with well-established technologies such as (ion-assisted) electron-beam beam evaporation and ion-beam sputtering. So far, highest layer deposition accuracy was demonstrated by means of the reactive dual magnetron-sputtering process with plasma/ion assistance [5, 8, 19, 20] due to time control, which therefore ideally lends itself for realizing HDMs.

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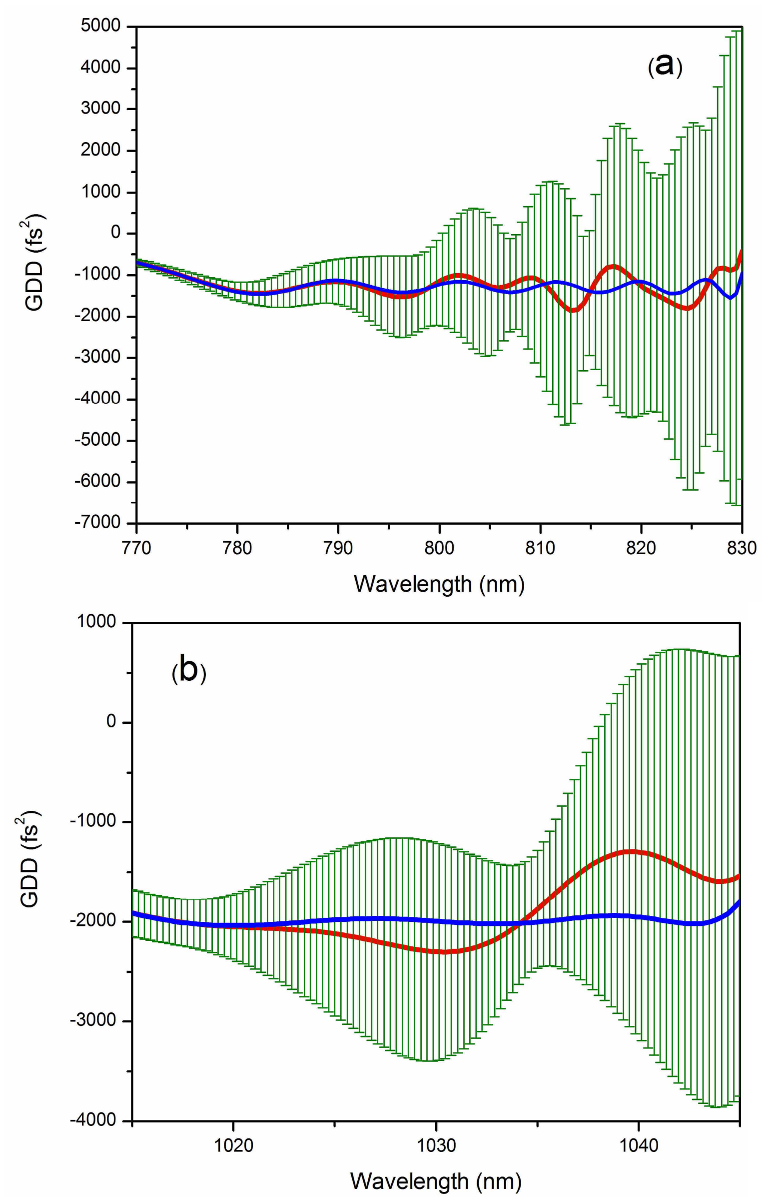

Fig. 4. Error analysis of the 800-nm (a) and 1030-nm (b) HDM designs. The envelopes of the green error bars represent worst-case boundaries for of +/-1 nm errors in the physical thicknesses of the layers. The red line is the average of 100 curves with random +/-1 nm errors. The blue line plots the calculated GDD curve. Worst-case deviations appear to be comparable to the nominal value of the mean GDD.

3. Manufacturing and characterization

The HDMs were produced by means of magnetron-sputtering (Helios, Leybold Optics) [5]. We chose Ta_2O_5 and SiO_2 as materials with high (2.12 @ 800 nm) and low (1.47 @ 800 nm) refractive index, respectively. These materials offer optimum trade-off between low loss and high difference in the refractive indices for the wavelength range around 800 nm [5, 19, 20]. The actual refractive indices of the coating materials were determined just before the coating process started for maximizing the degree to which the designs can be reproduced in the manufacturing process. The transmission spectra were measured with a spectrophotometer

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(Lambda 950, Perkin Elmer). The GDD was determined by using a home-built white-light interferometer with a spectral accuracy of 5 nm and the dispersion accuracy of ~10 fs^2. Fig. 5 summarizes the results of these measurements. Taking into consideration the high sensitivity of the mirror dispersion to manufacturing errors, the agreement between theory and experiment appears to be satisfactory. The reflectivity of the manufactured HDMs was measured with a precision loss meter (LossPRO, Novawave Technologies, Inc.) at wavelengths of 808 and 1030 nm, yielding excellent values of ~99.9%. This implies the feasibility of temporally stretching and/or compressing femtosecond pulses by a factor of a thousand or more with losses less than 10% with HDMs.

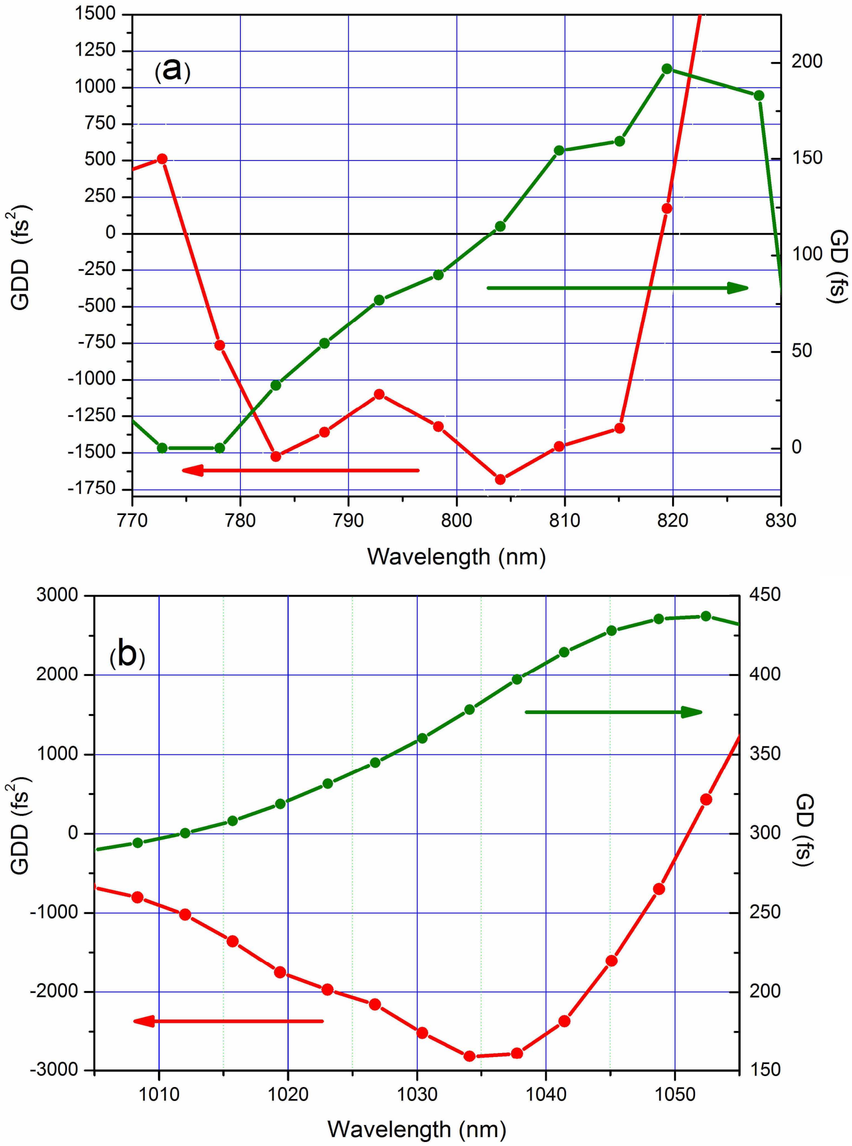

Fig. 5. The GDD (red) and group delay (GD, green) curves of two types of HDMs measured with white light interferometer. (a): a mirror for Ti:sapphire CPO, (b): a mirror for Yb:YAG oscillator.

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In spite of a quasi-periodic structure of HDMs shown in Fig. 1, they provide a variable delay of different spectral components, see Fig. 5. Together with the variable penetration depth of the electric field inside the multilayer structure shown in Fig. 6, these findings lead us to conclude that our HDMs function like conventional CMs except the large delay value they introduce.

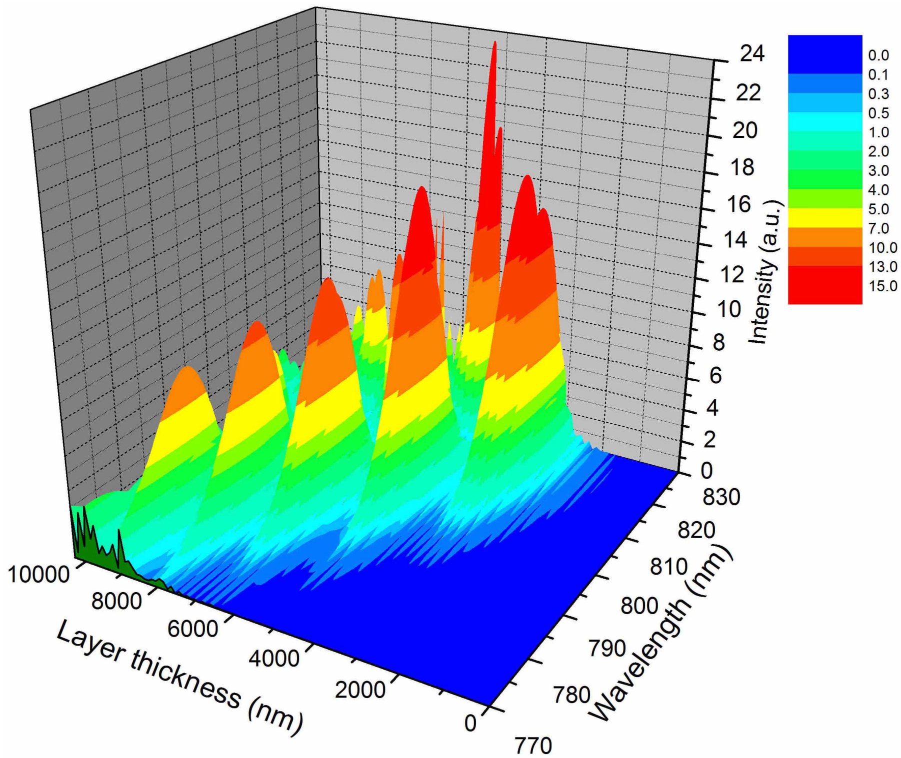

Fig. 6. The penetration depth of spectral components into the HDM structure shown in Fig.1a. Light enters the structure from the left side.

Strictly speaking, the layer structures shown in Figs. 1-6 do not match standard CMs nor to Gires-Tournois interferometer dispersion mirrors (GTIDMs). A purely classical CM is defined as a structure with gradual change in optical thickness from the beginning of the structure to the end. This is not the case for our HDM, see Fig. 1. More generally, a CM is a mirror that provides a controlled delay for different spectral components [2]. Fig. 6 shows the monotonic dependence of the penetration depth of different spectral components in agreement with this definition. On the other hand, a CM approach can not explain the large delay shown in Fig.5. A GTIDM has a few top layers (operating like an interferometer) affected by modification from a quarter-wave stack and can in principle provide a larger delay [2, 21, 22]. Owing to this structure, GTIDMs have 1) a robust design and 2) led to localization of electric field inside the cavities of the top layers (a few maxima). This is not the case for our HDMs as the design is sensitive to errors and further the penetration depth of the electric field gradually changes inside the HDM structure as function of wavelength. Additionally, as shown in Fig. 6, HDMs also exhibit multiple (at least 5) local maxima. In previous published reviews [5, 8-10] of our dispersive mirrors, the mirrors called as CMs were distinguished in that they all had several local maxima of electric field and variable penetration depth for different spectral components. The existence of multiple maxima indicates that each a-periodic multilayer structure has resonances of electric field due to multiple cavities inside the entire structure,

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which is unavoidable for a broad spectrum. On the other hand, a GTIDM approach helps us to explain the large temporal delay achieved in our HDMs (Fig. 5). The total GD in the HDM structure is a result of two combined effects, the penetration effect (used in CM) and the resonance effect found in (GTIDM). The penetration effect gives us a delay GD=$2L/c$, where L is the length in a multilayer structure until which the beam is penetrated and c – speed of light. In our case (see Fig.6) the optical path is 16 µm (8 µm is a physical length multiplied by the average refractive index which is about 2 for our structure). Thus the GD which can be obtained by the pure penetration effect is 100 fs. In the case of our HDMs (see Fig.5), we measure a total GD equal to 150 fs. Therefore, 50 fs of the delay can be attributed to resonance effects found in GTIDM. Based on the analysis above, we concluded that our HDM has properties of both CM and GTIDM. Therefore, we have decided to define them as high dispersive mirrors in this paper. Nevertheless, we propose to use in future the terminology "chirped mirrors" for all structures which provide a controlled delay of spectral components.

4. First applications of HDMs

To test the utility of the 800-nm HDMs presented above, we have used them for compressing the pulses delivered by a high-energy femtosecond Kerr-lens-mode-locked Ti:Sa CPO. Such an oscillator operates in the regime of positive intracavity GDD and delivers heavily-chirped ~2 ps pulses, which can be externally compressed to their bandwidth limit in the 30-60 fs range [9, 10, 23].

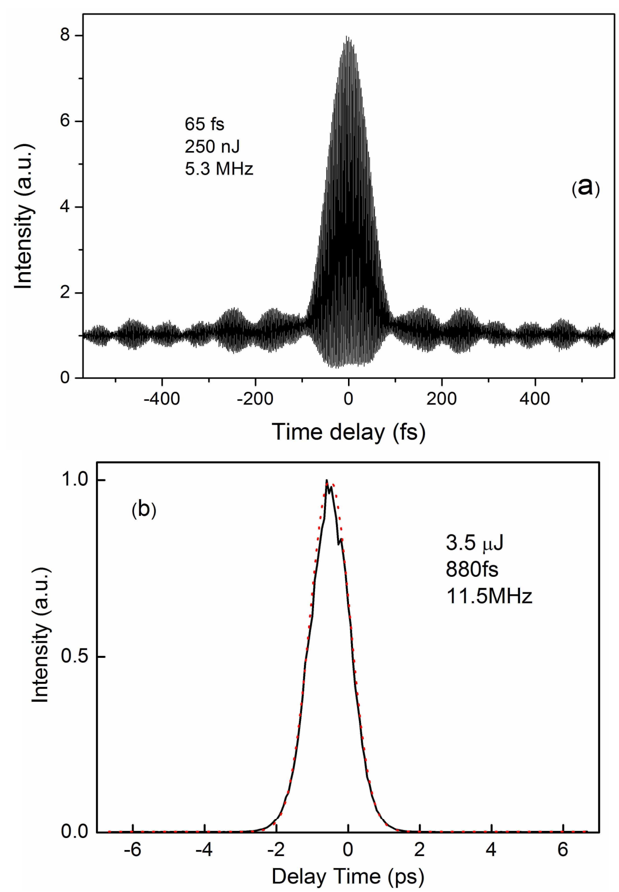

Fig. 7. (a): Interferometric autocorrelation trace of 0.25-µJ pulses delivered by a Ti:Sa CPO and compressed via 20 bounces off the 800-nm HDMs presented above. (b): Intensity autocorrelation trace of 3.5-µJ pulses produced by an Yb:YAG disk oscillator.

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In our experiments, the laser produced 250-nJ pulses at a 5 MHz repetition rate in the spectral range of 780-820 nm, see inset in Fig. 7(a). These pulses have been compressed in a 2-pass prism compressor (LaK 21 glass) to a duration of 65 fs with an energy throughput of ~50%. The relatively low throughput relates to the extended (~8m) compressor length, implying some clipping of the beam. The autocorrelation trace obtained with a second harmonic interferometric autocorrelator contained significant residual sidelobes and had a contrast lower than 8:1 [10]. This prism compressor was replaced by a our newly-developed HDMs. 20 reflections off the mirrors were sufficient to compress the pulses to their bandwidth limited duration of about 65 fs with an energy throughput efficiency of 98.0±0.6% in agreement with the loss measurements reported above.

The 1030-nm HDMs were tested in an Yb:YAG disk oscillator incorporating a 200-µm-thick Yb:YAG disk and three 1030-nm HDMs presented above for realizing a high negative intracavity dispersion to support stable soliton-like pulse formation. In this operation regime the mode-locked pulse duration τ relates to the group delay dispersion, *D*, and intracavity pulse energy, *W*, as given by $\tau \sim |D|/W$ [24, 25]. Stability requires this stationary pulse duration to exceed the inverse gain bandwidth. Consequently, increasing pulse energy implies the need for increasing intracavity dispersion. The 3 bounces off HDMs allowed stable operation of the laser in helium atmosphere up to output pulse energies of 5-µJ and durations of less than 1 ps, see Fig. 7(b), delivered at a 11 MHz repetition rate. The overall GDD value introduced by 3 HDMs is comparable to what was realized in [26] (11 dispersive mirrors). This laser will be described in detail in a forthcoming publication.

5. Dispersion versus bandwidth

Our studies have revealed that the broader the spectrum for which the GDD must be controlled the lower the nominal value of the GDD that can be achieved. In other words, relaxing the requirements on bandwidths allows for higher values of the GDD. This finding has been inferred from the design and manufacturing of 9 different CMs, described in Refs. [5, 8, 17, 20, 27], each of which represents the highest absolute value of the GDD obtained for a certain spectral width by using the same optimization technique, see Fig. 8.

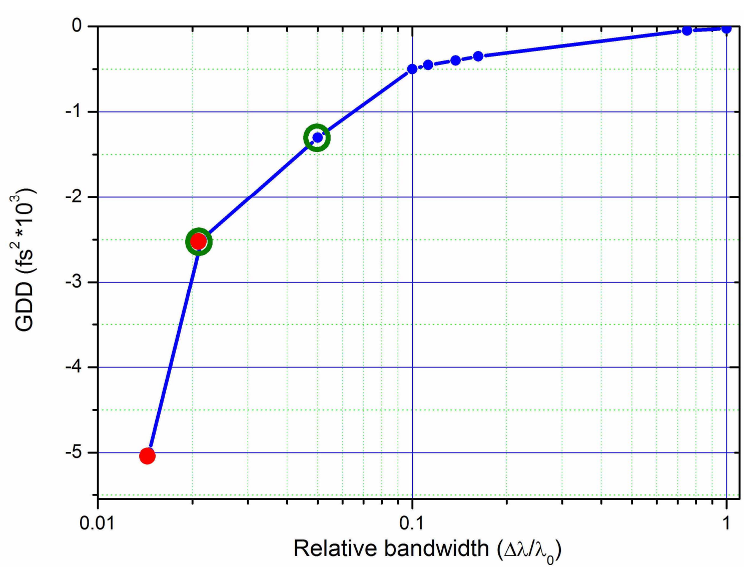

Fig. 8. The highest value of negative GDD realized with magnetron sputtering of the layer materials Ta_2O_5, Nb_2O_5 and SiO_2, as a function of the relative bandwidth, obtained at two different design wavelengths: 0.8 µm (blue dots) and 1 µm (red dots). Green circles mark the values realized with the HDMs described in this paper. The lines connecting the points serve as a guide to the eye.

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The actual values of the points along the GDD axis depend on the central frequency, layer materials and required reflectivity. The data provide a rule of thumb for the trade-off between the bandwidth and the dispersion achievable. Note that there is yet another trade-off to be appreciated, namely the one between the highest achievable GDD and the reflectivity. For example, for the spectral range of 780-820 nm, the reflectivity can be as high as 0.9995 for the main GDD value of about -1300 fs^2, but only 0.96 for the GDD=-2000 fs^2.

6. Conclusions

Hundreds of kHz-rate Ti:sapphire femtosecond CPA lasers are in use all over the world. Their operation relies on the stretching and recompressing the pulses before and after amplification. Currently, complex, rather lossy and alignment sensitive optical systems based on prisms and/or diffraction gratings are employed for this purpose. This work demonstrates that the required dispersion up to orders of 10^5 fs^2 can possibly be introduced by a set of high-dispersive chirped multilayer dielectric mirrors offering several advantages including simplicity, alignment-insensitivy, and the potential for increased efficiency. A first step in this direction has been demonstrated by employing the new HDM technology in µJ-level femtosecond laser oscillators.

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