All-dispersive-mirror compressor

V. Pervak

Ludwig-Maximilians-Universitaet Muenchen, Am Coulombwall 1, D-85748 Garching, Germany

E-mail: vladimir.pervak@physik.uni-muenchen.de

Received October 21, 2009

We report on the development of highly dispersive mirrors for chirped-pulse oscillators (CPOs) and amplifiers (CPAs). Low-loss and alignment-insensitive all-dispersive-mirror compressors can take over the role of prisms and gratings in conventional CPA systems, with the added benefit of shorter pulse duration due to high-order dispersion control and absence of self-phase modulation. The evolution of dispersive dielectric multilayer mirror technology within the last 15 years now allows us to report a new generation of low-loss and alignment-insensitive high-dispersion mirrors (HDMs). In this proof-of-concept study, we demonstrate the usability of highly dispersive multilayer mirrors for high-energy femtosecond oscillators, namely for a chirped-pulse Ti:Sa oscillator and an Yb:YAG disk oscillator. In both cases, a group delay dispersion (GDD) in the order of 2×10^4 fs^2 was introduced, accompanied with an overall transmission loss as low as about 2%. 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 compact, alignment-insensitive all-mirror compressors, which provide compensation of GDD and higher-order dispersion.

OCIS codes: 310.0310.

doi: 10.3788/COL201008S1.0152.

Currently, mJ-level lasers based on chirped pulse amplification (CPA)[1] and operated at kHz repetition rates are considered workhorses in dozens of research groups over the world. Since these are usually combined with hollow fibers that provide spectral broadening and act as further compression stages for achieving pulses shorter than 10 fs, existing lasers suffer from long pulses (>25 fs) and insufficient beam-pointing stability. The former is related to the fact that prisms in existing laser compressors are intrinsically incapable of compensating for higher-order dispersions, which leads to relatively long pulses and, therefore, to insufficient spectral broadening in a fiber. The latter is a result of long compressors that have to provide high compression ratios. Both these intrinsic obstacles can be overcome by a compact all-dispersive-mirror compressor, provided that the nominal dispersion of the dispersive mirror (DM) is sufficiently high. Specifically, based on recent progress in DM development[2−8], one can expect DMs with dispersion values of about 500 fs^2 and reflectivity of more than 0.995 for a typical spectral range of 130 nm around a central wavelength of 800 nm. The absolute value of the achievable dispersion of a DM can become higher as the spectrum becomes narrower. The potential discovery of high-dispersion mirrors (HDMs) could replace prisms and gratings in the compressors, giving researchers a cheap, compact device with stable output beam of pulses free of residual third-order dispersion (TOD) and high overall throughput of more than 90%.

HDMs are necessary for high-energy femtosecond laser oscillators such as Ti:Sa chirped-pulse oscillator (CPO) or Yb-based solitary pulse and CPO oscillators that operate at μJ-levels. Typically, oscillators generate longer pulses with correspondingly narrower spectra (20–50 nm) compared to CPA lasers, whereas the overall dispersion value for such oscillators to be compensated is at the same order as the dispersion of CPA compressors.

In order to initiate the fabrication of an all-dispersive-mirror compressor for CPA systems, we report two types of HDM sets for a high-energy Yb:YAG disk oscillator with a spectrum of up to 3 nm centered at 1030 nm and a high-energy Ti:Sa CPO[9,10] with a spectrum of 40 nm centered at 800 nm. The values of the dispersion observed in both cases represent the highest values reported thus far.

By definition, HDMs are characterized by the high group delay of different spectral components. As the delay is proportional to the optical thickness of the layers involved, an HDM has thick layers and a large total multilayer structure thickness. As such, the manufacture of HDMs requires a very stable deposition process that allows deposition of a thick multilayer structure with high accuracy. Because of the complexity of the problem, a 10% deviation from the design nominal value of the total group delay dispersion (GDD) in a manufactured HDM could be considered as acceptable.

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 deals with its own spectral part. Therefore, it has to have steep spectral shoulders to avoid undesirable overlap with neighboring spectral parts. This is the only means to achieve high-quality dispersion control.

OptiLayer software[11] was used for designing two HDMs. To perform synthesis of an HDM, needle optimization[12] and gradual evolution[13] algorithms were applied. An HDM for the 780–820 nm spectral range will be explained in detail in the following text. However, the problems, and the approach to these obstacles, are similar to the case of an HDM for the 1020–1040 nm range. The complementary mirror (CM) approach, usually used for providing a smooth average spectral GDD[8], is not efficient for optimizing an HDM due to high sensitivity of the GDD of such a mirror to manufacturing errors, as mentioned previously. Therefore, we limited this study to the use of the single-mirror

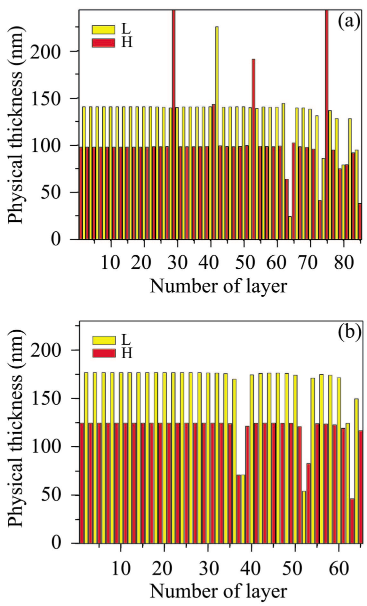

Fig. 1. Refractive index profile of HDMs:HDCM (a) for Ti:Sa CPO and (b) for Yb:YAG oscillator.

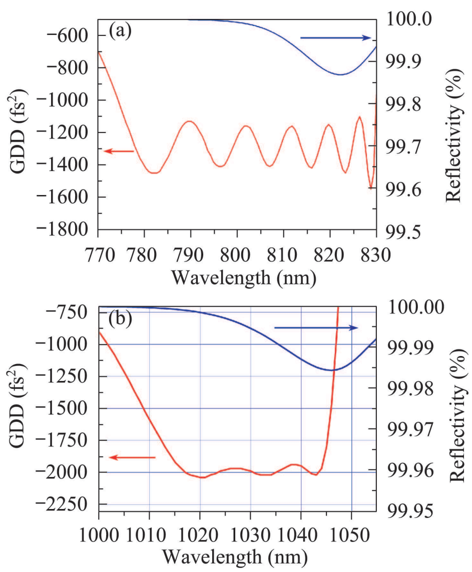

Fig. 2. Calculated GDD and reflectivity of HDMs:HDCM (a) for Ti:sapphire CPO and (b) for Yb:YAG oscillator.

approach (i. e., by relying on one type of a HDM in a set). This approach can potentially bring the additional problem of the appearance of spectral ripples (oscillations); however, this problem can be largely eliminated by a pair of CMs, which can cause mutual cancellation of the GDD ripples. In our one-mirror approach, the amplitude of the ripples can be sufficiently suppressed by the proper design procedure to make the upper layers operate as an antireflection coating. There are certain difficulties in producing efficient antireflection coatings for a broad spectral range. In such a case, the CM approach works well for smoothing the ripples. In the case of relatively narrowband HDMs, the antireflection coating effect can be sufficient to suppress ripples. Due to a high number of reflections needed in the compressor to compensate for the necessary amount of material dispersion, the tolerable relative ripple amplitude must be in the order of 10% or less of the nominal (mean) value of GDD.

The layer thickness structure of the HDM design for the 800-nm range is shown in Fig. 1. The resulting physical layer thicknesses are between 15 and 500 nm, whereas the total optical thickness of the structure is equal to approximately 10 μm, which is extremely high. The designed HDM provides negative GDD of around –1300 fs^2 at 800 nm together with a 99.95% reflectivity in the wavelength range of 780–820 nm (Fig. 2(a)). For the spectral range of 1030 nm, the designed high-dispersion compressor mirror (HDCM) has a dispersion of around –2500 fs^2 and a reflectivity of 99.98% (Fig. 2(b)).

It is worth mentioning that the highest dispersion values of the DMs obtained so far for the sub-20 nm spectral range were less than 1000 fs^2[14−17]. Here, we demonstrate HDM with a higher dispersion in a broader spectral range.

The total amount of GDD of an HDM compressor needed for obtaining chirp-free high-energy pulses out of a Ti:Sa CPO is in the order of 2.5×10^4 fs^2 at 800 nm. This value is achievable with only 20 bounces of the HDM (Figs. 1(a) and 2(a)). It is necessary to prove that such an amount of bounces will not deteriorate the incident test chirp-free pulse in terms of its duration and energy. The combined results of the temporal pulse analysis of the pulse reflected after several bounces of the HDM are shown in Fig. 3. In the analysis, the main part of the dispersion was eliminated and only residual GDD ripples were included. For the virtual compression experiment, we used an incident 60-fs pulse observed in the Ti:Sa CPO[10]. The reflected pulse does not become longer when the ripples are absent or small. Calculations show that after 20 bounces, two things are notable: a) the exiting pulse preserves its incident duration, and b) the main pulse contains >95% of the energy from the initial value. Based on the analysis above, we hope for the efficient compression of highly-chirped pulses exiting the CPO. In a Yb:YAG oscillator, HDM will provide sufficient negative dispersion for keeping high-energy soliton pulse inside the oscillator cavity.

The deposition sensitivity of an HDM is critical in explaining why it is extremely difficult, or even impossible, to manufacture an HDM with "standard" technologies such as electron-beam, ion-assisted electron beam evaporation, and ion-sputtering. Thus far, the smallest deposition errors were achieved only in the reactive dual magnetron-sputtering process with plasma/ion

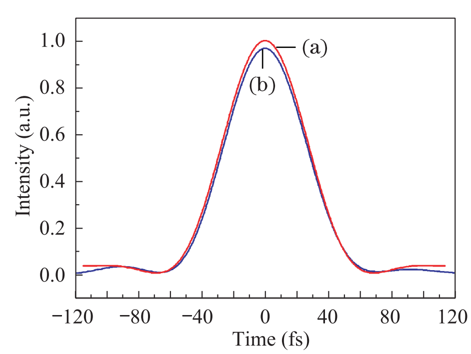

Fig. 3. Time domain analysis of a 780–820 nm HDCM. (a) shows the initial 60-fs pulse, (b) shows the pulse after 20 bounces (not normalized).

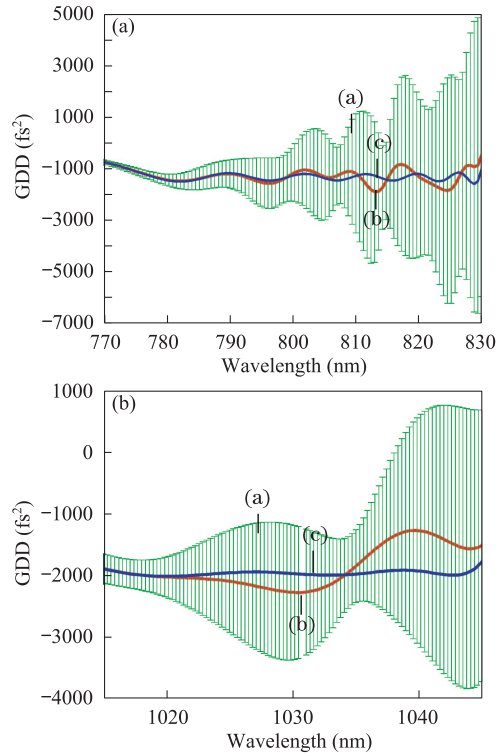

Fig. 4. GDD deposition error analysis. (a) shows the worst result of +/–1 nm errors in the physical thicknesses of the layers, (b) is the average of 100 curves with random +/–1 nm errors in physical thickness. (c) is the calculated GDD curve.

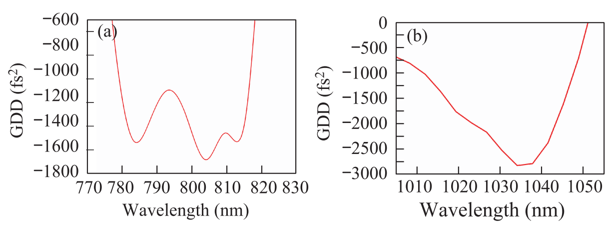

Fig. 5. GDD curves of two types of HDMs measured with white light interferometer: (a) a mirror for Ti:sapphire CPO and (b) a mirror for Yb:YAG oscillator.

assistance[8,18,19]. The predictable GDD curve of the design is shown with the red curve in Fig. 4. The curve was obtained with a standard procedure in Optilayer software[11] by averaging 100 designs with a random thickness error of 1 nm in each layer. The green-colored error bars on the graphs show the worst-scenario expectations. The lower the fluctuations of the red curve and the lower the green-colored error bars, the more robust the design is. As one can see, the worst-case-scenario deviations are in the order of the mean GDD value.

The HDMs were produced by means of magnetron-sputtering (Helios, Leybold Optics)[8]. We chose Ta_2O_5 with its refractive index of 2.15 at 500 nm as high-refraction-index material. SiO_2 was chosen as a material with low refractive index equal to 1.48 at 500 nm. These materials offer low losses and high differences in the refractive indices for wavelength range around 800 nm[5,8,19]. For higher accuracy, the actual refractive indices of the coating materials were determined immediately prior to the coating process.

The transmission spectra were measured with a PerkinElmer spectrophotometer (Lambda 950). The GDD was determined by using a white-light interferometer with a spectral accuracy of 5 nm and a dispersion accuracy of about 10 fs^2.

Spectral measurements of the HDMs show good agreement with the design in terms of their dispersion (Fig. 5).

One may expect higher losses for HDM in comparison to "standard" DMs. We measured the mirror losses at 808 and 1030 nm (LossPRO Novawave Technologies, Inc.) and compared them with those of DMs with low dispersion value[19]. The resulting average reflectivity values are surprisingly high: 99.95% for HDM and >99.98% for broadband DM. The former is sufficient for all visible applications in oscillators and compressors.

The first laser was a high-energy femtosecond Ti:Sa CPO operating in a positive dispersion regime. Oscilla-

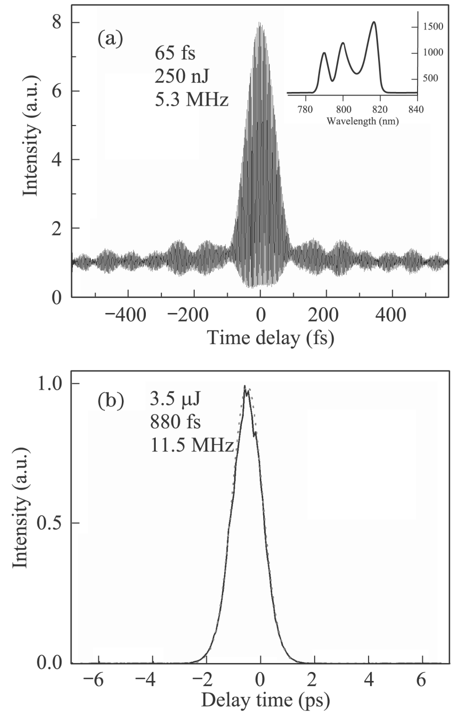

Fig. 6. (a) Autocorrelation trace of the pulses after the mirror compressor in a Ti:Sa CPO and (b) an autocorrelation function (ACF) trace of the pulses out of an Yb:YAG disk oscillator.

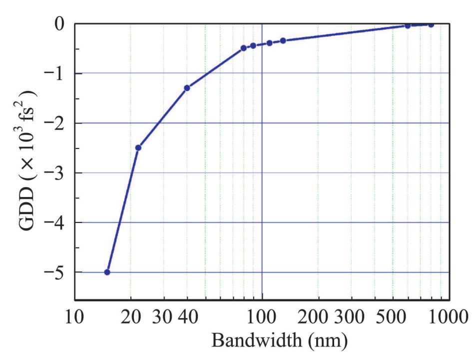

Fig. 7. The highest absolute value of GDD achieved with a Helios coating machine as a function of the spectral width. The very left points on the graph correspond to the mirrors described in the letter (the line connecting the points is only for better visibility).

tors of such type produce heavily chirped 1–2 ps pulses that, after external compression, become 30–60 fs long, depending on the spectrum width generated[9,10]. In the experiment, the output energy of a Ti:sapphire CPO was 280 nJ at 5-MHz repetition rate in a spectral range of 780–820 nm (Fig. 6(a) inset). First, we checked the system output pulse parameters after a 2-pass prism compression (LaK 21 glass). The pulse duration was 65 fs with an energy throughput of about 50%. The reason for the relatively low throughput is related to the compressor length (8 m), which led to the beam clipping of the prisms used. The autocorrelation trace obtained with a second harmonic interferometric autocorrelator contained significant residual sidelobes and had a contrast lower than 8:1[10]. A set of manufactured HDMs allowed us to exchange the prism compressor by using only 20 reflections. With such a reflectance, the calculated throughput of an all-chirped mirror compressor must be higher than 98%. The experimentally realized throughput was slightly more than 90% (250 nJ at the exit of the compressor).

The second laser was an Yb:YAG disk oscillator. It was built on the base of a laser module developed at ISW (Stuttgart) with a 200-μm disk in the conventional soliton regime scheme with negative net cavity dispersion. Its detailed description, which includes information on the stability of the pulse train, will be the subject of another publication. The pulse repetition rate was 11 MHz, the generated pulse was 800 fs, and the pulse energy was 6 μJ. The cavity consisted of ten mirrors, three of which were HDCMs with a nominal dispersion of –2500 fs^2. The high amount of net negative cavity dispersion needed was defined by the well-known relation:

$$\tau \sim |D|/E, \tag{1}$$

where D is the net cavity dispersion and E the pulse energy.

According to the relation and our experiment, the higher the pulse energy the more negative dispersion one needs for providing a stable mode-locking operation. The total amount of the negative intracavity dispersion is very similar to that of a 5-μJ oscillator reported in Ref. [17].

The broader the spectrum for which the GDD must be controlled, the lower the nominal value of achievable GDD. In other words, relaxing the requirements on bandwidths allows higher values of the GDD to be achieved (Fig. 7). The curve in Fig. 7 was obtained by interpolating 9 points corresponding to 9 different DMs[8,18,19]. Each point represents the highest absolute value of the GDD obtained for a certain spectrum width by using the same optimization technique.

The absolute values of the points on the GDD axis depend on the central frequency, material, and desirable reflectivity. The data provides a reference pattern for the trade-off between the bandwidth and the dispersion. There is yet another trade-off that needs to be observed and plotted, namely, the one between the highest values of achievable GDD and reflectivity.

In conclusion, an all-mirror compressor for CPA systems was described in this letter. A typical dispersion of an mJ-level CPA prism compressor is in the order of –5 × 10^4 fs^2 at 800 nm. For the mirror shown in Fig. 1, it would mean about 120 bounces with the overall transmission in the order of 84%. The temporal analysis of the pulse shape evolution in such a mirror compressor is still not possible because of the lack of information about the pulse phase in front of the compressor.

As a first step toward such an all-DM compressor, we have shown two sets of highly dispersive mirrors with both the bandwidth and the main value of the dispersion comparable to what one might expect in CPA lasers. The mirrors were manufactured and successfully tested in μJ-level laser oscillators.

This work was supported by the Deutsche Forschungsgemeinschaft through the Munich-Centre for Advanced Photonics DFG Cluster of Excellence (www.munich-photonics.de).

References

1. D. Strickland and G. Mourou, Opt. Commun. **56,** 219 (1985).
2. R. Szipöcs, K. Ferencz, C. Spielmann, and F. Krausz, Opt. Lett. **19,** 201 (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, Opt. Lett. **22,** 831 (1997).
4. N. Matuschek, L. Gallmann, D. H. Sutter, G. Steinmeyer, and U. Keller, Appl. Phys. B **71,** 509 (2000).
5. V. Pervak, S. Naumov, G. Tempea, V. Yakovlev, F. Krausz, and A. Apolonski, Proc. SPIE **5963,** 490 (2005).
6. G. Steinmeyer, Appl. Opt. **45,** 1484 (2006).
7. G. Steinmeyer and G. Stibenz, Appl. Phys. B **82,** 175 (2006).
8. V. Pervak, A. V. Tikhonravov, M. K. Trubetskov, S. Naumov, F. Krausz, and A. Apolonski, Appl. Phys. B **87,** 5 (2007).
9. A. Fernandez, A. Verhoef, V. Pervak, G. Lermann, F. Krausz, and A. Apolonski, Appl. Phys. B **87,** 395 (2007).
10. S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, New J. Phys. **7,** 216 (2005).
11. OptiLayer software: http://www.optilayer.com.
12. A. N. Tikhonov, A. V. Tikhonravov, and M. K. Trubetskov, Comp. Maths. Math. Phys. **33,** 1339 (1993).
13. A. V. Tikhonravov, M. K. Trubetskov, and G. W. DeBell, Appl. Opt. **35,** 5493 (1996).
14. S. V. Marchese, T. Südmeyer, M. Golling, R. Grange, and U. Keller, Opt. Lett. **31,** 2728 (2006).
15. S. Dewald, T. Lang, C. D. Schröter, R. Moshammer, J. Ulrich, M. Siegel, and U. Morgner, Opt. Lett. **31,** 2072 (2006).
16. G. Palmer, M. Siegel, A. Steinmann, and U. Morgner, Opt. Lett. **32,** 1593 (2007).
17. 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, Opt. Express **15,** 16966 (2007).
18. V. Pervak, F. Krausz, and A. Apolonski, Opt. Lett. **32,** 1183 (2007).
19. V. Pervak, S. Naumov, F. Krausz, and A. Apolonski, Opt. Express **15,** 13768 (2007).