

Comparison of dispersive mirrors based on the time-domain and conventional approaches, for sub-5-fs pulses.

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Abstract: Dispersive mirrors based on time-domain approach are compared with mirrors resulting from conventional phase target designs. Phase targets have been applied to complementary-pair dispersive mirrors, used for sub-5-fs pulse compression. While the phase approach has hitherto afforded the best performance for the shortest pulses, our new approach, based on time-domain targets and tailored for a specific input spectrum, appears to provide comparable performance for pulse compression for a pulse duration 4.6 fs. Experimental studies using dispersive mirrors made to both designs are described.

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1. Introduction

Ultrashort laser systems generate high-energy pulses with broad spectral bandwidth, which can be compressed to ultrashort pulse lengths by appropriate compensation of the laser's dispersive elements [1]. Ultrashort, compressed pulses, comprising only a few wave cycles, are pertinent to observation and utilization of nonlinear optical effects [2], medical applications, and attosecond pulse generation [3]. As a result, ultrashort pulse generation and compression has for decades been a central issue in optical and laser physics.

Broadband laser oscillators and amplifiers typically produce chirped pulses in which the instantaneous frequency of the pulse varies across the pulse envelope [1]. This chirp must subsequently be removed to obtain transform-limited ultrashort pulses. The origin of this unwanted chirp can be transmission in dispersive media (including, for example, air, gas, glass, fused silica, and Ti: sapphire), or the oscillator pulses can be purposely chirped prior to amplification to avoid damage in the amplifying gain medium. To remove the chirp, compensating dispersive elements must be introduced. Several different devices can be used for this purpose: i) a prism or grating compressor [1], ii) a pulse shaper utilizing an adaptive light modulator [4, 5], iii) or a compressor composed of dispersive mirrors (DM) [6]. Comparison of these three different elements shows that the prism or grating compressor supports only a limited bandwidth, and the adaptive pulse shaper dramatically increases the complexity of the optical scheme and limits the maximum pulse energy. In contrast, DMs can accommodate broadband spectra extending over more than one octave [7]. Additionally, DMs have a damage threshold that does not limit the output pulse energy. DM compressors are generally compact and trivial to align. These properties make them an attractive candidate for dispersion compensation.

DMs were first used for femtosecond pulse generation in 1994 [6] and were fabricated by the phase-target approach. Since then, DM design and fabrication have been continuously improved. All DMs were previously been designed on the basis of "phase" targets, i.e. optimized (minimized difference between the target and calculated dispersions) in respect of the phase or its frequency derivative, the group delay (GD) and the group delay dispersion (GDD) [6–19]. Phase-targeted designs will provide pulses with durations closer to a Fourier transform limited pulse (FTLP) when one has smaller differences in the phase characteristic between the design and target values. In theoretical studies, the record for the shortest output pulse was obtained by the original phase complementary approach [7], in which compression to 2 fs is reported. There are now several types of DMs which can be designed by means of phase targets: i) complementary pair [7, 9–12], ii) Brewster angle DM [13, 14], iii) double DM [15–17], iv) back-side coated DM [18] v) tilted-front-interface DM [19].

In practice, most frequently we are interested in how an optical pulse can most closely approach its Fourier limit, i.e. how light energy is most efficiently confined in the shortest possible time interval. When the frequency dependence of the phase characteristic is optimized, we are solved the problem indirectly by optimizing the phase target.

In this work we employ and compare a new method of designing DMs on the basis of a time-domain approach [20, 21], in which the final pulse duration and energy concentration are optimized [21] rather than the phase shift imposed on the reflected pulse by the DM, as close in previous approaches [7-19]. The theoretical and experimental performances of DM designs optimized by the time-domain and phase approaches are reported. We find that the phase designs currently support the broadest spectra [7, 12]. Nevertheless, the time-domain approach remains promising, because its design criterion is actually the parameter that experimentalists are most interested in [20]. While time-domain designs have not yet been achieved for use with the shortest pulses (sub-3 fs), theoretical comparison with phase designs for pulses in sub-5-fs duration range, shows that the time-domain approach provides comparable performance.

2. Time-domain approach - theoretical calculation

2.1. Introduction to time-domain optimization.

The design of DMs is a sophisticated thin-films optics problem. Solving it requires efficient approaches and powerful mathematic methods. The new time-domain approach we report here demonstrates in certain cases superior to that of the performance phase-target approach. DM design involves many free parameters requiring modern optimization algorithms. By using the time-domain approach, i.e. by optimizing the energy concentration in the optical pulse rather than targeting the phase, the algorithm is forced to pursue a goal of direct practical relevance.

Here, we describe a sequence of steps used to implement time-domain optimization with highest efficiency. The needle optimization technique, in which additional layers in the multilayer stack are inserted non-sequentially, was employed to achieve highest calculation performance [22, 23]. This procedure is widely used to phase target DM design. The details of our new time-domain approach have been described in a previous publication [21]. Here we focus on first experimental results. The idea behind time-domain optimization is shown in Fig. 1. A generalized transform-limited short pulse, which can be calculated by the inverse Fourier transform of an arbitrary input spectrum, propagates in a dispersive medium or set of dispersive materials. FTLF will be the shortest pulse which can be obtained with any design approach. The pulse will be spread in the dispersive media, owing dispersion of elements inside or outside the laser oscillator. A DM compressor can be employed to compensate this dispersion and thus compress the pulse. In the classical approach, the designer makes the mirror dispersion approach as closely as possible the dispersion of laser elements of opposite sign.

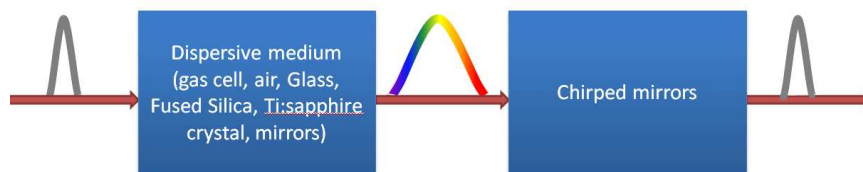


Fig.1. Basic scheme of time-domain target approach.

In the new time-domain design approach the algorithm needs structures allowing the best possible comparison of the pulse after passage through the dispersive medium and DMs (in Fig. 1).

This paper reports results of realization, application, and comparison of the two design approaches for sub-5-fs pulse compression. By changing the optimization parameters [21], the pulse duration can be traded off against the energy concentration.

The time-domain approach allows us to control the pulse duration directly. There are two experimental requirements: i) optimize the design so that the shortest pulse will be generated and ii) optimize the design so that the maximum energy will be concentrated in the main pulse

(in this case the pulse duration can be 10% longer). Here, we suggest using a novel merit function which will allow us to trade off the pulse duration against its energy concentration. The temporal shape of the output pulse is obtained with the help of a Fourier transform:

$$A_{out}(t) = (2\pi)^{-1} \int_{-\infty}^{+\infty} \hat{A}_{out}(\omega) \exp(i\omega t) d\omega \quad (1)$$

where $A_{out}(t)$ is the output intensity on the DM. We propose to introduce the following merit function to be optimized:

$$\Phi = (E_p)^{-q} \int_{-\infty}^{+\infty} (t-t_0)^2 |A_{out}(t)|^p dt, \quad q \geq 1, \quad (2)$$

where E_p is the normalization constant. In Eq. (2) t_0 is the center of the function $A_{out}(t)$ determined as its first moment. When the parameter q is more than 1, the energy concentration criterion is also taken into account in the merit function Φ (Eq. (2)). Indeed, the value of E_p increases with increasing energy of the output pulse A_{out} . Therefore, when $q > 1$, the merit function Φ is subjected to an additional decrease with increasing energy of the output pulse. Two parameters p and q provide us with a high degree of flexibility. Note that the case $p=2$ has a straightforward physical meaning. In this case $E = E_2$ is the energy of the pulse, t_0 is its center determined in accordance with the energy distribution.

Thus by trading off parameter p and q we will be able to control the pulse duration and its energy concentration. The advantages of time-domain methods have been given in a more detailed discussion in our publication [21]. In the case of phase optimization this trading off is not possible. The DM designed by the phase approach can be used for tunable relative narrow-band lasers, where only a fraction of the DM's bandwidth is "active" at a time. Time-domain optimized mirrors are not suitable for tunable laser application, because they have higher oscillation in comparison with the phase approach and are optimized for a specified spectrum. The time-domain approach requires additional information about the incoming spectrum while the phase approach can work without incoming spectrum data.

2.2. Designs with different optimization approaches.

We use a simulated compression experiment to compare the time-domain and phase-target DM design techniques. For fixed bandwidth and material dispersion, we design DMs for compensation, propagate an originally transform-limited pulse through the entire dispersive system numerically, and finally compare the output pulse characteristics.

To design a broadband complementary pair of DMs, using a phase target, a novel merit function [12] was used. In general terms, the merit function is an overall measure of the deviation of the designed mirror's actual phase and its desired phase, which would exactly compensate the material dispersion:

$$F = \frac{1}{L} \sum_{l=1}^L \left(\frac{R_p(\omega_l) - R^{(l)}}{\Delta R^{(l)}} \right)^2 + \left(\frac{\text{GDD}_p(\omega_l) - \text{GDD}^{(l)}}{\Delta \text{GDD}^{(l)}} \right)^2. \quad (3)$$

Here $\omega_l, l=1, \dots, L$ is a set of frequencies where the target values of the reflectance $R^{(l)}$ and group delay dispersion $\text{GDD}^{(l)}$ are specified. $R_p(\omega_l)$ and $\text{GDD}_p(\omega_l)$ are the corresponding theoretical values of the reflectance and GDD, $\Delta R^{(l)}$ and $\Delta \text{GDD}^{(l)}$ are the corresponding tolerances. The merit function F allows us to employ the needle-optimization technique to design a complementary pair of DMs. This novel merit function was recently used to design the broadest-band DM, reported so far spanning 1.5 octaves [7, 12].

Nevertheless, this merit function does not allow us to control the temporal shape of the pulse directly.

In the time-domain optimization we can trade off the peak of the pulse intensity against its duration. Additionally, the time-domain procedure is less sensitive to the starting design. By employing the needle-optimization procedure [21] together with a gradual evolution algorithm, a starting design with only one layer can be chosen. It works in an automatic regime with the commercial software, Optilayer (Optilayer Ltd.). A satisfactory solution can be found within several hours with a Pentium Xeon processor (4 cores, Intel Xeon X5345) by running the optimization in an automatic regime. The phase-target approach requires good designer skills and a powerful computer.

In a numerical simulation, we compress a pulse down to ~ 4.5 fs, which is near its transform limit. The DMs are designed to cover the wavelength range 550 to 1000 nm. The dispersion target is meant to compensate the material dispersion accumulated during propagation in fused silica and air. The input pulse in our simulation is the real laser spectrum (Fig. 2).

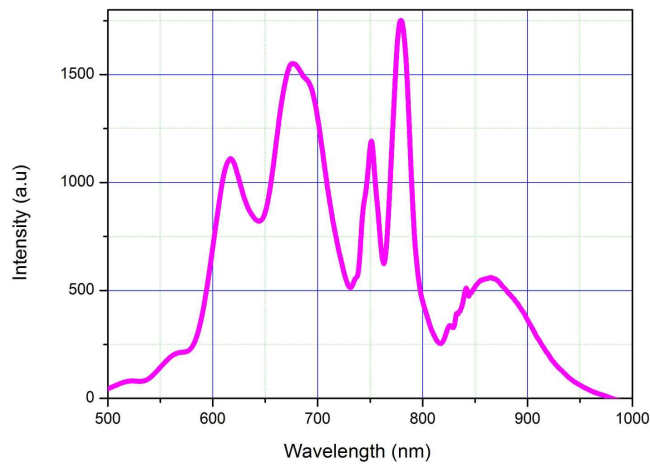


Fig. 2. The spectrum broadened in the hollow fiber after a Ti:Sa kHz laser was used as input for the time-domain design. The FTLP is 4.4 fs.

In our simulation the pulse is first broadened temporally by the assumed material dispersion. Next it is compressed in a DM compressor consisting of 8 mirrors. In the case of the phase design target DM, this corresponds to 4 complementary pairs.

DM structures designed with time-domain and phase targets are shown in Fig. 3 and Fig. 4, respectively. In the case of the phase target DM design, both final designs consist of 93 layers with physical thicknesses from 11 to 500 nm.

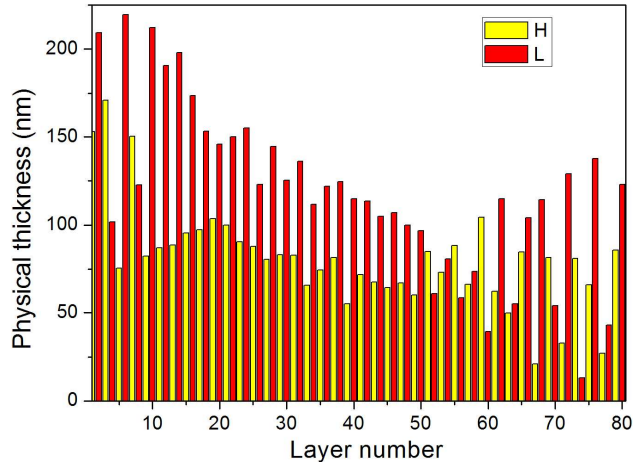


Fig. 3. Physical thickness versus layer number of time-domain optimized DM.

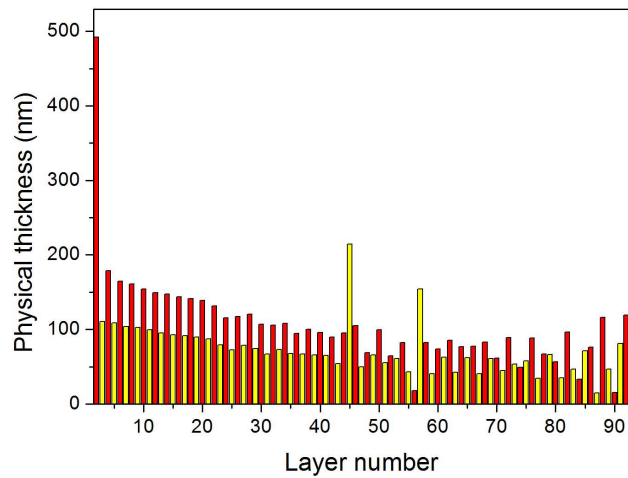
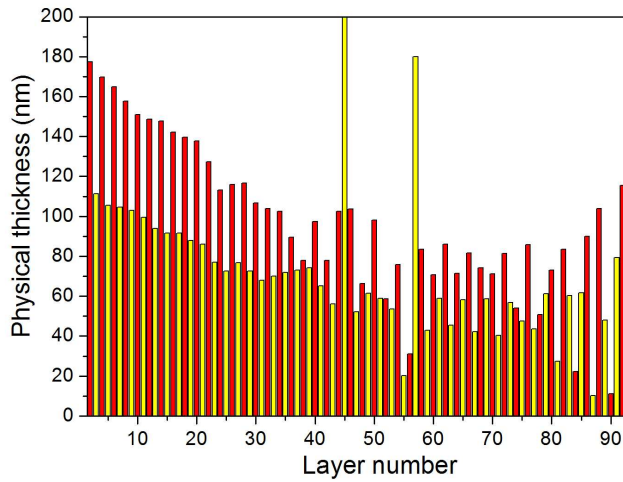


Fig. 4. Physical thickness versus layer number of complementary pair of DMs.

The final time-domain design consists of 80 layers with physical thicknesses from 27 to 220 nm. The thinnest layers for designs obtained by the time-domain and phase-target approaches are 27 nm and 11nm, respectively. Nevertheless time-domain optimization requires an incoming spectrum. In our case the laser spectrum is shown on Fig. 2.

The phase dispersion and reflectivity curves of complementary pair and time-domain optimized DMs are shown in Fig. 5 and Fig. 6, respectively. The ideal FTLP for obtained spectrum is 4.4 fs and shown in Fig. 7 by the red curve. After 8 bounces off a pair of complementary DMs the pulse is still close to FTLP (4.5 fs), as shown by the green curve in Fig. 7. The time-domain optimization, in this particular case, gives us similar results, shown in the Figure by the blue curve. The pulse optimized by applying the phase approach only for one mirror of the complementary pair is shown by the pink curve. The amplitude of pink curve is only 70% due to pronounce GDD oscillations of a single mirror from complementary pair in comparison to green curve of the complementary DM pair with smaller oscillations. Keep in mind that the complementary approach has a higher number of varying parameters (layers). The designs consist of 93 alternating Nb₂O₅/SiO₂ layers for both the classical and time-domains approaches. But in the case of the complementary approach the number of varying parameters (layers) is 186, while in the time-domain case the number is only 80.

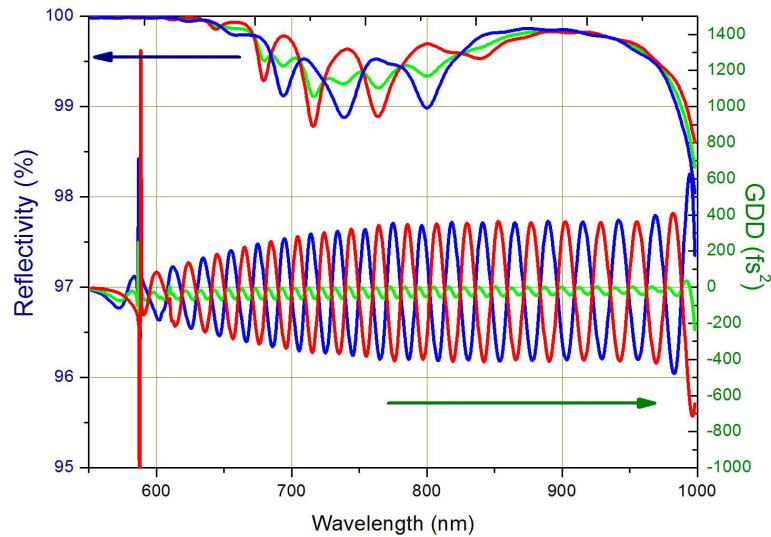


Fig. 5. DM designed by using the complementary approach. The GD (three lower curves) and reflectivity (three upper curves) of the complementary pair of DMs are shown. The green curve is the average of the GD and reflectivity of two different DMs per bounce. The red and blue are the GD and reflectivity of two different DMs.

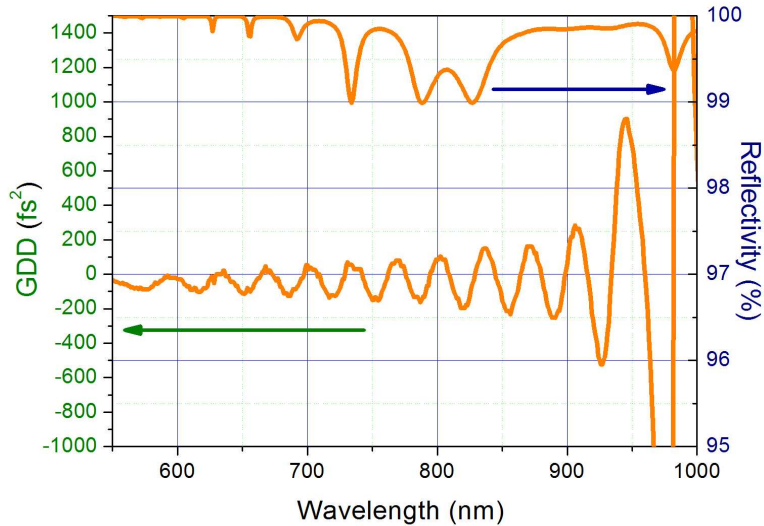


Fig. 6. DM designed by using the time-domain approach. Orange shows the theoretical curve of the GD and reflectivity.

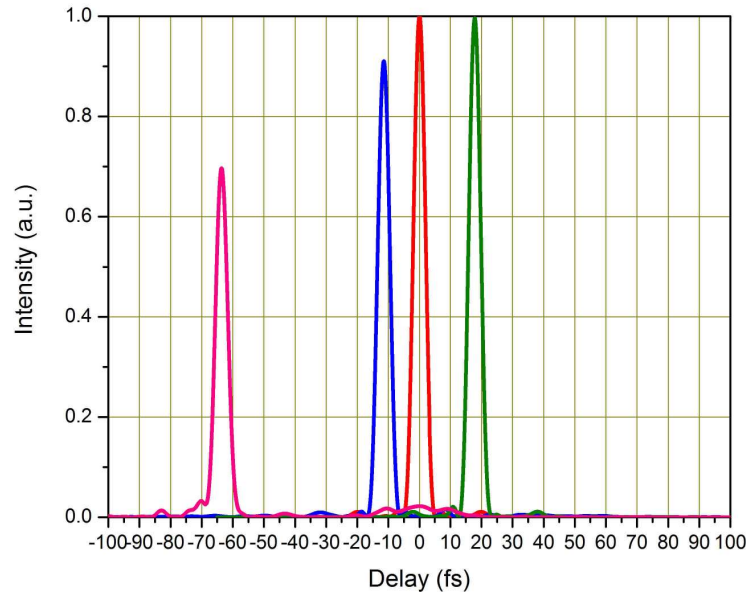


Fig. 7. The pulse envelope of the FTLP is shown by the red curve, the blue curve shows the pulse after 8 bounces off the time-domain optimized DM, the green one – after 8 bounces off the complementary pair of DMs, the pink – after 8 bounces off one of the complementary pair of DMs. The time delay between the pulses is artificial.

3. Manufacture of advanced DMs.

Successful fabrication of DMs can be as challenging as their design. For decades, the magnetron-sputtering [7, 12] and ion-sputtering processes have been most reliable in terms of sputtering rates and stability of the refractive index. Both of these technologies have been employed in DM manufacture [7, 12]. The DMs designed using the time-domain target and the complementary pair DMs designed using a phase target, for supporting ~ 4.6 -fs pulses, were fabricated with a magnetron-sputtering machine (Helios, Leybold Optics GmbH, Alzenau, Germany). Further details concerning magnetron-sputtering technology can be found in [7, 12, 24].

After fabrication, the GDD of the DMs was measured with a white light interferometer and is shown in Fig. 8 and Fig. 9 for a complementary pair of DMs and a time-domain optimized DM, respectively. The measured reflection curves for both the complementary-pair and time-domain approaches are in good agreement with the theoretical calculation. A small difference between the theoretical and measured GDD curves (Figs. 5, 6 and 8, 9, respectively) can be explained by a slight difference in the refractive index of the layers used in the calculation and the real refractive index.

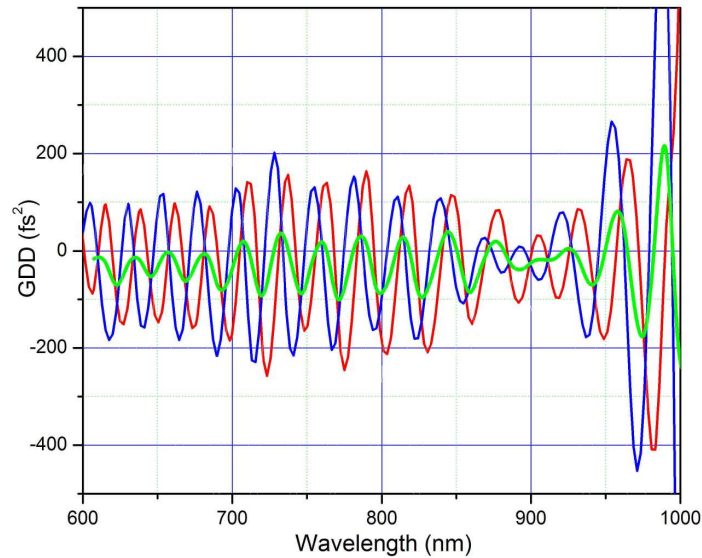


Fig. 8. Measurements of the GDD of 4.6-fs DMs. The green curve is the measured average GDD of the complementary pair of DMs per bounce. The red and blue ones are the GDD of each DM.

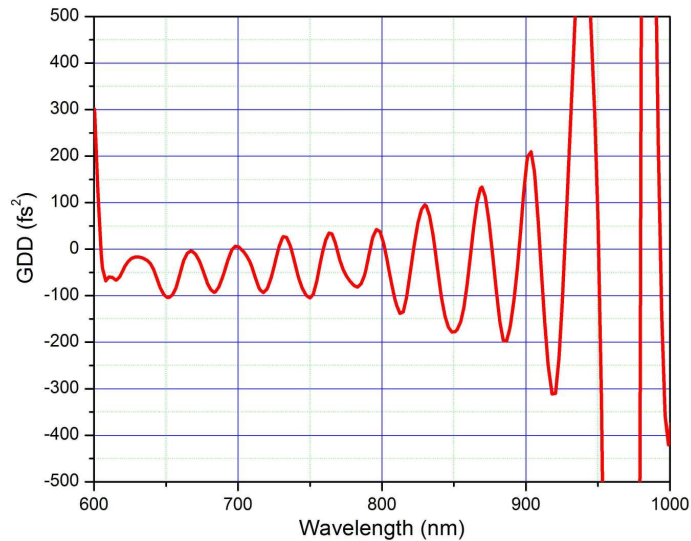


Fig. 9. Measurement of the GDD of 4.6-fs DMs. The curve shows the measured GDD of the time-domain optimized DM.

4. Laboratory compression experiments and discussion

The DMs fabricated according to the time-domain and phase designs, for sub-5-fs compression, were tested in real experiments to compare the two design approaches. In the compression experiments sub-5-fs pulses were used out of a hollow-core-fiber-broadened Ti:sapphire laser with the corresponding spectrum shown in Fig. 2. The spectrum can support 4.4-fs pulses in the case of a proper phase. After 8 bounces in the DM compressor, the pulse duration was measured by second-harmonic generation (SHG) interferometric autocorrelation, utilizing a 5- μm -thick, type-1 phase-matched, BBO crystal. The measured autocorrelation function is shown in Fig. 10.

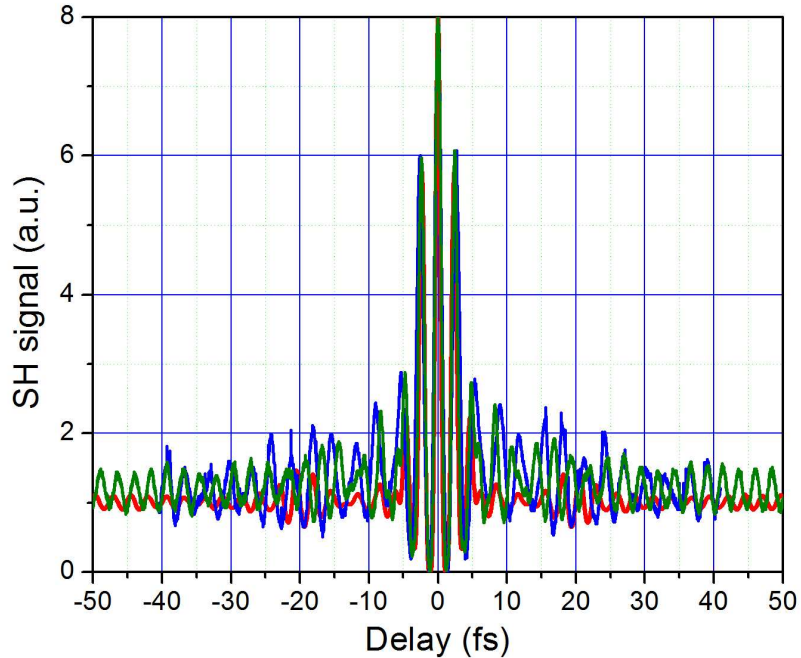


Fig. 10. Theoretical second-harmonic generation (SHG) interferometric autocorrelation corresponding to a 4.4-fs FTLP is shown in red; green and blue - the measured SHG interferometric autocorrelation function corresponds to a 4.6-fs pulse for the complementary pair of DM and time-domain optimized DM respectively.

The SHG interferometric autocorrelation of the pulses obtained by the both types of DMs corresponds to 4.6 fs, with slightly enhanced wings for the time-domain DM. On the basis of this first experimental check, we hope that the time-domain approach has room for improvement.

5. Conclusions

Two different approaches to designing dispersive multilayer mirrors were compared. The two (time-domain and conventional phase) approaches demonstrate similar performance. The time-domain approach has higher flexibility in controlling the pulse duration, and the pulse energy concentration has already been mentioned a couple of times. The phase approach is more complicated in fabrication than the time-domain DM approach. Moreover, as we show in the theoretical part of this work [21], such DMs can tolerate a certain deviation of the input spectrum, which makes them a strong competitor to the DMs made with the phase approach. Both approaches were found to provide comparable performance resulting in 4.6-fs pulses behind the hollow fiber in a kHz mJ-level Ti:Sa system. The authors believe that time-domain optimization procedure will become a powerful tool for designing high-performance DMs for

ultrashort pulse generation, once existing FFT routines have been successfully tailored for this application.

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