Chirped mirrors with low dispersion ripple

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Abstract: We demonstrate a chirped dielectric multilayer mirror (CM) with controlled reflectivity and dispersion in the wavelength range 760-840 nm. It exhibits a reflectivity of >99.9% and a mean group delay dispersion (GDD) of about -30 fs^2 with a theoretical GDD ripple of less than 0.5 fs^2 in the working spectral range. Deviations of the measured GDD from the calculated one are restricted to less than ± 3 fs^2, limited by our measurement system. Simulations reveal that a dispersive delay line composed of 120 bounces off these mirrors introduces negligible distortion to a femtosecond pulse and largely preserves its contrast. The mirrors constitute an ideal tool for precision intracavity or extracavity dispersion control in the range of several thousand fs^2, particularly if pulses with high contrast are to be generated.

OCIS codes: (320.5520) Pulse compression; (320.7160) Ultrafast technology; (310.1620) Interference coatings

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1. Introduction

Chirped mirrors, CMs, for dispersion control were proposed and demonstrated in 1994 [1] and since then have found widespread use for broadband dispersion control in ultrafast systems. CMs have proved ideal for controlling dispersion inside femtosecond oscillators [2-6]. In many cases a small net GDD, either negative or positive, nearly constant over a broad spectral range is required. In low-repetition-rate, high-energy femtosecond oscillators operated at slightly positive net cavity dispersion (chirped-pulse oscillators, CPO) [7, 8] this requirement is coupled with the need for a large number of bounces to introduce a multi-nanosecond delay with a compact setup. As a consequence, CMs with low loss and low fluctuations of the GDD from its target value (henceforth briefly: ripple) are required. Implementation of the concept with a Ti:sapphire laser, with the aim of efficiently producing sub-microjoule-energy pulses with durations of about 50 fs or shorter, calls for CMs with smooth GDD curve and an effective reflectivity higher than 99.9% over the wavelength range 770-830 nm. Even more severe restrictions are imposed on the characteristics of CMs when they are used inside an enhancement or build-up cavity [9, 10] serving for passively boosting the pulse energy by a factor of 10^2-10^3 by coherent superposition of subsequent pulses in the pulse train. To this end, the overall cavity round-trip loss must be less than 1% and the cavity round-trip dispersion must be close to zero over the entire spectral range of the seed pulse. In such a high-Q, zero-dispersion enhancement cavity (Q>100), designed to support the coherent build-up of sub-50-fs pulses, GDD fluctuations as little as several fs^2 may severely impede system performance.

Conventional CMs suffer from pronounced GDD ripple near the long-wavelength edge of the high-reflectivity range of the mirror. The effect was shown to originate from an effective Gires-Tournois interferometer [11]. A double Gires-Tournois interferometer (or double-chirped mirror) approach was adopted to solve this problem [12]. This approach is realized by means of optimization of the last few layers in the symmetrical quarter-wave layer stack. The resulted of design exhibiting larger tolerance to manufacturing errors.

CMs with low ripple have already been reported [11, 12]. By modifying the last 3-7 layers in a standard Bragg reflector stack, a flat GDD curve over the spectral range 750-850 nm with fluctuations of ± 10 fs^2 about a mean value of -40 fs^2 per reflection was demonstrated.

The need for compensating unavoidable third-order dispersion (TOD) in addition to GDD requires an appreciable number of top layers to be modified. This entails additional complications in the mirror design, making it difficult to realize a smooth GDD curve.

In this work we pursued the aim of developing a CM that affords i) a certain amount of TOD for precision compensation of material dispersion, ii) low variation (<1 fs^2) of GDD around its target (design) value, and iii) high reflectivity (>99.9%) over a spectral range sufficiently broad to support sub-50-fs pulses for the above-mentioned (and possibly other) applications. By drawing on the approach reported in Refs. [11, 12], we demonstrated CMs compensating for both second- and third-order dispersion that exhibit a reflectivity of >99.9% with an rms of the GDD about its target value of less than 2.15 fs^2 over the spectral range 760-840 nm. The usefulness of the mirrors was demonstrated by their application in an extended-cavity Ti:sapphire CPO.

2. CM: design and measurement

One of the main problems in optimizing a multilayer dielectric structure is that the merit function [13] usually has many local minima [14]. As a consequence, optimization routines often stop at one of the local minima, possibly far away from the “global” optimum (from the point where the solution is suitable for our application). In addition, TOD-compensating CMs have a reduced tolerance to manufacturing errors. For designing our CMs we used both the needle-optimization and gradual-evolution algorithms (the latter being a modification of the former) with a commercial software, Optilayer (Optilayer Ltd.). These algorithms offer the best performance in terms of approaching the global optimum pursued, owing to the analytical

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approach used in the Optilayer software. The designed multilayer structure was manufactured by magnetron sputtering machine (Helios, LeyboldOptics).

The target GDD was chosen to compensate for dispersion (incl. higher-order contributions) accumulating during propagation through air, fused silica and sapphire with propagation lengths of 120 m, 30 mm and 3 mm, respectively, in the range 770-830 nm, for use in a CPO oscillator described below. The distribution of the refractive indices of the optimized layer structure is shown in Fig. 1. The mirror consists of 14 pairs of alternating $\lambda_0/4$ Ta_2O_5 and SiO_2 layers and 20 chirped top layers.

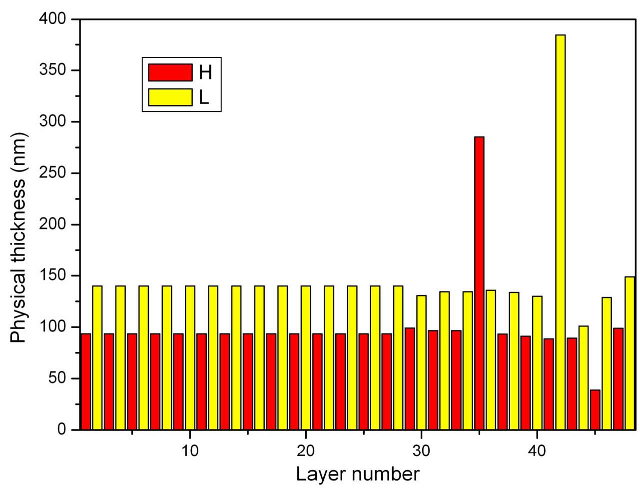

Fig. 1. Physical thicknesses of the layers of the optimized CM. H denotes the high-refractive-index material Ta_2O_5 (n_H=2.15 at 500 nm) and L stands for low-refractive-index material SiO_2 (n_L=1.48 at 500 nm).

The spectral transmission and GDD of the mirror are shown in Fig. 2. The designed GDD exhibits shallow ripple, with deviations of less than ±0.5 fs^2 from (approximately linear) the target curve over the spectral range of interest (770-830 nm). The rms deviation of the measured GDD (blue curve in the right panel of Fig. 2) from the target (red curve) amounts to 2.15 fs^2, which is close to the accuracy of our white-light interferometric measurement apparatus. An additional indication of the precise reproduction of the target structure can be inferred from the nearly perfect matching of the transmission spectrum of the mirror to the design curve (left panel in Fig. 2).

For the moderate bandwidth (~50 nm) required for sub-50-fs pulse generation, we endeavoured to avoid the complementary mirror approach [15]. The basis of the design is a standard quarter-wave stack which has zero GDD at the centre of its stop band with little variation over the entire high-reflectivity range. During optimization only a few layers on the top of the stack were varied. Owing to the lower number of aperiodic layers, this approach leads to a structure with smooth GDD that exhibits little sensitivity to deposition errors, as compared with broadband chirped mirrors [16].

The mirror was coated on a 75-mm substrate, with deviations of the total layer structure thickness across the substrate being less than ±0.5%. The unprecedented reproduction of the mirror reflectivity curve over a band spanning more than an octave (left panel in Fig. 2) demonstrates unparalleled reproducibility of the optical properties of the deposited layers, which is a key prerequisite for precision dispersion control of the multilayer structure.

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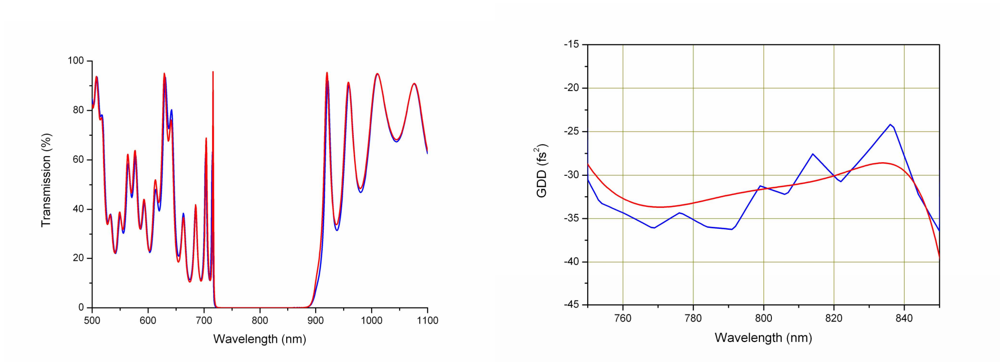

Fig. 2. The transmission spectrum (left) and GDD (right) of the realized chirped mirror; blue curves: measured, red curves: target.

The smooth dispersion curve can partly be attributed to the fact that the aperiodic layers act as an antireflection coating, suppressing GDD oscillations originating from interference of waves reflected from the top and inner part of the mirror in broadband chirped mirrors [15].

To check the quality of the design, we propagated a chirp-free Gaussian model pulse of 60-fs duration carried at 800 nm through a hypothetical delay line consisting of the designed mirrors with the target GDD removed. We then summed two spectral dispersion curves: one for material that must be compensated for (i.e. target dispersion), and another of opposite sign, for the designed dispersion of the mirror. The procedure takes into account all higher orders of the dispersions. The GDD fluctuations accumulated over 120 bounces affect merely the contrast of the pulse (left panel in Fig. 3), leaving its shape and duration unchanged (right panel in Fig. 3).

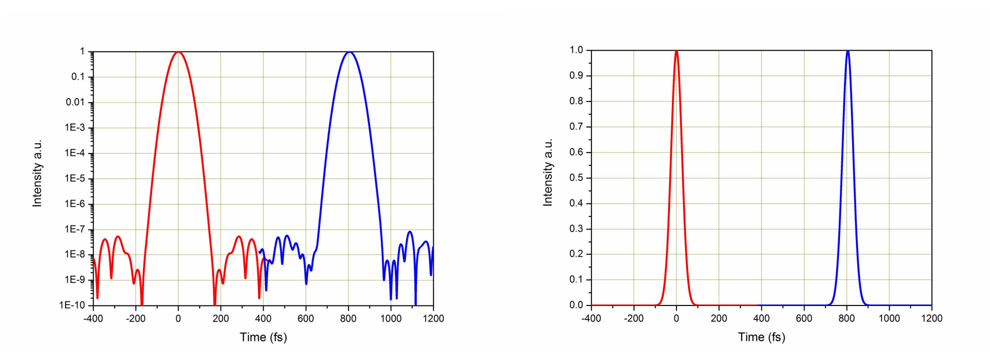

Fig. 3. Intensity profiles of a bandwidth-limited Gaussian model pulse (red lines) and its replica propagated through a hypothetical delay line incorporating 120 bounces off the designed CMs with their nominal GDD and TOD removed (blue lines) on a logarithmic (left) and a linear (right) scale. The amplitude of the pulse transmitted through the delay line is not normalized but can be directly compared with that of the input pulse, the temporal shift being artificial for better visibility.

3. Application in a chirped-pulse oscillator

To demonstrate the usefulness of the newly-developed CMs, we used them to construct a Ti.Sa CPO oscillator, the layout of which is shown in Fig. 4. The laser generates 65-fs 0.25-μJ pulses at a repetition rate of 5 MHz [8]. The autocorrelation trace and the spectrum of the generated pulses are shown in Fig. 4. The extension of the rectangular-shaped spectrum (insert in Fig. 4) is limited to the range 780-820 nm by the saturable Bragg reflector incorporated in

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the laser. The resonator contains two delay lines made up of the new CMs, resulting in 120 bounces off these mirrors upon a single round trip in the cavity. In spite of the large number of mirror bounces, the accumulated phase error was kept at a moderate level as revealed by the low satellites in the interferometric autocorrelation. The chirped pulses originating from the oscillator were compressed by a set of newly-developed high-dispersion CMs, allowing a more compact setup and improved pulse quality in comparison with extracavity GDD control with a prism compressor [8]. These high-dispersion CMs will be reported in detail in a forthcoming publication. Replacement of the previous CMs [10] in the cavity delay lines with the newly-developed low-ripple CMs resulted in a 10% increase in the output power of the laser. This increase in power and the good quality of the autocorrelation provide evidence of the low loss and smooth dispersion of the mirrors, respectively. To show the robustness of both the approach and the reproducibility of the manufacturing process, CMs of this type and of similar bandwidth were designed, produced and also successfully tested in a 60-nJ Ti:Sa CPO operating at a repetition rate of 70 MHz [7].

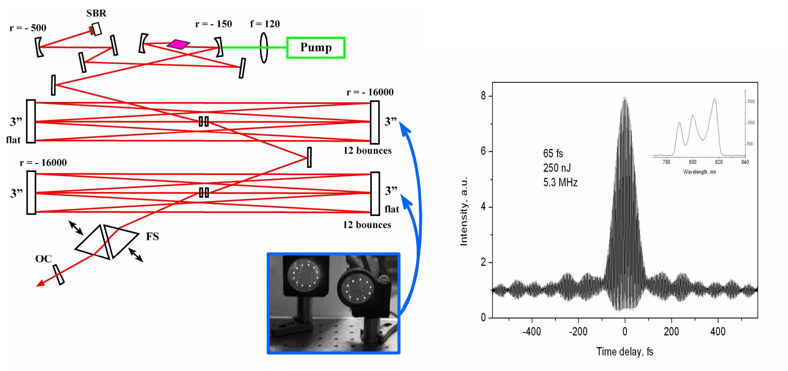

Fig. 4. Left: cavity configuration of the 5-MHz Ti:sapphire CPO. Insert: the beam spots on the CMs forming the delay line. All radii are given in mm. SBR: saturable Bragg reflector; FS: fused silica prisms for fine tuning intracavity GDD, OC: output coupler. Right: the autocorrelation trace of the generated pulses compressed by another set of (different) chirped mirrors external to the cavity (not shown). Insert: the generated spectrum.

4. Conclusions

A CM capable of compensating dispersion of real optical materials and having very low ripple has been designed, realized and successfully tested in Ti:sapphire CPO systems. Analysis shows that residual GDD fluctuations accumulated over 120 bounces off the CMs cause negligible degradation of the shape, peak amplitude and duration of a 60-fs Gaussian model pulse. CMs with small GDD ripple and low loss will be instrumental in advancing the state of the art of enhancement cavities [9, 10] as well as extended-cavity high-energy femtosecond laser oscillators. The concept presented is expected to permit the development of low-loss, smooth-GDD CM’s with bandwidths supporting pulses in the 20-fs range and below.

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