Octave spanning wedge dispersive mirrors with low dispersion oscillations

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Abstract: A novel concept for octave spanning dispersive mirrors with low spectral dispersion oscillations is presented. The key element of the so-called wedge dispersive mirror is a slightly wedged layer which is coated on a specially optimized dispersive multilayer stack by a common sputter coating process. The group delay dispersion (GDD) of a pulse reflected on a wedge dispersive mirror is nearly free of oscillations. Fabricated mirrors with negative GDD demonstrate the compression of a pulse down to 3.8 fs as good as double angled mirrors optimized for the same bandwidth.

OCIS codes: (310.4165) Multilayer design; (310.1620) Interference coatings; (320.5520) Pulse compression

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1. Introduction

The generation of optical pulses in the sub-5-fs regime relies on the precise compensation of dispersion introduced by material-dispersion and self-phase-modulation [1]. Specially designed dispersive mirrors are capable to compensate this dispersion enabling pulses with durations shorter than 3 fs [2]. These octave spanning dispersive mirrors exhibit strong spectral oscillations in the group delay dispersion (GDD), because of an impedance mismatch of the mirror and the ambient medium [3]. These modulations limit the minimal achievable pulse duration [1] and reduce the temporal contrast by generating satellite pulses [4]. Ways of optimizing the coating design were found to reduce the oscillations [5], but they are not successful enough for mirrors with an octave spanning bandwidth. Two general mirror design approaches exist to avoid GDD-oscillations. There are methods were one single mirror has already low oscillations and there are methods using pairs of mirrors which compensate the oscillations of each other. Both design approaches are explained below.

1.1 Single mirror approach

In the single mirror approach the generation of the oscillations is prevented by avoiding the Fresnel-reflection from the surface of the top layer, which is the interface to the ambient medium [5,6]. The reflected light from the surface interferes with the main beam and causes the dispersion ripples. One method to avoid this interference is to tilt the interface with respect to the coating-stack [7]. The tilted surface causes a separation of the reflected light from the top-layer and the main beam leading to an oscillation-free GDD. For manufacturing, a thin substrate is fixed on top of the coated mirror by optical contacting. Then the contacted substrate is polished down to a thickness of less than 100 μm. Simultaneously, the contacted substrate must have the necessary wedge angle. The realization is technically difficult. The yield of usable mirrors is low, because the polishing process is not well controlled. Even for the good mirrors only about half of the aperture can be used.

Another method is to provide ideal impedance matching between the coating and the incident medium by applying the dispersive coating on the back side of a substrate [8]. Also here the substrate must be very thin to avoid unwanted additional group velocity dispersion (GVD). The GVD of the substrate must be compensated by the coating. For example, an octave spanning dispersive coating can roughly compensate the GVD of only 1 mm fused silica. Then there is no way to introduce additional negative GDD, which is usually desired. Additionally a substrate with a thickness of 1 mm does not fulfill the requirement in flatness after being coated, since the intrinsic stress of the coating deforms the substrate too much. A stress-compensating anti-reflection coating [9] can be deposited on the front side.

One more way to provide ideal impedance matching is to use *p*-polarized light for the mirror at Brewster angle [4,10]. This concept suffers from the relatively low reflectance obtained for *p*-polarized light and the high angle of incidence (AOI) which makes the mirror unsuitable for many optical setups.

1.2 Mirror pair approach

There are concepts where the oscillations are not avoided at one mirror but they are heavily reduced by employing alternating mirror pairs. The first mirror pair concept is based on a complementary pair of mirrors [2,11,12]. The oscillations still exist after reflection at the first mirror, but they are compensated by a second mirror which has similar oscillations which are spectrally shifted to be in anti-phase. The result after an even number of bounces on these mirrors is a relatively smooth dispersion. A disadvantage of this method is that two different coatings are necessary which must be perfectly matched. The precision of the total thickness

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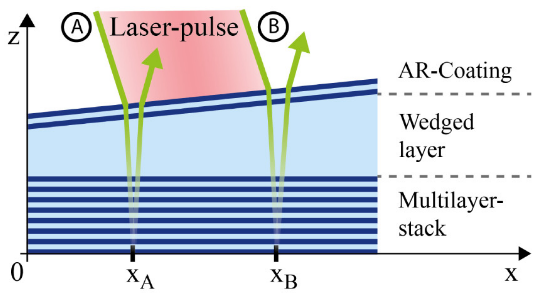
should be within 0.1% from one coating run to another. Higher deviations result in an increased amplitude of the residual oscillations.

Another way to get such a complementary pair from one single coating run are so called double angle mirrors [13]. Since the GDD-spectrum shifts to shorter wavelength when the AOI increases, there is an angle where the oscillations of two mirrors used under two different angles have an opposite phase. Since the mirrors are from one coating run, they don't need to be matched to be used in double-angle configuration. But when many mirrors are made in one coating run, the mirrors still must be matched because of the inhomogeneity in layer thicknesses caused by the coating plants. Another disadvantage of these mirrors is that they must be accurately aligned in order to meet the AOI of the coating design. Small deviations of the AOI lead to increasing GDD-oscillations.

Below we explain our novel wedge dispersive mirrors approach and compare them with conventional double angle mirrors, because nowadays they are one of the most common types of mirrors used for broadband pulse compression. The design target was the same for both mirror concepts in order to make the comparison feasible.

2. Wedge dispersive mirror

In a wedge dispersive mirror, the compensation of spectral GDD oscillations is realized in one single multilayer stack. It is thus a single mirror approach. The key element of the new mirror is a wedged layer which is coated onto a specially optimized dispersive multilayer stack (Fig. 1). The wedged layer has a thickness of about 8 μm on one side of the mirror and 6 μm on the other side. The thick layer introduces high frequent GDD oscillations which are shifted spectrally along the gradient of the wedge. This is illustrated by the two rays shown in Fig. 1 (left). The two rays A and B interact with the coating at two different positions x_A and x_B. The GDD curves for these two individual positions are given in Fig. 1 (right). In this idealized case the oscillations are in anti-phase and therefore cancel each other.



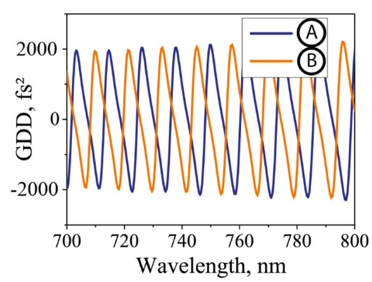


Fig. 1. Left: Concept of a wedge dispersive mirror. It consists of three major parts: The multilayer stack, the wedged layer and the anti-reflective coating to suppress interference fringes in the reflected beam. For illustrating the principle of operation the two rays A and B are drawn. They hit the coating on two different spots with a different thickness of the wedged layer. Right: The GDD spectral phases of the two rays differ and cancel each other.

Generally, the phase and its derivatives are not additive values, but the main contribution to the result is provided by focal plane zones of constructive interference, where phases are rather close. Zones of destructive interference have small contribution and can be neglected in this approximation. Therefore, the effective GDD a laser pulse with a beam profile $I(\mathbf{r})$ has obtained from a mirror can be considered as an integration of the GDD values along the diameter of the beam. In the focal spot, were all GDD components are superimposed, the effective GDD can be expressed as:

$$\overline{GDD}(\lambda) = \int GDD(\lambda, \mathbf{r}) \cdot I(\mathbf{r}) d\mathbf{r}$$

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Here λ is the wavelength and **r** is the radius of the beam. The averaged GDD for our wedge mirror design is shown in Fig. 2(b). For comparison the GDD of a state-of-the-art double angle mirror system is shown for both AOIs and the resulting effective values in Fig. 2(a). Both concepts have similar characteristics with the important difference that the novel wedge mirrors achieve this result after only one reflection.

The antireflective coating on the wedged layer effectively reduces front surface reflections and avoids interference fringes in the reflected beam without affecting the effective dispersion of the mirror.

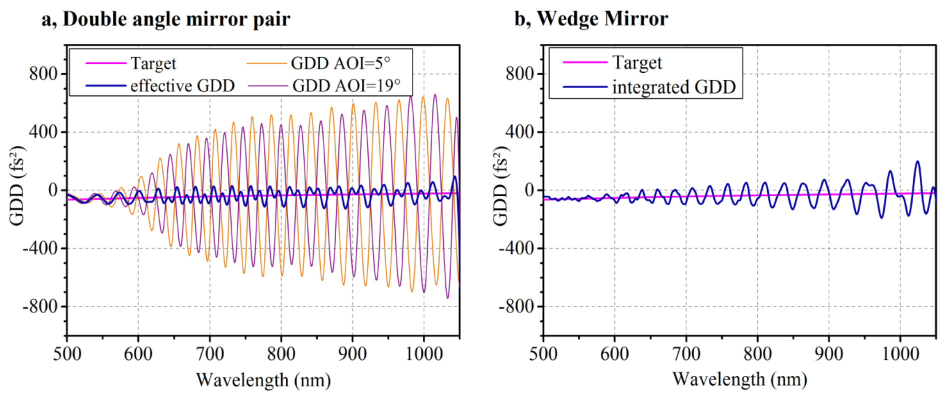

Fig. 2. Calculated group delay dispersion: The target (magenta line) was chosen to be the same for both mirror concepts. **a**, Double angle mirrors: The red and the black line show the GDD of one reflection at an angle of incidence of 5° and respectively 19°. Blue is the effective GDD. **b**, Wedge Dispersive mirror: The blue line is the integrated GDD for a pule with Gaussian beam profile.

The multilayer-stack and the antireflection coating were designed using the commercial software OptiLayer (OptiLayer GmbH, Germany). The dispersive multilayer mirror was optimized using the same target GDD-values as used for the double angle mirror. For the calculations fused silica was used as the incidence medium, taking into account that the silicon dioxide layer is deposited onto the stack. After fabrication of the mirrors discussed here we found that in future optimizations the amplitude of the GDD oscillations can be further reduced by using SiO_2 as incidence layer for the design calculations.

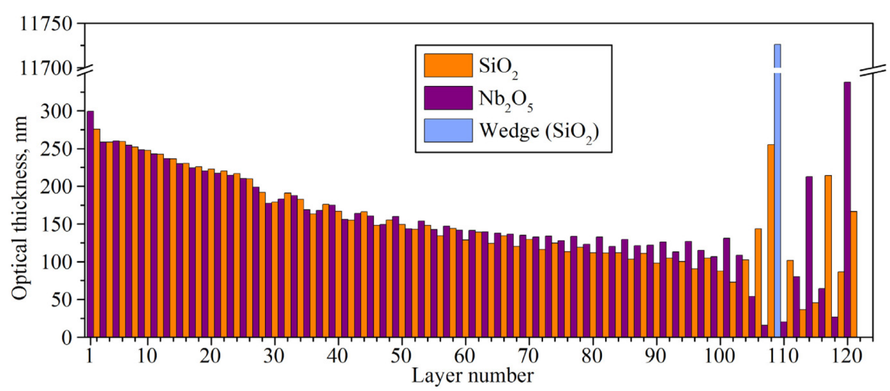

Fig. 3. Design of the wedge dispersive mirror with optical layer thicknesses plotted. The first layer is on the substrate, the last layer number 121 is exposed to air. Notify that the y-axis is discontinued for the thick wedged layer. The blue color was chosen for highlighting the wedged layer, but the same SiO_2 was also used for the other low index layers.

#259862 Received 25 Feb 2016; revised 12 Apr 2016; accepted 12 Apr 2016; published 19 Apr 2016

The obtained design with the optical layer thicknesses is presented in Fig. 3. For the production three coating runs are necessary. At first the actual dispersive layer stack is coated. Then the wedged layer is deposited, followed by the AR coating.

3. Production of the wedge dispersive mirror

The thin film design was deposited on fused silica substrates with 1” diameter using the magnetron sputtering plant Helios (Leybold optics, Germany). Well calibrated time monitoring combined with an optical broad-band monitor for in situ transmission measurements was used to control the layer thickness.

The wedge dispersive mirror is realized in three different coating runs. In the first run, the basic dispersive mirror structure is deposited having a homogeneous thickness all over the substrate. The fabrication of the wedged layer is the key step of the process. A novel technique was developed to apply the wedged layer using the same standard magnetron sputtering process. The samples are mounted in tilted fixtures. One part of the surface is closer to the magnetron and one part is farther away. The coating is then deposited inhomogeneously along one axis of the surface of the substrate resulting in a wedge-shaped layer. Here the advantage of using magnetron sputtering is that the sputtering target is very close to substrates and therefor the gradient of the wedge becomes very large. The orientation of the wedge gradient is marked on the substrate for later reference. After the wedged layer is finished the coated substrates are put in the standard fixtures to apply the anti-reflective coating homogeneously.

4. Characterization of the wedge dispersive mirror

To measure the GDD of the mirrors a homebuilt white light interferometer [14] was used. The results are shown in Fig. 4. The wedge dispersive mirrors are measured at an AOI of 8°. For comparison the two double angle dispersive mirrors were measured simultaneously at an AOI of 5 and respectively 19°. The result was then divided by a factor of 2 to get the so-called effective GDD, which embodies the value of one single mirror.

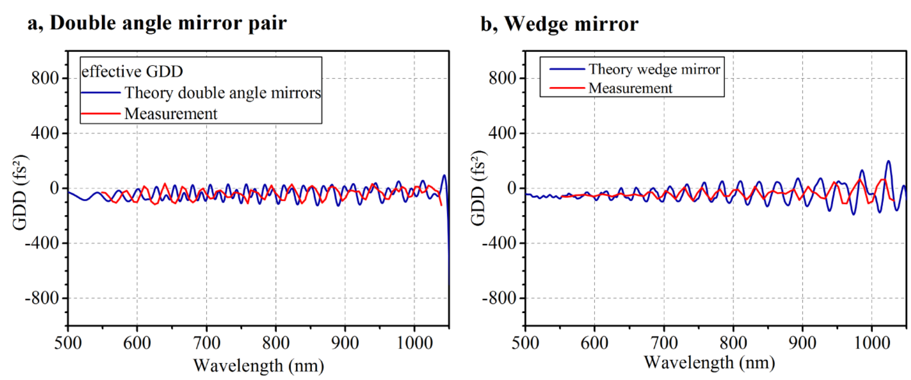

Fig. 4. Dispersion measurements using a white light interferometer: Measurement and Theory of the group delay dispersion (GDD) for one pair of double angle mirrors (a) and wedge dispersive mirror (b).

The new mirrors were also tested in a Ti:Sa based laser system whose pulses are spectrally broadened to one octave in a nonlinear hollow core fiber [15]. The emitted pulses are compressed by six of the wedge dispersive mirrors. For comparison six double angle mirrors aligned at an AOI of 5° and 19° were used. The power was 1.6 W. The pulse duration after the compressor was measured with FROG [16]. The traces for both types of mirrors are shown in Fig. 5 and are similar. The pulse duration is 3.8 fs for both types of mirrors. In case of the wedge mirrors we observe slightly less satellite pulse generation which means that more energy is concentrated in main pulse.

#259862 Received 25 Feb 2016; revised 12 Apr 2016; accepted 12 Apr 2016; published 19 Apr 2016

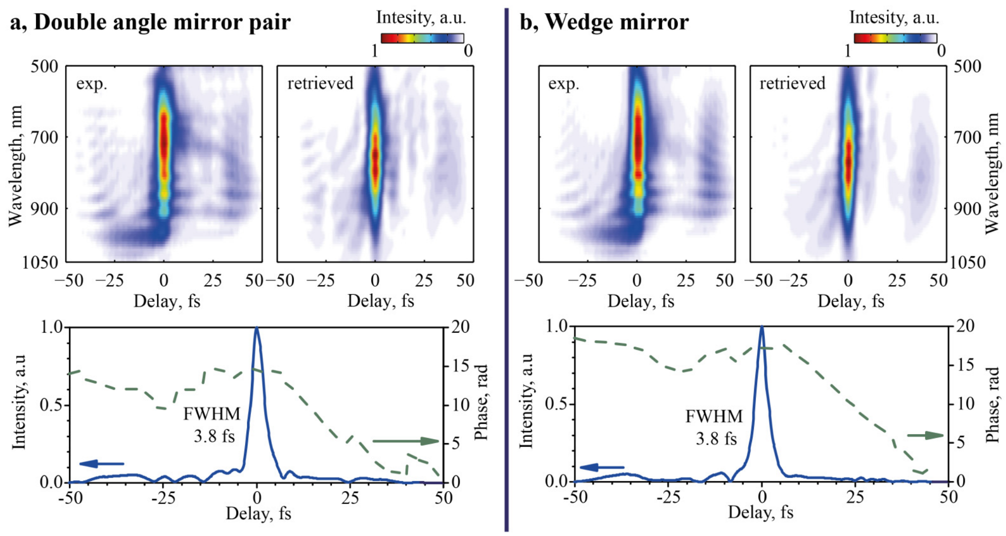

Fig. 5. Experimental FROG traces taken after the compression with six mirrors of conventional double angle mirrors (a) and wedge dispersive mirrors (b). Also the retrieved FROG traces are shown. The retrieved temporal profiles and the phases are below.

We also measured the beam profiles at the focal spot with and without the wedge mirrors. We observed minor changes in the beam profile when using the wedge mirrors. The reason is a lensing effect generated by the wedged layer, which is not uniformly produced yet. By rotating the six mirrors in respect to the wedge-gradient by 30 degrees, that means the rotation angles were [0° 30° 60° 90° 120° 150°], the lensing effect was sufficiently compensated. The coating process could be further optimized to get a more planar wedge, to avoid this lensing effect.

The FROG measurements prove that a pulse compressor consisting of our novel wedge dispersive mirrors generates pulses as short as using a compressor consisting of conventional double angle mirrors. But wedge dispersive mirrors are more convenient to use in an optical setup, because the angle of incidence must not be aligned with high precision and the number of bounces can also be odd. Another advantage is that the mirrors don't need to be matched as it is the case for double angle mirrors.

6. Conclusion

We designed, produced and characterized wedge dispersive mirrors which compress an energetic octave spanning near-infrared laser pulse down to a duration of 3.8 fs. The mirrors benefit of a newly discovered averaging effect of oscillations in the group delay dispersion by introducing a wedged layer. Because of this effect, the mirrors are more robust against layer deposition errors than mirror pairs. The new wedge mirrors combine the advantages of the two existing approaches of oscillation-free dispersive mirrors. Since the wedged layer can be realized by a standard thin-film coating process, the new mirrors are simpler to produce than mirrors basing on the conventional single mirror approach. Also the wedge mirrors are easier to implement in optical setups than double angle mirrors, since the AOI has wide working range.

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