Tilted-front-interface chirped mirrors

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One can achieve perfect impedance matching of dispersive mirrors to the environment over an arbitrarily broad spectral range by tilting the front interface with respect to internal interfaces of the multilayer. As a result, by drawing on this concept one can increase the bandwidth of the controlled dispersion of mirrors to a full optical octave, limited only by technological constraints (number of layers that can be coated and accuracy of thickness control). Additionally, the ratio of undesired fluctuations of the group-delay dispersion to optical frequency is dramatically reduced for tilted-front-interface mirrors compared with conventional chirped mirrors. © 2001 Optical Society of America

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An unprecedented degree of control of femtosecond-pulse generation was recently achieved[1,2] by electronical regulation of the evolution of the carrier-envelope phases of ultrashort light-wave packets. This parameter is relevant in strong field interactions with ultrashort pulses.[3] The absolute phase becomes an increasingly efficient means of coherent control, with pulses closely approaching the single-cycle limit. Pulses as short as 5 fs directly at the output of a Ti:sapphire oscillator were recently demonstrated,[4] and the duration of laser pulses emerging from fiber-compressors can be as short as 4 fs.[3,5,6] Yet the single-cycle limit (corresponding to a duration of 2.7 fs at 800 nm) is still out of reach, in spite of the generation by several means of pulses with spectra that cover more than 1 optical octave. For high-power amplified pulses, efficient spectral broadening can be achieved by nonlinear propagation in noble-gas-filled hollow fibers.[7,5] Similar results can be obtained by seeding of pulses produced by special high-power oscillators ($P_{\mathrm{peak}} > 1$ MW) in a standard monomode fiber.[2,6] With recently invented photonic crystal fibers,[8–10] extremely broad spectra can be produced, even with low-power ($P_{\mathrm{peak}} \sim 30\,\mathrm{kW}$) pulses. Progress in broadband dispersion management lags behind the advancement of spectral broadening techniques and currently sets the limit in generation of ultrashort pulses.

After their invention in 1994,[11] dispersive dielectric multilayers (chirped mirrors; CMs) were rapidly improved[12–14] and became key components in broadband delay lines used for generation of sub-10-fs pulses.[4,7,6] The replacement of design techniques that relied exclusively on computer optimization with algorithms to initiate performance[12–14] has allowed the bandwidth over which high reflectance and dispersion control are provided to be increased to 160 THz at 800 nm. Extending the bandwidth beyond this limit has been possible only at the expense of rapidly increasing unwanted oscillations in the frequency-dependent group-delay dispersion. These fluctuations can be partially suppressed by use of pairs of mirrors with complementary dispersion characteristics.[4,15] Both the bandwidth limitation and the undesired dispersion oscillations are consequences of imperfect impedance matching between the multilayer and the incident medium, air. One can overcome this drawback by replacing air with glass as the medium of incidence. This solution has been independently recognized and simultaneously published by Tempea *et al.*[16] and by researchers at ETH Zurich.[17] In Refs. 17 and 18 a delay line that incorporates both dispersive mirrors and prism pairs is proposed; here we demonstrate that dispersion can be controlled up to the fourth order over 1 octave by use of these novel-concept CMs exclusively. The dispersive behavior of prism pairs becomes unavoidably complex in the spectral range below 650 nm, impairing the quality of the higher-order dispersion control that is essential in few-cycle pulse generation. Furthermore, the use of prism pairs for dispersion management of high-power pulses is prevented by the accumulation of nonlinear distortions (e.g., self-focusing) on propagation of the beam through the thick glass.

The frequency dependence of the group delay experienced by a broadband pulse on reflection off a CM can be controlled by variation of the penetration depths of the various spectral components of the multilayer. Short-wavelength components must be reflected within the top layers, whereas long-wavelength components must penetrate deeper toward the substrate (and thus experience a longer delay) to produce the most-often required negative group-delay dispersion (GDD). We can initiate this behavior by decreasing the Bragg period of the multilayer from the substrate toward the top layer. Additional modulation of the layer thickness and computer optimization are required[12,14] for suppression of multiple internal reflections within the mirror's interfaces. Because of the

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large refractive-index difference between a multilayer and air, a nearly wavelength-independent reflectance of ~3% occurs at the front interface. This difference gives rise to unwanted interference between rays reflected at the air interface and rays reflected deeper in the coating, leading to strong distortions of the reflectance and particularly of the GDD characteristics of the mirror. This effect is exploited in Gires–Tournois mirrors,[19] which introduce a large negative GDD over a narrow bandwidth. In the case of broadband mirrors, such resonant interference effects lead to fast oscillation of the GDD about the target curve, impairing the quality of the compressed pulses. One can alleviate this adverse effect by coating an antireflection filter[12] or a narrow-band-stop filter[14] on top of the CM. Efficient suppression of GDD distortions calls for a reflectance that is significantly less than 10^{-3} at the air interface. This requirement can be met by use of antireflection coatings or bandpass filters over only a limited bandwidth, restricting the usable bandwidth for GDD control from a single CM to 150–160 THz at 800 nm.[12–14] Furthermore, residual interference effects, often enhanced by manufacturing errors, can lead to large fluctuations of the GDD-versus-frequency curve.

One can overcome the drawbacks mentioned above by tilting the front interface (the interface to the incident medium, which is most commonly air) with respect to other interfaces of the multilayer structure, as sketched in Fig. 1. In this manner adverse interference between the beam reflected at the air–dielectric interface (short-dashed line) and those reflected by internal interfaces (long-dashed line) can be completely eliminated. Demands on the antireflection coating on the tilted-front surface can be substantially relaxed, because residual reflectance at this interface merely introduces some loss, without influencing the phase shift experienced by the useful beam on reflection. To keep the overall reflectance high, one can reduce the front-surface reflectance below 0.2% over 500–1000 nm without introducing notable phase distortions by using an antireflection coating consisting of merely 13 layers.

To demonstrate the power of this concept, we have designed a tilted-front-interface chirped mirror (henceforth, briefly, a TFI mirror), which provides dispersion control up to (and including) the fourth order over 1 octave, from 500 to 1000 nm, for the first time of which we are aware. (Fig. 2). By employing several reflections off such a mirror, one can compensate for the spectral chirp imposed on a broadband wave packet when it travels several millimeters in, e.g., fused silica and tens of centimeters in air with an accuracy sufficient for the generation of pulses with durations of ~3 fs in the near-single-cycle regime. A first attempt to manufacture this mirror has already been made. The filled squares in Fig. 2 depict GDD data measured by white-light interferometry.[20] Deviations of the measured GDD curve from the designed curve are due to manufacturing errors, which need to be reduced in the future. The coating consists of 68 SiO_2 and TiO_2 layers. The need for the comparatively high number of layers is related primarily to the negative third-order dispersion required for compensating for material third-order dispersion of opposite sign. If only second-order dispersion were to be introduced, fewer layers would be required, and the absolute value of the GDD could be increased. However, to push the performance of pulse-compression techniques toward the single-cycle limit requires control of higher-order dispersion.

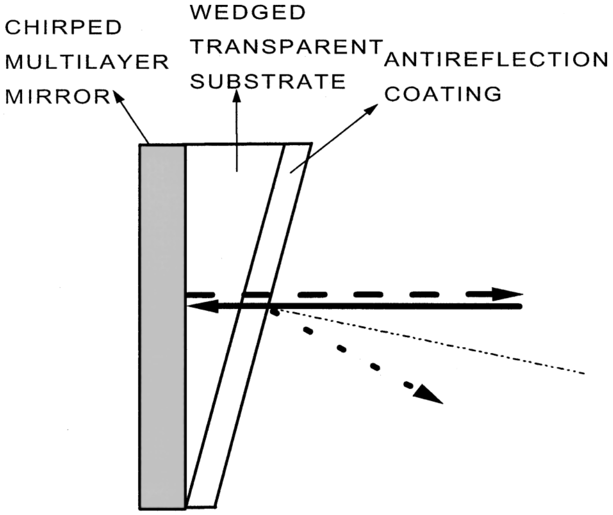

Fig. 1. Simplified schematic of a TFI CM coated upon a thin wedged glass substrate and illuminated from the substrate side. The substrate introduces additional positive dispersion, reducing the overall negative GDD of the mirror. Thus the wedged plate should ideally be thinner than 100^{-1} m. Different embodiments of TFI CMs and the involved technology are discussed at the end of the paper.

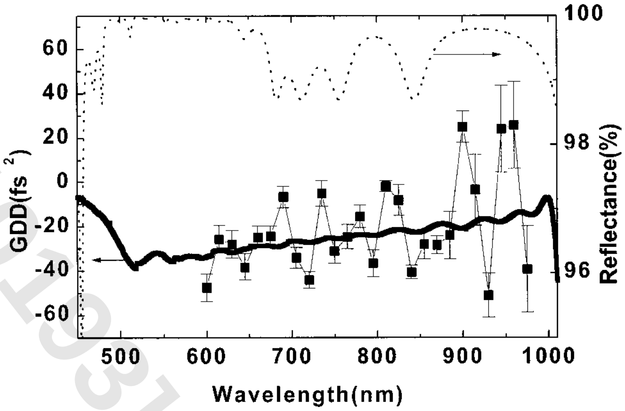

Fig. 2. Reflectance (dotted curve) and GDD (solid curve) of a TFI CM consisting of 68 SiO_2 and TiO_2 layers. The mirror precisely compensates for the dispersion introduced by a physical path of 0.45 mm in fused silica plus 15 cm in air. The GDD could not be measured below 600 nm because of bandwidth limitations in our white-light interferometer. The positive GDD introduced by the glass wedge (which can be as thin as 50^{-1} m if special technology is employed) is not taken into account.

Elimination of the impedance mismatch at the dielectric–air interface that is inherent in standard multilayer mirrors also improves transmittance outside the high-reflectance band, because higher-order interference bands are partly suppressed. This improved transmittance benefits the design and manufacturing of dichroic dispersive mirrors by producing improved characteristics. Figure 3 depicts a dichroic TFI mirror designed for coupling the pump radiation at 527 nm efficiently in a broadband Ti:sapphire laser. The mirror exhibits high reflectance and constant GDD in the wavelength range 600–950 nm as well as high transmittance (>97%) in the vicinity of the pump wavelength (520–540 nm).

With the problem of impedance matching to air being inherently resolved, the choice of the starting multilayer structure becomes less critical than for conventional CMs. As a result, even a linearly chirped initial structure leads to fast convergence of the computer optimization algorithm to the target specifications when the TFI concept is used. The GDD-versus-wavelength curve that is used is highly sensitive to manufacturing errors, because small deviations from the nominal thickness of the top layers can easily destroy the impedance matching implemented by conventional methods.[11,12,14] TFI designs are significantly more stable, because the impedance mismatch between the internal multilayer structure and the (tilted) air–mirror interface is eliminated independently of the layer structure. Statistical-error sensitivity analysis shows that the fluctuations of the GDD-versus-wavelength curve of a conventional CM that introduce a nominal GDD of $-45\ \text{fs}^2$ over 300 nm at 800 nm have a relative amplitude of 100% for a maximum absolute deviation of 0.5 nm from the nominal layer thickness (a uniform distribution was assumed for the manufacturing errors). By contrast, the maximum amplitude of the GDD oscillations is only 30% for a TFI mirror under the same conditions.

A straightforward way to enhance the bandwidth of a reflector draws on the use of large incidence angles and *s*-polarized light. Under these conditions the effective value of the ratio between the refractive indices of the coating materials increases, leading to a corresponding increase in bandwidth. We could not use this simple method in the design of dispersive mirrors. Although increasing the angle of incidence under *s*-polarized light does lead to an enhancement of the reflectance in terms of bandwidth and absolute value, it fully compromises the dispersive properties of the mirror. Along with the effective ratio between the refractive indices of the coating materials, the impedance mismatch at the air interface is dramatically enhanced under these conditions, giving rise to huge GDD characteristic oscillations. In a TFI mirror the reflectance of the air interface is fully decoupled from the dispersive properties of the mirror, and one can successfully employ large incidence angles and *s*-polarized light to enhance both the reflectance bandwidth and the bandwidth over which the mirror provides dispersion control.

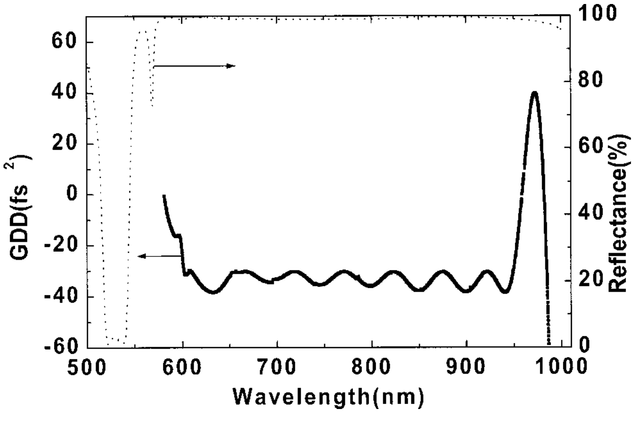

Fig. 3. Reflectance (dotted curve) and GDD (solid curve) of a dichroic TFI CM consisting of 49 SiO_2 and TiO_2 layers. The mirror exhibits high reflectance ($R > 99\%$) and constant GDD ($\sim 35\,\text{fs}^2 + \ \sim 15\%$) over most of the Ti:sapphire fluorescence bandwidth while efficiently transmitting the pump radiation ($R < 3\%$ from 520 to 540 nm).

Although the structure of the TFI mirrors is simple in principle, putting the concept into practice is not trivial. The difficulties arise from the fact that the front wedge must be very thin to keep the overall dispersion negative. An ultrabroadband TFI CM coating can typically compensate for the dispersion introduced by 0:5–0:7 mm of fused silica. Thus the wedge should ideally be thinner than 100^{-1} m. If the multilayer were coated on the back side of such a thin wedged glass substrate, the surface quality of the mirror would be severely affected by tensions that inherently arise in a coating consisting of 50 to 70 layers. Alternatively, one can coat the multilayer onto a standard (thick) optical substrate and subsequently apply a thin wedged plate onto the top of the structure. It is essential that perfect impedance matching (i.e., a reflection-free interface) be achieved between the glass wedge and the SiO_2 top layer. To this end, we have successfully tested two techniques: attaching the wedge to the multilayer by means of an index-matching fluid and optically contacting the wedged plate (patent pending). Although it is perfectly functional, the first solution has the disadvantage of requiring the fabrication and handling of a thin free-standing wedge plate; this plate will be floating upon a thin layer of index-matching fluid on the multilayer. According to our experience, it is difficult to use a wedge whose thinnest edge is less than 100^{-1} m in this implementation. The advantage of optical contacting resides in the fact that a plane parallel plate sufficiently thick to ensure excellent surface quality can be initially contracted to the multilayer. In a second step, the plate (fixed now upon the multilayer) will be polished to the desired wedge angle and thickness. Optical contacting leads to a bond of high optical quality without defects at the interface and therefore without refractive-index discontinuities if the materials in contact have identical optical properties. As it is most likely the result of hydrogen bonding across the interface, the optical contact exhibits remarkable strength and long-term stability if the diffusion of aqueous or nonaqueous solvents in the interface can be prevented. Subsequent heat treatments can be employed to improve the stability of the bond further. The strong bond achieved by optical contacting preserves the excellent surface quality of the wedge, even if the plate is polished to less than $40\ \text{m}^{-1}$.

In conclusion, one can achieve perfect impedance matching of CMs to the environment over an arbitrary broad spectral range by tilting the front interface with respect to internal interfaces of the multilayer. As a result, the bandwidth of CMs that draw on the TFI concept is limited only by technological constraints (number of layers that can be coated and accuracy of thickness control). Additional benefits that emerge from the TFI concept include (i) reduced sensitivity to manufacturing errors, (ii) higher transmittance outside the high-reflectance band, and (iii) potentially fluctuation-free dispersion characteristics. Combined with well-established spectral-broadening techniques,[6,7] these mirrors hold promise for opening the way toward generation of single-cycle optical pulses.

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