Dispersion Control Over 150 THz with Chirped Dielectric Mirrors

Gabriel Tempea, Ferenc Krausz, *Member, IEEE*, Christian Spielmann, and Kárpát Ferencz

***Abstract*—Ultrabroad-band chirped multilayer dielectric mirrors providing nearly constant negative group delay dispersion over the wavelength range of 640–950 nm and high reflectance between 590 and 970 nm are demonstrated. A key to this performance has been an improved design method, which also substantially reduces the computing time needed for ultimate optimization. The presented devices constitute an enabling technology for producing high-quality terawatt pulses in the sub-10-fs regime. The generation of 5-fs 0.1-TW pulses by using exclusively these mirrors as negative delay line demonstrates this potential.**

***Index Terms*— Coatings, mirrors, optical delay lines, optical pulse compression, ultrafast optics.**

I. Introduction

THE EVOLUTION of femtosecond technology characterized with landmarks such as the invention of titanium-doped sapphire [1], self-mode-locking [2]–[4], and chirped-pulse amplification [5] has now arrived at a point where the performance of state-of-the-art ultrashort-pulse sources is determined by the quality of dispersion control available. The shortest pulses achievable directly from laser oscillators [6]–[8], amplifiers [9]–[11] and by optical pulse compression [12]–[15] are limited by the bandwidth over which adequate control of the frequency-dependent group delay (dispersion) can be accomplished. In solitonlike femtosecond oscillators and pulse compressors, a group delay linearly decreasing for increasing frequency [≡ negative group delay dispersion (GDD)] is required. In amplifiers, the group delay should be constant over the spectral range of interest. The difficulty in meeting these requirements for shorter and shorter pulses lies in the fact that control of the group delay over *increasing* bandwidth with *increasing* precision is required. As a consequence, generation of the shortest optical pulses has thus far relied on the use of composite dispersive systems made up of more than one optical element (Table I). The presence of prisms in all previously realized sub-10-fs compressors restricted their use for low and moderate pulse energies.

A high-reflectance domain as broad as 400 nm could be previously [16] obtained only at the expense of large fluctuations in the group delay and higher order dispersion, calling for the use of prism pairs as main source of negative dispersion. Another previously proposed [17] way of improving the bandwidth was increasing the number of layers to a value (120), which is not properly supported by the currently available technology, while the strong GDD fluctuations are not reduced. In this paper, we report on the design and fabrication of ultrabroad-band chirped dielectric mirrors that: 1) provide dispersion management down to 5-fs pulse durations and 2) consist of less than 50 layers and can be reliably and reproducibly manufactured by standard electron–beam evaporation technology. These mirrors are capable of replacing composite dispersive delay lines used in previous sub-10-fs compressors and thereby obviate the need of extended optical path through dense optical material during compression. The capability of providing dispersion control over a bandwidth of 150 THz by the exclusive use of reflective optics now opens the way to extending optical pulse compression [14], [18] to unprecedented power levels in the sub-10-fs regime. In an attempt to demonstrate this potential, we have employed these mirrors for compressing the output of a gas-filled hollow fiber seeded by a 25-fs 1-kHz Ti:sapphire amplifier system, yielding 5-fs pulses with a peak power of 0.1 TW [19].

TABLE I
Components and Performance of Previously Demonstrated Sub-10-fs Optical Pulse Compressors

Nonlinear Element	Dispersive Delay Line	Pulse Width/Energy	Ref.
single-mode fiber	grating and prisms	6 fs @ 620 nm/≈1 nJ	[15]
single-mode fiber	grating and prisms chirped mirrors and prisms	5 fs @ 780 nm/≈1 nJ 4.5 fs @ 780 nm/≈10 nJ	[12] [13]
gas-filled hollow fiber	chirped mirrors and prisms	4.5 fs @ 780 nm/≈10 μJ	[14]

In simple terms, chirped mirrors [20] introduce a frequency-dependent group delay by reflecting different spectral components of the impinging radiation at different positions in the multilayer structure. The often required linear variation of group delay with frequency can, contrary to intuition, not be achieved by linearly chirping the multilayer period because spurious Fabry–Perot resonances emerge inside the structure. The undesired resonances can be eliminated over a limited bandwidth by extensive computer optimization [17], [20]. Typically thousands of iterations have been necessary to obtain a smooth dispersion curve. Recently, a technique based on modulating both the multilayer period and the ratio of the thickness of the low-index to that of the high-index layer within layer pairs has been reported [21]. The method

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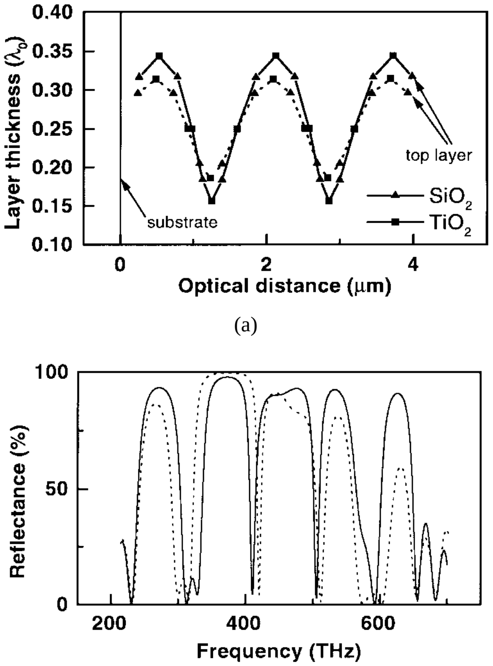
we describe here relies on superimposing a quasi-periodic modulation on a linear variation of the optical thickness of the layers (henceforth, layer thickness) across the structure. Appropriate amplitude and phase modulation of the modulation function dramatically reduces computational efforts needed for final optimization and allows the realization of nearly constant negative GDD over a bandwidth greater than 300 nm around $\lambda_0 = 780$ nm.

II. MULTILAYERS WITH SINUSOIDALLY MODULATED LAYER THICKNESS

The analytic Fourier transform (FT) method can be used for synthesizing graded-index (rugate) chirped mirrors with prescribed reflectance and phase behavior [17], [22]. Several attempts have been made to convert the synthesized rugate structures to discrete multilayer structures [23] or directly synthesize multilayers [24], but all these approaches have resulted in sophisticated multilayer structures relying on many different refractive indices. However, reliable technologies have only been developed for manufacturing two- or three-component structures so far.

The recognition that modulating the layer thickness in a two-component structure affects the mirror characteristics in a similar manner as a corresponding modulation of the refractive index in a rugate mirror can be used to derive a semi-empirical algorithm for the synthesis of two-component chirped mirrors with prescribed reflectance and phase characteristics. Fig. 1(a) depicts multilayer mirrors with sinusoidal modulation of the layer thickness and Fig. 1(b) plots the corresponding reflectance curves, which exhibit multiple high-reflectance (rejection) bands, with rejection strengths depending on the amplitude of the modulating function. If the latter is reduced, the rejection bands corresponding to the average tuning wavelength become stronger, while the others reduce their reflectance. The position of the rejection bands is entirely determined by the the period of the modulating function provided that the number of layers in a modulation period is fixed when the latter is changed, i.e., the ratio of the modulation period to the tuning wavelength λ_0 is kept constant. If the number of layers within the modulation period is high enough (≥ 5), these discrete two-component structures closely follow the behavior of rugate mirrors with a refractive index subjected to a corresponding sinusoidal modulation, except that in the rugate mirror a *single* rejection band arises.[1] It is known [22] that in the case of continuous-refractive index mirrors, a FT relation between the spatial refractive index profile and the complex amplitude reflectance can be derived. The emergence of several equally spaced high-reflectance bands in the above described example might indicate the existence of a discrete Fourier transform between the discrete function which modulates the layer thickness and the spectral amplitude reflectance. A discrete Fourier formalism has been already determined in the particular case of fixed layer thickness and arbitrary refractive indices [24]. Although the generalization is not straightforward, the considerations made above should motivate further investigations aiming to find a discrete Fourier synthesis method for two-component multilayer optical coatings.



(a)

(b)

Fig. 1. Multilayer structures with a sinusoidal modulation imposed on the layer thickness for (a) two different values of the modulation amplitude and (b) the respective reflectance-versus-frequency curves.

III. DESIGN METHOD

The performance of chirped mirrors critically depends on the accuracy achievable in controlling the penetration depth of the different spectral components. In a multilayer structure subjected to a simple linear chirp, this accuracy is severely impaired by the insufficient reflectance of the interfaces, resulting in many partially reflected/transmitted beams of comparable intensity. Resonant interference between these partial waves messes up the dispersion curve of the mirror. This should be avoidable by composing the mirror of narrow bandstop filters with gradually shifted center wavelengths, each consisting of more than two layers to provide high reflectance. Such a multiple bandstop filter structure can be constructed by drawing on the considerations in Section II, i.e., chirping the period of the sinusoidal layer-thickness modulation across the dielectric structure. This leads to the merging of the rejection peaks in Fig. 1(b), resulting in a continuous high reflectance band. The generic formula describing the variation of the layer thickness in such a system is given by

$$t(x) = t_0(x) + A(x) \sin\left(2\pi \frac{x}{\Lambda(x)}\right) \tag{1}$$

where x measures the distance of the respective layer from the substrate and the number of layers within a modulation period Λ must be kept constant, i.e.,

$$\Lambda(x) = \alpha t_0(x). \tag{2}$$

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[1] TFCalc v3.0, Application Notes, Software Spectra, Inc., 1995, Sec. 4, p. NF-2.

The parameter α determines the number of layers within a modulation period, and was set as $\alpha \approx 5$, i.e., equal to its minimum permitted value.

The parameters in (1) are determined by the frequency range $[\nu_{\min} = c/\lambda_{\max}, \nu_{\max} = c/\lambda_{\min}]$ over which high reflectance is required and by the prescribed group-delay-versus-frequency function within this range. For a nearly constant negative GDD over the high reflectance range we require

$$t_0(x) = \frac{1}{4}\left(\frac{\lambda_{\min} - \lambda_{\max}}{d}x + \lambda_{\max}\right) \tag{3}$$

which implies [according to (2)] a modulation period $\Lambda(x)$ linearly varying with x. The total optical thickness of the coating d should fulfill $d \geq d_\tau = |\tau(\nu_{\max}) - \tau(\nu_{\min})|c/2$, where $|\tau(\nu_{\max}) - \tau(\nu_{\min})| = 2\pi|D|(\nu_{\max} - \nu_{\min})$. One of the severe problems in chirped mirror design is achieving negative GDD at the shortest wavelength of the high-reflectance range. This difficulty relates to the fact that the shortest wavelength components have a limited penetration depth which tends to result in a constant group delay. This problem can be alleviated by increasing the amplitude $A(x)$ of the modulation as given by

$$A = \frac{A_2 - A_1}{d}x + A_1 \tag{4}$$

where A_1 and $A_2(> A_1)$ are the limits between which the amplitude is allowed to vary.

Equations (1)–(4) constitute a complete recipe for constructing a multilayer structure that, after some limited computer refinement, is expected to introduce constant negative GDD over an ultrabroad spectral range.

IV. PRACTICAL DESIGN EXAMPLE: RESULTS

The efficiency of the method has been tested by designing and fabricating chirped multilayer mirrors providing dispersion control over a bandwidth of >300 nm around $\lambda_0 = 780$ nm. The mirror structure represented by the full symbols in Fig. 2 has been generated by using a direct computer implementation of (1)–(4) with the input parameters $\lambda_{\min} = 600$ nm, $\lambda_{\max} = 950$ nm, $D = -60$ fs^2, $A_1 = 12.5$ nm, $A_2 = 62.5$ nm, $d = 10.5$ μm, and employing TiO_2 ($n \approx 2.35$) and SiO_2 ($n \approx 1.45$) as the layer materials. The unoptimized design exhibits a high ($R > 99\%$) reflectance over a 350-nm (170-THz) bandwidth as shown in Fig. 3, but the group delay is subject to large oscillations (dotted line in Fig. 3). Nevertheless, these undesirable oscillations can now be eliminated extremely efficiently by computer optimization. Using only 15 iterations of the variable metric algorithm of TFCalc (Software Spectra, Inc.)[1] with the design targets given by $R > 99\%$ and $D = -40$ fs^2 between 655 nm (458 THz) and 950 nm (315 THz) results in a dramatic improvement of the linearity of the group delay curve (dashed line in Fig. 3). The optimization is completed after as few as 80 iterations,[2] which takes some 12 min employing a personal computer equipped with a 150-MHz Pentium processor. This should be contrasted with the several thousand iterations (with the same algorithm) needed to obtain a limited-bandwidth chirped mirror in the case of a conventional initial design exhibiting some smooth (nonoscillating) modulation of the quasi-periodic quarterwave structure. The extremely fast convergence is substantiated by the close correspondence of the final to the initial mirror structure, as shown in Fig. 2.

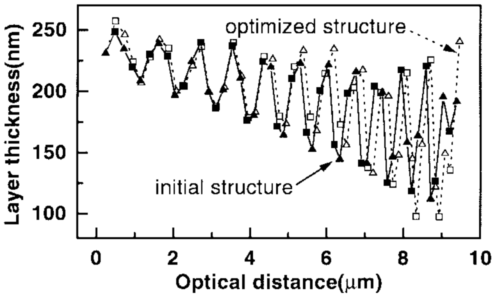

Fig. 2. The layer structure of a chirped mirror designed for broad-band negative GDD, before and after optimization, as described in the text.

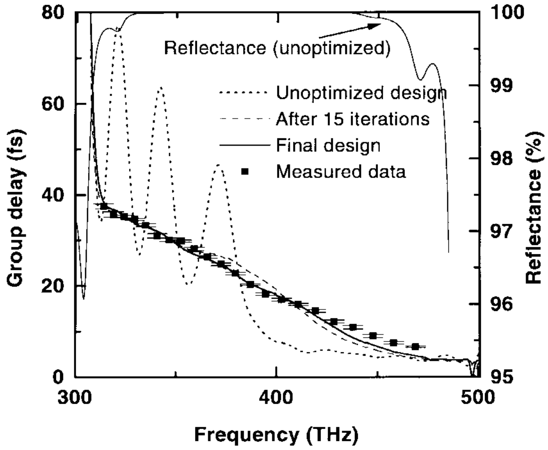

Fig. 3. Reflectance and group delay versus frequency of the chirped mirror before and after optimization as described in the text. The full squares with the error bars depict data obtained by white light interferometry, where the absolute value of the group delay was arbitrarily chosen. The spectral resolution of the measurement was 10 nm.

The ultrabroad-band chirped mirror has been fabricated by electron–beam evaporation. The group-delay variation versus frequency has been measured by using white light interferometry [25]. The measured data represented by full squares in Fig. 3 show excellent agreement with the theoretical group-delay curve. Recently, these mirrors have been used to compress self-phase-modulated 25-fs pulses to 5 fs and to a peak power of approximately 0.1-TW [19]. In combination with pulse compression techniques suitable for high-pulse energies [14], [18], the dispersive delay line made up of these chirped-mirrors providing ultrabroad-band GDD-control open up the way to the generation of high-quality terawatt pulses in the sub-10-fs regime.

Note Added in Proof: Using the method described in this paper, we have recently design a broad-band chirped mirror with the following properties: high reflectance (>99%) in the wavelength range 570–950 nm and nearly constant

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[2] The power of the merit function was set to 2 for the first 15 iterations and to 16 for the following 65.

negative group delay dispersion between 600 and 950 nm. The measured dispersion curve of the manufactured mirror has an average value of -40 fs^2 with ± 20 fs^2 fluctuations between 600–940 nm. The generation of 4-fs pulses has been demonstrated with these mirrors.

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Ferenc Krausz (M'92), for photograph and biography, see this issue, p. 184.

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