Chirped dielectric mirrors for dispersion control in femtosecond laser systems

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ABSTRACT

Optical thin film structures exhibiting high reflectivity and nearly constant negative group-delay dispersions, or optionally superimposed higher-order dispersions over frequency ranges beyond 80 THz are presented. This attractive combination makes these special laser mirrors well suited for intra- or extracavity dispersion control in broadband femtosecond laser systems. We address design issues and the principle of operation of these novel devices. Spectrally resolved white-light interferometry with high time and spectral resolution was used to measure the dispersion of the deposited mirrors. Experimental results on the operation of femtosecond laser systems utilizing dispersion compensating mirrors are given.

Keywords: optical coatings, femtosecond lasers, dispersion control, dispersion measurement, Ti:sapphire laser

1. INTRODUCTION

Femtosecond laser systems contain optical coatings as important functional elements, for instance high reflectors (HR), output couplers (OC), antireflection coatings (AR), beamsplitters (BS) and thin film polarizers (TFP)[1]. System performance strongly depends on the quality of such coatings: reflectances of HRs should approach the ideal 100% value over the entire operation range in order to decrease losses; input couplers should have nearly 100% transmittance at the pump wavelength(s); the output coupling of OCs should be set to a specific value - usually over a broad spectral range - to ensure optimum operation. In some applications, a continuous reflectance (or transmittance) versus wavelength function is desirable, e.g. in femtosecond solid-state laser amplifiers to compensate the gain narrowing effect[2] by spectral filtering of the pulse. Additionally, all the coatings listed above need to be optimized for phase characteristics to prevent the pulse shape from undesirable distortion[3,4]. Furthermore, for high-power laser systems a high damage threshold is essential, which is basically determined by the appropriate selection of coating materials and the deposition technology used. Since it would not be meaningful to list all the requirements that should be taken into consideration during optical coating design and manufacture, let us just mention economic considerations.

Because of the dominant role of soliton-like shaping in ultrashort pulse formation of solid-state lasers[4], femtosecond pulse generation relies on net negative intracavity group-delay dispersion (GDD). Until recently, Brewster-angled prism pairs[5] built into the laser cavity were the only low loss sources of broadband negative GDD. In prism-pair controlled broadband lasers a major limitation to ultrashort pulse generation originates from the variation of the intracavity GDD with wavelength. The principal source of this higher order dispersion, however, was found to be the prism pair[4,6,7]. If the lasers are operated in the vicinity of zero group delay dispersion, the spectra of sub-20-fs pulses from prism-pair controlled oscillators are asymmetric with a broad shoulder[8] or double-peaked[4,9] depending on whether the soliton-like pulses are, respectively, third-[8,10] or fourth-order[9] dispersion limited. This deviation from the ideal sech pulse spectrum causes a weak but nonetheless significant pedestal in the time domain, the length of which may substantially exceed the pulse duration defined as the full width at half maximum intensity. This degradation in pulse quality may be unacceptable in a number of spectroscopic applications requiring high temporal resolution. An additional problem in the time domain is the increased sensitivity of pulse width to cavity and prism alignment. Cavity mirror alignment changes the position of the resonator axis and thus the glass path through the prisms. Hence any small cavity realignment calls for subsequent readjustment of the prism positions and orientation to restore the original pulse width and the corresponding spectrum. This makes "turn-key" operation and thus the integration of these devices in complex systems (e.g. CPA systems, opto-electronic data processing systems) extremely difficult. Furthermore, the minimum prism separation sets a constraint on the resonator length and, in turn, the size and repetition rate of femtosecond pulse solid-state laser oscillators.

Recently, a new compact dispersion-compensating geometry for Kerr-lens mode-locked femtosecond lasers has been demonstrated that incorporates a prismatic end mirror and gain medium[11]. A specific design resulted in a pulse repetition rate of 1 GHz with pulse durations of 111 fs, but it seems that the requirement for GHz repetition rate operation can hardly be reconciled with sub-100-fs performance in this geometry.

Here, we introduce a novel technology for intra- and extracavity dispersion control, which is potentially free from all the drawbacks listed above. Our technology is based on the thin film technique. Special laser mirror designs exhibiting high reflectivity and negative GDD over frequency ranges beyond 80 THz are shown. The design technique, deposition technology and quality control permit higher-order contributions to the mirror phase dispersion to be kept at low values or to be chosen such that high-order phase errors introduced by other system components (e.g., the gain medium, prism pairs) are cancelled. By replacing the prism pairs with these novel devices we were able to build a Kerr-lens mode-locked Ti:sapphire laser, which delivers nearly bandwidth-limited 8-fs pulses[12] around 0.8 μm. In addition, this simplifies the cavity design and may permit the construction of compact, reliable, high-repetition-rate, sub-100-fs sources. First we present theoretical considerations on the operation of dispersion-compensating mirrors that we usually refer to as *chirped mirrors*. The formulae presented can be efficiently utilized to synthesize *graded index* dielectric mirrors with prescribed dispersion properties. Then representative dispersive mirror designs developed for a femtosecond Ti:sapphire laser and its amplifier are shown; these mirrors consist of alternate *discrete* layers of TiO_2 and SiO_2. By computing the electric-field distribution inside the dielectric mirrors as a function of wavelength, we derive their dispersive properties from the wavelength dependence of the penetration depth of the incident optical field in accordance with our theoretical considerations. Measured group-delay versus wavelength functions of the dispersive mirrors are presented. These were obtained by using an interferometric arrangement developed for fast, accurate dispersion measurements on dielectric mirrors. Finally, some practical applications of dispersion compensating mirrors are presented.

2. THEORY[13]

The Fourier-transform technique is widely used for designing gradient-index optical coatings with prescribed spectral properties[14-17]. Generally, there is an approximate Fourier-transform relationship between the refractive index profile $n(x)$ and $Q(k)$, which is an appropriate function of the desired spectral reflectance or transmittance:

$$\frac{1}{2}\int_{-\infty}^{\infty}\frac{d\ln[n(x)]}{dx}\exp(ikx)dx = Q(k)\exp[i\Phi(k)] \tag{1}$$

In Eq. 1, $k = 2\pi/\lambda$ is the wavenumber in air and x is twice the optical distance from the centre of the inhomogeneous layer to physical position z:

$$x = 2\int_{0}^{z} n(u)du \tag{2}$$

Using partial integration and a Fourier transform one can derive:

$$\ln\left[\frac{n(x)}{n_0}\right] = \frac{i}{\pi}\int_{-\infty}^{\infty} \frac{Q(k)}{k} \exp\{i[\Phi(k) - kx]\} dk \tag{3}$$

where $n(\infty) = n(-\infty) = n_0$, and $Q(k)$ and $\Phi(k)$ are even and odd functions of k, respectively.

Recently we demonstrated[13] that if one substitutes

$$Q(k) = |r(k)| \tag{4a}$$
$$\Phi(k) = \arg[r(k)] \tag{4b}$$

in Eq. 3, where $r(k)$ is the required complex amplitude reflectance, the formula is well suited to synthesize graded index dielectric high reflectors (rugate mirrors) with prescribed dispersion properties. In the following we take two examples which illustrate the powerfulness of the Fourier-transform technique. They also help us in understanding the operation of dispersion compensating mirrors consisting of discrete layers.

Our first example is a so called *multiline rugate mirror* design[13]. Substituting the following expression for the required complex amplitude reflectance in Eq. (3)

$$Q(k)\exp[i\Phi(k)] = \sum_{i=1}^{3} \exp\left[-\frac{(k-k_{0i})^2}{2\sigma^2}\right] \exp[ia_i(k-k_{0i})], \tag{5}$$

one obtains the refractive index profile shown in Fig. 1a. During its computation, we used the following parameters: $\sigma = 1.5\ \mu m^{-1}$, $k_{01} = 2\pi/0.4\ \mu m^{-1}$, $k_{02} = 5/3\ k_{01}$, $k_{03} = 7/3\ k_{01}$, $a_1 = 4\ \mu m$, $a_2 = 0\ \mu m$ and $a_3 = -4\ \mu m$. The refractive index of the surrounding medium has been set equal to $n_0 = 1.8$. As one would expect, the multiline rugate mirror design consists of three well defined substructures corresponding to the three separate reflection bands defined for wavenumbers k_{01}, k_{02} and k_{03}. The substructures are shifted relative to the geometrical centre of the inhomogeneous layer defined by shift parameters a_1, a_2 and a_3, as follows from the time shifting theorem of Fourier analysis[13].

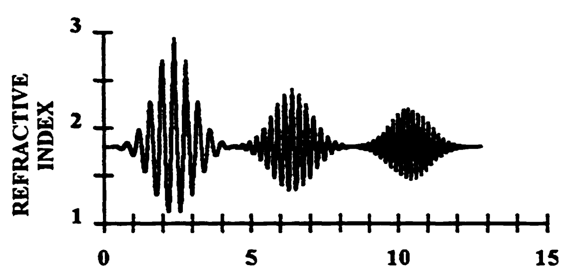

Fig. 1a Refractive index profile of a multiline rugate mirror synthesized by Fourier transform

The computed spectral reflectance of the index profile is shown in Fig. 1b. We find that the structure exhibits high reflectances only at $k_1 = k_{01} / 2 = 7.854\ \mu m^{-1}$, $k_2 = k_{02} / 2 = 13.09\ \mu m^{-1}$ and $k_3 = k_{03} / 2 = 18.176\ \mu m^{-1}$, respectively, as required.

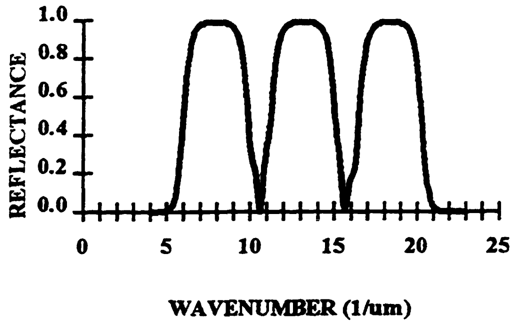

Fig. 1b Computed reflectance of multiline rugate mirror

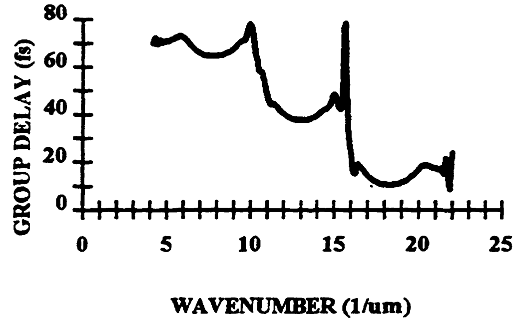

Fig. 1c Computed group delay of multiline rugate mirror

By calculating group delay versus the wavenumber function shown in Fig. 1c, we can conclude that a wavenumber (or frequency) dependent group delay function $\tau(k)$ can be tailored by placing graded index mirrors of corresponding periodicities (k_0) and finite bandwidths at different positions (Δx), which are determined by the following equations[13]

$$\tau = 2\,\Delta x / c \tag{6}$$

$$k_0 = 2\,k \tag{7}$$

It follows that in order to design a broadband high reflector exhibiting a linearly varying group delay versus frequency function, the different frequency components of the index profile have to be dispersed linearly along the propagation axis. For that purpose we have to define a second-order phase-shift versus wavenumber (or frequency) function[13]:

$$\Phi(k) = d_0 + d_1(k - k_0) + d_2(k - k_0)^2 \tag{8}$$

We define $Q(k)$, i.e. the modulus of the complex amplitude reflectance of our second example, as a Gaussian function:

$$Q(k) = \exp\left[-\frac{(k - k_0)^2}{2\sigma^2}\right] \tag{9}$$

Substituting Eqs. 8 and 9 into Eq. 3, we obtain the refractive index profile shown in Fig 2a. The parameters that we used during its computations were: $k_0 = 2\pi / 0.4\ \mu m^{-1}$, which corresponds to our selected mirror central wavelength of 0.8 µm, $\sigma = 1.4\ \mu m^{-1}$, $d_1 = 0$ rad, $d_2 = 0$ µm, $d_3 = -0.589\ \mu m^2$. The refractive index of the surrounding medium was set equal to $n_0 = 1.8$, as in the case of the multiline rugate mirror design. The second-order phase term in Eq. 8 results in a *chirped dielectric rugate* structure, as we expected.

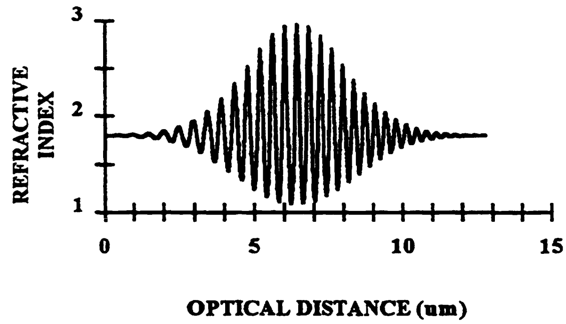

Fig. 2a Refractive index profile of a chirped graded index mirror synthesized by Fourier transform

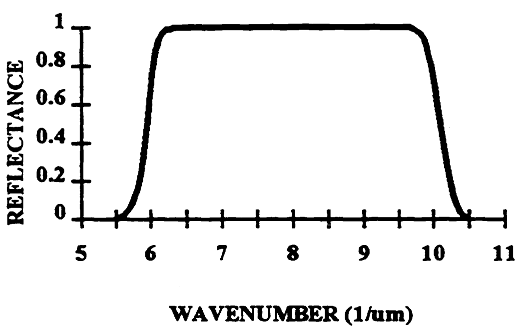

Fig. 2b Computed reflectance of chirped rugate mirror

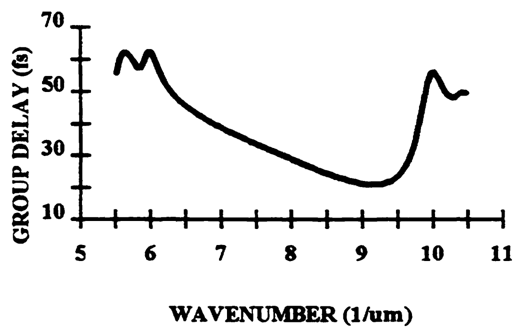

Fig. 2c Computed group delay of chirped rugate mirror

In Fig. 2b, the computed reflectance of the chirped structure is presented. It is worth noting that the structure exhibits practically 100% reflectance from wavenumbers of 6.35 μm^{-1} to 9.35 μm^{-1}, which correspond to wavelengths of 989 nm, and 671 nm, respectively.

Calculating the group delay introduced by the chirped mirror, the result of which is shown in Fig. 2c, we find that the group delay decreases monotonically as a function of wavenumber over most of the high reflectivity band of the mirror. The graded index mirror exhibits nearly constant negative GDD over the 6.5 - 9 μm^{-1} wavenumber range corresponding to the wavelength range of 966 - 698 nm.

Here, we would mention that a similar concept for dispersion cancellation and pulse shaping in optical telecommunication systems has been proposed and demonstrated utilizing different types of distributed Bragg devices such as volume reflection holograms[18,19], chirped Bragg gratings in optical fibres and waveguides[20-24]. Note, however, that in the case of graded index chirped dielectric mirrors, the refractive index modulation is substantially higher and the optical thickness is considerably smaller than those in the case of the Bragg devices mentioned above. The higher refractive index modulation and smaller optical thickness of chirped rugate mirrors result in a relatively high bandwidth but a small GDD.

3. DESIGN[12,25,26]

The graded index chirped mirror shown in Section 2 could be manufactured using state of the art optical coating deposition techniques[27-31]. However, up till now no graded index optical coatings have been manufactured for dispersion control. Limitations to the performance of similar practical designs are set by the index contrast, the total optical thickness and absorption/scattering losses of the dielectric coatings, which are basically determined by the coating materials available and the deposition technology used.

In the following, representative chirped mirror designs developed for a femtosecond Ti:sapphire laser and its amplifier are presented. The dielectric mirrors consist of alternate *discrete layers* of TiO_2 and SiO_2, thus they could be realized by the *standard electron-beam deposition technique*[3]. Thicknesses of the alternate high and low index dielectrics were determined by using a standard *computer optimization technique*[25,32,33]. Our computer refinement algorithm minimizes the quadratic deviation of the complex reflectivity-versus-frequency function of the actual design from the required specification by slightly adjusting the layer thicknesses during the optimization process. The only unconventional feature of our computer software is that the quadratic error is made up of two parts, viz. for the amplitude and phase characteristics, whose relative weights can independently be adjusted[25].

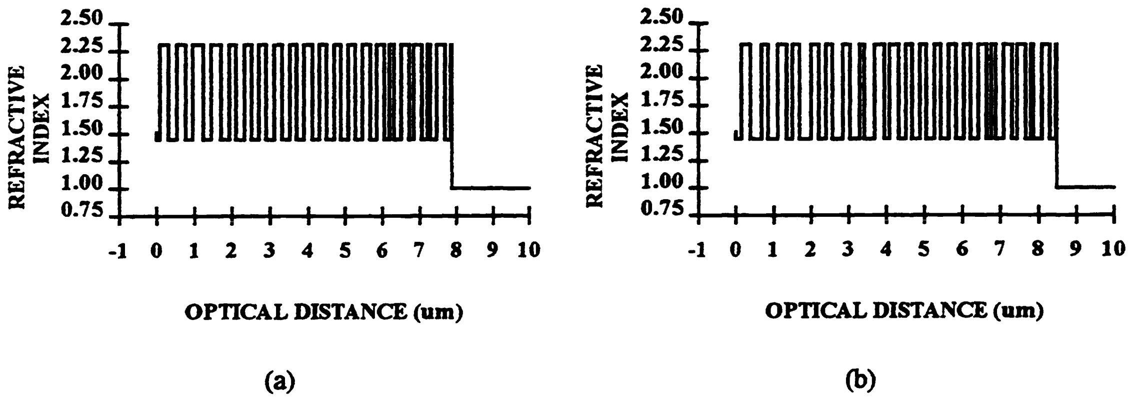

Fig. 3 Refractive index profiles of high-reflectivity TiO_2-SiO_2 chirped mirrors designed specifically for broadband dispersion control in (a) a femtosecond Ti:sapphire laser and (b) its amplifier

The first representative mirror design (Fig. 3a) was developed for full dispersion control in a femtosecond Ti:sapphire laser. The mirror exhibits high reflectivity and nearly constant negative GDD of -41 ± 5 fs^2 over a wavelength range from 720 nm to 910 nm, these are respectively plotted in Fig. 4a and 4b. The structure shows the feature of the increasing multilayer period toward the substrate, hence we call it a chirped mirror, even though the variation is far from what we consider linear.

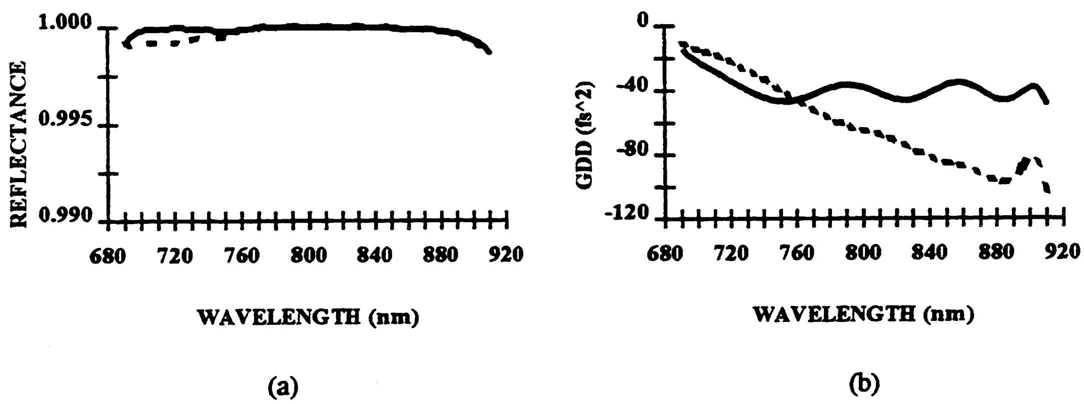

Fig. 4 Computed (a) reflectance and (b) group-delay dispersion of chirped mirrors shown in Fig. 3a (continuous lines) and Fig. 3b (dashed).

If the electric-field distribution inside this chirped mirror is computed as a function of the wavelength shown in Fig. 5a, it can be seen that the penetration depth (and thus the group delay) increases approximately linearly with the wavelength over the 720-910 nm range. The figure also gives clear evidence of the high reflectivity (R>99.5%) of the mirror between 685 and 925 nm, as indicated by the disappearance of the optical field at the substrate-coating interface (penetration depth 8). For comparative purposes, the electric-field distribution inside a traditional, low dispersion dielectric mirror consisting of 44 alternate quarterwave layers of TiO_2 and SiO_2 and centred at 770 nm is depicted in Fig. 5b. The penetration depth and thus the group delay is the smallest at the central wavelength of the quarterwave mirror and symmetrically increases with the detuning. This behaviour results in a positive third-order dispersion (TOD) of quarterwave mirrors[3]. It is clear that if one compares the electric-field distributions corresponding to the chirped mirror and the quarterwave mirror, chirped multilayer coatings have the potential for extending the bandwidth of standard low-dispersion quarterwave mirrors.

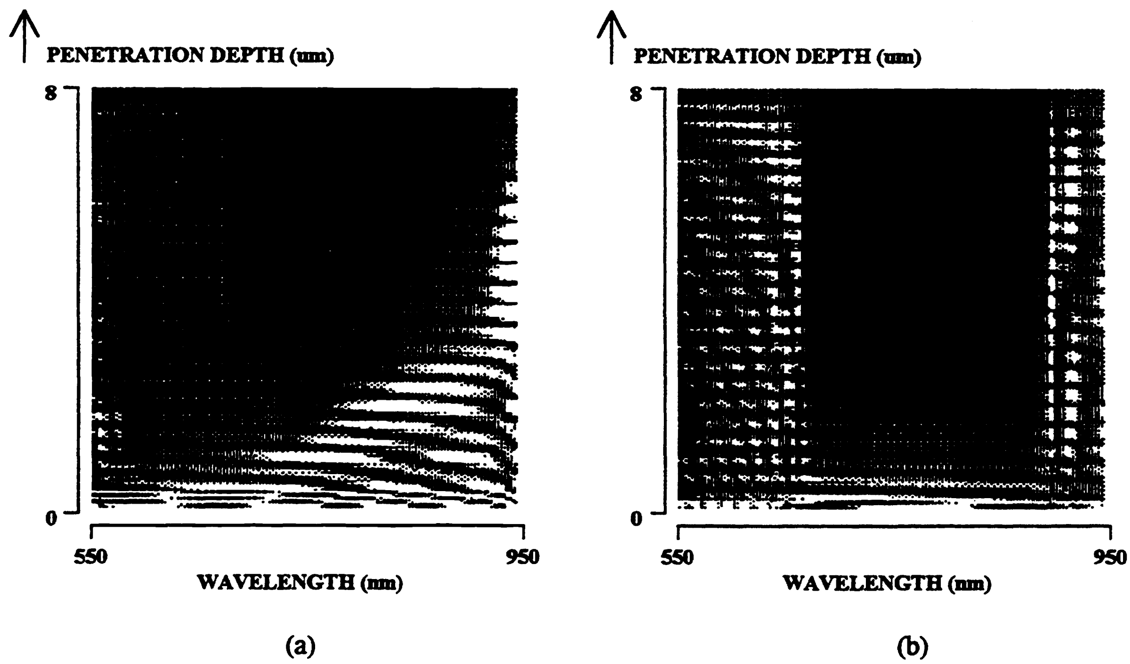

Fig. 5 Computed electric-field distribution as a function of wavelength in (a) the chirped dielectric structure shown in Fig. 3a and in (b) a 44-layer low dispersion dielectric mirror consisting of alternating quarterwave layers of TiO_2 and SiO_2

The second representative dispersive mirror design whose refractive index profile is shown in Fig. 3b, was developed for a femtosecond Ti:sapphire amplifier system. As expected, the multilayer period increases towards the substrate. This dispersion compensating mirror exhibits a negative second-order and a superimposed positive third-order dispersion over the spectral range from 660 to 885 nm, and high reflectivity (R>99.5%) from 660 to 925 nm. The computed reflectance and GDD of the design are shown in Fig. 4a and 4b, respectively. Combination of this mirror with prism pairs allows the independent adjustment of second- and third-order dispersion in our Ti:sapphire amplifier system.

The maximum achievable negative GDD of chirped mirrors is limited by the maximum group delay difference that can be obtained between the extremes of the reflectivity range. This latter in turn relates to the optical thickness of the coating. A simple approximate expression for the maximum achievable group delay difference can be written as

$$\Delta\tau_{\max} = \frac{2 \cdot (t_{chirped} - t_{qw})}{c} \tag{10}$$

where $t_{chirped}$ is the optical thickness of the chirped mirror and t_{qw} is that of a standard quarterwave high reflector ($R > 99.5\%$) consisting of the same pair of alternating layer materials. In simplified physical terms: the required high reflectivity of the dispersive mirror calls for a minimum optical thickness of t_{qw}, and only excess layers can introduce an appreciable frequency-dependent group delay around the centre of the high reflectivity band. Assuming the group delay to vary approximately linearly with frequency over the high reflectivity range, the corresponding upper estimate for the GDD is simply given by the ratio of $\Delta\tau_{max}$ to the mirror bandwidth $\Delta\omega$. For the specific case of TiO_2-SiO_2 mirrors centred around 0.8 µm we have approximately $t_{qw} = 4$ µm (21 quarterwave layers) yielding approx. $\Delta\tau_{max} = 27$ fs for our 8-µm-thick structures, in reasonable agreement with the results presented in the following section (Fig. 7). With the number of layers fixed, $\Delta\tau_{max}$ scales linearly with the chosen central wavelength of the dispersive mirror. For a selected operating wavelength, $\Delta\tau_{max}$ and thus the magnitude of broadband negative GDD can be increased only by increasing the number of layers, this number being limited by scattering and absorption losses due to structural defects and impurities in the deposited layers, respectively.[3] We expect that more sophisticated coating techniques (resulting possibly in graded index optical coatings exhibiting lower stress, higher density and thus higher optical thicknesses) will allow the production of the next generation of dispersive mirrors and thereby open the way towards the realization of more complex structures with higher negative GDD over considerably higher bandwidths.

4. MIRROR CHARACTERIZATION

The frequency-dependent group delay functions of these chirped mirrors are measured after the deposition process by spectrally resolved white light interferometry[34]. Briefly, our apparatus is a Michelson interferometer illuminated by a white-light source (tungsten halogen lamp). We place a low dispersion gold mirror in the "reference" arm and the dielectric mirror to be measured in the "sample" arm. When one of the mirrors is tilted around a horizontal axis and the other mirror is vertical, horizontal interference fringes (fringes of equal thickness) are generated by each spectral component of the white-light source at the exit plane of the interferometer. A transmission grating and an achromatic lens are used to create the spectrally dispersed image of a vertical section of the superimposed "white light" interference fringes on a CCD array; the section is created by a vertical slit. The interference patterns corresponding to different wavelengths are linearly dispersed in the horizontal direction (see Fig. 6).

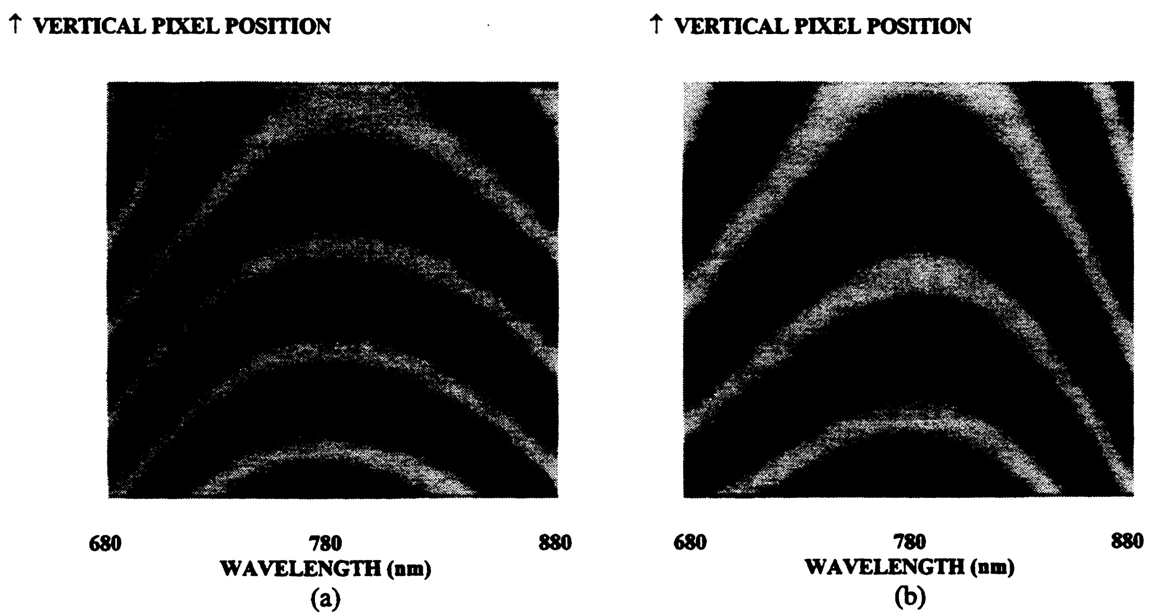

Fig. 6 Spectrally resolved white-light interference fringes recorded on a CCD, when pairs of chirped mirrors Fig. 3a (a) and Fig. 3b (b) are placed in one arm of a Michelson interferometer illuminated by a tungsten halogen lamp[34]

To record the images shown Fig. 6a and Fig. 6b, the chirped mirrors shown in Fig. 3a and Fig. 3b were respectively placed in the "sample" arm of the interferometer. The period of the interference fringes in the vertical direction is proportional to the wavelength when using ideal flat mirrors for the measurement. If the mirror in the sample arm were to have no phase dispersion, the vertical pixel positions corresponding to the same phase difference, e.g., minima and maxima, would be a linear function of the wavelength[34]. Because of the second-order phase shift of one sample mirror and the second-order phase shift with superimposed positive third-order dispersion of the other mirror we were able to record the images shown in Fig. 6.

By storing and computer-processing the spectrally resolved interference pattern detected on the CCD, we were able to obtain the group delay versus wavelength functions of the sample mirrors. The curves are plotted in Fig. 7a. For details on our experimental set-up and evaluation of the recorded images, we refer to Ref. 34. The measured group-delay function can be compared with the theoretical values shown in Fig. 7b.

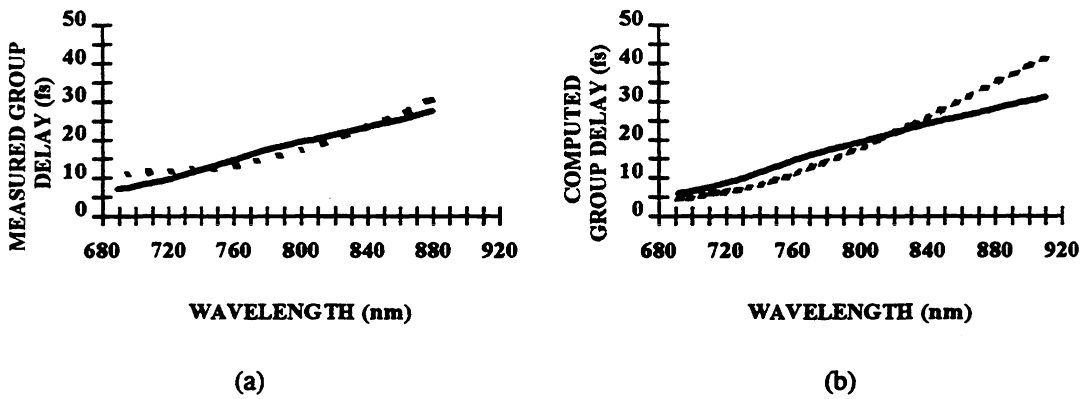

Fig. 7 (a) Measured and (b) computed group delay vs. wavelength functions of chirped mirrors shown in Fig. 3a (continuous lines) and Fig. 3b (dashed). The measured group delay functions were obtained by computer processing the images shown in Fig. 6

The method briefly described above[34] proved to be a fast and inexpensive means of measuring the group-delay function of dielectric mirrors over a broad spectral range with a time resolution of ± 0.2 fs. This method seems to be well suited for rapid quality control of dispersion compensating mirrors developed for femtosecond laser systems.

5. APPLICATIONS

The chirped mirrors shown in Fig. 3a have been used for full dispersion control in a Kerr-lens mode-locked Ti:sapphire laser, which consists merely of cavity mirrors, a 2 mm-thick gain medium and an intracavity aperture. By taking advantage of 9 bounces on these dispersive mirrors in the cavity, the laser was able to generate nearly bandwidth-limited 8-fs optical pulses around 0.8 μm[12,26], which is to our knowledge the shortest pulse duration generated directly from an oscillator to date. Our experiments indicate that the performance of mirror-dispersion-controlled (MDC) laser oscillators are likely to surpass their prism-pair controlled predecessors with some fundamental benefits, such as pulse quality (in terms of spectral symmetry and time-bandwidth product), stability and compactness[26]. By taking advantage of the extremely high stability of the pulse parameters in our MDC oscillator, we studied the propagation of electromagnetic wave packets through 1D photonic band gap materials with a time resolution of 0.3 fs (see Ref. 35).

We also tested chirped mirrors exhibiting a negative second-order and a superimposed positive third-order dispersion for a kHz-Ti:sapphire amplifier system. Combining these mirrors - the refractive index profile of these is shown in Fig. 3b - with a low dispersion prism pair, we could recompress stretched ≅ 3-ps pulses to nearly bandwidth limited 13-fs pulses.

The mirror designs presented here can be adapted to any broadband mode-locked solid-state laser or femtosecond parametric oscillator operating in the wavelength range of 0.4-1.5 μm by simply rescaling the layer thicknesses. Recently we reported on the operating characteristics of a femtosecond optical parametric oscillator (OPO) employing chirped mirrors for intracavity group velocity dispersion compensation[36]. The chirped mirror design had a negative GDD of -85 fs^2 from 1.1 to 1.4 μm for this application. Pumped by a self-mode-locked Ti:sapphire laser, this device delivered 100 fs near transform-limited pulses which were continuously tunable from 1.18 to 1.32 μm and had an average power between 100-180 mW with 750 mW pump power. The conversion efficiency of the OPO for the signal beam is 3 to 5 times higher than reported for OPOs employing prism pairs for intracavity dispersion control. This relates to the reduced losses compared with the prism-pair compensated system.

6. CONCLUSIONS

In conclusion, a novel thin-film technology for intra- and extracavity dispersion control has been presented. Special laser mirror designs exhibiting high reflectivity and negative GDD over frequency ranges beyond 80 THz have been demonstrated. The design technique, deposition technology and quality control permit higher-order contributions to the mirror phase dispersion to be kept at low values or to be chosen such that high-order phase errors introduced by other system components (e.g., the gain medium, prism pairs) are cancelled. By utilizing chirped mirrors for intracavity dispersion control in a femtosecond Ti:sapphire laser, the laser was capable of generating nearly transform-limited 8-fs pulses. In addition, utilization of the dispersive mirrors simplifies the cavity design and permits the construction of compact, reliable, high-repetition-rate femtosecond oscillators. Theoretical considerations on the operation of dispersion-compensating mirrors were reported. The formulae presented could be efficiently utilized to synthesize *graded index* dielectric mirrors with prescribed dispersion properties. Representative dispersive mirror designs developed for a femtosecond Ti:sapphire laser and its amplifier were shown consisting of alternate *discrete* dielectric layers. By computing the electric-field distribution inside the dielectric mirrors as a function of wavelength, the dispersive properties of these mirrors could be derived from the wavelength dependence of the penetration depth of the incident optical field. Measured group-delay versus wavelength functions of practical chirped mirror designs were shown, obtained by using spectrally resolved white-light interferometry. Finally, a few applications of chirped mirrors were presented.

7. ACKNOWLEDGEMENTS

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