High-damage-threshold broadband chirped mirror

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A high-energy broadband chirped mirror is designed for sub-10-fs high-energy chirped-pulse oscillators and amplification systems. This mirror consists of TiO_2/SiO_2 quarter-wave coatings for a broad bandwidth and optimized HfO_2/SiO_2 chirped coatings for increasing the laser-induced damage threshold (LIDT). The calculated results show that the mirror has low group delay dispersion (GDD) oscillation and can withstand high-energy chirped pulse laser in a wide range of 720−880 nm.

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Chirped mirrors (CMs), which allow the dispersion control of arbitrary spectrally shaped dispersions, were first proposed and demonstrated in 1994[1]. Owing to the development of quasi-analytical pre-design and optimization methods, various CMs have been designed, manufactured, and applied widespreadly applications in ultrafast systems, including laser oscillators, extra-cavity fiber compressors, and optical parametric amplifiers[2,3].

Recently, sub-15-fs TW laser pulses have been generated from a relatively compact laser system using tunable solid-state laser materials and a chirped pulse amplification (CPA) system. These pulses are useful for studies of high peak power laser-matter interaction such as ultrahigh-order harmonic generation, X-rays generation, and inertial confinement fusion[4]. However, further increasing the peak power available for such systems is currently limited by the damages to the optical components, particularly the optical coatings. In order to generate shorter (< 10 fs), higher power pulses, broadband chirped mirrors (> 150 nm at 800 nm) with high reflectivity, relatively low dispersion ripple, and practical resistance to high energy are needed. Such high-damage-threshold CMs are also required in high-energy femtosecond laser oscillators operating at the micro-joule level[5].

This study aims to develop a CM that affords high damage threshold in a broadband wavelength. The mirror consists of $\lambda/4$ TiO_2/SiO_2 broadband mirrors and HfO_2/SiO_2 chirped layers. In the operating wavelength range of 720−880 nm, the average group delay dispersion (GDD) of the CM is approximately -50 fs^2 with a very low ripple (< 5 fs^2), and the reflectivity above 99.96%. Moreover, the simulation indicates that the intensity is mainly distributed in the HfO_2/SiO_2 chirped layers, according to the high laser-induced damage threshold (LIDT) of the HfO_2 coatings[6,7], and that the newly designed CM can be applied in a higher practical energy pulse.

Conventionally, TiO_2, Ta_2O_5, and Nb_2O_5 are used as high-refraction index materials in chirped mirrors. Many high-performance CMs have been designed and manufactured, including ultra-broadband CM, complementary CM, and high-dispersion CM[8−10]. As verified experimentally, the HfO_2 coating has the higher damage threshold; however, its refractive index is smaller, which results in a relatively narrower spectral range. For example, a mirror with 20-pairs of $\lambda/4$-stack dielectric HfO_2/SiO_2 has a bandwidth (reflectance > 99%) of only 133 nm at the center wavelength of 800 nm, while the TiO_2/SiO_2 mirror has a bandwidth of 242 nm. Although chirped mirrors can be designed with a bandwidth above 200 nm, even 600 nm using HfO_2 as the high-refraction index material, many more layers are required, which result in low reflectance (< 99%) and severe dispersion oscillation[11,12].

In the newly designed CM, both the advantages of TiO_2 and HfO_2 are utilized, and SiO_2 is used as the low-refraction index material. The initial structure consists of 12 pairs of alternating $\lambda/4$ TiO_2/SiO_2 layers and 11 pairs of alternating $\lambda/4$ HfO_2/SiO_2 layers. The 12 pairs of $\lambda/4$-stack dielectric TiO_2/SiO_2 layers are placed near the substrate to provide a broad reflection bandwidth and high reflectance. The 11 pairs of HfO_2/SiO_2 layer are on top and are optimized to achieve the desired GDD. This combined structure has been previously utilized in a broadband reflective mirror, and has shown good performance in high-energy laser pulses[13].

Moreover, this initial design is based on a standard quarter-wave stack, which has zero GDD at the center of its stop-band, with little variation over the entire high-reflectivity range, and with only a part of the layers on the top of the stack being varied during optimization. Owing to these two properties, this approach leads to a multilayer with smooth GDD that exhibits little sensitivity to deposition errors compared with other broadband chirped mirrors[8].

For optimizing the proposed CMs, the variable metric

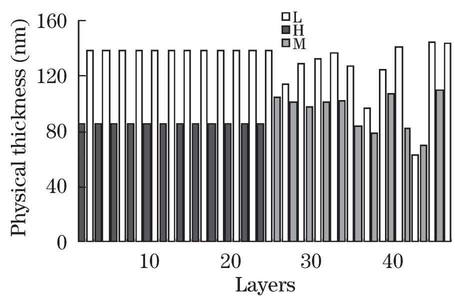

Fig. 1. Physical thickness and refractive indices of the optimized CM. H, L, and M denote the materials TiO_2, SiO_2, and HfO_2, respectively.

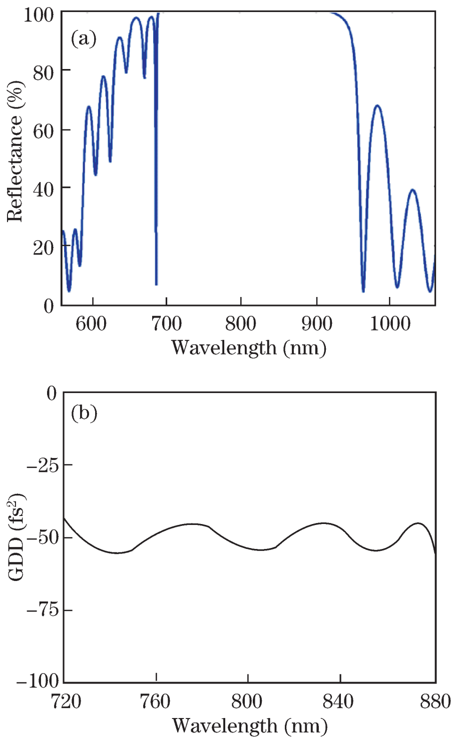

Fig. 2. (a) Reflectance spectrum and (b) GDD of the designed chirped mirror.

algorithm is used with the commercial software, TFCalc (Software Spectra, Inc.). Since the TiO_2/SiO_2 stacks are not optimized, this ensures that the reflectance is very high (> 99.9%) in the ultrabroad wavelength range. Hence, the design targets are only given by GDD = −50 fs^2 in the wavelength range of 720−880 nm. Optimization is completed after about 400 iterations, which is quite efficient.

Figure 1 shows the physical thickness and refractive indices of the optimized CM layers. H denotes the TiO_2 material (n = 2.32 at 800 nm), L stands for the SiO_2 material (n = 1.45 at 800 nm), and M is the HfO_2 material (n = 1.92 at 800 nm). The substrate is the BK7 glass. It is apparent that the thicknesses of the top 22 layers are varied. The total physical thickness is about 5 μm, in which all of the layers are neither too thick nor too thin (the thinnest layer is approximately 62 nm). This indicates that such a structure exhibits little sensitivity to deposition errors, and can be reliably reproduced and manufactured by the conventional electron beam evaporation method.

The spectral reflectance and GDD of the broadband high-damage CM are shown in Fig. 2. The calculated reflectivity is above 99.96% in the wavelength range of interest (720−880 nm). This ensures that the pulse loses only 10% energy after of 200 reflects by the CM, which is crucial in cases requiring large amounts of negative GDD. The designed GDD exhibits small oscillation, with deviations less than ±5 fs^2 from the target value (−50 fs^2) over the spectral range.

In order to test the damage threshold of the designed CM, intensity distribution was calculated inside the broadband CM at different wavelengths of the reflection band. The results are shown in Fig. 3. The incident intensity is assumed to be 1. It is evident that as the wavelength increases from 720 to 880 nm, the light penetrates deeper and deeper into the designed multilayer structure, which results in the various optical delays of various wavelengths. Most importantly, it is verified that the electric field is mainly distributed in HfO_2/SiO_2 chirped layers, and that the maximum electric field intensity in the TiO_2 layers for all the wavelengths is about 1.2, which is much lower than the intensity in HfO_2 layers (more than 3). It is widely accepted that the damage threshold of HfO_2 coating is much higher than that of the TiO_2 coating; therefore, the newly designed CM is expected to provide a higher damage threshold than the conventional CMs using TiO_2 and Ta_2O_5 as the high-refraction index materials.

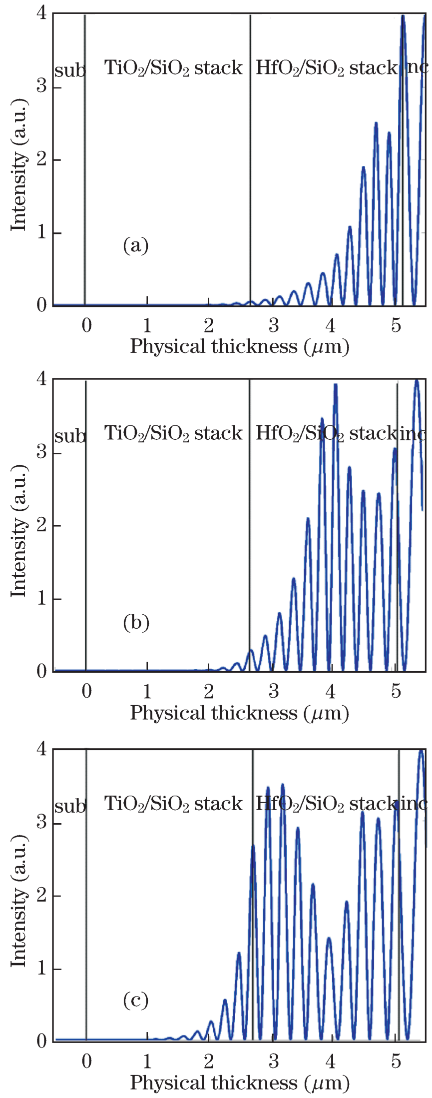

Fig. 3. Penetration of electric field intensity through the CM at different wavelengths.

In conclusion, by combining the broadband TiO_2/SiO_2 mirror and HfO_2/SiO_2chirped layers, we design a high-damage-threshold broadband CM with very high reflectance (> 99.96%) and low GDD ripple in the wavelength range of 720−880 nm. The proposed CM can be easily manufactured and be used to compensate for the dispersion in high-energy ultrashort pulse laser systems.

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