Design and analysis of different types of dispersion mirrors

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Three types of dispersion mirrors are designed and discussed. The first type is the complementary chirped-mirror pair used for providing smooth group delay dispersion (GDD) in the wavelength range of 550−1050 nm. Such mirrors are obtained by shifting the GDD oscillation period. The second type of mirror combines the characteristics of chirped mirrors and Gires-Tournois interferometer mirrors. It provides a high dispersion compensation of about −800-fs^2 GDD in the range of 780−830 nm and about −1150-fs^2 GDD in the range of 1020−1045 nm. The third type is a protected silver mirror with high reflectivity and low dispersion in the range of 650−1000 nm at 45°.

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Ultrafast pulse lasers are used in numerous applications, such as time resolved spectroscopy, precision material processing, and large bandwidth telecommunication. To generate femtosecond pulses, the positive dispersion from crystals, windows, and other such materials should be compensated[1], and additional dispersion for the laser system cannot be induced. Therefore, one of the key techniques of generating ultrafast pulse is the perfect management of different dispersions[2] such as broadband dispersions, high dispersions, and low dispersions. Ultrabroadband spectrum is a necessary specification for supporting an ultrafast laser pulse. Chirped mirrors (CMs)[3−6], which offer the possibility of imposing a "negative chirp", have found widespread use in broadband dispersion control for ultrafast systems. It can offer controlled group delay dispersion (GDD) with a spectrum covering more than one octave[7,8]. Low-loss, high-dispersion mirrors (HDMs) can assume the role of prisms and possibly gratings in conventional chirped-pulse amplifier (CPA) systems, with the added benefit of providing high-order dispersion control[4,9]. Silver mirrors are crucial for ultrafast applications because of its low pulse-broadening effect. These have also been used as end cavity mirrors for prevention of additional dispersion in the laser system[10,11]. In this letter, femtosecond laser optics are designed for different dispersion requirements.

The CM has a dispersive optical interference multilayer coating that has been optimized from the initial design. Layer-thickness modulation method[12] is one of the most widely used methods in CM design. In this method, multilayer mirrors with sinusoidally modulated layer thickness across the dielectric structure exhibit multiple high-reflectance bands, which leads to the merging of the reflectivity band of different wavelengths. The result is a continuous high reflectance over a broad spectral range. Undesirable oscillation can be efficiently eliminated by computer optimization.

The needle optimization technique[13,14] is a non-local design technique for obtaining good results. Based on calculations of the function used to identify the most appropriate position, the optimization of design for sequential insertion of new layers in the current multilayer coating can result in a further decrease in the merit function. Compared with other methods, needle optimization optimizes not only the thickness and the refractive index, but also the number of film layers.

The characteristics of the CM1 and CM2 pairs are shown in Fig. 1. The CM1 and CM2 pairs provide GDDs of around −50 fs^2 at 800 nm and high reflectivity ($>$ 99.5%) in the wavelength range of 550–1050 nm. The GDD curves in the CM pairs have the same oscillation. These curves show a relative shift of a half oscillation period between their spectrally oscillating dispersion characteristics. In combination, the ripple is strongly reduced to obtain comparatively smooth dispersion results. The CM pairs provide approximately −50−fs^2 GDD with less than 20-fs^2 oscillation in the range of 750–1025 nm and about 100-fs^2 oscillation on the edges of the 550- and 1050-nm wavelengths. Both corresponding film structures consist of 68 alternating layers of Nb_2O_5 (the infractive index is 2.26237 at 800 nm) and SiO_2 (the infractive index is 1.48677 at 800 nm) each with a physical thickness of 23−220 nm. The thickness measurements are shown in Fig. 2. From the electric field distribution shown in Fig. 3, it can be seen that CM1 has a

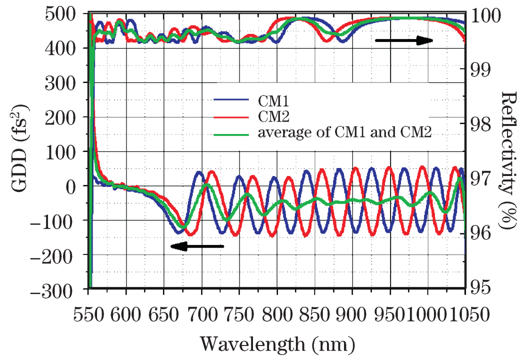

Fig. 1. Calculated reflectivities and GDDs of CM1 and CM2.

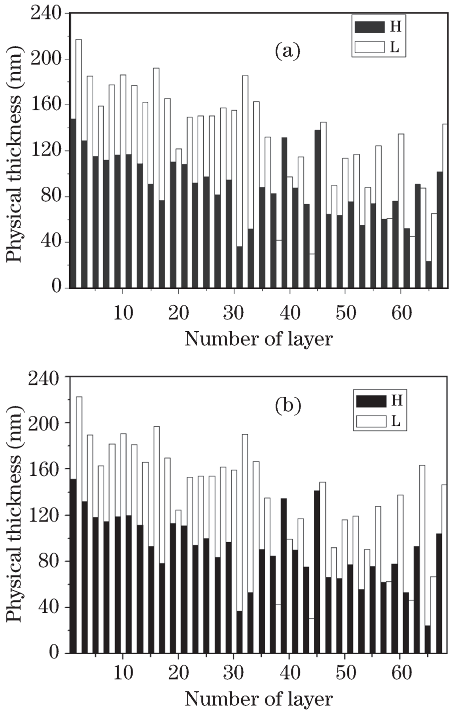

Fig. 2. Calculated physical thickness measurements of (a) CM1 and (b) CM2. (H represents the high infractive materials; L represents the low infractive materials.)

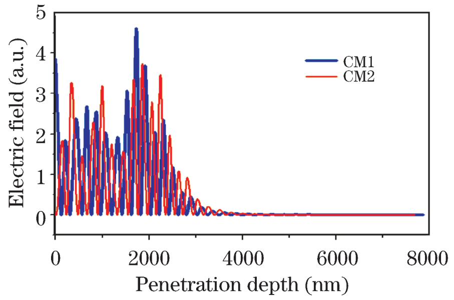

Fig. 3. Electric field distributions in CM1 and CM2 at 800 nm.

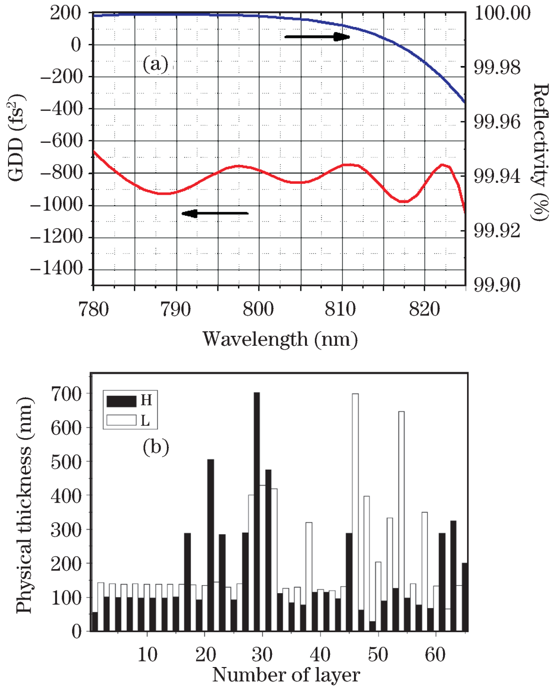

Fig. 4. Calculated HDM at 800 nm. (a) Reflectivity and GDD, (b) film structure.

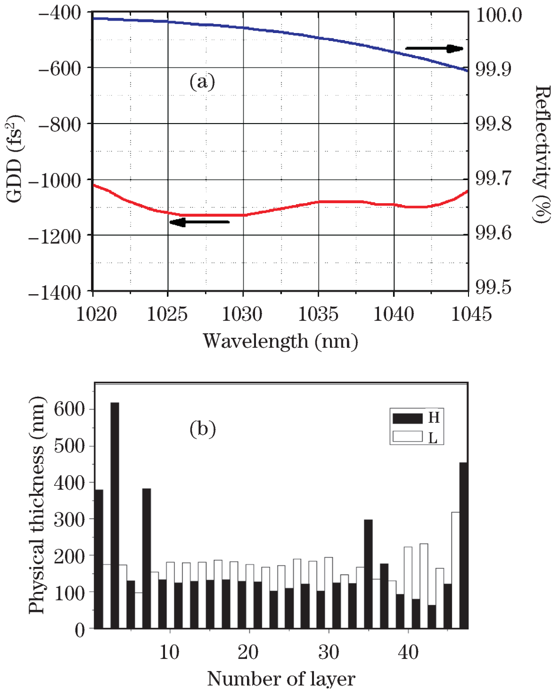

Fig. 5. Calculated HDM at 1035 nm. (a) Reflectivity and GDD, (b) film structure.

relative shift of one oscillation period compared with CM2. The peaks of electric distribution of the CM1 and CM2 pairs differ in different depths of penetration, which is in agreement with the dispersion curve decided by the electric distribution.

The HDM designed with a central wavelength at 800 nm in the wavelength range of 780–825 nm, which has a GDD of about -800 fs^2 and an average reflectivity of 99.99%, is shown in Fig. 4(a). The final design consists of 65 alternating layers of Ta_2O_5 (the infractive index is 2.06357 at 800 nm) and SiO_2 (the infractive index is 1.48677 at 800 nm), and the thinnest thickness is about 29 nm, as shown in Fig. 4(b). The multilayer structure of the -1150 fs^2 HDM design is shown in Fig. 5. The mirror provides a GDD of about -1150 fs^2 at 1035 nm, together with an average reflectivity of more than 99.95% in the wavelength range of 1020–1045 nm, as shown in Fig. 5(a). The final design consists of 47 alternating layers of Ta_2O_5 (the infractive index is 2.02663 at 1035 nm) and SiO_2 (the infractive index is 1.4825 at 1035 nm). The layer thickness range is 62−620 nm, resulting in a total physical thickness of the structure of approximately 8 μm, as shown in Fig. 5(b). The structures of both HDMs have layers whose thicknesses can reach up to more than 600 nm, even 700 nm. Its operation is similar to a Gires-Tournois interferometer (GTI) cavity. The characteristics of CMs and GTI mirrors are combined to obtain HDM with lesser layers.

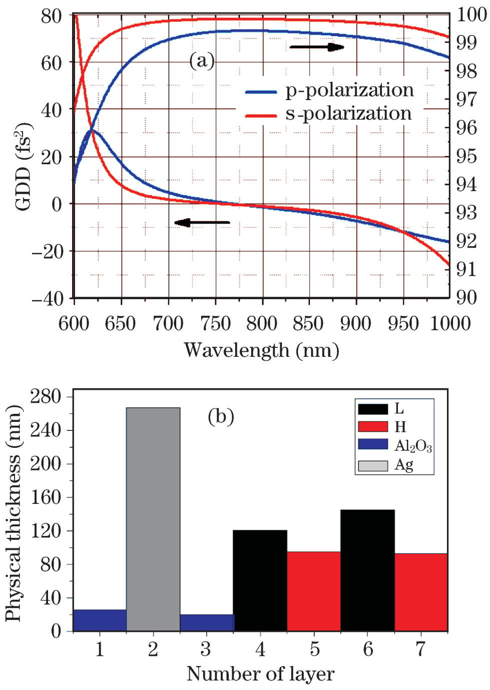

Fig. 6. Calculated low-dispersion protected silver mirrors. (a) Reflectivity and GDD, (b) film structure.

The reflectivity of silver mirrors can be enhanced by a dielectric overcoat, which can simultaneously protect Ag and prevent Ag from oxidation. For use in femtosecond lasers, the dielectric overcoat should be optimized to offer high reflectivity and low GDD. The optimized result of silver mirrors with enhanced reflectivity in the wavelength range of 650−1000 nm at 45° is shown in Fig. 6(a). It is evident that GDD is less than −10 fs^2, $R_\mathrm{p} > 99\%$ and $R_\mathrm{s} > 98\%$ from 650 to 1000 nm. The GDD of the protected silver mirrors approaches near-zero, especially in the wavelength range of 700−870nm. The corresponding layer structure consists of the following seven layers Al_2O_3-Ag-Al_2O_3-SiO_2-Ta_2O_5-SiO_2-Ta_2O_5 (from substrate to air), as shown in Fig. 6(b). The substance Al_2O_3 is used to connect the substrate to Ag and Ag to SiO_2. The protected silver mirrors minimize pulse broadening for ultrafast application because of low dispersion, and offer exceptionally high reflectance for both s- and p-polarizations in the 650−1000-nm spectral region, especially in the range of 700−870-nm at 45°.

In conclusion, three types of dispersion mirrors , broadband CM pairs, HDM, and low-dispersion protected silver mirrors, are designed and discussed. CM pairs with a relative shift of a half oscillation period between each other provide a GDD of around −50 fs^2 at 800 nm and a high reflectivity (>99.5%) in the range of 550−1050 nm. HDM provides high dispersion compensation with about −800-fs^2 GDD in the range of 780−830 nm and approximately −1150-fs^2 GDD in the wavelength range of 1020−1045-nm. Such mirrors combine the characteristics of CMs and GTI mirrors. Protected silver mirrors offer low dispersion and exceptionally high reflectance for both s- and p-polarizations in the 650−1000-nm spectral region, especially in the range of 700−870 nm at 45°. The reflectivity of silver mirrors can be enhanced by an optimized dielectric overcoat, which can simultaneously prevent Ag from oxidation and offers high reflectivity and low GDD.

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