Dispersive mirrors designed with mixed metal multilayer dielectric stacks

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A different approach to construct dispersive mirrors (DMs) for ultrafast applications is proposed based on the high reflectivity and constant phase property of a novel metal in ultrawide spectral band. A 200-nm bandwidth DM, a high dispersive DM, and a complementary DM are designed with mixed metal multilayer dielectric stacks. The results show that the mixed-metal multilayer dielectric DMs (MMDMs) have much less layers and total thickness compared with an all-dielectric DM under the case of comparable performance. Such an approach will save manufacturing time and remarkably improve the stress of the DM.

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Ultrafast lasers that generate high-energy pulses with broad bandwidth have found widespread applications in various fields, such as laser–matter interaction, medical applications, and attosecond pulse generation[1,2]. To generate femtosecond pulses, the material dispersion must be well compensated. Dispersive mirrors (DMs) can provide controllable and high-order dispersion over broadband spectra, making them key elements in ultrashort laser systems[3].

DMs were first proposed by Szipocs *et al.* in 1994[4]. Since then, various DMs covering a wavelength range from visible to infrared with a group delay dispersion (GDD) that ranges from zero to values of approximately –2000 fs^2 have been designed, manufactured[5−7], and utilized in ultrafast systems, including laser oscillators, extra-cavity fiber compressors, and optical parametric amplifiers[8]. Researchers continue the effort to develop novel design and fabrication method of DMs[9−13].

As verified experimentally, in order to provide high reflectivity and the required GDD, the DMs must always have many dielectric layers and very large total thickness, especially for the ultrabroadband and high DMs. Moreover, conventional DMs are usually manufactured by magnetron sputtering and ion-beam sputtering techniques. Such sputtering techniques operate at a slow deposition rate and high energy to improve the accuracy of the manufacture. Thus, the deposition processes are always very time-consuming, and the coatings possess very high stress, distorting the wave front[14]. One solution to these problems is to minimize the coating thickness. In this letter, the feasibility of mixed-metal multilayer dielectric DM (MMDM) is studied. Considering the high broadband reflectivity and the phase property of the metal, a metal layer is inserted between the substrate and some pairs of dielectric layers to constitute a novel DM. The design results show that MMDM can provide characteristics comparable to the all-dielectric DMs, but with much less layer number and thickness. Therefore, deposition time should be reduced, and the stress should be improved significantly.

We first focus on the DM with 200-nm bandwidth, which is required for a laser pulse shorter than 10 fs. We consider BK7 glass as a substrate, and tantalum pentoxide (Ta_2O_5) and silicon dioxide (SiO_2) as layer materials. The refractive indices of the layer materials are specified by the Cauchy formula[13]. Because silver has high reflectivity over the wavelength range of around 800 nm, it is used as the metal material for the proposed design. To design DMs in another wavelength, Al and Au could be good choices. The optical constants of silver are taken from Ref.[15].

The calculation of the design is obtained by the Optilayer software based on the needle optimization and

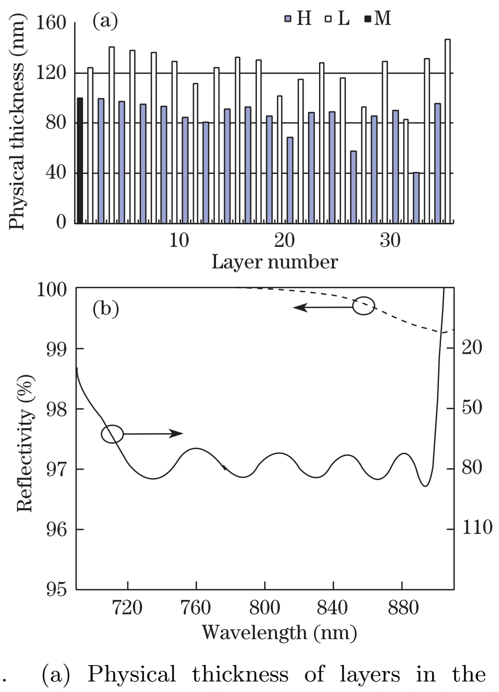

Fig. 1. (a) Physical thickness of layers in the designed MMDM, where H, L, and M represent the high-index material, low-index material, and metal, respectively; (b) calculated reflectivity and GDD of the MMDM.

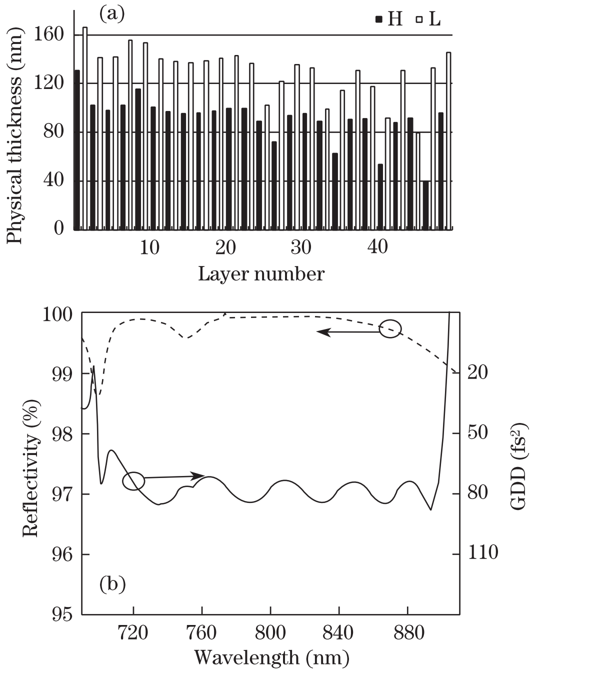

Fig. 2. (a) Physical thickness of layers in the designed all-dielectric CM. (b) Calculated reflectivity and GDD of the CM.

gradual evolution algorithms. The initial design is a silver film with two quarter-wave high and low index layers. The thickness of the silver layer is 100 nm, which will not be modified in the optimization process.

The design targets are given by reflectivity R=100% and GDD=–80 fs^2 in the wavelength range of 700–900 nm. The optimized multilayer structure of the 200-nm bandwidth DM design is shown in Fig. 1(a). The thickness of the silver layer is 100 nm; together with 35 dielectric layers of physical thicknesses from 40 to 150 nm, the total thickness is 3.7 μm. As shown in Fig. 1(b), the mirror provides a GDD that exhibits shallow ripple, with deviations of less than 10 fs^2 from the target value, together with an average reflectivity of 99.7% over the spectral range (in the absence of scattering losses).

A DM with the same targets is also designed using all-dielectric materials. Figure 2 shows the multilayer structure and the GDD and reflectivity. Compared with the MMDM shown above, the GDD is nearly the same, and the average reflectivity is slightly lower (approximately 99.4%). However, it consists of 50 layers with a total physical thickness of 5.5 μm; thus it is much thicker than the MMDM. To increase the reflectivity, more layers should be added.

As the two DM structures show, the last 35 layers of the structures are nearly the same. The silver layer is then removed in order to calculate the GDD and reflectivity. Figure 3 shows that the GDD is not significantly changed, whereas the reflectivity in the long wavelength is reduced significantly. This indicates that silver provides high reflectivity in the broadband spectral range, and the dispersion property is mainly generated by multilayer dielectric stacks. The optical constant of the silver film is very sensitive to the deposition process; thus, the errors of refractive indices and extinction coefficients are assumed to be in the range of 10%; the calculation results show that the GDD and reflectivity are almost not affected. Moreover, both DM designs are scrutinized by means of a statistical error of the particular layer thicknesses. The results show that the error sensitivity is similar in the two designs because the layers that provide the dispersion are more sensitive to manufacturing error.

The field distribution of the MMDM is also analyzed. The intensity in the silver layer is near zero, which means that damage will not be initiated by this metal material.

When using HfO_2 or binary oxide as high-index material to construct high-damage-threshold DMs[16,17], the low index ratio of the high- and low-index materials will result in a much larger thickness. Thus, the MMDM design will be more effective in this case and may not reduce the damage threshold.

High-dispersion DM (HDM) can provide large and controllable dispersion, and may replace the gratings and prisms in the chirped-pulse amplifier system. In order to achieve high dispersion, the HDM multilayer structure must have a high overall thickness. Figure 4 shows the mixed-metal multilayer high-dispersion mirror (MMHDM) design for Ti:sapphire chirped-pulse oscillators. The central wavelength is 800 nm with a bandwidth

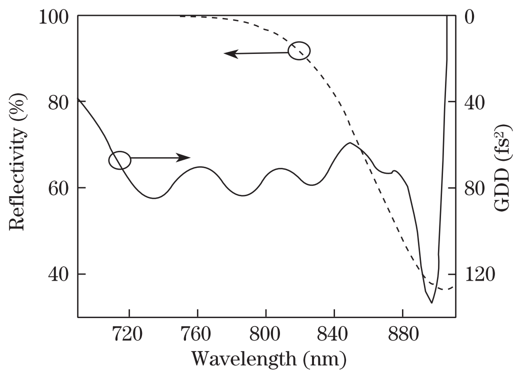

Fig. 3. Calculated reflectivity and GDD of MMDM without metal layer.

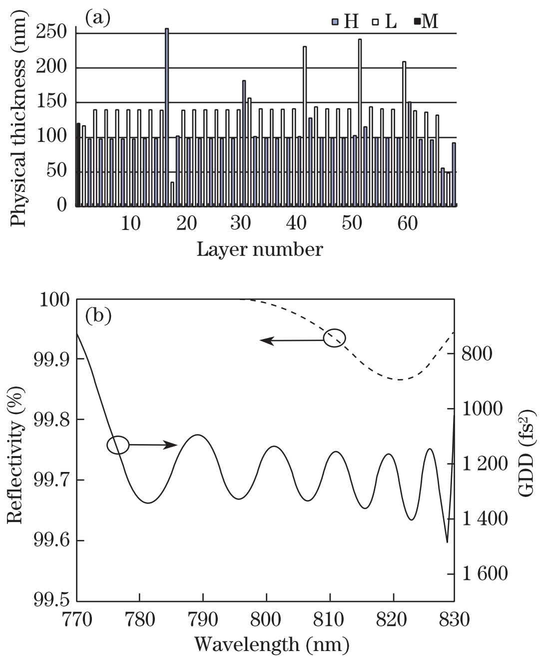

Fig. 4. (a) Physical thickness of layers in the designed MMHDM; (b) calculated reflectivity and GDD of MMHDM.

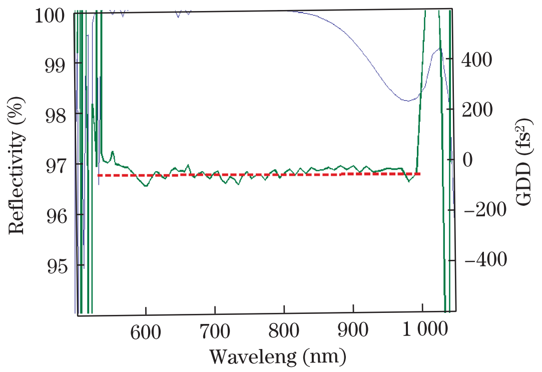

Fig. 5. (Color online) Ultrabroadband DM designed by the complementary approach. The green curve is the average of the GDD, and the thin blue curve is the reflectivity of two different DMs per bounce. The dashed line shows the target GDD.

of 50 nm. The design targets are the same as the design in Ref. [7] (e.g., R=100% and GDD=–1 300 fs^2). The proposed design consists of a silver layer and 68 dielectric layers, resulting in a total thickness of approximately 8.3 μm. The proposed design is approximately 15 layers and 1.8 μm thickness less than the design in Ref. [7]; however, the GDD resonance and the average reflectivity of the two designs are comparable.

The success in utilizing metal in the 200-nm DM and HDM drives have led us to design an ultrabroadband MMDM based on the complementary approach. In this example, we consider Nb_2O_5 as high-index material, and the refractive index is given by the Cauchy formula[6]. The DM is designed to cover the wavelength range of 550–1 000 nm, and the dispersion target is –50 fs^2.

The initial design with high reflectivity in the required spectra band is first synthesized by Optilayer, after which it is optimized using a multicoating module. As a result, both final designs consist of 54 layers with physical thickness range of 30–200 nm, and total thickness of approximately 10 μm. This design is obviously much thinner than the proposed ultrabroadband complementary DM[10]. Figure 5 shows that the GDD is approximately –45 fs^2, with a tolerable resonance, and that the average reflectivity is above 99%.

In conclusion, taking the advantage of the novel metal material, we design various DMs with mixed-metal and dielectric multilayers. The results show that MMCM is able to achieve the target with much less layers and total thickness compared with the all-dielectric DMs. The metal layer provides high reflectivity in the broadband spectral range, whereas the dispersion property is mainly generated by multilayer dielectric stacks. Such a novel structure may become a useful option in the design of high-performance DMs.

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