Broadband and high efficiency metal multi-layer dielectric grating based on non-quarter wave coatings as reflective mirror*

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(Received 12 January 2012; revised manuscript received 13 February 2012)

This article deals with designing broadband and high efficiency metal multi-layer dielectric grating (MMDG) used to compress and stretch ultra-short laser pulse. The diffraction characteristics of MMDG are analysed with the method of rigorous coupled-wave method. The multi-layer dielectric used as reflective mirror is made up of non-quarter wave coatings. Taking the diffraction efficiency of the −1 order as the value of merit function, the parameters such as groove depth, residual thickness, duty cycle, and reflective mirror are optimized to obtain broadband and high diffraction efficiency. The optimized MMDG shows an ultra-broadband working spectrum with the average efficiency exceeding 97% over 160 nm wavelength centred at 1053 nm and TE polarization. The optimized MMDG should be useful for chirped pulse amplification.

Keywords: grating, broadband, non-quarter wave coatings

PACS: 42.79.Dj, 42.79.–e, 61.05.J–, 46.40.Cd **DOI:** 10.1088/1674-1056/21/9/094218

1. Introduction

The achievement of high peak energy and ultra short pulses is becoming an important research subject in modern laser technology. The chirped-pulse amplification (CPA) system plays a critical role in the process of achieving the high peak ultra-short pulses.[1] Femtosecond ultra-short laser pulses are all generated in the CPA system. The core component of the CPA system is the pulse compression grating (PCG)[2,3] used for pulse broadening and compressing. The CPA system requests PCG to perform high diffraction efficiency and broadband as far as possible.

Multilayer dielectric gratings (MDGs)[4,5] are widely used based on the advantages of their flexible design, high diffraction efficiency, high damage threshold, and heavy caliber.[6] However, the internal stress increases with the number of films increasing.[7] The internal stress can lead to the grating vulnerable to physical damage, resulting in unstable performances. Along with the shortening of the laser pulse, the grating should have a broader spectral bandwidth to meet the dispersion effect of ultra-short pulse.[7] Metal multi-layer dielectric gratings (MMDGs)[8−12] combine the broad bandwidth properties of metal[13] and the high diffraction efficiency properties of dielectric grating.[14−16] The properties of pure dielectric grating is not comparable to the high diffraction efficiency bandwidth of the MMDG. In MMDG less dielectric layers are used to ensure the mechanical stability and performance stability. Because of the performance stability and broad high diffraction efficiency bandwidth, the MMDG has attracted much attention of investigators in recent years. Now the main work of MMDG is to optimize the high reflection mirror[7] and the surface relief.[8,10]

One common feature of the previous studies is that all the above MMDGs are based on quarter wave coating as reflective mirror. Up to now, there has been no report on MMDG based on non-quarter wave coating. This article aims at designing broadband and

*Project supported by the Program of Qingdao Municipal Science and Technology Bureau, China (Grant No. 12-1-4-2-(15)-jch), the National Natural Science Foundation of China (Grant Nos. 10804060 and 10904080), and the Taishan Scholars Program of Shandong Province, China.

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high diffraction efficiency grating based on irregular structure in which non-quarter wave coating is used as reflective mirror. In this study, a certain thickness of metal film is used to replace a few pairs of dielectric films of the mirror stack. This optimized MMDG exhibits high diffraction efficiency in a broad bandwidth. Furthermore, the decrease of the layers in stack can ensure the performance and stability of the grating.

2. Theory

Rigorous coupled wave analysis (RCWA) is an exact solution to the system of Maxwell equations built by the diffraction electromagnetic field from grating.[17−19] Using the enhancement transmission method to improve the traditional coupled wave analysis, the numerical instability problem encountered in calculating the etched grating is well solved.[20,21] Convergent and stable solution can be achieved by using the enhancement transmission method for TE and TM polarization. [22,23]

As depicted in Fig. 1, grating lies in x–z plane. A grating can be divided into four regions. Regions 1 and 4 are the input region and output region respectively. Region 2 is the rectangle grating region. Region 3 is the multilayer film region. The electromagnetic field through matching the electromagnetic boundary condition at the interface of each layer can be obtained by using RCWA to solve the system of Maxwell equations of each region. In this study, we consider a TE polarization plane wave as the incident light.

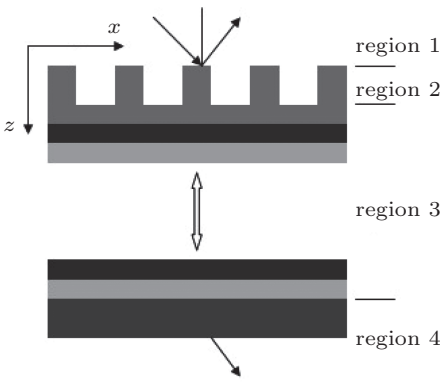


Fig. 1. Schematic diagram of multilayer grating.

3. Design of high reflection mirror for MMDG

Pulse compression grating can be divided into two parts: high reflection mirror and surface relief. These two parts can be optimized separately. The subjacent stack offers possible high reflection efficiency as the basis for the high diffraction efficiency of MMDG.[7] Surface relief modulates mainly the diffraction direction of the incident light.

3.1. Design of high reflection mirror

Reflection mirror that is alternately deposited by several pairs of high refractive index and low refractive index dielectrics can reach nearly 100% reflection at the required wavelength. Theoretically, the more the pairs of thin films and the bigger the ratio between the high and the low refractive indexes, the higher the reflection can be.[24] However, the increase of internal stress frequently leads to mechanical damage and performance instability resulting from the number of films increasing. Small number of films in MMDG stack ensures the stability of the grating and performance.

In this study, TiO_2 ($n_T = 2.3$, T) and SiO_2 ($n_L = 1.46$, L) are selected as the reflection mirror dielectric. Silver ($n_{Ag} = 0.04 + 7.369i$ at 1053 nm, Ag) is selected as the metal layer resulting from its low absorption to replace a few pairs of dielectric films in order to broaden the reflection bandwidth and reduce the number of films in stack. A thin chromium film ($n_{Cr} = 3.5 + 3.58i$ at 1053 nm, Cr) is inserted between silver layer and substrate to improve the bad adhesion. The G/CrAgTL structure is optimized to make reflection efficiency close to 100% over the range of 600–1400 nm centred at 1053 nm. Reflection efficiency (RE) curve of the optimized structure whose thickness of layers is not $\lambda_0/4n$ is shown in Fig. 2, where λ_0 is the reference wave length and n is the refractive index of the dielectric. The reflection efficiency exceeds 99% over the range 700–1400 nm. It demonstrates that the structure can be used as the

high reflection mirror for MMDG.

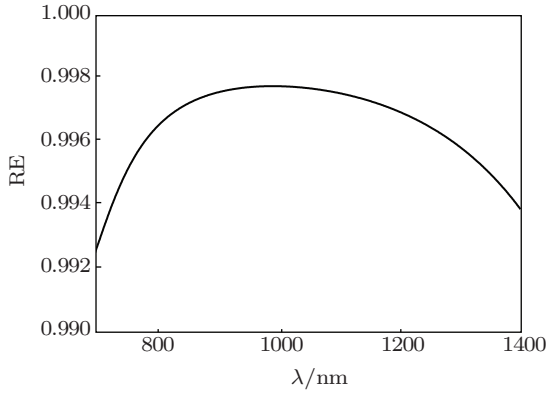


Fig. 2. Reflection spectrum of the high reflection mirror.

3.2. Fabrication tolerance analysis for mirror

A series of errors will possibly be introduced into the ideal structures in the manufacture process resulting from technological problems. Therefore, the structure should have enough fabrication tolerance to guarantee the characteristics of grating after manufacture.

Figure 3 shows the results of fabrication tolerance analysis for the designed high reflection mirror. When 10% errors of layer thickness and material refractive index are introduced into the structure, reflection efficiency can always keep above 99% over enough wavelength range although it is influenced in a way as shown in Figs. 3(a) and 3(b). Figure 3(c) shows that the reflection efficiency can keep flat higher than 99.5% in a quite broad incident angle range. The reflection mirror can be used in gratings working in various incident angle conditions. The damage characteristic of gratings is mainly related to the electric field distribution in stack.[6] A certain intensity of electric field (EFI) is existent in film interior, but it will reduce to zero and sharply come to the metal layers (Cr and Ag layers) as shown in Fig. 3(d). Therefore, the inserted metals have no influence on the damage characteristic of mirror. According to previous analysis we can know that the reflection mirror can supply high reflection efficiency over broad bandwidth and large fabrication tolerance for manufacture. The stable performance ensures that the mirror can serve as a high reflection mirror for metal and multilayer dielectric grating.

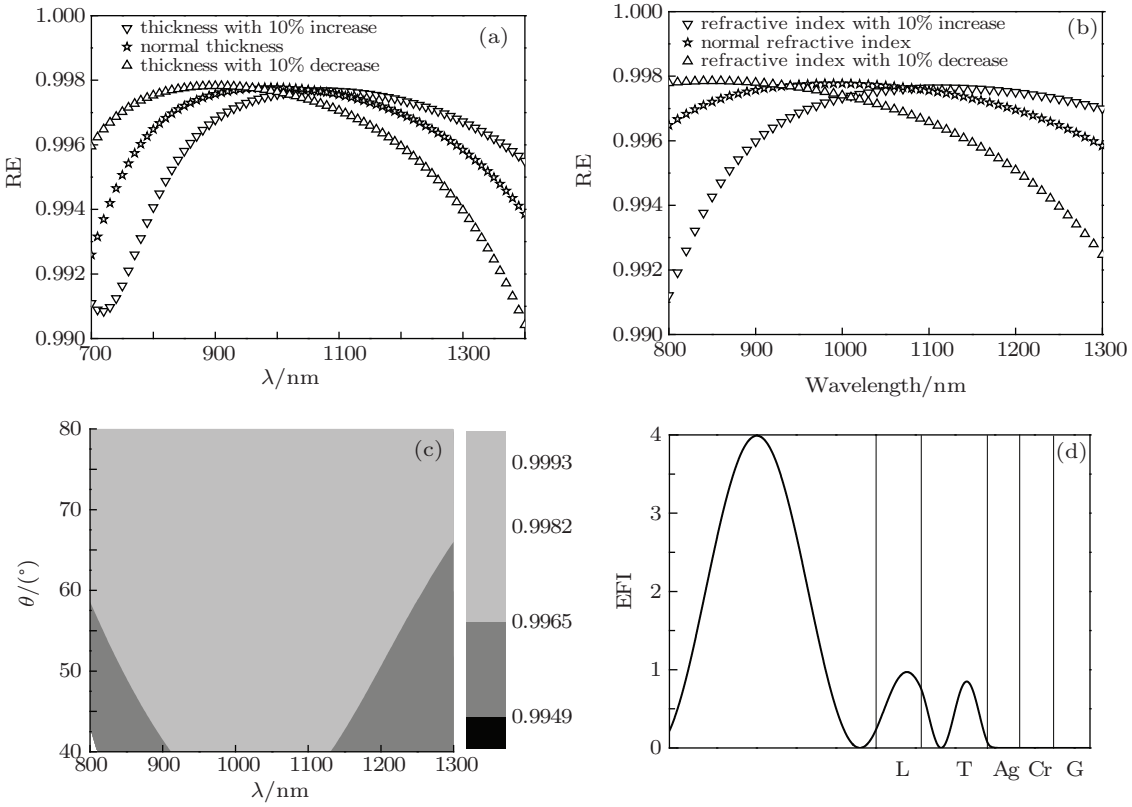


Fig. 3. Dependences of fabrication tolerances of thickness (a), refractive index (b), and incident angle (c) of reflection mirror on wavelength; and electric field distribution in stack (d).

4. Design of metal and multilayer dielectric grating

4.1. Parameters of MMDG

The diffracted light direction from grating is determined by the well-known grating equation, $\Lambda(\sin\theta_t + \sin\theta_i) = m\lambda$, where Λ is the duty cycle of grating, θ_t and θ_i are the diffraction angle and incident angle, m is the diffraction order, and λ is the incident wavelength. We can obtain the diffraction direction of the -1st order diffraction light from $|\theta_t| = \arcsin(\lambda/\Lambda - |\sin\theta_i|$. Since the incident light and diffracted light we need are on the same side of the grating normal, a proper angle separation should be considered between the incident light and diffracted light to avoid the influence of the two light beams.

The MMDG is designed to be used in the CPA system over the wavelength range centred at 1053 nm. Normally used line density 1480/mm is employed for the surface relief. It has been proved that duty cycle 0.2 is beneficial to expanding the bandwidth of high diffraction efficiency.[25] Incident angle is selected to be 58°. It will be proved suitable for the design in the following.

A certain layer below surface relief will not be etched in the manufacture process. The residual layer can be regarded as a waveguide exerting significant influence on diffraction efficiency.[26] Therefore, groove depth (D) and residual layer thickness (t_r) of grating are the key factors in design. HfO_2 ($n_H = 1.96$, H) is chosen as the surface relief material resulting from its high damage threshold. It is easy to obtain high diffraction efficiency over broad bandwidth and high damage threshold.

Taking the previous designed reflection mirror as the basis, HfO_2 is added above the mirror as the surface relief and waveguide layer. Figure 4 shows the curves of diffraction efficiency (DE) of MMDG as a function of residual layer thickness versus groove depth. The middle white region shows the parameter range in which the diffraction efficiency of the -1st order is over 97%. A few pairs of parameters from the region are optimized to obtain the diffraction efficiency with broad wavelength. The results are shown in Fig. 5.

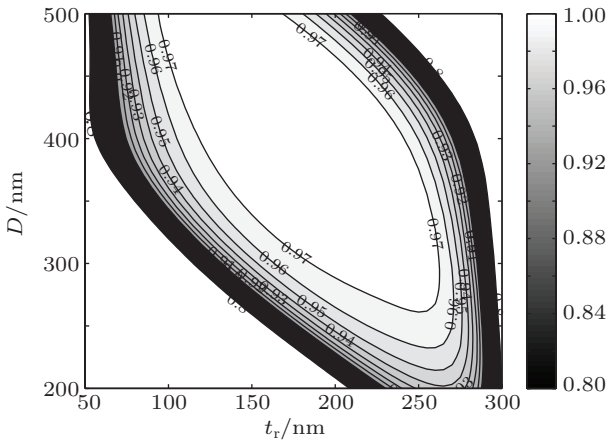


Fig. 4. Curves of diffraction efficiency as a function of groove depth versus residual layer thickness.

Figure 5 shows that we can obtain a wider bandwidth of high diffraction efficiency while the groove depth and thickness of residual layer are 400 nm and 200 nm respectively. The spectrum curve of the -1st order diffraction efficiency is shown in Fig. 6. The average diffraction efficiency higher than 97% for TE polarization light over 170 nm can be realized. When the wavelength of incident light changes from 980 nm to 1150 nm over the range, the corresponding diffraction angle would change from 37.03° to 58.64°. The diffracted light with diffraction angle higher than 58° would not be collected because it is overlapped with the incident light. Considering the separation of angle between incident light and diffracted light, when the largest wavelength is defined at 1140 nm, there will be an angle deviation of 1°. Therefore, we fix the parameters $\{\Lambda, \theta, D, t_r\}$ of the MMDG to be {675.7 nm, 58°, 400 nm, 200 nm}. The MMDG can supply diffraction efficiency higher than 97% with a bandwidth exceeding 160 nm.

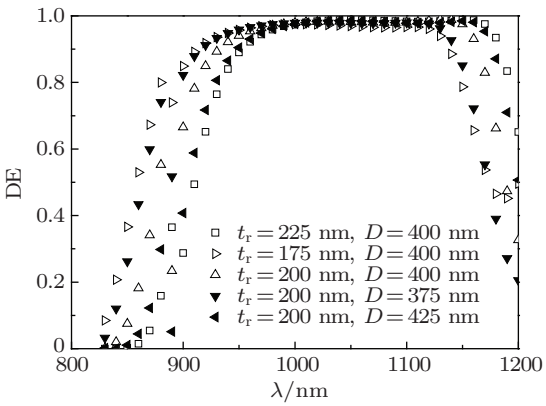


Fig. 5. Diffraction spectrum as a function of groove depth and residual layer thickness.

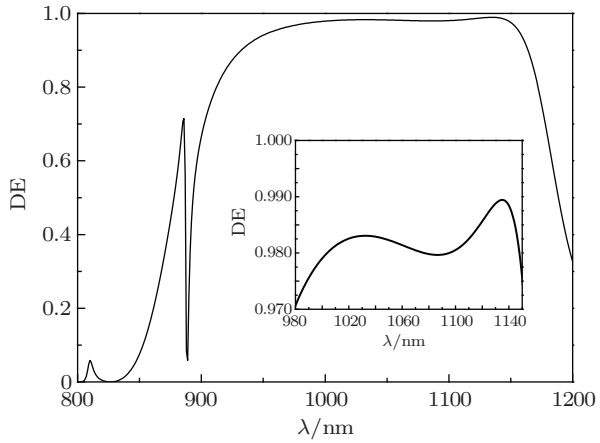


Fig. 6. Broad bandwidth diffraction spectrum when the groove depth and residual layer thickness are 400 nm and 200 nm, respectively.

4.2. Fabrication tolerance analysis for MMDG

The manufacture of grating surface relief is an extremely complex process. Therefore, the manufactured grating must be certainly different from the optimized structure. It is especially important whether the unavoidable errors will substantively influence the characteristic of grating. Favourable fabrication tolerance is extraordinarily necessary for the grating manufacture.

Figure 7 shows the fabrication tolerance of grating parameter. Figure 7(a) shows the diffraction efficiency as a function of groove depth versus wavelength. When the groove depth changes from 370 nm to 430 nm, the bandwidth is no less than 140 nm with diffraction efficiency higher than 97%. Figure 7(b) shows the diffraction efficiency as a function of residual layer thickness versus wavelength. Diffraction efficiency higher than 97% and bandwidth wider than 140 nm can be realized when the residual layer thickness is in a range from 180 nm to 220 nm. The fabrication tolerances of groove depth and residual layer thickness are good enough for the fabrication process. Duty cycle is the most difficult factor to control in the fabrication process. Several steps in the process would influence the final duty cycle. Figure 7(c) shows the diffraction efficiency as a function of duty cycle versus wavelength. Diffraction efficiency exceeding 97% and bandwidth wider than 140 nm can be obtained in a range of 0.18–0.22. The optimized duty cycle is easily controllable in the fabrication process. A large incident angle range can fulfill the bandwidth more than 140 nm with diffraction efficiency over 97% as shown in Fig. 7(d). Furthermore, the incident angle can be easily controlled by changing the grating placement. According to previous analysis, the considerable fabrication tolerance has provided perfect guarantee for grating fabrication and fine characteristic working in the CPA system.

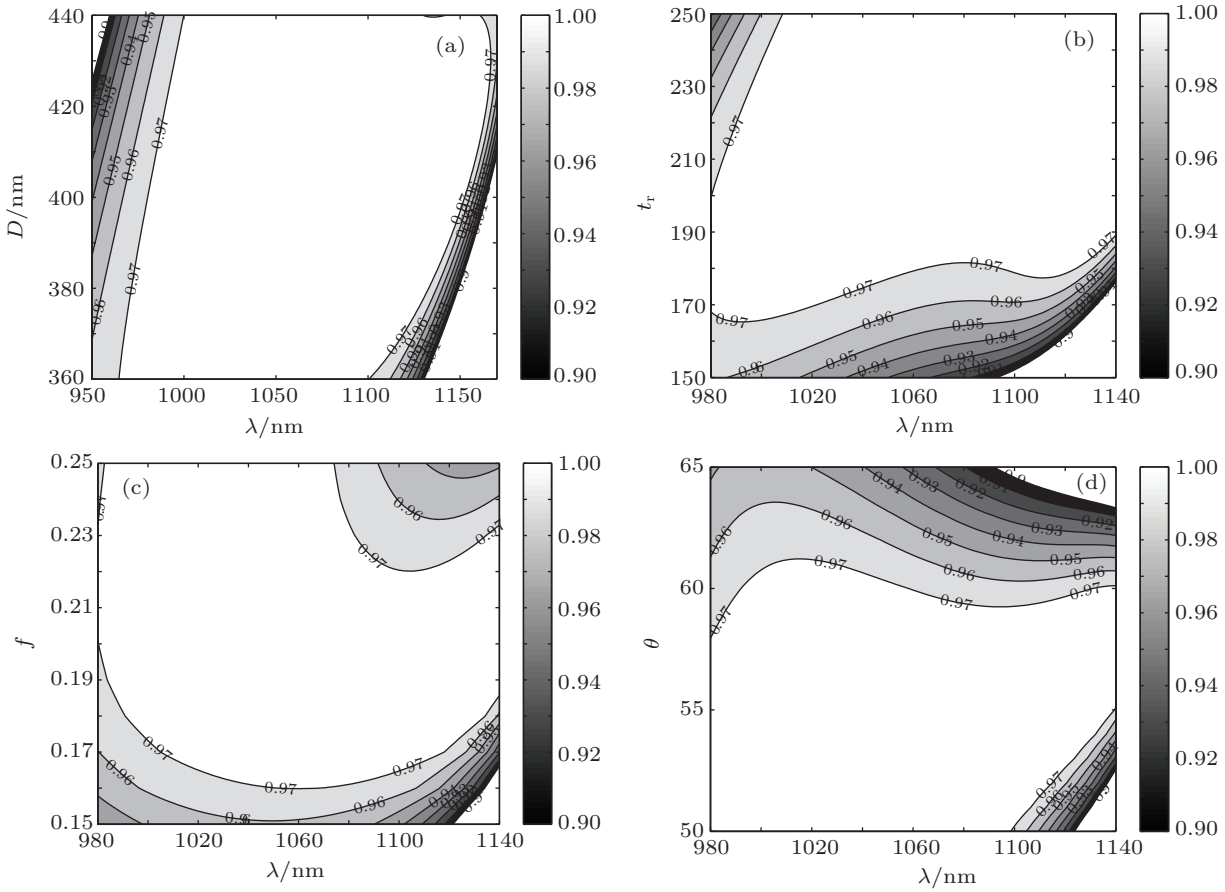


Fig. 7. Dependences of fabrication tolerances of groove depth (a), residual layer thickness (b), duty cycle (c), and duty cycle (d) on wavelength.

5. Conclusions

Rigorous coupled wave analysis is introduced to analyse and design the pulse compression gratings. A high reflection mirror based on non-quarter wave coating is obtained to optimize MMDG for the first time. The optimized MMDG with average diffraction efficiency higher than 97% for TE Polarization light over 160 nm can be realized. The characteristic of the grating is analysed in detail. It is evidenced that the optimized grating has good fabrication tolerance.

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