Analysis of restriction factors of widening diffraction bandwidth of multilayer dielectric grating*

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In order to design a multilayer dielectric grating with wide-bandwidth diffraction spectrum, the restriction factors of both the reflection bandwidth of multilayer dielectric high-reflectivity mirror and the guided-mode resonance phenomenon are studied in detail. The reflection characteristics of high-reflectivity mirror in zeroth and −1st transmitted diffraction orders are quantitatively evaluated. It is found that the reflection bandwidth of high-reflectivity mirror in −1st transmitted diffraction order, which determines the final diffraction bandwidth of multilayer dielectric grating, is evidently compressed. Furthermore, it is demonstrated that the reducing of grating period is an effective approach to the elimination of guided mode resonance over a required broad band range both spectrally and angularly. In addition, the expressions for calculating the maximum period ensuring no guided mode resonance in the required bandwidth are derived. Finally, two high-efficiency pulse-compression gratings with broad-band are presented.

Keywords: multilayer dielectric grating, broad band, diffraction bandwidth, reflection bandwidth, guided-mode resonance

PACC: 4225, 4225G, 4110H

1. Introduction

The multilayer dielectric grating (MDG) as a critical element in chirped pulse amplification (CPA) system[1,2] has drawn dramatically attention since it exhibits high reflectivity, low absorption, and therefore high optical damage threshold.[3−5] The work on MDG from the view points of design and fabrication are mostly focused on the diffraction efficiency[4,6,7] and laser induced damage threshold (LIDT).[8−10] However, in the ultrashort pulse laser system, light comprises the wavelengths over a broad bandwidth range, and thus the MDG is required to provide a wide-bandwidth diffraction spectrum and additionally to offer a high-efficiency over a broad angle range for some special applications. Consequently, the diffraction bandwidth has become the other concerned characteristic of MDG now.

Some factors restricting the widening of the diffraction spectrum of MDG make the design and the manufacture of broad band MDG become a challenge. The two most basic factors are the reflection bandwidth of multilayer dielectric high-reflectivity (HR) mirror and the guided-mode resonance (GMR) phenomenon.[11] It is well known that an HR mirror must provide a sufficient reflection bandwidth which has been mentioned in several studies.[5,12,13] However, the dependence of diffraction bandwidth of MDG on the reflection bandwidth of HR mirror has not been fully quantified in the literature. In addition, the existence of GMR in MDG would destroy the pulse spectrum shape and depress significantly the LIDT of MDG.[14] Although the GMR phenomenon has been widely investigated in the aspect of its usage,[15−20] few studies are developed in eliminating GMR in an MDG system. Therefore, it is necessary and important to study these two factors carefully for designing broadband MDG.

In this paper, first by analysing the effect of the reflection bandwidth of HR mirror on the diffraction bandwidth of MDG, the ultimate bandwidth expectable from an all-dielectric compression grating is

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determined. It is found that the reflection bandwidth of multilayer dielectric HR mirror is not only narrower than that of metal HR mirror inherently but also compressed in −1st transmitted diffraction (TD) order, which determines the final diffraction bandwidth of MDG. Then, according to the GMR condition, it is indicated that reducing the corrugation period is an effective method to avoid the GMR appearing in a required bandwidth range (both in wavelength and in angle). Moreover, the expressions for calculating the maximum period, which ensure no GMR in the required bandwidth, are derived. These results are significant for broad-band high-efficiency MDG design, and two kinds of gratings with high-efficiency over a wide wavelength range and no GMR are presented in this paper.

2. Bandwidth of multilayer dielectric HR mirror

The MDG comprises two subsystems of HR mirror and surface relief grating as illustrated in Fig. 1. It is a well-known concept that the multilayer mirror must be broadband spectrally and angularly, and must reflect both zeroth TD and −1st TD order. Figure 1 shows intuitively the dependence of the grating

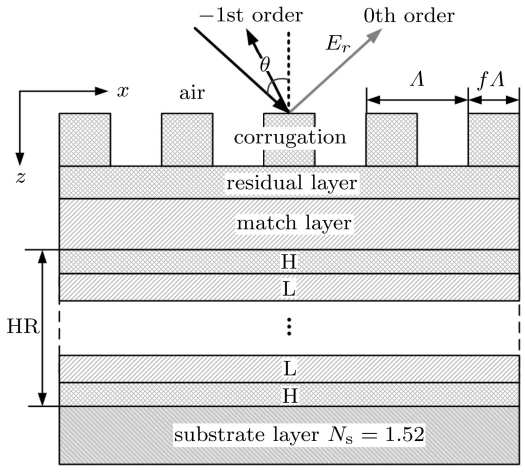


Fig. 1. Structure illustration of multilayer dielectric grating. The HR stack is composed of high refractive index layer H and low refractive index layer L. f denotes grating filling factor.

diffraction bandwidth on the reflection bandwidth of HR mirror according to the physical mechanism for MDG obtaining high-efficiency which was proposed by Wei and Li[21] and Flury *et al.*[22] separately. However, in general, what is concerned about is the reflection bandwidth of HR mirror calculated by thin film design software (such as Essential Macleod, TFCalc), but it is not the actual bandwidth providing for MDG. In this section, the relation between such two bandwidths are quantitatively discussed, and the ultimate diffraction bandwidth of MDG, which could be obtained actually, is determined.

A normal HR film, whose formula is $(\mathrm{HL})^n\mathrm{H}$ or $(\mathrm{H2L})^n\mathrm{H}$, can achieve over 200-nm wide spectrum with reflection efficiency >99%. H and L denote the quarter reference wavelength thickness layers of high and low index materials, respectively, and n is the repeat times. Such a broad diffraction spectrum bandwidth can fully meet the requirement for an ultrashort pulse laser system with 10 fs pulse. Actually, the bandwidth of MDG composed of such HR mirrors is far less than 200 nm.

The difference between two bandwidths provided by HR stack and MDG can be obtained from the grating diffraction equation

$$d(\sin\theta_i + n\cdot\sin\theta_{\mathrm{diff}}) = m\lambda,\ (m = 0, \pm1, \pm2, \ldots), \quad (1)$$

where m is the diffraction order, and d, λ, θ_i and θ_{diff} are the period of grating, incidence wavelength, incidence and diffraction angles, respectively. The diffraction angle of −1st TD order is

$$\theta_{\mathrm{diff}} = \arcsin(\lambda/d - \sin\theta_i)/n, \quad (2)$$

where n is the refractive index of each layer in MDG. The diffraction angle θ_{diff} in −1st TD order is a function of incidence wavelength. Angle θ_{diff} becomes smaller as the wavelength of incidence light becomes shorter, contrarily, θ_{diff} turns bigger as the wavelength becomes longer. For the central wavelength λ_0 impinging on the grating at incidence angle θ_i, when the incidence wavelength is shorter than λ_0, then $\theta_{\mathrm{diff}} < \theta_i$, the equivalent optical thickness of each layer increases, and thus, the reflection spectrum of HR mirror has a red shift close to the central wavelength. Similarly, when wavelength is larger than λ_0, then $\theta_{\mathrm{diff}} > \theta_i$, the equivalent optical thickness of each layer reduces, and thus the reflection spectrum of HR mirror has a blue shift also close to the central wavelength. Consequently, the reflection bandwidth of HR film in the −1st TD order is compressed.

Based on the above analysis, the ultimate bandwidth of MDG in −1st reflected diffraction (RD) order is determined by the reflection bandwidth of HR film in the −1st TD order direction. This would be

well demonstrated with the numerical results in Fig. 2. The MDG structure is shown in Fig. 1. The formula of HR mirror is $(H2L)^9H$, where H and L are the quarter reference wavelength thickness layers of high index material HfO_2 ($n_h = 1.96$) and low material SiO_2 ($n_l = 1.46$), respectively. The thicknesses of H and L layers are 107 nm and 144 nm, respectively. The corrugation is etched in the top low index layer. The thickness of the top layer and the depth of the grove are both 432 nm. The period and the fill factor of corrugation are 575 nm and 0.34, respectively. The incidence angle θ_i is 66.4°. In Fig. 2, the solid curve (a) indicates the reflection spectrum of HR film with all wavelength incident at θ_i. This is a common way to calculate the reflection spectrum of HR film. The dash curve (b) shows the reflection spectrum of HR film calculated with each wavelength under the corresponding −1st order angle of TD. Comparing the two curves shows that the later reflection bandwidth is compressed. Dash-dot curve (c) represents the diffraction spectrum in the −1st RD order of MDG. The bandwidth of curve (c) is approximate to that of curve (b). It is proved that the bandwidth of MDG is determined by the bandwidth of HR mirror for the −1st TD order. And the bandwidth is much less than that of HR film which is calculated with all wavelength light incident at the same incidence angles (curve (a)).

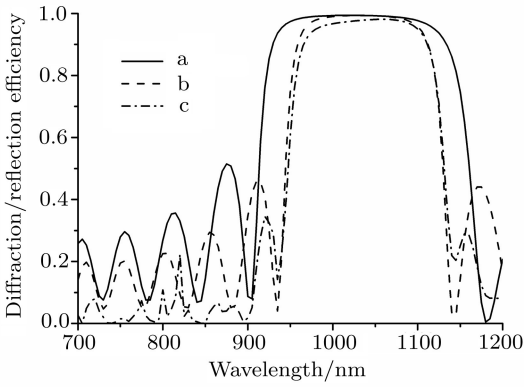


Fig. 2. Diffraction spectra of MDG and reflection spectra of HR film, where curve (a) is reflection spectrum of HR film calculated with the same incident angles for all incidence wavelengths, curve (b) is reflection spectrum of HR film considering different incident angles in the −1st order corresponding to each wavelength, and curve (c) is the diffraction spectrum of MDG with above HR mirrors in the −1st RD order.

Since the bandwidth of HR film at the −1st order TD direction restricts the bandwidth of MDG, the primary work on the widening of the bandwidth of MDG is to find an effective method to widen the bandwidth of HR mirror. This could be achieved with all-dielectric multilayer HR film. Furthermore, a feasible method to realize a broad-bandwidth high-efficiency grating has been reported by Canova *et al.*,[13] and Flury *et al.*[23] which is to replace the all-dielectric HR mirror with metal HR mirror. Another potential way is to use the two-dimensional (2D) photonic crystals, which would provide a broad-band high-reflectivity (>99.99%),[24,25] to substitute for the all-dielectric HR mirror.

3. Guided-mode resonance

Guide-mode resonance (GMR) is a ubiquitous phenomenon in grating devices, and it shows that when incidence wavelength or incidence angle changes slightly, the amplitude of reflected or transmitted light would vary rapidly. GMR has become a hot topic in recent years, and several groups have successfully designed resonant grating filters based on GMR. However, the existence of GMR in MDG would not only destroy the pulse spectral shape as pulse passes through a CPA system, but also lead the electric field enhancement in MDG structure which would significantly reduce the LITD of MDG. In an ultrashort pulse laser system, the pulse includes light over a broad spectral range and the GMR would be excited more easily. Therefore, to design broad band MDG, GMR must be inhibited firstly. In this section, it will be proved that the reducing of period of corrugation is an effective way to avoid the GMR existence in MDG over a required broad wavelength and/or angle range.

The MDG structure for the following study is shown in Fig. 1. The formula of HR stack is $H(L2H)^9$, where H represents an HfO_2 layer and $n_h = 1.96$, L denotes a SiO_2 layer and $n_l = 1.46$, and physical thicknesses of H and L layers are both quarter reference wavelength 740 nm. The thickness of top layer and the groove depth are both the same, i.e. 240 nm, and the thickness of matching layer is 30 nm. The central incident wavelength is 1040 nm, the period of grating is 847 nm and the corresponding −1st order Littrow angle is 37.9°. The fill factor of grating is $f = 0.3$. Refractive indices of cover and substrate layers are $n_c = 1$ and $n_s = 1.52$, respectively. Figure 3 shows the diffraction spectra corresponding to incidence wavelength (Fig. 3(a)) and to incidence angle (Fig. 3(b)), calculated by Fourier mode method (FMM)[26] respectively, and the GMR is shown obviously in Fig. 3.

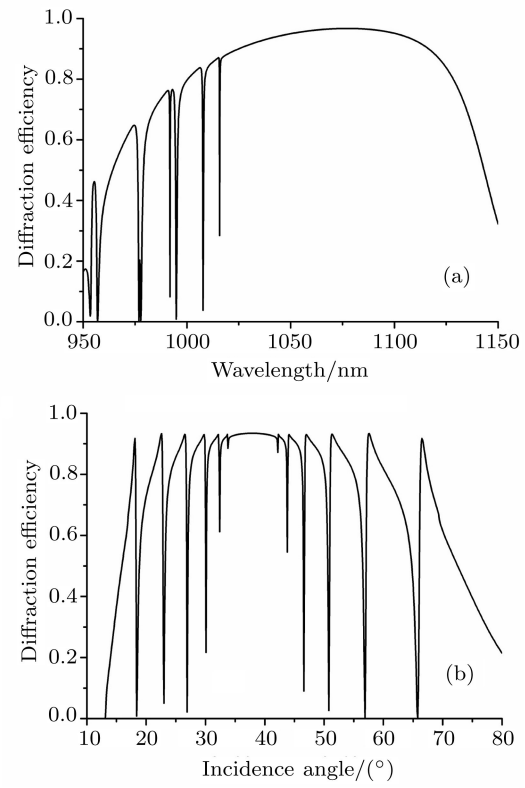


Fig. 3. Diffraction spectra according to incidence wavelength (a) and incidence angle (b), calculated by FMM. Incidence angle and wavelength of incidence light are 37.9° and 1040 nm, respectively. Period of gratings is 847 nm.

In the MDG structure, the high order diffracted evanescent light-wave can excite GMR. And the GMR conditions are given as follows:[27]

$$N = \beta_n/k_0 = m\lambda/\Lambda - n_{\rm c}\sin\theta_{\rm i}, \tag{3}$$

where m is the diffracted order ($m = 0, \pm1, \pm2, \ldots$), $n_{\rm c}$ is the refractive index of the cover layer, Λ is the grating period, and θ_i is the incidence angle. Let N denote the mode refractive index. And the negative value of mode refractive index N means that the evanescent wave propagates in the reverse direction. Here the value of incidence angle is defined as being negative, and the diffraction angles are negative when they are located on the same side with the incidence angle, otherwise they are positive. The necessary conditions, under which GMR can be excited, are expressed as

$$\max(n_{\rm c}, n_{\rm s}) < N < \max(n_{k,\rm eff}|k = 1, 2, 3, \ldots), \tag{4}$$

where $n_{\rm c}, n_{\rm s}, n_k$ and $n_{\rm eff}$ denote the refractive indexes of the cover layer, the substrate layer, the k layer, and the effective refractive index of corrugation layer, respectively. In MDG structure, the highest refractive indexes of all layers are all $n_{\rm h}$, and the refractive index of substrate $n_{\rm s}$ is larger than that of the cover layer $n_{\rm c}$ which is always of air. For MDG used in CPA system, the period of grating is less than using wavelength, and there are only 0th and -1st RD orders. So the lowest high-order evanescent waves are of $+1$st and -2nd orders. Then the necessary conditions for GMR become

$$n_{\rm s} < \lambda/\Lambda - n_{\rm c}\sin\theta_{\rm i} < n_{\rm h}, \tag{5}$$

or

$$n_{\rm s} < |-2\cdot\lambda/\Lambda - n_{\rm c}\sin\theta_{\rm i}| < n_{\rm h}, \tag{6}$$

which means that at least one of the $+1$st and -2nd order diffracted evanescent waves needs to meet the GMR conditions.

3.1. Eliminating GMR over broad wavelength range

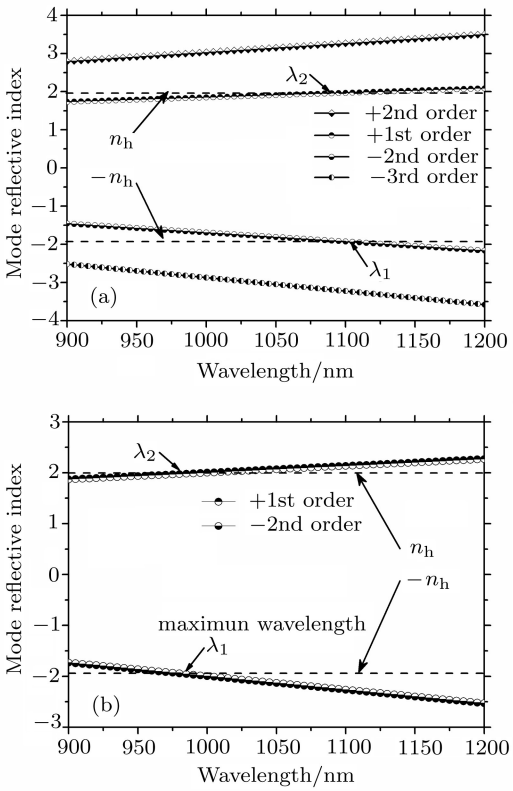


Fig. 4. Effect of incidence wavelength on two-order excited guided-wave mode indexes. The $n_{\rm h}$ is the highest refractive index in all layers. Grating periods in panels (a) and (b) are 847 nm and 750 nm, respectively. The other parameters are the same as those given in Fig. 3.

Figure 4(a) shows the mode refractive indices versus wavelength $\lambda_{\rm i}$ of incidence light of GMR excited by diffracted evanescent light for four orders ($m = -3, -2, +1, +2$). The parameters are the same as those given in Fig. 3. The incidence angle is 42°, which ensures that the diffracted light and incident

light are separate over 100-nm bandwidth centred at 1040 nm. λ_1 and λ_2 denote the wavelengths of incidence light at which the GMR with mode refractive index $N = n_{\rm h}$ will be excited by -2nd and $+1$st order diffraction evanescent waves, respectively. When incidence light $\lambda_{\rm i} < \lambda_1$, the necessary conditions (5) and (6) are satisfied and all incidence light will excite GMR. It is also shown that the higher-order light ($m < -2$ or $m > +1$) will not excite GMR because the corresponding mode refractive indices are larger than $n_{\rm h}$.

The mode refractive indexes of GMR excited by $+1$st and -2nd order diffraction evanescent waves are denoted as N_{+1} and N_{-2}, respectively. When the absolute values of N_{+1} and N_{-2} are equal, it can be deduced that $N_{+1} = |N_{-2}| = |3\sin\theta_{\rm i}|$ from Eq. (3), which are dependent only on incidence angle $\theta_{\rm i}$. The absolute value of the slope of mode refractive index curve corresponding to $+1$st order excitation is twice that corresponding to -2nd order excitation. If $|3\sin\theta_{\rm i}| > n_{\rm h}$, the maximum wavelength, less than which all incident light could excite GMR, is determined by $+2$nd order excitation, contrarily, it is determined by -1st order excitation. With the parameter in Fig. 4(a), $|3\cdot\sin(-45^\circ)| > 1.96$, so -2nd order excitation determines the maximum wavelength λ_1.

Furthermore, the period reduction of grating could increase the absolute values of the mode refractive index N_{+1} and $|N_{-2}|$ of GMR, which can be deduced from GMR conditions (3). It means that the small period would provide a broad spectral range without GMR as shown in Fig. 4(b).

A broadband MDG design requires a high diffraction efficiency in the wavelength range $\lambda_0 \pm \Delta\lambda$ and no GMR existence. The maximum wavelength range in which GMR can be excited must meet the condition of $\lambda_{\max} < \lambda_0 - \Delta\lambda$, and the design requirement can be fulfilled. When $|3\sin\theta_{\rm i}| > n_{\rm h}$, the -2nd order excitation determines the maximum wavelength. Combining Eq. (3) and $\lambda_{\max} < \lambda_0 - \Delta\lambda$, we can obtain the maximum period of grating that ensures no GMR over the required wavelength range as

$$\Lambda_{\max} = \frac{-2\cdot(\lambda_0 - \Delta\lambda)}{\sin\theta_{\rm i} - n_{\rm h}\cdot\sin\theta_{\rm t}}. \tag{7}$$

When $|3\sin\theta_{\rm i}| < n_{\rm h}$, the $+1$st order excitation determines the maximum wavelength. And the expression for calculating the maximum period of grating is obtained as

$$\Lambda_{\max} = \frac{\lambda_0 - \Delta\lambda}{\sin\theta_{\rm i} + n_{\rm h}\cdot\sin\theta_{\rm t}}. \tag{8}$$

Angle $\theta_{\rm t}$ in Eq. (7) or Eq. (8) is the maximum mode angle that can be supported by the MDG structure, and it can be calculated from the waveguide theory.

As an example of expression (7), the central wavelength is 1040 nm, and high diffraction efficiency bandwidth is 100 nm. The incidence angle $\theta_{\rm i} = 42^\circ$, and the maximum mode angle $\theta_{\rm t} = 90^\circ$. The highest refractive index $n_{\rm h}$ is 1.96 (HfO_2), so the maximum period of grating is 753.1 nm. Under this period condition, there is no GMR in MDG over the wavelength range 1040±50 nm.

3.2. Eliminating GMR over broad angle range

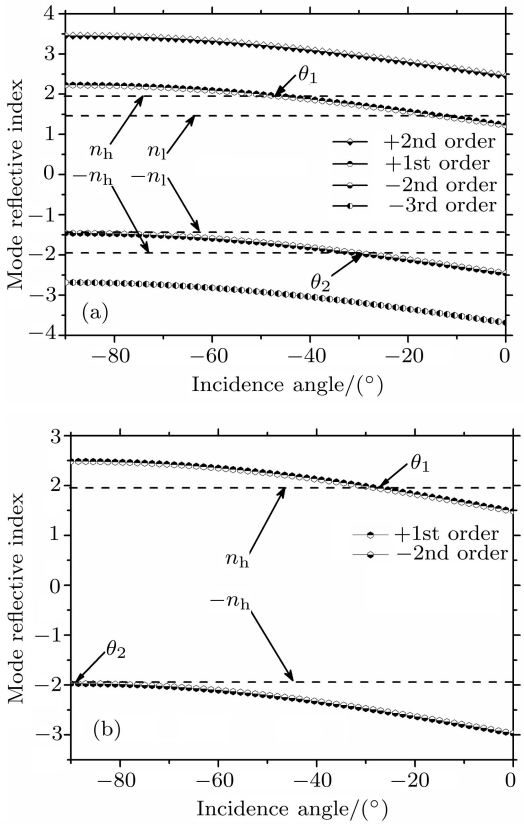


Fig. 5. Effects of incidence angle on guided-wave mode indices, with n_h being the highest refractive index in all layers, grating periods 847 nm (a) and 700 nm (b), and the other parameters are the same as those given in Fig. 4.

Figure 5(a) shows the mode refractive indices versus incidence angle $\theta_{\rm i}$ of GMR excited by the diffracted evanescent light of four high orders ($m = -3, -2, +1, +2$). The parameters are the same as those given in Fig. 3. The wavelength of incidence light is 1040 nm. θ_1 denotes the incidence angle at which $+1$st order diffraction evanescent wave might

excite GMR with $N = n_{\rm h}$. When the incidence angle $|\theta_{\rm i}| > |\theta_1|$, the necessary condition (5) cannot be satisfied and thus the +1st order light will not excite GMR any more. And thus only the −2nd order light excites GMR. Similarly, θ_2 denotes the incidence angle at which −2nd order diffraction evanescent wave can excite GMR with $N = n_{\rm h}$. When the incidence angle $|\theta_{\rm i}| < |\theta_2|$, the necessary condition (6) cannot be satisfied, and −2nd order light will not excite GMR any more. With the parameters given above, there exists $|\theta_2| < |\theta_1|$. So when the incidence angle satisfies $|\theta_2| < |\theta_{\rm i}| < |\theta_1|$, both +1st order and −2nd order light could excite GMR. It is also shown in Fig. 5(a) that the higher order ($m < -2$ or $m > +1$) light cannot excite GMR just because the corresponding mode refractive indices are larger than $n_{\rm h}$.

It can be deduced that if $|\theta_1| < |\theta_2|$ and the incidence angle meets $|\theta_1| < |\theta_{\rm i}| < |\theta_2|$, neither +1st order nor −2nd order light can excite GMR. It means that there is no GMR as the incidence angle in the range $\{|\theta_1|, |\theta_2|\}$. Based on GMR conditions of Eq. (3), it is found that the condition $|\theta_1| < |\theta_2|$ can be satisfied by reducing the period of grating as shown in Fig. 5(b).

For a requirement of broad-angular spectrum MDG which needs a high diffraction efficiency with no GMR over the incidence angle range $|\theta_{\rm center}| \pm \Delta\theta$, where $\theta_{\rm center}$ and $\Delta\theta$ are the central incidence angle and the half angular bandwidth, respectively, it can be set to be

$$\begin{aligned} |\theta_1| &= |\arcsin(n_{\rm h} \cdot \sin\theta_{\rm t} - \lambda/\Lambda)| \le |\theta_{\rm center}| - \Delta\theta, \\ |\theta_2| &= |\arcsin(n_{\rm h} \cdot \sin\theta_{\rm t} - 2\lambda/\Lambda)| \ge |\theta_{\rm center}| + \Delta\theta, \end{aligned} \tag{9}$$

where $\theta_{\rm t}$ is the maximum mode angle that can be supported by the MDG structure, and θ_t can be calculated from the waveguide theory.[28] When the condition (7) is met, it is ensured that there is no GMR over the incidence angle range $|\theta_{\rm center}| \pm \Delta\theta$. Furthermore, the maximum period of MDG can be calculated from expression (9).

In this section, it is shown that only +1st and −2nd diffracted orders of MDG can excite GMR based on normal MDG parameters. And it also demonstrated that the smaller period of grating would provide no GMR over broad incidence wavelength and angle range. The expressions for calculating maximum period which could avoid MDG appearing in the required broad angle and wavelength range are obtained. The further detailed discussion about GMR characteristic in MDG can be found in Ref. [29].

4. Broad band pulse-compression gratings with no GMR

The discussion about the two restriction factors in the two sections above is helpful for designing broad band pulse-compression grating. And in this section, two design examples of broad band grating with no GMR are illustrated.

The first example is based on an all-dielectric grating model (see Fig. 1), and the ideal grating is so designed that it has a high-efficiency over 100 nm bandwidth centred at 800 nm. As the multilayer dielectric thin film could excite GMR easily. Hence, it is needed, first, to determine the maximum period of grating according to the eliminating GMR conditions over broad wavelength (Eq. (7) or Eq. (8)). In this example, the incidence angle is 57°, and the highest refractive indexes of all materials are 2.04 (corresponding to the refractive index of Ta_2O_5). Then, the maximum period of grating can be derived to be 521 nm from Eq. (7) since $|3 \cdot \sin(-57°)| > 2.04$. Besides, because the MDG can obtain more easily a high-efficiency when the incidence angle is nearly −1st order Littrow angle, the grating period is chosen to be 510 nm, in which the optical geometry in CPA system is realizable. Furthermore, it is indicated in Section 2 that the reflection bandwidth of HR mirror needs to be widened, therefore, higher refractive index material (Ta_2O_5, $n = 2.04$) is used in HR mirror. As the LIDT of Ta_2O_5 is lower than that of HfO_2,[30] the later material is utilized for the top grating layer to meet the LIDT requirement. The low index material in this example is SiO_2 ($n = 1.46$). The spectrum design is based on the multi-parameter optimal method and the FMM. The reference wavelength for $\lambda/4$ HR mirror fabrication is 879 nm. The thickness of match layer (SiO_2) is 90 nm. The top layer thickness is 386 nm, and the groove depth is 242 nm. The duty cycle is 0.25. Figure 6 displays the broad diffraction spectrum of all-dielectric grating. The spectral bandwidth is over 100-nm wavelength centred at 800 nm with average diffraction efficiency > 97.5%. Moreover, there is no GMR in the whole spectral band range.

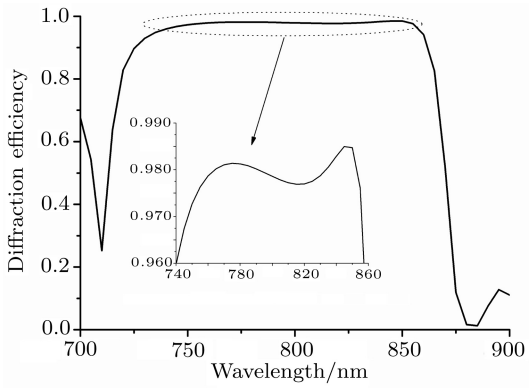


Fig. 6. Diffraction spectrum of all-dielectric multilayer grating.

The other example is based on metal layer as an HR mirror. Figure 7 illustrates a general metal-dielectric grating structure with an Ag HR mirror and two dielectric layers. As only two dielectric layers are included and the thickness of each one is less than half of using wavelength, GMR cannot be excited. Figure 8 shows an ultra-broad diffraction spectrum band (more than 250 nm centred at 1053 nm) with diffraction efficiency $> 95\%$. The incidence angle is 60°. The period and the duty cycle of corrugation are 675.7 nm and 0.25, respectively. The thicknesses of Ag ($e = -51 + 3.3\mathrm{i}$ at 1053 nm) layer and match layer (SiO_2, $n = 1.46$) are 200 nm and 130 nm, respectively. The high index material of top layer is HfO_2 ($n = 1.96$) with 470 nm in thickness, and the etched depth of top layer is 320 nm.

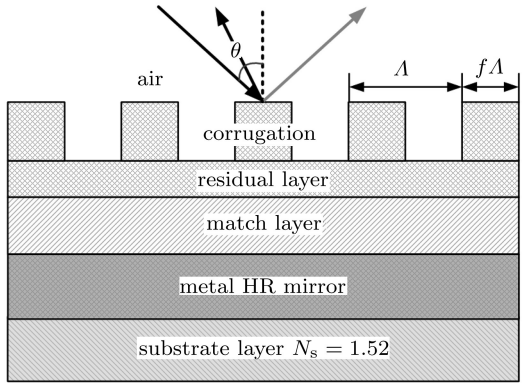


Fig. 7. Schematic structure of the metal-dielectric grating.

Compared with the all-dielectric grating, metal-dielectric grating provides wider diffraction bandwidth and less internal stress of thin film stack.[31] However, due to the introducing of meal material, metal-dielectric grating will absorb part of energy of incident light, and therefore cannot offer nearly 100% efficiency. Furthermore, the LIDT and the working life of such a grating are inferior to that of all-dielectric grating.

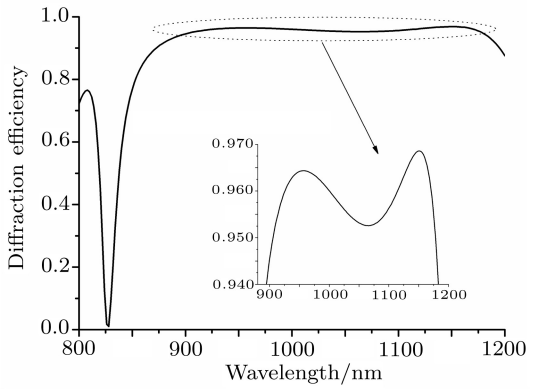


Fig. 8. Diffraction spectrum of metal-dielectric grating.

Two kinds of broadband pulse-compression gratings with no GMR are presented. The all-dielectric grating has the advantage in the diffraction efficiency and the anti-laser damage ability, while the metal-dielectric grating can provide ultra-broad spectrum band which meets sufficiently the requirement in 10 fs-pulse laser produce. Consequently, the trade-off between the merits and drawbacks of each grating is needed according to the engineering requirement to choose the grating.

5. Conclusions

For designing the broadband high-efficiency MDG, the two main factors restricting the widening of the diffraction spectrum is analysed in detail. The reflection bandwidth of dielectric HR mirror in -1st order is compressed, and it determines the final bandwidth of MDG. To obtain a broadband MDG, the reflection bandwidth of dielectric HR mirror in -1st order must be widened. Metal-dielectric grating is an effective way to realize broadband MDG.

Based on the discussion of GMR conditions, it is found that higher order light ($m < -2$ or $m > +1$) can excite GMR in MDG, and reducing the period of grating can effectively avoid the GMR appearing over required angle and/or wavelength range. Meanwhile, with the analysis in Section 3, the maximum period ensuring no MDG in MDG over required angle and/or wavelength range, can be determined.

These conclusions are beneficial to broadband pulse compression grating design. Hence, two kinds of broadband pulse compression gratings are obtained.

Additionally, the characteristics of those two gratings are compared. The grating fabrication is under way, and the more detailed performance about such a broadband grating will be reported in the later papers.

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