Design of shallow-etched multilayer dielectric grating with –1st order high diffraction efficiency

Jianpeng Wang (汪剑鹏)[1,2*], Yunxia Jin (晋云霞)[1], Shijie Liu (刘世杰)[1],
Jianda Shao (邵建达)[1], and Zhengxiu Fan (范正修)[1]

[1] *Key Laboratory of Material Science and Technology for High Power Lasers,*
Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
[2] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*
[*] *E-mail: janpo@siom.ac.cn*

Received November 5, 2009

A new design of shallow-etched multilayer dielectric grating (MDG) exhibiting a diffraction efficiency (DE) of approximately 100% in the –1st order at 1064-nm wavelength in Littrow mounting is reported. Particle swarm optimization algorithm and Fourier modal method are used to design MDG and calculate the DE of MDG. The thickness of the grating layer is less than 80 nm which is much shallower than that in the currently reported MDG design for a high DE, which is greatly helpful for the MDG etching process. Meanwhile, the bandwidth of DE which is more than 97.5% of MDG is 60 nm, and it is a meaningful result for MDG to be used in ultrashort pulse compression system.

OCIS codes: 050.0050, 050.1940, 050.1950, 050.2770, 310.0310.
doi: 10.3788/COL201008S1.0029.

Chirped pulse amplification (CPA) plays an important role in high-power laser systems[1]. As the critical elements in the compressors of CPA, diffraction gratings must meet the requirements of high diffraction efficiency (DE) and high laser-induced damage threshold. Owing to the inherent absorption loss of metals, the performance of metal gratings remains to be limited[2]. Thus, the Lawrence livermore national laboratory (LLNL) developed multilayer dielectric grating (MDG) in 1990s[3,4]. The MDG with the highest DE of more than 99.2% has been fabricated by LLNL[5].

However, the grove depths of MDG in these designs are very deep. For the corrugation etched in a high-index material, the grove depth is always required to be more than 300 nm. Further, the grove depth must be deeper for the corrugation is etched in low-index material. The deep grove brings more difficulties for MDG fabrication, and the rectangle ridge of corrugation will be destroyed. Destouches *et al.* have reported the leaky mode resonance grating model[6−10]. The resonance grating can obtain approximately 100% DE in the –1st order with a shallow grove depth of MDG[6].

In this letter, based on the two-layer leaky mode resonance grating model, an MDG with DE more than 97.5% in the -1st order over a 60-nm bandwidth centered at 1064 nm is obtained. The grove depth is no more than 80 nm which will be very helpful for MDG fabrication. The optimization design with particle swarm optimization (PSO) is also reported. Further, the ratio of the maximum electric field in the corrugation ridge and incident light is less than 2 which means that the MDG has excellent laser damage resistance capability. The DE and the electric field are calculated by the Fourier modal method (FMM)[11].

Figure 1 shows the general all-dielectric grating structure. There are two leaky mode propagating layers based on a dielectric high-reflection (HR) mirror. The physical mechanism of leaky mode resonant gratings with an approximately 100% DE in the –1st order reflected diffraction is explained as follows[8]. The amplitudes of two parts of light, which are reflected at the top of the corrugation directly and leaked from the wave-guided layers (Fig. 1), are equal, and their phases are 180° out of phase. There will be no light in the 0th order reflected diffraction; thus, the –1st order reflected diffraction is the only export for incident light, so that MDG obtains approximately l00% DE in the –1st order.

The layer for leaky mode propagation can be composed of many layers. Considering the fabrication of grating and the requirement of optimization, a two-layer model is chosen. The second layer is called as match layer (Fig. 1). The dispersion equation of a two-layer model for a TE leaky mode is[8]

$$k_2\left[(\tan k_2t_2-\phi_0)/2\right]-k_1\left[(\tan k_1t_1-\phi_{\rm m})/2\right]=0,\quad (1)$$

where t_1 is the thickness of the layer with a low index n_1, which is next to the HR mirror, and t_2 is the thickness of the top layer (or the equivalent grating layer) with the

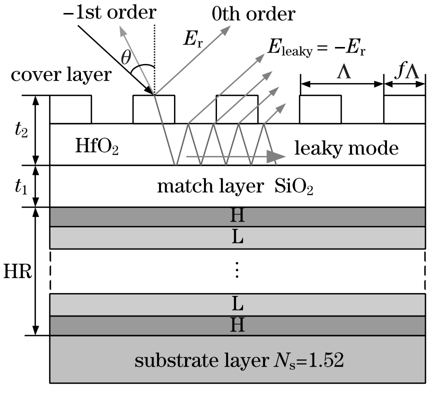

Fig. 1. Structure of grating with two leaky mode propagating layers based on dielectric HR mirror. f is the fill factor of corrugation.

1671-7694/2010/S10029-03

equivalent grating index (or high index n_{h}) where the corrugation will later be etched on. The phase items ϕ_0 and ϕ_{m} are the reflection phase shifts at the layer-cover interface and the mirror boundary as incident wave irradiates from the leaky mode propagating layer, respectively. In Eq. (1),

$$k_1 = k_0\sqrt{n_{\mathrm{l}}^2 - n_{\mathrm{c}}^2 \sin^2\theta_{\mathrm{i}}}, \qquad (2)$$

$$k_2 = k_0\sqrt{n_{\mathrm{h}}^2 - n_{\mathrm{c}}^2 \sin^2\theta_{\mathrm{i}}}, \qquad (3)$$

where $k_0=2\pi/\lambda$ and λ is the vacuum wavelength. θ_{i} is the incident angle in the cover layer with index n_{c}. When Eq. 1 is satisfied, MDG will obtain approximately 100% DE in the −1st order.

For the design requirement in this letter, the wavelength of incident light is 1064 nm, and the incident angle is 70°. The corresponding Littrow angle is 66.4°, which means that the period of corrugation is 574 nm. The formula of the multilayer dielectric HR mirror is $(\mathrm{H2L})^9\mathrm{H}$, where H and L denote the high-index layer ($\mathrm{HfO_2}$, n_{h}=2.12) and the low-index one ($\mathrm{SiO_2}$, n_{l}=1.48), respectively, and the optical thicknesses of the H and L layers are quarter reference wavelength, respectively. A match layer made of $\mathrm{SiO_2}$ is introduced to satisfy the leaky mode resonances over a broad wavelength range. A high-index layer is used to etch the corrugation, which will obtain high efficiency with a shallow-etched grove. This is very helpful for grating fabrication.

Based on the two-layer leaky mode resonance grating model, the parameters including grove depth t_{g}, thickness of the residual layer of the top high index layer t_{r}, thickness of the match layer t_1, fill factor f, and reference wavelength λ_{r} are chosen. Reference wavelength is chosen to control the thickness of each layer of the HR mirror in order to provide high reflectivity by using the wavelength range.

PSO introduced by Eberhart *et al.*[12], is a robust, stochastic, evolutionary strategy. It is inspired from the social behavior of animal species such as birds, bees, and others (particles) that are looking for their requirements in the searching area. The algorithm finds the optimal solution by moving the particles in solution space. PSO lets every individual within the swarm move from a given point to a new one with a velocity based on a weighted combination of the individual's current velocity, the best position ever found by that individual, and the group's best position. Owing to the convenience of realization and the promising optimization capability in various problems, PSO has becomes a hotspot in optimization design. It has been successfully utilized in the design of diffraction gratings with strictly specified spectral properties by Mehrdad and Magnusson[13].

The PSO algorithm is employed for the optimization design of shallow-etched MDG in this letter. The merit function is taken to be a root mean square error (RMSE) function

$$\mathrm{RMSE} = \left\{\frac{1}{N}\sum_{\lambda_{\mathrm{i}}}[100 - R_{\mathrm{opt}}(\lambda_{\mathrm{i}})]^2\right\}^{1/2}, \qquad (4)$$

where the desired DE of each wavelength is set as 100%, and $R_{\mathrm{opt}}(\lambda_{\mathrm{i}})$ is its optimized counterpart by PSO. N is the number of wavelength points. FMM is used to calculate the DE of grating.

All parameters included in this design are arrayed as $\{t_{\mathrm{g}}, t_{\mathrm{r}}, t_1, f, \lambda_{\mathrm{r}}\}$. The minimum and maximum values of each parameter are set as {10, 0, 10, 0.3, 800} and {80, 300, 300, 0.6, 900}, respectively. The unit of the first four parameters is nanometer. The optimization wavelength range is from 1030 to 1090 nm, and the interval is 5 nm, which means N=13 in Eq. 4. The minimum value of the RMSE that we obtained is 3.4387. The corresponding values of each parameter are {168.67, 70.58, 2.01, 0.491, 823.91}, and after simplification, all parameters are {169, 71, 2, 0.49, 824}. The DE of MDG with such parameters is shown in Fig. 2.

Figure 2 illustrates the top-hat spectra of all-dielectric grating calculated by FMM. Over a 60-nm-wide wavelength range (from 1030 to 1090 nm), the DE of MDG is more than 97.5%. Although the highest DE does not correspond to the center wavelength of 1064 nm, MDG provides a high DE over a broad range. This is very meaningful for MDG to be used in an ultrashort pulse laser system.

For the MDG used in a nanosecond pulse layer system that includes a less than 10-nm bandwidth spectrum, the MDG with a DE of more than 99% and an etching grove depth less than 80 nm can be the optimization design of PSO. Figure 3 shows the spectra of all-dielectric grating calculated by FMM. The parameters are {172, 70, 4, 0.45, 885}, where each parameter has some meanings as given in the last section. It can be found that the DE of MDG at the center wavelength of 1064 nm is more than 99.7%, and the bandwidth of DE more than 99% is more than 14 nm.

With the parameters given in Fig. 2, when light with

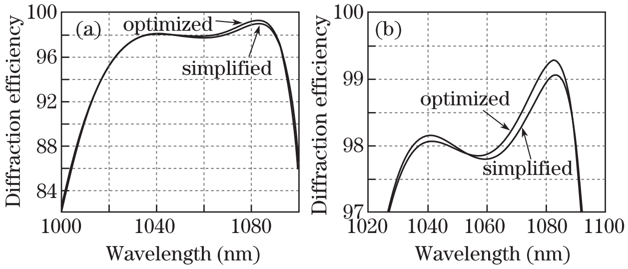

Fig. 2. (a) Spectra of MDG in the –1st order reflected diffraction designed by optical parametric amplifier (OPA) optimization; (b) partial enlarged detail of DE more than 97% part of (a).

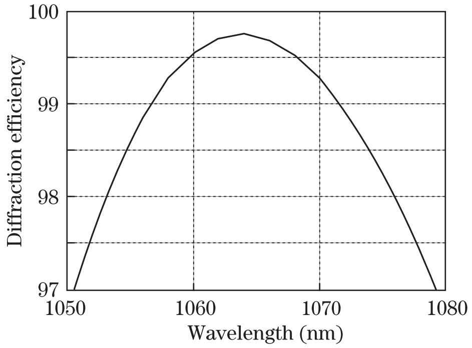

Fig. 3. Spectra of MDG in the –1st order reflected diffraction designed by OPA optimization.

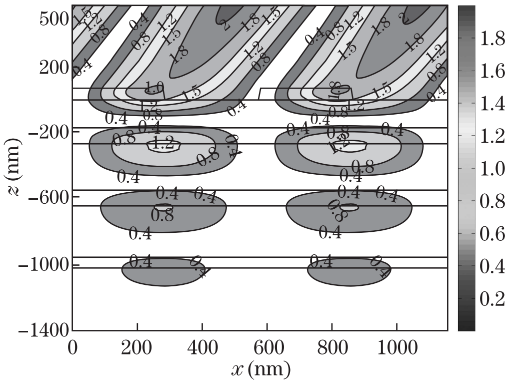

Fig. 4. Electric field of MDG with incident light of 1046-nm wavelength and 70° incident angle. The other parameters are as given in Fig. 2.

a wavelength of 1064 nm irradiates at 70°, the corresponding DE is more than 99.5%, and the electric field of MDG calculated by FMM is shown in Fig. 4. It can be found that the maximum value of the electric field in the ridge (HfO_2 layer) of MDG is 1.8 times of the value of the incident electric field. This indicates that the MDG design result has good laser damage resistance capability.

In conclusion, an MDG with DE more than 97.5% over a 60-nm-wide wavelength range centered at 800 nm and a grove depth less than 80 nm has been designed by PSO algorithm and FMM. It is very useful for MDG fabrication and can be used in ultrashort pulse laser system. Another MDG with DE more than 99.7% at wavelength of 1064 nm is also obtained, and it can be used in nanosecond pulse laser system. The electric field of MDG is calculated, and it is found that shallow-etched MDG also has good laser damage resistance capability.

This work was supported by the National Natural Science Foundation of China under Grant No. 10704079.

References

1. M. Pessot, J. Squier, G. Mourou, and D. J. Harter, Opt. Lett. **14,** 797 (1989).
2. R. D. Boyd, J. A. Britten, D. E. Decker, B. W. Shore, B. C. Stuart, M. D. Perry, and L. Li, Appl. Opt. **34,** 1697 (1995).
3. M. D. Perry, R. D. Boyd, J. A. Britten, D. Decker, B. W. Shore, C. Shannon, and E. Shults, Opt. Lett. **20,** 940 (1995).
4. B. W. Shore, M. D. Perry, J. A. Britten, R. D. Boyd, M. D. Feit, H. T. Nguyen, R. Chow, G. E. Loomis, and L. Li, J. Opt. Soc. Am. A **14,** 1124 (1997).
5. P. P. Lu, K. X. Sun, R. L. Byer, J. A. Britten, H. T. Nguyen, J. D. Nissen, C. C. Larson, M. D. Aasen, T. C. Carlson, and C. R. Hoaglan, Opt. Lett. **34,** 1708 (2009).
6. N. Destouches, A. V. Tishchenko, J. C. Pommier, S. Reynaud, and O. Parriaux, Opt. Express **13,** 3230 (2005).
7. F. Canova, R. Clady, J.-P. Chambaret, M. Flury, S. Tonchev, R. Fechner, and O. Parriaux, Opt. Express **15,** 15324 (2007).
8. M. Flury, A. V. Tishchenko, and O. Parriaux, J. Lightwave Technol. **25,** 1870 (2007).
9. M. Flury, S. Tonchev, R. Fechner, A. Schindler, and O. Parriaux, J. Euro. Opt. Soc. Rap. Public. **2,** 07024.1 (2007).
10. N. Lyndin, M. Flury, S. Tonchev, R. Fechner, and O. Parriaux, J. Euro. Opt. Soc. Rap. Public. **2,** 07019.1 (2007).
11. L. Li, J. Opt. Soc. Am. A **10,** 2581 (1993).
12. R. Eberhart, and J. Kennedy, in *Proceedings of IEEE International Conference on Neural Networks*, 1942 (1995).
13. S. S. Mehrdad and R. Magnusson, Opt. Lett. **32,** 894 (2007).