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Fabrication of broadband, high-efficiency, metal-multilayer-dielectric gratings

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ABSTRACT

Fabrication procedures and testing results of broadband, high-efficiency, metal-multilayer-dielectric gratings (MMDG) for high power laser pulse compression applications are reported. Gratings of 1740 line/mm line density to operate at 53 degrees incident angle and TE polarization were engraved in the top three layers of metal-multilayer-dielectric substrates. The groove depth was controlled to be between 310 nm and 320 nm by monitoring the diffraction efficiency of grating at—1st-order in Littrow mounting using a He–Ne laser with a wavelength of 632.8 nm. The duty cycles of masks was controlled with a range from 0.14 to 0.17 and the duty cycles of MMDGs was controlled with a range from 0.15 to 0.19. The bandwidth of a fabricated MMDG at a level of diffraction efficiency higher than 90% was 169 nm and the peak value was 95.1% at wavelength of 810 nm.

1. Introduction

Pulse compression gratings (PCG) in high power femtosecond chirped pulse amplification (CPA) laser systems [1,2] must have high diffraction efficiency, high laser induced damage threshold (LIDT), and large spectral bandwidth [3]. The first CPA laser systems used gold gratings, in which the diffractive structure was coated with a thin gold film. The optimized gold gratings of sinusoidal corrugation present a more than 200 nm wide quasi-top-hat diffraction efficiency spectrum for TM polarization, but the rather low damage threshold [4] of such gratings limits the performances of these facilities. Multilayer dielectric (MLD) gratings with high LIDT and diffraction efficiency were first proposed by Svakhin et al. [5] and later developed at Lawrence Livermore National Laboratory by Perry et al. [6], but the bandwidth of MLD gratings was generally less than 100 nm [3,7–13]. In order to get broadband, high-efficiency PCG, Canova et al. [3] and Neauport and Bonod [12] replaced the multilayer dielectric mirror stack with a metal mirror and multilayer dielectric stack combination. It is called metal-multilayer-dielectric grating (MMDG). A rectangular-groove MMDG with an over 200 nm wavelength wide top-hat diffraction spectrum centered at 1053 nm and average efficiency exceeding 97% was designed by Wang et al. [9], but no fabrication results were reported. A high-efficiency broadband MMDG with rectangular corrugation etched in the top hafnia layer was designed by Flury et al. [14]. They experimentally obtained the—1st-order average diffraction efficiency of 95.7% in wavelength between 710 nm and 840 nm.

Most designed MMDGs reported in the literature have rectangular groove profiles etched in the top high-index material layer, but the faceting phenomenon in the ion-beam etching process [15–19] makes the grating profile trapezoidal [20]. We design a MMDG with ridges consisting of a high-index layer sandwiched between two low-index layers, taking into account the trapezoidal shape of the ridges. The details of the design work have been reported elsewhere [21]. This design provides high diffraction efficiency and broad bandwidth, but the fabrication of sandwich ridge MMDG is challenging. In the fabrication process, for the thick top SiO_2 layer and photoresist mask, deposition of HfO_2 will increase the duty cycle of MMDG and decrease the sidewall angle. Thus, the correlation of the duty cycle and sidewall angle of MMDG with mask duty cycle should be experimentally researched. The original photoresist mask should have a duty cycle smaller than that of the designed MMDG. The photoresist mask with a duty cycle small than 20% is difficult to fabricate. Meanwhile, deposition of HfO_2 decreases etch rate of the photoresist mask. To make the monitoring model suitable for general use, mean etch rate in actual etch process should be experimentally determined. And, the end-point of etching process should be insensitive to sidewall angle and duty cycle of MMDGs.

Duty cycle and groove depth of a MMDG determine the ultimate diffraction efficiency and bandwidth; therefore, both

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profile parameters should be accurately controlled [15]. The duty cycle of a MMDG can be controlled by adjusting the duty cycle of the photoresist mask. Thus, monitoring the groove depth accurately during the ion beam etching process is the key to fabricating a broadband, high-efficiency MMDG. Huang and Terry [22] applied spectroscopic ellipsometry to the in-situ measurement of grating structures, but the complexity of the measurement system and the large computational load limit its application in real-time process monitoring. Bosch-Charpenay et al. [23] monitored the etch depth of trench structure through measurement and analysis of the infrared reflectance spectrum that was taken by using a FTIR spectrometer. Chao et al. [24] applied an in-situ monitored reactive ion-beam etching method to fabricate low-threshold InGaAs/GaAs ridge waveguide lasers. They monitored the etching depth by recording the change of substrate surface reflectivity. Lin et al. [25] reported an in-situ end-point detection technique for ion-beam etching of multilayer dielectric gratings (MLDG) by monitoring the evolution of diffraction intensity. However, to our knowledge there is no report on similar work for MMDG. The previously reported end-point detection techniques are not directly applicable to fabrication of MMDGs because of the multi-material ridge structure and the high reflectivity of the metal layer beneath it.

In this paper, fabrication procedures for high-efficiency, broadband MMDG are investigated. First, we describe the fabrication objectives and the principle of the monitoring method. Then, we describe the fabrication procedures in detail, which is mainly about the fabrication of photoresist mask and ion-beam etching. Finally, we report the experimental results. The groove depth and duty cycle, especially the groove depth, can be controlled accurately. The bandwidth of fabricated MMDG is 169 nm (> 90% between 705 nm and 874 nm) with 95.1% peak value at a wavelength of 810 nm.

2. Fabrication objectives and principles

2.1. Fabrication objectives and tolerance analysis

Our MMDG is designed to comprise a metal mirror and a multilayer dielectric (SiO_2 and HfO_2) thin-film stack with grooves engraved in the top three layers, as shown in Fig. 1. The thicknesses of the etched three dielectric layers, from top to bottom, are 100 nm, 149 nm, and 57 nm. A thin Cr layer (10 nm) is deposited by thermal evaporation to improve the adhesion [21] between the gold film and the fused silica substrate. The fabrication objective is to get broadband, high-efficiency MMDGs with 1740 line/mm line density operating at an incident angle of 53°, TE polarization and having a top-hat spectral band over 90 nm centered at wavelength of 800 nm for the−1st-order diffraction efficiency greater than 90%.

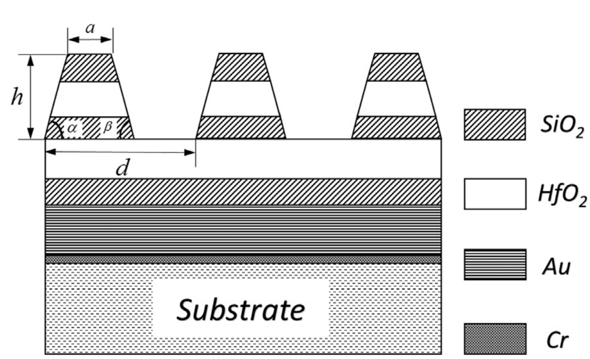

Fig. 1. Structure of a MMDG. Au layer thickness is 200 nm and Cr layer thickness is 10 nm.

Five parameters, period d, groove depth h, left and right sidewall angles α and β, and top width a, uniquely define a trapezoidal profile as shown in Fig. 1. Our MMDGs ridges are symmetrical, so $\alpha=\beta$. The duty cycle of MMDG is defined as the ratio of the top width to period, $\Delta=a/d$. Note that here we use the top width in the definition because it is this width that is directly related to the bottom width of the photoresist grating mask at the end of the ion-beam etching process. The designed MMDG's groove depth and duty cycle are 306 nm and 0.15, and the sidewall angle is 73°. To analyze the fabrication tolerance, we use the computer software KAPPA [26] to calculate the diffraction efficiencies of different combinations of groove depth, duty cycle, and sidewall angle over the wavelength range from 700 nm to 900 nm.

The sidewall angle was determined by the deposition of HfO_2 during etching and by the relative etch rates between HfO_2, SiO_2, and photoresist. Our reactive ion beam etching (RIBE) system renders the sidewall angles distributed between 70° and 75°. To investigate fabrication tolerance of groove depth, the effect of groove depth on MMDG bandwidth was calculated with $\alpha=73°$, $\Delta=0.15$, as shown in Fig. 2. When groove depth changes from 250 nm to 350 nm, the bandwidth of MMDG is larger than 90 nm for diffraction efficiency greater than 90%. We also calculated the lower and upper limits of the duty cycle that could meet the bandwidth requirement with different sidewall angles (70°, 73°, and 75°) and different groove depths (250–350 nm), as shown in Table 1.

2.2. Requirements on photoresist mask

While the photoresist mask pattern was transferred to the dielectric layers, the photoresist is removed isochronously, so the

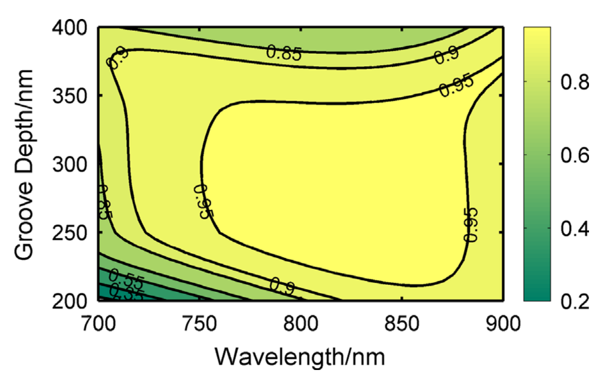

Fig. 2. Calculated contours of constant the−1st-order diffraction efficiency of a MMDG operating at an angle of 53° as a function of etch depth and wavelength. The sidewall angle is 73° and the duty cycle is 0.15.

Table 1
Fabrication tolerance of duty cycle for different sidewall angles and groove depths.

Groove depth (nm)	70°		73°		75°	
	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit
250	0.04	0.17	0.07	0.20	0.09	0.22
260	0.04	0.18	0.07	0.21	0.09	0.23
270	0.05	0.18	0.07	0.21	0.09	0.23
280	0.05	0.18	0.07	0.21	0.09	0.23
290	0.05	0.18	0.07	0.21	0.09	0.23
300	0.05	0.18	0.07	0.21	0.09	0.23
310	0.05	0.18	0.08	0.21	0.09	0.23
320	0.05	0.18	0.08	0.21	0.09	0.23
330	0.05	0.18	0.08	0.21	0.10	0.23
340	0.05	0.19	0.08	0.22	0.10	0.24
350	0.05	0.19	0.08	0.23	0.10	0.25