Effect of Electric Filed Enhancement on Laser-induced Damage Morphology of Multi-layer Dielectric Grating*

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Abstract: The effect of electric field enhancement on laser-induced damage morphology of multi-layer dielectric gratings was investigated. Electric field distribution was calculated by using the Fourier mode method. Numerical treatment shows that the peak electric field occurs at the groove edge opposite to the incident direction by nearly a magnitude of two. Laser-induced damage threshold of 6.61 J/cm^2 was obtained for 12 ns pulses at 1 064 nm with TE mode and 51.2° incident. Scanning electron microscopy (SEM) of damage morphology shows that the initial damage occurs from the place where the electric filed is strongly enhanced.

Key words: Electric field enhancement; Laser induced damage threshold; Multi-layer dielectric grating

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0 Introduction

Though traditional gold coated gratings have a diffraction efficiency of 95%, those gratings have a low laser-induced damage threshold because of its absorbing character[1]. The limitation led to the development of multi-layer dielectric gratings (MDGs) which is first put forward by Sychugov[2] for laser application. Research on design and manufacture technology of MDGs has been performed in a number of groups due to its high diffraction efficiency and high laser resistance during the past years[3-4]. To perfect the performance of MDGs, methods to improve the diffraction efficiency and laser-induced damage threshold (LIDT) are therefore still a subject of intense interest in long time[5-6]. The constructive interference of multi-layer dielectric stack brings the diffractive behavior for MDGs[7]. Meanwhile, the effect also creates considerable field enhancement, which results from the structure of the corrugated surface[8]. Previous study shows that LIDT is associated with the effect of field enhancement[9-10]. To achieve high laser resistance, it is important to understand the effect of electric field enhancement[11].

In this contribution, we describe the forms and characteristics of damage morphology, which is dominated by the electric field enhancement in the groove of MDGs. The damage threshold is tested by employing 1-on-1 stand method and the field enhancement effect is simulated by the Fourier mode method.

1 Experiment

1.1 Sample preparation

The combination of a multi-layer dielectric stack to provide reflection and the corrugated surface to provide diffraction makes it possible to achieve high diffraction efficiency[12]. The parameters such as groove depth, duty cycle and remaining thickness of the top layer after etching are optimized to have diffraction efficiency of 99.5%. Vacuum coating, interference lithography and ion-beam etching are applied to manufacturing the optimized grating. Four MDGs with average diffraction efficiency of 96% at 1 053 nm for TE mode and an incidence angle of 51.2° are fabricated for laser-induced damage test.

1.2 Damage test system

The experimental system for damage testing as shown in Fig. 1 involves a 1 064 nm Nd: YAG laser, a 632.8 nm laser for light path alignment, beam splitters, attenuator, lens, two dimensional adjustable sample platform, CCD, and power meter. The energy density of each pulse is determined by the attenuator. The initial damage morphology is observed by CCD and the intensive observation is employed by the scanning electron microscope. The adjustable platform allows testing the sample at the angle of 51.2°. The pulse on the sample is governed by the computer.

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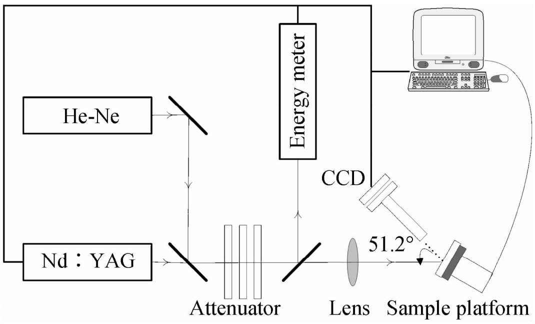

Fig. 1 Schematic setup for laser-induced test

1.3 Result and damage morphology

In our experiment, the optical damage resistance was conducted according to ISO 11254-1[13]. The damage sites are observed with CCD and the number is recorded. The operation is repeated at different energy density to deduce the damage probability as the last null point of the statistic. Fig. 2 shows the LIDT simulation of the MDGs at 1 064 nm for an incidence angle of 51.2° and TE mode. Seen from Fig. 2, the measured LIDT is 6.61 J/cm^2 for 12-ns pulse according to the method of 1-on-1.

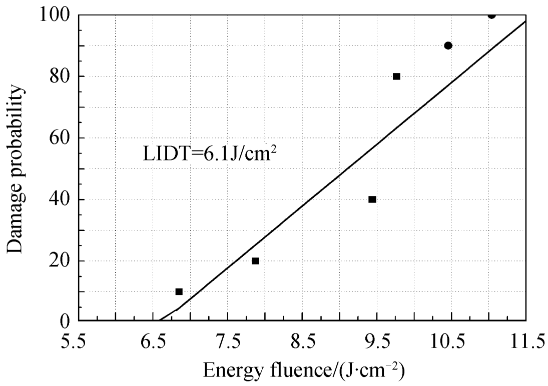

Fig. 2 LIDT simulation of MDGs at 1 064 nm, 51.2°, TE mode, 12 ns with 1-on-1 method

Fig. 3 gives the damage micrograph of the fabricated grating under different power density. As is shown in the micrograph, the morphology presents the form of ablation and evaporation by the energy deposited with the conversion from conductive electron to lattice. Then, the damage originates at the edge of the gratings ridges, which is due to the electric field enhancement induced by the constructive interference. Finally, the damage has a statistical nature and the measure threshold shows a little fluctuation.

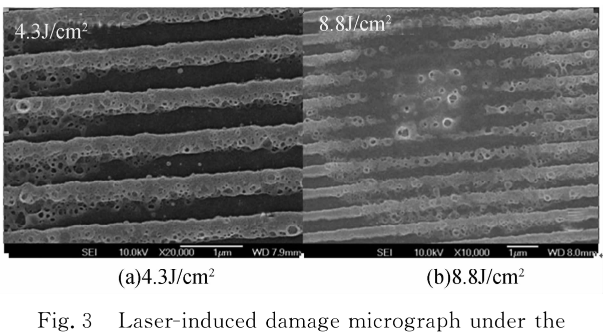

Fig. 3 Laser-induced damage micrograph under the power density of 15 J/cm^2

2 Discussion

2.1 Electric filed distribution in MDGs

The electric filed distribution in MDGs is analyzed with Fourier mode method[14]. Fig. 4 gives the electric field distribution across the structure of MDGs. The depth and duty cycle is 180 nm and 0.3 respectively, which make the MDGs to achieve a diffraction efficiency of 99.5%. As shown in Fig. 4, the field distribution of this multi-layer dielectric and surface corrugated structure presents a standing wave effect above the surface, which is formed by the interference between the input normalized electric filed and the -1st order diffractive light. Within the corrugated surface structure of grating groove, the enhancement of electric filed shows a dependence of nodes and antinodes with different magnitude, which is the result of interference as the upward and downward traveling waves. Furthermore, the same standing wave pattern distribution of nodes and antinodes can be seen within the high reflective multi-layer dielectric stack with antinodes aligning across the interface. Meanwhile, we can see that there are two regions in which the constructive interference is the peak electric filed distribution. One is at the corner of the grating with the field enhancement as large as twofold of the input normalized electric field. The other is at the first interface of high-index material and the low-index material. The interface is sensitive to the damage with high filed distribution. So it will benefit the potential laser resistance to move the peak filed into materials rather than in the interface.

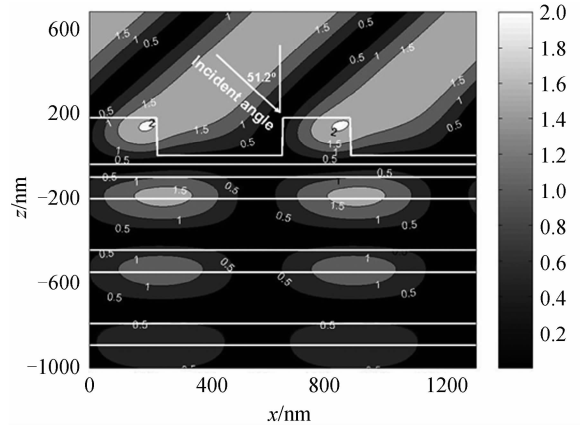

Fig. 4 The electric field enhancement effect in MDGs with diffraction efficiency above 96%

2.2 Enhancement effect on laser morphology of MDGs

As can be seen from the damage morphology in Fig. 3(a), the initial damage occurs under the energy density of 4.3 J/cm^2. When the input energy density increases, the damage extends from the groove to the surface and forms some bubbles along the corrugated structure. The bubbles diffuse and connect into a patch among the surface. As the energy density increases to 8.8 J/cm^2, the damage is evident by melting the groove and forms a small hole across the surface. The diffractive function of the MDGs is destroyed under this pulse.

According to the laser-induced damage process, the striking damage morphology is that the damage initiates on the opposite side of the grating groove, where the standing wave field enhancement reaches its peak by a factor of two. The strong effect of field strength on ablation and evaporation leads to the damage area at the corner of the groove.

Since the peak electric field enhancement appears at the interface of high and low index materials, it is desirable to modify the structure of HR stack and optimize the corrugated surface such as groove, depth and duty cycle to lower the field enhancement at the sensitive palace to improve the LIDT.

3 Conclusion

In conclusion, we have investigated the electric field enhancement in multi-layer dielectric grating by using the Fourier mode method. LIDT of MDGs is tested with 1-on-1 method. The damage morphology taken by scanning electron microscope shows the initial damage occurs at the place, where the field enhancement reaches its peak value. Measures, which are adopted to optimize the electric filed distribution to obtain high diffraction efficiency with high laser resistance, are under ongoing.

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References

[1] BOYD R D, BRITTEN J A, DECKER D E, *et al*. High-efficiency metallic diffraction gratings for laser applications[J]. *Appl Opt*, 1995, **34**(10): 1697-1706.

[2] SVAKHIN A S, SYCHUGOV V A, TIKHOMIROV A E. Efficient diffraction elements for TE-polarized waves[J]. *Sov Phys Tech*, 1991, **36**(9): 1038-1040.

[3] PERRY M D, BOYD R D, BRITTEN J A, *et al*. High-efficiency multiplayer dielectric diffraction gratings[J]. *Opt Lett*, 1995, **20**(8): 940-942.

[4] HEHL K, BISCHOFF J, MOHAUPT U, *et al*. High-efficiency dielectric reflection gratings: design, fabrication, and analysis[J]. *Appl Opt*, 1999, **38**(30): 6257-6271.

[5] SHORE B W, PERRY M D, BRITTEN J A, *et al*. Design of high-efficiency dielectric reflection gratings multi-layer dielectric film for pulse compressed gratings [J]. *Acta Photonica Sinica*, 2006, **35**(1): 84-88.

[6] NICOLAS B, JEROME N. Optical performance and laser induced damage threshold improvement of diffraction gratings used as compressors in ultra high intensity lasers[J]. *Opt Commu*, 2006, **260**(2): 649-655.

[7] LIU Shi-Jie, MA Jian-yong, SHEN Zi-cai, *et al*. Optimization of thin-film design for multi-layer dielectric grating[J]. *Appl Sur Sci*, 2007, **253**(7): 3642-3648.

[8] OLIVER J B, KESSLER T J, HUANG H, *et al*. Thin-film design for multilayer diffraction gratings[C]. *SPIE*, 2005, **5991**: A1-7.

[9] STUART B C, FEIT M D, HERMAN S, *et al*. Ultra-short pulse optical damage[C]. *SPIE*, 1996, **2714**: 616-627.

[10] KONG Wei-jin, SHEN Zi-cai, SHEN Jian, *et al*. Investigation of laser-induced damage on multi-layer dielectric gratings[J]. *Chin Phys Lett*, 2005, **22**(7): 1757-1760.

[11] WEI Chao-yang, LIU Shi-jie, DENG De-gang, *et al*. Electric field enhancement in guided-mode resonance filters[J]. *Opt Lett*, 2006, **31**(9): 1223-1225.

[12] BRITTEN J A, PERRY M D, SHORE B W, *et al*. High-efficiency, dielectric multiplayer gratings optimized for manufacturability and laser damage threshold[C]. *SPIE*, 1996, **2714**: 511-520.

[13] HE Hong-bo, HU Hai-yang, TANG Zhi-ping, *et al*. Laser-induced damage morphology of high-reflective optical coatings [J]. *Appl Sur Sci*, 2005, **241**(3): 442-448.

[14] LIU Shi-jie, SHEN Zi-cai, KONG Wei-jin, *et al*. Optimization of near-field optical field of multi-layer dielectric gratings for pulse compressor[J]. *Opt Commun*, 2006, **267**(1): 50-57.

电场的增强作用对介质膜光栅损伤形貌的影响

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摘　要：研究了电场在介质膜光栅结构中的增强效应对其抗激光损伤阈值的影响. 使用傅里叶模式方法计算了电场在介质膜光栅浮雕结构内的分布. 数值分析表明：电场在介质膜光栅中增强的最大值为入射光的 2 倍，其最大的位置出现在相对于入射光对面的光栅槽侧壁。实验测试介质膜光栅样品在 1 064 nm 和 12 ns，51.2°和 TE 偏振光入射时，其抗激光损伤阈值为 6.61 J/cm². 对损伤形貌进行扫描电镜精确分析，发现介质膜光栅的初始损伤产生于电场在介质膜光栅内增强最大的位置处.
关键词：激光损伤阈值；电场增强；介质膜光栅

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