HIGH-EFFICIENCY BLAZED DIFFRACTIVE OPTICAL ELEMENTS FOR VIOLET WAVELENGTH FABRICATED BY ELECTRON-BEAM LITHOGRAPHY

Teruhiro Shiono, Tetsuya Hamamoto*[1]and Koji Takahara*[2]
Matsushita Electric Ind. Co., Ltd. and Osaka Science and Technology Center*.
3-1-1, Yagumo-Nakamachi, Moriguchi, Osaka 570-8501, Japan
TEL: +81-6-6906-0267 FAX: +81-6-6906-4096
E-mail: shiono@drl.mei.co.jp

1. Introduction

Optical information systems which have been constructed mainly by refractive / reflective optical elements are expected to be reduced at their size, weight and cost by using diffractive optical elements (DOEs). Among the fabrication technology of the DOEs, electron-beam (EB) lithography[1-3)] attracts increasing attention, because high-efficiency blazed DOEs can be formed by a single process in addition to its potential for submicron patterning. The single process of making blazed structure is very important for the fabrication of high-performance DOEs, because the optical aberrations can be minimized without misalignment of the grating patterns such as in binary optics lithography[4)].

There have been many reports about EB-lithographed blazed DOEs, but the experimental values of the first diffraction efficiency have been lower than the theoretical values. It was, for example, 84%[5)] at the period of 8μm for red wavelength (λ=0.633μm), and excellent blazed structure was not demonstrated in the small period region (< ~4μm).

We have studied improvement of the diffraction efficiency of blazed DOEs especially for violet wavelength (λ ~0.4μm) in the period range of 10 to 0.5μm. The DOEs for violet wavelength could be key devices in high-density DVD optical disk systems in the next generation.

2. Theoretical Efficiency for Violet Wavelength

Using the electromagnetic theory[6)], we solved Maxwell's equation at violet wavelength to satisfy the grating boundary conditions. The first-order diffraction efficiency is

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[1] T. Hamamoto is now with Dainippon Screen Mfg. Co., Ltd., Kyoto, Japan.

[2] K. Takahara is now with Minolta Co., Ltd., Osaka, Japan.

defined as the ratio of the power of the first-order diffracted wave to the power of the transmitted wave through the substrate without gratings. Calculated diffraction efficiency curves are shown in Fig. 3 as a function of the period when the plane wave is incident vertically from the substrate. The solid and dotted lines show the efficiency when the incident wave is TE and TM polarized, respectively. The groove depth was taken as $L=\lambda/(n-1)=0.8\mu m$ where $\lambda=0.407\mu m$ and the refractive index of blazed layer $n= 1.51$. As shown in Fig. 3, the theoretical efficiency exceeds 80% when period $\Lambda > \sim 2\mu m$. But it decreases rapidly when $\Lambda \leqq \sim 2\mu m$ and a peak appears at $\Lambda = 0.54\mu m$ ($\Lambda/\lambda=1.3$) before the efficiency drops to zero. The peak appearance is considered because the Bragg condition is satisfied at that period.

3. Fabrication by EB Lithography

The blazed structure can be formed[1)] because the resist thickness remaining after development depends on the electron dose. Figure 1 shows the fabrication process. A positive electron-beam resist of PMMA was spin coated on a glass substrate, and a conductive polymer film was also coated on it, which is necessary to avoid electrical charge buildup during the writing. For the precise measurement of the diffraction efficiency, AR coating was provided at the backside of the substrate to remove multiple reflections within the substrate. The electron-dose distribution was achieved by controlling

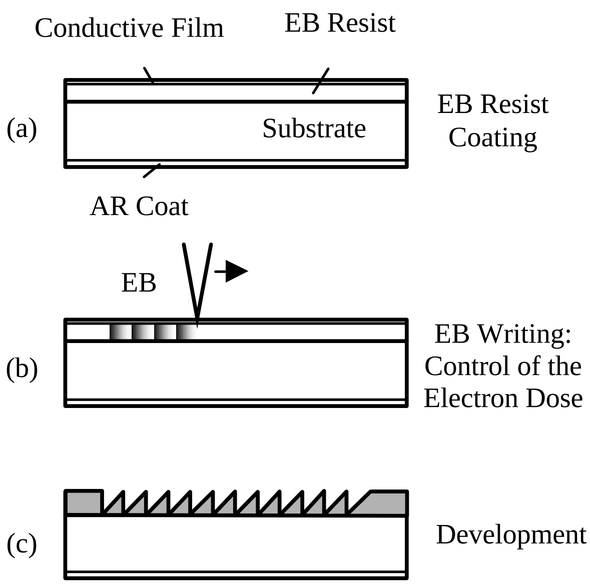

Fig.1 Fabrication process of blazed DOE by EB lithography.

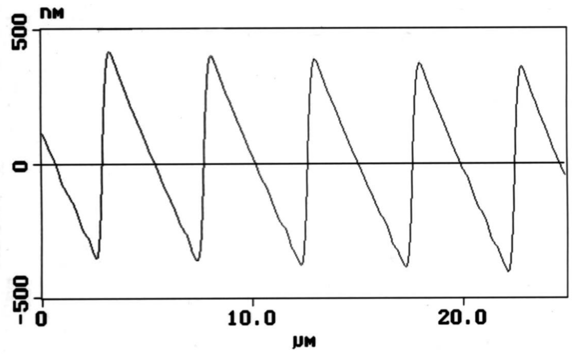

Fig. 2 (a) The surface profile of the fabricated blazed grating with the period of 5μm which was measured by AFM.

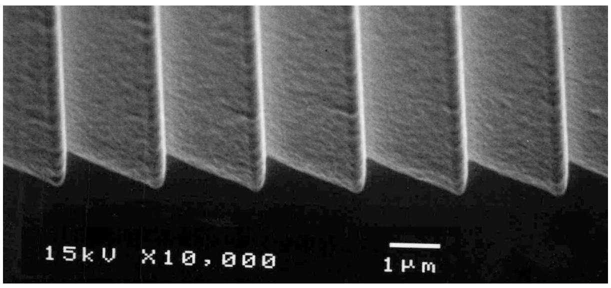

Fig. 2 (b) Cross-sectional SEM photograph of the fabricated blazed grating with the period of 2μm.

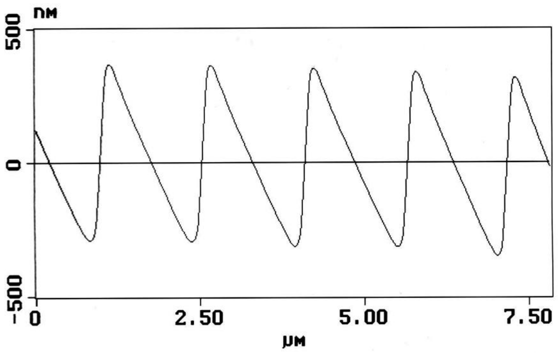

Fig. 2 (c) The surface profile of the fabricated blazed grating with the period of 1.5μm that was measured by AFM

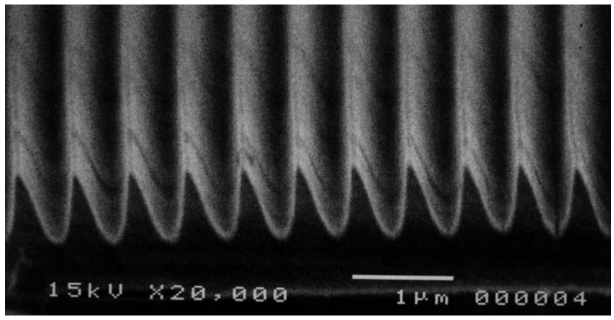

Fig. 2 (d) Cross-sectional SEM photograph of the fabricated blazed grating with the period of 0.54μm.

the EB scanning speed in consideration of the resist-sensitivity curve, which depends on the groove period. Development of the resist achieved the desired relief structure. As an EB writing system, we used JEOL JBX-5000SI with a laser interferometer, where the accelerating voltage and the current of the EB during the writing were 50kV and 0.5~1nA, respectively. The superposition accuracy of patterning was ~60nm in the area of 1.5mm. Eight kinds of linear blazed gratings with uniform period (Λ=10, 5, 3, 2, 1.5, 1.2, 1.0 and 0.54μm) were fabricated by optimizing experimentally writing parameters and electron-dose distributions. The gratings were designed to have the groove depth of 0.8 μm and the area of $1.3\times1.3mm^2$. The surface profiles of the fabricated gratings were shown in Fig. 2, where Fig. 2 (a) and (c) are the profiles measured by AFM and Fig. (b) and (d) show the cross-sectional SEM photographs. It was found that excellent blazed structure without roughness was formed. Even in the fine period of 0.54μm, the blazed structure was made better than our expectation.

4. Optical Measurements

A violet laser diode light (λ=0.407μm) illuminated the blazed gratings vertically from the substrate and the diffraction efficiency was measured. The experimental results were shown in Fig. 3. The solid circles and solid triangles exhibit the values when

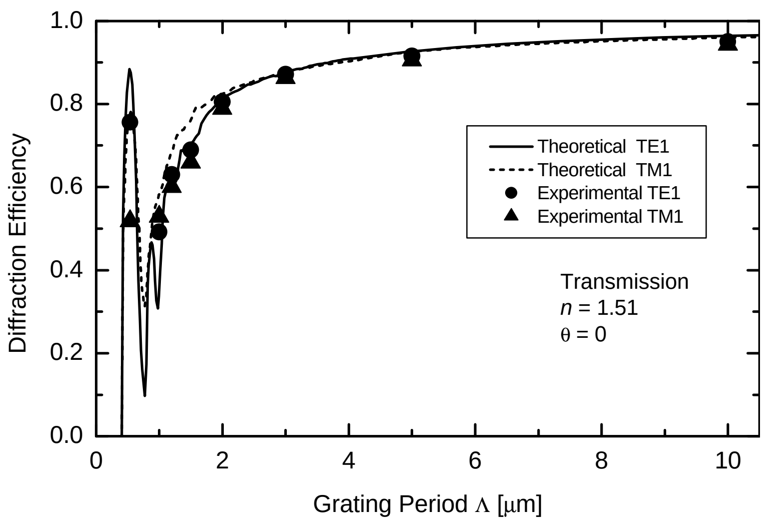

Fig. 3 The theoretical and experimental values of first-order diffraction efficiency of blazed gratings.

the incident wave is TE and TM polarized, respectively. The diffraction efficiency of 95% was obtained for TE polarization at the period of 10μm. The experimental values at other periods also agreed well with the theoretical ones, where the differences were only within a few percent at $\Lambda \geqq 2\mu m$. It is noted that at submicron period of 0.54μm, a peak appearance of 75.6% (TE) was confirmed experimentally for the first time.

A wave aberration of the first-order diffracted wave from the fabricated DOEs was measured by a Fizeau interferometer system (ZYGO DVD-400) to be as small as ~0.01λ (rms) at λ=0.405μm. We can also fabricate various types of high-performance DOEs such as diffractive microlenses with high efficiency and small aberrations.

5. Conclusion

The blazed DOEs were studied for violet wavelength by using EB lithography. The rigorous theoretical diffraction efficiency was calculated by electro-magnetic theory. By optimizing EB writing parameters and electron-dose distributions, eight kinds of gratings (Λ=10~0.54μm) with excellent blazed structure were fabricated. It has been demonstrated that the measured diffraction efficiency values agreed well with the theoretical ones. In fine period of 0.54μm, a peak appearance of 75.6% (TE) was confirmed experimentally. A wave aberration as small as ~0.01λ (rms) was obtained for the first-order diffracted wave from the fabricated DOEs. It is expected that the blazed DOEs could be used as key devices in optical information systems such as high-density DVD optical-disk pickup by the development of a precise replication technology from the EB lithographed elements.

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