Development and Evaluation of the Binary Hologram Elements

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The binary hologram master for hologram color filter were developed and evaluated in their characteristics. The chirped diffraction grating was fabricated by electron-beam lithography. EB direct-writing has an excellent lateral accuracy and uses only one exposure step. This effect leads to undesired exposure of the resist in regions adjacent to those actually addressed by electron beams. The authors design binary surface-relief gratings, optimization of groove profiles of the EB master hologram, thereby efficiently coupling light was achieved into the first diffracted order. The authors have produced gratings that have 1st-order diffraction efficiencies greater than 90%. This manufacturing process was consisting from a volume hologram master and contact print process. The mass production of such HOEs (Hologram Optical Elements) would be possible by the development of a precise replication technology from EB lithographed elements.

Keywords: electron beam lithography, holographic grating, hologram color filter, diffraction efficiency, diffractive surface

1. Introduction

Electron-beam (EB) lithography has proved to be excellent for manufacturing diffractive optics surface [1]. The holographic grating based on both the surface relief structure and refractive index modulation has potential applicability for optical elements and devices [2]. In particular, surface relief structures have many interesting applications in the area of nanotechnology and furthermore the fabrication of diffractive elements such as zero-order grating [3], slanted surface relief grating for planar optical interconnects [4], and subwavelength infrared optics [5] represents one aspect of their uses. There have been a number of efforts that use binary structures to approximate different types of materials. For example, Born and Wolf have shown that gratings of wavelength periods exhibit form birefringence [6]. Cesato fabricated holographic quarter-wave plates based on this idea [7]. Hutley and Gaylord have also used fine surface-relief gratings to achieve antireflection behavior [8] [9].

By applying microfabrication using photolithography, significant success has been achieved in fabricating patterns finer than of sub-micron order. Recently, pattern of 100nm size have been realized using an electron beam or excimer laser as the light source. Direct-writing electron-beam lithography is a useful technique for fabricating continuous resist profile for a high-efficiency diffractive optical element. Since the electrons scatter in the resist layer and the resist contrast curve is generally to obtain the desired resist profile. Determining the optimum electron dose is called proximity correction. Some methods of proximity correction have been proposed, which are classified...
according to estimation methods of a resist profile. The authors investigate an adequate cell size, and fabricate the chirped-period grating according to result of the proximity correction.

In this paper the authors design binary surface-relief gratings, optimization of groove profiles of the EB master hologram, thereby efficiently coupling light into the first diffracted order. The authors have produced gratings that have diffraction efficiencies greater than 90%. According to the scalar theory of diffraction, such binary gratings have very near the theoretical limits reported by M. Moharam [10].

2. Experimental
2.1 Materials and Measurements.

ZEP-520 is the EB positive resist supplied by Nippon Zeon Co.Ltd. The holographic recording material for Omnidex 352 is a panchromatic photopolymer supplied by Dupont. Holograms are recorded on the photopolymer using an argon ion laser beam (514.5nm) at an output 5W. After recording, the photopolymer is exposed to ultraviolet (UV) light. The molecular weights of the resists were estimated by gel permeation chromatography (GPC) with polystyrene standards using a model CCPP-D GPC (TOSOH Co.) system equipped with a G-4000H (108 mm × 1D 600 mm) and AS-8070 column at 40°C in THF. A 50 KeV EB exposure system (Hitachi) was used in the evaluation of the resist performance such as sensitivity and resolution capability. After exposure, the blank was hard baked (post-exposure baked) by heating on a hot-plate and then developed with a developing system, APTCON 3100 series (Fairchild-Convac), equipped with a spray nozzle. Fig.1 illustrates the process flow for sample preparation and measurements. Binary gratings of this master is formed of chrome pattern on a photomask blank. The substrate was wet etched in an ammonium cerium nitrate solution or dry etched in a mixture gas of dichloromethane and oxygen. The resist was stripped by dryashing or a wet process, and the substrate was cleaned. The resist patterns were observed with a scanning electron microscope (SEM).

Fig.2 Schematic diagram of experimental set up to measure the optical properties

Fig.2 shows the schematic diagram of the experimental setup for the holographic grating and observing the intensity of the diffracted beam. The sample is mounted in a holder, and the diffraction efficiency of the grating is determined by measuring the diffracted beam. A prism was attached to the back surface of the sample with index matching fluid in order to couple the diffraction beam out of the substrate for measurements. The laser beam was collimated. The quarter-wave plate and polarizer were used to adjust the polarization of the beams. A nonpolarized He-Cd laser beam was used a probing beam. The power density of the beams was 27mW/cm². The diffraction efficiency of the +1st order diffracted beam from the gratings in transmission mode was monitored as a function of time using an optical powermeter (Newport, 1815-C).

2.2 Principle of the HCF

HCF (Hologram Color Filter) is a HOE that separates white light into primary colors [11]. This HCF can realize a single-panel system with
the high brightness that is equivalent to the 3 panel system. Fig. 3 shows the principle of the HCF, which we are supplying with [12]. Hologram lens elements are located in front of reflecting electrode at a distance of just focal length of the hologram lens. The center pitch is as fine as 0.41 μm. White light from a light source is converted to s-polarization by a polarizing device, and impinges on HCF at a slant angle. This beam is focused and dispersed through the diffraction of the HCF, so that a color spectrum pattern is generated on the plane of liquid crystal. The light beam is converted by reflecting electrode. The reflected beam impinges on the HCF again.

Fig. 3 Design of a hologram color filter (HCF)

The beam doesn’t diffract and pass through the HCF because of following reasons. First, the HCF has selective effect of polarization and diffracts s-polarization light more efficiently than p-polarization light. Second, re-entrance light impinges on a different point from a first pass point in the HCF plane, and consequently doesn’t match Bragg’s condition. After passing a polarizer, the image is enlarged and projected to a screen by projection lens. The production process is composed of 4 steps: that is design of a grating pattern, making of a binary hologram master, making of a volume hologram master and contract print to a final hologram.

3. Results and Discussion
3.1 Design of the binary surface relief gratings

The first task is to design a surface relief binary grating that efficiently couple with light into the first diffracted order. The authors assume that the grating is in air and the grating material has an index of折射率. For convenience, let \( \Delta = n_0 - 1 \). From scalar theory we know that a graded-index grating

![Design of Grating of height h with a superlattice period d_1 and minilattice period d_2](image)

Fig. 4 Design of Grating of height h with a superlattice period d_1 and minilattice period d_2.

can achieve high diffraction efficiency into the first order if the period-to-wavelength ratio \((T/\lambda)\) and the period-to-depth ratio \((T/h)\) are obtained. These conditions of the grating modeled are shown in Fig. 4. The duty cycle \( t \) of this grating is defined as

\[
t = \frac{(d_2 + d_1)}{d_2}
\]

(1)

This is the ratio of the filled Cr part of the microstructure to one period. First, the part of the light falling on the tops of the step is considered. One can derive, as in ref. [13], an equation for the phase of the reflected beam \( \phi_r \) from a loss Cr layer:

\[
\phi_r = \arctan \left( \frac{2k \lambda}{n^2 + k^2 \cdot 1} \right)
\]

(2)

where \( n \) is the real part of the complex refractive index of the Cr layer, and \( k \) is its imaginary part. The angular and wavelength deviation of the illumination light, the liquid crystal pattern and pattern number of the projection lens are required to design the HCF. A self-made ray-tracing simulation program is utilized to estimate the color chromatics, where the parameter such as diffraction angle, focal length of the HCF, and wavelength of peak diffraction efficiency are varied. Then interference fringes are designed according to simulation results, as shown in Fig. 5. Grating pattern of HCF is designed to satisfy the specification. The binary hologram master is made from the grating pattern data. The grating

![Simulation result of the diffraction efficiency depending on groove depth](image)

Fig. 5 Simulation result of the diffraction efficiency depending on groove depth.
pattern data is generated by computer, like ordinary computer generated hologram (CGH). This grating is composed of linear line and space and has gradation pitch for the cylindrical focusing function. The diffraction grating lens (a cylindrical lens) was 280 μm in width, and its focal length was 1000 μm. The maximum grating period was 750 nm at the middle point of the gratings, and the minimum period was 150 nm at the grating ends.

3.2 Development of the binary hologram master (EB lithography)

The authors fabricated the chirped-period diffraction grating according to the calculated electron dosage. The simulation was carried out with a 50 nm × 50 nm cell. For the EB writing system, Hitachi HL-700C, was used. The authors selected a high accelerating voltage of 50 KeV. In order to improve of patterning a small beam current of 130 nA and the 50 nm in the field of 80 μm × 80 μm were optimized. From our experiment, we found that the subfield boundaries could almost be removed by adjusting the subfield size including the proximity of the EB. The electron dosage was modulated by 32-64 levels, which depend on the grating periods.

The EB resist was spin coated on glass substrate, and was also coated with a conductive polymer film, which is necessary to avoid electrical charge buildup during EB writing. For precise measurement of the diffraction efficiency, antireflection coating was provided at the backside of the substrate to remove multiple reflections within the substrate. Development of the resist achieved the desired relief structure. In this process, the control of the electron-dose distributions was most important. A distribution of the absorbed energy density for focused electron beam is calculated by the Monte Carlo method. In this case, the diffraction efficiency improved by repeating the experiments.

The authors optimized the electron-dose distributions and EB exposure parameter in accordance with the grating period. It is found that the subfield boundaries were removed by adjusting the subfield size including the proximity of the EB writing. The optimum distributions depended on the grating period because of the proximity of the EB exposure. The substrate was wet etched in an ammonium cerium nitrate solution or dry etched in a mixture gas of dichloromethane and oxygen, because of insufficient etch selectivity between the substrate and the photoresist layer. Fig.6 shows relationship between dry-etching time and CD shift. Development and dry etching are repeated until the desired depth is reached. A scanning electron micrograph of a part of the fabricated grating is shown in Fig.7. The grating has a good appearance for lens. Fig.8 shows a part of fabricated resist profile measured by atomic force microscopy (AFM).

The measured grating profile agrees well with the estimated profile. The gratings were designed to have a groove depth of 0.35 μm and to be 150-270 nm in size.

Fig.6 Relationship between dry-etching time and CD shift

Fig.7 Scanning electron micrograph of resist pattern (Cross section) Size: ↔ 170nm

Fig.8 Part of Cr surface profile measured by atomic force microscopy (AFM)
It is found that the fabricated grating structure has a smooth surface, a sharp edge with an almost right 85° angle, and qualities that are necessary to achieve high efficiency.

3.2 Evaluation of the HCF

The amplitude hologram is adopted into this HCF, for index-matching fluid must be used at the contact copy process. If relief type is used, the index matching fluid fills up the groove of the relief, and eliminates the diffraction effect. In the resist patterning and chrome patterning process, precise quality control was needed. There are several reasons because grating pitch has a gentle gradation, zero defect and complete uniformity are required, and grating pitch is as fine as 0.410 μm on the center. Then the authors make the volume hologram master for mass-production process, which has higher light production. The volume hologram master is made by contact print method from the binary hologram master. To get a final hologram with high diffraction efficiency, 0th order beam and +1st order beam of the volume hologram master must have approximately the same diffraction efficiency. To satisfy this condition, the hologram materials were controlled thickness of hologram layer and mass-production conditions. A recording plate for a final hologram is brought into contact with the volume hologram master. The volume hologram master is illuminated by printing beam through a coupling prism. Apart of printing beam go through hologram layer as 0th order beam, and other part is diffracted as 1st order beam. Interference fringe by these two beams is recording material as a final hologram. By this method, the final hologram can have a designed focal distance and simultaneously doesn't have gap nor overlap between neighboring lens elements in the hologram plane. Index matching fluid and an absorption layer are used to prevent the unwanted reflection at each surface. The diffraction power was measured by adjusting the rotation of the hologram sample. The diffracted beam was collected in the detector. The diffraction efficiency was defined as the intensity ratio of the diffracted light to that of the total diffracted light. Fig.9 is shown samples of diffraction efficiency of the binary hologram master. Those results were fitted with the Kogelnik coupled-wave theory [15] [16] to determine the amplitude of refractive index modulation of Δn, as shown in Fig.10. The p-polarized incident light is parallel to the grating grooves. A very high diffraction efficiency of 97% was achieved and the maximum Δn was estimated to be 0.045. The diffraction efficiency of the volume hologram is almost theoretically and the optical efficiency in each color has been improved. Then, the optical efficiency and chromaticity of the CHF samples were measured. The measuring optical system consisted of the HCF, light source, projection lens and screen. The arrangement of the test image with patterned black matrix is shown in Fig.11. The patterned back matrix was
used for measuring each color, consisting of four areas which had one cell aperture corresponding to each of RGB and white colors. The spectral optical efficiency in each color has been improved. There were different intensities among each RGB colors because of the diffraction efficiency variation depending on the wavelength and profile variation of the metal halide lamp. In the volume hologram master, 0th order beam and +1st order beam have approximately same diffraction efficiency. Final hologram's efficiency is 85 ~ 93%. As a result, the superior and optical characteristic imaging was performed.

4. Conclusion

By optimizing EB writing parameters and electron-dose distributions, binary grating with excellent phase structures was fabricated. The grating profiles utilized as a binary hologram master was evaluated by regarding the +1st order and +2nd order diffracted light. Grating depth 0.35 \( \mu \text{m} \) of duty ratio 1.52 was achieved in the maximum diffraction efficiency of the HCF.

The measured efficiency of 90% for diffraction into the first order is much higher than the efficiency expected from a conventional binary phase grating. The measured efficiency is 7% lower than the predicted theoretical limit. This may be explained by slight departures in the actual grating dimensions from the design. These include variations in groove width, etch depth across the structure, and groove profile. Also, a fabrication defect was resulted in a few missing grating feature. Additional factors are the finite aperture of the grating and scattering from sample surfaces. Although fabrication of this type of structure is demanding, the potential has been demonstrated for high-efficiency optical elements for HCF.

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Reference