

Fabrication of a Binary Diffractive Lens for Controlling the Luminous Intensity Distribution of LED Light

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To control the luminous intensity of an light-emitting diode (LED), we designed and fabricated a binary diffractive lens by electron beam lithography on a poly(ethylene terephthalate) (PET) film. We showed that it is possible to control luminous intensity distribution using the binary diffractive lens. To improve the diffraction efficiency, we then designed a binary blazed diffractive lens with a focal length of 140 μm . With a binary blazed diffractive lens having a focal wavelength of the order of micrometers, it is possible to create a small, thin light source for controlling the distribution of luminous intensity. © 2009 The Optical Society of Japan

Keywords: binary diffractive lens, electron beam lithography, LED, luminous intensity, optical films, binary blazed diffractive lens

1. Introduction

Light-emitting diodes (LEDs) are used in solid-state lighting because of their low-energy consumption and long life.^{1–3)} For application in lighting devices it is necessary to improve the performance of LEDs, such as light efficiency, color temperature, color rendering, and light distribution. Lamp-type LEDs, the lenses of which are made of resin, are usually used to control the light distribution. This type of LED produces a beam-like light distribution. However, in order to use LEDs in lighting devices, it is necessary to control the light distribution in an arbitrary way to produce a planar or linear distribution.

We have studied the use of optical films to produce thin, convenient LED light sources with a controllable distribution of luminous intensity. Controlling the distribution of luminous intensity using gratings or microlens arrays has been tried.⁴⁾ However, this has not proved easy because of the difficulty of realizing a thin light source, and a uniform distribution of illuminance has not been obtained because conventional LEDs use round lenses for controlling the distribution of illuminance. In this shape, the distance between the LED chip and the top of a round lens is about 5 mm. In order to realize a thin LED light sources, it is necessary to narrow the distance between the LED chip and the lens to control light distribution. Furthermore, it is difficult for LEDs to realize a uniform distribution of illuminance because of a point light source. On the other hand, the Fresnel lens is effective for controlling the luminous intensity distribution of LEDs, but it is necessary to fabricate structures whose dimensions are the same as the wavelength of light in order to realize a thin LED light source. It is also difficult to fabricate lens structures with curvature by electron beam (EB) lithography or nanoimprint technology.

In this study, we fabricated several kinds of diffractive lenses, that is binary diffractive lenses and binary blazed diffractive lenses, on optical films in order to produce a thin, convenient LED light source with a controllable distribution of luminous intensity. The reason for using optical films is that they are expected to realize the thin LED light source instead of round lenses made from resin. Some authors have reported the design of binary blazed diffractive lenses,^{5,6)} but there are few reports on their fabrication. This is because it is difficult to fabricate binary blazed diffractive lenses with nano structures by EB lithography or nanoimprint technology due to the limit of resolution for their technologies or the difficulty of fabricating continuously variable nano structures.

2. Design and Fabrication of the Binary Diffractive Lens

As stated above, this study focused on binary diffractive lenses and binary blazed diffractive lenses. In this chapter, the design and fabrication of former lenses are described. They were fabricated on poly(ethylene terephthalate) (PET) films. PET films are often used as optical sheets for liquid crystal displays. There are many kinds of optical films such as polycarbonate (PC), poly(methyl methacrylate) (PMMA), and so on. In this study, the EB lithography process was used for fabrication of diffractive lenses; this process requires optical films to endure high temperature and chemicals, which makes PET films more suitable than PC or PMMA. Furthermore, the refractive index of PET films and the resist for EB lithography (ZEP-520A), which are measured by ellipsometry, are almost the same in the visible region—about 1.58. Thus, the binary blazed diffractive lens structures of EB resist were fabricated here by developing an EB resist on PET films. Development of the EB resist can be regarded as processing the surface of a PET film. The optimum results obtained using diffractive lenses fabricated

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by EB lithography, such as period, width and height of the fabricated binary blazed diffractive lenses, are useful for fabricating the molds of thermal type nanoimprint.

The fabricated binary diffractive lens was based on the micro-Fresnel lens. In this study, part of two level zone plates with a pattern of lines and spaces was fabricated. The radius of the m th zone r_m is

$$r_m = 2mf\lambda + (m\lambda)^2, \quad (1)$$

where f is the focal length of the designed lens and λ is the dominant wavelength of LED light. In this simulation, $f = 2 \text{ mm}$ and $\lambda = 566 \text{ nm}$.

PET films with a thickness of $125 \mu\text{m}$ were used as the substrate. The surface was spin-coated with a positive resist and this was followed by pre-baking. The EB lithography system used (Crestec CABL-8000) was equipped with a ZrO/W thermal field emission cathode. The acceleration voltage was 30 kV . The electrons accelerated by this voltage are able to penetrate resists of such thickness, which is about 600 nm measured by an electron beam three-dimensional surface roughness analyzer. After exposure, the resist was developed. The size of the patterns for binary diffractive lens was $2 \times 2 \text{ mm}^2$. Figure 1 shows the scanning electron microscopy (SEM) image of the fabricated binary diffractive lens on the PET film. A diffractive lens, the width of which was almost same as the designed lens, was obtained.

The optical characterization of the fabricated binary diffractive lens was carried out. The luminous intensity distribution of the LED ($\lambda = 566 \text{ nm}$) for the binary diffractive lens was characterized using a luminous intensity distribution system (Asahi Spectra IMS5000-LED). The fabricated lens was then mounted on the LED chip and the spectral irradiance in the vertical direction was measured; Fig. 2 show the distribution of the irradiance. Most of the LED light was focused as shown in Fig. 2(a); the light distribution angle became narrow (30°) on using the binary diffractive lens. As shown in Fig. 2(b), spectral irradiance around 0° with this lens was 1.5 times greater than that without the lens. On the other hand, there are two side peaks in these data, and it is believed that they are caused by light getting out of the fabricated binary diffractive lens. From these results, it is clear that it is possible to control the distribution of luminous intensity using this type of lens.

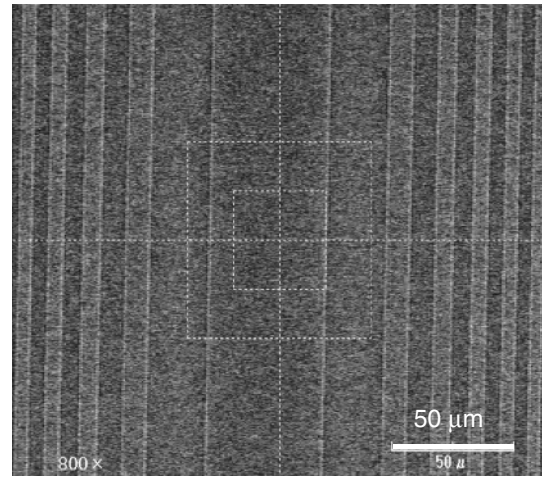


Fig. 1. SEM image of fabricated binary diffractive lens on a PET film.

3. Design of the Binary Blazed Diffractive Lens

Although the binary diffractive lens was effective in controlling the luminous intensity, diffraction efficiency was reduced when the diffraction angle was decreased.^{5,6} Furthermore, the focal length of the fabricated binary diffractive lens is 2 mm . In order to realize a thin LED light source, the focal length has to be shorter. In this chapter, to improve the diffraction efficiency and to shorten the focal length, we designed the binary blazed diffractive lens which defined as shown in Fig. 3. It had subwavelength structures within the large-period structure. The period (Λ) of the subwavelength structure was shorter than the wavelength (λ). Because the refractive index was controlled by changing the subwavelength structure, the arbitrary refractive index distribution was also obtained by controlling this structure. The period (d) corresponds to the period of one blazed diffractive lens in the Fresnel lens. By controlling the period (d) of the large-period structure, the focal point of the binary blazed diffractive lens can be changed. In this study, a binary blazed diffractive lens with a focal length of about $150 \mu\text{m}$ was designed and light propagation of the plane wave was simulated by the finite domain time difference (FDTD) method. Figure 4 shows the field intensity distributions for

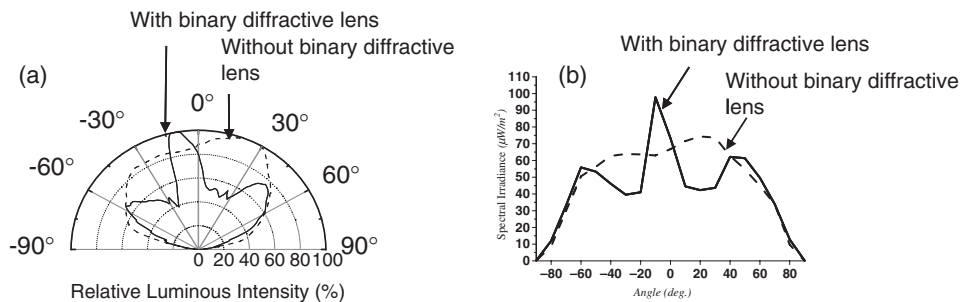


Fig. 2. Distribution of spectral irradiance. (a) Angle dependence of normalized spectral irradiance. (b) Angle dependence of the absolute value of spectral irradiance.

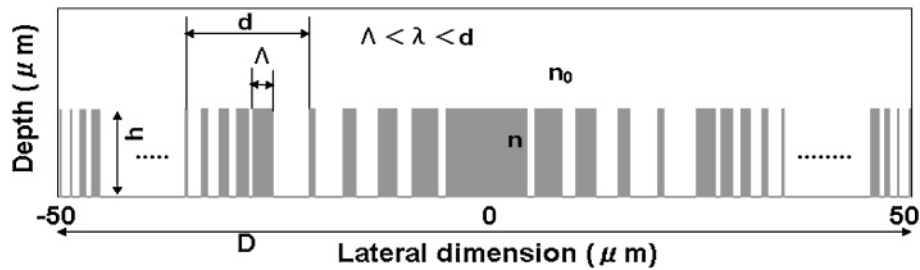


Fig. 3. The calculated model of the binary blazed diffractive lens.

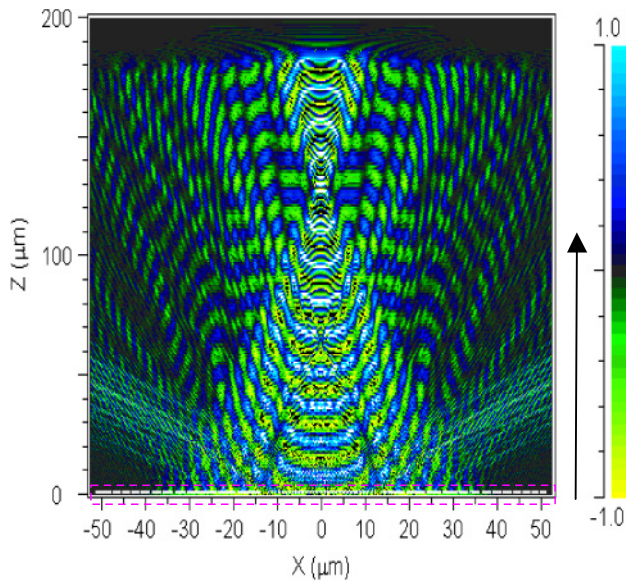


Fig. 4. (Color online) FDTD results for the binary blazed diffractive lens.

transverse electric (TE) polarization of the binary blazed diffractive lens. The simulation parameters were $\lambda = 632$ nm, $D = 100$ μm , $h = 0.962$ μm , $n = 1.575$ (refractive index of PET film), and $n_0 = 1.0$ (refractive index of air). The value of parameter d in part of the fringe was smaller than that in the centre. The designed lens was placed along the x -axis ($z = 0$). The light was incident from $z = 0$ to the $+z$ direction, resulting in, the light being focused at $x = 0$ μm and $z = 140$ μm . After focusing, the light was spread with time due to diffraction. Therefore, a binary blazed diffractive lens with a micrometer-order focal wavelength would be expected to give a small and thin light source for controlling

the distribution of luminous intensity. Based on the results of preceding chapter, it is speculated that the LED light can be focused at 140 μm .

4. Conclusions

In summary, we designed and fabricated a binary diffractive lens to control the luminous intensity of an LED by EB lithography on a PET film, thereby showing that it is possible to control the distribution of luminous intensity using this type of lens. To improve the diffraction efficiency and to realize a thin LED light source, we then designed a binary blazed diffractive lens with a focal length of 140 μm . This type of lens with focal wavelength in the micrometer range can produce a thin LED light source to control the distribution of luminous intensity.

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