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Fabrication of Binary Diffractive Lens on Optical Films by Electron Beam Lithography

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1. Introduction

Two types of lenses can focus light: an optical lens using refraction phenomenon and a diffractive lens using diffraction phenomena. Table 1 shows the characteristics of each lens. The focal length of the diffractive lens is controlled by the structures of the lens, as mentioned in detail in Section 2.2. This suggests that the focal length of the diffractive lens is independent of refractive index and curvature. Thus, application of diffractive lenses to UV optical elements or thin optical elements is possible.

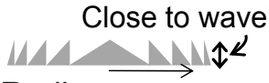
	Refractive lens	Diffractive lens
Principle	Refraction	Diffraction
Structure	 Radius of curvature R	Close to wavelength  Radius r_m
Focal length f	$f = \frac{R}{2(n-1)}$	$f = \frac{r_m^{\,2} - (m\lambda)^2}{2m\lambda}$
Control of f	n, R (depending on material)	r_m (m=1,2,・・・)
Short wavelength light such as UV and X-ray	Difficult	Possible (depending on material)
Thin structure	Difficult	Possible (wavelength order)
Controlling light distribution	Difficult	Possible

Table 1. Comparison of characters between refractive lens and diffractive lens

Recently, the emitting efficiency of light emitting diodes (LEDs) has improved; thus, they are used in lighting devices. To this end, miniaturizing the LEDs for smaller lighting devices and controlling the luminosity of LEDs are required. The conventional oval lamp-type LEDs cannot realize these requirements because the lens height of such LEDs is approximately 5 mm and its distribution of luminosity is determined by its shape. In this study, instead of the oval lamp-type lens, we used the diffractive lens on the optical films, as shown in Fig. 1. If the diffractive lens with short focal length (order of micrometer) can be fabricated, miniaturization of the lens system and consequently the LED lighting devices can be achieved. In order to realize the refractive lenses with the short focal length, large curvature radius is needed, thus making it difficult to realize it easily. Therefore, the diffractive lenses are suitable for realizing the short focal length lenses. Furthermore, by modifying the structure of the diffractive lens, it is easy to control the luminosity of the LEDs and the far-field pattern. Therefore, in this study, we focused on the diffractive lens because it enabled us to reduce the thickness of the lens, control the luminosity distribution of LEDs, and facilitate the realization of the binary structure.

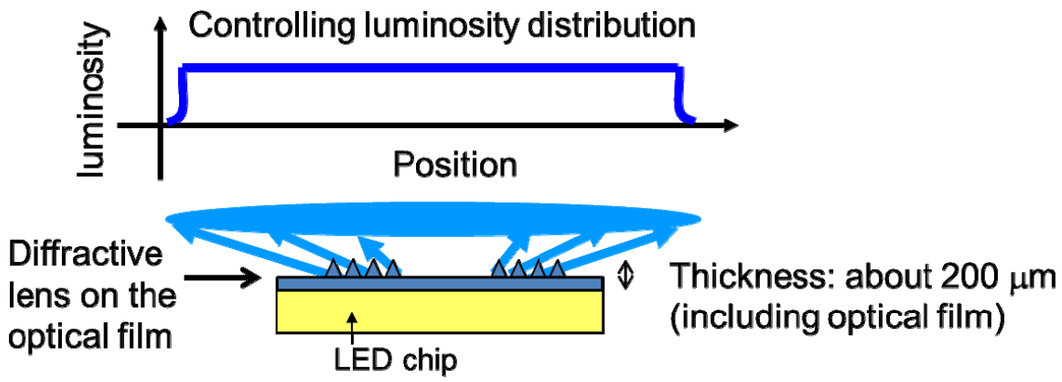


Fig. 1. Schematic representation of diffractive lens on the optical film

The zone plate was the first diffractive lens invented by I. L. Solet in 1875. To improve light efficiency, kinoform was invented by J. A. Jordan (Jordan et al., 1970). Recently, binary optics technology was developed using CAD design and VLSI technology (Swason and Veldkamp, 1989). The diffractive optical elements with multi-level grating having step-like cross-section have been developed. By controlling thestructure of the multi-level gratings, an optical effect almost same as that of the kinoform can be obtained (Orihara et al., 2001 & Yamada et al., 2004).

On the other hand, subwavelength structures (SWSs), which are equivalent to a blazed structure, were suggested by P. Lalanne (Lalanne et al., 1999 & Mait et al., 1999). These structures are fabricated binary SWSs converted from Fresnel lenses. These structures are fabricated easily than those of the multi-level gratings because they can be fabricated by electron beam lithography (EBL) or nanoimprint lithography (NIL). Furthermore, in the case of photolithography, combining some masks is not necessary. By using these structures, achromatized diffractive lenses were reported (Kleemann et al., 2008).

We aim to realize a highly effective short focal length diffractive lens using the binary diffractive lens fabricated by EBL, and expect the equivalent effect with the diffractive lens of the saw-like structure. NIL or photolithography can easily fabricate these structures at

low cost and over a large area. However, EBL does not use any molds or masks. Therefore, it is convenient to examine EBL in detail to obtain optimum structures.
In this study, we carry out the design and fabrication of the binary diffractive lens with 2-mm focal lengths for controlling the luminosity distribution and the binary diffractive lens with the 100-μm-order focal length. Furthermore, to improve the diffraction efficiency, we characterize the detailed relationship between the lens structure and the light intensity.

2. Experimental procedure

In this section, the methods of design, fabrication, and characterization of the binary diffractive lens are described.

2.1 Basic optical characteristics of materials related to binary diffractive lens

The binary diffractive lenses, on which this study is focused, were fabricated on the poly(ethylene terephthalate) (PET) films. The PET films are often used as optical sheets for liquid crystal displays. There are many types of optical films such as polycarbonate (PC) and poly(methyl methacrylate) (PMMA). In this study, the EBL process was used for fabricating the binary diffractive lenses; this process required the optical films to endure high temperature and chemicals, making them more suitable than PC or PMMA.
In this study, the binary diffractive lens was fabricated by developing the resist for EBL (ZEP-520A, ZEON Co.) on the PET films (Teijin® Tetoron® Film, Teijin DuPont Films, Japan). If the refractive indexes of both materials are almost same, the binary diffractive lens can be fabricated by developing the resist instead of etching the PET films. Therefore, the refractive indexes of the PET films and the resist are evaluated by ellipsometry (M-2000DI, J.A. Woollam Co., Inc.). Fig. 2 shows the wavelength dispersion of the PET film and the resist on the PET film, including the data from the catalog of ZEP-520A. D2 and halogen lamps were used for this measurement. The refractive index of the PET film is relatively

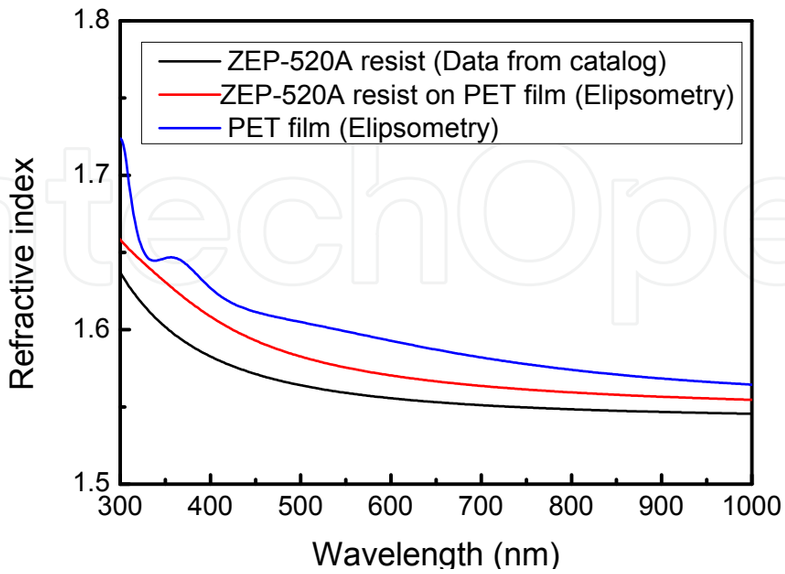


Fig. 2. Wavelength dispersion of the PET film and the resist on the PET film, including the data from the catalog of ZEP-520A

higher than that of the resist; however, in the visible region, their refractive indexes are between 1.58 and 1.60. Thus, in this study, these values are considered to be almost same. Furthermore, by using ellipsometry, the thickness of the resist is estimated using the multilayer model. Fig. 3 shows the relationship between the thickness of the resist and the number of rotations of the spin coater. The thickness of the resist varies from 760 to 460 nm and increases with the number of rotations. Thus, in this study, the binary diffractive lens structures of the electron beam (EB) resist were fabricated by developing an EB resist on the PET films. The development of the EB resist can be regarded as processing the surface of a PET film. The thickness of the resist is equivalent to the height of the binary diffractive lens.

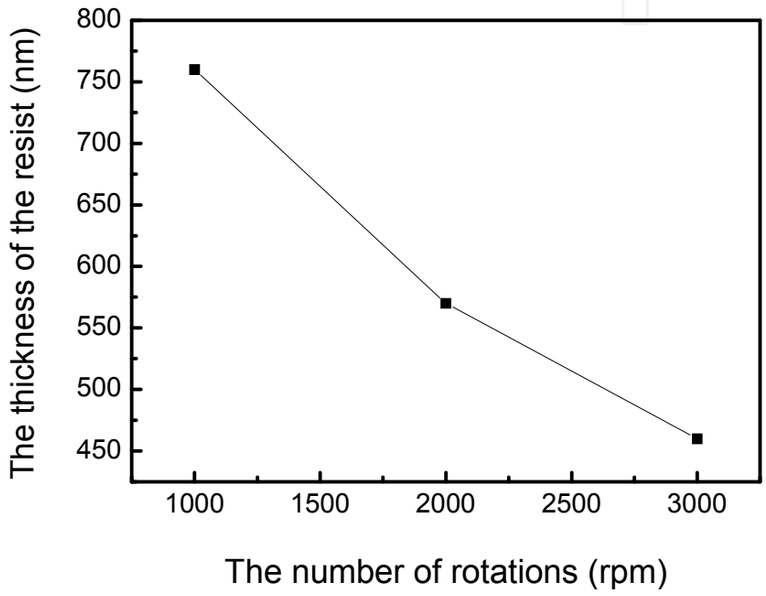


Fig. 3. Relationship between the thickness of the resist and the number of rotations of the spin coater

2.2 Design of diffractive lens

The fabricated binary diffractive lens was based on the micro-Fresnel lens. In this study, a part of two-level zone plates with a pattern of lines and spaces was fabricated. Radius of the mth 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. Equation 1 is based on the imaging theory of the diffractive lens (Buralli et al., 1989).

Then, mth period of this lens d_m is determined by $r_m - r_{m-1}$. In period d_m, the blazed structure is approximated to a step-like structure with n steps and then the step-like structures is converted to the relief structures by duty ratio of height $t_i = 1 - h(x_i)/h_{max}$ in each interval g, as shown in Fig. 4 (a). In the interval, the width of the air part is given by g^*t_i. In the binary diffractive lens, N is the number of the relief structures in a period. Examples of the structures are shown in Fig. 4 (b) and the complete structure of this lens is shown in Fig. 4 (c).

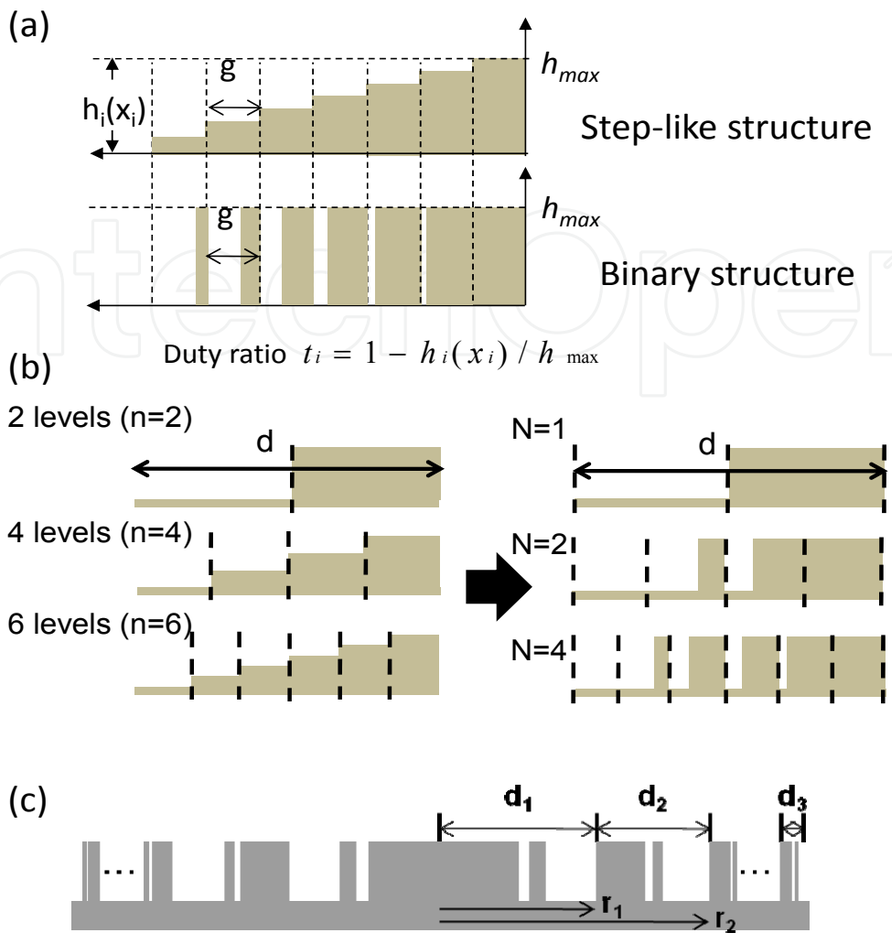


Fig. 4. Structure of the binary diffractive lens, (a) the conversion of the step-like structure to the binary structure, (b) the examples of the structures, (c) the complete structure

2.3 Fabrication of binary diffractive lens on optical films by EBL

The 125-μm-thick PET films were used as the substrate. Fig. 5 shows the procedure for the fabrication of the binary diffractive lens on the optical films by EBL. Before spin coating the EB resist, hexamethyldisilazane (HDMS) was spin coated on the surface of the PET film to improve the adherence between the PET film and the EB resist (Fig. 5 (a)). The surface was spin coated with an EB positive resist followed by pre-baking (Fig. 5 (b)). Then, the charge-up prevention was spin coated on the EB resist (Fig. 5 (c)).

The EBL system (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 were able to penetrate the resist (Fig. 5 (d)). After exposure, the resist was developed and the binary diffractive lens could be obtained from these procedures (Fig. 5 (e)). The size of the patterns for the binary diffractive lens ranged from 100 × 100 μm² to 2 × 2 mm².

The optimum results obtained using the diffractive lenses fabricated by EBL, such as period, width, and height of the fabricated binary diffractive lenses, are useful for fabricating the molds of the thermal-type nanoimprint.

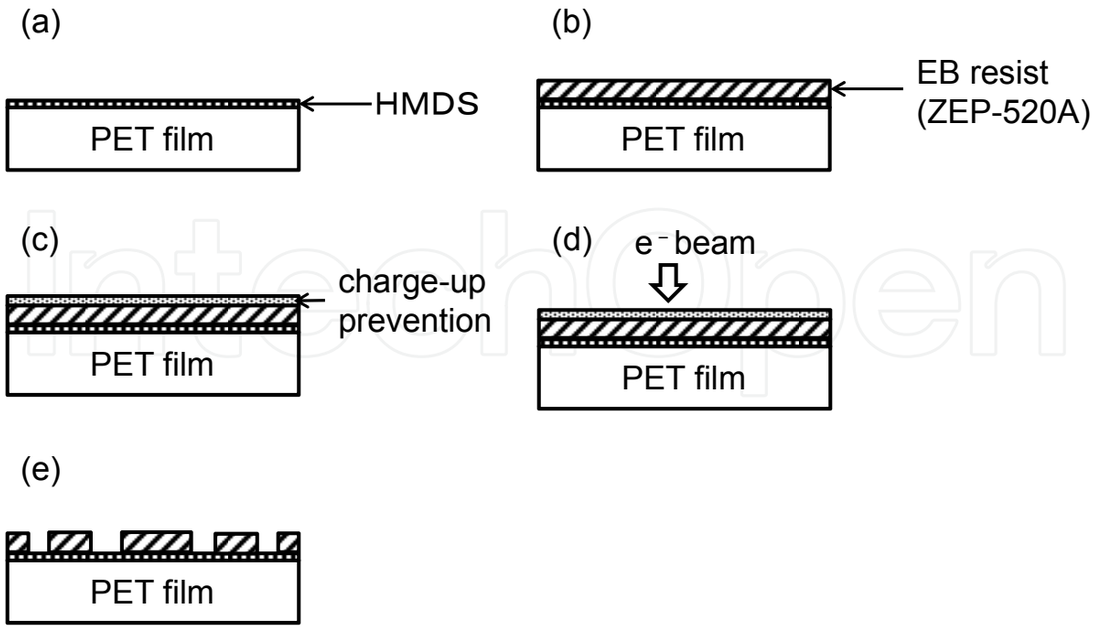


Fig. 5. Procedure for the fabrication of the binary diffractive lens on optical films by EBL, (a) spin coating HMDS, (b) spin coating EB resist and pre-baking, (c) spin coating charge-up prevention, (d) exposing e^- beam, (e) developing the resist and obtaining the binary diffractive lens

3. Results and discussion

In this section, we describe and discuss the experimental results. There are two types of the binary diffractive lenses: (1) the binary diffractive convex lens with a 2-mm focal length for controlling the luminosity of LED light and (2) the binary diffractive convex lens with a 150-μm focal length.

3.1 Binary diffractive convex lens with 2-mm focal length for controlling luminosity of LED light

The binary diffractive convex lens with 2–mm focal length was fabricated on the PET film. Fig. 6 shows the scanning electron microscopy (SEM) image of the fabricated binary diffractive lens on the PET film. The diffractive lens having width almost same as that of the designed lens was obtained.

Optical characterization of the fabricated binary diffractive lens was carried out. The luminous intensity distribution of the LED (λ = 566 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 spectral irradiance in the vertical direction was measured; Fig. 7 shows the distribution of the irradiance. Most of the LED light was focused, as shown in Fig. 7 (a); the light distribution angle became narrow (30°) using the binary diffractive lens. As shown in Fig. 7 (b), spectral irradiance around 0° with this lens was 1.5 times higher than that without the lens. On the other hand, two side peaks in these data were observed and believed to be due to light escaping from the

fabricated binary diffractive lens. From these results, it is clear that the luminous intensity distribution can be controlled using this type of lens.

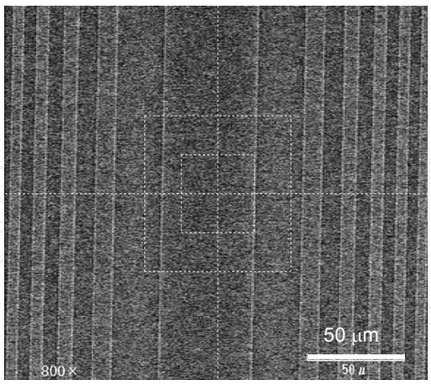


Fig. 6. SEM image of the fabricated binary diffractive convex lens with 2-mm focal length on the PET film.

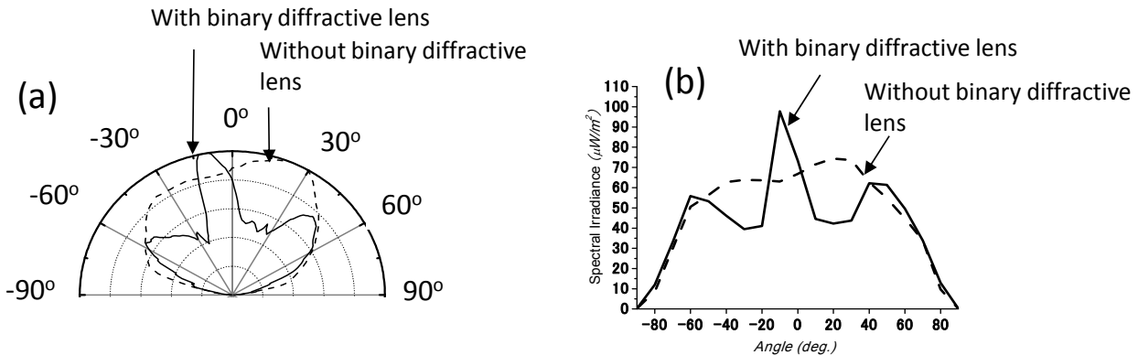


Fig.7 Ddistribution of the irradiance. (a) Angle dependence of normalized spectral irradiance. (b) Angle dependence of the absolute value of spectral irradiance

3.2 Binary diffractive convex lens with 150-μm focal length

Although the binary diffractive lens was effective in controlling the luminous intensity, diffraction efficiency was reduced when the diffraction angle was decreased (Lalanne et al., 1999; Kleemann et al., 2008). 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 section, to improve the diffraction efficiency and shorten the focal length, we designed the binary diffractive convex lens with 150-μm focal length.

In this study, a binary diffractive lens with a focal length of approximately 150 μm was designed and light propagation of the plane wave was simulated by the finite domain time difference (FDTD) method. Fig. 8 shows the field intensity distributions for TE polarization of the binary diffractive lens. The simulation parameters were λ = 632 nm, n = 1.575 (refractive index of the PET film), and n_0 = 1.0 (refractive index of air). The value of the period in part of the fringe was smaller than that in the center. 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 because of diffraction. Therefore, a binary diffractive lens with a micrometer-order focal wavelength is expected to provide a small and thin light source for controlling the luminous intensity distribution. On the basis of the results of section 3.1, we speculated that the LED light can be focused at 140 μm.

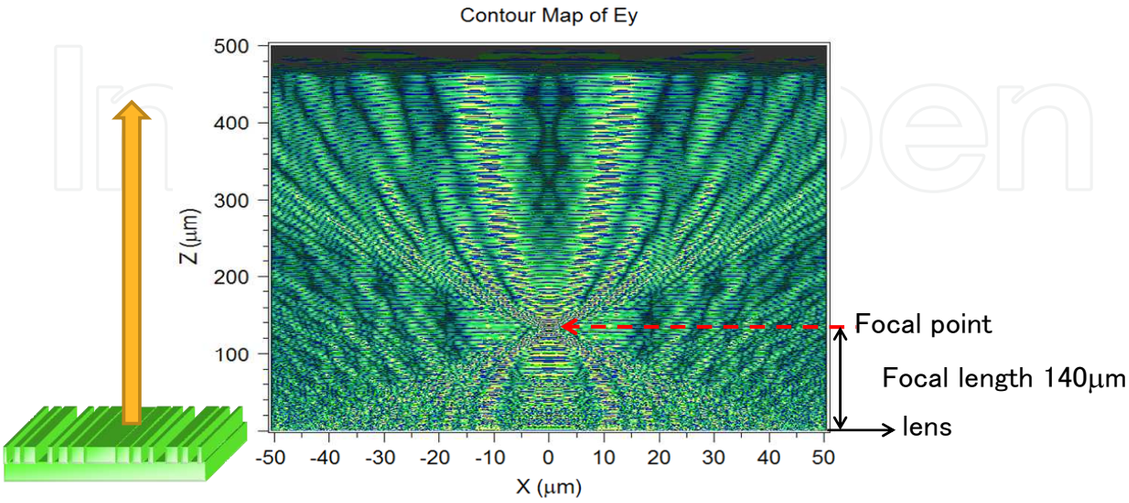


Fig. 8. Field intensity distributions for TE polarization of the binary diffractive lens

The binary diffractive lens with a 150-μm focal length was fabricated; its size was 100 × 100 μm² and thickness was 570 nm, as measured by ellipsometry. Fig. 9 shows the SEM image of the fabricated binary diffractive lens (N = 4) on the PET film. The diffractive lens, whose width was almost the same as the designed lens, was obtained.

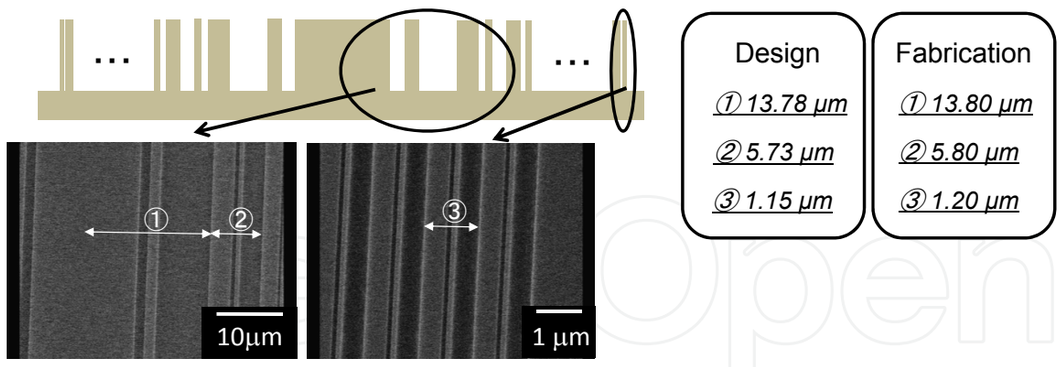


Fig. 9. SEM image of the fabricated binary convex diffractive lens with a 150-μm focal length (N = 4) on the PET film

The far-field transmitted intensity distribution of the fabricated lens is characterized by red laser light (λ = 635 nm). The aperture with a diameter of 100 μm was used for eliminating the light escaping from the edge of the lens. Fig. 10 shows the far-field transmitted intensity distribution of the fabricated lens with different N values (1, 2, 4). The focal length of this lens, which is estimated from this distribution, is approximately 160 μm, which is almost same as that in the FDTD simulation. For higher N values, the intensity of first-order diffraction decreases.

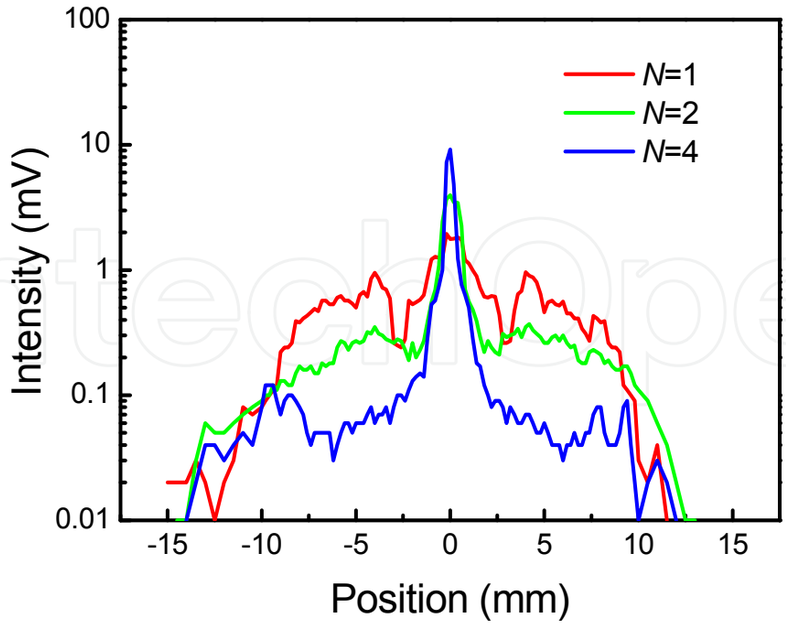


Fig. 10. Far-field transmitted intensity distribution of the fabricated lens

To determine the reason for these results, the binary diffractive lenses with only first period (d_1 = 13.78 μm) and 12th period (d_{12} = 2.12 μm) were fabricated. Fig. 11 shows the far-field light distribution of both lenses. In the case of d_1 = 13.78 μm, the first-order diffraction is observed when N = 4. Because d_1 is considerably larger than the wavelength of light, the first-order diffraction cannot be observed when N is small. On the other hand, in the case of d_{12} = 2.12 μm, the first-order diffraction is observed when N = 1, and it disappears by increasing the number of N. Therefore, in order to improve the diffraction efficiency of the diffractive lens, it is necessary to control the intensities of the zero- and first-order diffractions by choosing the binary structures.

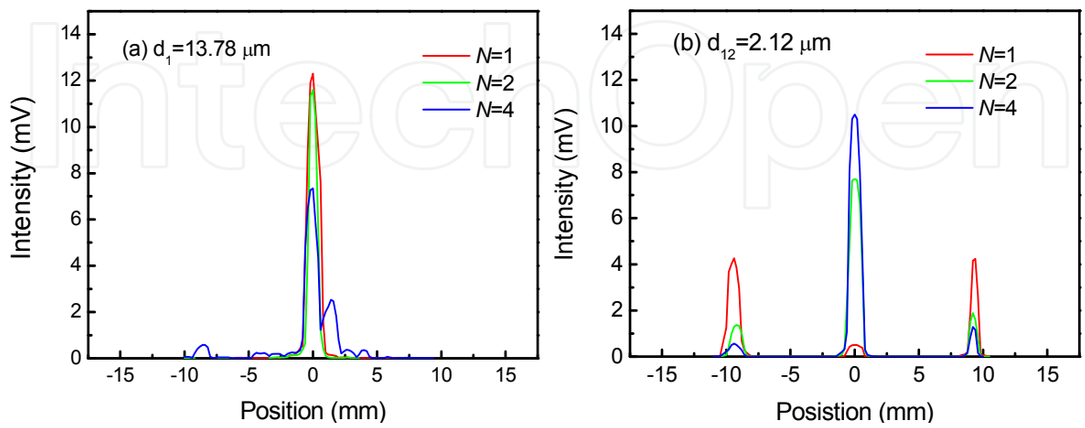


Fig. 11. Far-field light distribution of the binary diffractive lenses in the case of (a) d_1 = 13.78 μm and (b) d_{12} = 2.12 μm

4. Conclusion

In summary, we designed and fabricated two types of binary diffractive convex lenses using EBL on a PET film. In the case of the binary diffractive convex lens with 2-mm focal length, it is possible to control the luminous intensity distribution. To improve the diffraction efficiency and realize a thin LED light source, we designed a binary diffractive lens with 140-μm focal length. This type of lens with focal wavelengths in the micrometer range can produce a thin LED light source to control the luminous intensity distribution.
To realize the binary diffractive lens with the 100-μm-order focal lengths, we characterize the relationship between the diffractive lens structure and its light intensity. It is clear that the intensities of the zero- and first-order diffractions are controlled by the structure of the binary diffractive lens. By using this lens, wide luminous intensity distribution can be obtained.

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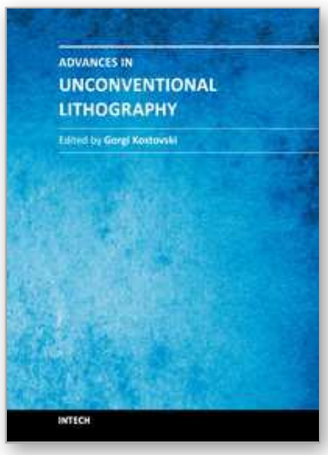
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Advances in Unconventional Lithography

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The term Lithography encompasses a range of contemporary technologies for micro and nano scale fabrication. Originally driven by the evolution of the semiconductor industry, lithography has grown from its optical origins to demonstrate increasingly fine resolution and to permeate fields as diverse as photonics and biology. Today, greater flexibility and affordability are demanded from lithography more than ever before. Diverse needs across many disciplines have produced a multitude of innovative new lithography techniques. This book, which is the final instalment in a series of three, provides a compelling overview of some of the recent advances in lithography, as recounted by the researchers themselves. Topics discussed include nanoimprinting for plasmonic biosensing, soft lithography for neurobiology and stem cell differentiation, colloidal substrates for two-tier self-assembled nanostructures, tuneable diffractive elements using photochromic polymers, and extreme-UV lithography.

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