Design and fabrication of submicron period grating as an imprinted light guide plate for a backlight unit

Hwan-young Choi

Mechanical Design Engineering, Korea University of Technology and Education, Cheonan City, Korea (the Republic of)

ABSTRACT

The imprinted light guide plate (LGP) fabricated through a diffractive grating was studied for the edge-lit display. Such kind of backlight unit (BLU) can save prismatic sheets. The grating dimension was determined through preliminary experiments, modeling, and computation. Based on the designed parameters, a submicron period grating was fabricated and was transferred to the LGP. Consequently, the outcoupling luminous flux, on-axis luminance, and homogeneousness and chromatic dispersion were measured through the prototyped samples. Compared to the conventional BLU, the imprinted diffractive grating works well as the light extractor but still needs to be improved to meet the illumination characteristics required for the liquid crystal display (LCD) BLU.

ARTICLE HISTORY

Received 30 May 2019
Accepted 4 September 2019

KEYWORDS

Diffractive grating; imprinted; light extraction; edge-lit BLU

1. Introduction

According to the location of the light source, there are two types of illumination for the liquid crystal display (LCD): the edge- and direct-lit backlight units (BLUs). Nowadays, the direct-lit technique is essential for realizing a high-dynamic-range (HDR) LCD. Besides, for HDR purposes, the direct-lit technique is preferred due to its effectiveness in reducing the display power consumption. The typical edge-lit BLU consists of several optical sheets, a polymeric light guide plate (LGP), and a reflector as well as a set of light sources placed at one side of the LGP. The function of the BLU is to transform the light flux from the point or line source into the areal illuminator towards the LCD panel. Light is usually extracted from the LGP by the micro-optical structures and/or printed dots on the surface of the LGP [1–8]. Instead of modifying the surface of the LGP, several contributors have proposed the use of the scattering polymer, where the optical transmission particles inside the LGP work to extract the light [9–11]. All these kinds of BLU, however, require at least one or two prismatic sheets to redirect the outcoupled or dispersed light towards the normal direction of the LCD panel. On the other hand, in some approaches, Ochiai and Lee have introduced the diffractive grating as the light extractor [12,13], but there are insufficient explanations of the optical performance and manufacturing method of BLU. G. Chen and M. Parikka have reported the performance of diffractive diffusers for displays [14,15], but their studies were focused on the diffusive function of the LGP rather than on light extraction. Several contributors have studied the diffraction grating as a light extractor and have reported its optical performance in terms of diffraction efficiency [16–20]. This paper highlights the optical performance of the newly developed BLU in terms of BLUs’ illumination characteristics, including its luminance, its homogeneousness over the whole area, and its chromatic performance, as well as its design and manufacturing process. Section 2 presents the design process of the diffraction grating with preliminary tests; section 3, the fabrication and measurement method; section 4, the study results and their discussion; and section 5, a summary of the paper.

The proposed BLU is shown in Figure 1. The left and right parts of Figure 1(a) stand for the conventional and imprinted BLUs, respectively, while Figure 1(b) on the right side enlarges the surface of the LGP where the diffraction grating is imprinted. As shown in Figure 1(b), at the diffractive grating imprinted on the LGP, the incident light acquires a transmitted momentum, which is different for each wavelength but sufficient to overcome the total internal reflection (TIR) condition.
2. Preliminary experiment and simulation

2.1. Diffraction grating equation

The design parameter of the diffractive grating involves the period and fill factor, depth, and shape, which should be determined to meet the major specifications of BLU described as the peak luminance, the homogeneity over the whole area, and the chromatic variation criteria.

As shown in Figure 2, if the grating is engraved on the surface of either material, where light enters from the material with refractive index $n_i$ and is transmitted towards another material whose refractive index is $n_t$, the diffraction equation for a grating with a period $\Lambda$ and for the light of wavelength $\lambda$ at the diffraction order $m$ is described as equation (1).

$$n_i \sin \theta_i \cos \varphi_i - n_t \sin \theta_t \cos \varphi_t = \frac{m\lambda}{\Lambda} \quad (1)$$

$n_i$, $n_t$: refractive indices of the materials; $\theta_i$, $\theta_t$: incident and outcoupling polar angles; $\varphi_i$, $\varphi_t$: incident and outcoupling azimuthal angles; $m$: diffraction order; $\lambda$: wavelength of light; $\Lambda$: grating period

First of all, to analyze the diffractive outcoupling characteristics of the grating-imprinted LGP, it is necessary to decide the range of incident angles of the light that travels inside the LGP in terms of polar and azimuthal angles. Based on the waveguide optics, the incident angle range of the incoming light to the grating is determined by the critical angle of refraction, as described in equation (2). The material of the polymeric LGP usually consists of polymethyl methacrylate (PMMA, $n = 1.492$), polycarbonate (PC, $n = 1.580$), or other transparent polymer or a glass substrate whose refractive index is approximately $1.5$ [21].

$$\theta_c \leq \theta_i \leq 90^\circ \quad (2)$$

The emitting angles of an ordinary light source like the light-emitting diode (LED) usually have a $0^\circ \leq \theta \leq 90^\circ$, $-90^\circ \leq \varphi \leq 90^\circ$ range, and the peak luminous intensity usually exists at $\theta = 90^\circ$, $\varphi = 0^\circ$. Due to the TIR condition between the two different materials’ refractive indices, the emitted light whose angle was lower than the critical value was fully reflected on the LGP. Therefore, the range of the radiation angles of the light incident into the LGP was reduced, as shown in Table 1. At the interfacial surface of diffraction, the light propagation direction ($\theta_i$, $\varphi_i$) is a function of its incident angle ($\theta_i$, $\varphi_i$), its wavelength $\lambda$, its diffraction order $m$, and its polarization state. For any incident parameter $\theta_i$, $\varphi$ and $m$, light propagation direction $\theta_i$, and $\varphi_i$ can be represented by the following equation (3).

$$\cos \theta_i = \sqrt{1 - \left(\frac{n_i}{n_t} \sin \theta_i \cos \varphi_i + \frac{m\lambda}{n_t\Lambda}\right)^2 - \left(\frac{n_i}{n_t} \sin \theta_i \sin \varphi_i\right)^2}$$

$$\cos \varphi_i = \frac{1}{\sin \theta_i} \left(\frac{n_i}{n_t} \sin \theta_i \cos \varphi_i + \frac{m\lambda}{n_t\Lambda}\right) \quad (3)$$

where $n_i$, $n_t$ are the refractive indices of the two materials in the interface.

Table 1. Emitting angle of the light source and incident angle range.

|                  | PMMA ($n = 1.492$) | PC ($n = 1.580$) |
|------------------|---------------------|------------------|
| **Emitting angle** |                     |                  |
| of the light source in the air $(n = 1.0)$ |                     |                  |
| Polar angle      | $0^\circ \leq \theta \leq 90^\circ$ | $48^\circ \leq \theta \leq 90^\circ$ |
| Azimuth angle    | $-90^\circ \leq \varphi \leq 90^\circ$ | $-51^\circ \leq \varphi \leq 51^\circ$ |

Table 2. Candidate grating period range with respect to the LGP material.

|                  | PMMA ($n = 1.492$) | PC ($n = 1.580$) |
|------------------|---------------------|------------------|
| **Period range** | $357 \text{ nm} \leq \Lambda \leq 480 \text{ nm}$ | $337 \text{ nm} \leq \Lambda \leq 453 \text{ nm}$ |
Figure 3. Angular luminance distributions in the preliminary experiments for three different grating periods: (a) 0.70 um; (b) 0.43 um; and (c) 0.36 um.
2.2. Preliminary experiment to decide the grating period

For the first design stage to determine the period of grating, let it be assumed, for approximation purposes, that the incident ray's azimuthal angle is limited to $\varphi_i = \varphi_t = 0$, and that the diffraction order is $m = -1$. Then equation (1) will be simplified as follows:

$$n_t \sin \theta_t - n_i \sin \theta_i = -\frac{\lambda}{\Lambda}$$

(4)

As the purpose of grating is to extract the light and direct it towards the normal direction to the panel, let $\theta_t = 0$ and specify the wavelength as green light ($\lambda = 532$ nm). Then the range of the grating period can be acquired as shown in Table 2, using equation (4) and Table 1.

Based on trial and error, preliminary experiments were carried out to specify the grating period when the outcoupled light would be diffracted towards the normal direction to the surface ($\theta_t = 0$). As for the three cases with different grating periods shown in Figure 3, the peak luminance was observed at $\theta_t = 0$ when the grating period was 0.43 um. The preliminary experiment results imply that the amount of outcoupled diffraction rays in the normal direction is maximized when the grating is made at period $\Lambda = 0.43$ um. Utilizing the grating equation (4), the incident angle is estimated to be 52° in the case of the PMMA LGP.

2.3. Diffraction efficiency with respect to the grating depth

Through the rigorous coupled wave analysis method [22,23], the transmission efficiency is computed assuming that the period is 0.43 um and the incident angle is 52°. Figure 4(a) shows the computational results of the diffraction efficiency with a 0.43 um period for the three representative wavelengths and two polarization states at the 52° incident angle. The computational results show that the diffraction efficiency in the range of visible light can be maximized at a grating depth ranging from 0.15–0.35 um. Figure 4(b) shows the experiment result of the diffraction efficiency for each representative wavelength under the same input conditions of period and incident angle that were used for the computation. Comparing the results, they are in good agreement with each other, and the diffraction efficiency of each incident wavelength shows the maximum value at the grating period of around 0.25 um.

3. Fabrication and measurements

The features of the designed grating in terms of period and depth were outside the region of the conventional manufacturing. In this study, for the generation of sinusoidal shape grating and ease-of-size extension, interferometer lithography was used. The 441.6-nm-wavelength He-Cd laser beam (coherence length: $\sim 30$ cm) is divided into two paths by a beam splitter. In each path, the beam passes through an objective lens to enlarge the spot diameter, and through a pinhole to eliminate the high-frequency noise in the spatial-intensity distribution. These two incident beams interfere at the master plate, which is the sensitive photoresist film on the glass substrate.

After exposure, the photoresist is developed. The period of grating is determined with the interference angles of the two incident beams. The depth and shape of the grating mainly depend on the sensitivity of the photoresist film, the exposure time, the intensity of the
Figure 5. Fabrication flows of the master pattern (a) and the replication process (b).

Figure 6. Cross-sectional photograph of the submicron period grating with respect to the different regions from P1 to P9 over the whole area.

Figure 7. Designated point of the LGP to measure the areal uniformity.
To replicate the stamp pattern on the PMMA substrate, a UV-curable material (acryl resin) is used to fill up the space between the stamp and the substrate. With UV light exposure, acryl resin is solidified and attached to the substrate because the resin and substrate have the same chemical properties. During UV exposure, the substrate is pressed to improve its replication. The most important thing in this process is to completely copy the pattern engraved in the stamp. For the improvement of the shape copying, many conditions were studied in this work. The UV light exposure intensity, exposure time, pressing force, and viscosity of the replication material are the main factors influencing the transfer rate.
Table 3. Luminance, luminous flux, and efficiency values of the proposed and conventional BLUs.

| Performance                        | BLU type   | LGP   | Diffuser | Prism #1 | Prism #2 |
|------------------------------------|------------|-------|----------|----------|----------|
| Peak luminance at the middle point (cd/m²) | Conventional | 5,529 | 1,890    | 1,670    | 2,211    |
|                                    | Proposed BLU | 9,331 | 1,782    | NA       | NA       |
| Luminous flux (lm/m²) and efficiency (%) | Conventional BLU | 2,502 (90%) | 2,316 (83%) | 2,128 (77%) | 1,973 (71%) |
|                                    | Proposed BLU | 2,100 (76%) | 1,993 (72%) | NA       | NA       |

|† Light sources: LED 3ea x 15 mA. |

Figure 9. Appearance of the assembled BLU: (a) conventional and (b) proposed.

The transfer rate can be defined as the ratio of the depth of grating. By optimizing the above main factors, a 95% transfer rate was accomplished for a 0.25 um depth, a 0.43 um period, and a sinusoidal grating by means of UV curing. The whole fabrication process is shown in Figure 5.

Figure 6 shows a cross-sectional photograph of the submicron period grating with respect to the different regions from P1 to P9 designated in Figure 7.

4. Results and discussion

The light supplied from the LED source is incident on the side surface of the LGP and is emitted in the vertical direction from the upper surface of the LGP on which the diffraction grating is imprinted.

As shown in the top part of Figure 8 and in Table 3, the light emitted from the LGP of the conventional BLU is transmitted through the diffuser and the two prism sheets to provide the maximum luminance in the vertical direction. There is an unnecessary luminance distribution caused by the large-angle outcoupling light, namely the side lobe. In the case of the proposed BLU, no redirecting film such as a prismatic sheet is required because the maximum brightness is observed in the vertical direction from the LGP. For the measurement results, the peak luminance at the center of the BLU was shown to be 2,211 cd/m² in the conventional BLU and 1,782 cd/m² in the proposed BLU. The peak luminance of the conventional BLU was higher than that of the proposed BLU. The luminous flux and efficiency of the proposed BLU, however, were shown to be 1,993 lm/m² and 72%, respectively, while those of the conventional BLU were shown to be 1,973 lm/m² and 71%. There was no significant difference in luminous flux. As the white LED, which is

Figure 10. Color dispersion characteristics of the conventional BLU (a) and the proposed BLU (b) on the chromaticity diagram.
Table 4. Optical performances of the proposed and conventional BLUs.

| Optical performance          | Conventional BLU | Proposed BLU |
|------------------------------|------------------|-------------|
| Luminous flux (lm/m²)        | Mean 1,973       | 1,993       |
|                              | Uniformity 86%   | 75%         |
| Peak luminance (cd/m²)       | Mean 2,144       | 1,870       |
|                              | Uniformity 88%   | 72%         |
| White balance and color dispersion | Mean x 0.335  | 0.339       |
|                              | Mean y 0.353     | 0.387       |
|                              | Δx 0.007         | 0.020       |
|                              | Δy 0.006         | 0.037       |

mostly color-converted from blue light, has almost all the wavelengths in the visible-light region, chromatic dispersion inevitably occurs due to the intrinsic nature of the diffraction grating. Therefore, to smoothen the peak brightness and to minimize the color dispersion, the proposed BLU needs a diffuser sheet with proper haze characteristics. The angular distribution of luminance and the luminous flux were measured to evaluate the performances of the imprinted LGP along with the designated nine regions compared with those of the conventional BLU. As shown in Figures 9 and 10, the white balance and chromaticity dispersion were measured and depicted in terms of the color coordinates. As summarized in Table 4, the white-balance performance was shown to be (0.339, 0.339), which was not particularly problematic compared to that of the conventional BLU, but the color dispersion, which was twice as large, might have adversely influenced the display quality. The chromatic dispersion can be improved by using a strong haze diffuser, but in this case, the on-axis luminance deteriorates. As the peak of on-axis luminance and the chromatic dispersion have a trade-off relationship, further research is needed to explore the ultimate solution to the dispersion problem.

5. Summary

In this study, for the edge-lit backlight unit (BLU), a novel BLU primarily composed of an imprinted light guide plate (LGP) was proposed and investigated. The diffractive grating period was designed to be 0.43 μm through the preliminary experiments and simulation; as a result, the front brightness was maximized. The efficiency of the diffraction grating in the submicron order was computed with respect to the grating depth, and the depth was determined to be 0.25 μm. Based on the designed parameters, a submicron period grating was fabricated and was transferred to the LGP. The performance comparison of the prototyped sample with the conventional BLU in terms of the outcoupling light flux, peak luminance, luminance homogeneity, and chromatic dispersion yielded the following results:

1) The adequately designed diffraction grating was found to be capable of extracting the light in the normal direction to the surface where the conventional extractors need an additional prismatic sheet to redirect the outcoupled light vertically.

2) The luminous flux of the proposed BLU was shown to be 1,993 lm/m², which is equivalent to the total outcoupled light flux of the conventional BLU.

3) The proposed BLU showed a poor chromatic dispersion performance and needs to be improved accordingly to satisfy the display quality. As there is a trade-off relationship between the peak luminance and the chromatic dispersion, a further study regarding a color dispersion level that does not sacrifice the on-axis luminance is required.

Acknowledgements

This work was supported in partial by the intramural research fund for the newly-appointed professors in year 2018 of Korea University of Technology and Education.

Notes on contributor

Hwan-Young Choi received his B.S. and M.S. degrees in mechanical engineering from Yonsei University, Seoul, South Korea in 1984 and 1986, respectively. He received his Ph.D. degree in information storage engineering from the Graduate School of Yonsei University in 2004. He joined Samsung Electronics Company (SEC) in 1986 and had been working on emerging technology development to strengthen the competitiveness of strategic business and/or to prepare for pioneering new business in mid-term future. During the year 2001 to 2012, he was the leader of display optics R&D group in Samsung Advanced Institute of Technology (SAIT) and later in LCD R&D Centre in SEC. In 2016, he moved to Korea University of Technology and Education (KOREATECH) and he is currently an assistant professor in department of Mechanical Design Engineering. His research interest includes the flat panel display architecture design and manufacturing equipment as well as opto-mechanical simulation, lighting device, and material.

ORCID

Hwan-young Choi http://orcid.org/0000-0002-6100-2283

References

[1] K. Käläntär, S. Matsumoto, T. Onishi, and K. Takizawa, SID Symposium Digest 31, 1029–1031 (2000).
[2] T. Ide, H. Numata, H. Mizuta, Y. Taira, M. Suzuki, M. Noguchi, and Y. Katsu, SID Symposium Digest 33, 1232–1235 (2002).
[3] K. Käläntär, J. of the SID 11, 641–645 (2003).
[4] S. Aoyama, A. Funamoto, and K. Imanaka, Appl. Opt. 45, 7273–7278 (2006).
[5] J.-W. Pan, and C.-W. Fan, Opt. Express 19, 20079–20087 (2011).
[6] C.-Y. Li, and J.-W. Pan, Appl. Opt. 53, 1503–1511 (2014).
[7] B. Joo, and J. Ko, J. Optical Society of Korea 19 (02), 159–164 (2015).
[8] B. Joo, and J. Ko, Current Optics and Photonics 1 (2), 101–106 (2017).
[9] A. Tagaya, M. Nagai, Y. Koike, and K. Yokoyama, Appl. Opt. 40, 6274 (2001).
[10] A. Tagaya, S. Ishii, K. Yokoyama, E. Higuchi, and Y. Koike, Jpn. J. Appl. Phys. 41, 2241–2248 (2002).
[11] T. Okumura, T. Ishikawa, A. Tagaya, and Y. Koike, J. Optics A: Pure and Applied Optics 5, S269–S275 (2003).
[12] S. Ochiai, U.S. patent 5,703,667 (1997).
[13] M. Lee, et al., U.S. patent 7,253,799 (2007).
[14] G. Chen, et al., U.S. patent 7,085,056 (2006).
[15] M. Parikka, et al., Appl. Opt. 40 (14), 2239–2246 (2001).
[16] J.H. Min, H.Y. Choi, M.G. Lee, J.S. Choi, J.H. Kim, and S.M. Lee, J. of the SID 11, 653 (2003).
[17] A.K. Aristov, et al., J. Opt. Technol. 70 (7), 480–484 (2003).
[18] H.Y. Choi, and Y.P. Park, J. of Information Display 5/1, 11–19 (2004).
[19] S.R. Park, et al., Opt. Express 15, 2888–2899 (2007).
[20] Y. Ye, D. Pu, Y. Zhou, and L. Chen, Applied Optics 46 (17), 3396 (2007).
[21] J. Kimmel, J. of the SID 20 (5), 245–258 (2012).
[22] P. Lalanne, and G. Michael Morris, J. Opt. Soc. Am. A 13, 779 (1996).
[23] S. Peng, and G. Michael Morris, J. Opt. Soc. Am. A 12, 1087 (1995).