Design and Fabrication of a Multifunctional Light-Guide Plate for LCDs

Sumitomo Chemical Co., Ltd.
IT-Related Chemicals Research Laboratory
Kiman KIM*
Tsukuba Research Laboratory
Masaaki KUBOTA
IT-Related Chemicals Research Laboratory
Kiyoharu NAKATSUKA

A two-step design method of diffractive optical elements is developed. Diffraction angle and polarization splitting property are optimized separately in two successive steps. Using this method we designed a multifunctional light-guide plate for LCDs that combines the functions of light-guide plate, prism sheet, diffusion sheet, and polarization splitting film. The optical properties of fabricated multifunctional light-guide plate substantially met the design targets.

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Introduction

The prevalence of liquid crystal devices in television, computer, telephone and other displays are notable. These liquid crystal devices use many films and sheets for better optical performance and improved efficiency of light utilization. Just for backlighting, light-guide plate, brightness enhancing film, and more than one reflective sheets, prism sheets, diffusion sheets are used. On the other hand, there is a need to reduce the number of components in order to reduce energy consumption and environmental impact and manufacturing costs. In this paper, we discuss "multifunctional light guide plate" we developed recently. This is a single plate that combines the optical functions of a light-guide plate, prism sheet, diffusion sheet and polarization splitting film.[1)]

Design

The multifunctional light guide plate combines several functions of a light-guide plate, prism sheet, diffusion sheet and polarization splitting film in a single light-guide plate, but the function of each sheet or film must be properly maintained. If possible, we want to improve the characteristics.

The functions of these are:

1) Light-guide plate: Linear or point light sources, such as cold cathode fluorescent lamps (CCFL) and light emitting diodes (LEDs), are formed into a uniform planar light source
2) Prism sheet: The front luminance is increased by condensing the light exiting from the light-guide plate
3) Diffusion sheet: Corrects the unevenness of luminance caused by the reflective structure of the light-guide plate and the prism sheet
4) Polarization splitting film: The *p*-polarization and *s*-polarization are split from natural light, and the unused polarization component is recycled to improve the light utilization efficiency

We proposed forming grooves with a specific angle in the surface opposite to the output surface of a light guide plate as a method for combining the waveguide plate and the polarization splitting film.[2)] In addition, a multilayer structure has also been proposed for the light guide plate.[3), 4)] All of these structures split polarization by surface reflection at Brewster's angle, but if the light propagating in the light guide plate is not highly collimated, the polarization splitting is insufficient. Wire grids[5)] that use metallic diffraction grating with sub-wavelength period are also used for polarization splitting, but there is a strong dependency on the angle of incidence, and improvements

∗ Currently employed by Dongwoo Fine-Chem Co., Ltd.

are necessary for use in light guide plates. Two of our members proposed the method of making the metal wire thicker and larger as opposed to the normal configuration of a wire grid for combination with light guide plates.[6] However, integrating the functions of prism sheets and diffusion sheets is still difficult.

It might be possible to combine the light guide plate, prism sheet, diffusion sheet and polarization splitting film as a holographic diffraction grating. There are two methods for making a holographic grating. One is 2-flux interference method and the other is computer-generation method (computer-generated hologram (CGH)). By the 2-flux interference method it is hard to incorporate all of the functions described above due to the difficulties inherent of the instrumental setup. Only combining a light guide plate and polarization splitting film is considered to be possible.[7] Diffusion sheet with controlled angular distribution of forward scattering and minimized back scattering can be easily made by 2-flux interference.[8] Light guide plate that combines diffuser with a prism sheet has been proposed,[9] but in this case, polarization splitting is not expected. On the other hand, no restriction of apparatus is there in case of CGH, so it is possible to combine all the functions. The combination of a light-guide plate, prism sheet and polarization splitting film, as well as the addition of a color filter function, has been proposed.[10] If the color filter is produced by a diffractive element, such as CGH, a maximum of approximately threefold improvement in light utilization efficiency can be expected. This makes use of the fact that the grating becomes a perfect polarizing beam splitter when the sum of incidence and diffraction angles does equal 90 degrees.[7], [10] However, this method requires that the incident light be highly collimated. Since it is difficult to prevent the generation of speckle noise and various types of other noise, it is extremely difficult to obtain the desired characteristics with holographic grating. Another reason of this is that the incident beam is polychromatic, incoherent and differs from the coherent reference beam needed in the recording or production process of holograms.

<Two Step Design Method>

We can presume that, rather than a complex grating like that for holograms, a diffraction grating with simple structure is suitable for obtaining uniform output light without noise. The incidence angle of light on the output surface of the light guide plate is determined by the refractive index of the light guide plate material. If this refractive index is set at 1.45, the angle of incidence to the light output surface is in the range of approximately 44 to 90°. If this incident light is out-coupled by a diffraction grating that only gives rise to lower order diffracted light of around ±2nd orders, we can expect the exit angle range of approximately ±23° (90 – 44)/2°). On the other hand, not only the period, but also the fill factor and height of the diffraction grating have a large influence on the polarization splitting. Therefore, there is a possibility to control the exit angle and the polarization splitting independently to a certain extent. Focusing on this point, we developed a two step design method for a "multifunctional light guide plate" that combines functions of light guide plate, prism sheet, diffusion sheet and polarization splitting film.[1]

1. Objectives

The multifunctional light guide plate combines a light guide plate, prism sheet, diffusion sheet and polarization splitting film, and backlight system is completed by attaching CCFL, LED or other light source and a cover formed from a reflective sheet. Therefore, we should evaluate the characteristics of backlights completed with the multifunctional light guide plate. Other than absolute surface luminance, chromaticity and other characteristics that are determined by the light source, such as CCFL and LED, the main characteristics of backlights are range of exit angle, light utilization efficiency and uniformity. The goal is making these characteristics equal to or better than current products. However, accurate simulation of light utilization efficiency is difficult. In case of reflection type polarizing beam splitter, the polarization splitting ratio (s/p ratio) is directly connected to recycling rate of unused polarization, so the light utilization efficiency was replaced with the s/p ratio. The target values are:

1) Range of exit angle: –20 to 20°
2) Polarization splitting ratio: 19 or more
3) Uniformity: 70% or higher

The polarization splitting ratio of 19 corresponds to degree of polarization of 90%.

2. Simulation Method

Range of exit angle (1) and polarization splitting performance (2) were considered being independently controllable to a certain extent, so we employed a two-step design method that optimized these separately.

(1) Controlling Exit Angle

The angle of incidence θ_i and exit angle θ_d are expressed by the angle formed by the incident light and the diffracted light, respectively, with the normal to the light output surface of the light guide plate. Letting the refractive indices of the light guide plate and the output medium (air in case of transmission, the light guide plate in case of reflection) be n_1 and n_2, respectively, the wavelength λ of the light, the period Λ of the diffraction grating, the relationship between the angle of incidence θ_i and exit angle θ_d is expressed by the following grating equations.[11)]

$$\Lambda = \frac{m \cdot \lambda}{n_2 \cdot \sin\theta_d - n_1 \cdot \sin\theta_i} \quad \text{(Eq. 1)}$$

or

$$\sin\theta_d = \frac{m \cdot \lambda + \Lambda \cdot n_1 \cdot \sin\theta_i}{\Lambda \cdot n_2} \quad \text{(Eq. 2)}$$

Here, m is an integer expressing the order of diffraction. When the order of diffraction is zero, that is, when $m = 0$, Eq. 2 is the same as the equation expressing Snell's law, and the exit angle of zero order diffracted beam follows the laws of refraction and reflection. If the right side of Eq. 2 exceeds 1.0, θ_d does not exist, and no propagating refracted light is generated. If the period Λ of the grating is selected appropriately against the wavelength λ of the light, it can be made so that higher order diffracted light does not appear. In particular, a grating where only zero order diffracted light appears is called a zero order grating, and the wire grid is a zero order grating within the range of operating wavelengths.

This equation just shows the relationship between the angle of incidence and the diffraction angle, and it does not give any information about the intensity and polarization of the diffracted light. It shows that, even if the intensity or amplitude of the diffracted light differ according to the direction of the polarization, the angle of diffraction does not change. In addition, only the refractive indices of the light guide plate and the medium of exit side are in this grating equation, and the refractive index of the grating itself is not in it. This means that even if the grating itself is a dielectric or a light absorbing medium such as metal, the exit angle of the diffracted light does not change. This is one of the bases for the two-step design method. In this first step, only the period Λ of the grating is adjusted so that the range of the exit angle is –20 to 20°.

(2) Controlling the Polarization Splitting Performance

Scalar wave theory that ignores polarization of light is insufficient, so the electromagnetic theory is necessary. Maxwell's equations must be solved, but other than for extremely limited cases, such as Mie equation for light scattering by spherical particle, analytical solutions have not been found, so numerical calculations are necessary. Here we use rigorous coupled wave analysis (RCWA),[12)] which is suitable for analyzing periodic structure like diffraction grating. All diffracted lights of incident beam within the plane perpendicular to grating lines arise within the same plane regardless of incident angle. Under these conditions, the space can be restricted to a two dimensional plane. The polarization at this time can be divided into *p*-polarization parallel to and *s*-polarization perpendicular ("senkrecht" in German) to this plane. When the incident light is not in the plane perpendicular to the grating lines, the diffracted lights do not lie in the plane, and it spreads out in a three-dimensional cone shape. Therefore, *p*- and *s*-polarization cannot be defined. Diffraction of this sort that spreads out in three dimensions is called conical diffraction.[13)] Here we will carry out the two-dimensional calculations where widely used classification of *p*- and *s*-polarization is possible.

In this second step, we adjust the fill factor, height and refractive index of the grating in order to optimize the polarization splitting ratio and the diffraction efficiency without changing grating period.

3. Design

We use LEDs as light source. The wavelength and the full width at half maximum are 555nm and 40nm respectively, and the angular distribution of intensity has the cardioid shape shown in **Fig. 1**.

PMMA is generally used for the light guide plate, but a quartz plate with a refractive index of 1.45 is chosen for its amenability to photolithography and etching. The light output surface of this quartz plate and the opposite surface (back surface) are parallel,

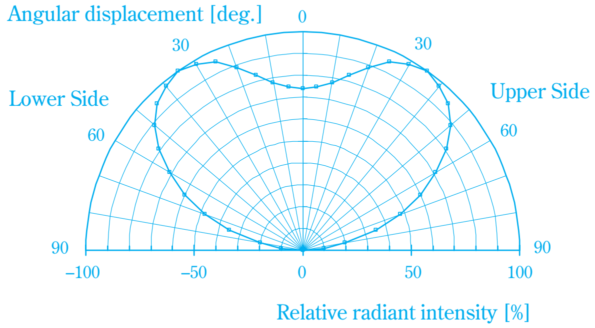


Fig. 1 The angular distribution of the LED used for the developed Multi Functional Light Guide Plate.

i.e. the plate is not a wedge shape. Since the index of refraction is 1.45, the total reflection angle is 43.6°, and the angle of incidence at the incident edge of the light guide plate for the light from the light source is in the range of ±43.6°. This means that the angle of incidence to the light output surface which

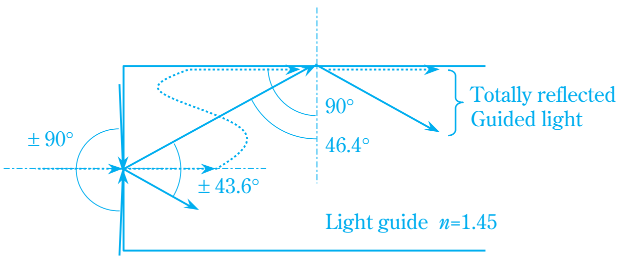


Fig. 2 Incident angles at entrance plane and exit plane of light guide plate.

is perpendicular to the incident surface of the light guide plate is 46.4 to 90° as shown in **Fig. 2**, and the light is propagated within the light guide plate by total reflection.

(1) Grating Period Λ

Since the angle of incidence of the light propagating in the light guide plate to the light output surface, that is, the grating surface, is in the range of 46.4 to 90°, this light would be diffracted to the outside within the exit angle range of ±20°. The period Λ is calculated to be 0.420 μm from the grating equation. The details of the incident light and diffracted light are shown in **Fig. 3** and **Table 1**. The transmissive diffraction is only first order, and zero order diffracted ray does not transmit. Retro-diffracted rays appear in 0th, –1st and –2nd orders. Of these, the incident angles of the 0th and –2nd order rays exceed the critical angle, so they are once again propagated within the light guide plate. The –1st order retro-diffracted ray is reflected by the back surface and impinges on the grating once again. The angle of incidence at this time is in a range of –10.8 to 5.1°, and the only transmissive diffracted light is zero order, and the exit angle range is –15.8 to 7.4°. The guided light impinges on the grating at an angle range of 46.4 to 90°, out-coupled at an exit angle within a range of a ±15.8°. This satisfies the target of an exit angle range of ±20°.

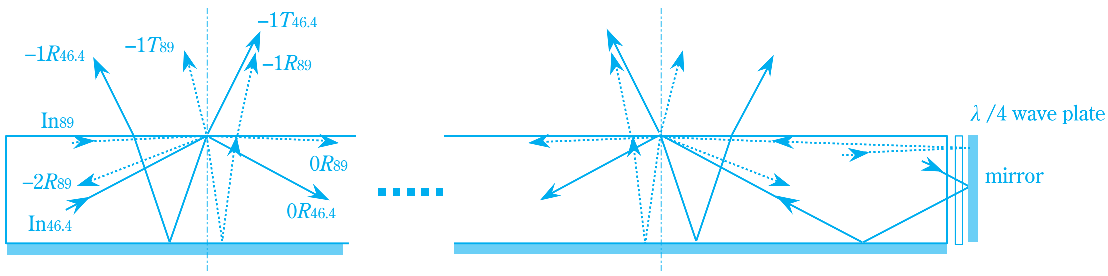


Fig. 3 Incident angle and diffraction angle
Subscripts are incident or diffraction angles, respectively. *T* and *R* indicate transmitted and reflected waves, respectively. 1, 0, –2 depict diffraction orders.

Table 1 The diffraction angles diffracted by the multifunctional light guide plate

θ_i [deg]	θ_d [deg]							
	1*T*	0*T*	–1*T*	–2*T*	1*R*	0*R*	–1*R*	–2*R*
46.4	none	none	15.8	none	none	46.4	–10.8	none
89.0	none	none	–7.4	none	none	89.0	5.1	–55.4

(2) Refractive index, Fill factor and Height of Grating

First of all, we define the light extraction efficiency *Ee* from the grating surface and polarization splitting ratio (*s*/*p* ratio) *PSR*. All rays exiting from output surface of the light guide plate are only –1st order transmissive and –1st reflective rays as described previously. Therefore, we have the following definition.

$$PSR = \frac{E^{s}_{-1R} + E^{s}_{-1T}}{E^{p}_{-1R} + E^{p}_{-1T}} \quad \text{(Eq. 3)}$$

$$Ee = \frac{E^{s}_{-1R} + E^{s}_{-1T} + E^{p}_{-1R} + E^{p}_{-1T}}{2}$$

Here, E is the diffraction efficiency for each order of the reflective and transmissive diffracted light, and this can be calculated by RCWA, which was described previously. The subscript for E indicates the order of diffraction, and R and T indicate reflective and transmissive diffracted rays, respectively. The *s*- and *p*-polarization are indicated by the superscripts *s* and *p*, respectively.

The LED light source is in close contact with the incident surface of the light guide plate. Therefore, spherical wave of light with the angular intensity distribution shown in **Fig. 1** is incident on the light guide plate. This wave will produce many reflected and diffracted rays while propagating in the light guide plate, and then the rays interfere with each other and many spurious fringes are formed. On the other hand, light emitted by LEDs is substantially incoherent, so we must consider these fringes to be noise. Therefore, we developed a design method so that these fringes do not arise.[14] In this method space and incident wave front are divided into several parts so that mutual interferences do not arise, and then calculate the intensity distribution of the diffracted light of each part at the light output surface, and these are added to obtain the total intensity distribution. Here we broke down the light in arbitrary wave front, such as spherical wave, into multiple plane waves with different orientations and amplitudes, calculated the diffraction efficiencies E for each of the plane waves separately and added these E values. The dividing interval of incident wave was 10°and the amplitudes of these waves were found from **Fig. 1**.

Next, assuming that the grating material was non-absorbing dielectrics, the effect of refractive index of grating material was investigated. We calculated the maximum values for the light extraction efficiency *Ee* at the refractive index of 1.50, 1.75 and 2.05 and at the polarization splitting ratio *PSR* of 3, 7, 11, 15 and 19. As is shown in **Table 2**, the refractive index of grating material of 2.05 or higher is necessary to have the target of 19 or higher for the polarization splitting ratio *PSR*. This refractive index of 2.05 is the value for tantalum oxide (Ta_2O_5). If titanium oxide which has a higher refractive index of around 2.50 were used, higher performance would be obtained, but for the sake of easy manufacturability, we selected tantalum oxide in this time.

Table 2 *s*/*p* ratio and maximum light extraction efficiency of gratings having several refractive indices

s/*p* ratio	Light extraction efficiency		
	n = 1.50	*n* = 1.75	*n* = 2.05
> 3	0.18	0.51	0.54
> 7	0.09	0.28	0.37
> 11	–	0.17	0.31
> 15	–	–	0.30
> 19	–	–	0.24

When the wavelength of light was set at 555nm, the refractive index of the substrate at 1.45, the refractive index of the grating at 2.05, the period at 0.420 μm, the fill factor at 0.155 and the height of the grating at 0.065 μm, the maximum value of the polarization splitting ratio *PSR* was 22.6 and the light extraction efficiency *Ee* 0.112. This was the optimal value. However, the errors shown in **Table 3** could arise in the fabrication process of the grating. Here, overetching is the phenomenon where the quartz substrate is eroded by the etching process of tantalum oxide. The changes in the characteristics of the grating corresponding to the maximum error condition are shown in **Table 3**. When overetching reaches the maximum limit, the polarization splitting ratio *PSR* does not reach the target value, but

Table 3 Fabrication error and grating characteristics

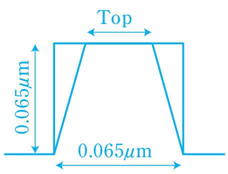
		PSR	*Ee*
width [μm]	± 0.015	20.4 ~ 22.6	0.048 ~ 0.192
height [μm]	± 0.010		
over etching [μm]	0.07	13.9 ~ 22.6	0.087 ~ 0.192

the optimum values of fill factor and height could stay at the 0.065 μm.

Furthermore, it is likely that the grating shape will be degraded by processing errors. To investigate the effect of this, we calculated the polarization splitting ratio *PSR* and the light extraction efficiency *Ee* when the rectangular shape was compromised to a trapezoidal shape. As is shown in **Table 4**, the results were that *PSR* was hardly affected at all, and *Ee* decreases as the upper part of the trapezoidal shape narrows down.

Table 4 Effect of trapezium deformation of grating by fabrication errors

Top [μm]	*PSR*	*Ee*
0.065	22.56	0.112
0.060	22.51	0.105
0.055	22.17	0.095
0.050	21.87	0.087



Fabrication

The multifunctional light guide plate we designed was fabricated by x-ray lithography and etching. A grating was formed on the central 10×10mm part of a 100×100mm quartz substrate with a thickness of 1mm. A scanning electron microscopic (SEM) photograph of the finished grating is shown in **Fig. 4**. In addition, the results of measurements of the dimensions of each part are given in **Table 5**. It was finished with the expected maximum value of 20 to 25%.

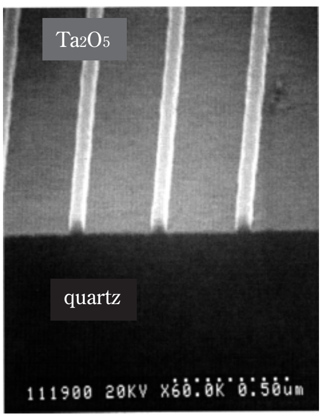


Fig. 4 SEM image of the fabricated Multifunctional Light Guide Plate

Table 5 Measured size of fabricated grating

	size [μm]	error [μm]
period [μm]	0.420	± 0.000
width [μm]	0.065 ~ 0.069	+ 0.004
height [μm]	0.065	± 0.000
over etching [μm]	0.013	+ 0.013

In addition, we found almost no degradation of the shape.

An LED was attached to the fabricated multifunctional light guide plate, and a mirror with a reflectivity of 99% was attached to the back surface. The surface opposite to the light output surface was left open. A polarizing film was applied to the light output surface, and the brightness and uniformity of the *s*- and *p*-polarized light are shown in **Fig. 5**. The results of measurements of the angular distribution for the luminance at the center are shown in **Fig. 6**. Because of an positioning error of the LED, the peak was shifted approximately 1° off, but the output rays exited within a range of ±15° as designed. The measured

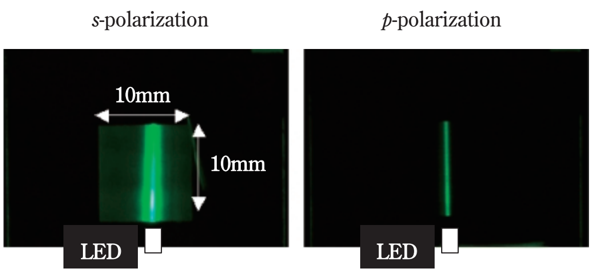


Fig. 5 Polarization splitting characteristics and luminance uniformity of the fabricated Multifunctional Light Guide Plate

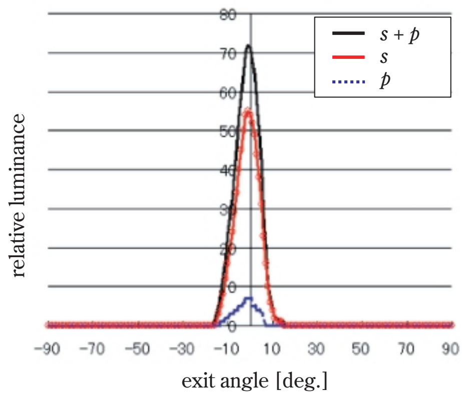


Fig. 6 Angular distribution of exit light from the fabricated Multifunctional Light Guide Plate

polarization splitting ratio was 9.3 instead of designed value of 23.0. These *s/p* ratios were converted into degree of polarization of 80.4% ad 90.7% respectively. The difference between the measured and the design values of degree of polarization can be thought as effect of conical diffraction, but more precise measurements and three-dimensional calculations are necessary.

Conclusion

We developed a two-step design method for independently adjusting the range of the exit angle and the polarization splitting ratio, and we designed and fabricated a multifunctional light guide plate that brings together a light guide plate, prism sheet, diffusion sheet and polarization splitting film into one plate to achieve thinness, lightweight, robustness and low cost. The prototype multifunctional light guide plate exhibited characteristics that met the design targets. However, (1) there was a somewhat large difference with the design target for the polarization splitting ratio; (2) it is difficult to produce large sizes because of the limitations of micro fabrication process; and (3) the design was made only for green light with a wavelength of 555nm, so it was not optimized for red and blue light. We must solve these problems in order to move forward. For (1), it is considered that it can be improved by three dimensional RCWA. The demerit in (2) is not a problem when making large LED backlights where small edge-lit backlights are put together in a tile formation, and it becomes to be possible to use in television backlights. For (3), we have developed a method for fabrication by combining multiple diffraction gratings for red, green, blue, etc.,[15] and we are continuing the development for practical use.

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PROFILE

Kiman KIM

Sumitomo Chemical Co., Ltd.
IT-Related Chemicals Research Laboratory
(Currently employed by Dongwoo Fine-Chem Co., Ltd.)

Kiyoharu NAKATSUKA

Sumitomo Chemical Co., Ltd.
IT-Related Chemicals Research Laboratory
Senior Research Specialist

Masaaki KUBOTA

Sumitomo Chemical Co., Ltd.
Tsukuba Research Laboratory
Research Associate