45.2: Moiré-Free Collimating Light Guide with Low-Discrepancy Dot Patterns

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Abstract
Using the notion of discrepancy, we developed a new technique for generating uniformly distributed dot patterns. We designed and prototyped a light guide having prismatic grooves and micro scatterers on the surface. We experimentally confirmed that the new pattern of the micro scatterers effectively prevents moiré patterns, and improves the luminance homogeneity.

1. Introduction
Edge-lit backlight (BL) units have been widely used in notebook computers because of their thinness and their uniform luminance. As the personal computer market grows, liquid crystal displays must meet stricter requirements for uniformity, physical dimension, and luminance, while controlling manufacturing costs.

To refine conventional BL units, several authors have proposed BL units including integrated light guides (LGs) using parallel prismatic cuts on the light-emitting surface [1, 2]. There have also been several proposals to replace the conventional diffusing white spots printed on the bottom surface with carefully

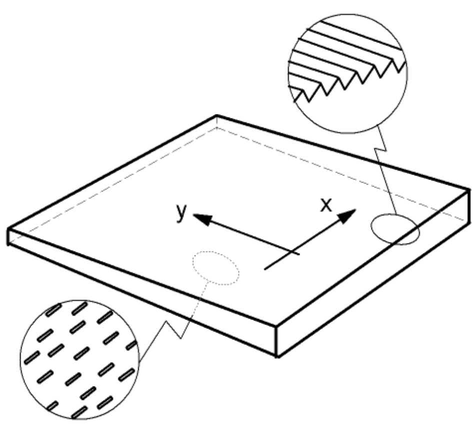

Fig. 1. Light-guide with prismatic grooves.

designed micro-structures [3]. Figure 1 shows such a LG, where many light-scatterers are densely located on the bottom surface while the top surface has a prismatic cut. Because of the integration with one prism sheet, such BL units can considerably reduce manufacturing costs when combined with recent development in high-precision injection molding techniques. By appropriately designing the prism configuration and the shape of the micro-structures, the LG also produces highly collimated light with lower loss than conventional LGs.

However, the structural simplicity tends to cause certain problems. The most crucial one is the occurrence of moiré patterns, which are caused by optical interference between the pattern of the scatterers and other elements with a periodic structure, such as the prismatic grooves, prism sheets, and liquid crystal cells. Randomizing the arrangement of the scatterers is an effective way to avoid moiré patterns. Taniguchi, Hira, and Mori proposed such a method, where the random dot pattern is based on sequential generation of pseudo-random numbers [4]. However, methods of this kind exhibit several drawbacks: the generated patterns unavoidably have unevenness peculiar to pseudo-random numbers, and it is difficult to realize density distributions having areas with higher density.

In this paper, we report on a moiré-free collimating LG created by utilizing a novel theoretical approach to generating super-uniform irregular dot patterns [5].

2. Dynamical LDS Method
To evaluate the qualities of dot patterns, we introduce a measure of discrepancy [6]. For a point set defined in a 2-dimensional unit domain $[0,1]^2$, its discrepancy under the $L_{\max}$-norm is defined by

$$D_N = \sup_{(x,y)\in[0,1]^2} \left| \frac{\#E(x,y)}{N} - xy \right|,$$

here N is the total number points, and $\#E(x,y)$ represents the number of points within $E(x,y) \equiv [0,x) \times [0,y)$. By definition, the discrepancy is zero if the percentage of the number of points in an arbitrary subspace is the same as the percentage of the area of the subspace. Thus, discrepancy can be a measure of the uniformity of point sets. There is a known class of sequences called low-discrepancy sequences (LDS), and a systematic algorithm exists to add disorder for these sequences [6]. Considering the density distributions as the occupation probabilities of the dots [5], these sequences provide a good means to generate initial dot patterns. To the best of authors'

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knowledge, the present work is the first attempt to utilize the notion of discrepancy for designing physical dot patterns.

Since the dots for optical use have a finite diameter, there is some inter-dot overlap in the initial states that are generated using LDS. For optical uses, the overlap is undesirable since it caused anomalous kinds of scattering. To remove the overlap, we employ a theory from molecular dynamics as schematically explained in Fig. 2, where square dots interact based on repulsive force. By controlling the average interaction energy, we obtain appropriate dot patterns without abnormal clustering. We call this approach the dynamical LDS (DLDS) approach.

Figure 3 shows the resultant dot patterns after a common relaxation process for initial states generated with (a) a pseudo-random number and (b) LDS. As shown in the figure, DLDS patterns keep the discrepancy low in spite of the relaxation process, so that they are visibly and quantitatively different from patterns generated with pseudo-random numbers.

3. Prototype

We made two acrylic 15-inch-diagonal LGs with an injection molding method. As shown in Fig.1, both have prismatic grooves

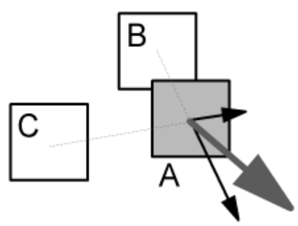
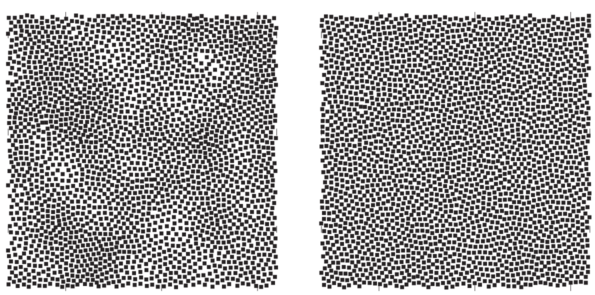


Fig. 2. Molecular-dynamical model.



(a) pseudo-random number (b) LDS

Fig. 3. Visible roughness due to pseudo-random numbers and the uniformity of a DLDS pattern.

and densely-distributed rectangular dimples as light-scatterers. Their detailed dimensions are shown in Figs.4 and 5. The longer axis of the dimple is parallel to the *x*-axis of the LG.

To place the scatterers, we employed two different algorithms for randomizing. One is based on a known method [4], where coordinates of each scatterer are determined by using a small displacement according to pseudo-random numbers, starting from a rectangular lattice point. We denote this method as the pseudo-random perturbation (PRP) method. This has been the *best* randomization method known so far.

The other method, our proposed algorithm, uses no lattice points. For the initial state, each dot can occupy any point. As shown in Fig. 3, methods of this kind unavoidably give rise to visible roughness when pseudo-random numbers are used. Thus, LDS is of great significance in the random pattern generation.

4. Results

Figure 6 shows a comparison of the distributions of the dimples near the center of the thicker edge of the LGs, using (a) the PRP method and (b) the DLDS method. Both patterns are of good homogeneity and randomness, but a close inspection shows that

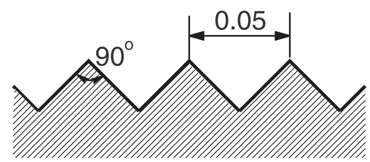


Fig. 4. Prismatic groove (in mm).

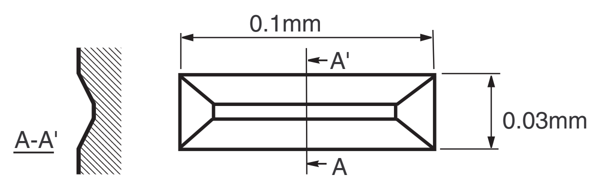


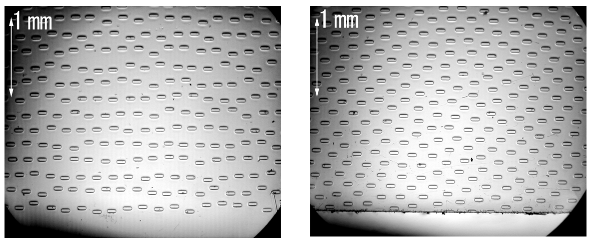
Fig. 5. Light-scatterer.

there are traces of a lattice in Fig. 6(a), where the vertical spacing between the horizontal traces is about 0.193 mm on average. It becomes larger for the dots closer to the center of the LG (not shown). On the other hand, the pattern in Fig. 6(b) shows much better homogeneity in spite of its randomness, without any traces of a lattice on a directly visible scale[3].

Although seemingly slight, the above difference brings about a major difference in observed luminance distributions. Figure 7 shows a comparison of snapshots of each LG through a 15-inch-diagonal UXGA liquid crystal (LC) cell. For illumination, a cold cathode fluorescent lamp (CCFL) is placed parallel to the *x*-axis, and an Ag-reflective sheet is placed beneath each LG. The bottom edge of the pictures is near the center of the CCFL. The height of the shown area is 68 mm. One can see a clear moiré pattern in Fig. 7(a), while no such interference pattern is observed in (b) with its much more homogeneous luminance distribution[4].

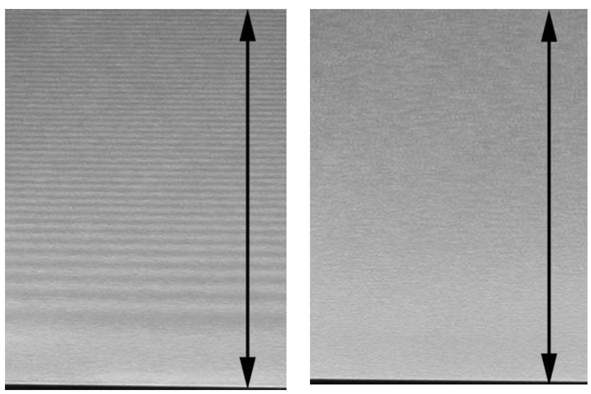
[3] Although there might be observed traces of an oblique lattice structure in Fig. 6(b), the pattern disappears on a scale larger than a few centimeters, i.e. the DLDS patterns have substantially no long-range order.

[4] Even for realistic backlight configurations with an additional prism sheet, the PRP-LG still exhibits a moiré pattern.



(a) PRP method (b) DLDS method

Fig. 6. Snapshots of the dimple patterns using (a) the PRP method and (b) the DLDS method.



(a) PRP method (b) DLDS method

Fig. 7. Snapshots through an LC cell using (a) the PRP method and (b) the DLDS method.

In the PRP method, the periodic spacing of the horizontal moiré pattern becomes larger from the top to the bottom. This is due to the decreasing spacing of the original lattice, and will be discussed in the next section in detail.

Figure 8 shows a comparison of the measured relative luminance distributions corresponding to the vertical cross sections shown by arrows in Fig. 7. We can see from Fig. 8(a) that the wavelength of the moiré pattern increases from about 0.84 mm to 13.0 mm while going from the top to the bottom in Fig. 7(a). We can also estimate the luminance amplitude as about 5nit. In Fig. 8(b), there is observed only an aperiodic irregularity in luminance, with the luminance amplitude estimated as 2 to 3 nit. Figures 7 and 8 definitely show that the DLDS method has a great advantage over the PRP method, the best previously known.

5. Discussion

Let us consider the moiré pattern shown in Figs.7 (a) and 8 (a). Using a Fourier domain approach [7], the interference effects between the multiple periodic patterns are well described in terms of multiplicative superposition of the transmittance functions. When light is transmitted through two optical components with the periodic structures of wave number vectors $\mathbf{k_1}$ and $\mathbf{k_2}$, respectively, the transmitted light will include a Fourier component as

$$\exp(\pm i\mathbf{k}_1 \cdot \mathbf{r}) \times \exp(\pm i\mathbf{k}_2 \cdot \mathbf{r}) = \exp[\pm i(\mathbf{k}_1 \pm \mathbf{k}_2) \cdot \mathbf{r}],$$

due to multiplicative superposition. Therefore, when the two periodic structures are arranged in parallel, the resultant wave includes at least a wavelength of

$$l = \frac{2\pi}{|k_1 - k_2|} = \frac{l_1 l_2}{|l_1 - l_2|},$$

where $k_i = |\mathbf{k}_i| = 2\pi / l_i$ for i =1 and 2. This gives the wavelength of the first order moiré patterns.

The observed interval of the periodic moiré patterns can easily be derived from this formula. We have just estimated the nearest-neighbor spacing of the original lattice as l_1 = 0.193 mm in Fig. 6 (a). For the UXGA LC cell with a spacing of l_2 = 0.190 mm, this lattice should cause a moiré pattern with l = 13.6 mm, which is very close to the measured periodic spacing of 13.0 mm. Similarly, the measured wavelength of 0.840 mm near the top of Figs. 7(a) and 8(a) is derived from the UXGA spacing of 0.190 mm and combined with an experimentally estimated original lattice spacing of 0.245mm. The quantitative analysis presented here can also be applied more generally.

This modulation of the moiré patterns is a result of that of the original lattice of the PRP method. For practical designs, we need to enhance the density of the dimples near the corners and CCFL in order to make the luminosity even. Generally, it is very difficult to calculate continuous and seamless mesh patterns faithful to a given distribution. Even if a continuous mesh is successfully generated, some strong optical interference will probably be observed because the mesh includes a wide range of wavelengths, including certain ranges which cause visible moiré patterns. The DLDS method, on the other hand, has no drawbacks of this kind, as well as none of the roughness peculiar to pseudo-random numbers.

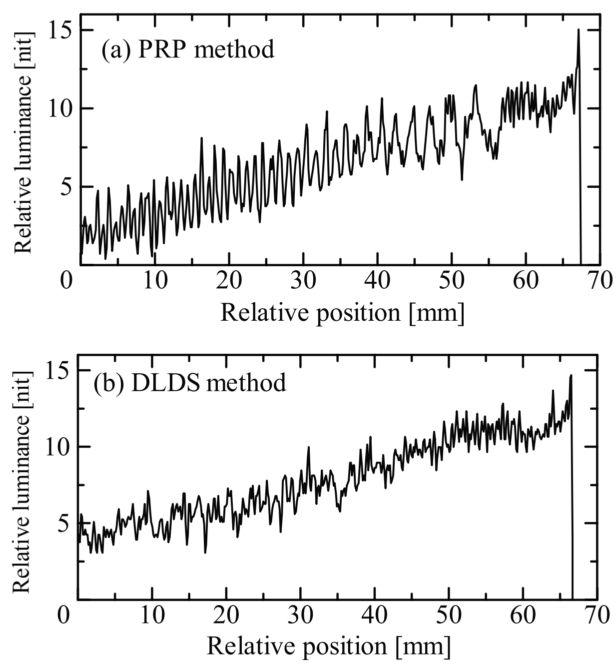


Fig. 8. Relative luminance distribution along the arrows in Fig. 7 for LGs using (a) the PRP and (b) the DLDS methods.

The moiré pattern as shown in Fig. 7(a) is considerably weakened if diffuser sheets are inserted into the backlight unit. This is not a good solution, however, because it harms the collimating nature of the original design. For this reason, we feel our approach will be essential for the next generation of highly collimated backlighting systems.

6. Concluding Remarks

Based on a new technique for random dot pattern generation, a moiré-free collimating light guide was designed and prototyped. We experimentally confirmed that the new irregular pattern of the light-scatterers effectively eliminates moiré patterns, and greatly improves luminance homogeneity. This technique will play an essential role in the next generation of high-luminance BL units.

These super-uniform dot patterns can be also applied for other optical devices such as diffuser sheets, or used for some problems in computer science. Detailed descriptions of other applications will appear elsewhere.

7. Acknowledgements

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