A novel dot pattern generation to improve luminance uniformity of LCD backlight

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Abstract— We report on a novel theoretical approach to generate irregular dot patterns, providing an integrated solution to difficulties peculiar to collimated-type backlight units. By applying this technology to a light guide and a diffuser film, the luminance uniformity is greatly improved.
Keywords— collimated backlight, light guide, masking pattern, irregular dot pattern, luminance uniformity

1. Introduction

By analogy with white paper, the conventional design of backlight units for liquid crystal displays (LCDs) has aimed at creating a planar light source having uniform angular and spatial distributions of light. Recently, an alternative approach was proposed to reduce light losses when passing through a liquid-crystal cell by collimating the light bean to be as perpendicular as possible to the light-emitting surface. Figure 1 (a) shows such a backlight unit, which is referred to as a collimated back light (CBL) hereafter, with a comparison to a conventional design shown as Fig.1 (b).

The major feature of the CBL is a collimating light guide. In the conventional designs, the light guides have a periodic pattern of diffusing white spots on the bottom surface. There have been several proposals to replace the conventional diffusing white spots with the carefully designed micro-structures [1], which are employed in the CBL. In addition, the CBL minimizes light losses due to surface effects by removing some of optical sheets: The CBL uses an integrated-type light guide with parallel prismatic cuts on the light-emitting surface [2, 3]. The wedge angle of the light guide is arranged so as to produce more collimated light than a conventional light guide. A diffuser film with lower diffusing power and a single prism sheet are placed above the light guide. However, the structural simplicity of the CBL tends to cause certain problems. The most crucial one is the occurrence of moiré patterns 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. Moreover, one often observes local muras (a technical term for a cloudy defect derived from a Japanese word) around the corners and the edges because of the reduced diffusing effect of the optical system. It is generally very difficult to eliminate these muras using conventional techniques without impact on the collimating properties.

In this paper, we report on a novel theoretical approach to create irregular dot patterns, providing a solution to these difficulties. By generating a pattern of the scatterers on the light guide using our technology, the moiré patterns can be eliminated without any. In addition, a diffuser film

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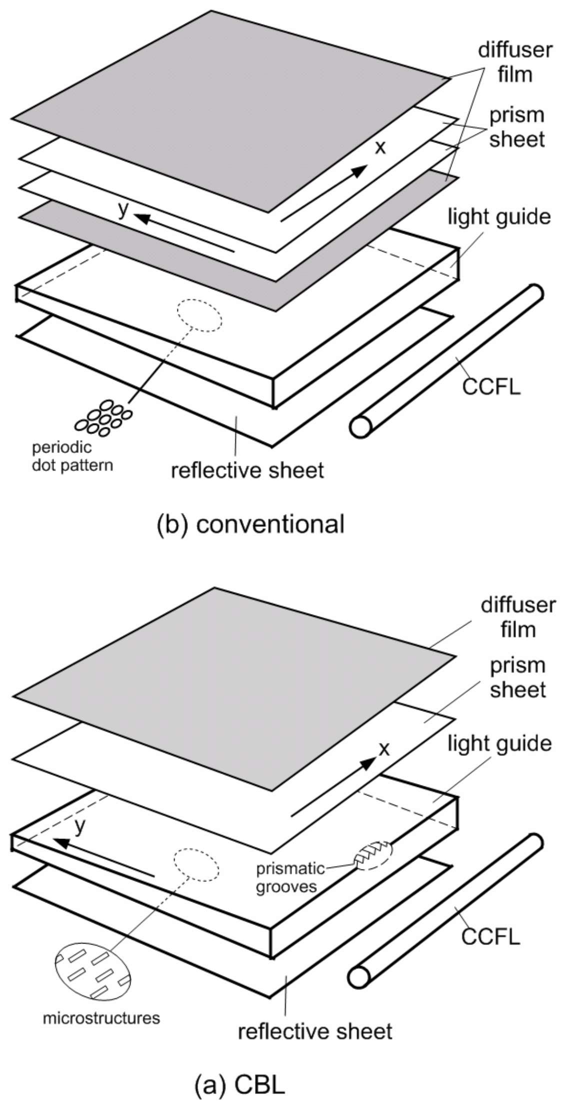


Fig. 1 Comparison between the conventional backlight and the CBL.

with a masking pattern generated by our technology greatly improves the luminance uniformity of the CBL. We will review in Section 2 the concept of low-discrepancy sequences, and the difficulties in conventional methods based on pseudorandom numbers. In Section 3, we will briefly explain how to remove abnormal clustering between dots from an initial pattern. In Section 4, we show some experimental results with a prototype CBL. In Section 5, we will briefly give concluding remarks.

2. Quality of Irregularity

Randomizing the arrangement of the dots, which abstractly denote either the microstructures on light guides or printed spots on diffuser films, is an effective way to avoid moiré patterns. For optically useful dot patterns, most of the practical randomization techniques known so far are based on pseudorandom numbers. However, pseudorandom numbers have several drawbacks as known in the field of digital halftoning [4]. Instead, we utilize the notion of low discrepancy.

To evaluate the qualities of dot patterns, we introduce a measure of discrepancy [5]. For a point set defined in a 2-dimensional unit domain $[0,1]^2$, its discrepancy under the L_∞-norm is defined by

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

where N is the total number of 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.

Fortunately, there is a known class of infinite sequences called low-discrepancy sequences (LDS), which satisfy the inequality

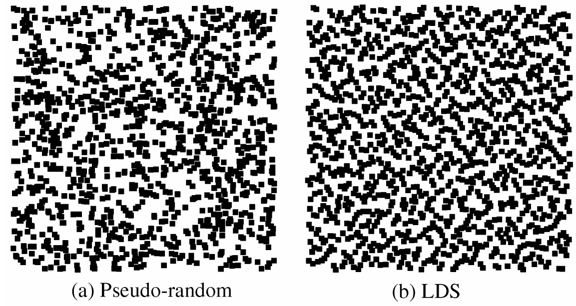


Fig.2 Comparison between (a) pseudorandom number and (b) LDS.

$$D_N(\mathrm{LDS}) \le C\frac{(\log N)^2}{N}$$

for the first N points in the sequences, where C is an N-independent constant. This may be compared with the results of random numbers [5],

$$D_N(\mathrm{random}) = O\left(\sqrt{\frac{\log\log N}{N}}\right).$$

Roughly speaking, one finds that the ratio of the discrepancy of pseudorandom numbers compared to that of the LDS tends to be infinite as N increases.

Figure 2 shows the comparison between the LDS and pseudorandom numbers. In this figure, we utilized the generalized Niederreiter sequence [6] for the LDS, and the rand() function of Microsoft Visual C++ 6.0 for the pseudorandom numbers. The figure clearly shows that the dot pattern using the LDS is more homogeneous than that of the pseudorandom numbers. In our experience, the mura of the pseudorandom pattern is hard to eliminate with any post processing method. This demonstrates the utility of LDS in LCD design.

There is inter-dot overlap in both patterns because of the finite diameter of dots. For optical uses, this overlap is undesirable since it causes anomalous scattering. To remove the overlap within pseudorandom-number-based approaches, Taniguchi, Hira, and Mori proposed a method, which we call the pseudorandom perturbation (PRP) method. Their strategy is simple: If inter-dot overlap is found, the coordinates of the overlapping dots are regenerated based on pseudorandom numbers [7]. The initial pattern is generated based on periodic lattice points. Such hit-or-miss methods are, however, unsuitable for the CBL, because they unavoidably have the nonhomogeneity peculiar to pseudorandom numbers, and because the periodicity of the

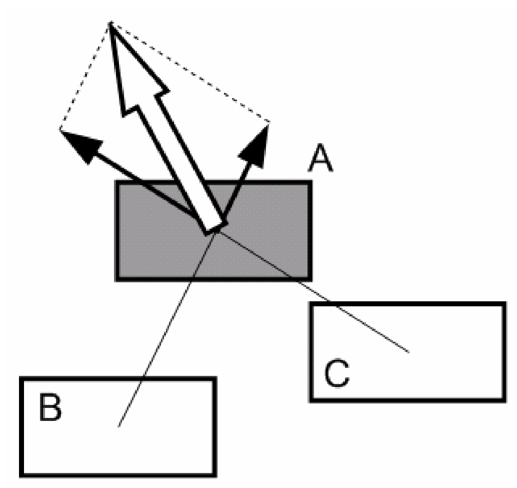


Fig.3 Dynamical post processing through repulsive interaction

original lattices survives to a greater extent when the density of the dots is higher. It is also difficult to realize density distributions having certain areas with higher density.

3. Dynamical Post Processing

3-1 dynamical model

We impose a requirement on our redistribution method that it should have complete permutation symmetry between any two arbitrary dots. It should not be such a "discriminatory" method that discriminates between some dots whose coordinates are regenerated and other dots whose coordinates remain the same, as in the PRP method. The equation of motion of mechanics having two-body interaction satisfies this requirement. For constants *m* and *c*, it is written as

$$m\frac{d^2\vec{r}_i}{dt^2} + c\frac{d\vec{r}_i}{dt} = \vec{F}_i \equiv \sum_j \vec{f}_{ij},$$

where represents a (typically repulsive) interaction force between dot *i* and *j*. For the initial conditions of the coordinates of the dots, we use an irregular dot pattern generated with the LDS. As time proceeds, the abnormal clustering between dots should be removed because of the repulsive force. In Fig. 3 we illustrates the repulsive

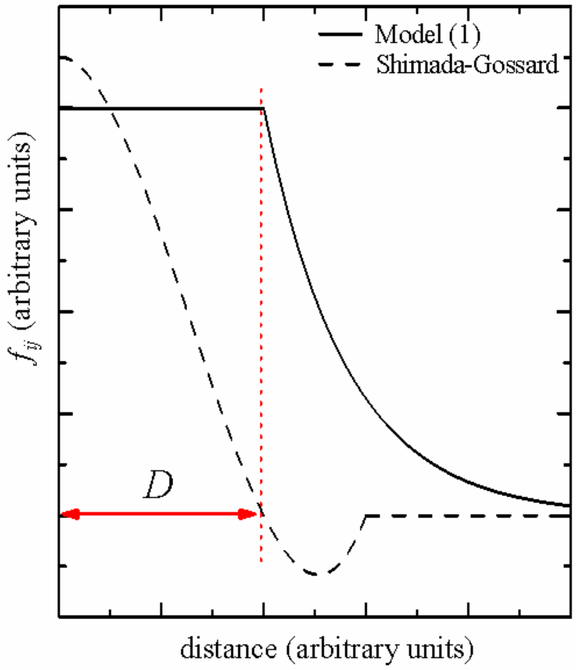


Fig.4 Comparison between inter-dot force models

interaction between dots. Note that the situation is not one-sided. The dots B and C are also affected by the surrounding dots, showing the perfect permutation symmetry in the relaxation algorithm.

Assuming the arbitrary constant *c/m* is infinitely large, we solve the equation of motion iteratively as

$$\vec{r}_i(t+\Delta t)-\vec{r}_i(t)=\frac{1}{c}\Delta t\vec{F}_i(t),$$

where Δt is a small parameter formally representing a time interval. This is the nontrivial lowest order approximation with respect to the interaction force. In our experience, the degree of approximation barely affects the overall quality of the resultant patterns, where the number of dots is sometimes on the order of one million.

3-2 Inter-dot forces

Various kinds of force models can be used [8]. For example, consider a central force model whose magnitude is given by

$$f_{ij}=\begin{cases}1 & \text{for } r<D \\ \exp[-(r-D)/L] & \text{for } r\geq D\end{cases}, \quad (1)$$

where r represents the distance between dot *i* and *j*. D and L denote constants. Figure 4 illustrates this force model as compared to another model with a minimum point. That model was used in the bubble mesh technique, which is somewhat similar to our redistribution method, in the field of automatic mesh generation for finite element analysis (Shimada-Gossard [9]). As far as the LCD applications are concerned, our observations show that models without any minimum point give better irregular dot patterns than the Shimada-Gossard model. This is because our dynamical system is a highly "frustrated" system, whose energy landscape would be very complicated due to the irregularity introduced in the initial state. In contrast to the bubble-mesh system, our system would not have a clear equilibrium state.

Although the models discussed above have no angular dependence, it is interesting to see patterns brought about by anisotropic models. For instance, Fig. 5 shows an irregular dot pattern generated using

$$f_{ij}=\begin{cases}1 & \text{for } r<D \\ \exp[-(\max\{x,y\}-D)/L] & \text{for } r\geq D\end{cases} \quad (2)$$

Here we used the standard notation

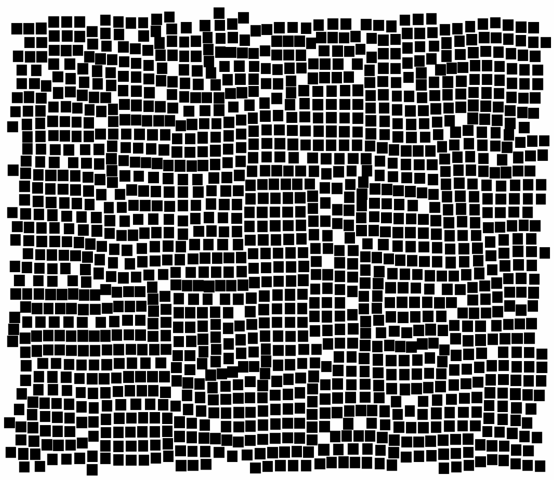
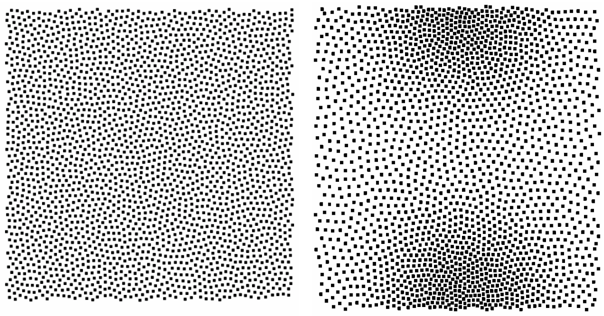


Fig. 5 Calculated irregular dot pattern using the force model (2), which is not suitable for a CBL.



(a) (b)

Fig.6 Dot patterns calculated with the DLDS method for (a) a uniform density and (b) a density distribution with a steep gradient.

$r=\sqrt{x^2+y^2}$, and the initial pattern was generated with the LDS under a uniform density distribution. Although the generated pattern is not suitable for the LCD applications, we see that our model is capable of producing various types of dot patterns.

Figure 6 shows the resultant dot patterns when an LDS initial pattern was post-processed using the Model (1). As shown in the figure, the patterns exhibit no visible mura even for a steep density gradient. For additional techniques to create such density distributions, see Ref. [10]. We call the present approach the dynamical LDS (DLDS) approach.

4. Applications

4-1 light guide [11]

Figure 7 shows a comparison of the distributions of the microstructures of the integrated-type light guide near the center of the thicker edge of the light guide, using (a) the PRP method and (b) the DLDS method. The microstructures are rectangular-shaped with a size of 100 μm by 30 μm. Both patterns are of good homogeneity and randomness, but a close inspection shows that there are traces of a lattice in Fig. 7(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 light guide (not shown). On the other hand, the pattern in Fig. 7(b) shows much better homogeneity in spite of its randomness, without any traces of a lattice on a directly visible scale.

Although seemingly slight, the above difference brings about a major difference in

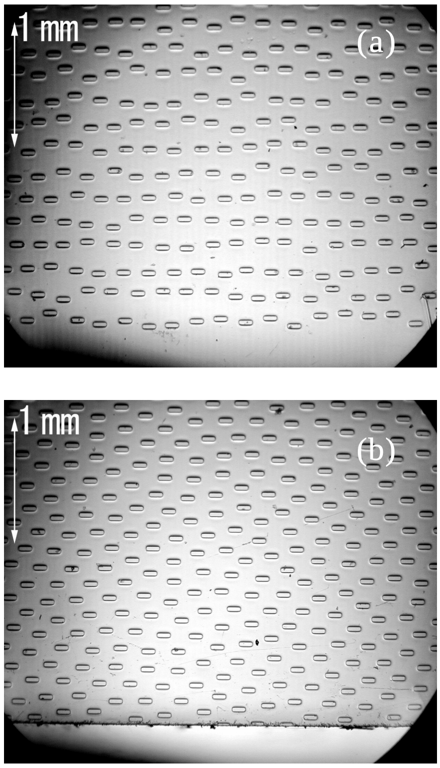
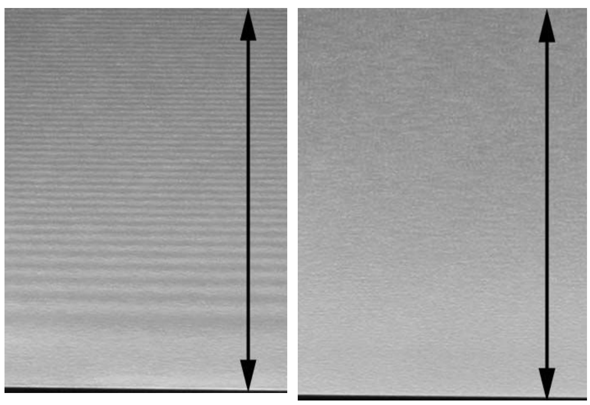


Fig. 7. Snapshots of the bottom surface of light guide using (a) the PRP method and (b) the DLDS method.



(a) (b)

Fig. 8. Snapshots through a liquid-crystal cell using (a) the PRP method and (b) the DLDS method.

observed luminance distributions. Figure 8 shows a comparison of snapshots of each light guide through a 15-inch-diagonal UXGA (ultra extended graphics array) liquid crystal cell. For illumination, a cold cathode fluorescent lamp (CCFL) was placed parallel to the x-axis, and an Ag-reflective sheet was placed beneath each light guide (see Fig. 1(b)). The bottom edge of the pictures is near the center of the CCFL. The height of the area is 68 mm. One can see a clear moiré pattern in Fig. 8(a), while no such interference pattern is observed in (b) with its much more homogeneous luminance distribution. For more details on the application to light guides, see Ref. [11].

4-2 masking pattern on diffuser film

The DLDS method can generate uniform irregular dot patterns with arbitrary density distributions. As shown, by using an appropriate distribution for the micro-scatterers on the light guide, most of luminance muras can be reduced from the CBL. However, it is difficult to completely eliminate such undesirable muras as depicted in Fig.9. A diffuser film having weak diffusing power printed with a local masking dot pattern can be a good

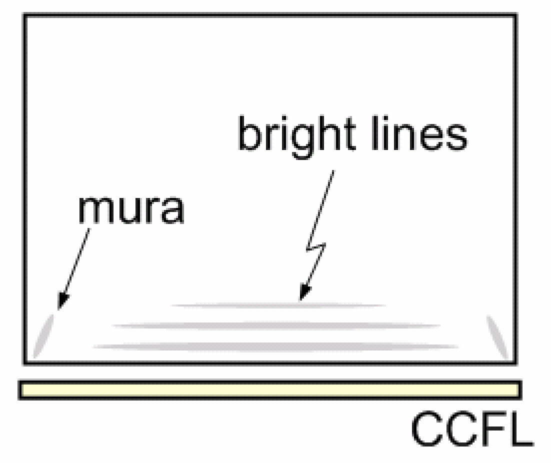


Fig. 9 Schematic depiction of the undesirable bright lines and muras observed in the CBL.

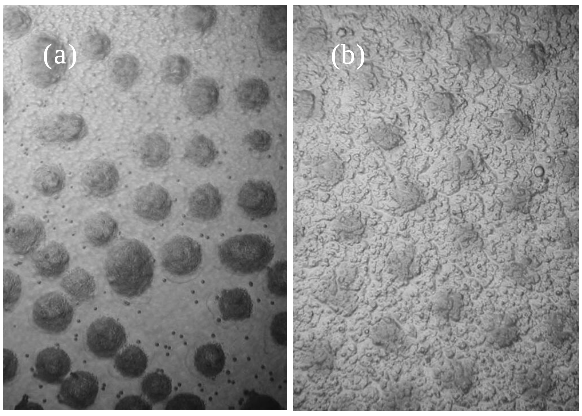
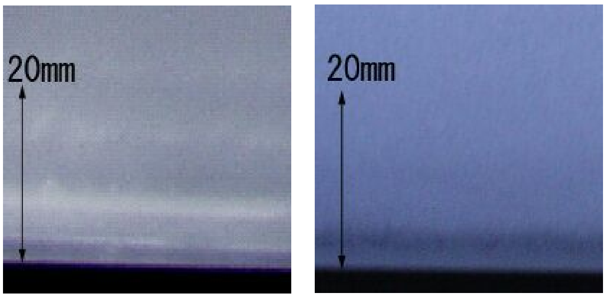


Fig.10 Masking pattern on the diffuser films.

solution for the CBL, where the collimating properties should not be weakened by using strong diffusers.

Figure 10 shows close-up photos for the masking patterns using (a) the PRP method and (b) the DLDS method. The masking spots are printed using a silkscreen technique, and their diameter is on the order of 100 micrometers. The density distributions of the spots are optimized to eliminate the muras according to a measured luminance distribution. The resultant density distribution includes regions having area densities greater than 50% as well as steep density gradients. For the DLDS pattern, we use a relatively thin ink medium to keep the diffusing power low. As in Fig. 7, the DLDS pattern exhibits more homogeneity than that of the PRP pattern. While these pictures are taken at a relatively low density area, the PRP pattern tends to have abnormal clustering and mura, which are directly visible to the eye in higher density areas. This is especially true for the thin ink medium.

Figures 11 and 12 demonstrates the improvement of luminance uniformity. We see that the bright lines and the corner muras are eliminated after the DLDS masking pattern is used. If the same masking pattern is generated with the PRP method, visible inhomogeneity is observed as shown in Fig.13, which is taken in the same

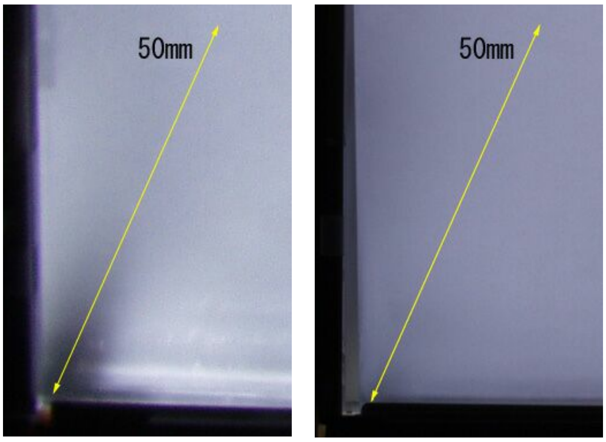


(a) (b)

Fig. 11 Elimination of the bright lines.

position as Fig. 11. This again confirms that the DLDS method plays an essential role for designing high light-use-efficiency backlight units as the CBL.

The relative luminance distribution along the vertical arrows in Fig.11 as well as the oblique arrows in Fig. 12 are shown in Fig.14 (a) and (b), respectively. When there is no masking pattern, one can recognize in Fig. 14 (a) at least three bright lines at 4, 8 and 16 mm, which are eliminated when the DLDS masking pattern is used. We also observe that the undesirable shadowing around the corner is eliminated in Fig. 14 (b).



(a) (b)

Fig.12 Elimination of the corner mura.

5. Concluding Remarks

Using the notion of discrepancy, we have discussed a molecular-dynamical method to generate irregular dot patterns. The DLDS method provides both irregularity and uniformity with very high quality. We confirmed that the DLDS method provides an integrated solution to eliminate muras in highly collimating backlight units.

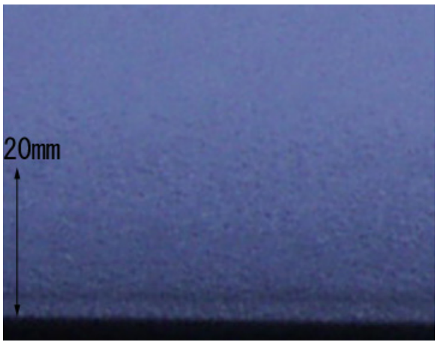


Fig. 13 Visible inhomogeneity observed when a masking pattern generated with the PRP method is used.

The DLDS approach gives a way of generating a dot pattern for an arbitrary density distribution. However, it gives no answer about how to optimize the density distribution itself. Currently, it is difficult to precisely calculate an actual luminance distribution from given dot patterns used in LCDs. The first reason that modeling the phenomena of complicated reflections and absorptions at the edges of light guides is generally a tough task. These phenomena cause the crucial muras as in Fig. 9, and therefore must not be neglected. Second, if the complicated conditions could be faithfully modeled, ray-tracing simulations would not be practically feasible due to the enormous number of dots (more than one million).

There are also several other issues to be solved in the field of optical simulation in LCDs. It was only very recently that the automated measurement of luminance muras became possible [12] in spite of its importance. By developing evaluation techniques of this kind, as well as theoretical design methodologies such as the DLDS method, it is needed to promote optical design automation.

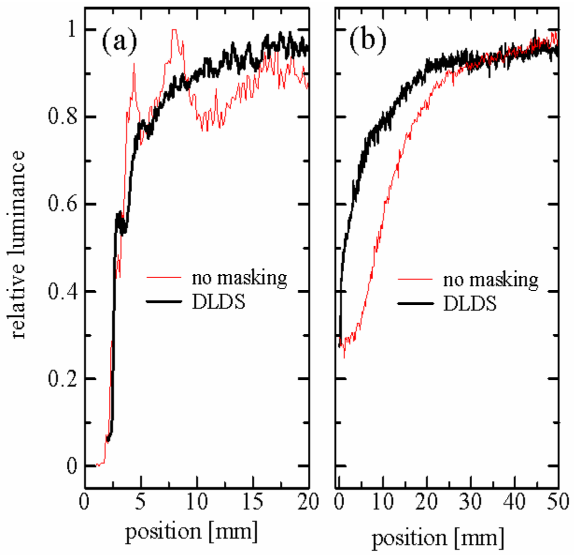


Fig. 14 Comparison of relative luminance distribution between with and without the DLDS masking pattern corresponding to (a) Fig.11 and (b) Fig.12.

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