



Generation of random non-overlapping dot patterns for light guides using molecular dynamics simulations with variable r -cut and reflective boundary techniques

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Abstract

This paper presents a molecular dynamics (MD) scheme for the automatic generation of dot patterns for the light guides used in LCD backlight modules. Several MD computational techniques are integrated with the conventional MD scheme to enable the adjustment of the dot density in specific regions of the light guide in order to create a dot distribution with a high dot density variation and a high spatial uniformity. These techniques include the cell division technique, the variable r -cut technique, the boundary smoothing technique and the reflective boundary condition. The reflective boundary condition enables a precise control of the dot density within each cell, and is instrumental in achieving a dot distribution with both a high dot density variation and a high spatial uniformity. The performance of the proposed dot generation scheme is verified by considering the practical example of the dot pattern design of a light guide with a single LED light source located in the lower-right corner. The numerical results confirm the ability of the proposed method to achieve an even luminance condition by establishing a dot pattern whose density increases concentrically with an increasing distance from the light source.

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1. Introduction

The generation of random non-overlapping dot patterns is of fundamental concern since appropriate arrangements of such patterns can be used to construct higher-order geometric elements such as lines and surfaces, and so forth. The generation of random non-overlapping dot patterns has many applications in a diverse range of fields. For example, in finite element analysis problems, dot patterns can be used to construct a mesh of the computational domain in which each dot represents a discretized variable to be solved [1]. In an alternative application, designing appropriate non-overlapping dot patterns on the base of the light guides used in LCD products is essential if an even

luminance of the display panel is to be achieved [2]. Although, these two applications are very different, certain aspects of the dot pattern design task are similar in both cases. For example, in both applications, it is necessary to increase the density of the dot distribution in certain regions of the domain of interest, e.g., at the point of a high gradient change of the field variable in the grid generation problem, and in the region of the light guide furthest removed from the position of the light source in the light guide design application. A second similarity between the two cases is that the schemes used to generate the dot patterns must provide the ability to adjust the initial dot pattern by increasing or decreasing the dot density in response to some form of feedback in order to optimize the final solution. In the case of adaptive mesh generation for 2D or 3D finite element applications [3], this feedback takes the form of the field solution error [3], while in the light guide design application, the original dot pattern design is adjusted in accordance with the illumination results obtained during the detailed optical design

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phase [4]. Accordingly, a requirement exists for powerful algorithms capable of developing dot patterns with appropriate dot density variations to meet the requirements of the particular problem and possessing the means to optimize the original dot pattern in accordance with a given criterion.

Idé et al. [5] developed a dot pattern generation scheme based on molecular dynamics (MD) simulations. In their approach, an initial dot pattern was generated using low-discrepancy sequences (LDS) rather than a truly random function, and the MD method was then used to regulate the inter-dot spacings in order to obtain a final random dot distribution. However, their scheme lacked sufficient flexibility to allow for the creation of a dot distribution with a high dot density variation. Since the MD method is considered a powerful tool to understand nano-science [6,7] and technology [8,9], the development of the dot generation scheme to accommodate the needs for the subsequent optical design phase for the optimization of the dot distribution is necessary. In [4], the current authors developed a MD scheme for designing the dot pattern of a light guide in a backlight module. In the proposed scheme, the computational domain was divided into an array of sub-domains of equal area. By allowing the dot density to vary freely from one sub-domain to the next, the scheme successfully met the requirement to create a dot pattern with a high dot density variation. Furthermore, it was demonstrated that the original dot pattern, specified to satisfy the illumination requirements of the light guide, could be successfully adjusted in accordance with the results of the optical design phase to produce an optimized dot pattern, i.e. a dot distribution which yielded an even luminance condition. However, controlling the evolution of the dot pattern such that the final dot density distribution corresponded exactly to the original dot density specification was difficult since the movements of the individual dots during the MD simulations were governed by unitary force relationship.

The objective of the current study is to enhance the performance of the MD dot generation scheme presented in [4] by applying various computational techniques to improve the controllability of the dot density in each cell in order to achieve a dot distribution with a high dot density variation and a good spatial uniformity. These techniques include the cell division technique, the variable r -cut technique, the boundary smoothing technique and the reflective boundary condition. Having systematically examined the effectiveness of each of these techniques in improving the dot density variation and spatial uniformity of the dot pattern, the performance of the proposed method is verified by considering the practical example of the dot pattern design of a light guide with a single LED light source located in the lower-right corner.

2. Mathematic formulation

2.1. Displacement of atoms during MD simulations

In designing the light guide pattern, an initial specification for the dot density distribution is generated in accordance with the required optical performance of the light guide. The MD dot generation scheme is then applied to adjust the positions of the

dots in each cell in order to obtain a uniform dot distribution which satisfies the original dot density variation specification. In the present MD simulations, the individual dots in the dot pattern are treated as atoms and it is assumed that their displacements are described by Newton's law of motion, i.e.

$$m \frac{d^2 r_i}{dt^2} + c_d \frac{dr_i}{dt} = \sum_j^n f_{ij}(r_i, r_j), \quad (1)$$

where r_i is the position of the i th atom; m is the atom mass; c_d is a damping term; f_{ij} is the force exerted on atom i by neighboring atom j ; and n is the total number of neighboring atoms around atom i .

In the conventional MD approach [10], the simulations consider the thermal motion of atoms in an equilibrium state in a perfect damping-free system, and an assumption is made that the motions of the atoms are governed by both repulsive and attractive forces. However, in the current simulations, the objective is to establish a quasi-static solution of a non-overlapping dot distribution via a process of force regulation. In establishing this solution, it is assumed that the motions of the atoms are governed by repulsive forces only and that the atoms move in a damped system. Consequently, a damping term, c_d , is introduced into the equation describing the displacement of the atoms (see Eq. (1)), and a force model which imposes a purely repulsive force between the atoms is used in place of the potential function used in conventional MD simulations.

2.2. Force function and cell division technique

Fig. 1 shows the variation of the magnitude of the repulsive force between two atoms as a function of the distance between them. The r -cut [10] parameter shown on the x -axis of this figure indicates the distance within which the two atoms will interact with one another. Specifically, if the distance separating the two atoms is less than the r -cut distance, a repulsive

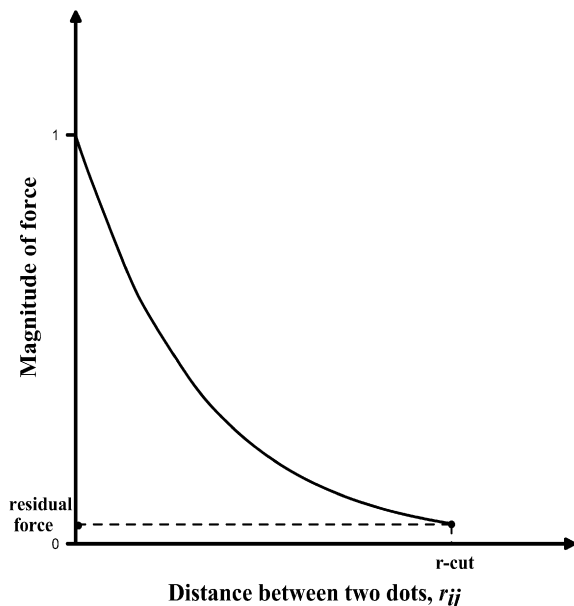


Fig. 1. Variation of repulsive force as function of atomic distance, r_{ij} .

force is established and the atoms are mutually repelled with a force of magnitude:

$$f(r_{ij}) = \frac{r_{ij}}{|r_{ij}|} \cdot e^{-(r_{ij} \cdot c_{kl})}, \quad (2)$$

where $f(r_{ij})$ is the shorthand representation of $f_{ij}(r_i, r_j)$ and c_{kl} is the force control parameter. As shown in Fig. 2(a), the original domain is sub-divided into an array of cells, identified by the subscripts k and l indicating the column and row number of the cell, respectively. In the MD dot pattern generation scheme proposed in this study, the dot densities prescribed for individual cells can be different from those prescribed for the neighboring cells. In Eq. (2), the force control parameter applied in an individual cell, c_{kl} , is dependent on the value of the dot density in that cell, i.e.

$$c_{kl} = \frac{-\ln f_{re}}{r_{cut,kl}}, \quad (3)$$

where f_{re} is the residual force at the r -cut distance in the cell. It is noted that $f_{re,k}$ tends to zero when r_{ij} is greater than or equal to the r -cut distance, $r_{cut,k}$. Furthermore, the greater the residual force, the higher the repulsive force between the atoms, and consequently, the greater the distance by which the two atoms are driven apart. During the force calculations, the neighboring atoms of each atom are identified using the Verlet list technique [10,11] in order to reduce the n^2 search to an n search, and the force control parameter is calculated based on the distance between them.

As described above, the proposed MD dot generation algorithm separates the domain of interest into a prescribed number of individual rectangular cells in order to enhance the flexibility of the dot density adjustment procedure. In cell (k, l) , the dot density is defined as:

$$D_{kl} = \frac{A_{dot}}{A_{cell}} = \frac{m_{kl} \cdot \pi \cdot r^2}{A_{cell}}, \quad (4)$$

where m_{kl} is the total number of dots in cell (k, l) and r is the radius of the individual dots. Note that r remains constant throughout the domain.

2.3. Variable r -cut technique

To ensure that all of the dots in one cell can interact with all of their neighboring dots, the total area enclosed by the r -cut radius, $A_{r,kl}$, defined as the reactive area, must extend beyond the boundaries of the cell. In the limiting case, the smallest reactive area, $A_{r_min,kl}$, in cell (k, l) is given by:

$$A_{r_min,kl} = \frac{A_{cell}}{m_{kl}}. \quad (5)$$

Eq. (5) provides the minimum r -cut value. The actual r -cut value in cell (k, l) can then be obtained from:

$$r_{cut,kl} = a_m \cdot \sqrt{\frac{A_{cell}}{\pi \cdot m_{kl}}}, \quad (6)$$

where a_m is a multiplier and $m_{kl} = D_{kl} \cdot A_{cell} / \pi r^2$ from Eq. (4). Eq. (6) indicates that the r -cut value is increased as the

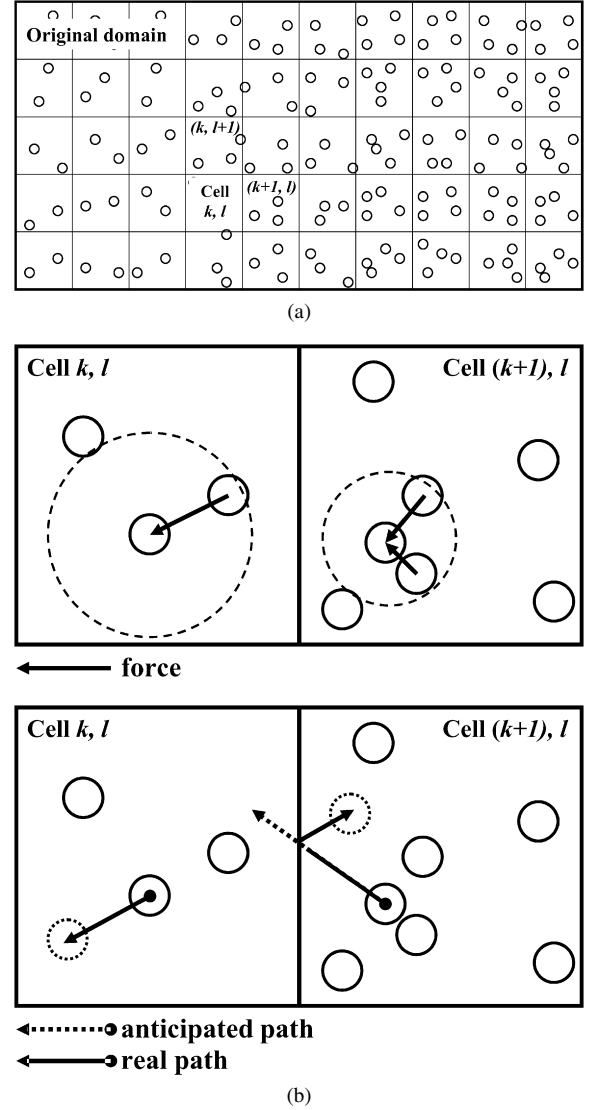


Fig. 2. (a) Schematic diagram of cell division and cell notation; (b) schematic diagram of variable r -cut technique (upper) and reflective boundary condition (lower).

dot density, which is inversely related to m_{kl} , decreases. Conversely, the r -cut value reduces as the dot density increases, as illustrated in the upper panel of Fig. 2(b). In this study, the process of scaling the r -cut value in proportion to the cell dot density is referred to as the variable r -cut technique.

2.4. Boundary smoothing technique

Although the cell division approach permits the dot density to be fine-tuned in order to achieve a uniform luminance condition over the surface of the backlight, it is difficult to ensure a uniform distribution of the dots across the cell boundaries. Therefore, an average force control parameter is introduced to ensure a smooth transition between the dot distributions in adjacent cells. As stated above, the r -cut value is adjusted in accordance with the dot density in each cell. Furthermore, from Eq. (3), it is observed that the force control parameter, c_{kl} , varies inversely with changes in the r -cut value. Therefore,

in order to maintain a smooth dot distribution across the cell boundary, the value of the control parameter in cell (k, l) is averaged with that of the adjacent cell, e.g., $(k, (l + 1))$, when the region enclosed by $r_{\text{cut},kl}$ extends beyond the boundary into cell $(k, (l + 1))$. In other words, the average force parameter is defined as:

$$c_{\text{boundary}} = \frac{c_{kl} + c_{k(l+1)}}{2}, \quad (7)$$

where c_{boundary} is the force control parameter applied to a dot located at or near the boundary.

2.5. Reflective boundary technique

In order to achieve a high density variation of the dot pattern over the entire light guide surface, the number of dots per cell specified in advance to achieve the required cell dot density, D_{kl} , should change as little as possible during the force regulation process. However, due to the repulsive force acting on neighboring dots within the specified r -cut distance, dots may leave their original cell and enter an adjacent cell during the force regulation process. The problem of dot migration from one cell to another is particularly acute in the case where a high dot density difference exists between neighboring cells. The present study overcomes this problem by applying a simple technique referred to as the reflective boundary condition to prevent the dots from leaving their original cells during the force regulation step. This technique is illustrated schematically in the lower panel of Fig. 2(b). As shown, when the reflective boundary condition is applied, any atom attempting to cross the cell boundary is reflected back to a position within its original cell which exactly mirrors the location which it would otherwise have traveled to in the adjacent cell.

3. Results and discussion

This section commences by considering the application of the proposed MD dot generation scheme to the construction of a dot pattern with a uniform distribution. The analysis then considers the case of a non-uniform dot distribution with a high dot density variation. In the following, the performance of the proposed dot generation scheme is evaluated in terms of $T_N^{(k)}$, an indicator of the uniformity of a random distribution, and RDF, the radial distribution function of the dots in the dot pattern.

The uniformity of a random distribution, $T_N^{(k)}$, is defined as [12]:

$$(T_N^{(k)})^2 = \frac{1}{N^2} \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} \prod_{i=1}^k (1 - \max(x_n^{(i)}, x_m^{(i)})) - \frac{2^{1-k}}{N} \sum_{n=0}^{N-1} \prod_{i=1}^k (1 - (x_n^{(i)})^2) + 3^{-k}, \quad (8)$$

where k is the dimension of the random dot distribution and N is the total number of dots.

The radial distribution function (RDF) is defined as:

$$g(r) = \frac{n(r)}{\rho 2\pi r \Delta r}, \quad (9)$$

where ρ is the average density and is equal to the total number of dots divided by the area occupied by these dots; $2\pi r \Delta r$ is the shell area between two concentric circles; and $n(r)$ is the number of dots in the shell area $2\pi r \Delta r$.

3.1. Uniform dot arrangement

Fig. 3(a) illustrates the uniformity of the dot distributions generated by the present MD algorithm with and without the reflective boundary condition, respectively, for different numbers of dots in the simulation domain. The results obtained in [5] using a dynamic low-discrepancy sequence (DLDS) scheme are also presented for comparison purposes. The uniformity data are calculated by substituting the coordinates of each dot in the distribution into Eq. (8). In the figure, the solid line and the dashed line represent the least-squares fit to the uniformity data obtained by the MD scheme with and without the reflective boundary condition (RBC), respectively. Meanwhile, the dashed-dotted line is plotted directly from the data presented in [5]. As shown, the best-fit line for the uniformity data obtained using the RBC condition is described by $0.109N^{-1.48}$, while that for the uniformity data obtained without using the RBC condition has the form $0.017N^{-1.17}$. In other words, both the slopes and the amplitudes of the two lines are different. Here, a slope of -1.48 and an amplitude of 0.109 result in a smaller value of $T_N^{(2)}$ and therefore indicate a more uniform distribution trend as a function of N . Therefore, it is observed that the MD scheme in which the RBC condition is imposed achieves a higher uniformity than that in which this boundary condition is not employed. This result is logical since if the reflective boundary condition is not imposed, dots may migrate from their original cell to an adjacent cell during the force regulation process resulting in an unequal number of dots in each cell in the final distribution. Further evidence of the dot migration phenomenon is shown in Fig. 3(b), which plots the variation of the average dot difference with the total number of dots in the simulation domain. Note that the results are obtained without using the RBC condition and are presented for the cases of 25 and 100 cells in the simulation domain, respectively. Here, the average dot difference is defined as the summation of the difference between the final number of dots in each cell and the average number of dots in each cell divided by the total number of cells. It can be seen that in both the 25- and the 100-cell domains, the average dot difference ratio increases with a wave-like form with an increasing number of dots. The maximum average dot difference is approximately 2.3 and arises in the case of 2500 dots evenly distributed throughout 25 cells. This result implies that for each cell containing 100 dots in the original distribution, an average of 2.3 dots enter or leave the cell during the force regulation process. Although the change in dot number within each cell is very small, it will nevertheless prevent the distribution from converging to a fully uniform solution. A close inspection of the data plotted using cross symbols in Fig. 3(a) (without RBC, 25 cells) shows that the uniformity trend with an increasing number of dots in the simulation domain has a similar wave-like variation to that shown in Fig. 3(b). In other words, it is apparent that the change in the number of dots in

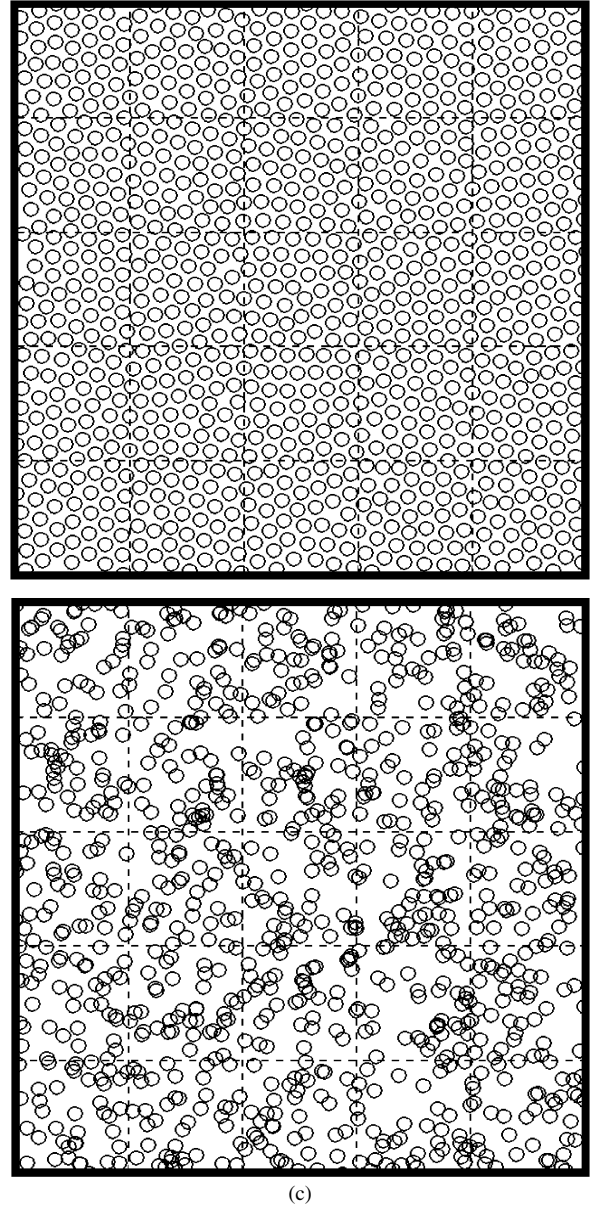
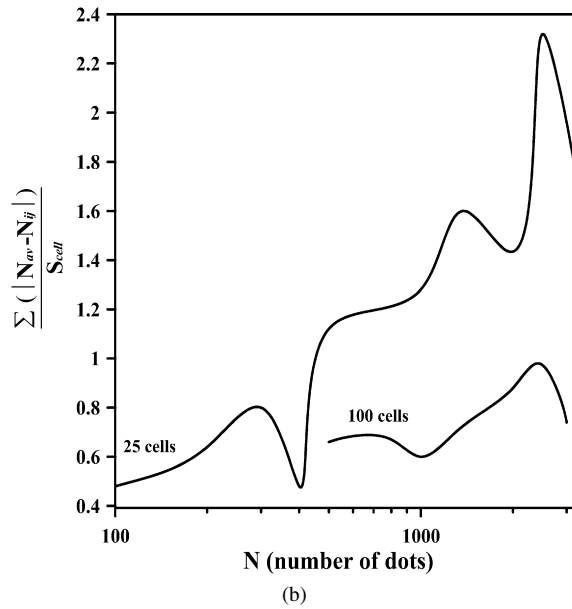
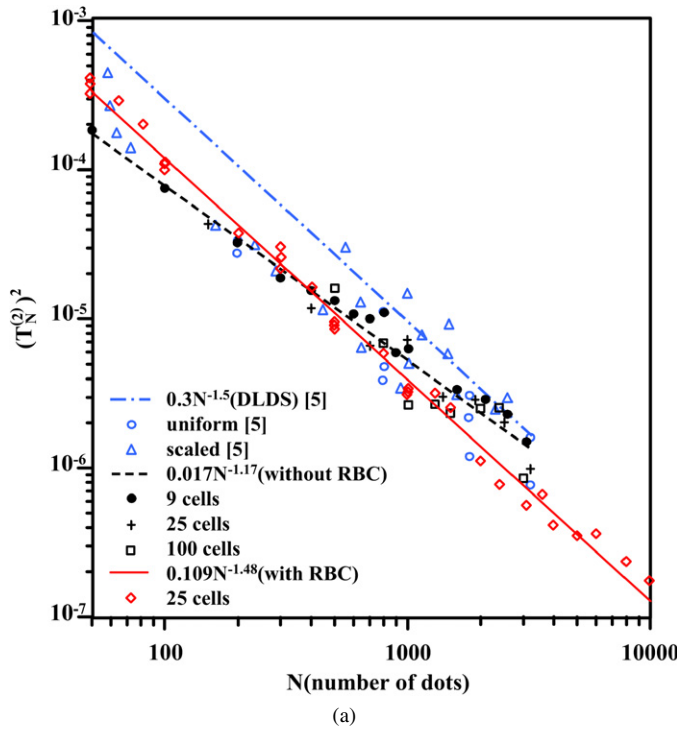
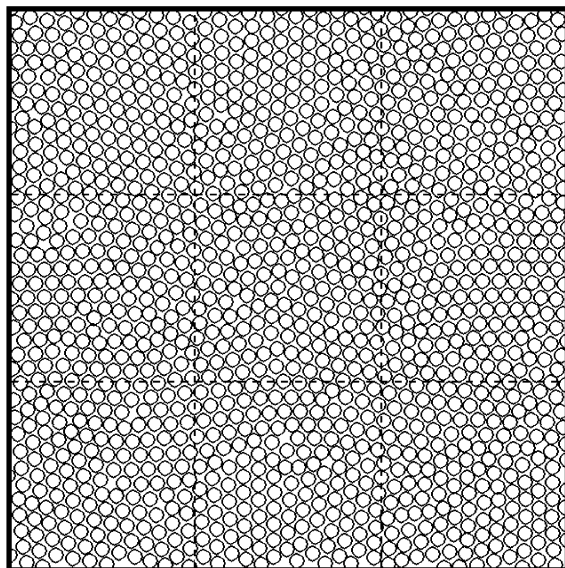
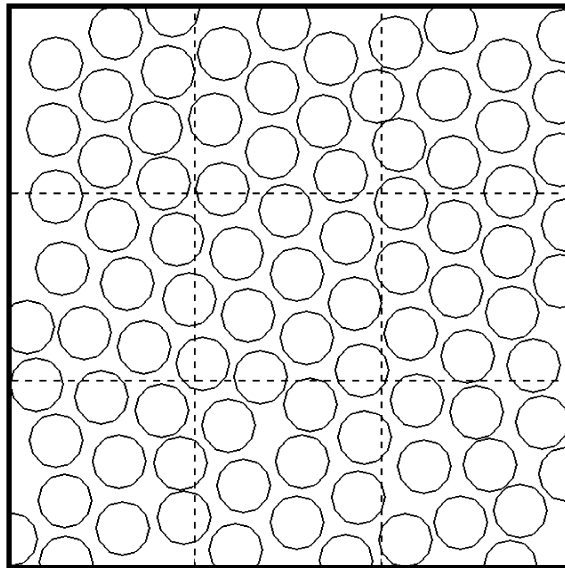
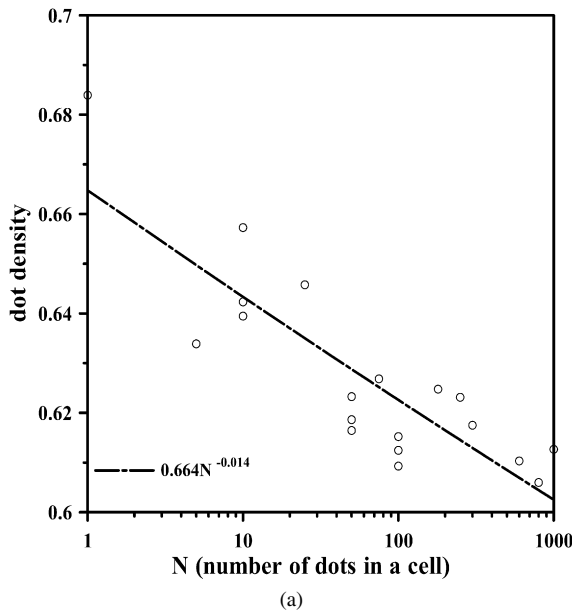


Fig. 3. (a) Comparison of dot distribution uniformity obtained by MD dot generation scheme with and without reflective boundary condition, respectively, and uniformity achieved by DLDS scheme in [5]; (b) average dot difference with no reflective boundary condition for 25 and 100 cells in the simulation domain, respectively; (c) dot distributions obtained by MD scheme for simulation domains containing 1000 dots in 25 cells with reflective boundary condition (upper). Note bottom panel shows initial random dot distribution before force regulation process.

each cell during the force regulation process results in a poorer uniformity of the final dot pattern. The upper panel of Fig. 3(c) shows the dot distributions obtained by the MD scheme with the reflective boundary condition, respectively, for a total of 1000 dots arranged in 25 cells. The lower panel in Fig. 3(c) presents the original dot distribution, i.e. prior to the force regulation process. Comparing the final distributions obtained by the MD scheme after the force regulation process (upper panel) with the original dot distribution (lower panel), it is apparent that the MD dot generation scheme is capable of achieving a highly uni-

form dot distribution regardless of the initial arrangement of the dots in each cell.

Comparing the two best-fit lines for the dot distribution uniformity data obtained using the MD dot generation scheme with the dashed-dotted line representing the uniformity results obtained using the DLDS scheme in [5], it can be seen that the MD scheme with the RBC condition (solid line) obtains a more uniform distribution trend as a function of N , i.e. the exponent of -1.48 and amplitude of 0.109 results in a higher uniformity, i.e. a lower value of $T_N^{(2)}$, than the exponent of -1.5 and



(b)

amplitude of 0.3 of the distribution obtained using the DLDS scheme. The conservation of the number of dots in each cell during the force regulation process performed using the reflective boundary condition ensures that the uniformity of the final distribution converges to a fully uniform solution, even for a very high total number of dots in the simulation domain. From Fig. 3(a), it is apparent that this uniformity convergence condition is maintained even with as many as 10,000 dots in the simulation domain, which is far higher than the 3000 dots considered in [5].

Finally, note that, actually, the data to obtain the best-fit line of DLDS scheme [5], which is presented by hollow circles and hollow triangles, overlap with our data that include the RBC condition. This means that some initial data prepared by the DLDS scheme can obtain comparable uniform distribution or even a more uniform distribution than our data after their MD relaxation process [5]. However, in comparison with our data, due to the more relatively scattered data pattern they present the predicted trend of the uniformity of the distribution as a function of N lies above our prediction. The scattered final uniformity presented was explained in Ref. [5] as due to the different initial conditions of the DLDS scheme. The more concentrated data of the current study shows a lower dependency of the final uniformity on the initial prepared data. Actually, in our calculation, the data is prepared by a random number generator as shown at the bottom panel of Fig. 3(c).

Fig. 4(a) illustrates the variation of the maximum attainable dot density as a function of the number of dots in each cell. The maximum dot density which can be achieved for a cell is an important characteristic of any dot generation scheme. In the current problem of designing an appropriate dot pattern on the base of a light guide, a very high dot density is required in the region furthest from the light source to compensate for the progressive loss of luminous flux as the light is redirected through the light guide. In the present simulations, the dot density is found by establishing the minimum distance between two dot locations which ensures that the non-overlapping condition holds and then calculating the total filling dot area by multiplying the square of the dot radius, which is equal to one half of this minimum distance, by the π constant and then by the total number of dots per cell. Finally, the value of the dot density is obtained by dividing the filling area by the cell area. In Fig. 4(a), it can be seen that the dot density decreases as the number of dots in the cell increases and approaches a value of approximately 60% as the total number of dots increases to 1000. This result implies that the present MD dot generation scheme can easily achieve a dot density of more than 60% provided that the number of dots in each cell does not exceed 1000. In designing the dot pattern for a light guide, the dot size is generally known in advance and the cell size is then specified in accordance with an estimate of the highest dot density required to satisfy the luminance requirements. Fig. 4(b) shows the dot distributions for the case of cells with 10 dots and a fill-

Fig. 4. (a) Variation of dot density with number of dots in cell; (b) dot distributions for cells containing 10 dots with dot density of 0.640 (upper) and cells containing 150 dots with dot density of 0.614 (lower).

ing dot density of 0.640 (upper panel) and cells with 150 dots and a filling dot density of 0.614. From these results, it can be inferred that the dot density will be increased if the simulations are based on a smaller cell size, or equivalently, a larger dot size. Comparing the two panels in Fig. 4(b), the dot density of the distribution in the lower panel appears to be very dense, i.e. there is very little space separating the individual dots. However, the dot density (0.614) is actually less than that of the more sparse distribution in the upper panel (0.640). This arises because the total sum of the vacant area in the lower distribution is greater than that in the upper distribution. In the MD force regulation procedure, irrespective of the number of atoms (i.e. dots) in the simulation domain, a small distance must be maintained around each atom to prevent an overlapping condition. Consequently, as the number of dots increases, the amount of vacant area in the domain also increases, giv-

ing rise to the lower dot density observed in the lower panel of Fig. 4(b).

3.2. Non-uniform dot arrangement with high dot density variation

The discussions above have considered the use of a constant r -cut value in achieving a dot distribution with a uniform dot density over the simulation domain. Conversely, this section discusses the use of the MD scheme in generating a dot pattern with a non-uniform dot density distribution by varying the value of the r -cut parameter and applying the boundary smoothing technique and the reflective boundary condition.

3.2.1. Variable r -cut technique

Fig. 5 (a) to (c) show the final dot distributions obtained after the force regulation process using different r -cut techniques.

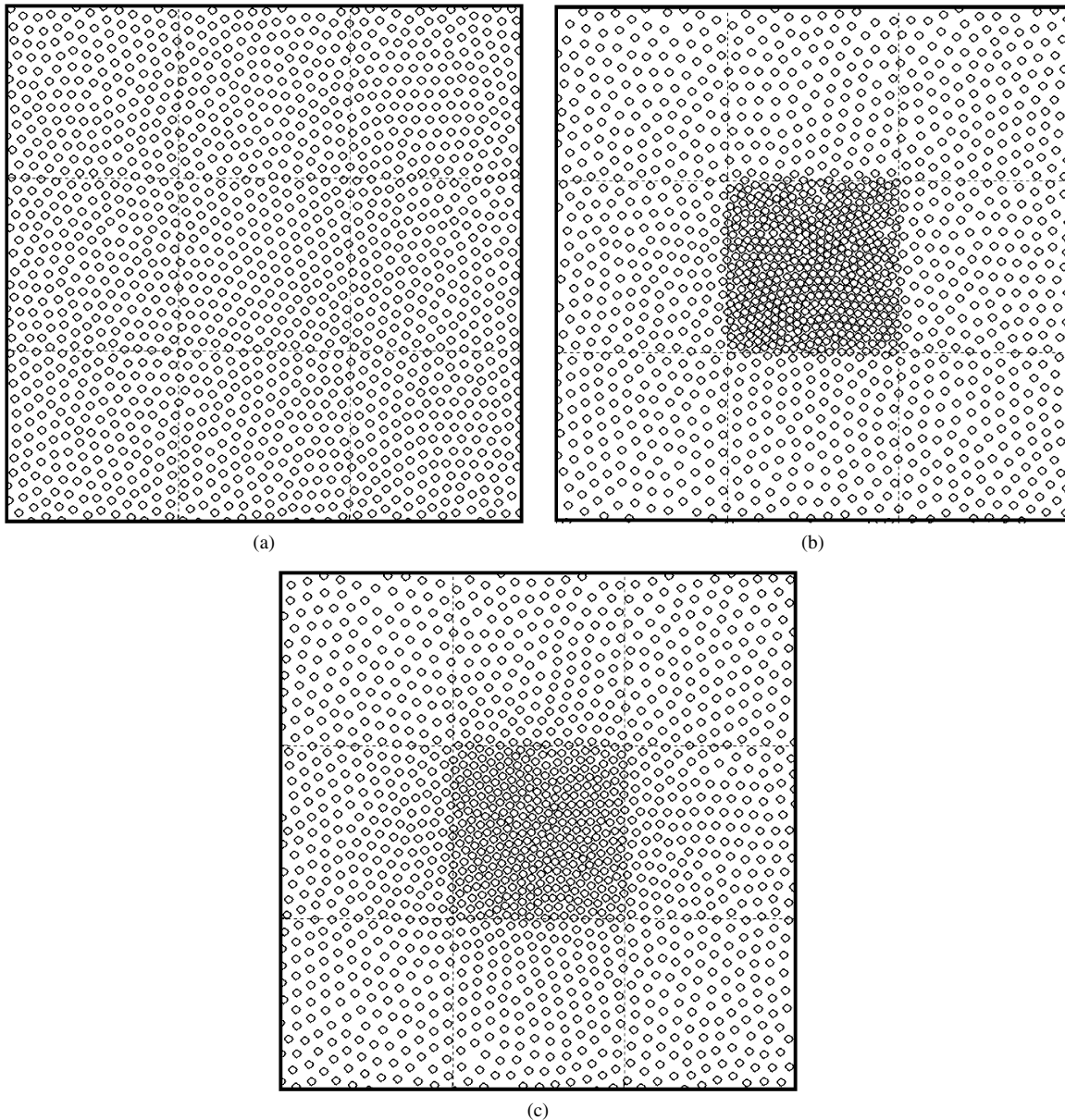


Fig. 5. Dot distributions for different r -cut situations, (a) fixed r -cut value; (b) predefined r -cut value; (c) variable r -cut value.

In Fig. 5(a), the distribution is generated using a constant r -cut value in all of the cells. In Fig. 5(b), the distribution is constructed using an r -cut value which varies from cell to cell in accordance with the original estimate of the dot density variation required to achieve the desired luminance condition and remains constant during the force regulation process (abbreviated hereafter to the predefined r -cut technique). In Fig. 5(c), the distribution is produced using an r -cut value which varies from cell to cell and is automatically adjusted during the force regulation process. In the initial dot density specification, the central cell is assigned a dot density value four times higher than that of the surrounding cells. In Fig. 5(a), it is observed that this dot density variation is not preserved during the force regulation process, i.e. a uniform dot density distribution results because the use of a fixed r -cut value drives all of the atoms to an approximately equal distance from one another. In Fig. 5(b), a different r -cut value is specified for each cell and this value remains unchanged during the force regulation process. Although this technique successfully preserves the original dot density variation, the dots have a non-uniform distribution. Observing the central cell, it can be seen that the dots are rather crowded and that vacant areas exist, particularly in the vicinity of the cell boundaries. In Fig. 5(c), the r -cut value is automatically adjusted during the force regulation process to take account of the migration of dots from one cell to another. (Note that the reflective boundary condition is not imposed). Comparing the distributions in Fig. 5 (c) and (b), it is apparent that while both r -cut techniques preserve the original dot density variation, the use of a variable r -cut parameter results in a less crowded distribution in the high-density cell and a smoother transition of the dot pattern across the high- to low-cell density boundaries. The improved distribution shown in Fig. 5(c) demonstrates the effectiveness of adapting the value of the r -cut parameter in accordance with the dynamic changes which take place in the cell density as atoms either leave or enter the cell during force regulation. By adopting this approach, the distances by which the atoms within a cell are mutually repulsed reflect the current cell density and hence a more uniform distribution is obtained.

3.2.2. Boundary smoothing technique

Fig. 6(a) shows the radial distribution function, $g(r)$, of the dot distribution across the boundary separating a high-density cell and a low-density cell. Two cell density variation cases are considered. In the first case, the density ratio of the high-density cell to the low-density cell is 2:1, while in the second case, the density ratio is 4:1. The radial distribution function is presented for the cases where the variable r -cut technique is implemented with and without the boundary smoothing technique, respectively. It is observed that the drop in the magnitude of $g(r)$ across the cell boundary is more pronounced in the case of a higher dot density ratio. However, for both density ratios, the fall in the value of $g(r)$ across the boundary is reduced when the boundary smoothing technique is employed. In addition, the variations of $g(r)$ in the regions close to the boundary are smoother when the boundary smoothing technique is applied, particularly in the lower dot density ratio case. Fig. 6

(b) and (c) present the final dot distributions obtained by the MD scheme for dot density ratios of 2 and 4, respectively. In Fig. 6(b), the upper panel shows the distribution obtained when the boundary smoothing technique is employed, while the lower panel shows the distribution when boundary smoothing is not applied. Meanwhile, in Fig. 6(c), the upper panel shows the distribution obtained using the boundary smoothing technique, the central panel shows the distribution obtained without boundary smoothing, and the lower panel shows an enlarged view of the inset region marked in the upper panel. A close inspection of the dot distributions shows that the distance between the dots in the vicinity of the cell boundary gradually changes when the boundary smoothing technique is employed. Comparing the two panels in Fig. 6(b), it can be seen that the use of the boundary smoothing technique blurs the original cell boundary when the dot density ratio between the high- and low-density cells has a value of 2:1. However, when the dot density ratio is increased to 4:1, the cell boundary can be clearly identified regardless of whether or not boundary smoothing is applied because a large difference exists between the dot densities of the central cell and the surrounding cells, respectively. Nonetheless, a close inspection of the cell distribution in the vicinity of the cell boundary (see lower panel) reveals that the boundary smoothing technique results in a smoother transition of the dot pattern across the boundary.

3.2.3. Reflective boundary technique

Fig. 7(a) shows the dot density ratio of two adjacent cells, i.e. A and B (see Fig. 7 (b) and (c)), after the force regulation process for different values of the initially specified dot density ratio. In Fig. 7(a), m_A indicates the number of dots originally specified in cell A and the bold solid line represents the ideal case in which the final dot density is equal to the originally specified dot density, i.e. the line has a slope of 1. It can be seen that for all values of m_A , the final dot density is less than that originally specified (note that the reflective boundary condition is not imposed). In other words, the number of dots in cell B following the force regulation process is lower than in the original dot density specification, while the number of dots in cell A is higher. This reflects the fact that the dots tend to migrate from denser cells to less dense cells during force regulation. Overall, this trend reduces the dot density variation over the entire simulation domain. Fig. 7(a) also shows that the discrepancy between the initial dot density specification and the final dot density increases as the number of dots specified in cell A decreases. To ensure that the final dot distribution maintains the original high dot density variation, it is necessary to prevent the individual dots from leaving their original cells during force regulation. In the present simulations, this is achieved using the reflective boundary condition. This condition not only preserves the original dot density variation specification, but also achieves a uniform dot distribution, as discussed previously in Section 1. Fig. 7 (b) and (c) shows the dot distributions obtained for an originally specified dot density ratio of 9:1 for the cases of $m_A = 10$ and 25, respectively. Note that in both figures, the upper panel shows the distribution obtained using the reflective boundary condition while the lower

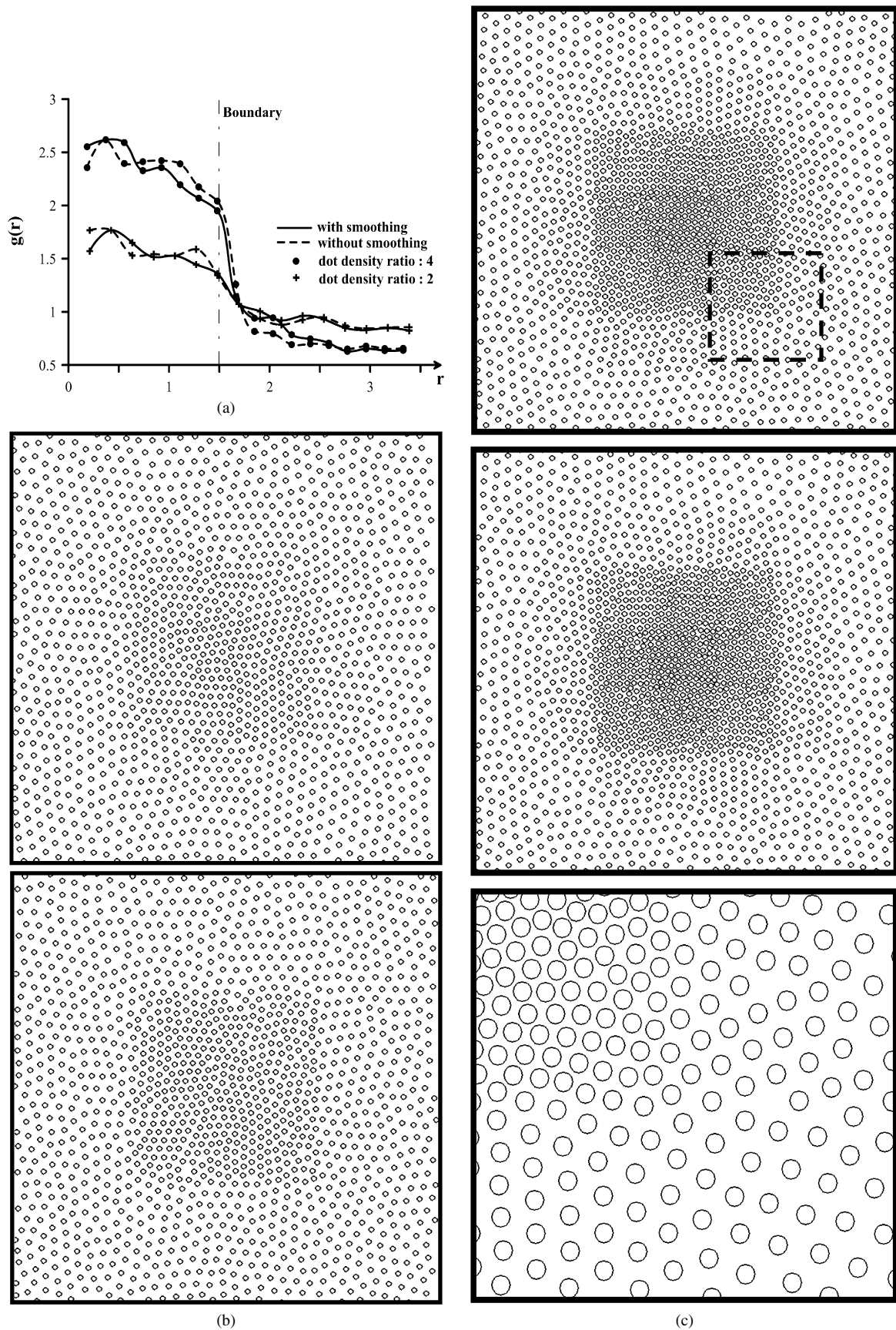
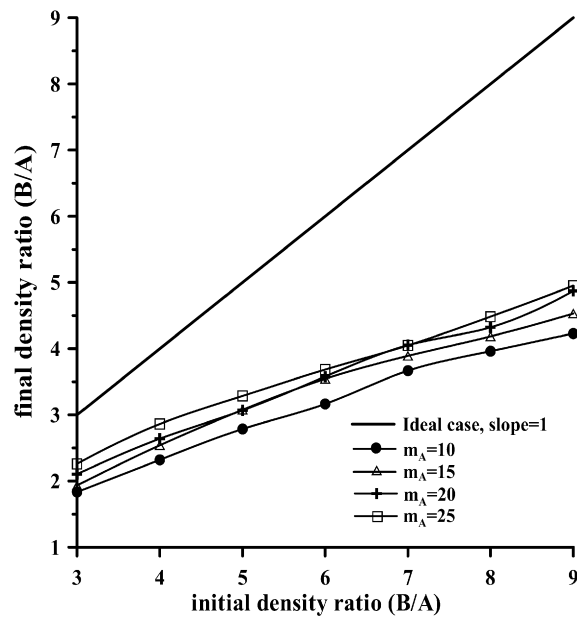
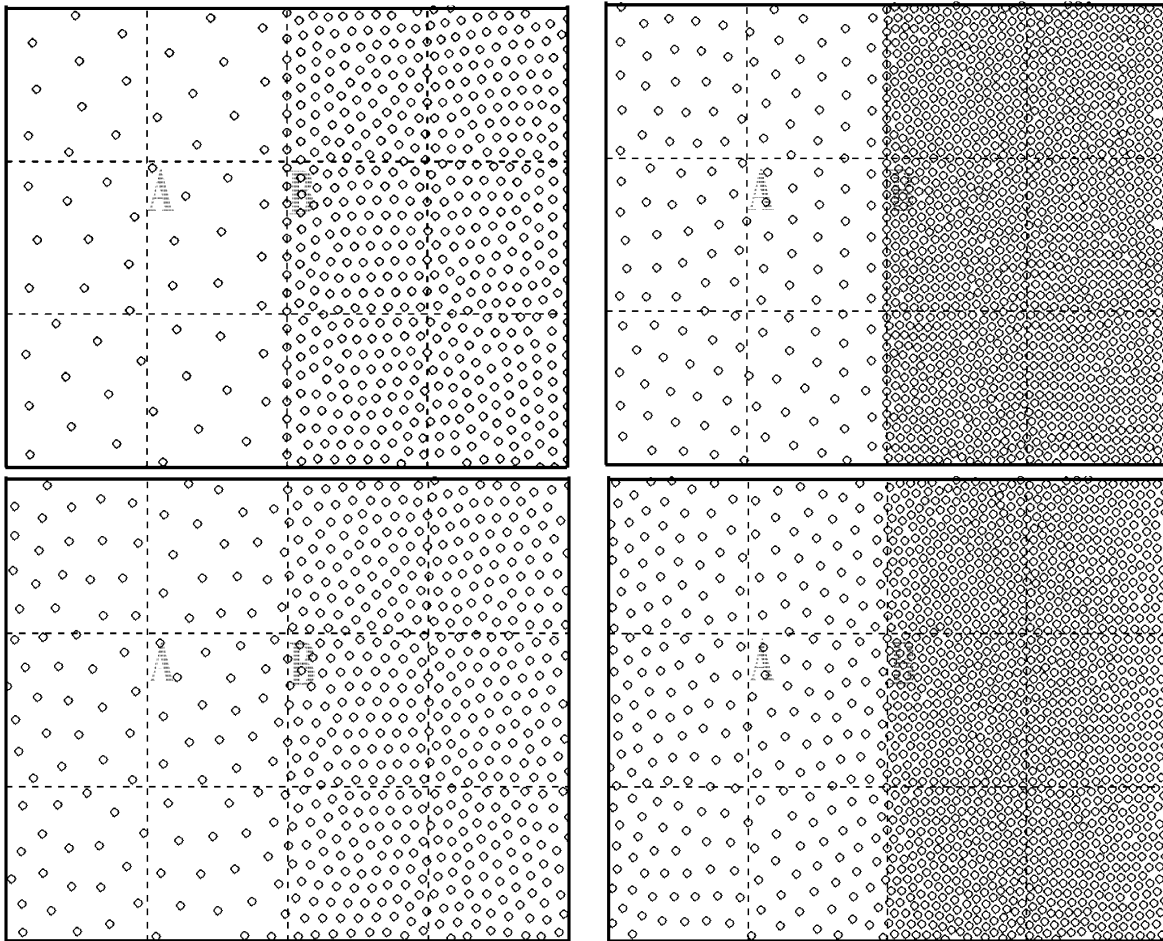


Fig. 6. (a) Radial distribution function, $g(r)$, for dot density ratios of 2:1 and 4:1; (b) dot distributions with (upper) and without (lower) boundary smoothing technique for dot density ratio of 2:1; (c) dot distributions with (upper) and without (middle) boundary smoothing technique for dot density ratio of 4:1. Note lower panel shows enlarged view of inset area in upper panel.



(a)



(b)

(c)

Fig. 7. (a) Final dot density ratio of two adjacent cells A and B for different initial values of dot density ratio; (b) dot distribution for $m_A = 10$ with reflective boundary condition (upper) and without reflective boundary condition (lower); (c) dot distribution for $m_A = 25$ with reflective boundary condition (upper) and without reflective boundary condition (lower).

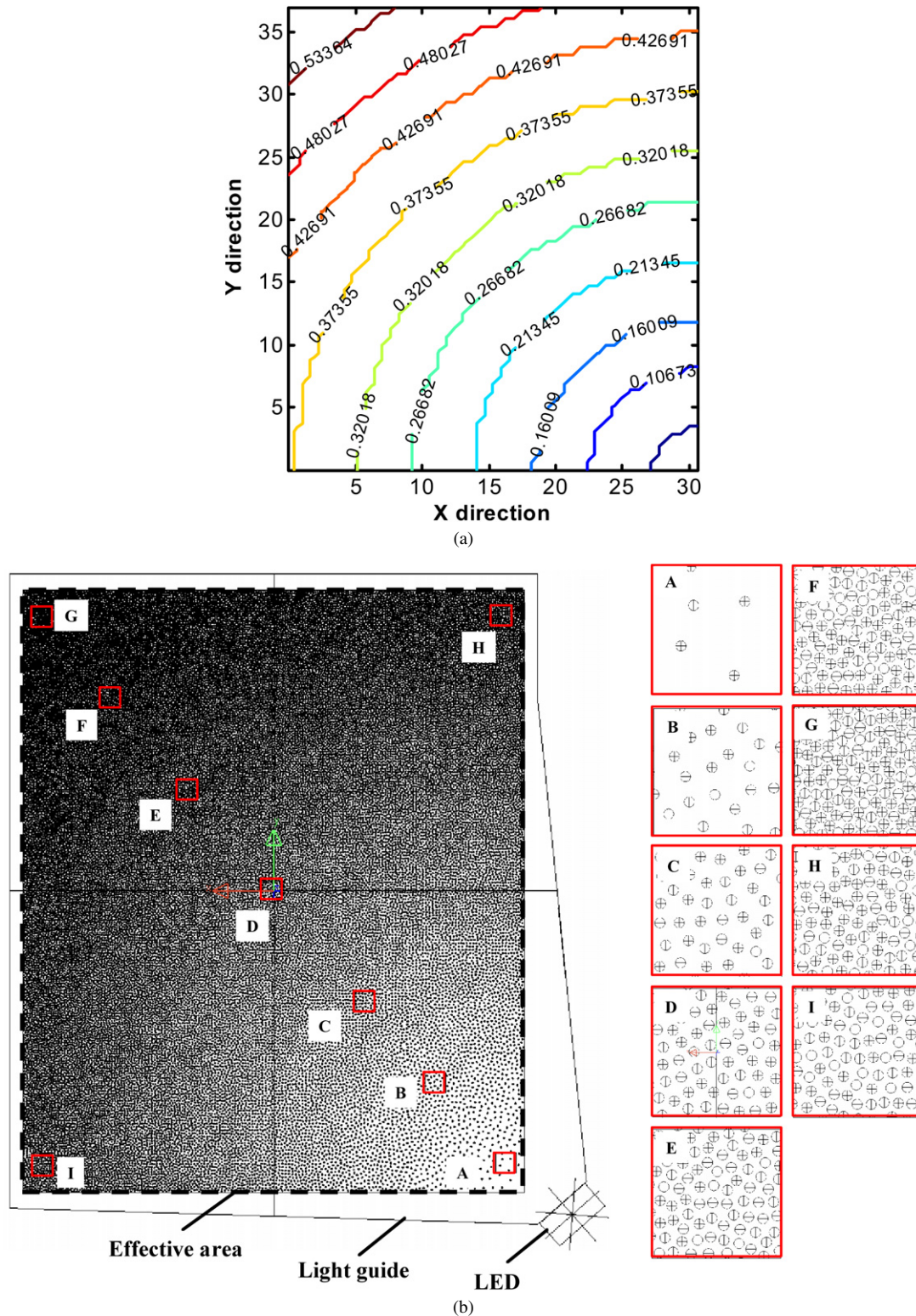


Fig. 8. (a) Dot density contours specified for light guide with single light source in bottom-right corner; (b) dot distribution following MD force regulation process; insets show dot distribution at different locations.

panel shows the distribution for the case where the dots are free to migrate to adjacent cells. It can be seen that the number of dots in each cell remains constant before and after force regulation and that a dot distribution with a high dot density variation is achieved.

4. Verification example

To verify the performance of the MD dot generation scheme proposed in this study, the scheme is applied to construct the dot pattern for the light guide of a backlight module illuminated us-

ing a single LED light source. In general, the appropriate dot pattern design for a light guide is dependent on several factors, including the type of light source used, the number of sources used, the position(s) of the light source(s), the size of the light guide, and so forth. However, the intention in all cases is to obtain an even luminance condition across the surface of the light guide. In the current example, it is assumed that the backlight is used for a 1.5" display and is illuminated by a single LED light source located in the bottom-right corner of the light guide. In such a design, the dot density distribution should increase concentrically from low to high density with an increasing distance from the light source in order to achieve an equal luminance condition. In designing the light guide pattern, an initial specification for the dot density distribution is generated in accordance with the required optical performance of the light guide and the MD dot generation scheme is then applied to adjust the positions of the dots in each cell in order to obtain a uniform dot distribution which maintains the overall dot density variation specification. In a practical application, this dot pattern design is then adjusted iteratively in accordance with feedback received from the optical design stage. However, in the current verification exercise, this step is omitted.

Fig. 8(a) shows the initial specification for the dot density of the light guide. As shown, the dot density increases from a low value in the bottom-right corner (corresponding to the position of the LED source) to a high value in the upper-left corner (corresponding to the maximum distance from the light source). In the simulations, the computational domain is subdivided into an array of 50×60 cell divisions in the x - and y -directions, respectively. A random number generator is then used to generate different numbers of dots in each cell according to the dot density specification given in Fig. 8(a). The MD force regulation process is then triggered to adjust the original dot distribution. The results of the force regulation process are presented in Fig. 8(b). It can be seen that the dot distribution density increases smoothly and concentrically from the bottom-right corner to the upper-left corner. In other words, an even luminance condition of the light guide is obtained. Significantly, this concentric distribution is obtained despite the fact that the computational cells have a rectangular shape. Hence, the effectiveness of the reflective boundary condition and boundary smoothing technique is confirmed.

5. Conclusion

This paper has presented a MD dot generation scheme for designing suitable dot patterns for the light guides used in backlight modules. Several MD computational techniques have been proposed to accommodate the need to generate a dot pattern with a high level of dot density variation and a uniform spatial distribution. These techniques include the cell division technique, the variable r -cut technique, the boundary smoothing technique, and the reflective boundary condition. The cell division technique and the variable r -cut technique enable the dot

density in each cell to be uniquely specified such that a high dot density variation and a uniform dot distribution can be obtained over the light guide surface. Meanwhile, the boundary smoothing technique ensures a smooth transition of the dot pattern across the boundaries of cells with different dot densities. Finally, the reflective boundary condition ensures that the dot density variation of the final dot distribution conforms precisely to the original specification. The performance of the proposed MD dot generation scheme has been verifying by considering the example of creating a suitable dot pattern for a light guide with a single LED source located at its bottom-right corner. The results have shown that the scheme successfully achieves an even luminance condition by generating a dot pattern in which the dot density increases concentrically with an increasing distance from the light source. Although this study has focused on the generation of dot patterns for light guides, the computational techniques implemented in the MD dot generation scheme are equally applicable to the automatic grid generation problem in finite element analysis applications.

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