Grid Optimization of Large-Area OLED Lighting Panel Electrodes

Haoning Tang, Yibin Jiang, Ching Wan Tang, and Hoi-Sing Kwok, *Fellow, IEEE*

***Abstract*—Luminance loss resulting from potential drop on the transparent indium tin oxide (ITO) electrode due to its relatively high resistivity is one of the most essential issues in the design of large-area organic light-emitting diode (OLED) lighting panels. One solution is to pattern metal grid with low sheet resistance on the ITO electrode. However, the shape, height, and width of the metal grid element have a great influence on the final luminance uniformity of the device. In this paper, a method is proposed to optimize these parameters in order to get the best luminance uniformity for large-area OLED lighting panels. The method takes two grid geometry parameters—height and width—into account and predicts the highest relative luminance by finite element method simulations under different operating voltages.**

***Index Terms*—Electrode, large-area, luminance uniformity, metal grid, OLED lighting.**

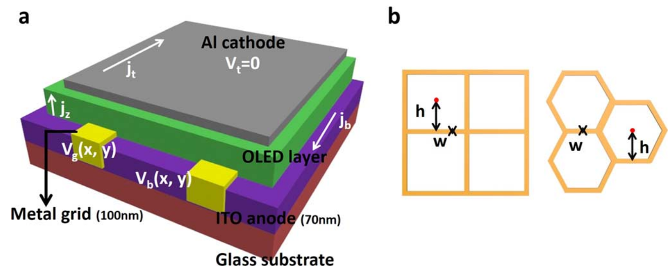

Fig. 1. (a) OLED lighting panel made of Al cathode and ITO transparent anode with metallic grid applied. (b) Top view of metal grid for square and hexagonal shape: apothem h and width w are the same for both hexagonal and square shape.

I. Introduction

OLED LIGHTING panel has the advantages of high efficiency and excellent form factor [1]. It is one of the solid state lighting technologies being investigated and commercialized. However, even though OLED displays have been manufactured in large quantities, OLED lighting panels face a different set of problems. Because of the much larger emitting area, luminance and temperature non-uniformity are serious problems as the potential drop across the large ITO electrodes becomes large [2]–[4]. Moreover, larger emitting area is more sensitive to the defects introduced during the fabrication process, which cause the current leakage and even the detrimental short circuit [5].

It has been shown that device uniformity and efficacy is poor if the electrodes are made of bare ITO [3], [6]. OLED lighting panel with metal grid on ITO shows significant improvement on luminance uniformity [7]. With the same amount of area and transmittance, homogeneity can be further improved by geometrically optimizing the metal grid. Among the investigated three shapes, including triangle, square and hexagonal shape, hexagonal metal grid is more effective in reducing potential drop losses while keeping the same transmittance [8], [9]. A centrally aligned structure of square-shaped metal grid was proved to have a better enhancement on uniformity [8]. It has been demonstrated that a Poisson equation model can provide a calculation on the potential distribution on the electrode [6], [9]. A method for calculating average luminance by given geometry parameter has also been demonstrated [9].

When designing the panel electrodes, the geometry parameters of the metal grid also need to be considered because of the trade-off between transmittance loss and potential drop. In this paper, a simulation method for the design and optimization of the OLED lighting panels with various metal grid geometries is presented. Geometric parameters such as height and width of the metal grid are used as the input for the simulation. The theoretical results are further compared with the performance of the actual devices, which will be discussed in detail.

II. Method

Fig. 1 shows the device structure and the electrode grid arrangements. It can be seen that a bottom emission structure is used [3], [10]. Fig. 1 also shows the geometries of the two metal grid studied, i.e. hexagonal and square. The geometrical dimensions of w and h are indicated, where w refers to the width of metal grid, and h refers to the apothem of unit cell (one unit of reduplicated shape element).

A. Voltage and Luminance Distribution

In a typical OLED lighting panel model, three basic parts need to be considered: bottom electrode (anode) which includes transparent ITO electrode and metal grid, top electrode (cathode) which usually uses metal like Al, and the sandwiched organic functional layers. The resistance and thickness of the ITO bottom electrode and the metal grid are defined as R_b and R_g and d_b and d_g, respectively. Assuming the cathode is an ideal conductor and the organic layers are infinitely large resistors [6], the potential distribution on the ITO bottom electrode and the metal grid can be represented as $V_b(\mathrm{x}, y)$ and $V_g(x, y)$. Proportional to the potential of the electric field

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across the organic layers and the material resistivity, the current density in the OLED is represented by j_z. The calculation is conducted using the following assumptions.

1) The top cathode is regarded as a perfect conductor that is connected to ground, $V_t = 0$ [6].
2) The organic layers have a much higher resistivity than that of the ITO bottom electrode. Also, considering the thin thickness of the ITO electrode, the potential and current in the electrode can drop the z-coordinate dependence and be just written as $V_b(x, y)$, $j_z(x, y)$ [6].
3) For the same reason, the potential of the metal grid is also independent of the z-coordinate. And the relationship of the ITO electrode and the metal grid can be illustrated as $V_{\rm g}(\rm x, y) = V_b(\rm x, y)$ [9].

The current density in the electrode layers is proportional to the potential of the electric field, where [9]

$$\nabla^2 V_g(x, y) = R_g j_b(x, y) \tag{1}$$
$$\nabla^2 V_b(\rm x, y) = R_b j_z(\rm x, y) \tag{2}$$
$$R_{b,g} = \frac{1}{\sigma_{b,g} d_{b,g}}, \qquad \text{where } \sigma_{b,g}. \tag{3}$$

There are four boundary conditions for the above equations [6], [9], which are:

1) area connected to the voltage source,

$$V_{g,\rm b}(\rm x_0, y_0) = V_0 \tag{4}$$

2) boundaries of ITO interface with variable voltage source,

$$V_b(\rm x_0, y_0) = V_g(\rm x, y) \tag{5}$$

3) electrodes that are not in contact with a variable voltage source, where $\rm n_b$ is the vector normalized to bottom electrode,

$$grad(V_b) \bullet \rm n_b = 0 \tag{6}$$

4) areas where only one electrode is connected,

$$\nabla^2 V_{b,t}(\rm x, y) = 0. \tag{7}$$

Assuming a linear voltage [6], we can estimate the potential on the electrode by the I–V characteristic curve, obtained from the small size pixel (2×2 mm^2) luminance-current density-voltage (L–J–V) data given in Fig. 2. We consider a square OLED panel with side length $a = 80$ mm and solve the differential equation of lateral potential distribution of the bottom electrode by finite element method [11], [12]. Luminance distribution can be estimated by piecewise regression of the L–V characteristic curve (Fig. 2) and matrix operation.

$$L = f\left(V_b(\rm x, y)\right). \tag{8}$$

B. Optimization by Grid Height and Width

There are two main reasons for the voltage non-uniformity: the voltage drop on the metal grid and the voltage drop on the ITO [9]. Dimensional analysis yields the following relations, where R_{eff_g} represent effective grid sheet resistivity [4]:

$$\Delta V_{\rm ITO} = A j_z R_b h^2 \tag{9}$$
$$\Delta V_{\rm grid} = A j_z R_{eff\_g} a^2 \tag{10}$$

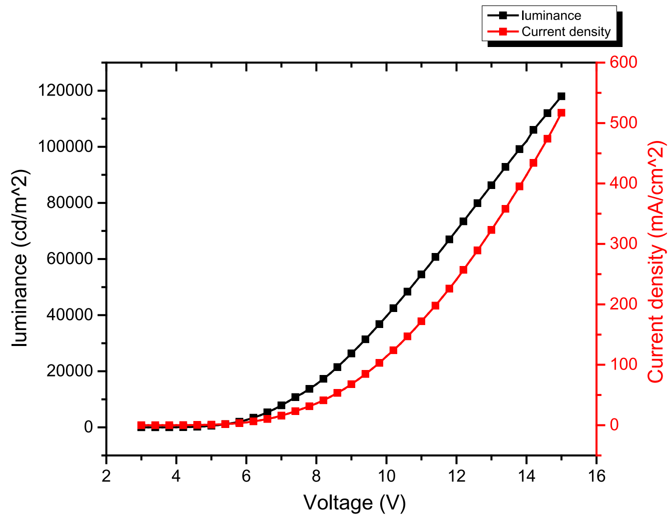

Fig. 2. Measured (a) I–V characteristic curve (red), and (b) L–V characteristic curve (black) of small size OLED device.

$$R_{eff\_g} = \frac{h}{2w} R_g \tag{11}$$
$$T = \left(\frac{h}{h + w/2}\right) \approx 1\frac{w}{h} \tag{12}$$
$$\Delta L = T \cdot k\left(V_b(\rm x, y)\right)\left(\Delta V_{\rm ITO} + \Delta V_{\rm grid}\right) \tag{13}$$

where a is the lighting panel size. According to the dimensional analysis of ohm's law [13], A is defined as a dimensionless constant that only related to the shape of grid geometry. The value of A can be found by the simulation result of the potential distribution on electrode. The approximation of (11) and (12) is controlled within tolerance of 5% such that any value of h&w that violate the approximation is not counted. The luminance loss of an OLED lighting device consists of two parts: losses caused by the potential drop on ITO and metal grid, and light blocked by grid lines. The latter can be represented by (12) [4], [14]. Differentiation of (13) as a function of $u = h/w$ gives the minimum luminance loss. Relative Luminance ε evaluates the luminance uniformity of OLED lighting device, which can be calculated by (14).

$$\varepsilon = 1 - \frac{\Delta L}{L_{\rm max}}. \tag{14}$$

C. Experimental Details

To validate our model, we developed 10×10 cm^2 OLED lighting panels with square or hexagonal grid type structure (Fig. 3). The panels are fabricated on ITO coated glass with four steps. First, ITO anode is patterned by conventional photolithography and wet-etching processes. The second step is to form metal grid on the ITO anode with photolithography, sputtering and lift-off technologies. After that, the panels are loaded into the vacuum chamber to do organic layers and aluminum cathode deposition. At last, the panels are transferred into the glove box to encapsulate the devices under glass lid using UV-cured epoxy resin. Organic layers for green light OLEDs (same stack as the small pixel OLED) are evaporated onto the pattern electrode and covered with Al cathode [15]. For measurement convenience, devices were encapsulated with

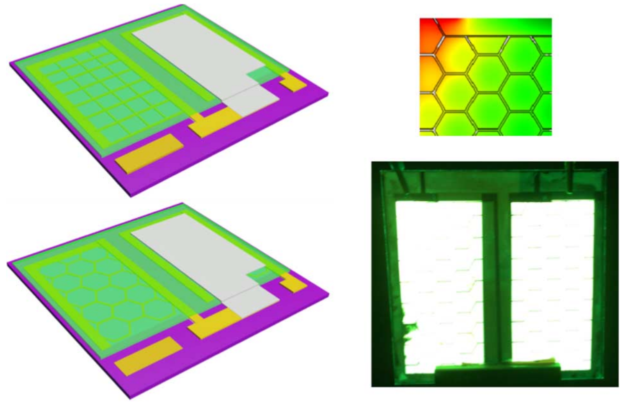

Fig. 3. 3D simulation and real device photograph of 10 × 10 cm² OLED lighting panels with square and hexagonal grid structure. The luminance at $V_0 =$ 14 V is 5000 cd/m².

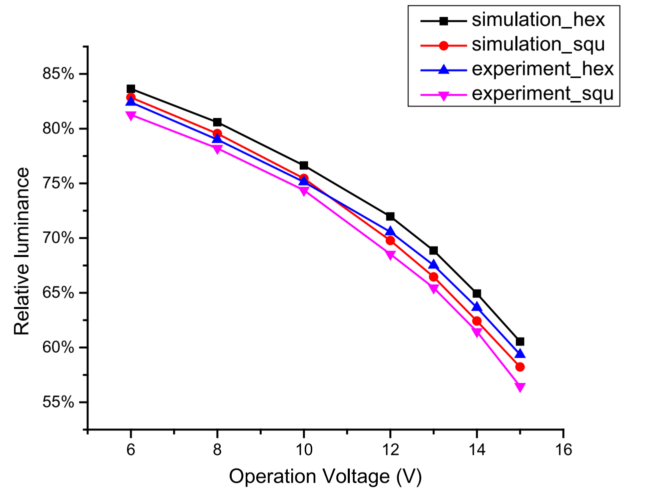

Fig. 4. Relative luminance of simulation results and experiment results for hexagonal and square shape of metal grid.

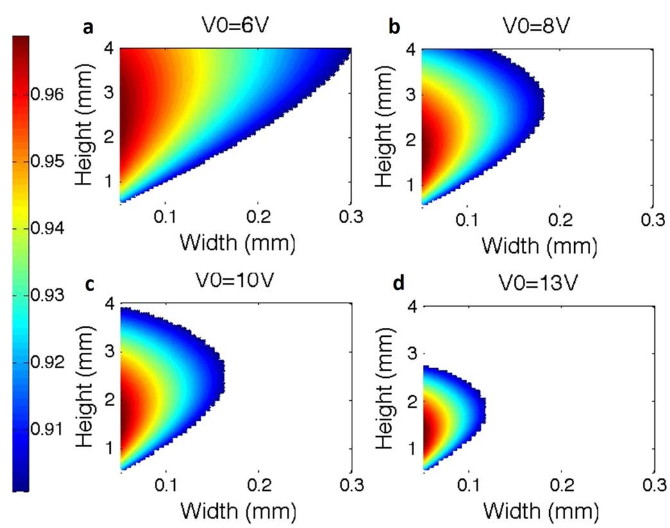

Fig. 5. Relative luminance as the function of h and w with different operation voltage V_0. For color area, relative luminance was regulated so that $\varepsilon \geq 90\%$. The device resistivity is $R_b = 25\ \Omega/\square$, $R_g = 0.1\ \Omega/\square$. The operation voltage V_0 is (a) $V_0 =$ 6 V. (b) $V_0 =$ 8 V. (c) $V_0 =$ 10 V. (d) $V_0 =$ 14 V.

desiccative sticks. Measurements of scanning L–V data of the panels were taken by SpectraSacn 650 with driving voltage from 6 V to 15 V [16]. Relative luminance was calculated by (14), taking the minimum luminance and edge luminance of the devices.

III. Result and Discussion

A. Experiment Verification

To validate the feasibility of our simulation, we fabricated several 10 × 10 cm² OLED devices (Fig. 3) with square and hexagonal metal grids respectively. Hexagonal shape was proved to have better performance than that of square shape [9]. The geometrical parameter are $w =$ 0.25 mm and $h =$ 5 mm. The experimental result shows a good agreement on the profile of data lines with that of the simulation (Fig. 4). The simulated highest relative luminance is 83.6% (hexagonal) and 82.8% (square) respectively. Experimentally, the results were found to be 82.4% (hexagonal) and 81.3% (square) respectively at an operating voltage of 6 V. According to Fig. 4, relative luminance decreases largely as the operating voltage increases. Hexagonal shape metal grid shows better performance on uniformity than that of the square shape over the entire operating voltage range, proved by both simulation and experiment result.

B. Relative Luminance Regulation

We can simulate the center luminance (cd/m^2) and relative luminance of the device for various combinations of metal grid height and width. An effective matrix of height and width as well as the corresponding relative luminance can be found for optimization.

Fig. 5 shows a series of these matrixes for $R_b = 25\ \Omega/\square$ $R_g = 0.1\ \Omega/\square$ and $\varepsilon \geq 90\%$ with different driving voltages. The combination of h (0.5 mm $< h <$ 4 mm) and w (0.05 mm $< h <$ 0.3 mm) should only be selected from the color area. Within this range, even a 97% relative luminance can be achieved at a specific h&w combination. As the operation voltage V_0 changes from 6 to 14 V, area that can achieve high value of relative luminance ($\varepsilon \geq 90\%$) shrinks. It implies a more concentrated arrangement of metal grid is needed for devices operated under high voltage.

Notice that for different ITO bottom electrode resistance (R_b) and metal grid resistance (R_g), the area that we can obtain $\varepsilon \geq 90\%$ is different (Fig. 6). Smaller R_b and R_g offers a wider selection of h and w.

C. Optimization

For the design of the OLED lighting panel, usually the width of the metal grid is the first geometrical dimension to be considered. A reasonable grid width can reduce process complexity. When the width of the metal grid was determined, the height of the metal line that produces the best luminance uniformity can be determined by first order differentiation of (13). However, different operation voltage corresponds to different matrix of the optimized geometric parameters (Fig. 5). For example, when $w = 0.25$ mm and operation voltage is 6 V, a best output can be obtained if $h =$ 5 mm.

Previous research showed that hexagonal shape metal grid has a better performance on reducing luminance loss than that

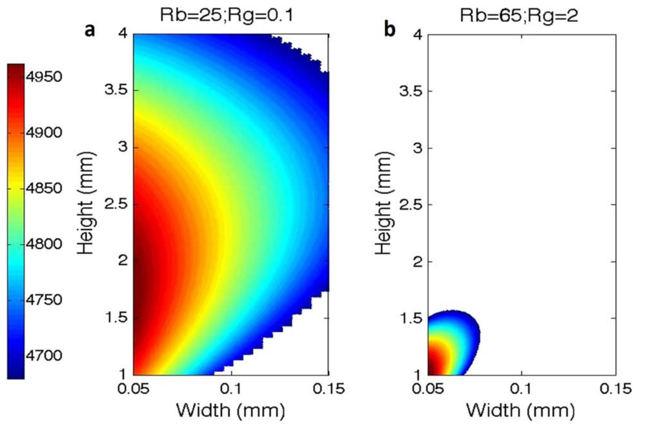

Fig. 6. Central luminance as the function of h and w, devices working in same operation voltage (V_0 = 8 V) and $\varepsilon \geq 90\%$. Device resistivity is (a) $R_b = 25\ \Omega/\square$, $R_g = 0.1\ \Omega/\square$ (b) $R_b = 65\ \Omega/\square$, $R_g = 0.1\ \Omega/\square$.

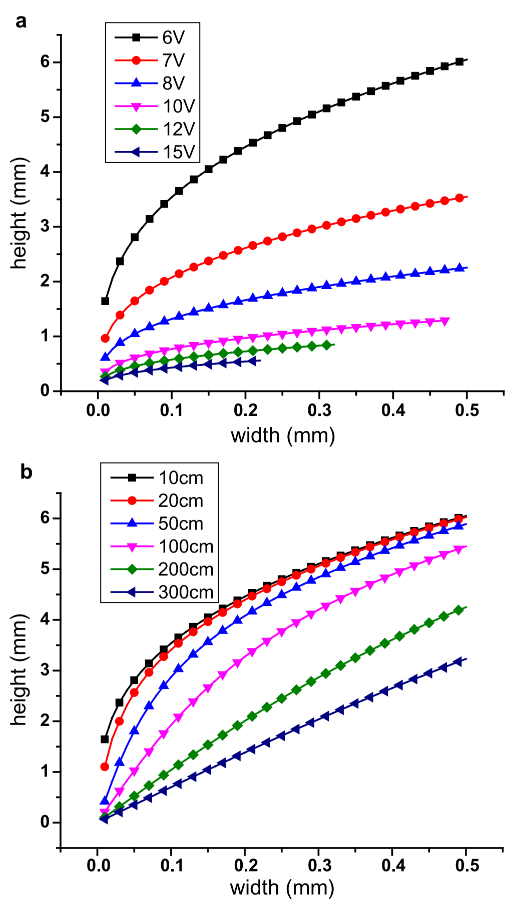

Fig. 7. Calculated optimized height-width relation of OLED lighting devices with given R_b, R_g and device size under different operation voltage. (a) Nonlinear relationship when lighting panel size is small (a = 10 cm). (b) Approximately linear relationship when lighting panel size is large ($a >$ 200 cm).

of the square shape [8]. But for different shapes (hexagonal and square), the optimized height and width are the same since physically, the only difference between hexagonal and square shape is a dimensionless parameter. Height-width relation is non-linear if the lighting panel size is small, [Fig. 7(a)], while it is a linear characteristic as lighting panel size increases [Fig. 7(b)]. The height-width relation is highly sensitive to operation voltage as illustrated by Fig. 7(a). When the operation

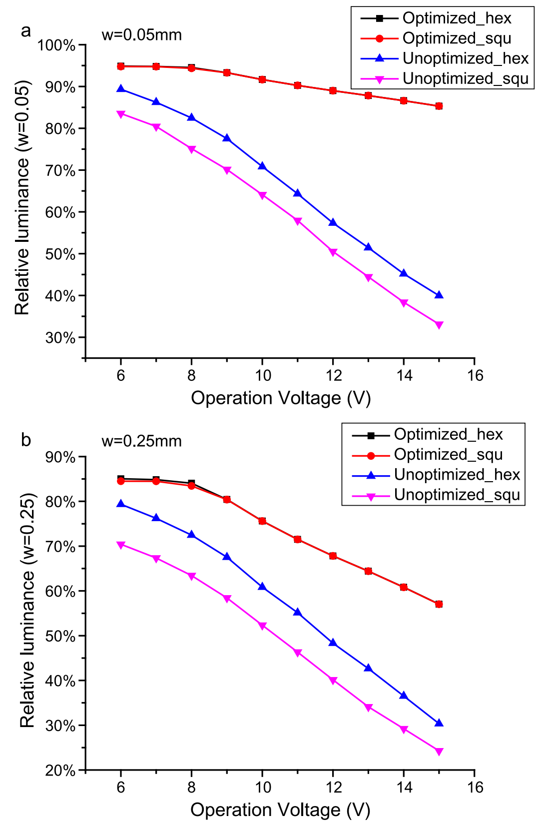

Fig. 8. Relative luminance versus operation voltage result (uniformity) of optimized and unoptimized examples for hexagonal and square shape. (a) w = 0.05 mm and (b) w = 0.25 mm.

voltage increases, tighter grid geometry is required to obtain better uniformity.

Optimized relative luminance can be simulated once the best height, width and operation voltage are determined (Fig. 8). Two example of optimization are demonstrated here using w=0.05 mm and w = 0.25 mm and compared with the unoptimized geometry (free set parameters of width and height, h = 5 mm). The result of the optimization can achieve a large enhancement on the relative luminance (uniformity) and reduce shape sensitivity, in the other words, a square metal grid can also obtain same level of uniformity as a hexagonal metal grid.

D. Selection Method

To determine which geometric parameter should be used in fabrication, multiple factors need to be considered. These include the requirement on luminance transmittance, the lower bound of uniformity (relative luminance) and the desired operating voltage (related to overall device luminance). A parameter space optimization diagram is presented in Fig. 8. Here the blue, green and red lines respectively represent the three factors for the optimization: relative luminance line (greens) which comes from the regulation discussed in Section III-B, optimization line (red) for the w-h optimization mentioned in Section III-C, and transmittance line (blue) required by the luminance transmittance consideration.. One can choose a section of h and w value under determined operation voltage, range of transmittance and tolerable uniformity. For example, if we intend to select the value of w and h under the condition: V_0 = 10 V, $0.97 \leq T$

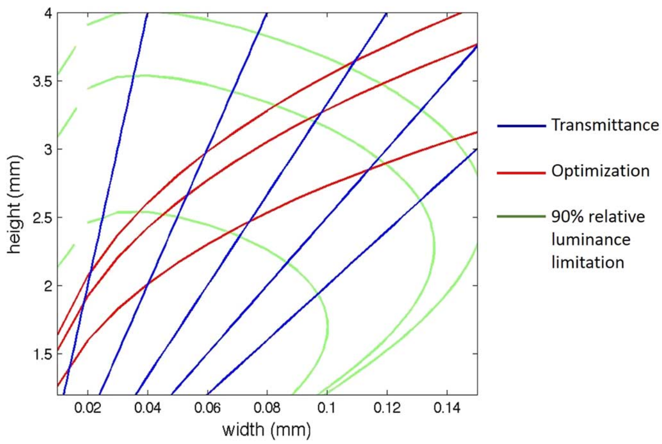

Fig. 9. Parameter space of h and w for large-area OLED lighting panel optimization under different transmittance, regulation of relative luminance, operation voltage requirements.

≤ 0.98, $\varepsilon \geq 90\%$. Then the section of red line between point (0.55, 2.6) and (0.097, 3.21) is the selection result of h and w.

IV. Conclusion

In this paper, we presented a comprehensive study on the geometrical dimensional relationship of the metal grid on a large-area OLED lighting panel electrode. The aim is to produce a structure having the best luminance uniformity and brightness. A method to find the optimized solution of height and width under given operation voltages is discussed, using differential equations and finite element method simulations. Experiments were further performed to verify the simulation results. For a given uniformity requirement, combinations of potential height and width can be obtained. An optimization of geometrical parameters for various operating voltages was demonstrated. It has been found by simulation that the optimization of height and width parameters can maximally reduce the inhomogeneity of OLED lighting panel. A method of selection on the value of h and w was given, based on the simulation data.

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