Effects of unit size on current density and illuminance of micro-LED-array*

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A 300 μm×300 μm light emitting diode (LED) chip is divided into nine 80 μm×80 μm units with 30 μm spacing between adjacent ones. After arraying, the total saturation light output power and the maximum injection current are enhanced by 5.19 times and nearly 7 times, respectively. In addition, the test results demonstrate that the illuminance uniformity on the receiving surface reaches the optimum when the spacing between the arrays is equal to the maximum flat condition. The larger the number of arrays, the greater the area with uniform illuminance on the receiving surface.

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Compared with traditional light emitting diodes (LEDs), micro-LED arrays show more favorable electrical and optical performance and can maintain high electric current density (>10 kA/cm^2)[1-5]. In addition, the luminous efficiency and output efficiency can be remarkably enhanced, contributing to a great potential in market applications[6-9]. According to existing researches, the LED luminous efficiency would increase as size decreases (for a fixed input power density) due to the heating effect[10-14].

This paper focuses on light intensity variation after traditional LED chips are arrayed, and the array size effects on the distribution of current densities for various sub-units. Moreover, the effects of chip number and chip spacing on the LED array illuminance on the receiving surface are also explored.

The LED chip size and electrode structure also affect the electric properties. Specifically, the chip size mainly affects sub-unit internal current density through the chip current expansion length. Fig.1 shows the cross section of unit's current spreading.

According to the theory proposed by Guo[15,16], the current expansion length L_S can be written as:

$$L_S=\sqrt{\left(\rho_c+\rho_p t_p\right)t_n/\rho_n}\quad , \tag{1}$$

where ρ_p and ρ_n represent the p-type and n-type layer resistivities, respectively, t_p and t_n represent the p-type and n-type layer thicknesses, respectively, and ρ_c represents the p-type specific contact resistivity. When the vertical resistance drop R_u far exceeds kT/e (i.e., $IR_u=J(\rho_c+\rho_p t_p)>>kT/e$, where k represents the Boltzmann constant, T represents the temperature, and e represents the electron charge), the one-dimensional current density can be written as:

$$J(x)=J_0\exp\left(-\frac{x}{L_S}\right)\quad , \tag{2}$$

where J_0 represents the injected current density of the electrode-covering part on the chip. Since the electrode-covering part is generally on the chip center and the current transported in the unit is symmetric, we can choose the right side of the LED chip for calculation. By dividing the light-emitting area along both the unit length (L) and the unit width (W), the current density along L direction can be written as[17,18]:

$$J(L)=J_0\left(\frac{L}{L_S}\right)^{-1}\left[1-\exp\left(-\frac{L}{L_S}\right)\right]. \tag{3}$$

According to the above formulas, we can calculate the current density distributions for four different L values, as shown in Fig.2.

As shown in Fig.2, for a larger L unit, the current

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crowding phenomenon is more significant and the current density near the electrode is larger. And the current distribution becomes more nonuniform with the chip size increases. In order to make the current density distribution more uniform, the sub-unit size should be designed following L/L_S<<1.

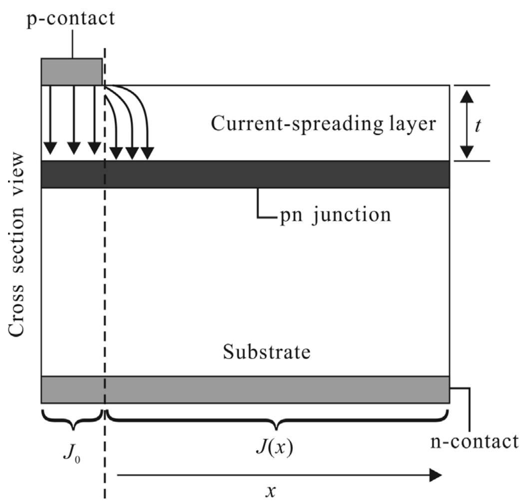
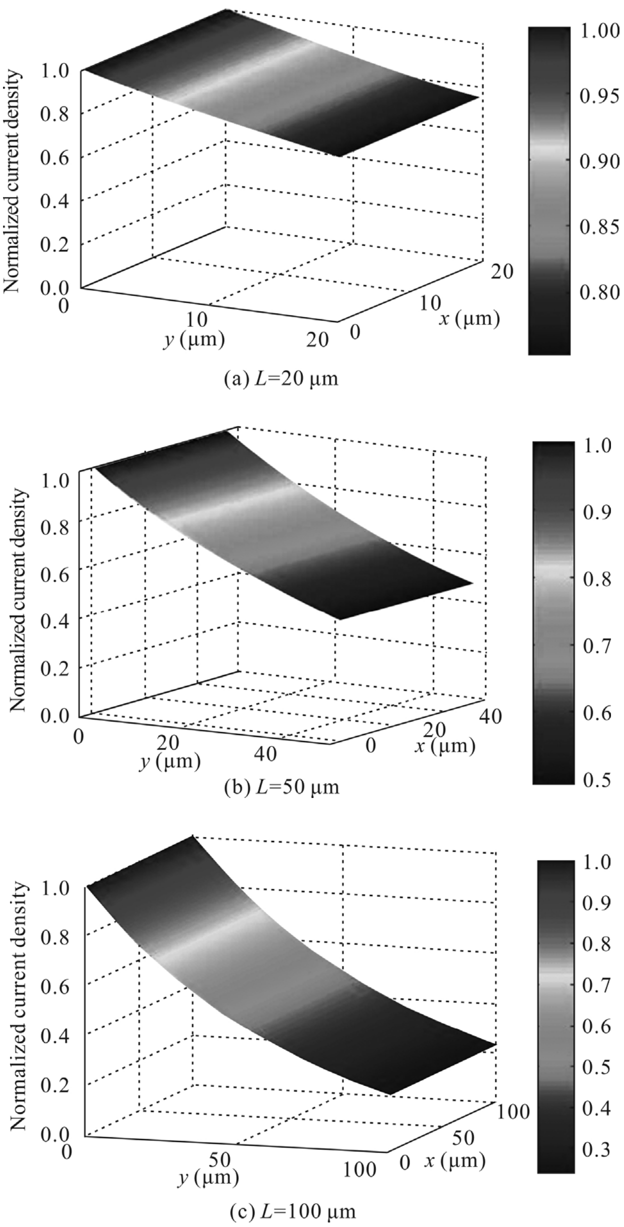


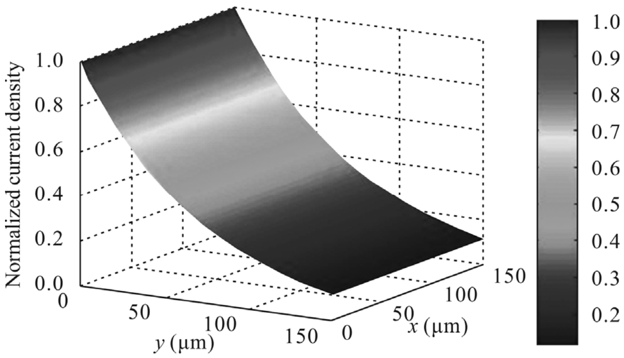
Fig.1 Cross section of current spreading for a single unit

In general, the injection current should be increased to enhance LED illuminance, the junction temperature will increase and the chip current will become more crowded[19], which limits the saturation optical power output and reduces the local efficiency, probably damaging the LED. In order to overcome or alleviate the current crowding effects, LED chips are divided into several micro sub-units. Considering commercial products, we select a 300 μm×300 μm LED unit as an example for analysis. This unit is divided into nine 80 μm×80 μm sub-units, with a 30 μm spacing between adjacent sub-units. Fig.3 shows the LED structures before and after arraying.

The electrode covering area for an array unit is fixed at 80 μm×15 μm. Since the electrode covering ratio in the entire chip is the same, the electrode covering area for the 300 μm×300 μm chip is 300 μm×56.25 μm, and its effective light-emitting area is 73 125 μm^2 in the forward direction. The total positive light-emitting area for the LED array with nine sub-units is 46 800 μm^2, which is 64% of the total light-emitting area of the whole chip. The array shows spacing and side light-emitting surfaces, which increases the effective light output area and enhances the probability of light escaping from the chip.

Fig.4 shows that the saturation light output powers for the whole and the divided LED chips are approximately 2.6 mW and 1.5 mW, respectively. The total saturation light output power of the arrayed LED chips is 13.5 mW, which is 5.19 times larger than that of the whole LED chip. For the whole LED chip (when the injection current reaches 80 mA), the light output power approaches saturation and decades as the injection current further increases. For the LED array, the light output power is saturated when the injection current reaches 60 mA and then decades as the injection current further increases. In terms of the saturation regime, the total current reaches up to 540 mA, which is nearly 7 times larger than that of the whole LED chip (80 mA). The results indicate that an LED array can sustain a larger injection current and output a larger saturation light power. However, the light output power for the whole LED chip significantly decreases as the injection current increases. Even more seriously, the chip would fail. This is mainly due to the fact that the light-emitting efficiency of each unit chip is enhanced after arraying, the current crowding weakens significantly, and the system becomes more stable. As a result, it can sustain a larger saturation input current.





(d) L=150 μm

Fig.2 Normalized current density distributions for chips with different sizes

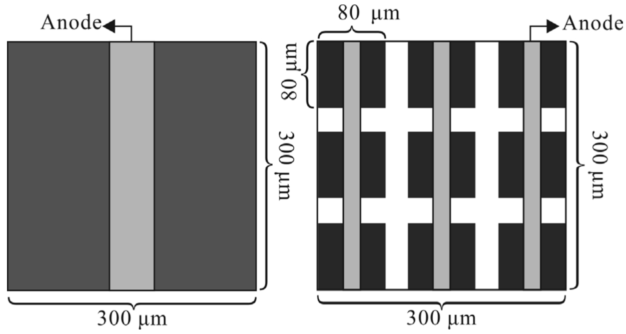


Fig.3 LED chip diagrams before and after arraying

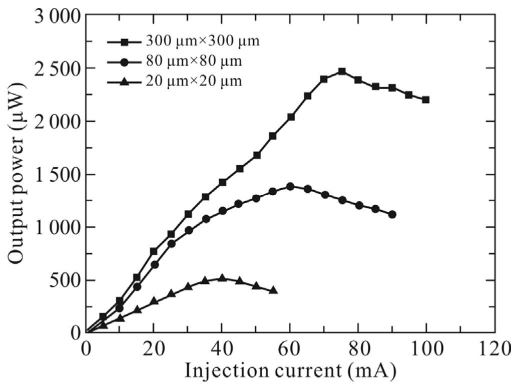


Fig.4 Variations of output power with injection current in different-sized LEDs

Next, multiple LED arrays are arranged with a regular spacing d, as shown in Fig.5.

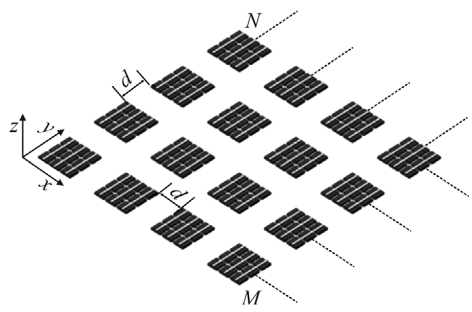


Fig.5 Multi-LED-array arrangement at a regular spacing of *d*

Illuminance uniformity is commonly used to evaluate the illuminance distribution on a projected area. The illuminance variation on the receiving surface can be calculated by[20]:

$$\Delta E = \frac{E_{\max} - E_{\min}}{E_{\max}} \quad , \tag{4}$$

where $E_{\max}$ and $E_{\min}$ represent the maximum and minimum illuminances at the receiving surface, respectively. Both $E_{\max}$ and $E_{\min}$ have units of W/m^2.

The light rays from a whole LED chip follow a Lambertian distribution, and the illuminance distribution satisfies the following expression[21]:

$$E(r,\theta) = E_0(r)\cos^m \theta \quad , \tag{5}$$

where θ represents the view angle, $E_0(r)$ represents the LED's illuminance at a distance r away from the LED along the optical axis, and m is a constant. When m=1, the light source can be regarded as an ideal Lambertian irradiator. In practice, m is greater than 1 and may be expressed as:

$$m = \frac{-\ln 2}{\ln\left(\cos\theta_{1/2}\right)} \quad , \tag{6}$$

where $\theta_{1/2}$ represents the view angle when the illuminance is half of that of θ=0°.

Assuming that the receiving surface is a plane and the whole LED chip is located at (X,Y,0), the illuminance at an arbitrary point P (x,y,z) on the receiving surface can be written as:

$$E(x,y,z) = \frac{z^m I_{\mathrm{LED}}}{\left[(x-X)^2 + (y-Y)^2 + z^2\right]^{\frac{m+2}{2}}} \quad , \tag{7}$$

where $I_{\mathrm{LED}}=L_{\mathrm{LED}}A_{\mathrm{LED}}$ represents the LED chip light intensity (W/sr), L_{LED} represents the LED radiance (W/m^{2}sr), and A_{LED} represents the LED light-emitting area.

When only two LED chips are used for illumination, the illuminance on the receiving surface can be calculated by superimposing the illuminances from the two LED chips:

$$E(x,y,z) = z^m I_{\mathrm{LED}} \left\{ \left[\left(x-\frac{d}{2}\right)^2 + y^2 + z^2\right]^{-\frac{m+2}{2}} + \left[\left(x+\frac{d}{2}\right)^2 + y^2 + z^2\right]^{-\frac{m+2}{2}} \right\}, \tag{8}$$

where d represents the spacing between two adjacent LED chips. According to the Sparrow law, let $(\partial^2 E)/(\partial x^2)=0$ when x=0 and y=0. Thus, the maximum flat condition for d can be written as:

$$d_{\max} = \sqrt{\frac{4}{m+3}}\,z \quad , \tag{9}$$

where z represents the distance between the LED chip and the receiving surface. It can be concluded that $d_{\max}$ is tightly related with m and z.

Assuming that the LED chip group is an array consisting of $N\times M$ light emitting groups (N and M are odd numbers), the illuminance at the receiving surface $P(x, y, z)$ can be described as[22]:

$$E\left(x,y,z\right)=z^{m}A_{\mathrm{LED}}L_{\mathrm{LED}}\times\sum_{i=\frac{-(N-1)}{2}}^{\frac{N-1}{2}}\sum_{j=\frac{-(M-1)}{2}}^{\frac{M-1}{2}}\left[\left(x-id\right)^{2}+\left(y-jd\right)+z\right]^{-\frac{m+2}{2}}. \tag{10}$$

When N and M are even numbers, the illuminance at $P(x, y, z)$ on the receiving surface can be described as:

$$E\left(x,y,z\right)=z^{m}A_{\mathrm{LED}}L_{\mathrm{LED}}\times\sum_{i=\frac{-(N-2)}{2}}^{\frac{N}{2}}\sum_{j=\frac{-(M-2)}{2}}^{\frac{M}{2}}\left[\left(x-\left(2i-1\right)\frac{d}{2}\right)^{2}+\left(y-\left(2j-1\right)\frac{d}{2}\right)^{2}+z^{2}\right]^{-\frac{m+2}{2}}. \tag{11}$$

Considering the above-described theory and application requirements, the following parameters are used to investigate the effects of spacing and chip number on the illuminance at the receiving surface: z=10 mm and $\theta_{1/2}$=12°. We obtain m=32 and $d_{\max}$=3.38 mm through calculation.

The illuminance for the whole LED chip follows a Gaussian distribution, and that at the receiving surface is the superposition of the illuminances from all LED chips. As shown in Fig.6, when $d=d_{\max}$, the uniform illuminance area at the receiving surface increases as the chip number increases. When $d>d_{\max}$, the LED chip group illuminance distribution approximates that for a single LED chip (i.e., the LED chips are independent from each other, and the illuminance uniformity at the receiving surface decreases). Fig.7 shows the corresponding simulation results.

According to the simulation results, when $d>d_{\max}$, both the magnitude and illuminance uniformity at the receiving surface decrease. Furthermore, the illuminances of the light-emitting chips in the array are nearly independent. When $d=d_{\max}$, the illuminance shows a uniform distribution at the receiving surface, and the illuminances of the light-emitting chips superimpose with each other to form a uniform illuminance area. When $d<d_{\max}$, the uniform illuminance distribution area at the receiving surface decreases (i.e., the light source's space is wasted and the illuminance ratio for use is reduced). Therefore, in order to improve the illuminance uniformity at the receiving surface and expand the light area, $d=d_{\max}$ should be observed in the LED chip arrangements.

To clarify the difference between the LED module illuminance distributions before and after arraying, two module groups of nine 300 μm×300 μm LED chips and nine LED arrays consisting of 80 μm×80 μm LED chips are chosen for analysis. In these two structures, $d=d_{\max}$=3.38 mm.

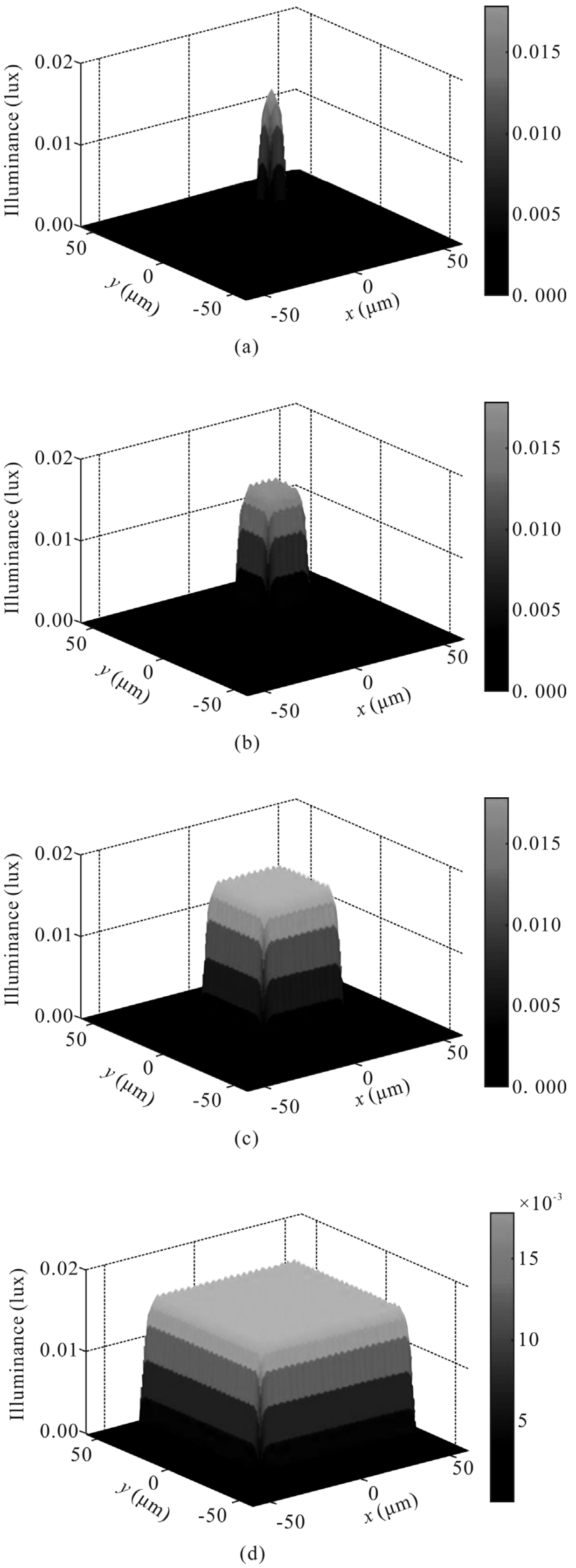


Fig.6 Simulated 3D illuminance distributions for different chip groups when $d=d_{\max}$: (a) 3×3; (b) 7×7; (c) 13×13; (d) 25×25

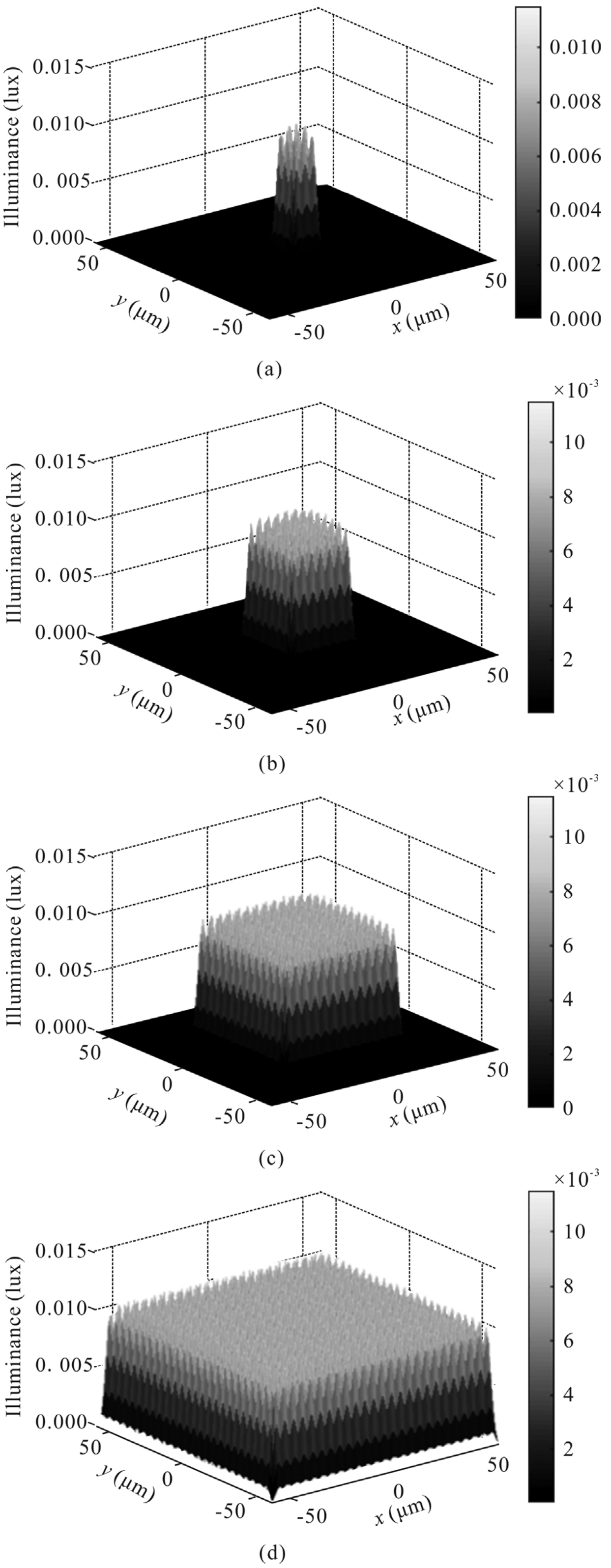


Fig.7 Simulated 3D illuminance distributions for different chip groups when $d>d_{max}$: (a) 3×3; (b) 7×7; (c) 13×13; (d) 25×25

It can be concluded that these two different LED module groups have almost the same illuminance uniformity at the receiving surface. However, the illuminance for the nine LED arrays (each array includes nine 80 μm×80 μm LED chips) is over three times larger than that of the module group consisting of nine 300 μm×300 μm LED chips. This is because when using either the chip group or module group for illumination, the illuminance uniformity depends on the spacing between the chips or modules, while the illuminance magnitude depends on the chip/module light intensity. Thus, the LED arrays can significantly improve the illuminance at the receiving surface.

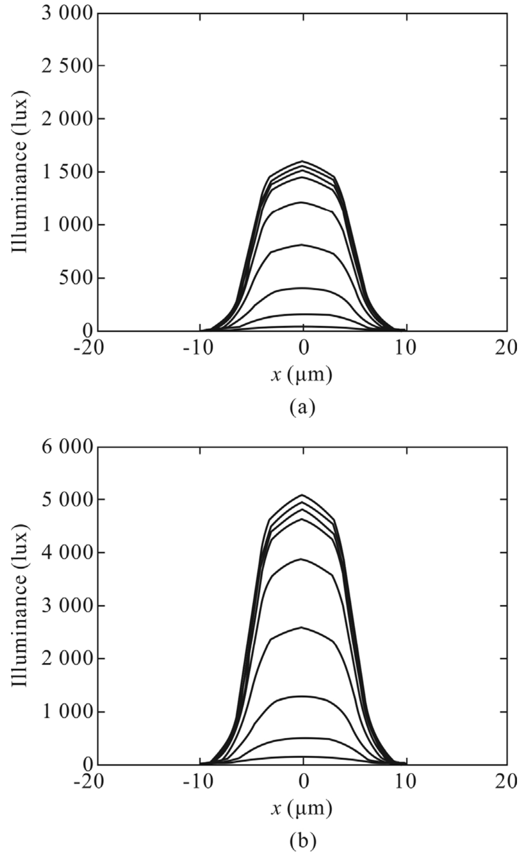


Fig.8 1D illuminance distributions at the receiving surface for two different LED module groups: (a) 300 μm×300 μm LED chips ($d=d_{max}$=3.38 mm); (b) Nine 80 μm×80 μm LED arrays ($d=d_{max}$=3.38 mm)

In summary, the LED arrays can enhance the light source intensity and illuminance uniformity at the receiving surface. To achieve a uniform current density distribution, the sub-unit size should follow $L \le L_S$. In addition, the spacing between sub-units should consider processing feasibility, application requirements, and heat dissipation. We also investigate the effects of sub-unit spacing and number on the illuminance distribution at the receiving surface. The results show that under the maximum flat condition ($d=d_{max}$), the illuminance distribution at the receiving surface is optimized. Additionally, when $d=d_{max}$, the area with uniform illuminance increases along with the number of LED chips. The LED array luminous effects can be optimized by rearranging the LED chips, more specifically, by varying the spacing between sub-units.

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