Optimization and integration of LED array for uniform illumination distribution*

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(Received 29 May 2014)

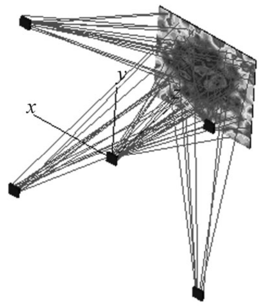
A design method for light-emitting diode (LED) array is proposed to achieve a good uniform illumination distribution on target plane. By using random walk algorithm, the basic LED array modules are optimized firstly. The optimized basic arrays can generate uniform illumination distribution on their target plane. The optimized basic LED array modules can be integrated into a large LED array module with more than tens of LEDs. In the large array, we can select a sub-array with K LEDs (K>7), which can produce the good uniform illumination distribution. By this way, we design two LED arrays which consist of 21 and 25 LEDs, respectively. The 21-LED array and 25-LED array can generate uniform illumination distributions with the uniformities of 95% and 90%, respectively.
Document code: A **Article ID:** 1673-1905(2014)05-0335-5
DOI 10.1007/s11801-014-4096-5

Currently, light-emitting diode (LED) arrays are used in various illumination applications, such as street light, display technology, traffic light and backlight[1-7]. In order to get high output power, we often use multiple LEDs to form an LED array. Optimizing and designing LED array are essential to generate uniform illumination distribution. Various methods are proposed to design LED array for uniform illumination distribution. In the earlier research works, all-analytical method is always used[8-12]. In Ref.[13], we employed the numerical optimization method to design LED array for the first time. However, with the number of LEDs increasing, it becomes time-consuming. In this paper, we propose a new method to design large LED array effectively. Firstly, the basic LED array modules with 4–7 LEDs are optimized by random walk algorithm. The basic LED array modules can be further integrated into a large LED array module with more than tens of LEDs. In the large array, we can select a sub-array with K LEDs (K>7), which can produce a good uniform illumination distribution. By this way, a 21-LED sub-array is selected in a large array, which is made up of many basic 5-LED array modules. In this array, each LED has Lambertian luminous intensity distribution. In addition, we also design a 25-LED array, in which each LED has a special luminous intensity distribution. Both the two large arrays can generate highly uniform illumination distribution. The method offers a preferable choice for the design of large LED array. It is the first time to use the integrating method to generate a general LED array with any number of LEDs. This method can be applied to the LED arrays not only with Lambertian intensity distribution but also with special intensity distribution.

As shown in Fig.1(a), an LED array consisting of several LEDs illuminates a target plane. It is assumed that there is a random point with the coordinate of (x_p, y_q, z) on the target plane. The irradiance at the point on target plane can be obtained by

$$E(x_p, y_q, z) = \sum_{i=1}^{n} \frac{z^{m+1} I_0}{[(x_p - X_i)^2 + (y_q - Y_i)^2 + z^2]^{\frac{m+3}{2}}}, \quad (1)$$

where (X_i, Y_i, 0) is the coordinate of the ith LED in array, and n is the total number of LEDs.



(a)

* This work has been supported by the Opening Project of Shanghai Key Laboratory of All Solid-State Laser and Applied Techniques (No.2012ADL03).
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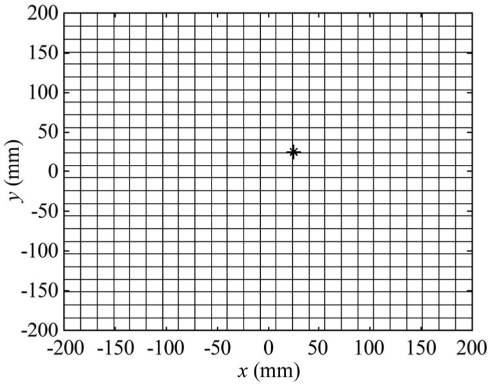


(b)

Fig.1 (a) Schematic diagram of LED illumination; (b) Target plane with *M*×*N* grids

The target plane is divided into $M\times N$ grids as shown in Fig.1(b). Therefore, the average irradiance on the target plane is expressed as

$$\overline{E}=\frac{1}{M\times N}\sum_{q=1}^{N}\sum_{p=1}^{M}E(x_p,y_q,z)\ . \tag{2}$$

Various approaches are used to reflect the uniformity of LED array illumination distribution[14,15]. Here, the uniformity is defined as the ratio of the average irradiance to the maximum irradiance[14], which is expressed as

$$U=\frac{\overline{E}}{E_{\max}}\ . \tag{3}$$

For the purpose of optimizing the LED array, it is necessary to define an evaluation function as

$$F(X_1,Y_1,\cdots,X_i,Y_i,\cdots,X_n,Y_n)=1-U\ . \tag{4}$$

It is evident that the independent variables in the evaluation function are all the coordinates of LEDs. By minimizing the evaluation function, the LED array can achieve a good uniform illumination distribution.

Random walk algorithm is a global optimization algorithm, which can be used to seek the maximum or minimum value of a function. In this paper, we use a random walk algorithm to minimize the evaluation function by optimizing the coordinates of all LEDs. The optimized LED array can yield a highly uniform illumination distribution on the target plane.

The random walk algorithm is designed as follows[16]. (I) The vector $\boldsymbol{x}$ is set as the initial value to seek the minimum function value $f(\boldsymbol{x})$ with the walk step of λ, which is expressed as

$$\boldsymbol{x}=\begin{bmatrix}X_1 & Y_1\\ \vdots & \vdots\\ X_i & Y_i\\ \vdots & \vdots\\ X_n & Y_n\end{bmatrix}; \tag{5}$$

(II) For generating a proper iteration number j, k is set as 1 at the beginning; (III) When $k<j$, n two-dimensional (2D) random vectors $\boldsymbol{u}$ are generated, whose values are in the range from –1 to 1. Let $\boldsymbol{x}_1=\boldsymbol{x}+\lambda\boldsymbol{u}$, so there are n vectors of $\boldsymbol{x}_1$. One of $\boldsymbol{x}_1$, which makes $f(\boldsymbol{x}_1)$ minimum, is selected as the walking objective; (IV) Calculating the function values, if $f(\boldsymbol{x}_1)<f(\boldsymbol{x})$, we obtain a vector which is better than the initial one. Thus k is reset as 1, and program goes to step (II), or $k=k+1$, and program goes to step (III); (V) If the program does loop for j times, but it still cannot find the optimal value, the step λ will be reduced to $\lambda/2$, and the program will go back to step (I) to start a new walk.

By employing the random walk algorithm, we first optimize the arrays with 4, 5, 6 and 7 LEDs, respectively. In these arrays, each LED has a perfect Lambertian intensity distribution. Fig.2(a)–(d) show the optimized arrangements of the LED arrays with 4, 5, 6 and 7 LEDs, respectively. Fig.3 shows the irradiance maps of the optimized LED arrays with different LEDs simulated by the optic software Tracepro[17]. It is clearly shown that the illumination distribution of the optimized LED arrays is symmetric and fairly uniform.

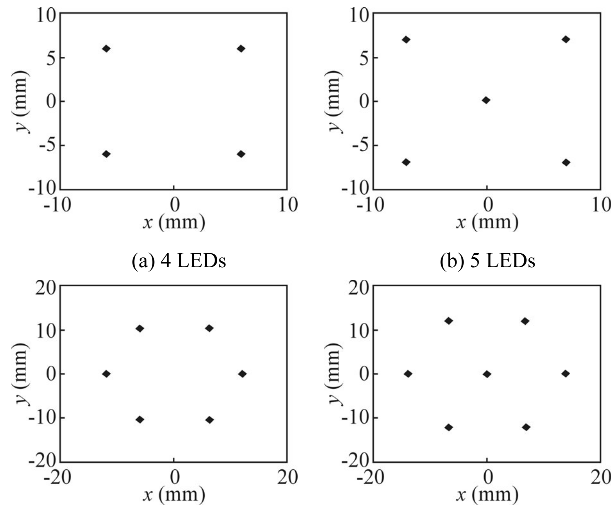
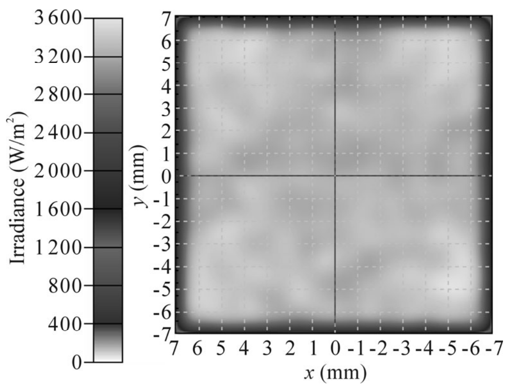


Fig.2 The optimized arrangements of LED arrays with different numbers of LEDs



(a) 4 LEDs

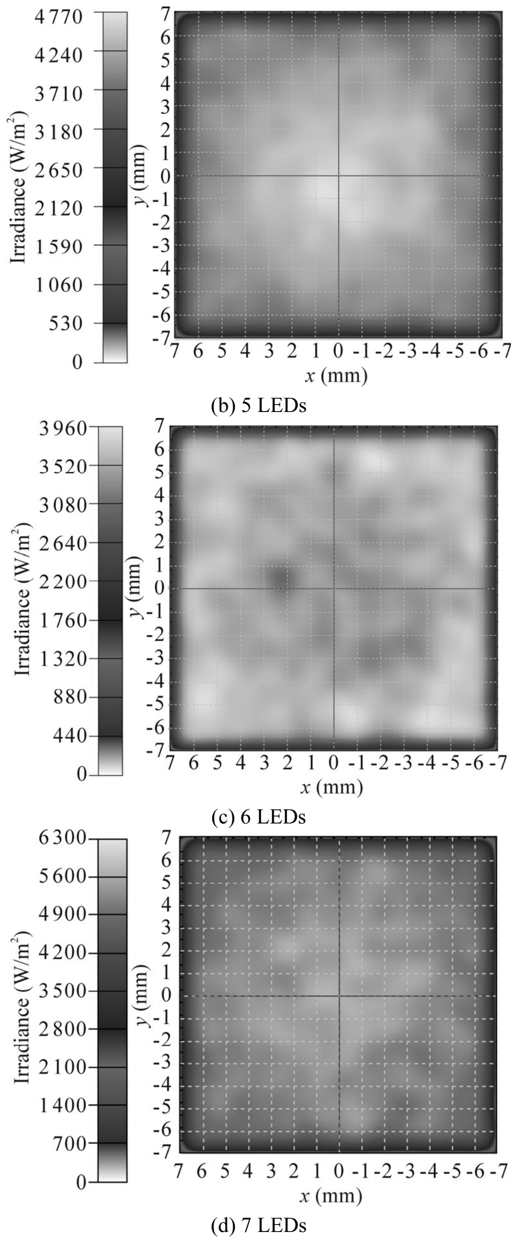


Fig.3 The irradiance maps generated by the optimized arrays with different numbers of LEDs

The random walk algorithm is used to optimize the arrangements of LED arrays with 4–7 LEDs. However, much more time will be needed to optimize the LED array with larger number of LEDs. So we design a method by integrating the basic LED array module into a large LED array module, where the basic arrays mean those with 4–7 LEDs optimized by random walk algorithm above. The basic arrays should keep the number of LEDs as less as possible, and can integrate the large arrays with any number of LEDs. As an example, we demonstrate how to integrate some 5-LED arrays into a large array as shown in Fig.4. In order to simplify the problem, we extend the array along x-axis at first. In Fig.2(b), the optimized basic array with 5 LEDs has a rectangular arrangement. One LED locates at the center of the rectangle, and the other 4 LEDs locate at the 4 vertices of the rectangle. In Fig.4, the array in the left box can be regarded as a mother array, and the array in the right box can be regarded as a duplicate array. It is clear that the mother array and the duplicate array share two common LEDs. Then we can regard the duplicate array as a new mother array to produce another duplicate array in the same way. Also, we can extend the array along y-axis. Thus a 2D large LED array can be formed in Fig.4. In the large array, we can select a sub-array with K LEDs (K>7). A sub-array can be called as a general array. By this way, we select 21 LEDs as a general array marked by a hexagon in Fig.4. Fig.5 is an enlarged arrangement of the general array with 21 LEDs. As shown in Fig.6, the 21-LED array module produces a uniform illumination with a uniformity of 95%. While selecting some LEDs as a general array, we should keep the array arrangement as symmetrical as possible. With the method, the general array with any number of LEDs can be generated.

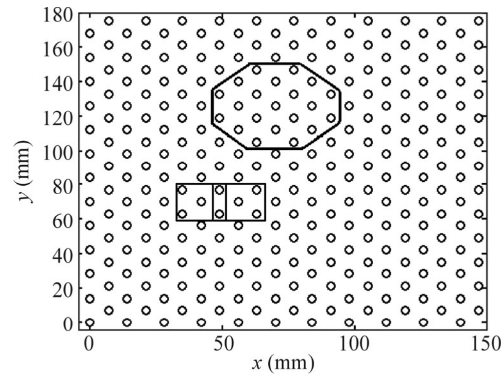


Fig.4 Illustration of how to integrate the 5-LED arrays into a large array and how to select some LEDs as a general LED array

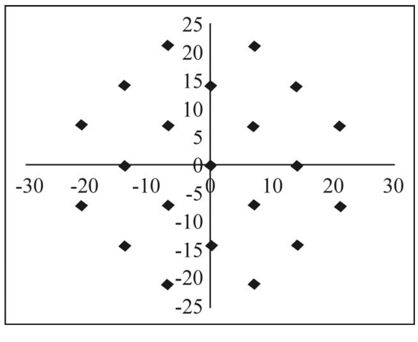
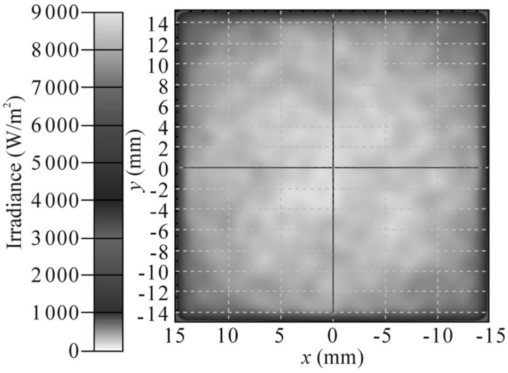
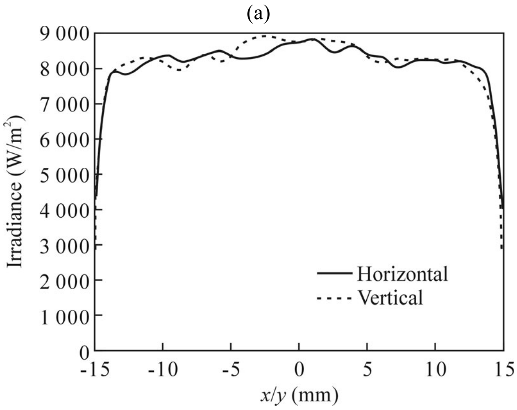


Fig.5 The enlarged illustration of the 21-LED array arrangement

Next, we design a large LED array in which each LED has a special luminous intensity distribution as shown in Fig.7. It is clear that the intensity distribution of this kind of LED is more complicated. Here, we use the random walk algorithm to optimize a basic array with 5 LEDs in which each LED has the special intensity distribution shown in Fig.7. The optimized basic LED array is shown in Fig.8(a). The basic array can generate the uniform illumination distribution as shown in Fig.9. By array integrating method, we design a large array with 25 LEDs as shown in Fig.8(b). The large array also produces highly uniform illumination distribution (Fig.10) with uniformity of 90%.



(a)



(b)

Fig.6 (a) The irradiance map and (b) the irradiance profile of the general array with 21 LEDs

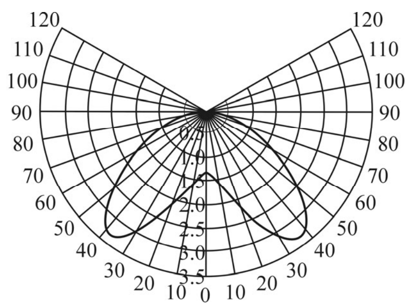
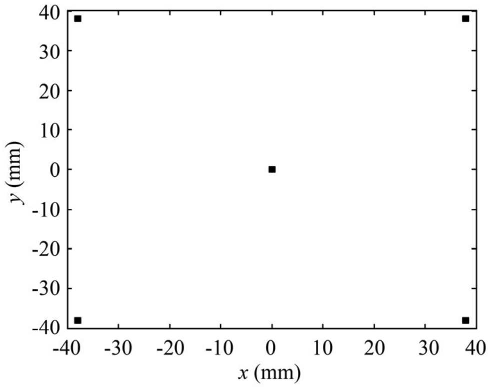
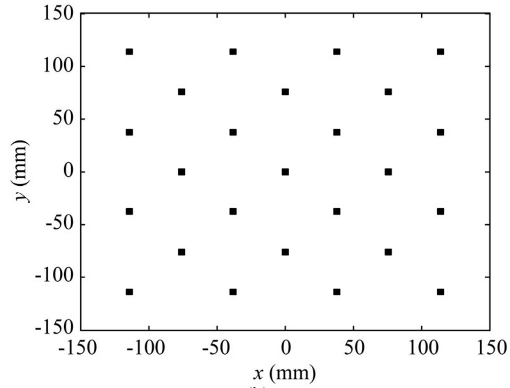


Fig.7 The special luminous intensity distribution of LED

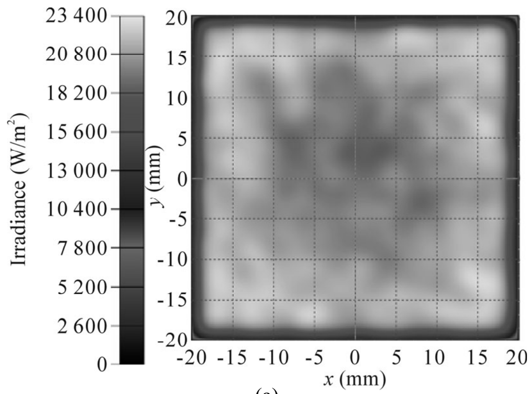


(a)

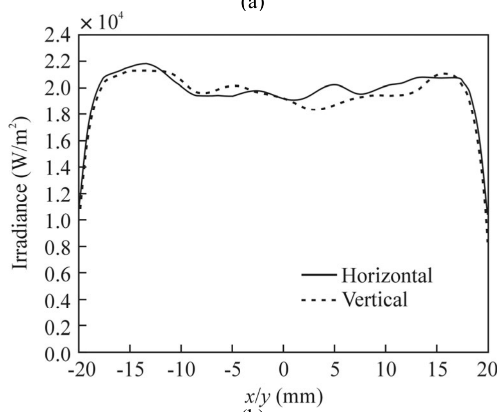


(b)

Fig.8 (a) Basic 5-LED array and (b) integrating 25-LED array made up of LEDs with special luminous intensity distribution

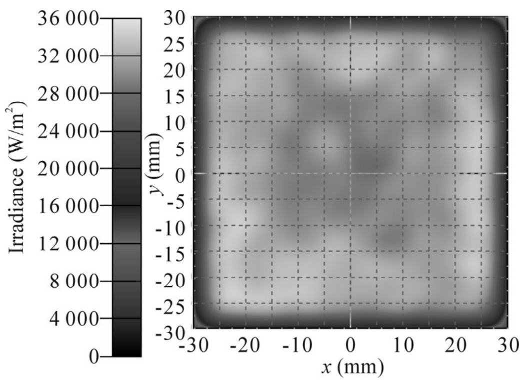


(a)

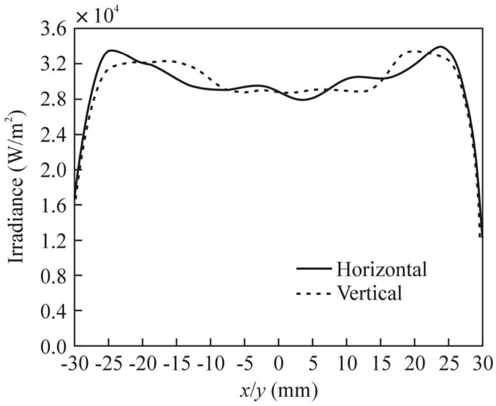


(b)

Fig.9 (a) The irradiance map and (b) the irradiance profile of 5-LED basic array made up of LEDs with special luminous intensity distribution



(a)



(b)

Fig.10 (a) The irradiance map and (b) the irradiance profile of 25-LED array made up of LEDs with special luminous intensity distribution

In conclusion, the random walk algorithm is used to optimize the coordinates of each LED in the array so that the evaluation function can reach the minimum. By using the method, the basic LED arrays with 4–7 LEDs are optimized, respectively. All the basic LED arrays can produce good uniform illumination distribution, and each LED in these arrays has a Lambertian intensity distribution. The basic LED array modules can be further integrated into a large LED array. In the large array, we can select a sub-array with K LEDs (K>7), which can produce good uniform illumination distribution. By this way, a 21-LED sub-array is selected in a large array made up of many basic 5- LED array modules. The 21-LED array module produces highly uniform illumination distribution. In addition, we also design a 25-LED array, in which each LED has a special luminous intensity distribution. The 25-LED array yields uniform illumination distribution with the uniformity of 90%. By this method, the general array with any number of LEDs can be generated.

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