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一种兼顾照明与通信的环形光源布局模型

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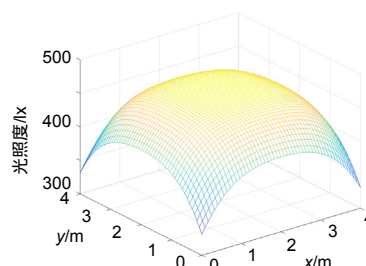
摘要: 传统基于阵列的光源布局方式在室内难免存在光照度及系统误码率不均匀现象, 为提高系统照度均匀性及通信可靠性, 需合理对光源进行优化布局。本文以 $4\text{ m} \times 4\text{ m} \times 3\text{ m}$ 的房间为模型, 设计了单 LED 阵列+灯带的环形光源布局模型。模型中间采用 6×6 LED 阵列, 阵列内部灯珠之间的距离为 0.3 m ; 四周采用环形灯带形式, 灯珠个数为 316 个, 灯珠之间的距离为 0.05 m 。仿真结果表明, 该模式下系统光照度均值为 437.08 lx , 光照度均匀性为 93.9% , 同时, 系统误码率均值为 2.8716×10^{-7} 。因此, 本文所设计的环形光源布局模型兼顾了室内光照度分布的均匀性和通信的可靠性, 可同时满足室内照明和通信, 为室内可见光通信光源布局提供了一种优化方法。

关键词: 可见光通信系统; 光照度; 误码率; 阴影效应

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An annular light source layout model for both lighting and communication reliability

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Abstract: The traditional layout of light source based on array will inevitably lead to uneven illumination and BER in the room. In order to improve the illumination uniformity and reliability of the system, it is necessary to optimize the layout of the light source reasonably. In this paper, a $4\text{ m} \times 4\text{ m} \times 3\text{ m}$ room is used as the model to design a ring light source layout model with a single-LED array and lamp belts. In this model, the distance between the inner lamps of the 6×6 LED array is 0.3 m . The number of surrounding lamp beads is 316 and the distance between the lamps is 0.05 m . The simulation results show that the system illumination is about 437.08 lx and the illumination uniformity is 93.9% . At the same time, the system error rate is about 2.8716×10^{-7} . The annular light source layout model designed in this paper takes into account the uniformity of indoor illumination distribution and the reliability of communication simultaneously, which can meet the indoor lighting and communication at the same time and also can provide an optimization method for the layout of indoor visible light communication.

Keywords: visible light communication system; light intensity; bit error rate; shadow effect

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1 引言

室内可见光通信系统的发展日益进步,利用 LED 作为光源不仅具有照明功能,而且具有良好的通信作用^[1-4]。一般来说,房间的大小以及室内环境条件都是各不相同,所以影响通信及照明的主要原因是光源布局及光源数量。目前国内外对室内光照度及可见光通信可靠性研究的文献很多^[4-8],但大多都是基于传统阵列布局模型,该模型环境下,光照度起伏方差较大,分布不够均匀,为了避免室内可见光通信中的盲区,本文搭建了 4 m×4 m×3 m 的房间仿真模型,结合光照度补偿原理,将 LED 阵列和 LED 灯珠结合起来进行整体布局,使得布局结构简单、美观,室内接收平面光照度及可靠性分布均匀,能够有效地避免阴影效应,提高照度均匀性及通信可靠性。

2 光照度及可靠性模型

如图 1 所示,以 4 m×4 m×3 m 的房间一角作为坐标原点建立三维坐标系,接收平面位于距离地面 0.75 m 的办公桌上,在光源发射角为 φ 的情况下,接收平面某点的水平照度 E_n 可表示为^[9]

$$E_n = I(0) \cos^m(\varphi) \cdot \cos(\psi) / d^2, \quad (1)$$

其中: $I(0)$ 表示 LED 的中心发光强度, d 为光源到接收平面的距离, m 为光源的辐射模式:

$$m = \frac{-\ln 2}{\ln(\cos \varphi_{1/2})},$$

其中: $\varphi_{1/2}$ 为发射功率半角。本文中光源的型号是草

帽 8 mm 白光 LED 灯珠,仿真参数如表 1 所示。

假设点光源的坐标为 $(x_n, y_n, 3)$, 在距离地面 0.75 m 的接收面上某一点坐标为 $(x, y, 0.75)$, 则 d 可以表示为

$$d = \sqrt{(x - x_n)^2 + (y - y_n)^2 + 2.25^2}. \quad (2)$$

由于每个 LED 灯珠的位置不同,到达接收面上同一点所接收到的光照度也会有所不同,且 LED 光源为非相干光源,所以在接收平面上某一点接收到的光照度为各点光源到该点的光照度的叠加。所以接收平面上某点 $(x, y, 0.75)$ 接收到的光照度为

$$E(x, y) = \sum_{n=1}^M E_n, \quad (3)$$

其中 M 为总的光源个数。

接收平面光照度均值,可用公式表示为

$$\bar{E} = \frac{1}{S} \iint_{(x,y)} E(x, y) dx dy, \quad (4)$$

其中 S 为接收平面面积。

接收端探测器接收到从 LED 阵列传输过来的总光源功率 P_{rx} 可表示为

$$P_{rx} = \sum_{n=1}^M P_t H_n(0), \quad (5)$$

其中: P_t 为单个 LED 灯的功率, $H_n(0)$ 为信道的直流增益^[4]。

系统信噪比 SNR 可表示为^[10]

$$SNR = \frac{(RP_{rx})^2}{\sigma_1^2 + \sigma_2^2}, \quad (6)$$

其中:

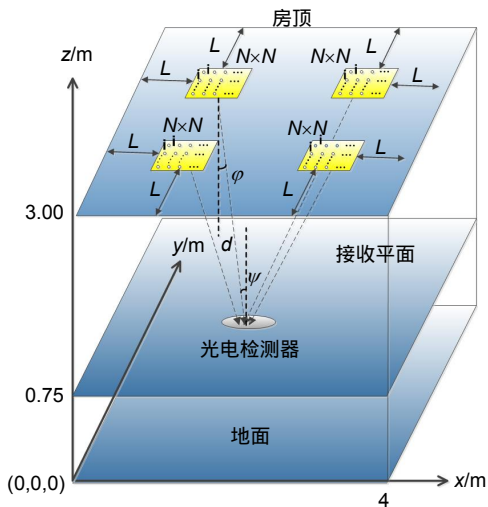


图 1 4 个 LED 阵列布局模型

Fig. 1 Layout model of 4 LED array

表 1 仿真参数

Table 1 Simulation parameters

参数	值
房间大小	4 m×4 m×3 m
单个 LED 功率 P_t /W	0.5
LED 灯半功率角 φ /deg	60
LED 的中心发光强度 $I(0)$ /cd	21.5
噪声带宽因子 I_1	0.562
系统数据传输速率 R_p /(Mbit/s)	10
放大器噪声电流 I_a /(pA/ $\sqrt{\text{Hz}}$)	5
放大器带宽 B_a /MHz	50
背景光的噪声功率 P_n /mW	0.2
光电探测器转换效率 R	0.4

$$\begin{cases} \sigma_1^2 = 2qR(P_{rx} + P_n)B_n \\ \sigma_2^2 = I_a^2 B_a \end{cases}, \quad (7)$$

R 为光电探测器转换效率, σ_1^2 为系统散粒噪声, q 为电子电量, P_n 为周围环境背景光产生的噪声功率, σ_2^2 为放大器噪声, I_a 为放大器噪声电流, B_a 为放大器带宽, B_n 为噪声带宽, $B_n = I_l R_b$, I_l 为噪声带宽因子, R_b 为系统数据传输速率。具体参数见表 1。

由式(6)得出系统 SNR 之后, 系统误码率 BER 可表示为

$$\begin{cases} BER = Q(\sqrt{SNR}) \\ Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2}\right) dy \end{cases} \quad (8)$$

则接收平面的误码率均值 $\overline{BER(L, i)}$ 为

$$\overline{BER(L, i)} = \frac{1}{S} \iint_{(x, y)} BER(x, y) dx dy \quad (9)$$

3 传统阵列布局模型

图 1 为传统阵列布局模型, 从图中可以看出影响室内光照度大小的因素主要有三个: 1) LED 阵列的大小 $N \times N$; 2) 每个 LED 阵列距离墙壁的距离 L ; 3) 每个 LED 阵列内部 LED 灯珠之间的距离 i 。随着 L 和 i 以及 LED 灯珠 $N \times N$ 这三个量任意一个的改变, 都会使得接收平面上同一点处总的接收光照度不相同。

运用 4 个 LED 阵列, 图 2 为当 $N=9$ 时不同 L 和 i 值接收平面光照度最小值分布, 由图中可以看出, 已经存在部分 L 和 i 值的布局方式, 能够满足室内国际照度标准要求^[11]。

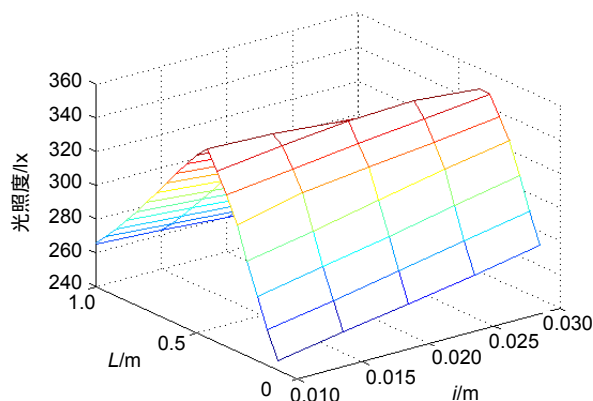


图 2 $N=9$ 时接收平面光照度的分布

Fig. 2 The distribution of plane illumination when $N=9$

3.1 均匀性分析

在传统 4 个 LED 阵列布局方式中, 当 $N=9$, $L=0.35$ m, $i=0.03$ m 时, 室内照度均匀性最佳, 图 3 所示在均匀分布的 4 个 LED 阵列的正下方, 光照度的值会达到整个房间光照度的最大值, 最大值达 451.2 lx。在靠近四条边的中心位置处, 因为光线较弱, 所以光照度为整个房间的最小值, 最小值为 348.1 lx, 其余地方的光照度也不太相同, 接收端平面上光照度分布的均匀度为 89.36%。

3.2 可靠性分析

由于光照度的不均匀性, 使得接收平面不同点处的误码率几乎是不同的, 如图 4 所示。4 个 LED 阵列

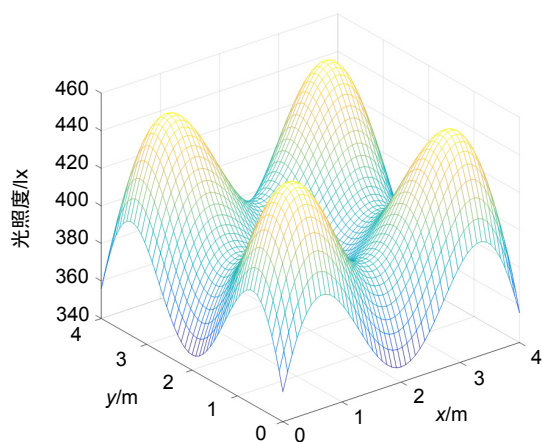


图 3 4 个 LED 阵列的光照度分布图

Fig. 3 Light intensity distribution map of 4 LED array

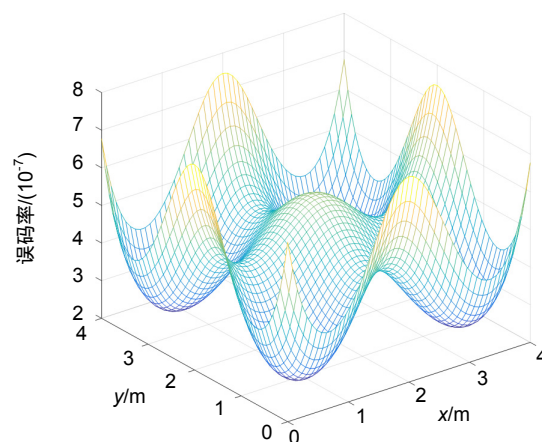


图 4 4 个 LED 阵列的误码率分布图

Fig. 4 Error rate distribution map of 4 LED array

直射到的地方的误码率相对较小,其他墙角处或者远离这4个LED阵列的地方的误码率相对较大,误码率的均值为 4.065×10^{-7} 。

4 环形光源布局模型

传统4阵列布局,虽然在整个接收平面上的光照度都符合国际照明标准,但是照度均匀性及误码均匀性仍有待提高,根据光照度补偿机制,本文采用环形光源布局模型来对接收平面照度均匀性及可靠性进行改善。

如图5所示,在天花板中心放置一个6×6的LED

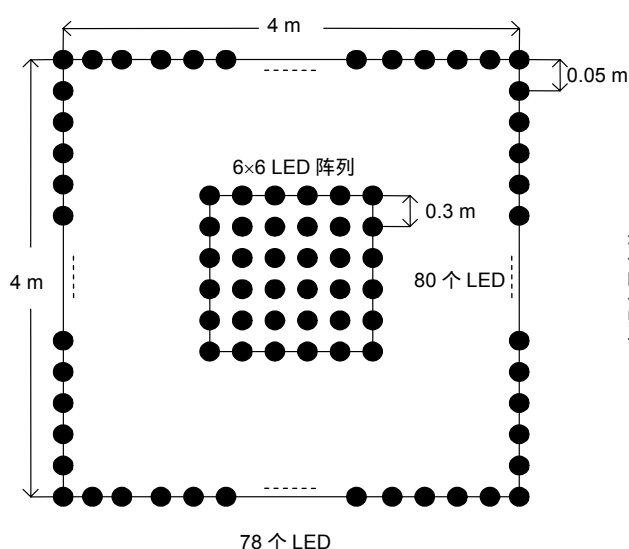


图5 单个LED阵列+灯带在天花板上的分布

Fig. 5 Distribution of the model with single-LED array and camp belts

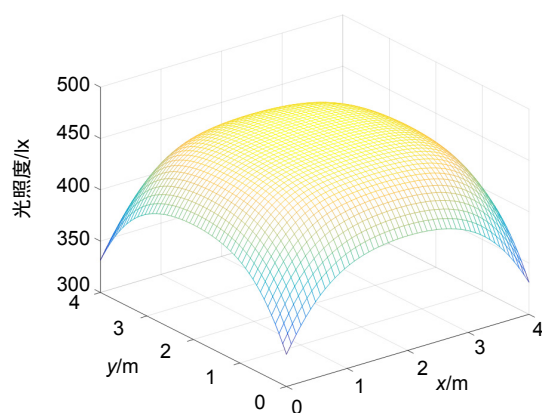


图7 单个LED阵列+灯带模型的光照度分布图

Fig. 7 The light distribution map of the model with a single-LED array and light belts

阵列,然后在这个大的LED阵列的四周环绕放置一圈的LED灯珠,即变成了LED灯带。四周灯带之间的距离用 i_1 表示,中间单LED阵列灯珠之间的距离用 i 表示。

运用环形光源布局模式,图6所示存在很多 i_1 和 i 值,在这些布局方式下,室内最小光照度已经满足300 lx。

4.1 均匀性分析

在环形光源布局方式中,当四周灯带的长度取80个LED灯珠,宽度取78个LED灯珠,共用 $80 \times 2 + 78 \times 2 = 316$ 个LED灯珠,并且每个LED灯珠之

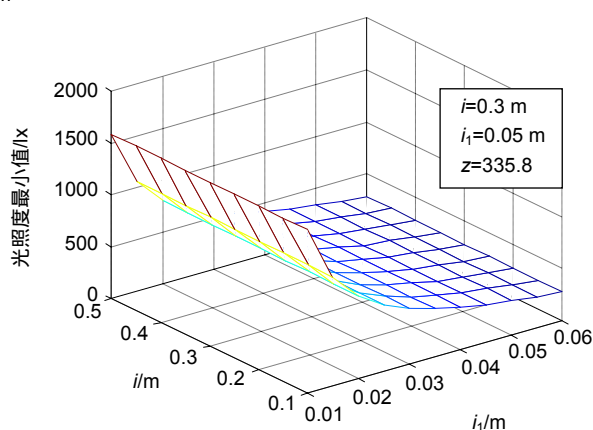


图6 不同 i, i_1 取值时光照度最小值分布

Fig. 6 The minimum value of light distribution with different values of i and i_1

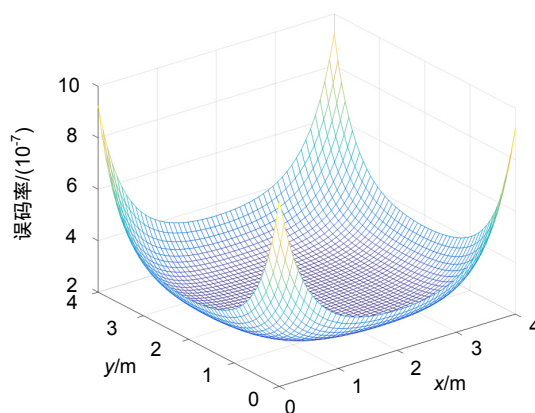


图8 单个LED阵列+灯带模型的误码率分布图

Fig. 8 Error rate distribution map of the model with a single-LED array and light belts

间的距离 i_1 为 0.05 m ;中间的 LED 阵列的大小为 6×6 ,灯珠之间的距离 $i=0.3$ m 时 ,室内照度均匀性最佳 ,如图 7 所示 ,整个接收平面光照度在 300 lx~470 lx 之间 ,最大光照度为 465.1 lx ,最小为 331.4 lx ,最小值分别位于墙角处。接收端平面上光照度均值为 437.0751 lx ,均匀度为 93.9%。与传统 4 阵列布局模式相比 ,光照度更加均匀 ,均匀性增加了 4.54%。

4.2 可靠性分析

由图 8 可得 ,整个平面上的误码率取值较为均匀。只有在四个墙角处的误码率取值相对较高 ,最大值为 9.228×10^{-7} 。在整个平面的大部分位置 ,误码率的取值相对接近 ,误码率均值可达 2.872×10^{-7} 。与传统 4 阵列光源布局模型的误码率相比较来说 ,环形光源布局模型系统平均误码率更低一些 ,可有效地提高通信系统可靠性。

5 总 结

本文以 $4 \text{ m} \times 4 \text{ m} \times 3 \text{ m}$ 的房间为模型 ,通过对光照度及系统可靠性进行数学建模 ,在原有阵列布局模型的基础上 ,通过光照度补偿原理 ,设计了单 LED 阵列+灯带的环形光源布局模型 ,通过数值分析不同布局参数条件下系统接收平面光照度最小值、系统光照度均匀性 ,得出当中间固定一个 6×6 的单 LED 阵列 ,阵列内部灯珠之间的距离为 0.3 m ;四周灯带长度取 80 个 LED 灯珠 ,宽度取 78 个 LED 灯珠 ,共用 $80 \times 2 + 78 \times 2 = 316$ 个 LED 灯珠 ,并且每个 LED 灯珠之间的距离 i_1 为 0.05 m 时 ,室内照度均匀性最佳 ,均匀性可达 93.9% ,同时误码率分布也最均匀 ,误码率均值为 2.872×10^{-7} 。本文设计的环形光源布局模型在数学建模时均可进行参数化设定 ,因此该模型理论上可以拓展到任意尺寸房间 ,在搭建实验模型时 ,可以抽象微型化室内空间模型对系统光照度分布均匀性及可靠性进行实验验证 ,从而为室内可见光通信提供一种有效的光源布局方式。

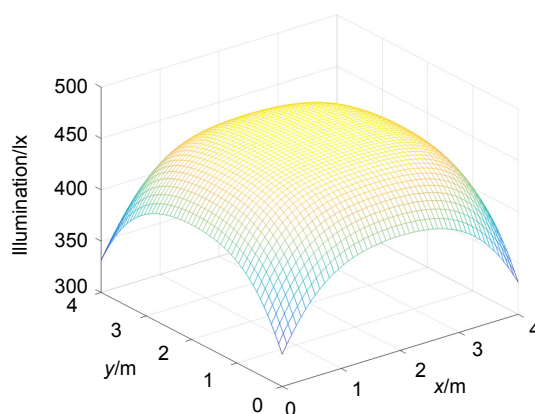
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The light distribution map of the model with a single-LED array and light belts

Overview: Indoor visible light communication technology is a new wireless data transmission method based on white light LED. With the rapid development of wireless transmission and the increasing tension of the current wireless spectrum resources, the research of visible light communication has become a research hotspot in the field of communication. The light source LED should take the dual functions of lighting and communication into consideration at the same time. In order to effectively ensure uniformity of lighting and the reliability of communication, a reasonable layout of the light source is needed to get a simple and beautiful layout structure and can effectively avoid the shadow effect and improve the uniformity of lighting and the reliability of communication. At present, there are many literatures on indoor illumination and visible light communication reliability at domestic and foreign, but most of them are based on the traditional array layout model that has the weaknesses of large illumination variance and uneven illumination distribution. In order to avoid these problems in traditional array layout model, a 4 m×4 m×3 m indoor model is adopted as the real space transport model to calculate the indoor illumination distribution and communication reliability, and a ring light source layout model with a single-LED array and lamp belts is designed based on the principle of illumination compensation. Through the numerical analyses of the minimum illumination and the uniformity of illumination under different layout parameters, it is concluded that the entire receiving plane illumination is between 300 lx~470 lx when the distance between the inner lamps of the 6 × 6 LED array is 0.3 m and the number of surrounding lamp beads with distance of 0.05 m is 316. Under this layout model, the maximum and minimum illuminations of the system are about 465.1 lx and 331.4 lx, respectively. Furthermore, the mean light intensity is about 437.0751 lx, and the uniformity of about 93.9% can be achieved. Compared with the traditional 4-LED array layout model, the illumination uniformity is increased by 4.54%. At the same time, the average BER of the annular light source model is about 2.8716×10^{-7} that is lower than that of the 4-LED array layout model. Therefore, the annular light source layout model designed in this paper can not only meet the uniformity of indoor illumination distribution but also ensure the reliability of communication, thus providing an effective layout method for indoor visible light communication.

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