光学学报

近场分布式平面光源光强测试方法

胡少杰[1], 王洪远[2], 何泽浩[2], 朱巧芬[1], 曹良才[2*]

[1]河北工程大学数理科学与工程学院, 河北 邯郸 056038;

[2]清华大学精密仪器系, 北京 100084

摘要 对近场分布式光度测量方法及测量机理进行研究,基于自主搭建的近场光源发光特性测量装置采集平面光源不同方向的亮度图像,分析了近场光度参量之间的转换关系及亮度数据处理方法,最终实现了近场分布式平面光源空间光强分布测量。通过构建平面光源发光模型,基于光度学和几何光学原理分析发光平面各个方向的光线分布,完成对光源不同方向的发光状态表征。与远场测量相比,所提近场分布式测量方法结果与远场配光曲线吻合良好,在所采用成像式亮度计亮度相对误差优于6.51%的情况下,所测得的光强相对误差小于8.38%,0°配光曲线匹配指数高达98.33%,验证了所提方法在近场光度测量中的有效性。

关键词 测量; 分布光度计; 近场分布式光度测量; 成像式亮度计; 光强; 配光曲线

中图分类号 O432 **文献标志码** A **DOI:** 10.3788/AOS231565

1 引 言

近年来,随着发光材料与照明技术研究的不断深入,人们对光源的需求已经不仅仅是高效、节能和环保,正在向着健康、舒适的照明品质转变[1],这对光源发光特性测量技术提出了更高的要求。为了满足光源照明设计与市场应用的需求,需要研究光度精细化测量方法以及高效测试设备以获取光源空间中的光强分布,进而为提升光源照明品质以及精准配光提供详细的光度数据[2],并且有望在助航灯具的光强检测、阵列面光源的优化设计等领域中发挥重要的应用价值[3-4]。

目前,光源发光特性测量方案主要分为远场分布式光度测试和近场分布式光度测试两种[5]。远场分布式光度测试将光源视为点光源,所有出射光线始于同一点,将光度探头作为探测器,要求其与固定待测光源的机械结构距离必须足够远,测量距离至少为被测光源最大发光尺寸的5倍[6],受测量体积限制,该方法难以实现大尺寸光源的光度检测。近场分布式光度测量装置通常被称为近场分布光度计,一般将光源视为面光源,所有出射光线始于光源表面。近场分布光度计通常将成像式亮度计作为光度探测器,其敏感元件直接接收光源在不同视角下的全部光线信息,进而获取所测平面的全空间亮度分布,最终基于光线追踪技术实现对光强、照度、光通量等光度学参量的测量[7-13]。

相比于远场测试,近场分布式光度测量方法能够更精细、更完整地表征光源发光特性,逐渐成为光源发光特性测量技术的研究热点。国外方面,德国TechnoTeam公司生产的RiGO 801近场分布光度计可以快速完成对LED及其模组的近场数据测量,且能够完整表征光源发光特性[14];美国Radiant公司制造的SIG-400可生成高精度近场模型[15-16];雅典理工大学、匈牙利潘诺尼亚大学、比利时鲁汶大学分别针对近场光度检测领域的系统结构设计、探测器误差消除及不同测量方式对光源光强和总光通量的差异等方面开展了相关研究[17-19]。国内方面,浙江大学金耀辉[20]探讨了成像式亮度计和机械装置所导致的测量误差,并开展了误差校正相关方法研究;杭州远方光电信息股份有限公司自主研发了小型近场分布光度计GO-NR1000,适用于灯珠、模组等小型光源[21];大连工业大学杨继乾[22]和胡博[23]基于CA2000成像式亮度计搭建了近场光度测试系统,比较了近场和远场光度测试的光强分布差异。然而,国内近场分布式光度测试系统的研发尚处于起步阶段,在测量尺寸或测量精度上存在一定局限,难以满足光源发光特性的测量需求。因此,准确测试空间光强分布对表征光源发光特性至关重要。

针对上述问题,本文对近场分布式光度测量方法和测量机理进行研究,基于自主研发的近场光源发光特性测量装置采集光源近场亮度图像,通过平面光源发光模型对亮度元数据进行处理,最终由光源近场亮

收稿日期: 2023-09-18; **修回日期**: 2023-11-08; **录用日期**: 2023-11-27; **网络首发日期**: 2023-12-12

基金项目: 国家重点研发计划(2022YFF0705500)

通信作者: *clc@tsinghua.edu.cn

度分布实现平面光源空间光强分布特性测量。实验结果证明，所采用方法在近场分布式光度测量过程中行之有效，具有较高的工程实践应用价值。

2 近场分布式光度测量基本原理

2.1 近场分布式光度测量方法

基于成像式亮度计的近场分布式光度测试方法是当前测试光源特性的重要方式，其主要优势在于该方法可以表征发光体近场空间发光的分布状态，进而有针对性地实现对光场信息的调控以及发光器件配光设计的优化。其测量方法如图 1 所示，成像式亮度计首先围绕发光体做三维空间球面扫描运动，在扫描球面上捕获发光体各个角度的近场亮度图像信息，然后基于发光体角向亮度分布数据进行配光计算，最终实现发光体空间光强分布等光学特性信息的获取。其中，成像式亮度计作为近场分布式光度测试系统的核心部件之一，能够快速、准确测量待测目标的光学特性信息，其单幅亮度图像包含 2×10^{6} pixel[24]。

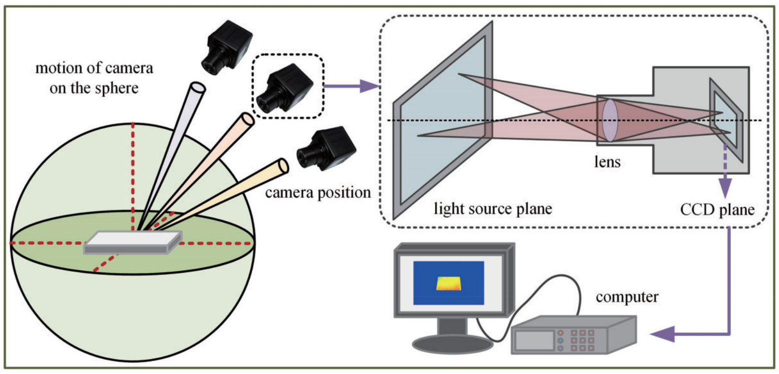

图 1 近场分布式光度测量方法

Fig. 1 Method for near-field distributed photometric measurement

2.2 光源近场测试模型

近场分布式光度测试方法利用角向亮度图像信息构建光源近场模型，通过光度学参量转换，反演光源发光特性，同时可获取光源出射的起点和传播方向等特征信息。因此，近场测试结果更接近光源的真实发光情况，并可应用于 Zemax、TracePro 等仿真软件[25]。针对平面光源展开研究，采用平面发光模型将发光体等效为由点光源阵列组成的平面发光模型，由亮度图像中百万级像素亮度信息计算光源的发光特性，进而获取光源空间光强分布。

如图 2 所示，为准确描述光源发光特性，建立以发光面中心为原点的世界坐标系 $X_wY_wZ_w$，以旋转轴起始方向所在直线为 X_w 轴，以垂直于发光面并指向成像式亮度计方向所在直线为 Z_w 轴，并以垂直于 X_w 和 Z_w 轴方向所在直线为 Y_w 轴。初始状态下，光源与成像式亮度计的距离为 l，成像式亮度计焦距为 f，可以由光源发光位置 (x, y, z) 确定成像位置 (x_0, y_0, z_0)。成像式亮度计跟随机械结构绕 Z_w 轴转动角度 α，再绕 Y_w 轴转动角度 β，则转动后位置变为 (x_p, y_p, z_p)，该过程可表示为

$$\begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix} = \boldsymbol{R}_{Y_w}(\beta)\boldsymbol{R}_{Z_w}(\alpha)\begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} + T, \tag{1}$$

式中：T 为平移矩阵；$\boldsymbol{R}_{Y_w}(\beta)$ 为成像式亮度计绕 Y_w 轴转动角度 β 的旋转矩阵；$\boldsymbol{R}_{Z_w}(\alpha)$ 为成像式亮度计绕 Z_w 轴转动角度 α 的旋转矩阵。两个旋转矩阵的具体表达式为

$$\boldsymbol{R}_{Y_w}(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}, \tag{2}$$

$$\boldsymbol{R}_{Z_w}(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}。 \tag{3}$$

将所测得的百万级像素亮度信息中每个像素视为一个发光点，像素 (i, j) 分别对应发光位置 (x, y, z) 和自身空间位置 (x_p, y_p, z_p)，由此确定光线方向向量 (n_x, n_y, n_z)。θ_s 为光线与世界坐标系 Z_w 轴正方向夹角，φ_s 为光线在 X_wY_w 平面上的投影与 X_w 轴正方向夹角，两者计算过程为

$$\theta_s = \arccos\frac{n_z}{\sqrt{{n_x}^2 + {n_y}^2 + {n_z}^2}}, \tag{4}$$

$$\varphi_s = \arctan\frac{n_y}{n_x}。 \tag{5}$$

由式(4)、(5)计算光线传播方向 (θ_s, φ_s) 后结合式(1)即可得到光源亮度分布 $L(x, y, \theta_s, \varphi_s)$，进一步获取光源空间光强分布 $I(\theta_s, \varphi_s)$，

$$I(\theta, \varphi) = \int_S L(x, y, \theta_s, \varphi_s)\cos\theta_s \mathrm{d}S, \tag{6}$$

式中：θ 为俯仰角；φ 为旋转角；$\mathrm{d}S$ 为发光面元；S 为发光面表面积。

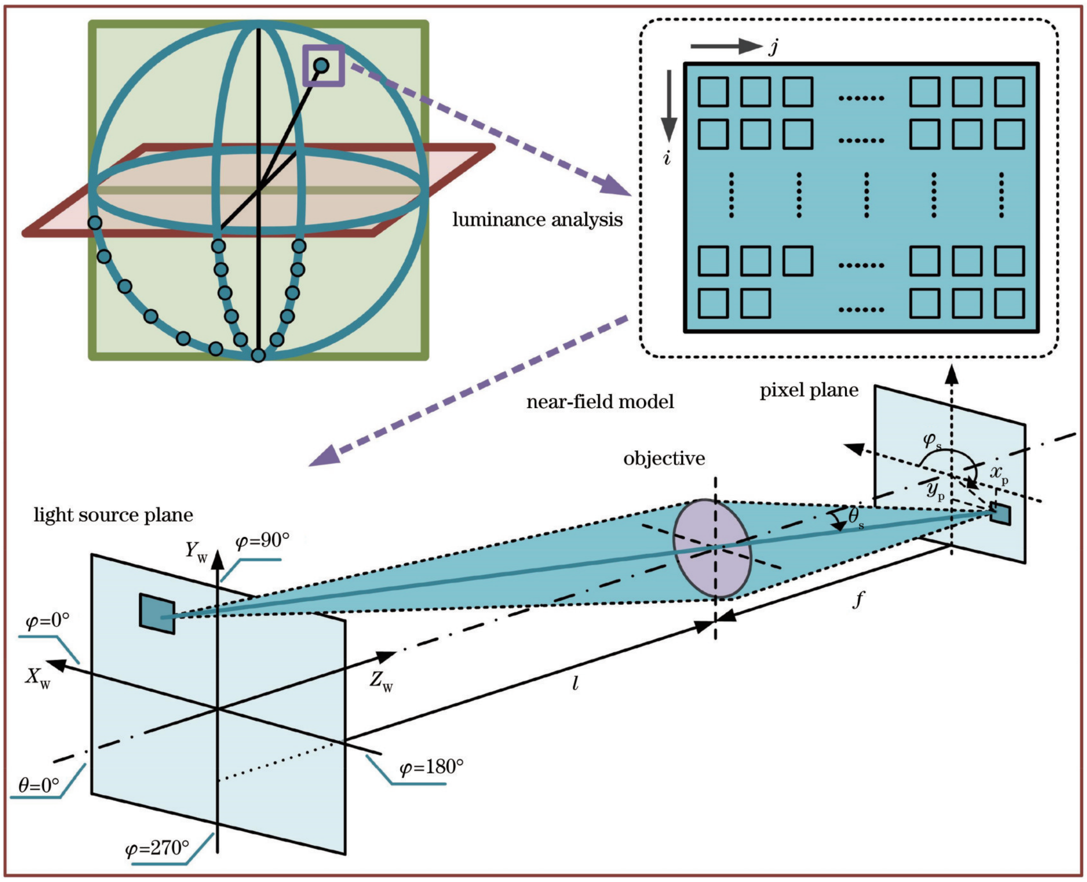

图 2　近场光源发光特性测试原理图

Fig. 2　Schematic for luminescence characteristic test of light source under near-field condition

3　近场光度测量实验及结果分析

3.1　近场光度测量实验

采用清华大学自主研制的近场光源发光特性测量装置，基于光源固定不动而亮度计空间转动的测量方式实现光源近场三维空间亮度数据采集。实验装置示意图如图 3 所示，整个系统的主体结构分为内框架和外框架，主要由机械转台、成像式亮度计、被测光源和主控制器等组成。硬件设计方面，因内部框架安装有成像式亮度计等需要依靠线缆供电的器件，因此在回

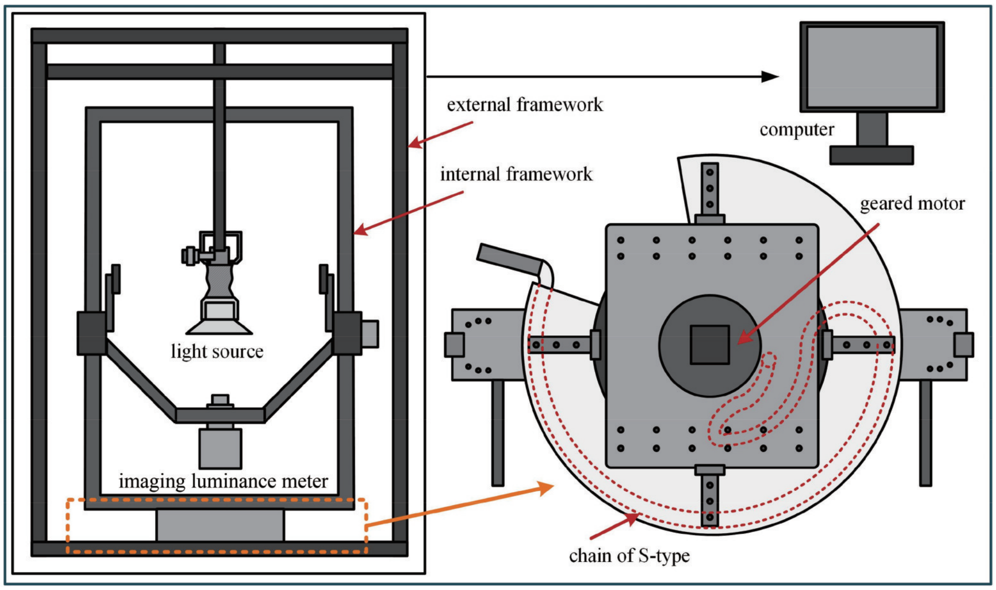

图 3　实验装置示意图

Fig. 3　Structure of experimental device

转电机连接板的外圈和回转减速机的内圈之间安装特殊设计的S型拖链回转线缆结构,线缆穿过S型拖链并从回转减速机法兰开孔处引出,避免了线缆在回转运动过程中发生缠绕,从而确保内框架顺利进行旋转运动。软件设计方面,为实现近场测试系统软、硬件的协同工作,软件控制流程图如图4所示。系统采用比例-积分-微分自动控制算法驱动伺服电机以控制机械转轴实现高精度空间位姿状态调节,机械转轴和成像测量部分采用C++语言进行编译与操控,机械转轴执行转动命令,亮度计快速完成测量并将数据传送至主控制器,从而实现机械转轴和成像式亮度计的协调工作,最终完成近场亮度元数据的获取。

为减少测量误差,必须避免杂散光对近场光度测量实验的影响,因此实验需在暗室环境下进行。实验前,将被测光源固定在机械旋转轴与俯仰轴的交点正上方,调整成像式亮度计使光线能够对焦在发光面上,且保持光源发光面中心、成像式亮度计中心及机械转轴交点对准。在光源固定、安装对准后,需进行预热处理,待光源稳定发光后开始测量。

针对平面光源进行实验,需对平面光源发光范围的2π空间中各个方向上的光度参数进行测量。实验采用国产成像式亮度计作为光度探测器件,成像分辨率为1920 pixel×1200 pixel,焦距为8 mm。测试时,成像镜头与光源的测试距离设定为0.30 m,成像亮度计采集光源在旋转角在0°~175°、俯仰角在−80°~80°范围内的亮度图像数据,实验角度间隔为5°。待成像式亮度计绕旋转轴转动固定步长后,俯仰轴在设定范围内连续、循环转动直至完成待测光源的空间亮度数据采集。

3.2 结果分析

3.2.1 亮度测试

成像式亮度计搭载在机械转台上完成2π空间摆扫,采集光源空间不同方向上的近场亮度图像。以旋转轴转动角度为0°,俯仰轴转动角度分别为−75°、−50°、−25°、25°、50°、75°处测得的光源亮度图像为例,从图5中可以看出,随着俯仰轴的转动,成像式亮度计所探测到的发光面积先增大后减小。此外,由图5分析可知,光源表面的亮度分布并不是完全一致,而近场亮度数据可为均匀发光设计提供有效的数据支持。

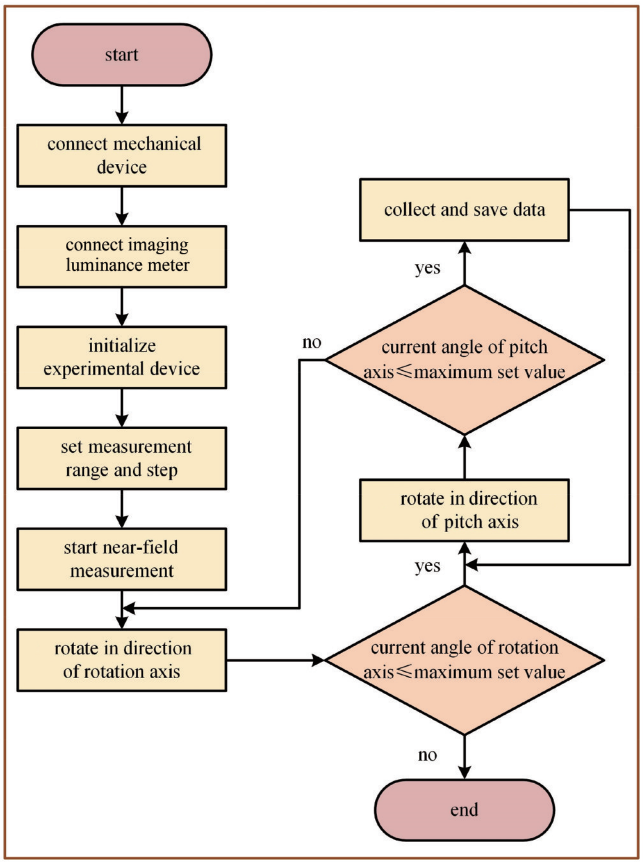

图4 近场测试系统软件控制流程图

Fig. 4 Flow diagram for control software of near-field test system

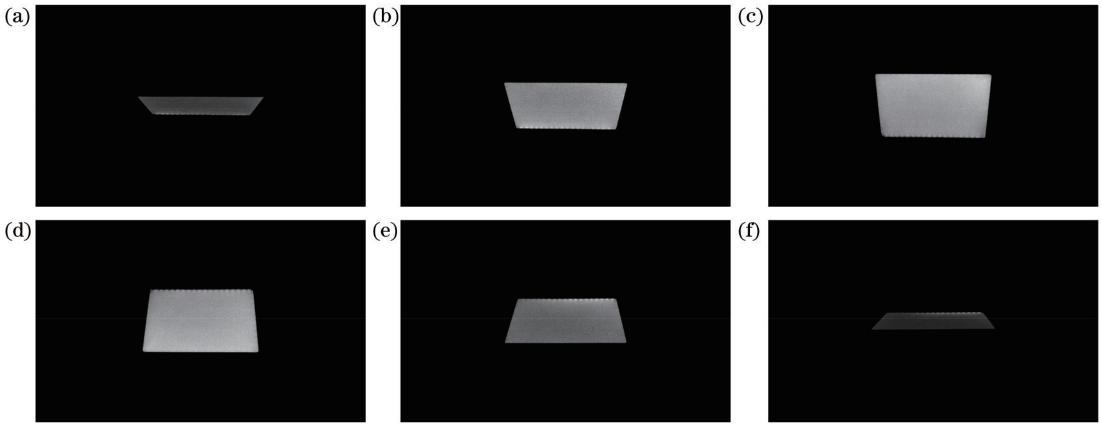

图5 平面光源在不同俯仰轴转动角度下的亮度图像。(a)−75°;(b)−50°;(c)−25°;(d)25°;(e)50°;(f)75°

Fig. 5 Luminance images of plane light source at different pitch axis rotation angles. (a) −75°; (b) −50°; (c) −25°; (d) 25°; (e) 50°; (f) 75°

准确测试光源空间光强分布的前提是为了获取精确的亮度元数据，因此首先对成像式亮度计的亮度测量精度进行校准。亮度标准值可以溯源至中国计量科学研究院，采用经校准的高精度瞄点式分光辐射亮度计 CS2000 测量光源中心点发光亮度；提取近场所测光源亮度图像相同位置的亮度标准值，在 $\varphi=0°$ 条件下，对比所测亮度值与亮度标准值，对比结果如图 6 所示。分析可知，二者角向分布趋势基本一致，测量值与标准值之间误差不超过 1015.52 cd/m²，相对误差优于 6.51%。

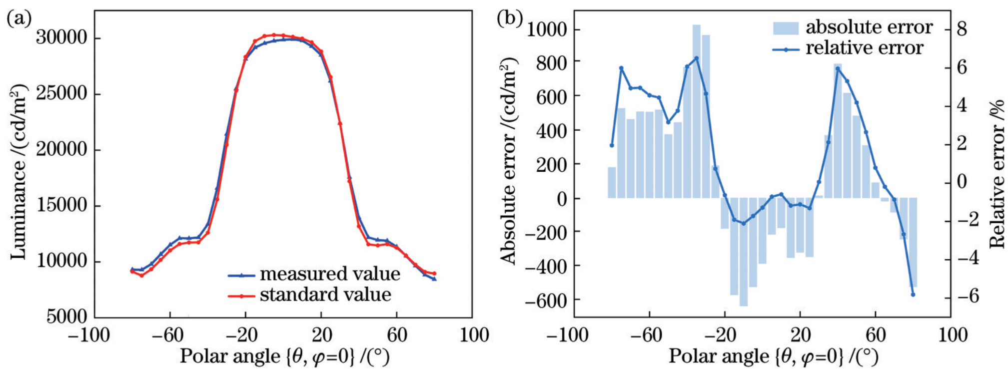

图 6 成像式、瞄点式亮度计测试结果对比。(a)亮度对比结果；(b)亮度绝对误差及相对误差

Fig. 6 Comparison of measurement results between imaging and aiming point luminance meters. (a) Comparison results of luminance; (b) absolute and relative errors of luminance

3.2.2 光强测试

远场分布式测试方法通过光度探头测量光源单一方向上的照度值，并依据距离平方反比定律获得光强分布；近场分布式测试方法利用成像式亮度计测量光源所有方向上的亮度值，根据发光平面各方向的光线分布反演空间光强分布。为验证所提近场分布式平面光源空间光强分布测试的有效性，将实验中 $\varphi=0°$ 下的近场分布式测量结果与远场分布式光度测试所得结果进行对比，结果如表 1 所示。经分析可知，两种测试方法得到的结果有较好的一致性，光源发光平面正下方俯仰角为 0° 处的光强最大，随着俯仰角的增大，光强逐渐减小；同时，该平面光源空间光强分布较为对称，在俯仰角为 −50°～50° 范围内发光接近于高斯分布，其发光强度大于 100 cd，在俯仰角为 −80°～−50°、50°～80° 范围内呈现近似线性分布。

表 1 近场、远场光强对比测试结果

Table 1 Comparison test results of luminous intensity between near-field and far-field measurements

Pitch angle θ/(°)	Near-field /cd	Far-field /cd	Pitch angle θ /(°)	Near-field /cd	Far-field /cd
−80	18.37	18.51	0	385.38	393.57
−75	31.33	31.12	5	382.24	390.85
−70	45.94	45.48	10	373.94	383.67
−65	62.31	61.44	15	358.29	370.01
−60	79.03	77.92	20	330.79	343.89
−55	93.69	92.71	25	288.06	298.10
−50	105.82	103.63	30	233.80	234.23
−45	120.37	113.83	35	179.84	170.81
−40	148.05	136.60	40	139.41	128.70
−35	192.41	185.38	45	116.73	109.49
−30	247.34	251.80	50	104.04	99.48
−25	299.61	313.18	55	92.21	88.03
−20	339.00	353.74	60	77.23	73.09
−15	363.69	375.30	65	60.87	56.95
−10	377.51	386.66	70	44.91	41.70
−5	383.58	392.24	75	30.63	28.28
0	385.38	393.57	80	17.79	16.64

从图 7 中可以分析出，近场与远场测试光强角向分布曲线重合度较高。远场光强采用经过校准的全空间快速分布光度计 GO-R5000，通过远场方式完成测量，光源与探测器间的距离为 2.60 m，所提方法中近场方式光强测试结果与远场测量值相比，绝对误差不超过 14.74 cd，相对误差小于 8.38%。

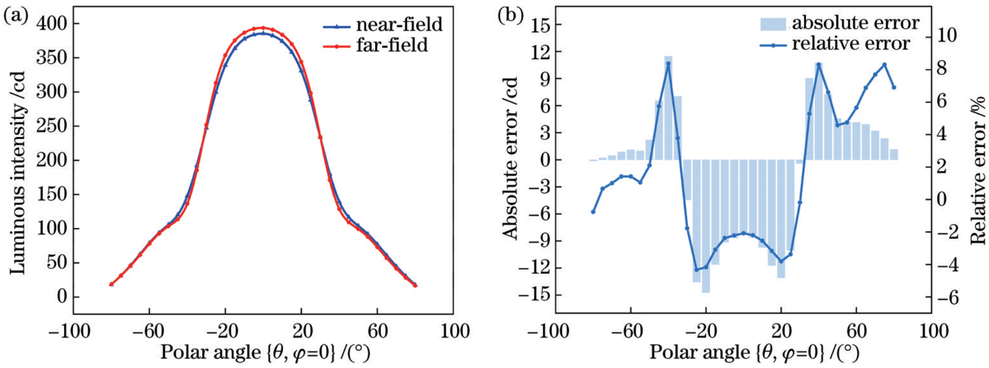

图 7 近场、远场光强测试结果对比。(a)光强对比结果；(b)光强绝对误差及相对误差

Fig. 7 Comparison results of luminous intensity between near-field and far-field measurements. (a) Comparison results of luminous intensity; (b) absolute and relative errors of luminous intensity

考虑光强真值接近于 0 时，将会导致相对误差计算结果在整个测量范围内失去参考价值。仅考虑最大相对误差，将影响对测试结果的全面评估。因此，这里采用光强匹配指数 $f_{\text{luminaire, fit}}$ 对近场测试与远场测试的配光曲线匹配程度进行评价[26]。光强匹配指数 $f_{\text{luminaire, fit}}$ 的表达式为

$$f_{\text{luminaire, fit}}=\left\{1-\sqrt{\frac{\sum_{\varphi=0}^{2\pi}\sum_{\theta=0}^{\pi}\left[I_1(\theta,\varphi)-I_2(\theta,\varphi)\right]^2}{\sum_{\varphi=0}^{2\pi}\sum_{\theta=0}^{\pi}\left[I_1(\theta,\varphi)+I_2(\theta,\varphi)\right]^2}}\right\}\times 100\%, \tag{7}$$

式中：$I_1(\theta,\varphi)$ 为远场测试结果；$I_2(\theta,\varphi)$ 为近场测试结果。利用式(7)计算得到 0° 配光曲线匹配指数高达 98.33%，实验结果验证了所提方法在近场光度测量中的有效性。

4 结 论

基于自主搭建的近场光源发光特性测量装置采集近场亮度数据，使用光源近场测试模型，通过光度学和几何光学原理分析发光平面在空间各个方向上的光线分布，进而完成平面光源在近场条件下的配光计算，且近场测试与远场测试配光曲线结果一致。在所采用成像式亮度计亮度相对误差优于 6.51% 的情况下，光强相对误差小于 8.38%，0° 配光曲线匹配指数高达 98.33%，测量结果表明所提方法可实现近场分布式光度测量，在照明、显示等领域具有较高的工程应用价值。

参 考 文 献

[1] 俞安琪，居家奇，陈大华．LED 在功能性照明优势的探讨[J]．中国照明电器，2018(10): 10-17.
Yu A Q, Ju J Q, Chen D H. Discussion on the advantages of LED in functional lighting[J]. China Light & Lighting, 2018(10): 10-17.

[2] 胡红英，郭志军，李倩．LED 路灯全空间快速分布光度计系统[J]．照明工程学报，2009，20(S1): 59-61.
Hu H Y, Guo Z J, Li Q. Full-field goniophotometer system for LED road lights[J]. China Illuminating Engineering Journal, 2009, 20(S1): 59-61.

[3] 侯启真，马秉正．基于误差反馈的 LED 阵列近场光强检测[J]．计量学报，2021，42(8): 993-999.
Hou Q Z, Ma B Z. Near-field intensity detection of LED array based on error feedback[J]. Acta Metrologica Sinica, 2021, 42(8): 993-999.

[4] 桂立，尹韶云，蔡文涛，等．基于光源近场模型的 LED 光学扩展量测量方法[J]．光子学报，2017，46(1): 0112004.
Gui L, Yin S Y, Cai W T, et al. Measurement method of LED etendue based on near-field source model[J]. Acta Photonica Sinica, 2017, 46(1): 0112004.

[5] Rykowski R F, Wooley C B. Source modeling for illumination design[J]. Proceedings of SPIE, 1997, 3130: 204-208.

[6] 国家质量监督检验检疫总局，中国国家标准化管理委员会．灯具分布光度测量的一般要求：GB/T 9468—2008[S]．北京：中国标准出版社，2009.
General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China. General requirements for the photometry and goniophotometry of luminaries: GB/T 9468—2008[S]. Beijing: Standards Press of China, 2009.

[7] Ashdown I. Comparing photometric distributions[J]. Journal of the Illuminating Engineering Society, 2000, 29(1): 25-33.

[8] Bizjak G, Lindemann M, Sperling A, et al. Determination of stray light at the PTB goniophotometer facility[J]. MAPAN, 2009, 24(3): 163-173.

[9] López M, Bredemeier K, Schmidt F, et al. Near-field goniophotometry: a metrological challenge[EB/OL]. [2023-06-05]. https://www.cenam.mx/sm2010/info/pjueves/sm2010-jp02b.pdf.

[10] López M, Bredemeier K, Rohrbeck N, et al. LED near-field goniophotometer at PTB[J]. Metrologia, 2012, 49(2): S141-S145.

[11] Schmähling F, Wübbeler G, Lopez M, et al. Virtual experiment for near-field goniophotometric measurements[J]. Applied Optics, 2014, 53(7): 1481-1487.

[12] Rotscholl I, Trampert K, Krüger U, et al. Spectral near field data of LED systems for optical simulations[J]. Proceedings of SPIE, 2019, 11144: 111440P.

[13] Gassmann F, Krueger U, Bergen T, et al. Comparison of luminous intensity distributions[J]. Lighting Research & Technology, 2017, 49(1): 62-83.

[14] TechnoTeam Bildverarbeitung GmbH. General specification: model series 1400, 1500, 1800, 2000[R]. Ilmenau: TechnoTeam Bildverarbeitung GmbH, 2015. http://light-all.com/Writable/Resource/product/TT/Specification_RiGO801_1400_1500_1800_2000_eng-signed.pdf.

[15] Radiant Vision Systems. ProSource software[R]. Redmond: Radiant Vision Systems, 2020. https://www.radiantvisionsystems.com/sites/default/files/library-documents/Radiant_SPEC_ProSource_EN.pdf.

[16] Radiant Vision Systems. SIG-400: source imaging goniometer [R]. Redmond: Radiant Vision Systems, 2022. https://www.radiantvisionsystems.com/sites/default/files/library-documents/Radiant_SPEC_SIG-400-Source-Imaging-Goniometer_EN.pdf.

[17] Gonos I F, Triantafillopoulou E K, Topalis F V. Development of a low-cost automated goniophotometer[EB/OL]. [2023-06-05]. http://users.ntua.gr/igonos/2000/MMA2000-Goniophotometer.pdf.

[18] Csuti P, Szabó F, Dubnicka R. Comparison of luminous intensity distributions measured on luminaire turning and mirror goniophotometer[C]//2016 IEEE Lighting Conference of the Visegrad Countries (Lumen V4), September 13-16, 2016, Karpacz, Poland. New York: IEEE Press, 2016.

[19] Audenaert J, Acuña R P C, Hanselaer P, et al. Practical limitations of near-field goniophotometer measurements imposed by a dynamic range mismatch[J]. Optics Express, 2015, 23(3): 2240-2251.

[20] 金耀辉. 近场分布光度测量技术的研究[D]. 杭州: 浙江大学, 2017.
Jin Y H. Study on photometric measurement technology of near-field distribution[D]. Hangzhou: Zhejiang University, 2017.

[21] 李晓妮, 陈聪, 吕杰, 等. 近场光度测量技术及其应用实例分析[J]. 中国照明电器, 2018(9): 28-32.
Li X N, Chen C, Lü J, et al. Measurement technology and application analysis of near-field photometry[J]. China Light & Lighting, 2018(9): 28-32.

[22] 杨继乾. 基于CA2000二维亮度计的近场光度测试系统的设计与实现[D]. 大连: 大连工业大学, 2016.
Yang J Q. Design and build of near-field goniophotometer based on CA2000[D]. Dalian: Dalian Polytechnic University, 2016.

[23] 胡博. 远场和近场分布光度测试系统的比较分析[D]. 大连: 大连工业大学, 2019.
Hu B. Comparative analysis of far-field and near-field distribution photometric testing systems[D]. Dalian: Dalian Polytechnic University, 2019.

[24] Ashdown I, Salsbury M. A near-field goniospectroradiometer for LED measurements[C]//International Optical Design, June 4-8, 2006, Vancouver, Canada. Washington, DC: OSA, 2006: TuD5.

[25] 范红忠, 曹民, 李抒智, 等. 光源近场测量在LED光学设计中的应用与研究[J]. 光学学报, 2012, 32(12): 1222001.
Fan H Z, Cao M, Li S Z, et al. Application and investigation of near-field goniophotometer measurements in LED optical design [J]. Acta Optica Sinica, 2012, 32(12): 1222001.

[26] Bergen A. A practical method of comparing luminous intensity distributions[J]. Lighting Research & Technology, 2012, 44(1): 27-36.

Luminous Intensity of Plane Light Source Based on Near-Field Distributed Photometry

Hu Shaojie[1], Wang Hongyuan[2], He Zehao[2], Zhu Qiaofen[1], Cao Liangcai[2*]

[1]*School of Mathematics and Physics Science and Engineering, Hebei University of Engineering, Handan* 056038, *Hebei, China*;

[2]*Department of Precision Instrument, Tsinghua University, Beijing* 100084, *China*

Abstract

Objective People's demand for light sources contains not only efficiency, energy conservation, and environmental protection, but is shifting towards healthy and comfortable lighting quality, which puts higher requirements on the measurement technology for luminescence characteristics of the light sources. At present, there are two main methods for measuring the luminescence characteristics of light sources, including far-field and near-field distributed photometric measurements. The far-field distributed photometric measurement based on a point light source model employs a single point photometric detector for spherical scanning to obtain the light intensity, which makes it difficult to accurately demonstrate the luminous information in the near-field distance. The near-field photometric measurement utilizes luminance images from different directions to build a near-field source model. By the conversion of photometric parameters and the processing method of luminance data, the luminescence characteristics of light sources can be characterized, and characteristic information such as the origin and propagation direction of light sources can be obtained. Although the near-field photometric measurement model is more complicated, it can more finely and completely characterize the luminescence characteristics of light sources. However, facing the application requirements for accurate luminescence characteristic measurement of light sources, the development of domestic near-field distributed photometric measurement systems is still in preliminary stages. Meanwhile, some systems have limitations in measurement size or measurement accuracy, which makes it difficult to characterize the luminescence characteristics of light sources. Therefore, by studying the near-field photometric measurement method and its measurement mechanism, we measure the luminous intensity distribution of a plane light source based on the self-developed near-field photometric measurement device.

Methods The spatial distribution of luminous intensity information of a plane light source is obtained by a luminescence model of the plane light source. To build the model, firstly, the imaging luminance meter driven by the mechanical structure performs three-dimensional spherical scanning motion around the luminous body, while capturing luminance images of various directions on the scanning sphere. Therefore, the luminance spatial distribution information of the light source is obtained. Secondly, a luminescence model of the plane light source is built, which is composed of the point light source array. According to the transformation of the coordinate system and the conversion of photometric parameters, the light distribution in each direction of the luminous plane is obtained. Thirdly, the acquisition of the near-field luminous intensity distribution requires the luminous distribution calculation of the light source from multiple directions. Finally, the results of near-field-distributed photometric measurement are analyzed. The luminance measured value in our paper extracted from the center position of luminance images is compared with the luminance standard value traced to the National Institute of Metrology, China. Additionally, the calculated results of the near-field distributed photometric measurement are compared with far-field distributed photometric measurement by GO-R5000 photometer in far-field conditions.

Results and Discussions The luminance images of the plane light source in different directions are collected by the imaging luminance meter driven by a mechanical turntable to complete 2π space swing scanning. Under the fixed rotation axis angle, the luminous area detected by the imaging luminance meter first increases and then decreases with the rotation of the pitch axis. The luminance distribution curves of measured and standard values are consistent. The absolute error of the measured luminance value is less than 1015.52 cd/m^2, and the relative error is better than 6.51%. The coincidence degrees of luminous intensity distributions obtained from near-field and far-field photometric measurements are relatively high. The absolute error of the near-field measurement is less than 14.74 cd, and the relative error is less than 8.38%. Meanwhile, the matching index between the luminous intensity distribution of near-field and far-field photometric measurements is calculated for overall evaluation. The matching index of the 0° photometric curve is as high as 98.33%. The results verify the effectiveness of the proposed method for near-field photometric measurement.

Conclusions We collect the luminance data of the light source based on the self-developed near-field photometric measurement device and the light distribution of the luminous plane in all spatial directions is analyzed by the principle of photometry and geometric optics based on the luminescence model of a plane light source. Additionally, the luminous intensity distribution of the plane light source in near-field conditions is calculated. The results show that the luminous intensity distribution curves in the near- and far-field photometric measurements maintain good consistency. When the relative luminance error of the adopted imaging luminance meter is better than 6.51%, the relative error of luminous intensity from near- and far-field photometric measurements is less than 8.38%. The matching index of the 0° photometric curve is as high as 98.33%. The results show that the proposed method has yielded near-field distributed photometric measurement, and our study has high engineering application significance in lighting, displays, and other fields.

Key words measurement; goniophotometer; near-field distributed photometry; imaging luminance meter; luminous intensity; photometric curve