

激光无线能量传输发射光学系统研制

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Development of emission optical system for laser wireless power transmission

Meng Xiangxiang, Shang Han, Xin Mingrui, Wang Xudong, Qiu Mingjie

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激光无线能量传输发射光学系统研制

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摘要: 为了提升激光无线能量传输系统光能传输效率, 避免使用准直镜头导致在数百米距离处接收端光斑边界模糊和照度均匀性差现象的发生, 开展了基于共轭成像原理的可调焦发射光学系统研制。首先理论分析了准直法和共轭成像法的设计原理, 然后针对光纤输出的 808 nm 半导体激光光源, 采用共轭成像法设计了焦距 550 mm、口径 260 mm 的发射光学系统, 通过光纤端面的移动实现调焦设计, 分析了不同调焦距离下光纤端面的移动量, 并与准直法设计结果调焦后对比, 在 200 m~1 km 处的波像差明显较小。利用 Lighttools 软件模拟对比了调焦前后的照射光斑, 验证了调焦的作用。模拟结果显示, 通过对基于共轭成像原理设计的发射光学系统增加调焦机构, 可在不同距离处得到清晰的光斑边界。最后对激光发射光学系统进行了加工, 经测试, 波像差 RMS 为 0.092λ (λ=632.8 nm)。结果表明: 激光无线能量传输系统使用基于共轭成像原理设计的可调焦发射光学系统可获得边界清晰、更加均匀的照明光斑。

关键词: 激光无线传能; 发射光学系统; 共轭; 调焦

中图分类号: O439 **文献标志码:** A **DOI:** 10.3788/IRLA20230115

0 引 言

激光无线能量传输系统利用激光束作为能量载体、光伏电池作为接收端光电转换器件, 是远距离无线充电的重要方式^[1-5], 其具有能量光束准直性好、体积和质量小、移动灵活的优点, 已在无人机远距离充电^[6-7]、飞艇间传能^[8]、传能通信一体化^[9]等领域进行了深入的研究。

由于 GaAs 光伏电池在 808 nm 左右波段的光电转换效率高, 发射端常采用电光转换效率较高的 808 nm 波长半导体激光器^[10] 作为激光光源。而高功率的半导体激光器光束质量相对较差, 在激光无线传能系统发射端需采用激光发射光学系统压缩光束发散角才能提高传输距离, 减轻接收端体积和质量。发射端激光器采用矩形纤芯光纤可提高光斑均匀度, 而且光伏电池也是矩形^[11-12], 不仅降低了光电池的排布

难度, 而且提高了接收端的占空比。

目前, 激光无线传能系统的发射镜头多为准直镜头。2013 年, 何滔等^[12] 采用准直镜头搭建了传输距离为 10 m 的激光无线传能系统, 并开展了传输效率实验研究。2019 年, 时振磊等^[13] 针对采用准直镜头的无人机激光无线传能系统开展了跟踪瞄准设计研究; 此外, 于 2014 年完成的两飞艇之间的激光无线能量传输试验^[8] 亦是采用了准直镜头作为激光发射系统。准直镜头采用光纤准直原理和光学设计软件的无焦模式进行设计, 将光纤端面置于镜头物方焦面处, 轴上、轴外光束均以平行光的形式对外发射。实际装调中以标准平面镜反射光束的最优波像差来确定光纤端面的固定位置。由于光纤端面有一定的物高, 轴外出射光束和轴上出射光束之间存在一定的几何发散角, 对于像面在无穷远的准直镜头, 在较近距离处的被照射面上, 轴上光束和轴外光束呈现出交错

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叠加的状态。即使采用矩形纤芯的出射端面照度分布是均匀的,在传能被照射面上的光斑仍呈现出由中心逐渐向四周减弱的高斯分布,光斑边界亦不清晰,降低了激光无线能量传输系统的光能传输效率。

文中采用共轭成像原理设计了激光无线传能发射光学系统,增加调焦机构改变物距,在不同距离处均可得到边界清晰、照度分布与光纤端面一致的照射光斑,最终完成了可调焦发射镜头的研制与测试。

1 分析与设计

1.1 理论分析

传统准直镜头的设计原理如图 1(a) 所示,光纤端面置于准直镜头的物方焦面处,此时与光纤端面共轭的像面在无穷远处。在设计时通常采用无焦模式或者理想透镜聚焦的方式。准直镜头出射光束的发散角 θ 如下:

$$\theta = \arctan\left(\frac{D}{2f'}\right) \quad (1)$$

式中: D 为光纤纤芯直径; f' 为准直镜头焦距。这种准直镜头的设计方法适用于接收端在几十、数百千米的系统,比如激光通信。而在百米、千米级激光无线能量传输系统中使用这种准直镜头作为激光发射光学系统,会导致轴上平行光束和轴外平行光束交错叠加,接收端接收到的光斑界线不清晰,光斑直径偏大,影响激光充电效率。出现这种现象的原因是接收端在较近距离处已不再和置于准直镜头物方焦面的光纤端面共轭。此时,激光发射光学系统的设计原理如图 1(b) 所示。

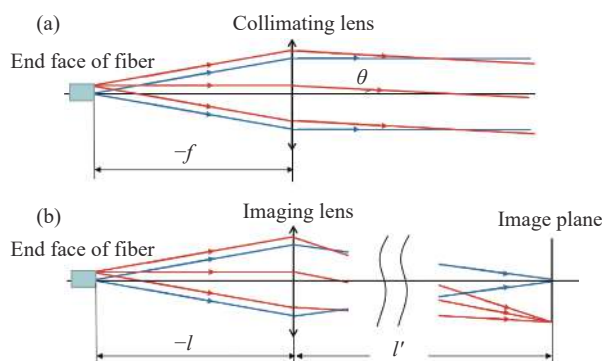


图 1 (a) 准直镜头高斯光路; (b) 成像镜头高斯光路

Fig.1 (a) Gaussian optics of collimator lens; (b) Gaussian optics of imaging lens

图 1(b) 中光纤端面和光伏接收面呈物像共轭关系,满足高斯成像公式:

$$\frac{1}{l'} - \frac{1}{l} = \frac{1}{f'} \quad (2)$$

式中: $-l$ 为光纤端面到发射镜头主面的距离,即发射镜头的物距; l' 可为近似为光伏接收面到发射镜头的距离; f' 为发射镜头焦距。由公式 (2) 可知,图 1(a) 为图 1(b) 在 $l' \rightarrow \infty$ 时的特殊情况。因此,可通过设置调焦机构,改变 $-l$ 的大小,得到共轭的 l' ,使得光伏接收面在不同传能距离处均可得到边界清晰、照度分布与光纤端面一致的照射光斑。

1.2 光学设计

光纤准直镜头的常用设计方法有两种,一种是采用光学设计软件的无焦模式,以平行光的波像差作为评价条件;另一种是在准直镜头后增加一个理想透镜,优化理想透镜的聚焦光斑。这两种方法都可以看做是光纤端面与无穷远共轭。针对数百米、千米级的激光无线传能系统,激光发射镜头可直接采用有限距共轭成像法进行设计。

文中面向的激光无线传能系统要求为:针对 808 nm 半导体激光器,当尾纤参数为 $N40.22$ 、纤芯为 $600 \mu\text{m} \times 600 \mu\text{m}$ 时,在 200 m 处光斑边长在 200~220 mm 之间;当尾纤参数为 $N40.22$ 、纤芯 $200 \mu\text{m} \times 200 \mu\text{m}$ 时,在 1 km 处光斑边长在 360~380 mm 之间;同时保证 200 m~1 km 之间光斑边界清晰。利用公式 (2) 及垂轴放大倍率公式计算,该设计要求可用定焦镜头结合调焦实现,综合考虑系统总长限制,确定激光发射镜头设计参数如表 1 所示。

表 1 中,设计波长加入了 632.8 nm 是为了装配后检测波像差。设计中,对 808 nm 和 632.8 nm 波长采用多重结构,在 632.8 nm 波长结构中的光纤端面前加入平行平板,用来消除与 808 nm 波长的色差,使两波长的物方焦面位置重合。装配检测时,在设计位置加入平行平板,利用 632.8 nm 波长检测;实际使用时,去掉平行平板,转变成 808 nm 波长的光路。

由于要求在 200 m~1 km 之间光斑边界清晰,设计中,首先固定像距为 500 m,在该距离下设计满足要求后,再固定所有透镜半径、材料及透镜间隔,使像距在 200 m~1 km 范围内变化,优化光纤端面与第一透镜的间距,得到不同像距下的光纤端面位置。

表 1 激光发射光学系统设计参数

Tab.1 Design parameters of laser emission optical system

| Parameter | Specification |
|-------------------|---------------|
| Wavelength/nm | 808 & 632.8 |
| Focal length/mm | 550 |
| Aperture/mm | ≥240 |
| Optical length/mm | ≤660 |
| Focusing range/m | 200-1000 |

该激光发射光学系统视场小、口径大，主要像差为球差，为降低加工成本，避免使用大口径的非球面镜片，采用三透镜的“正-正-负”结构，加入负透镜的目的为补偿正透镜产生的球差；两正透镜在前，可以起到压缩口径的作用，使系统通光口径尽可能接近理论值。固定像距为 500 m 的设计结果如图 2(a) 所示，焦距 550 mm，光学总长 650.01 mm，最大通光口径 243 mm。图 2(b) 为 500 m 距离处不同视场光线的聚焦结果。

采用多重结构对 808 nm 波长和 632.8 nm 波长分别设计。在 500 m 像距下，系统在两波长的波像差如

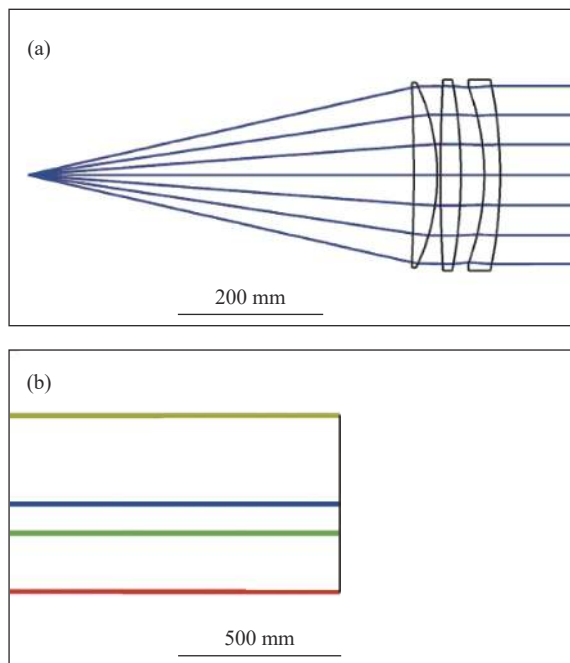


图 2 (a) 像距 500 m 时的设计结果; (b) 500 m 距离处不同视场光线的聚焦效果

Fig.2 (a) Design results of 500 m image distance; (b) Focusing effect from different fields at 500 m

图 3 所示。对于 808 nm 波长，波像差 RMS 为 0.116λ ($\lambda=632.8$ nm); 对于 632.8 nm 波长，波像差 RMS 为 0.084λ 。

以 500 m 像距下的光纤端面位置为零位，其位置移动量与像距的关系如图 4 所示，其中光纤端面向左移动为负，向右移动为正。由图 4 可知，200 m~1 km 调焦范围对应的光纤端面总移动量为 1.19 mm。

对比该设计与无焦模式设计的传统准直镜头移动光纤端面在 200 m~1 km 调焦时各像距处的波像差结果，如图 5 所示。由图 5 可知，与无焦模式设计的

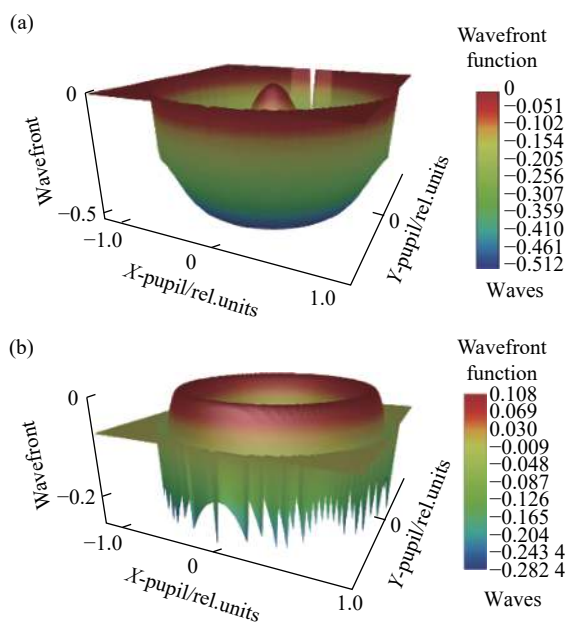


图 3 (a) 波长 808 nm 波像差; (b) 波长 632.8 nm 波像差

Fig.3 (a) Wavefront aberration of wavelength 808 nm; (b) Wavefront aberration of wavelength 632.8 nm

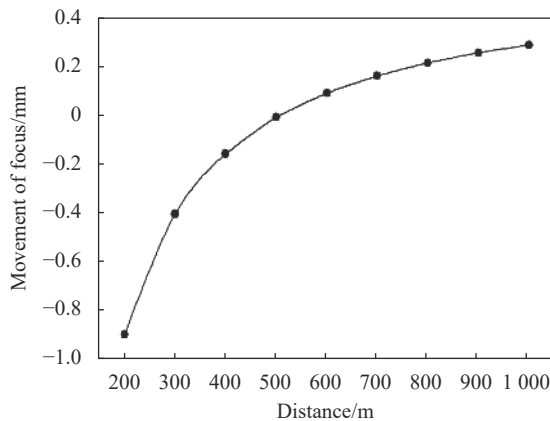


图 4 不同调焦距离下的光纤端面移动量

Fig.4 Optical fiber end face movement at different focusing distances

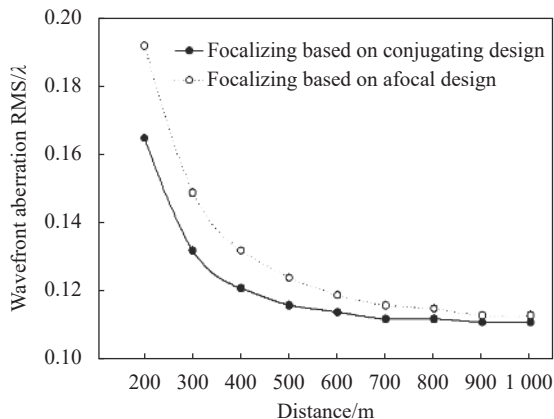


图 5 两种设计方法调焦后的波像差对比

Fig.5 Comparison of wavefront aberration of two design methods after focusing

传统准直镜头在 200~500 m 调焦后的波像差相比, 该设计的波像差明显较小。

2 模拟仿真

采用 Lighttools 对系统进行仿真, 以面光源作为光纤端面, 空间分布设置为均匀分布, 依照图 4 调节光纤端面位置, 模拟尾纤参数为 NA0.22、纤芯 600 μm×600 μm 时, 在 200 m 处的光斑如图 6(a) 所示, 光斑边长约为 220 mm; 模拟尾纤参数为 NA0.22、纤芯 200 μm×200 μm 时, 在 1 km 处光斑如图 6(b) 所示, 光斑边长约为 360 mm, 均满足设计要求。

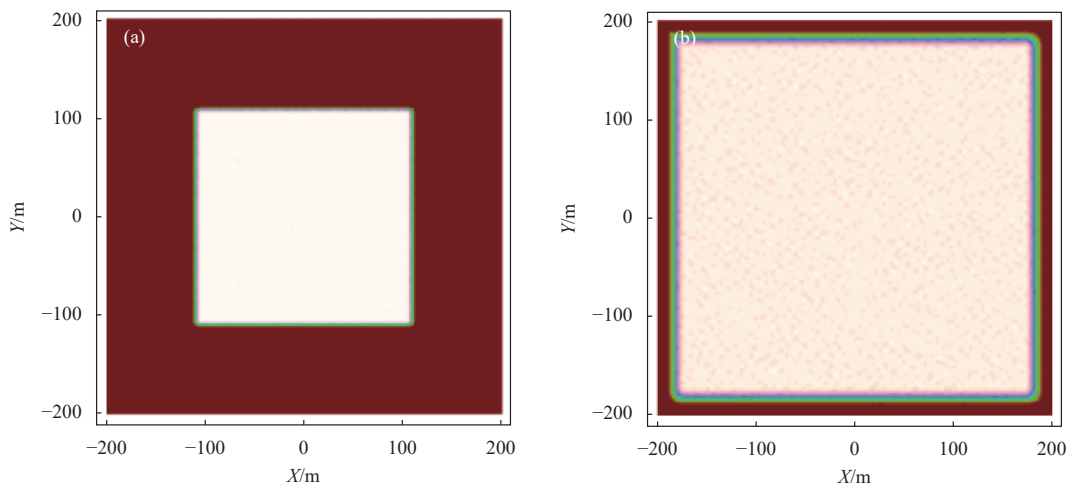
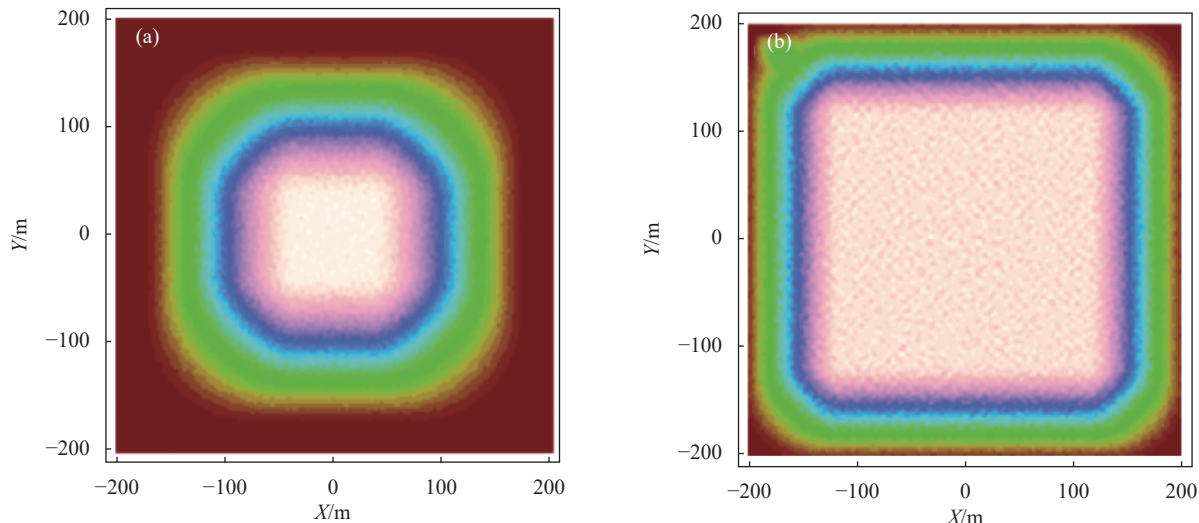


图 6 (a) 纤芯 600 μm×600 μm 时, 在 200 m 处的光斑; (b) 纤芯 200 μm×200 μm 时, 在 1 km 处的光斑

Fig.6 (a) Spot at 200 m with fiber core of 600 μm×600 μm; (b) Spot at 1 km with fiber core of 200 μm×200 μm

设计要求在 200 m~1 km 之间光斑边界清晰, 选取表 2 中 200、300 m 波像差较大的距离, 尾纤参数为 NA0.22、纤芯 600 μm×600 μm, 模拟在不调焦时照明

光斑如图 7(a)、(b) 所示, 依照图 4 调焦后的照明光斑如图 7(c)、(d) 所示, 对比可见, 调焦设计对于保证光斑边界清晰具有重要作用。



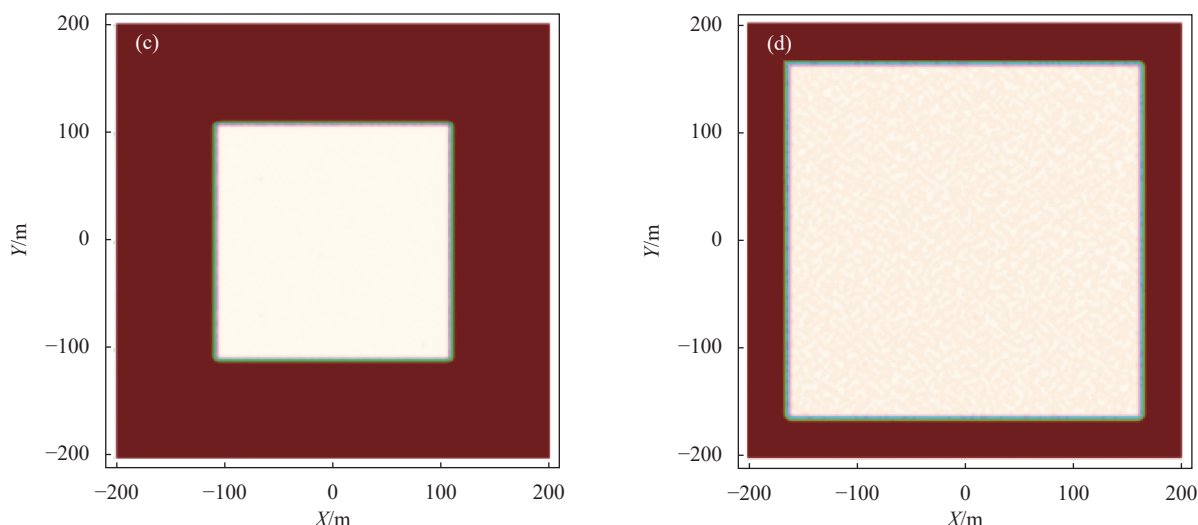


图 7 (a) 200 m 处未调焦光斑; (b) 300 m 处未调焦光斑; (c) 200 m 处调焦后光斑; (d) 300 m 处调焦后光斑;
Fig.7 (a) Unfocused spot at 200 m; (b) Unfocused spot at 300 m; (c) Focused spot at 200 m; (d) Focused spot at 300 m

3 研制测试

对激光发射光学系统进行结构设计, 整体三维模型如图 8 所示, 放大之处为光纤端面调焦结构, 调焦结构件转动 360°, 光纤端面移动 2 mm, 满足 200 m~1 km 距离范围内光纤端面总移动量 1.19 mm 的要求。

激光发射光学系统研制完成后如图 9(a) 所示, 图 9(b) 为激光发射光学系统置于激光无线传能发射

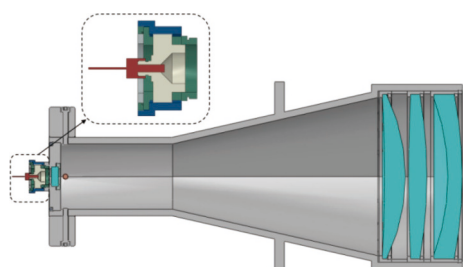


图 8 激光发射光学系统整体三维模型

Fig.8 Three-dimensional model of laser emission optical system

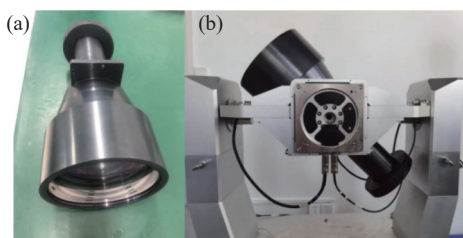


图 9 (a) 研制的激光发射光学系统; (b) 置于转台上

Fig.9 (a) Developed laser emission optical system; (b) Installed on rotational platform

端的转台上。

将激光发射光学系统调焦至无穷远, 采用 ZYGO 干涉仪、标准镜头以及平面反射镜搭建光路, 测试激光发射光学系统波像差, 结果如图 10 所示, 调焦至无穷远时, 系统波像差为 0.092λ。

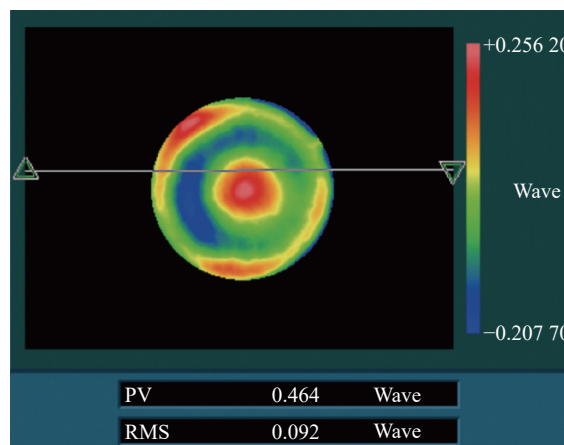


图 10 波像差 RMS 测试结果

Fig.10 Test result of wavefront aberration RMS

4 结论

文中研制了一台以光纤输出 808 nm 半导体激光器为光源的可调焦激光发射镜头, 适用于百米级与千米级距离的激光无线能量传输。通过理论分析, 针对非无穷远的传输距离, 采用共轭成像原理设计了焦距 550 mm、口径 260 mm 的激光发射光学系统, 分析了

不同传能距离与调焦移动量的关系,仿真对比了不同距离处调焦前后的光斑变化,对系统进行了加工,完成装配后的波像差RMS为0.092 λ 。该系统通过调焦机构改变光源位置,能够在200 m~1 km距离处均可得到边界清晰且照度分布与光纤端面一致的传能光斑,可提升激光无线能量传输接收端的光电转换效率。

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Development of emission optical system for laser wireless power transmission

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Abstract:

Objective The emission lens of the laser wireless power transmission system is mostly a collimated lens, which is designed using the optical fiber collimation principle and the non-focus mode of the optical design software. The end face of the optical fiber is placed at the focal plane of the lens, and the beam on and off the axis is emitted

externally in the form of parallel beam. Because the end face of the optical fiber has a object height, there is a geometric divergence angle between the on-axis beam and the off-axis beam. For the collimated lens with the image plane at infinity, the off-axis beam and the on-axis beam present a staggered superposition state on the illuminated surface at a relatively close distance. Even if the illuminance distribution of the rectangular fiber core is uniform, the light spot on the receiving surface of the power transmission still presents a Gaussian distribution that gradually weakens from the center to the periphery, and the light spot boundary is not clear, which reduces the power transmission efficiency of the laser wireless power transmission system. In order to improve the optical power transmission efficiency of the laser wireless power transmission system and avoid the blurring of the light spot boundary and the poor illumination uniformity at the receiving surface at a distance of hundreds of meters caused by the use of a collimated lens, the development of a focusing transmission optical system based on the conjugate imaging principle was carried out.

Methods Firstly, the design principles of collimation method and conjugate imaging method are analyzed theoretically. Then, aiming at the 808 nm semiconductor laser light source output by optical fiber, a transmitting optical system with a focal length of 550 mm and an aperture of 260 mm is designed using conjugate imaging method (Fig.2). Focusing design is realized through the movement of optical fiber end face. The movement of optical fiber end face under different focusing distances is analyzed (Fig.4). Compared with the design results of collimation method after focusing, the wave aberration at 200 m-1 km is smaller (Fig.5). Lighttools software is used to simulate and compare the illumination spot before and after focusing.

Results and Discussions The simulation results show that by adding a focusing mechanism to the transmission optical system designed based on the conjugate imaging principle, clear light spot boundaries can be obtained at different distances (Fig.6). The structure of the laser emission optical system is designed. The focusing structure rotates 360° and the end face of the optical fiber moves 2 mm, which meets the requirement of 1.19 mm of total end face movement of the optical fiber in the range of 200 m-1 km. The laser emission optical system is processed. The test optical path is built with ZYGO interferometer, standard lens and plane reflector. The wave aberration RMS of the laser emission optical system when focusing to infinity is 0.092λ ($\lambda = 632.8$ nm) (Fig.9). The results show that the laser wireless power transmission system can obtain a clearer and more uniform illumination spot by using the focusing emission optical system designed based on the conjugate imaging principle.

Conclusions A focusing laser emission optical system is developed, which can be used for laser wireless power transmission at different distances. Through theoretical analysis of the collimation method and the conjugate imaging principle, the design method of the laser emission lens is determined in the case of non-infinite distance. The optical system design is carried out. The relationship between the focusing movement and the energy transfer distance is analyzed. The changes of the light spot before and after focusing at different distances are simulated and compared. Finally, the equipment development is completed, and the optical performance test is carried out to meet the design requirements.

Key words: laser wireless power transmission; emission optical system; conjugate; focusing

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