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多功能太阳模拟器光学系统设计

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摘　要:设计了一种可同时实现准直式和发散式太阳光模拟的多功能太阳模拟器光学系统.阐述了光学系统中聚光镜的设计与光学积分器的优化技术.采用 Zemax 软件中序列与非序列功能结合的方式对光学积分器的参数进行优化,并设计了准直物镜.利用 LightTools 软件对光学系统进行模拟仿真,结果表明:设计的光学系统实现准直式太阳光模拟功能时,辐照面可达 $\Phi300$ mm,且辐照不均匀度优于±6.1%;通过改变准直物镜的位置,发散式太阳光模拟功能时,辐照面可达 $\Phi1\,500$ mm,且辐照不均匀度优于±6.7%.

关键词:太阳模拟器;光学系统设计;辐照面;辐照不均匀度
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Design of Optical System for Multifunctional Solar Simulator

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Abstract: A multifunctional optical system for solar simulators, which could achieve collimating and divergent sunlight simulation simultaneously, was designed. The design of condensers used in the optical system, and the optimization techniques of optical integrators were described. The parameters of the optical integrator was optimized with both the sequential and non-sequential functions of Zemax software. Also the collimator objective was designed. According to the analog simulation results of the optical system with LightTools, when the collimating sunlight simulation was achieved in the designed optical system, the irradiated surface reached $\Phi300$ mm, and the irradiation nonuniformity superior to ± 6.1%; when the divergent sunlight simulation was achieved by changing the position of collimator objective, the irradiated surface could reach $\Phi1\,500$ mm and the irradiation nonuniformity superior to ± 6.7%.

Key words: Solar simulator; Optical system design; Irradiated surface; Irradiation nonuniformity
OCIS Codes: 230.0230;230.4040;220.0220;220.4840;220.2945

0 Introduction

As a device used for simulating solar radiation in the outer space of the earth, solar simulators are being widely used in the ground experiment, testing and accuracy calibration of sun sensors. Solar simulators can be classified into collimating solar simulators and divergent solar simulators[1-4]. Report from home and

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abroad, a collimating solar simulator can simulate a small irradiated surface (less than Φ300 mm) but with higher irradiation nonuniformity (lower than ± 5%), while a divergent solar simulator can simulate a larger irradiated surface (more than Φ300 mm) but with lower irradiation nonuniformity (more than ±5%)[5-8]. To meet the simulation requirements of a larger irradiated surface and higher nonuniformity[9-11], there is need for solar simulators that integrate the higher irradiation nonuniformity of collimating solar simulators and the larger irradiated surface of divergent solar simulators.

Considering engineering application and observed needs of solar sensor, in view of the fact that collimating solar simulation and divergent solar simulation can′t be achieved simultaneously in existing solar simulators, a kind of multifunctional optical system for solar simulators was designed in this paper, in an effort to make a technological breakthrough[12].

In the paper, elaboration was made of the design of condensers used in the optical system and the optimization techniques of optical integrators. Also it proposed to optimize the optical integrator parameters with both the sequential and non-sequential functions of Zemax software, and designed the collimator objective system.

1 Components and working principle of multifunctional solar simulator

A multifunctional solar simulator is mainly composed of power supply for xenon lamp, xenon lamp, condenser, reflector I, reflector II, optical integrator[13], collimating objective, off-course slewing gear, pitching-angle slewing gear, and computer-controlled system. Of them, the collimating objective is not fixed and can be mounted and dismounted based on specific functions of the solar simulator. The components and working principles of the multifunctional solar simulator are shown in Fig. 1.

The axially symmetric short-arc xenon lamp that has similar solar spectrum is used as light source. The on-and-off of the short-arch xenon lamp is controlled by the power supply of the xenon lamp. The condenser focuses the light source (of the short-arc xenon lamp) from the first focal point on the second focal point to form irradiance distribution at the incidence plane (the field lens group) of the optical integrator, which will be symmetrically segmented by various lens elements of the optical integrator and then stacked to produce images. When the collimator objective is installed in the multifunctional solar simulator, the simulator will achieve collimating sunlight simulation. The optical integrator is installed in the focal plane of the collimator objective. When the collimator objective is dismounted from the multifunctional solar simulator, the simulator will achieve divergent sunlight simulation. In addition, reflectors I and II will be added to the optical path to reduce the external dimension of the multifunctional solar simulator through a reflected optical axis.

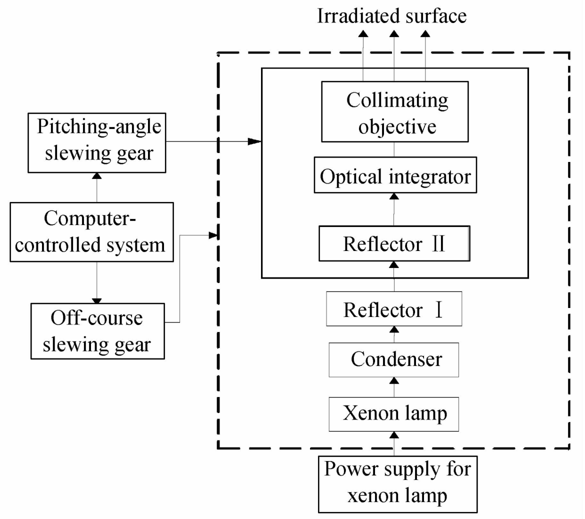


Fig. 1 Components and working principle of a multifunctional solar simulator

2 Optical system design

2.1 Condenser design

Condensers are used to fully collect the radiation flux from the light source (of a short-arch xenon lamp) to form a desired irradiance distribution at the incidence plane of the optical integrator, which will exert a direct influence on the irradiation nonuniformity of the solar simulator[14]. During the design of a condenser, the power and model of the xenon lamp should be selected first in accordance with the optical requirements of the solar simulator, followed by design of the condenser′s first focal length f_1, second focal length f_2, and caliber D, based on the structural parameters of the xenon lamp. The computational formula is shown in Eq. (1) and the overall dimension schematic diagram

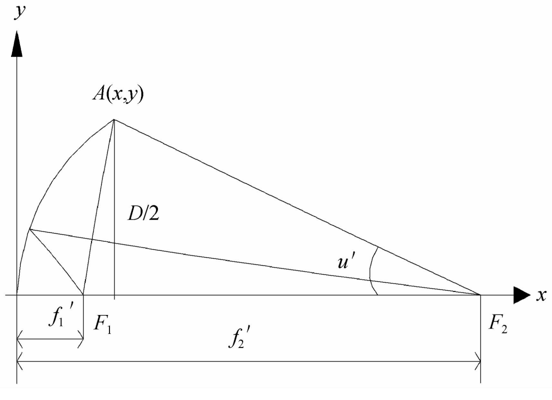


Fig. 2 Overall dimension schematic diagram of a condenser

shown in Fig. 2. Finally, based on the current manufacturing technologies of condensers, the major condenser design parameters are calculated.

$$y^2=2x\left(\frac{2f_1f_2}{f_1+f_2}\right)-\left[1-\left(\frac{f_2-f_1}{f_2+f_1}\right)\right]x^2 \qquad (1)$$

where $f_2 = M_0 f_1$, M_0 is the paraxial imaging magnification of an ellipsoidal condenser, u' is the aperture angle of image space.

2.2 Optical integrator design

2.2.1 *Components of an optical integrator and its working principle*

An optical integrator is composed of supplementary lens I, field lens group, projection lens group and supplementary lens II[15-16]. Installed in the second focal point of the ellipsoidal condenser, the field lens group segments the xenon lamp images and forms images in the projection lens group. The latter stacks the images segmented by the field lens group and then forms images on the irradiation plane through supplementary lens I and collimator objective. As a matter of fact, this is a differential-to-integral process. The optical integrator's structure diagram is shown in Fig. 3.

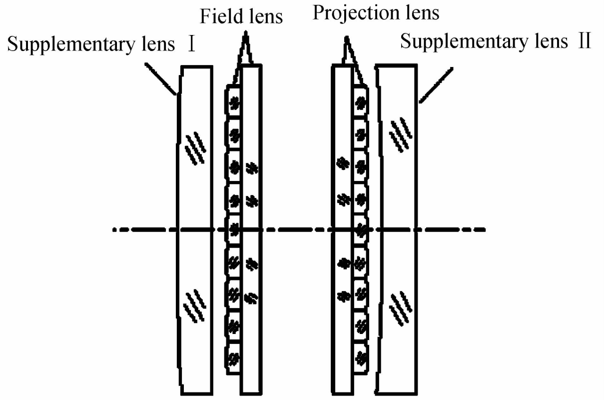


Fig. 3 Structure diagram of optical integrator

The field lens group is fixed on the light source image plane formed by the condenser. The illuminance is distributed in a large gradient within the image plane, but distributed in axial symmetry with the principal system optical axis. The illuminance distribution within the caliber of each field lens element is much smaller in gradient than that within the caliber of the entire field lens group. During the stacking imaging of the optical integrator, the illuminance distribution gradients in the calibers of field lens elements arranged in symmetry with the principal optical axis are mutually supplementary. In this way, the dodging effect will be achieved in optical integrator.

2.2.2 *Optimization of optical integrator*

Optical integrator parameters were optimized in the paper with both the sequential and non-sequential functions of Zemax. The optical integrator sequence was optimized from the perspective of imaging relationship, and then the model of the optimized optical system was established with the non-sequential function of Zemax. By way of ray tracing, the respective irradiation diagram of the stacking image plane of various lens elements before and after the optimization of the optical integrator was obtained, shown in Figs. 4 and 5. The diagram shows that the optimized lens element features better stacking effect, significantly improving the nonuniformity of the irradiated surface.

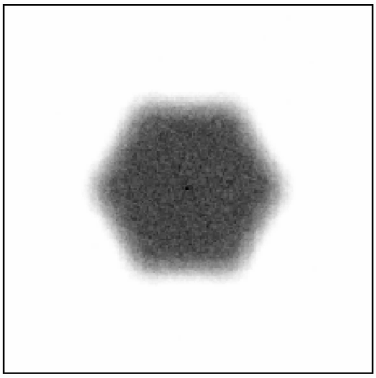


Fig. 4 Respective irradiation diagram of the stacking image plane of various lens elements before optimization of the optical integrator

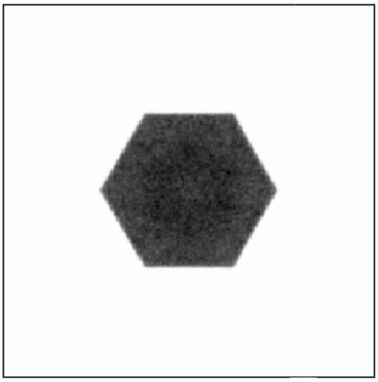


Fig. 5 Respective irradiation diagram of the stacking image plane of various lens elements after optimization of the optical integrator

2.3 Collimator objective design

As a typical lamp optical system, the optical system of a solar simulator imposes no strict requirements on aberration. However, to reduce the parallelism error of output beam (subject to spherical aberration and axial chromatic aberration of collimator objective) and collimating angel error (subject to various off-axis aberrations), it is necessary to calibrate the spherical aberration, coma aberration, axial chromatic aberration and other aberrations. The two-dimensional optical structure diagram of collimator objective and optimized aberration graph are shown respectively in Fig. 6 and 8.

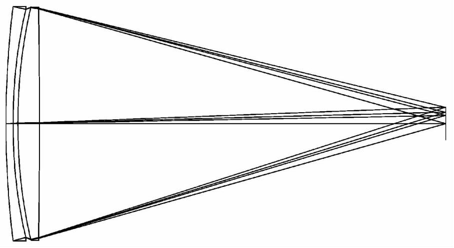


Fig. 6 Construction diagram of collimator objective

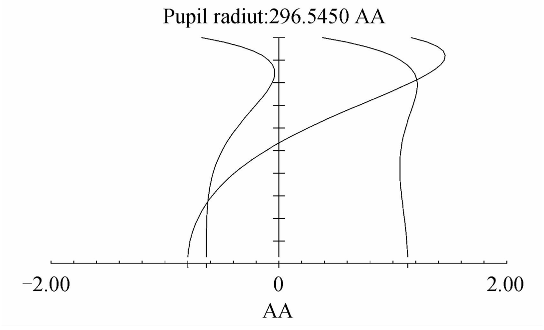


Fig. 7 Characteristic curves of system aberration

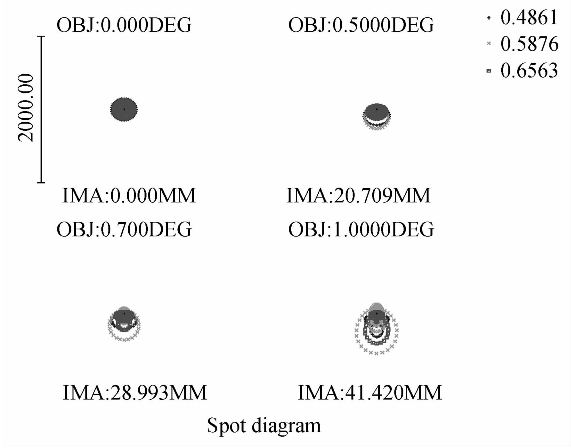
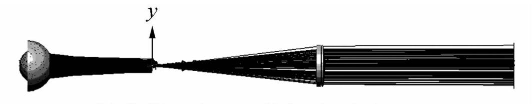


Fig. 8 Spot diagram

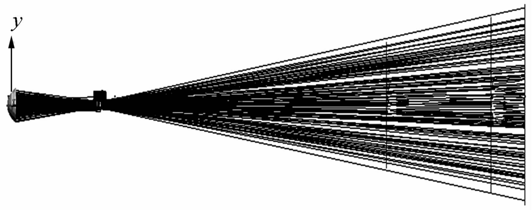
We can see from the Figs. 6 ~ 8 that both the spherical aberration and sine difference meet the requirements and that the off-axis aberration of various fields of view is relatively even. As a result, the selected double-dissociation lens, after optimization, can satisfy the aberration requirements of the multifunctional solar simulator optical system. In this way, the desired parallel beam can be produced.

3 Simulation analysis of the optical system

With the application of LightTools, simulation analysis was made of the irradiance and irradiation nonuniformity of the multifunctional solar simulator optical system. In the meanwhile, the optical system simulation models of collimating sunlight simulation and divergent sunlight simulation were established respectively, as shown in Fig. 9.



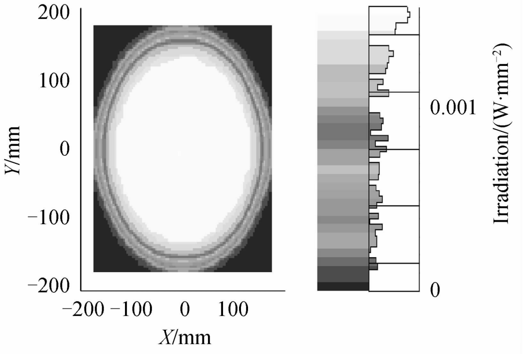
(a) Collimating sun light simulation



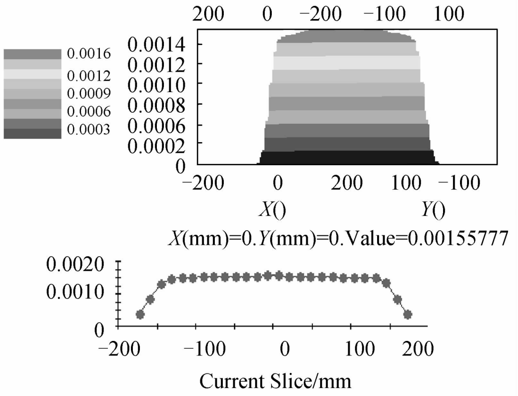
(b) Diverging sunlight simulation

Fig. 9 Optical system simulation model

Based on the design parameters, Monte Carlo ray tracing was conducted and the design parameters were corrected in accordance with the simulation results. In the end, the simulation results of the optical system with collimating simulation functions were shown in Fig. 10, and the simulated data was shown in Table 1.



(a) Irradiance chart



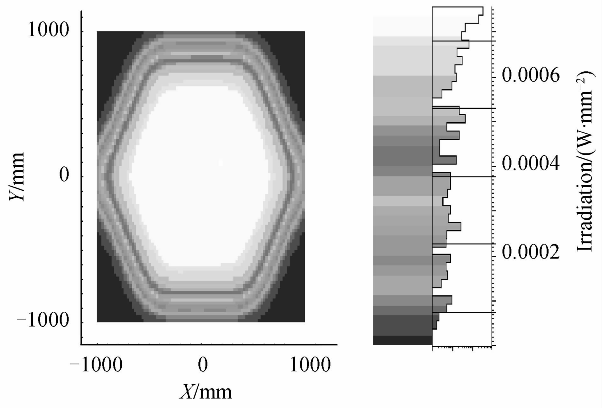
(b) Three-dimensional chart of nonuniformity

Fig. 10 Simulation results for the optical system

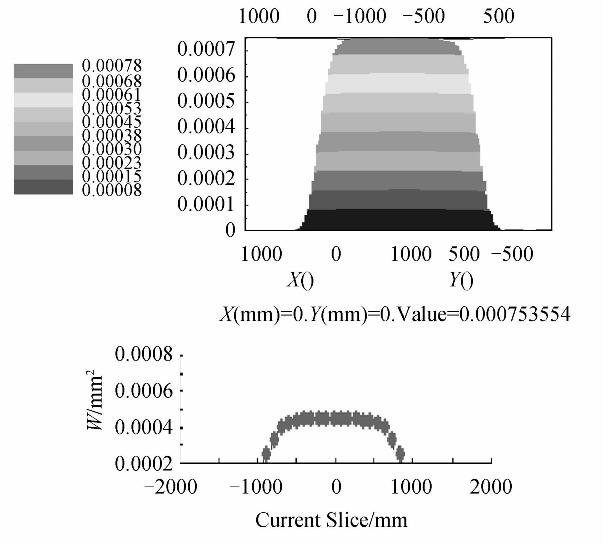
Table 1 Simulation results of the optical system with collimating simulation

Irradiated surface/mm Irradiance/($\mathrm{W\cdot m^{-2}}$)	Φ100	Φ200	Φ300
Max	1877.8	1877.8	1877.8
Min	1841.5	1760.2	1661.9
Nonuniformity	±0.98%	±3.23%	±6.10%

The simulation results of the optical system with diverging simulation functions were shown in Fig. 11, and the simulation data was shown in Table 2.



(a) Irradiance cnart



(b) Three-dimensional chart of nonuniformity

Fig. 11 Simulation results for the optical system

Table 2 Simulation data of the optical system with diverging simulation

Irradiated surface/mm Irradiance/(W·m^{-2})	Φ400	Φ800	Φ1500
Max	490.9	490.9	490.9
Min	482.3	466.9	429.2
Nonuniformity	±1.6%	±2.51%	±6.7%

4 Conclusions

The multifunctional optical system for solar simulators, composed of a condenser, an optical integrator and a collimator objective, was designed in this paper. And functions like collimating and divergent sunlight simulation were achieved in the multifunctional solar simulator by changing the position of the collimator objective. Besides, modeling and simulation analysis of the optical system were made with LightTools. The simulation results prove that the designed multifunctional solar simulator has achieved the functions of collimating sunlight simulation and divergent sunlight simulation. When collimating sunlight simulation is achieved, the irradiated surface can reach Φ300 mm, and the irradiation nonuniformity superior to ±6.1%; while the divergent sunlight simulation is achieved, the irradiated surface can reach Φ1 500 mm, and the irradiation nonuniformity superior to ±6.7%.

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