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# Designing an optical system of a high precision solar simulator for meteorological application

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**To satisfy meteorological observation and measurement needs, the general composition and optical system of a high precision solar simulator is designed to the calibration requirements for high precision solar radiation meters. Given the light source characteristics of the solar simulator, an ellipsoid convergent lens is employed so as to enhance the energy utilization ratio of the light source; the optical integrator and the collimator are optimized in design with the aid of Zemax software, resulting in improved irradiation uniformity and output beam alignment. The test results suggest that, at a working distance of 1000 mm and with an effective irradiation aperture of Ø60 mm, the solar simulator generates an irradiance of up to 1222 W/m$^2$ and the irradiation nonuniformity is 0.83%, satisfying the requirements for meteorological observation and measurement.** 

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## 1. INTRODUCTION

With global warming becoming more and more serious, meteorological monitoring and disaster warning are playing a prominent and important role. The demand for high precision solar radiation meters is growing because of climate forecasting, meteorological radiation observation, and solar energy resource observation, but the under-developed measuring equipment is the bottleneck that constrains the development and production of these meters. At present, existent measuring equipment consists mainly of solar simulators, the precision of which is, however, not quite up to the requirements for meteorological observation, measurement, and testing. It is therefore imperative to develop solar simulators with higher performance indices.

As a type of test and inspection equipment used on the ground and capable of accurately simulating solar irradiance, alignment, and spectral characteristics, traditional solar simulators are extensively applied to environmental simulation testing of spacecraft, inspection of photovoltaic devices, and solar interference testing of missile armaments. By addressing the measurement requirements of high precision solar radiation meters used in climate forecasting, meteorological radiation observation, and solar energy resource observation, the work described in this paper attempts to design an optical system of a solar simulator for meteorological application that may satisfy meteorological observation, measurement, and inspection requirements [1]. The focus is on how to solve the simulation problem with solar irradiance and non-uniformity. The work is of great significance to improving the calibration level of solar radiator meters as well as meteorological monitoring and the disaster warning capability of China.

## 2. COMPOSITION AND WORKING PRINCIPLE

The optical system of a solar simulator for meteorological application mainly consists of a short-arc xenon lamp, an ellipsoid convergent lens, a turning plane mirror I, an optical integrator, a view field diaphragm, an optical filter, a collimation optical system, and a turning plane mirror II. Figure 1 shows both the general structure and a photo of a solar simulator for meteorological application.

The working principle of the optical system of such a simulator is illustrated in Fig. 2. A short-arc xenon lamp of axial asymmetry that resembles the Sun in optical spectrum is utilized as the light source and is placed at the first focus of the ellipsoid convergent lens. The beam emitted by the lamp converges on the second focus of the convergent lens and forms an irradiance distribution on the incidence end face of the optical integrator, i.e., the location of the battery of the field lens. This distribution is divided symmetrically by the channels of the integrator and, after being superimposed and re-imaged, passes through the view field diaphragm and collimator, and then exits in parallel rays, forming radiance with uniform irradiance on the incident face. The radiation rays, when viewed from a point

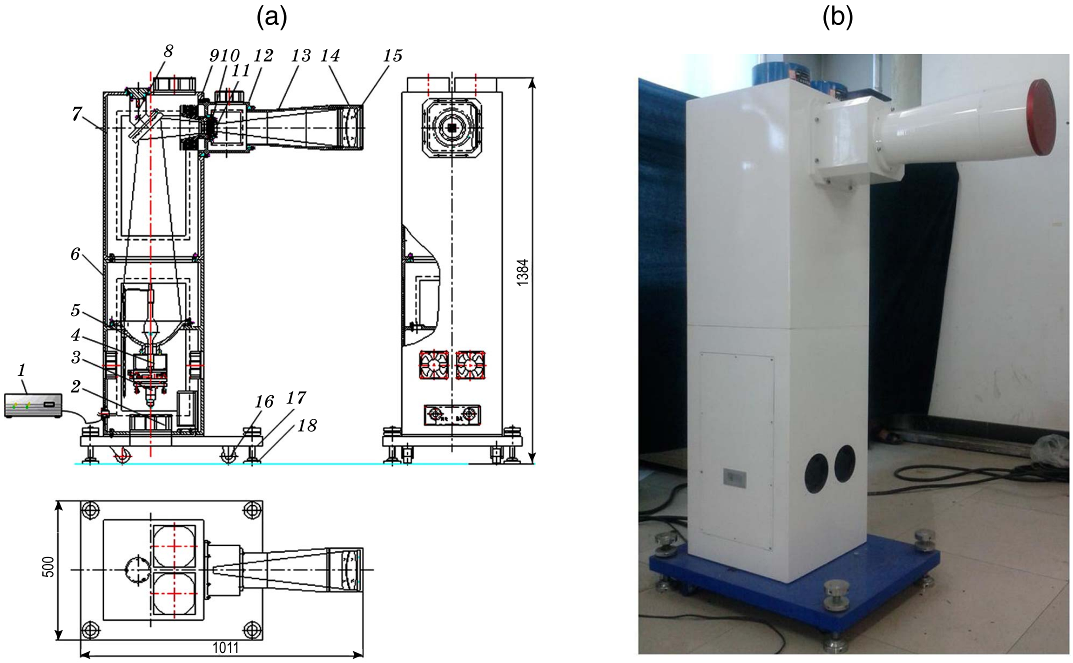


**Fig. 1.** General structure and a photo of a solar simulator for meteorological application. (a) Structure. (b) Photo.

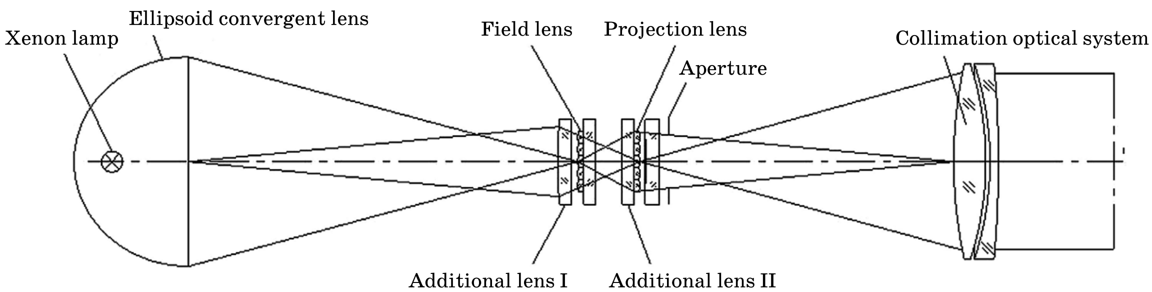


**Fig. 2.** Working principle of the optical system of solar simulator.

in front of the collimator, look like they are coming from the optical integrator located at the collimator focal plane, just as the solar rays do from the "infinitely far" Sun, hence simulating solar irradiation [2].

## 3. DESIGN OF THE OPTICAL SYSTEM

The optical system of solar simulators for meteorological application is a complicated lighting system. In the design, consideration must be given to proper choice of the optical system, optimal optical parameters, and maximization of irradiance uniformity in the testing space while trying to maximize the energy utilization ratio of solar simulators.

### A. Design of the Condensing System

In order to converge sufficiently the radiation flux emitted by the xenon arc of the lamp, the condensing system shall have a larger included angle so that a condensing effect with a high utilization ratio may be attained when used together with the short-arc xenon lamp and also so that the system structure is compact and the optical path is short.

The design formula of the ellipsoid converging lens is given by Eq. (1), for which the origin of the Cartesian coordinate system coincides with the apex of the converging lens and the optical axis acts as the $x$ axis. The xenon arc on the first focal plane of the ellipsoid convergent lens, under the action of the convergent lens, radiates its rays to the second focal plane of the convergent lens and forms an irradiation distribution on the plane of incidence of the optical integrator.

$$y^2 = 2R_0x - (1 - e^2)x^2, \tag{1}$$

where $f_1$ is the first focal length of the ellipsoid convergent lens; $f_2$ is the second focal length of the ellipsoid convergent lens; $e$ is the eccentricity of the ellipsoid, $e = (f_s - f_1)/(f_s + f_1)$; $R_0$ is the paraxial radius of curvature of the ellipsoid (apex), $R_0 = 2f_1f_2/(f + f_2)$; and $M_0$ is the paraxial imaging multiplying factor of the ellipsoid convergent lens, $M_0 = f_2/f_1$.

### B. Design of the Optical Integrator

The optical integrator is designed to interweave and superimpose the rays coming from the ellipsoid convergent lens and to convert them into radiation rays, which are then projected to the collimator so as to ensure the uniformity of the exiting parallel rays. Also, the exit pupil plane of the convergent lens is imaged on the focal plane of the collimator and the xenon arc of the short-arc xenon lamp is imaged on the optimum incident face [3–5].

The optical integrator consists of two $5 \times 5$ channels of microlens arrays, i.e., the battery of the field lens and the battery of the projection lens. For the purpose of enhancing the irradiation uniformity, the imaging sharpness, and the imaging energy on the incident face, two additional lenses are installed on the optical path: additional lens I and II, as shown in Fig. 3.

### C. Design of the Collimator

The collimator operates to produce parallel light radiation and ensures the irradiation uniformity within a certain depth along the collimation optical axis. The collimator features a double-separation structure, as shown in Fig. 4, the benefit of which includes good rectification of spherical aberration, chromatic aberration, and sinusoidal error along with improvement of alignment and irradiation uniformity of exiting rays.

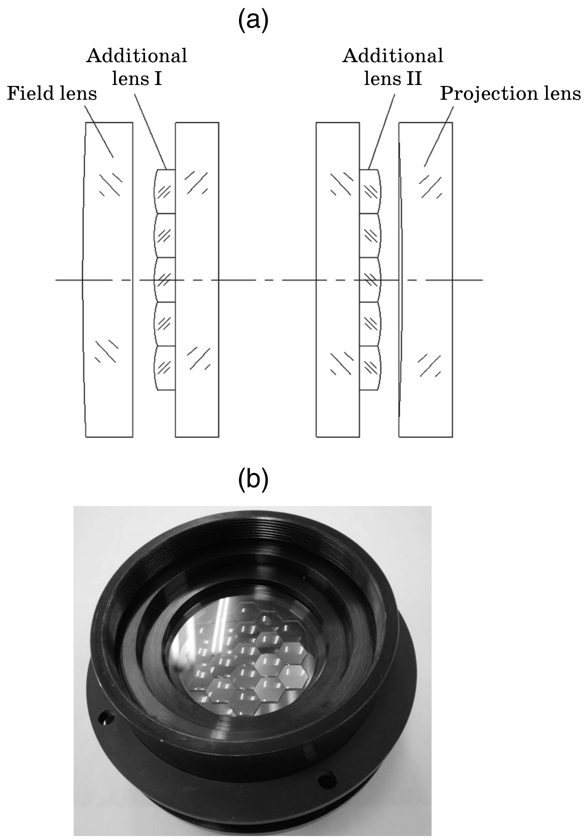


**Fig. 3.** Optical integrator. (a) Structure. (b) Photo.

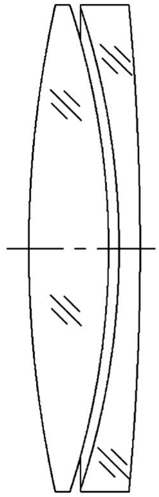

**Fig. 4.** Collimator.

As an energy transfer system, the optical system is primarily concerned with the system energy utilization ratio and the uniformity on the incident face, imposing no strict requirement on rectification of aberration. However, for the sake of alignment accuracy, the chromosphere aberration, coma, and axial chromatic aberration inherent in the collimator, which affect the alignment accuracy, must be rectified satisfactorily. Figure 5–7 display the aberration curves of the collimator.

Figure 5 suggests that, after optimization, the dispersion spot on the image plane is small and the view fields do not differ much from one another. It is clear from Figs. 6 and 7 that spherical aberration correction has been performed with respect to the central wavelength, achromatic treatment has been made to the 0.707 view field, and the system operation is not affected by the secondary spectrum that exists. Figure 7 tells us that off-axis aberration has been corrected, resulting in a smaller coma.

In summary, the selected double-separation lens, after optimization, is able to generate desirable parallel light beams and guarantee acceptable alignment precision.

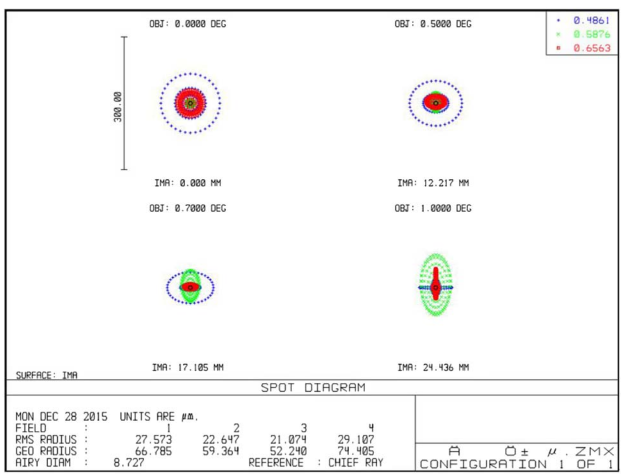


**Fig. 5.** Spot.

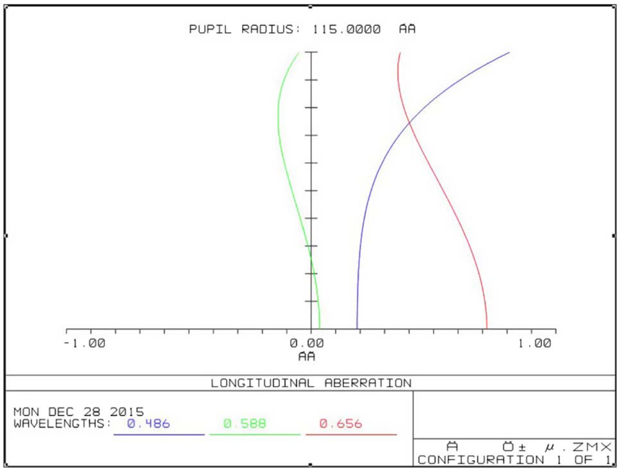


**Fig. 6.** Plot of the spherical aberration and axial chromatic aberration.

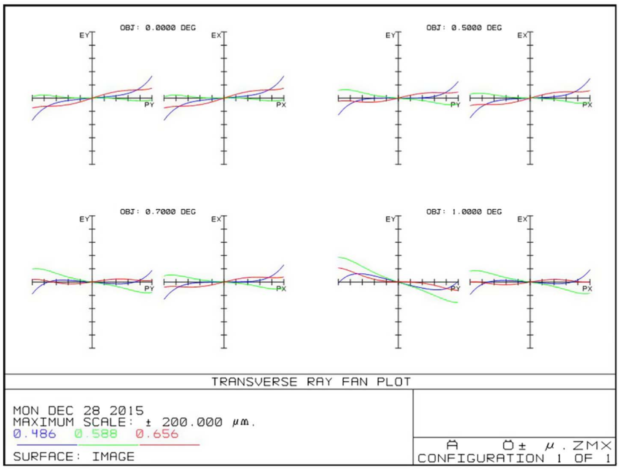


**Fig. 7.** Aberration plots.

## 4. TEST RESULTS

The solar simulator for meteorological application was put to practical testing to evaluate its radiation intensity and non-uniformity [6,7]. Figure 8 is the distribution schematic of the tested points on the effective irradiation area. Figure 9 shows the test results of radiation intensity on this area, and it gives the test results of non-uniformity on this area at a radiation intensity of 1200 W/m$^2$.

It can be inferred from these figures that the irradiance is better than 1222 W/m$^2$ and the irradiation non-uniformity is superior to 0.83% at a working distance of 1000 mm and with an effective irradiation aperture of Ø60 mm.

## 5. SUMMARY

This paper describes the design of the optical system of a solar simulator according to the requirements for meteorological observation and measurement. It explains the composition and working principle of the optical system and describes the optimization of the condensing system, optical integrator, and collimator, which helps improve significantly the energy utilization ratio, irradiation uniformity, and irradiation alignment and succeeds in producing parallel exiting light, satisfying the need for distance simulation of solar irradiation. The test results suggest that, at a working distance of 1000 mm and with an effective irradiation aperture of Ø60 mm, the solar simulator generates an irradiance of up to 1222 W/m$^2$ and the irradiation non-uniformity is 0.83%, superior to Level A of the Chinese national standard, hence satisfying the requirements for meteorological observation and measurement.

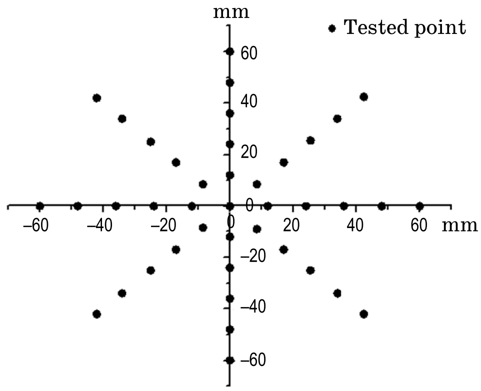


**Fig. 8.** Distribution schematic of the tested points on the effective irradiation area.

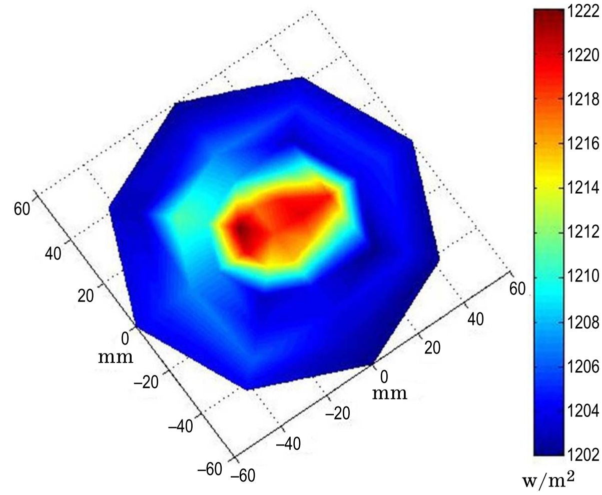


**Fig. 9.** Test results of radiation intensity.

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