Stray light suppression in BRDF measurement infrared optical system

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A set of system based on personal computer for the bi-directional reflectance distribution function (BRDF) measurement was developed, whose laser wavelengths cover 0.6328, 1.34, 3.39, and 10.6 μm from visible to infrared. Stray light in BRDF measurement system was analyzed. It can be reduced and suppressed by the design of the system light path in BRDF measurement system, the choice of the measuring scheme, the processing to the optoelectronic signal, and the radiation control of the optical components and mechanical equipments. So the minimum measurable value of BRDF is less than 10^{-5}/sr.

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Stray light is referred to the non-imaging light spreading to the surface of the optical system. It comes from the external radiation sources of the system (such as sunlight, light, earthlight etc.), internal radiation source (such as the optical components, mechanical parts etc.) and the non-imaging light on the scattered surface (such as the reflection light from the refractive surface of the optical system and the wall of the instruments etc.). Stray light influences the image definition, reduces the contrast of the image surface, and in the serious case forms the stray faculae with different sizes and even leads to invalidation of the optical system.

From the beginning of the 20th century, stray light has been studied. 1970's later, with the need in many fields such as environment, resources and military remote sensing etc., the research on stray light analysis and control has been rapidly developed. In 1977, the effect of unwanted stray radiation in optical system was analyzed qualitatively by R. P. Breault of the Optical Science Center of the University of Arizona[1]. H. E. Bennett of the Michelson Laboratories of Naval Weapons Center of California investigated the reduction of stray light from optical components[2]. In 1986, small angle stray light from optical components in BRDF/BTDF measuring instruments was investigated by W. W. Lee etc.[3]. 1990's later, suppression of stray light is particularly important in the design of the infrared (IR) optical system, such as SIRTF (Shuttle Infrared Telescope Facility), COBE (Cosmic Background Explorer), IRAS (Infrared Astronomy Satellite), and infrared bi-directional reflectance distribution function (BRDF) measurement system.

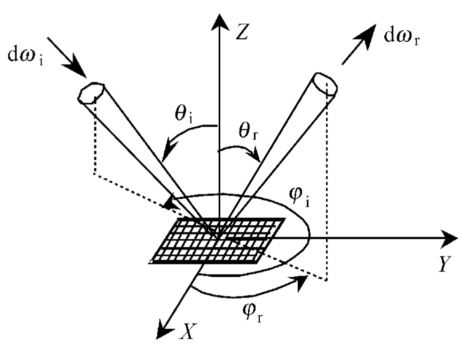

Fig. 1. Beam and sample geometry of BRDF.

The angular distribution of light scattered from optical surfaces is described perfectly by the BRDF. With the development of the optical design and detector, stray light control becomes one of the key techniques for increasing the signal-to-noise in the research on measuring BRDF.

According to the Nicodemus definition, the BRDF is a ratio of the reflected radiance in direction $(\theta_\mathrm{r}, \varphi_\mathrm{r})$ to the incident irradiance from direction $(\theta_\mathrm{i}, \varphi_\mathrm{i})$[4]

$$f_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) = \frac{\mathrm{d}L_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r})}{\mathrm{d}E_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i})} = \frac{\mathrm{d}L_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r})}{\mathrm{d}L_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i}) \cos\theta_\mathrm{i} \mathrm{d}\omega_\mathrm{i}}, \tag{1}$$

where θ and φ are zenith and azimuth angles in normal spherical coordinates, the subscripts 'i' and 'r' refer to incident and reflected directions, respectively. It depends on four angles (two for the incident radiation and two for the reflected radiation) and is a function of the surface condition and different material. Figure 1 depicts the beam and sample geometry of BRDF.

The BRDF is defined for the ratio of two infinitesimals and is inapplicable to practical measurement. The $f_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r})$ is approximately the constant of non-zero intervals in concrete BRDF measurement, it can be found from

$$L_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) = f_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) \int L_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i}) \mathrm{d}\Omega_\mathrm{i} = f_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) E_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i}),$$

then Eq. (1) can be written

$$f_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) = \frac{L_\mathrm{r}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r})}{E_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i})}. \tag{2}$$

A set of system based on personal computer for the

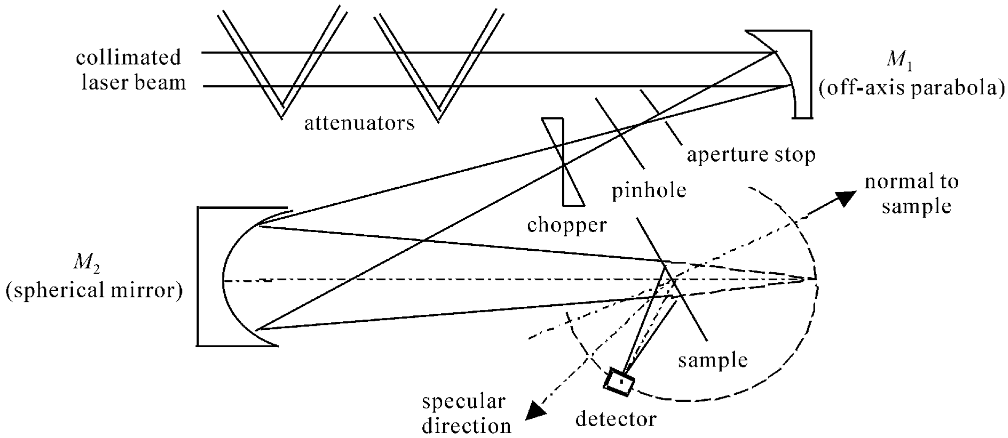

Fig. 2. Arrangement for BRDF measurement.

BRDF measurement is developed[5], typical arrangement for measuring BRDF is shown in Fig. 2. The collimated laser beam passing through the optical attenuators in order to attenuate the optical signal can meet the need of typical BRDF measurement. At the same time, the attenuators can be used to eliminate the disturbance from the background to the stray light due to the big wavelength differences between the background radiation and infrared rays. To avoid back reflections, each attenuator module consists of a pair of glass elements with 60° intersecting angle. The reflected light is guided out in order to prevent stray light, caused by beam shifting on angle and reflecting back to the attenuator.

Attenuated and collimated laser beam is focused by mirror M_1 (an off-axis parabola is used), and it passes through an aperture stop and onto a pinhole. The aperture stop is conjugate to the sample plane and is used to limit the maximum extent of the incident beam radiation to the sample within about 1 – 3-cm diameter. The pinhole is selected experimentally to be several times larger than the focused beam spot, which serves as a spatial filter. The beam is away from the pinhole and passes a rotating reflection-transmission chopper with the chrome-plated strong reflection coating. So the influences on the measurement can be minimized and even eliminated, which are caused by the element wall of the system, stray radiation of large background of the target and the dark-current of the optoelectronic detector. The modulated alternate beam is refocused by a spherical mirror M_2 and is reflected by the sample. To minimize scattering, this spherical mirror has been refinedly polished and is coated with a single layer of aluminum. The detector is mounted on a turn-table centered at the sample. The scattered light from the sample is measured as a function of reflected angle (θ_r, φ_r). A small focused beam system in front of the detector is located to improve the signal-to-noise for measuring BRDF.

Even if proper baffles and stops are implemented in the system, stray light could still pass along the optical path onto the detector used for measuring BRDF. For suppressing the stray light, a single reference measurement method has been chosen. The radiance is measured from a voltage reading of a detector, then Eq. (2) can be written in the following simplified expression

$$f_{bS} = f_{br} \cdot \frac{V_S}{V_r} \cdot \frac{\cos\theta_r}{\cos\theta_S}, \tag{3}$$

where f_{bS}, f_{br} denote the measured BRDF values of the sample and the reference, respectively. V_S, V_r denote the scattered power by the sample and the reflected power by the reference onto the detector, respectively. θ_S, θ_r denote the zenith angle of the sample and the reference versus the detector, respectively.

The measuring method of BRDF chosen insures that the stray light can be minimized in the system.

Lock-in amplifier can demodulate in the phase to the weak optoelectronic alternate signal. It can pick-up, restore and intensify the measured signals from the background noise and other stray radiation with strong disturbance. The scheme of the self-design lock-in amplifier is illustrated in Fig. 3, and its center frequency can be adjusted to 800 Hz.

The energy variations in laser can be eliminated by using the way, in which the signals from the radiometer and monitor detector behind the chopper are demodulated and integrated.

The corresponding measurements to eliminate the other sources of stray light are adopted. For example, in the lens the spacer rings are used to obstruct the stray light in the ground edges of the lens elements, the inside edges of the spacers are cut at an angle and blackened, they cannot be threaded and so specular reflections are avoided. The stray light causing by the multiple reflections between lens surfaces was minimized by covering the lenses with the antiflection coating. The manufactured sample holder and other mechanical components are sandblasted and black anodized. The field of view of the detector is limited by aperture stop. The sizes of the incident beam and the measured sample are limited in the certain range.

As mentioned before, in the design of the BRDF measurement system, many techniques used to control stray light have been described. Stray light has been suppressed effectually, and so measurement precision and small angle resolution are improved. The minimum measurable value of BRDF is less than 10^{-5}/sr.

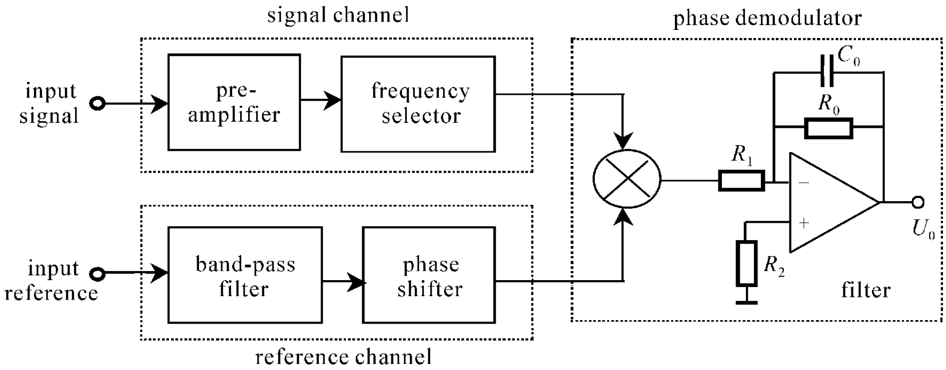

Fig. 3. Scheme of the lock-in amplifier.

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