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光学镜面洁净度对激光传输特性的影响

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摘　要:光学系统性能的优劣与光学镜表面的散射情况息息相关.根据米氏理论并利用 MATLAB 软件,对可见光(0.632 8 μm)、近红外光(1.053 μm)和热红外光(10.6 μm)三种激光在干净、基本洁净(洁净度 200)、轻度污染(洁净度 500)及重度污染(洁净度 750)四种光学镜面洁净度下镜面的双向反射分布函数进行了模拟计算.结果表明:光学镜面的表面粗糙度和表面洁净度影响镜面的双向反射分布函数.进而对光学系统的性能会产生显著的影响,且波长越短,双向反射分布函数越大,散射越复杂.这为光学工程中光学镜面的污染评估和镜面清洁提供有益帮助.

关键词:散射;双向反射分布函数;米氏理论;洁净度

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Influence of Optical Mirror Surface Cleanliness Levels on Laser Transmission Characteristics

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Abstract: Performance of optical systems is closely related to the scattering characteristics of optical mirror surface. According to Mie theory, the bidirectional reflectance distribution function of optical mirror surface under four cases of mirror surface cleanliness levels such as clean, basic clean (cleanliness level 200), slight pollution (cleanliness level 500) and severe pollution (cleanliness level 750) was simulated and computed by MATLAB software when incident laser wavelengths are the visible light (0.632 8 μm), near infrared light (1.053 μm) and thermal infrared light (10.6 μm), respectively. The results show that the bidirectional reflectance distribution function of mirror surface is affected by mirror surface roughness and clean lines level, which will make a very important impact on properties of optical system. If wavelength is shorter, bidirectional reflectance distribution function will be greater, and scattering becomes more complicated. Useful help will be provided to estimate the pollution of optical mirror and clean the mirror surface in optical engineering.

Key words: Scattering; Bidirectional Reflectance Distribution Function (BRDF); Mie theory; Cleanliness level

OCIS Codes: 290.0290; 290.1483; 290.4020; 290.5825; 290.5850

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0 Introduction

As the important component of optical system, scattering characteristics of optical mirror are of major impact on properties of overall system. Scattering characteristics of optical mirror can be described by Bidirectional Reflectance Distribution Function (BRDF). BRDF is widely used for natural disaster monitoring, climate research, geographic information, marine development, space remote sensing, military information, and so on. BRDF of various materials surface have been studied theoretically and experiment[1-8].

Optical systems in great optical engineering, such as lider, large photo-electric theodolite, are placed at complex external environment usually. Suspended particles in the air (for example dust) will deposit on optical mirror surface, polluting the mirror and adding scattering. The influence of contamination particles on scattering characteristics of optical mirror can be researched according to Mie scattering theory[9]. The theory can also predict the scattering from the particles deposited on optical mirror surface[10]. The pollution of optical mirror surface can be described by surface cleanliness level in engineering application field[11]. The higher cleanliness level is, the more serious pollution of mirror will be.

Due to BRDF can be affected by the different cleanliness levels of optical mirror surface significantly, laser transmission characteristics under four cases of mirror surface cleanliness levels such as clean, basic clean (cleanliness level 200), slight pollution (cleanliness level 500) and severe pollution (cleanliness level 750) were studied when incident lasers were the visible light (0.632 8 μm), near infrared light (1.053 μm) and thermal infrared light (10.6 μm) respectively. It will provide useful help to estimate the pollution of optical mirror and clean the mirror surface in optical engineering.

1 BRDF model

The scattering of energy can be described by BRDF when distant light source irradiates the optical mirror[12]. The scattering of contaminated mirror surface have two aspects: the scattering from clean mirror surface and the scattering caused by particles on the mirror surface. The sum of two aspects is the total BRDF

$$\mathrm{BRDF}=\mathrm{BRDF}_{\mathrm{m}}+\mathrm{BRDF}_{\mathrm{p}} \tag{1}$$

The subscripts "m" and "p" represent the BRDF of clean mirror and contaminates, respectively.

In regard to clean mirror, if $\sigma \ll \lambda$, the BRDF is given by the following empirical expression[7-8]

$$\mathrm{BRDF}_{\mathrm{m}}=\frac{2}{\pi}\frac{k^4\sigma^2 l^2}{1+[kl(\beta-\beta_0)]^2} \tag{2}$$

where l is autocorrelation length, σ is rms surface roughness; $k=2\pi/\lambda$ is wave vector, λ is wavelength; θ_s is the polar angle of scatter (measured from mean surface normal); $\beta=\sin\theta_s$ is the direction cosine with respect to the y axis; θ_0 is the polar angle of incidence (measured from mean surface normal); $\beta_0=\sin\theta_0$ is the direction cosine of the incident angle.

For polluted mirror, the scattering from contamination particles on mirror surface is described by Mie scattering[9]. Geometry for particle scattering is shown in Fig. 1. The incident wave propagates along the z axis and its electric vector is in the x axis direction. The scattered wave can be observed along θ, ϕ direction. This direction and that of incident wave make up the scattering plane. a is the radius of the scattering particle and $\boldsymbol{r}$ is the radial distance between the particle and the point of observation.

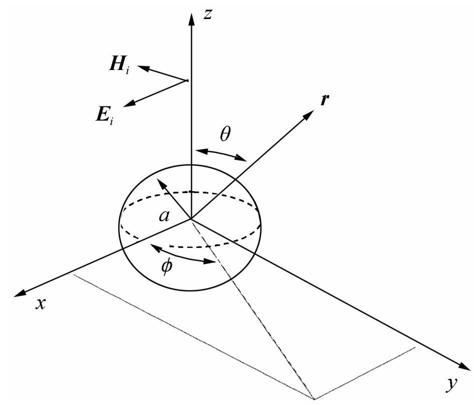

Fig. 1 Geometry for particle scattering

The scattering is caused by contaminants on the mirror surface, the BRDF is given as

$$\mathrm{BRDF}_{\mathrm{p}}=\frac{\lambda^2 D}{4\pi^2\cos\theta_{\mathrm{r}}}i_1 \tag{3}$$

where D is the particle density on the mirror. θ_r is with respect to the mirror surface normal in the scattering plane (y-z, Fig. 1). i_1 is intensity function, which was given by Mie theory as

$$i_1=\left|\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}(a_n\pi_n+b_n\tau_n)\right|^2 \tag{4}$$

Usually, the pollution of optical mirror is shown by surface cleanliness level. Generally speaking, using the standard MIL-STD-1246C describes the particles distribution on surface approximately[11]

$$\log N_a=0.926[(\log X_1)^2-(\log X)^2] \tag{5}$$

where X represents particle size (μm); X_1 represents surface cleanliness level; N_a represents the number of particles per ft^2 greater than or equal to X.

The relationships between cleanliness levels (200, 500, 750) and particles distribution on surface are shown in Table 1.

Table 1 Particulate contamination as quantified by MIL-STD-1246C

Cleanliness level	Particle size/μm	Count per ft^{-2}	Count per 0.1 m^{-2}
200	15	4 189	4 520
	25	1 240	1 340
	50	170	184
	100	16	17.3
	200	1.0	1.08
500	50	11 817	12 800
	100	1 100	1 190
	250	26	28.1
	500	1.0	1.08
750	50	95 807	105 000
	100	8 900	9 630
	250	214	231
	500	8.1	8.75
	750	1.0	1.08

The relationship curve between cleanliness levels and percent area coverage is presented in Fig. 2. Surface percent area coverage can be defined as ratio of the sum of all particles' projected area to surface area when incident wave was irradiated on mirror surface perpendicularly.

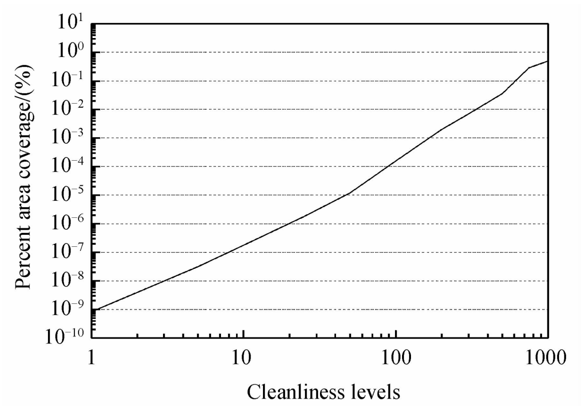

Fig. 2 The relationship between cleanliness levels and percent area coverage

In order to research and analyze easily, it is assumed: 1) all contamination particles distribute on mirror surface uniformly; 2) all contamination particles do not overlap mutually, the intervals between particles are greater than three times particle radius.

2 Simulation results and analysis

2.1 The BRDF of clean mirror

For $\sigma \ll \lambda$, the diversification of BRDF about clean mirror with incident wave (λ), surface roughness (σ) and autocorrelation length (l) is shown in Fig. 3. The BRDF as shown in Fig. 3(a) is indicated when incident wavelengths are 0.632 8 μm, 1.053 μm and 10.6 μm, respectively. The BRDF varies inversely with incident wavelength significantly . When incident wave is thermal infrared light, the BRDF has a few changes with the scattering angle and scattering is relatively stable. Fig. 3 (b) shows the effects of surface roughness on clean mirror BRDF when scattering angle and autocorrelation length are specified. It is shown that if scattering angle and incident angle are basically equal, the BRDF curve of mirror surface varies slightly. On the contrary, the BRDF reduces rapidly and the curves' slope is almost identical. When incident wavelength and surface roughness are specified, the effects on BRDF caused by autocorrelation length are presented in Fig. 3(c). It is shown that when scattering angle is small, bigger the autocorrelation length is, greater the BRDF of mirror will be. Every curve's

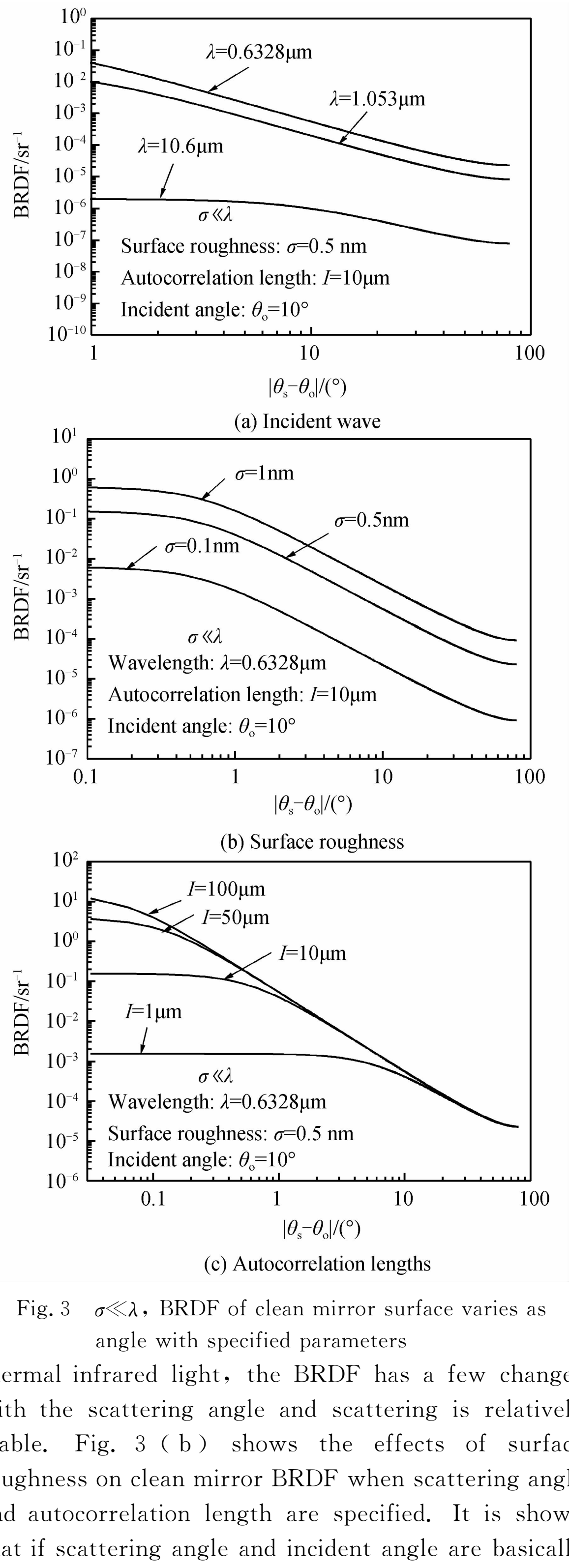

Fig. 3 $\sigma \ll \lambda$, BRDF of clean mirror surface varies as angle with specified parameters decrement becomes obvious when scattering angle is big enough, and the slopes of the clear part of curve attenuation are equal nearly. In addition, if autocorrelation length becomes smaller, the difference between incident angle and scattering angle will be greater when the reduction of BRDF becomes evident.

2.2 The BRDF of mirror with different cleanliness levels

Fig. 4 illustrates the BRDF of mirror with different cleanliness levels (200, 500 and 750) when the incident wavelength is specified as 0.632 8 μm in Fig. 4(a), 1.053 μm in Fig. 4(b) and 10.6 μm in Fig. 4(c), respectively. It can be seen that no matter which light is, the BRDF is in proportion to cleanliness level. That conforms to the actual situation. Higher cleanliness level means greater probability of large particle deposited on mirror surface. Because of this, the scattering from mirror surface is more powerful.

The relationships between BRDF and incident wavelengths (0.632 8 μm, 1.053 μm and 10.6 μm) are presented in Fig. 5. The cleanliness levels are specified as 200, 500 and 750. From this figure it seems, the tendency of BRDF curves are agreed roughly under the same cleanliness level, and the increment of cleanliness level has a few effects on the value of BRDF. For the visible light 0.632 8 μm and near infrared light 1.053 μm, when the scattering

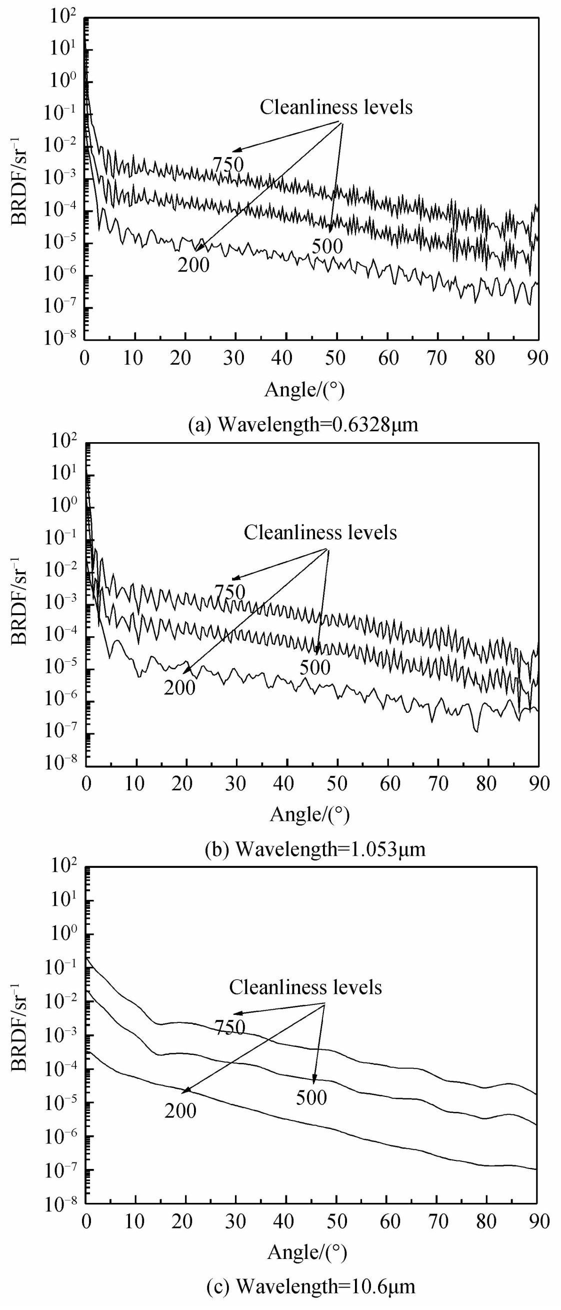

Fig. 4 BRDF of particles on mirror surface for different incident wavelengths

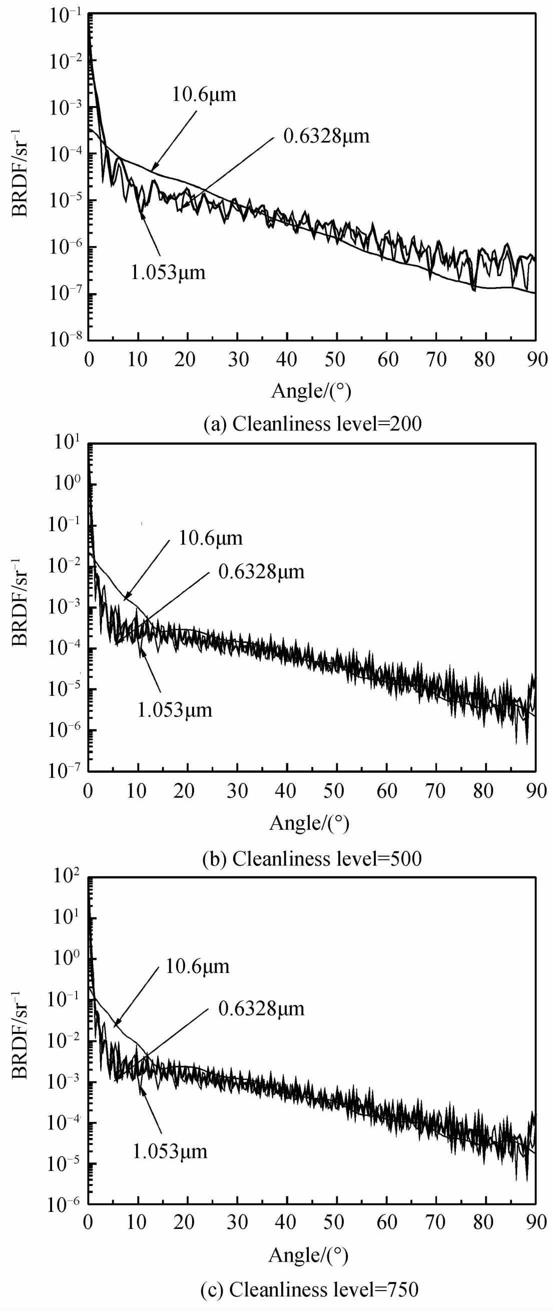

Fig. 5 BRDF of particles on mirror surface for different cleanliness levels

angle is very small, the BRDF curve degrades much speedily and the attenuation amplitude is up to three orders approximately. However, if the scattering angle is up to a special value, the BRDF attenuation will become slow obviously. While the thermal infrared light 10.6 μm, the change above is not clear. In addition, the attenuation trend of BRDF curve is inversely proportional to incident wavelength and the curve fluctuation is more and more unconspicuous. It means that the scattering is more complex with shorter wavelength.

Furthermore, comparing Fig. 3(b) with Fig. 5(a), it can be seemed that if surface roughness is small and the mirror is basic clean (cleanliness level 200), a few contamination particles will make effects on scattering properties of optical mirror the same as surface roughness under the scattering angle about 20 deg. So, the scattering caused by contamination particles is of major part of scattering from optical mirror surface.

3 Conclusions

The BRDF of mirror surface was significantly affected by the surface roughness and different cleanliness level of optical mirror. Particle contaminations on the mirror surface make a very important influence to laser transmission characteristics. So, manufacture technology should be developed to reduce surface roughness in the process of manufacture of optical mirror, and cleaning method should be improved to reduce the cleanliness level of mirror surface as much as possible.

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