Optik 124 (2013) 6194–6196

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

A new proof of Mie effect in light scattering

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ARTICLE INFO

Article history:
Received 8 December 2012
Accepted 30 April 2013

Keywords:
Scattering
Mie effect
Sphere

ABSTRACT

In detecting particles on a substrate, two-white-spots phenomenon was observed. This gives an illusion that light scattering is caused by two spheres, in fact it is just caused by one sphere. This phenomenon makes particle detection by light scattering much more complicated. Analysis on this phenomenon shows that Mie effect is the reason of formation of two white spots. This experiment demonstrates the images of Mie effect, and provides a strong evidence of theory of Mie effect.

1. Introduction

As an important optical phenomenon, light scattering was studied by many researchers [1–4]. It is extensively used in measurement of particle size and particle counting in a homogeneous medium (air, water, solution), and it is also used to detect contamination particles on a substrate in semiconductor industry and optical thin-film field. Compared with light scattering from a sphere in a homogeneous medium, light scattering from a sphere on a glass plate is much more complicated because of electromagnetic interaction between a particle and a substrate [3].

In 1908, Mie [5] presented a reasonable explanation for the coloration of metal suspension. This model also can be extended to describe light scattering by many spheres if it is assumed that spheres have same diameters and components, they are distributed randomly, and the distance between them is much larger than the incident wavelength. He also believed that with the increment of sphere size, there is a departure from symmetry, more light being scattered in the forward direction than in the opposite direction. This phenomenon is often called the Mie effect. However, no strong, experimental evidence has been given to prove Mie effect theory.

In this paper, we explore the reason of formation of two-white-spots phenomenon in laser light (532 nm) scattering from a sphere on a glass plate, and then give the experimental evidence of Mie effect.

2. Experiment

The experiment is shown schematically in Fig. 1. A sphere was deposited on a substrate, a laser light hits on a sphere, partial light scattered by the sphere is detected by a CCD camera. The light is 532-nm p-polarized laser beam.

Both sides of a fused silica substrate were polished, the roughness (RMS) measured by atomic force microscopy (AFM) is approximately 0.7 nm. The substrate with thickness of 5 mm was cleaned carefully by traditional process before it was used. The cleaned substrate was checked by dark field microscopy, there was only 0–5 particles/mm^2 on it; the size of left contamination particles was less than 100 nm. Silica and polystyrene spheres, respectively, were deposited on the substrate. The nominal size of the sphere ranges from 100 to 2000 nm, and the size deviation is less than 10 nm, and the particle density on the substrate is 30–60 particles/mm^2.

3. Results and discussions

We only used experimental results of silica spheres because polystyrene and silica spheres have similar experimental phenomena.

3.1. Two-white-spots phenomenon

Fig. 2 shows light scattering by spheres of different size on a glass plate. The incident angle of laser light is 65°. Every sphere has circular diffraction fringes in images. There is only green color in images when sphere size is in the range of 100–400 nm. White spot appears besides green color when sphere size is 500 nm, and

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http://dx.doi.org/10.1016/j.ijleo.2013.06.001

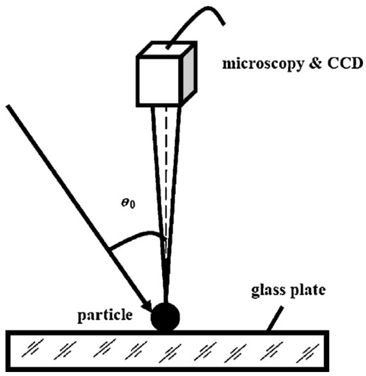

Fig. 1. Schematic diagram of the experiment.

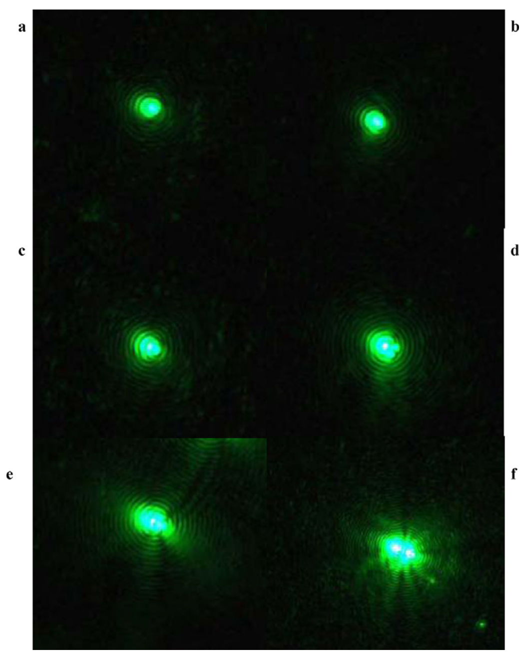

Fig. 2. Images of light scattering by spheres with different nominal sizes: (a) 400 nm, (b) 500 nm, (c) 600 nm, (d) 700 nm, (e) 1000 nm, and (f) 2000 nm.

then two white spots emerge when sphere size is 2000 nm. White spots become much more apparent as particle size increases. It is obvious that the white spots are caused by saturation of the detector.

Two-white-spots phenomenon presents an illusion that those who scatter light may be two particles, but in fact, only one 2000 nm sphere. We used different microscopies to determine the number of spheres that scatter light. Fig. 3a is a CCD image of light scattering from a 2000 nm sphere. Fig. 3b is an image of differential interference contrast (DIC) microscopy of the same sphere, and the size of the particle measured in this image is approximately 2000 nm. DIC

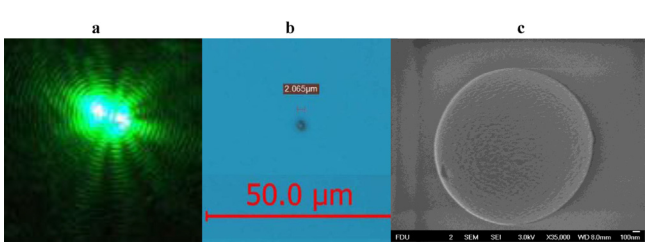

Fig. 3. Images of (a) light scattering, (b) differential interference contrast (DIC) microscopy, and (c) SEM of the same 2000 nm sphere.

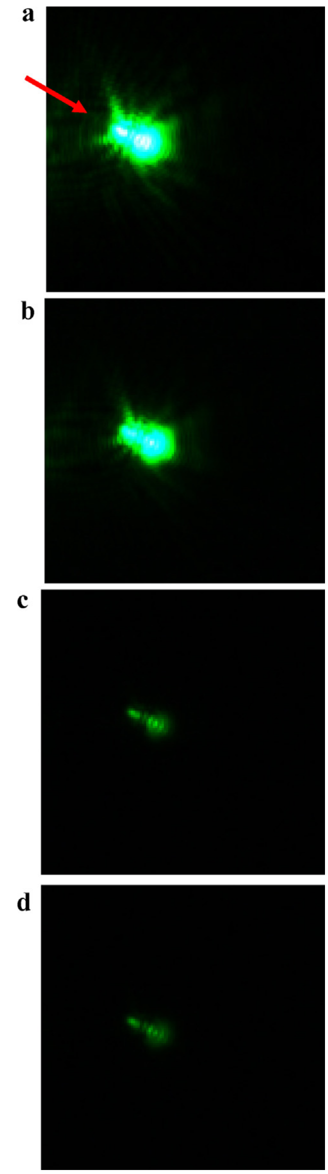

Fig. 4. Images of two white spots in light scattering by a 2000 nm sphere on a glass plate at different light intensity: (a) 100%, (b) 50%, (c) 20%, and (d) 10%. The light is incident from the left (as shown by a red arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

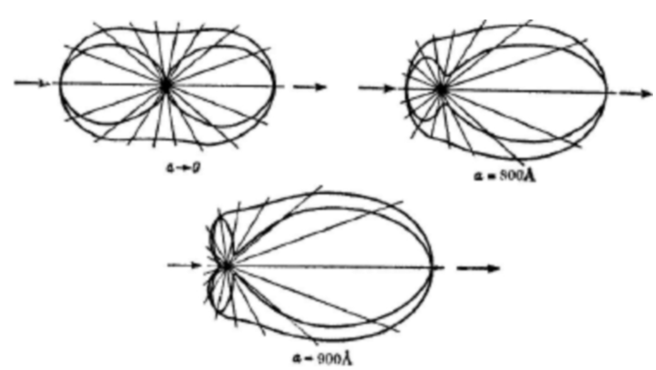

Fig. 5. Polar diagrams for the scattering of linearly polarized light by a spherical gold particle [6].

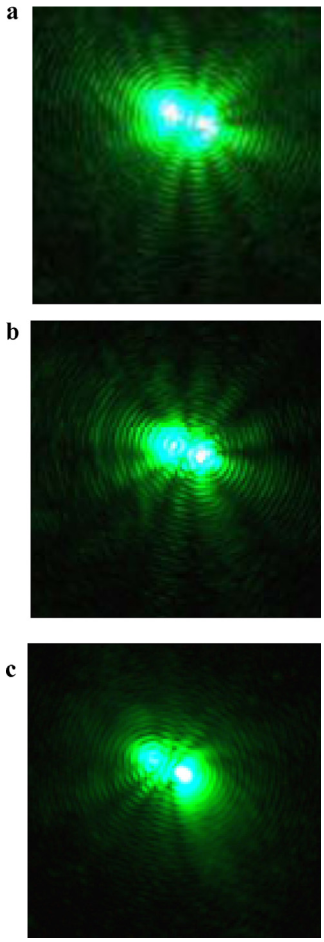

Fig. 6. Images of light scattering by a 2000 nm sphere on a glass plate at different incident angles ((a) 65°, (b) 75°, and (c) 85°) of light.

microscopy detects particles by interference of polarized light and transformation of amplitude difference into phase difference, and light scattering has no significant influence on DIC, so the sphere size measured by DIC is the correct one. Fig. 3c is a SEM image of a 2000 nm sphere. To one-to-one correspondence, we used a pen to circle the detected sphere as a mark by microscopy, and put the sample in SEM to observe. Although the area of the circle was large, we still did not find any aggregations in this circular area thanks to good dispersion of silica spheres. The DIC and SEM images reveal that the formation of two white spots arises from light scattering from just one 2000 nm sphere. Thus, two white spots are not aggregation of two or more spheres, and only one sphere with the size of 2000 nm is situated here. Two-white-spots phenomenon just gives us an illusion.

3.2. *Effect of light intensity on two-white-spots phenomenon*

Fig. 4 shows the influence of light intensity on two white spots in light scattering by a 2000 nm sphere on a glass plate. The incident angle of laser light is 75°. It should be noted that the light is incident from the left (as shown by a red arrow). As the light intensity decreases, two white spots become obscure at 50% intensity and disappear at 20% intensity. Surprisingly, two asymmetric distinct green zones appear in light scattering at 20% and 10% intensity, and the left zone (the opposite direction of light scattered) is smaller than the right one (the forward direction of light scattered), which is a strong proof of Mie effect. That is, with the increment of sphere size, there is a departure from symmetry, more light being scattered in the forward direction than in the opposite direction [6], and two asymmetric distinct zones are formed (as shown in Fig. 5). Fig. 5 is cited from reference [6], and it shows that the intensity and the unpolarized proportion of the scattered light as functions of the angle θ of observation for spheres of various sizes. It should be noted that the incident angle is 75°, and light can be divided into components parallel and perpendicular to the substrate, and Mie effect of parallel component mainly contributes to formation of asymmetric distinct zones in our experiment. Thus, we can conclude that one white spot caused by saturation of the detector is formed in each zone due to Mie effect, which is the formation mechanism of two white spots. In addition, two distinct zones in light scattering from a sphere only can be observed when the sphere size is 2000 nm in our experiment.

3.3. *Effect of incident angle of light on two-white-spots phenomenon*

Fig. 6 shows images of light scattering by a 2000 nm sphere on a glass plate at different incident angles (65°, 75°, and 85°) of light. The range of the incident angle is just from 65° to 90° because of instrument limitation. One white spot at the left of the image becomes weaker and smaller at 75° (Fig. 6b), and then disappears at 85° (Fig. 6c). The reason for this phenomenon is that there is an increase in the parallel component of the incident light as the incident angle increases, and more light is scattered in the forward direction. Thus, white spot in the zone of the backward direction first disappears due to weak light intensity. This phenomenon also can be observed in Fig. 4b.

4. Conclusion

White spots were observed in 532 nm-light scattering from a sphere on a glass plate, and they were caused by saturation of the detector. Two white spots only emerge in light scattering from 2000 nm spheres. Analysis shows that this is caused by one sphere, not by two spheres. Two white spots emerge because two asymmetric distinct zones are formed as a result of more light being scattered by larger spheres in the forward direction than in the opposite direction (Mie effect), and this provides a strong proof of Mie effect theory.

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