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随机分布多粒子侧向散射光偏振特性分析

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摘要: 为了研究随机分布的复合多粒子侧向散射光偏振度和粒子直径大小之间的关系, 采用直径 0.22μm 或0.494μm 的粒子与过滤的蒸馏水混合构成不同浓度的悬浮液, 作为研究粒子侧向散射光偏振特性散射介质的实验方法, 进行了理论分析和实验验证, 取得了直径 0.22μm 的粒子侧向散射光强在不同深度、不同角度的偏振度和直径 0.22μm 或 0.494μm 的粒子在 3 种浓度中侧向散射中水平偏振度、垂直偏振度的数据。结果表明, 粒子侧向散射光的退偏振对粒子直径的变化非常敏感, 直径小的粒子其散射光水平方向偏振度远大于直径大的粒子, 而其散射光垂直方向的偏振度却远小于直径大的粒子。这一结果对多粒子存在状况下的粒子直径检测是有帮助的(尤其适用于粒子直径小于 1μm 的情况)。

关键词: 散射; 偏振度; 激光; 多粒子

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Analysis of the polarization degree of laser radiation side-scattered by randomly distributed particles

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Abstract: In order to study the polarization property of a laser radiation side-scattered by randomly distributed particles in different diameters, various concentrations of suspending liquid, consisting of distilled water and particles in diameters of 0.22μm or 0.494μm, was served as the scattering medium. Through theoretical analysis and experiments, the data of polarization degree in different depths and at different angles scattered by 0.22μm particles were acquired, and the data of horizontal polarization and vertical polarization scattered by 0.22μm and 0.494μm particles in three different concentrations of suspending liquid were also obtained respectively. The experiment results show that the de-polarization of radiation side-scattered by the particles is very sensitive to the variation of the diameters of the particles, i. e., the horizontal polarization degree of the radiation scattered by the particles in smaller diameters is much higher than that scattered by the particles in larger diameters. However, it is inverse for the vertical polarization degree. The result is helpful to test the diameter of particles under the condition of multiple particles (especially for the particles' diameter less than 1μm).

Key words: scattering; polarization degree; laser; multiple particles

引 言

在现代科学和工程中, 由随机分布多粒子对激光产生侧向散射的研究已经得到了广泛应用[1-6]。本文实验中的散射介质是由直径 0.22μm 或 0.494μm 的粒子与过滤的蒸馏水混合构成。作者对由多粒子产生的水平散射和垂直散射进行了研究, 发现粒子的直径越小, 其散射光水平方向偏振度越大, 反之其散射光垂直方向的偏振度越小。研究结果可用于多粒子存在状况下的粒子直径检测(尤其适用于粒子直径小于 1μm 的情况)。

1 基本原理

假定一束由小直径粒子($d < \lambda$, d 为粒子直径, λ 为激光波长)产生的偏振光束, 如图 1 所示。粒子位于原点 O, 随机光束在 x-z 平面内产生偏振, $+z$ 方向是光传播方向, 方位角 φ 存在于 x-y 平面内, ψ 和 θ 分别是散射方向(OP)和 $+x$ 轴及 $+z$ 轴之间的夹角。z 轴和 OP(或 OQ)组成散射面, OQ 是 OP 在 x-y 面内

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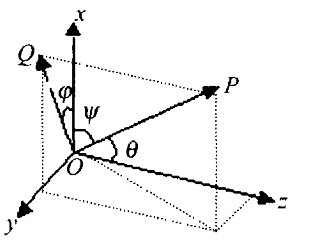

Fig. 1 Geometry expression of classic scattering

的投影。

文中讨论的情况是多种粒子共同存在状态下的散射,而非单一粒子存在的情况,因多种粒子的存在,必然会造成 x-y 平面内散射光的光强和偏振的改变,且这些改变还可能是由集中度和散射面内空间大小所导致的,根据 Mie 定理,从位于 O 处的一球形粒子散射到 P 点处的强度是:

$$I = \frac{\lambda^2}{4\pi^2 R^2}|S|^2 \quad (1)$$

式中,R 为 OP 的距离,$|S|^2 = |S_1|^2 + |S_2|^2$,$S_1$,$S_2$ 分别为 x-z 面内和 x-y 面内的散射光的幅值强度公式:

$$S_1 = \sum_{i=1}^{\infty} \frac{2i+1}{i(i+1)}[a_i\pi_i(\cos\theta) + b_i\tau_i(\cos\theta)] \quad (2)$$

$$S_2 = \sum_{i=1}^{\infty} \frac{2i+1}{i(i+1)}[b_i\pi_i(\cos\theta) + a_i\tau_i(\cos\theta)] \quad (3)$$

式中,$\pi_i(\cos\theta)$ 和 $\tau_i(\cos\theta)$ 为米氏散射理论基本角度公式,π_i,τ_i 与散射角 θ 有关,可以用 $\cos\theta$ 的勒让德和1阶缔合勒让德函数表示。a_i 和 b_i 是米氏系数。偏振度是由下式来决定:

$$p = \frac{|S_1|^2 - |S_2|^2}{|S_1|^2 + |S_2|^2} \quad (4)$$

文中随机辐射是线性偏振,在与光传播方向垂直平面内散射光的强度分布是:

$$I_t = \frac{\lambda^2}{4\pi^2 R^2}\{|S_1|^2\sin^2\varphi + |S_2|^2\cos^2\varphi\} \quad (5)$$

关注 x-y 平面,$\theta = \pi/2$,所以:

$$I_t = pI\sin^2\varphi + \frac{\lambda^2}{4\pi^2 R^2}|S_2|^2 \quad (6)$$

于是:

$$\frac{I_t(\varphi)}{I_t(\varphi = 0)} = 1 + \left[\frac{|S_1|^2}{|S_2|^2} - 1\right]\sin^2\varphi = A(\varphi) \quad (7)$$

因此,把(4)式进行简化,可定义多粒子散射时散射光的偏振度[7-12]为:

$$p = \frac{A(\varphi) - 1}{A(\varphi) - 1 + 2\sin^2\varphi} \quad (8)$$

2 实验过程

实验装置如图2所示。整个实验装置放置在光学

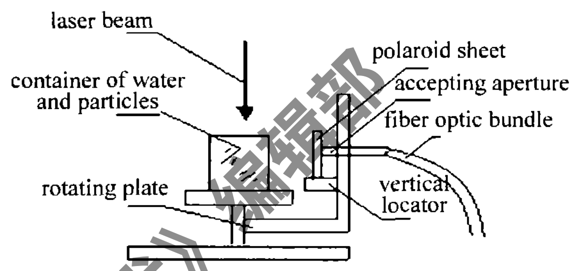

Fig. 2 Experimental setup

隔振平台上。对照图1选取坐标,激光入射方向为 z 方向,图平面为 y-z 平面,x 方向垂直纸面向外。光纤接收窗可以平行于 x-y 的平面内绕 z 轴以任意角度旋转。线偏振光(波长为0.6328μm)沿 $+z$ 轴方向垂直入射到粒子与水的混合液,偏振方向为 x 方向,混合液置于圆柱形玻璃器皿中。实验中每隔5°取1个探测点,测得粒子场在该角度处侧向散射中3种散射光强:全部散射光强,实验中不加检偏器;水平方向偏振光强,检偏器透光轴平行于 x-y 平面;垂直方向偏振光强,检偏器透光轴垂直于 x-y 平面。

3 实验结果

表1是根据(8)式估算的偏振度,就是对粒子直径为0.22um、质量分数为0.000025的粒子场侧向散射总光强相对值的退偏振估计。表中的值是在不同的角度不同的深度探测到的结果。可以看出,在每一个角度上,散射光的总光强变化不大,随深度的下降而略有降低。这充分说明复合散射的总体效果与单个粒子的散射偏振理论计算有很好的近似。

Table 1 Polarization degree of the side-scattered intensity in different depth and at different angles (for 0.22μm particles with mass fraction of 0.000025)

angle/(°)	polarization degree/(°)							
90	0.8868	0.8775	0.8585	0.8351	0.8280	0.8181	0.8000	0.7949
75	0.8914	0.8811	0.8654	0.8340	0.8199	0.8222	0.8034	0.7953
60	0.8953	0.8902	0.8742	0.8500	0.8442	0.8400	0.8285	0.8210
45	0.8965	0.8982	0.8727	0.8621	0.8397	0.8571	0.8369	0.8432
30	0.9000	0.9118	0.8888	0.8789	0.8666	0.8666	0.8521	0.8425
15	0.8972	0.9257	0.8948	0.8818	0.8816	0.8818	0.8815	0.8678
depth/cm	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5

表2～表5中分别给出两种粒子在3种质量分数的侧向散射中水平偏振和垂直偏振的偏振度。

Table 2 Horizontal polarization degree of scattered radiation (for 0.22μm particles with three mass fractions)

angle/(°)	polarization degree/(°)		
90	0.827	0.892	0.927
75	0.8308	0.8882	0.9278
60	0.835	0.895	0.929
45	0.8523	0.9111	0.9310
30	0.8466	0.9161	0.9333
15	0.8610	0.9273	0.9372
mass fraction	0.000125	0.00005	0.000025

Table 3 Horizontal polarization degree of scattered radiation (for 0.494μm particles with three mass fractions)

angle/(°)	polarization degree/(°)		
90	0.5204	0.6727	0.7392
75	0.5071	0.6758	0.7524
60	0.5268	0.6822	0.7585
45	0.5192	0.7354	0.8092
30	0.5370	0.7432	0.8322
15	0.5728	0.7920	0.8988
mass fraction	0.000125	0.00005	0.000025

Table 4 Vertical polarization degree of scattered radiation (for 0.22μm particles with three mass fractions)

angle/(°)	polarization degree/(°)		
90	0.010	0.011	0.025
75	0.0158	0.0158	0.0361
60	0.038	0.032	0.079
45	0.0825	0.1379	0.1666
30	0.2187	0.3055	0.3506
15	0.5630	0.6417	0.7112
mass fraction	0.000125	0.00005	0.000025

Table 5 Vertical polarization degree of scattered radiation (for 0.494μm particles with three mass fractions)

angle/(°)	polarization degree/(°)		
90	0.0032	0.0910	0.1200
75	0.0046	0.1011	0.3253
60	0.1620	0.2610	0.4827
45	0.3242	0.4871	0.6969
30	0.6527	0.7433	0.8684
15	0.8966	0.9303	0.9690
mass fraction	0.000125	0.00005	0.000025

4 结 论

(1)在垂直方向上，直径小的粒子的偏振度均大于直径较大的粒子。

(2)在水平方向上，直径小的粒子的偏振度均小于直径较大的粒子。

(3)水平方向上的偏振度随着散射角的变化而产生相对剧烈的变化。

(4)在实验中的质量分数范围之内(0.000125 ~ 0.000025)各种散射光强其所对应的偏振度均随浓度的减小而增大。

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