Numerical simulation and analysis on far-field scatter for micro-bubbles

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Abstract: The depolarization effect and scattering strength were simulated by CST, and far-filed scattering theory also was analyzed, linearly polarized light at the frequency of 563 THz (wavelength 532 nm, green light) was taken as the probe light. The far-field scattering filed performance of influencing factors were analyzed based on the method of finite integral of CST. Simulation result shows this new model can accurately analyze and reflect forward and backward scattering, all directions of the scattering strength and depolarization characteristics can be got in figures, these characters also affected by the bubble radius, scatter angle and water absorption coefficient. These results provides important basis for subsequent research.

Key words: absorption coefficient; linearly polarized light; detector; simulation

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微小气泡远场散射模型的仿真与分析

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摘 要: 利用商用电磁场计算软件 CST 仿真了线偏振光经过气泡散射后散射强度分布以及其退偏效应的变化,分析了气泡的远场散射理论,并利用频率为 563 THz(波长为 532 nm)的激光为入射光,在基于时域有限积分法(FDID)的基础上分析了远场散射的影响因素。仿真结果表明:这种新的仿真方法可以精确地分析和反映前向与后向散射的光强分布,以及退偏特性分布,并且这些分布特性会随气泡半径大小、散射角、水体的吸收系数的变化而变化。此结论为后续的研究提供了重要依据。

关键词: 吸收系数; 线偏振光; 探测器; 仿真

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0 Introduction

Ship wake detecting and their associated features have been extensively studied and used more and more widely, such as wake homing searching by laser, the differences characters of back scattering or forward scattering for ship wakes are utilized to guide. Therefore, the laser scattering properties of ship wakes are very important, and many researches on the optical properties and testing technology of single bubble or multiple bubbles have been studied[1-4]. Very small bubbles can survive for several hours and stretch for hundreds of kilometers, so we can detect these bubbles to track the ship.

However, the traditional simulation models have small amount of information[5-7], especially they hadn't calculated the far-field scatter. Because When the detecting distance between aim bubble and photo detector, which is always further than 20 times of wavelength (about 10 μm), so it should be better to use far-filed scatter modeling to analyze.

In this paper, far-field light scatter of wake bubbles are simulated by CST software and the linearly polarized light at the frequency of 563 THz as probe light. The far-field scattering field of effect factors such like bubbles radius, absorption coefficient (The laser could be used in the sea water for the reason of light's wavelength in the range of 450~580nm absorption is minimum, and the absorption coefficient is between 0.02~0.05 m^{-1}[8].) in the sea water are analyzed based on the method of finite integral of CST. At the same time we can also get the different characters of axial ratio and directivity for the bubbles when the angle theta is changed .This model has got more information which facilitates the analysis and the evaluation on the computing results.

1 Theoretic analysis

Mie theory is based on the Maxwell electromagnetic wave equations in the boundary conditions, which gets homogeneous spherical particle in a plane monochromatic light through strict mathematical derivation. Light along the **z** axis positive propagation the Mie coefficients $\mathbf{a}_m$ and $\mathbf{b}_m$ to compute are the amplitudes for the scattered field.

$$\mathbf{a}_m=\frac{\varphi_m(\mathbf{x})\varphi_m'(\mathbf{nx})-\mathbf{n}\varphi_m'(\mathbf{x})\varphi_m(\mathbf{nx})}{\mathbf{Z}_m(\mathbf{x})\varphi_m'(\mathbf{nx})-\mathbf{nZ}_m'(\mathbf{x})\varphi_m(\mathbf{nx})} \tag{1}$$

$$\mathbf{b}_m=\frac{\varphi_m(\mathbf{x})\varphi_m'(\mathbf{nx})-\varphi_m'(\mathbf{x})\varphi_m(\mathbf{nx})}{\mathbf{nZ}_m(\mathbf{x})\varphi_m'(\mathbf{nx})-\mathbf{Z}_m'(\mathbf{x})\varphi_m(\mathbf{nx})} \tag{2}$$

Where **n** is the refractive index of the sphere relative to the ambient medium, **x=kD** is the size parameter, **D** the radius of the sphere, $\mathbf{k}=2\mathbf{pn}_0/l$ is the wave number, and l is the wavelength in the ambient medium.

The desired quantity in this detecting of ship wake is the intensity of the far-field scattered light. Bubbles in the far-field scattering cross sections from the derivation is

$$\sigma=\frac{4\pi}{\mathbf{k}^2}(\cos^2\varphi\mathbf{s}_2(\theta)\mathbf{s}_2(\theta)^*+\sin^2\varphi\mathbf{s}_1(\theta)\mathbf{s}_1(\theta)^*) \tag{3}$$

Parallel polarized direction $\mathbf{s}_1(\theta)$ and vertical polarization direction $\mathbf{s}_2(\theta)$ of the relative light intensity are respectively scattering angle in relation to the amplitude function, expression as follows

$$\mathbf{s}_1(\theta)=\sum_{m=1}^{\infty}\frac{2\mathbf{m}+1}{\mathbf{m}(\mathbf{m}+1)}(\xi_m\mathbf{a}_m+\tau_m\mathbf{b}_m) \tag{4}$$

$$\mathbf{s}_2(\theta)=\sum_{m=1}^{\infty}\frac{2\mathbf{m}+1}{\mathbf{m}(\mathbf{m}+1)}(\mathbf{x}_m\mathbf{a}_m+\mathbf{t}_m\mathbf{b}_m) \tag{5}$$

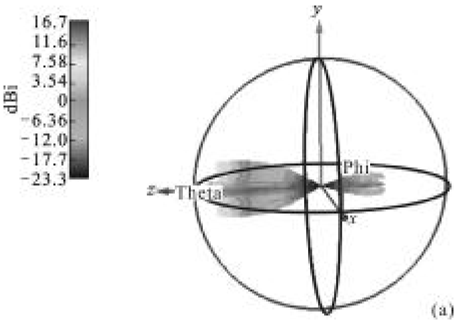
Extinction, scattering, and absorption efficiencies are expressed through scattering, amplitudes in the usual way

$$\mathbf{Q}_{sca}=\frac{2}{\mathbf{x}^2}\sum_{m=1}^{\infty}(2\mathbf{m}+1)[(|\mathbf{a}_m|^2)+(|\mathbf{b}_m|^2)] \tag{6}$$

$$\mathbf{Q}_{ext}=\frac{2}{\mathbf{x}^2}\sum_{m=1}^{\infty}(2\mathbf{m}+1)\mathrm{Re}(\mathbf{a}_m+\mathbf{b}_m) \tag{7}$$

$$\mathbf{Q}_{abs}=\mathbf{Q}_{ext}-\mathbf{Q}_{sca} \tag{8}$$

In the CST figure (Fig. 1, Fig. 2, Fig. 3) tot.effict (Total Efficiency) is theoretically equivalent to $\mathbf{Q}_{ext}$, and



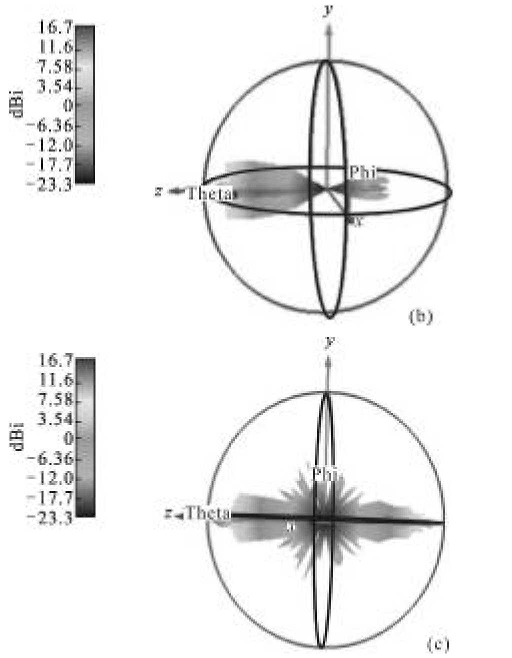


Fig.1 Radius 10 m, scatter angle theta respectively 1°, 5° and 15° for bubble in water

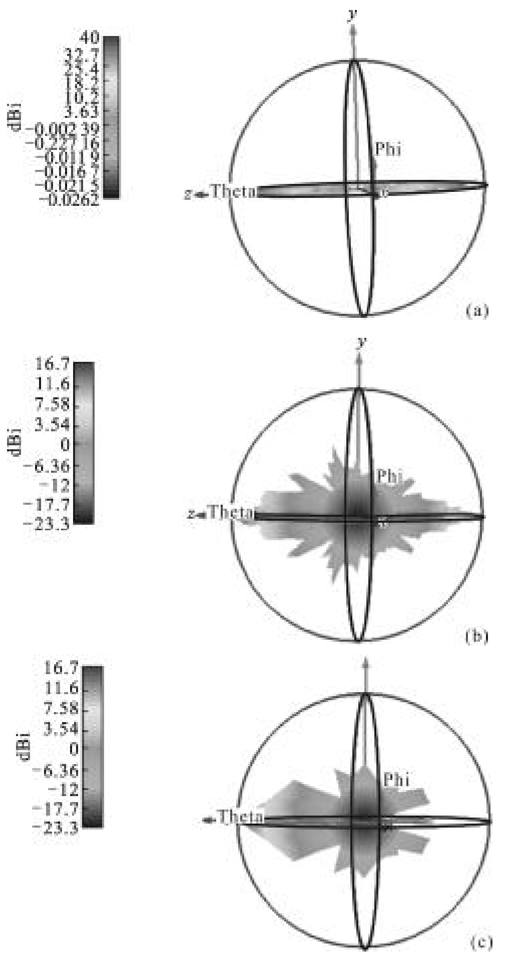


Fig.2 Respectively axial ratio of radius 5 μm, 10 μm, and 30 μm for bubble

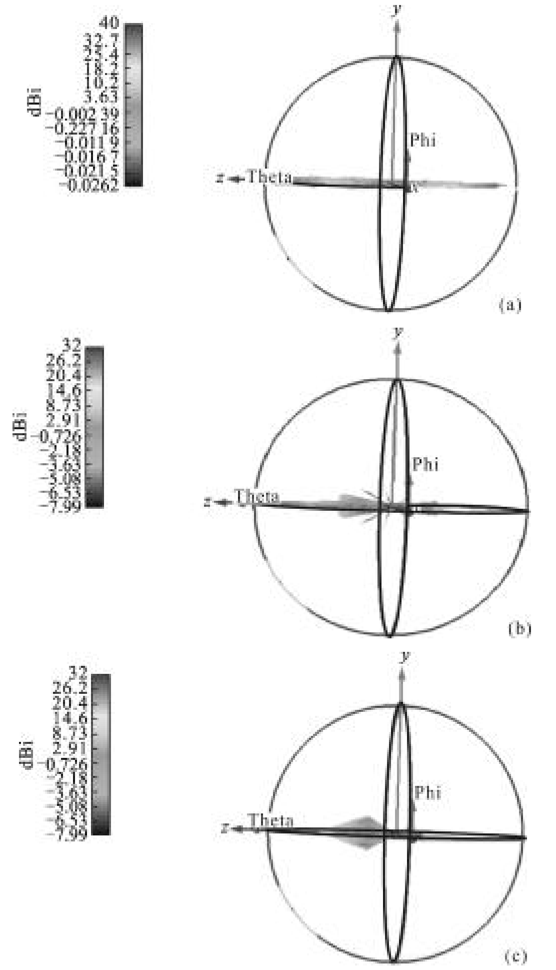


Fig.3 Respectively axial ratio of scatter angle theta 1°, 5° and 15° for bubble

rad.effic (Radiation Efficiency) is theoretically equivalent to Q_{scat}, Q_{abs} is the absorption intensity.

2 Numerical results and discussion

The scattering streng th for circularly polarized light is theoretically equivalent to natural light, and the elliptically polarized light is theoretically equivalent to the partially polarized light[9-10]. Electric field effect is the main character in the scatter strength, so the electric field effect is the same as light scatter strength; Axial ratio in figures is defined as: the ratio of the long axis to the short axis of elliptically polarized light. Theta: the theta component of the electric field $\mathbf{E}_T$. Phi: the phi component of the electric field $\mathbf{E}_P$. Radial: the radial component or the electric field $\mathbf{E}_R$. Axial ratio: following IEEE-Standard, the axial ratio is the ratio of the major axis to the minor axis of the polarization ellipse, It is calculated as follows:

$$AR=\sqrt{\frac{|E_T|^2+|E_P|^2+|E_T^2+E_P^2|}{|E_T|^2+|E_P|^2-|E_T^2+E_P^2|}} \quad (9)$$

If the laser light scattering axis ratio is 1(0dB), it is natural light, else it is partially polarized light. This proved that the CST electromagnetic wave theory is in accordance with light wave theory (Fig.4 and Fig.5).

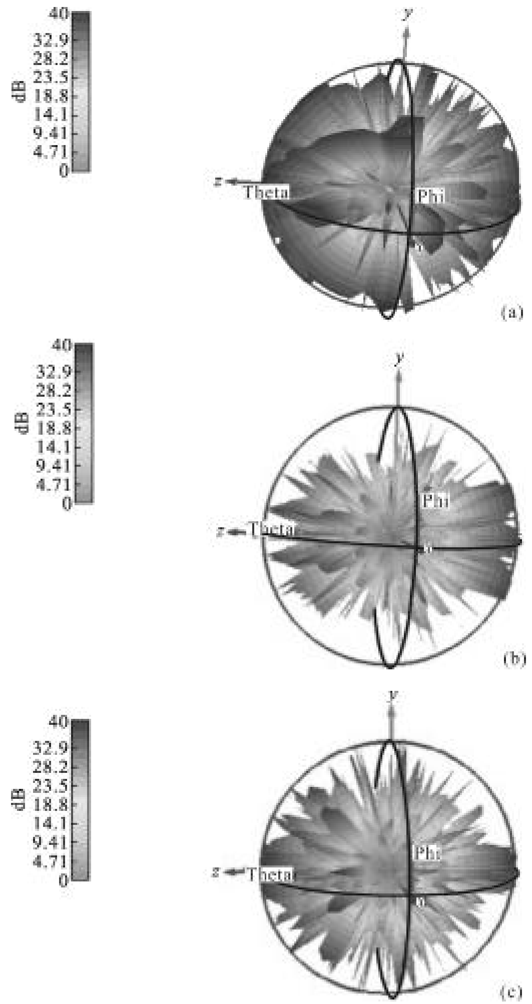
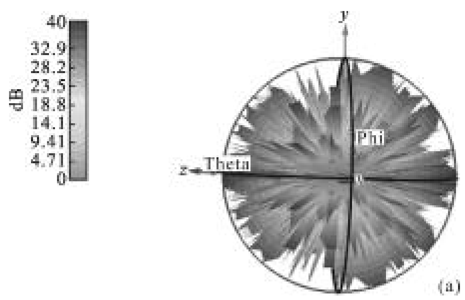


Fig.4 Respectively 0 m^{-1}, 0.005 m^{-1} and 0.03 m^{-1} absorption coefficient for bubble in sea water



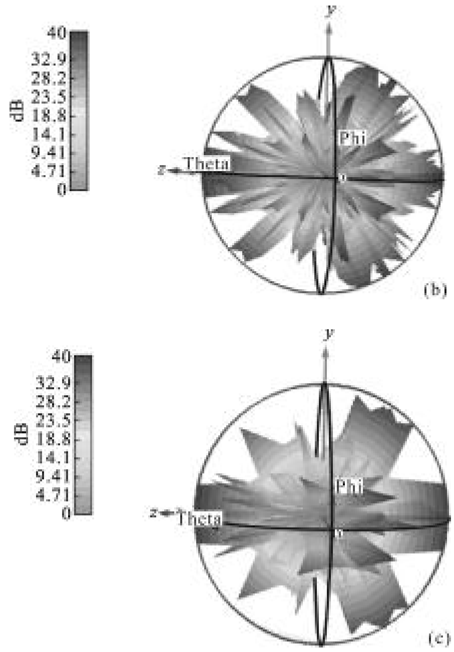


Fig.5 Radius 10 m, scatter angle theta respectively 1°, 5° and 15° for bubble in sea water

3 Conclusions

A simulation model based on CST microwave studio is presented to investigate the far-field scatter for micro-bubbles of ship wake. Through the simulations we can obtain the following conclusions.

(1) The results depend on the bubble radius and scatter angle. We can get the information from figures that forward axial ratio much more different form the backward axial ratio with the bubble radius increasing, as polarized light has strong depolarization; Simultaneous, that different scatter angle theta has different axial ratio, so signal may extracted from these characters.

(2) It is also seen in figures the radiation efficiency and directivity are not much different when absorption coefficient is changed in 0 -0.03 m^{-1} in seawater.

(3) It is observed that with different scatter angles when bubble respectably in sea water and water, the directivity are different, the results show that bubble in water directivity is higher than that in sea water, this indicates a stronger absorption

efficiency in sea water.

The results show that simulation model are very similar to real environment when bubbles are in seawater. This simulation method are much more accuracy, at the same time it is consistent with Mie Theory simulation results[11]. In this paper's research background, we need to simulate different sizes bubbles, But this time the CST software have a drawback that is with the increasing of the radius for bubbles, we need much more time to simulate it. In other words, it's more suitable for smaller bubbles or particles' simulation.

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