Study on the scattering characteristics of dual frequency laser proximity fuze

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Abstract: Laser fuze works in the near-infrared band. Due to its advantages of strong ability of resisting electromagnetic interference, high ranging accuracy and good directivity, near-infrared laser fuze has been widely used as an important type of fuze system. Obtaining the scattering characteristics of the target by analyzing the changes of the infrared light field plays an important role in improving the performance of the infrared fuze. Based on this, a novel dual frequency infrared laser fuze system was proposed. The theoretical calculation of the scattering properties of the infrared light field with different targets and analysis of the physical factors that affect the scattering phase function were carried out. The results show that when the particle size is smaller than the infrared laser wavelength, the scattered light is mainly backscattered. When the particle size is larger than the infrared laser wavelength, the main scattering light is mainly forward scattering. Therefore, a new identification method for different targets was proposed and proved the feasibility and practicability of this method.

Key words: laser fuze; Mie scattering; dual frequency laser; scattering phase function

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双频激光近炸引信散射特性研究

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摘　要: 激光近炸引信工作于近红外波段,因其具有抗电磁干扰能力强,测距精度高以及方向性好等优点作为一种重要引信体制而被广泛应用。通过分析红外光场的变化来获取目标的散射特性,对于提高激光近炸引信的性能有着重要作用,基于此提出一种双频红外激光近炸引信方案,计算了红外光场与不同尺寸颗粒目标的散射特性,并分析了影响单个粒子散射相位函数的物理因素。研究结果表明,当粒子尺度小于激光波长时,散射光主要以后向散射为主;而当粒子尺度大于激光波长时,散射光主要以前向散射为主,进而探索出了一种可用于激光近炸引信的目标识别方法,证明了该方法的可行性和实用性。

关键词: 激光引信;　Mie 散射;　双频激光;　散射相位函数

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0 Introduction

The laser fuze working in near-infrared band is a fuze using the change of infrared light field to obtain the target information. According to the formation method of the working light field, the laser fuze can be divided into two kinds: passive type and active one. The passive infrared fuze relies on a large number of infrared radiation field radiated from the target, and uses the infrared sensor of the fuze receiving system to initiate the execution level. The active infrared fuze relies on the infrared light field generated by the fuze to detect the difference of reflection between the target and the surrounding environment to control the fuze initiation. Compared with the radio fuze, the laser fuze has the advantages of good directivity, long working distance and strong ability of resisting artificial electromagnetic interference[1-4]. At present, the typical missile with infrared fuze system is French rattlesnake missile, British Pk-4 air-to-air missile and American AIM-9 air-to-air missile[5]. The bottleneck of the development of laser fuze is the high false alarm rate caused by the radiation difference in different environment and the background radiation of sun and cloud[6-7]. Therefore, it is very important to study the target characteristics of infrared light field to improve the performance of laser fuze. Fan Meng et al used the T-matrix method and general multi-particle Mie scattering method based on diffusion limited condensation theory for studying the light scattering radiation characteristics of a variety of aerosol particles at 1.6 μm and 2.0 μm bands[8]. Liu Xichuan et al studied the influence of rainfall on the attenuation of laser propagation in the atmosphere. The scattering and attenuation characteristics of raindrops in visible and near infrared bands are calculated by ray tracing method, and the effects of raindrop spectral distribution and rainfall intensity on the attenuation of laser transmission in visible and near infrared bands are discussed and analyzed.

1 Dual-frequency IR Mie scattering theory model

There are varieties of suspended particles in the atmosphere. When the laser beams pass through such inhomogeneous media, parts of them deviate from the original propagation direction. This type of scattering is closely related to the size of particles and spatial refractive index. In general, particles are often approximated as spheres in the course of research. An equivalent diameter is specified in a local range, and the scattering of light by different diameters of spherical particles is generally divided into three forms: Rayleigh scattering, Mie scattering and no selective scattering. When the particle size is far less than the laser wavelength, it is called Rayleigh scattering, which mainly refers to the atmospheric molecules to the laser scattering. When the particle size and laser wavelength are in the same order, the resulting scattering is mainly Mie scattering, and when the scale of the particle is much larger than the wavelength, it produces no selective scattering. Generally, near-infrared band is between 0.78-2.5 μm. Therefore, the Rayleigh scattering in the infrared band of the atmospheric molecule is not considered, and the scattering mechanism of the atmospheric particles, such as aerosol, smog and rain, is generally at micron level, and it is mainly Mie scattering. According to Mie scattering theory, the scattering characteristics of particles are only related to the size of the particles and the optical properties of the particles. When the light intensity $I_0(\lambda)$ parallel irradiate to a spherical particle, the classical formula of scattering intensity can be obtained:

$$I=\frac{\lambda I_0}{8\pi^2 r^2}\left[i_1(\alpha,m,\theta)+i_2(\alpha,m,\theta)\right] \tag{1}$$

where r stands for transmission distance of scattered light, i_1 and i_2 are the intensity function of scattering light in vertical direction and horizontal direction respectively, which are relevant with the function of $\alpha=\pi D/\lambda$ (D is the radii of particle), spatial refractive index m and scattering angle θ. The expression of scattering intensity function is:

$$\begin{cases} i_1(\alpha,\ m,\ \theta)=\left|S_1(\theta)\right|^2\cdot \\ \sum\limits_{n=1}^{\infty}\dfrac{2n+1}{n(n+1)}\left[a_n\,\pi_n(\cos\theta)+b_n\,\tau_n(\cos\theta)\right] \\ i_2(\alpha,\ m,\ \theta)=\left|S_2(\theta)\right|^2\cdot \\ \sum\limits_{n=1}^{\infty}\dfrac{2n+1}{n(n+1)}\left[a_n\,\tau_n(\cos\theta)+b_n\,\pi_n(\cos\theta)\right] \end{cases} \tag{2}$$

where S_1 and S_2 are complex amplitude function of scattered light, which is the infinite series composed of Bessel function and Legendre function, a_n and b_n are relevant with scale parameters and refractive index of spherical scattering particles, which is called Mie coefficient as follows:

$$\begin{cases} a_n=\dfrac{\psi'_n(m\alpha)\psi_n(\alpha)-m\psi_n(m\alpha)\psi'_n(\alpha)}{\psi'_n(m\alpha)\zeta_n(\alpha)-m\psi_n(m\alpha)\zeta'_n(\alpha)} \\ b_n=\dfrac{m\psi'_n(m\alpha)\psi_n(\alpha)-\psi_n(m\alpha)\psi'_n(\alpha)}{m\psi'_n(m\alpha)\zeta_n(\alpha)-\psi_n(m\alpha)\zeta'_n(\alpha)} \end{cases} \tag{3}$$

where

$$\begin{cases} \psi_n(\alpha)=(\pi\alpha/2)^{1/2}J_{n+1/2}(\alpha) \\ \zeta_n(\alpha)=(\pi\alpha/2)^{1/2}H_{n+1/2}^{(2)}(\alpha) \end{cases} \tag{4}$$

here, $J_{n+1/2}(\alpha)$ and $H_{n+1/2}^{(2)}(\alpha)$ are the half integer order Bessel function and the second-class Hankel function, respectively. For the expression of amplitude function, the scattering angle function π_n and τ_n are as follows:

$$\begin{cases} \pi_n(\cos\theta)=\dfrac{1}{\sin\theta}P_n^{(1)}(\cos\theta) \\ \tau_n(\cos\theta)=\dfrac{\mathrm{d}}{\mathrm{d}\theta}P_n^{(1)}(\cos\theta) \end{cases} \tag{5}$$

where $P_n^{(1)}(\cos\theta)$ stands for Legendre polynomial. Therefore, the scattering angle function is only related to the backscattering angle θ. Thus, by substituting the relevant initial value and according to the recursive relation, we can obtain a_n, b_n, π_n and τ_n, and then get the intensity of the scattering light.

The ratio of the total scattering intensity of particles to the projected cross-section of the particles in each direction in space can be expressed by scattering coefficients, and the expression is as follows:

$$Q=\frac{2}{\alpha^2}\sum_{n=1}^{\infty}(2n+1)\left[\left|a_n\right|^2+\left|b_n\right|^2\right] \tag{6}$$

The spatial distribution of the laser energy after being scattered by the particles can be characterized by the scattering phase function. For the expression of the scattering phase function in the non-polarization state[11-12]:

$$P(\theta)=\frac{i_1(\alpha,\ m,\ \theta)+i_2(\alpha,\ m,\ \theta)}{Q} \tag{7}$$

Therefore, when the wavelength of the selected incident infrared laser λ, particle size function α and the optical index of the medium m are conformed, the scattering phase function of the incident beam passing through the particles can be obtained. The dual-frequency detection system can acquire different scattering phase functions for the target in the same state, then determine the target′s state via the difference of the scattering phase function, and improve the ability of accurately identifying the target, the principle expression is as follows:

$$\Delta P(\theta)=P_2-P_1 \tag{8}$$

where P_1 and P_2 stand for scattering phase functions of different incident light waves, respectively.

2 Calculation and analysis of dual-frequency infrared Mie scattering

In order to analyze the scattering characteristics of the infrared laser beam in different environments, the simulated calculation of the common water fog particles was carried out. Table 1 is the parameters of different water fog particle sizes and the calculation of the selected infrared wavelength, n_{re} and n_{im} are the real and imaginary parts of the optical refractive index, respectively. Usually, the high transmittance of the spectral range is known as the atmospheric window in the atmosphere. The infrared band atmospheric window consists of 0.3 –1.3 μm and 1.5–1.9 μm. In this paper, the selected wavelength range 0.86 μm and 1.72 μm are in the range of atmospheric window, which can guarantee high transmittance. Besides, the choice of two wavelengths is just the frequency doubling relation. A system can be used to produce two bundles of infrared beams with different wavelengths after beam splitting in the practical application, which may reduce the cost and realize the small volume design.

Tab.1 Water mist particle parameters and wavelength selection

λ/μm	D/μm	n_{re}	n_{im}
0.86	0.5, 1.0, 2.0	1.329	2.93×10^{-7}
1.72	0.5, 1.0, 2.0	1.312	1.15×10^{-4}

According to the previous analysis, the scattering phase function represents the scattering energy in the unit stereo angle, which reflects the difference of scattering energy at different angles. Figure 1 shows that when the space particle size is 0.5 μm, the scattering phase function of the dual-frequency incident infrared beams varies with the scattering angle.

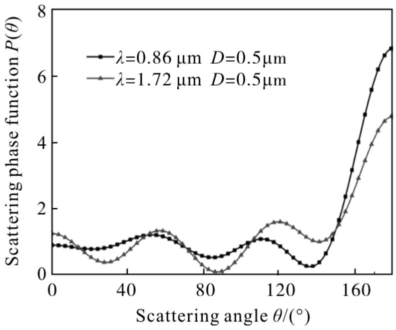

Fig.1 Scattering phase function of dual-frequency infrared beam when the particle size is 0.5 μm

The horizontal axis represents the space scattering angle, which is defined as the angle between the scattering light and the incident light. Because of the spatial symmetry, the value range is 0°–180°, and the ordinate represents the size of the scattering phase function, In general, the scattering angle near 0° is called forward scattering, and when the scattering angle approaches 180°, it is called backscattering. The infrared wavelength of the dual-frequency incident is 0.86 μm and 1.72 μm. Both of them are larger than the particle size. With the increase of the scattering angle, the scattering phase function has fluctuation and some extreme points, and most of the scattering energy is concentrated on backscattering, which indicates that most of the infrared beams can bypass the particles and leads to the dominant position of backscattering. At the same time, for the infrared spectra of different wavelengths, the infrared spectra of 0.86 μm show stronger backscattering characteristics. This means that the spectra 1.72 μm has more energy absorbed in the atmospheric window.

Figure 2 shows that when the particle scale is 1.0 μm, the scattering phase function of the particles for the dual-frequency incident infrared wave varies with the scattering angle. Since the particle scale is between two infrared wavelengths, the scattering phase function shows different characteristics with the increase of scattering angle. When the incident wavelength is 0.86 μm, the scattering energy is concentrated on the forward scattering region and the increase of oscillation reduces the trend with the increase of the scattering angle. However, the scattering energy of 1.72 μm infrared beam is mostly concentrated on the backscattering region and the forward scattering intensity is lower. As a result, when the size of the particles increases, most of the infrared beams with shorter wavelengths are reflected back, resulting in the forward scattering increase.

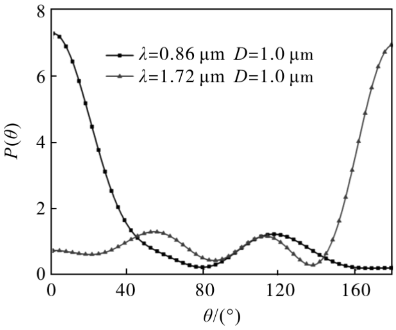

Fig.2 Scattering phase function of dual-frequency infrared beam when the particle size is 1.0 μm

Figure 3 shows the scattering phase function with the particle scale 2.0 μm varies with the scattering angle. It can be seen that when the particle size is larger than both two infrared wavelengths, the forward scattering is dominant, and the backscattering is relatively small. In addition, when the incident wavelength is 0.86 μm, the forward scattering energy is larger, which means that once the scale of the space particle increases, the wavelength 0.86 μm differs greatly from the particle size, which causes more infrared beams to be reflected by the particles and improves the forward scattering intensity of the infrared wave.

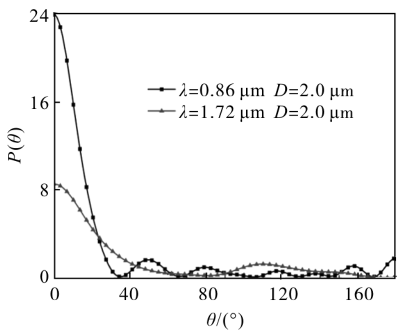

Fig.3 Scattering phase function of dual-frequency infrared beam when the particle size is 2.0 μm

Dual-frequency infrared scattering phase function curves can be determined by comparing the dual-frequency scattering phase functions at different particle scales, as shown in Fig.4. When the particle size is smaller than the wavelength (the scale is 0.5 μm), the scattering light is mainly scattered back. The difference of scattering phase function is small and oscillating in a small range. When the particle scale is between two incident wavelengths (the scale is 1.0 μm), the shorter wavelength beam is mainly scattering forward, and the longer wavelength beam is mainly backscattering. Differences in the scattering phase function change greatly in the range of forward scattering angle and backscattering angle. However, when the particle size is larger than both wavelengths (the scale is 2.0 μm), the scattering light is the mainly scattering forward. The difference of the scattering phase function changes greatly in the forward scattering stage and changes little in the subsequent scattering angle range.

Therefore, based on the different characteristics of the scattering phase function of the dual-frequency infrared laser beam at different particle scales, the spatial physical characteristics of the target can be retrieved, and the different environmental states are identified, which will help to reduce the false alarm rate of the laser fuze and enhance its scope of application.

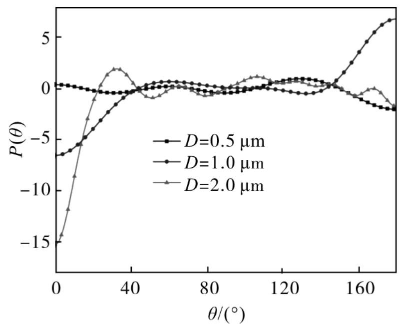

Fig.4 Variation of dual frequency infrared scattering function at different particle sizes

3 Conclusion

The forward and backscattering of the dual-frequency infrared laser beam propagating through the medium of aerosol is the result of the combination of many particles. For the complex transmission system, this paper analyzes the influence of different scale particles on the dual-frequency infrared laser fuze by using the difference of the scattering phase function of the single particle with the dual-frequency infrared beam, which is helpful to analyze the scattering characteristics of the whole system. The results show that, for different scale particles, the dual-frequency infrared laser incident beams can show different scattering characteristics, and when the particle size is smaller than the laser wavelength, the scattering light is mainly backscattering, and when the particle size is larger than the laser wavelength, the scattering light is mainly scattering forward. Therefore, according to the different characteristics of the scattering phase function of the dual-frequency infrared laser beam at different particle scales, it can be used to identify different targets, and can play an important role in improving the anti-jamming performance of laser fuze working in near infrared band.

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