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Analysis of attenuation characteristics of carbon nanofibers to 94GHz millimeter wave

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Abstract. In order to investigate the interference characteristics of carbon nanofibers to 94GHz millimeter wave, we established the corresponding electromagnetic field integral operator equation according to the conductivity and dielectric properties of carbon nanofibers, and solved the equation by the method of moments. The mass extinction coefficient of carbon nanofibers to 94GHz millimeter wave was calculated and analyzed. Lamber-Beer law was used to analyze the attenuation characteristics of carbon nanofibers smoke to 94GHz millimeter wave. The relationships between transmittance and size, conductivity, smoke concentration and smoke thickness of carbon nanofibers were obtained. The results show that the optimum conductivity of carbon nanofibers is related to their size. The longer the length of carbon nanofibers is, the smaller the diameter is, and the more significant the attenuation effect to 94GHz millimeter wave is.

1. Introduction

Millimeter wave is an electromagnetic wave between microwave and light wave. In recent decades, remarkable progress has been made in millimeter wave components and integrated circuit technology, which strongly promotes the development and application of millimeter wave technology. Current applications focus on several atmospheric 'window' frequencies, such as 35 GHz, 94 GHz, 140 GHz and 220 GHz. Compared with microwave equipment, millimeter wave radar has the advantages of wide bandwidth, narrow antenna beam, low sidelobe, strong anti-jamming ability, small size, light weight, high guidance accuracy, good tracking performance and high Doppler resolution. Compared with laser and infrared equipment, millimeter-wave radar has the advantages of lower atmospheric attenuation, stronger ability to penetrate clouds, fogs, dust and battlefield smoke in its transmission window frequency range, and can work normally under low visibility conditions such as space, rain, fog and battlefield smoke. At present, millimeter wave radar is widely used in many important civil and military fields, such as target surveillance, capture, tracking and missile terminal guidance system. In order to deal with the threat of millimeter wave detection and millimeter wave guidance weapon, all countries are actively taking the corresponding countermeasures. Due to the great technical obstacles of active countermeasures, the passive countermeasure technologies gain widely attention, but the effect of conventional passive interfering materials to millimeter wave is limited for their large size and short residence time.

Carbon nanofibers (CNFs) are a new kind of nanomaterials ^[1-3]. They are discontinuous graphite fibers prepared by pyrolysis of gaseous hydrocarbons. The diameter of CNFs is between 100nm and 500 nm, i.e. carbon nanofibers are between carbon fibers and carbon nanotubes. Carbon nanofibers have high aspect ratio, perfect graphitized structure, high strength, high elasticity, high thermal conductivity and conductivity, and have shown great potential in some aspects^[4-5]. In this paper,



according to the theory of electromagnetic field, the attenuation characteristics of carbon nanofibers to 94GHz millimeter wave are analyzed and calculated.

2. Theoretical analysis

Carbon nanofibers are different from ordinary dielectrics and have both conductive and dielectric properties. According to the theory of electromagnetic field, the integral equation satisfied by the induced current of carbon nanofibers can be obtained^[6-7].

$$\frac{1}{\pi a^2 [\sigma + j\omega(\varepsilon - \varepsilon_0)]} \cdot I(z) + j\omega\mu \int [1 + \frac{1}{k^2} \frac{\partial^2}{\partial z^2}] I(z') G(z, z') dz' = E_{iz} \quad (1)$$

Where, a is the radius of carbon nanofibers, σ is the conductivity of carbon nanofibers, and E_{iz} denotes the component of the incident field along the fiber axis.

Equation (1) is a complex operator equation, which can be solved by the method of moments (MOM)^[8-9]. Firstly, the carbon nanofibers with L length are evenly divided into N segments, the n -th segment is denoted as L_n , and the entire integral can be written as the sum of N sub-intervals. The domain representation of the induced current is as follows

$$I = \sum_{n=1}^N I_n p_n \quad n=1, 2, \dots, N \quad (2)$$

For the n -th segment L_n , $p_n=1$, while in other positions, $p_n=0$. Substitute equation (2) into equation (1), and multiply the both ends of the equation (1) by testing functions $\omega_m = \delta(z - z_m)$, then integrate it, the following equation (3) can be obtained

$$\tau \cdot \sum_{n=1}^N I_n \delta_{mn} + j\omega\mu \sum_{n=1}^N I_n \int_{L_n} [1 + \frac{1}{k^2} \frac{\partial^2}{\partial z^2}] G(z_m, z') dz' = E_{iz}(z_m) \quad m=1 \dots N \quad (3)$$

Introducing impedance matrix $Z(m, n)$

$$Z(m, n) = \tau \delta_{mn} + j\omega\mu \int_{L_n} [1 + \frac{1}{k^2} \frac{\partial^2}{\partial z^2}] G(z_m, z') dz' \quad m, n = 1, 2, \dots, N \quad (4)$$

First, the impedance matrix $Z(m, n)$ is calculated, and then the induced current can be obtained according to equation (5).

$$I = E_{iz} / Z \quad (5)$$

After calculating the induced current, the formula for calculating the scattering field of carbon nanofibers can be obtained under the far field condition^[7].

$$\bar{E}_s(r) = \hat{\theta} \frac{\eta_0}{4\pi} \frac{\exp(-jkr)}{r} \text{tg} \theta \sum_{n=1}^N I_n \{ \exp(jkn\Delta l \cos \theta) - \exp[jk(n-1)\Delta l \cos \theta] \} \quad (6)$$

Where, $\eta_0 = (\mu_0 / \varepsilon_0)^{1/2}$. According to the definition of scattering cross section C_s and absorption cross section C_a , the formulas are obtained as follows:

$$C_s = 2\pi \int_0^\pi |\bar{E}_s|^2 r^2 \sin \theta d\theta \quad (7)$$

$$C_a = \frac{\sigma \eta_0}{\pi a^2 |\sigma + j\omega(\epsilon - \epsilon_0)|^2} \sum_{i=1}^N |I_n|^2 \Delta l \quad (8)$$

The Extinction cross section is the sum of absorption cross section and scattering cross section

$$C = C_a + C_s \quad (9)$$

The attenuation of a large number of particles on electromagnetic waves is usually represented as the mass extinction coefficient, which is calculated as

$$\alpha = \frac{C}{m} \quad (10)$$

Where, m is the mass of single carbon nanofibers.

3. Extinction characteristic calculation

It is assumed that TE plane electromagnetic waves with unit amplitude incident perpendicularly to the fiber axis. Based on the idea of solving the integral equation by the method of moments, the programs for calculating the induced current and the mass extinction coefficients of carbon nanofibers was compiled by using MATLAB language. The relationships between the mass extinction coefficients of carbon nanofibers to 94GHz millimeter wave and the size of the fibers were obtained.

The length of carbon nanofibers is taken as 30 μ m. The relationship between the mass extinction coefficients and fiber diameter D is calculated as shown in Fig.1. The results show that the extinction decreases with the increase of the diameter of carbon nanofibers with diameters ranging from 100nm to 400nm. The smaller the diameter of the fiber is, the stronger the extinction of 94 GHz millimeter wave is.

The diameter of carbon nanofibers is taken as 200nm. The relationship between the mass extinction coefficients and fiber length L is obtained by calculation as shown in Fig.2. The results show that extinction increases with the increase of fiber length with length ranging from 5 μ m to 50 μ m. The longer the fiber length is, the stronger the extinction of 94 GHz millimeter wave is.

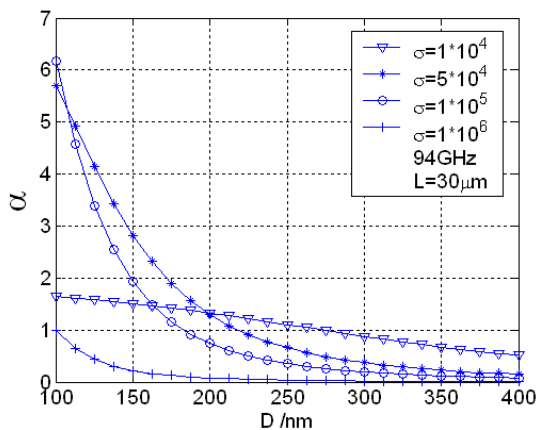


Figure 1 The relationship between mass extinction coefficient and fiber diameter

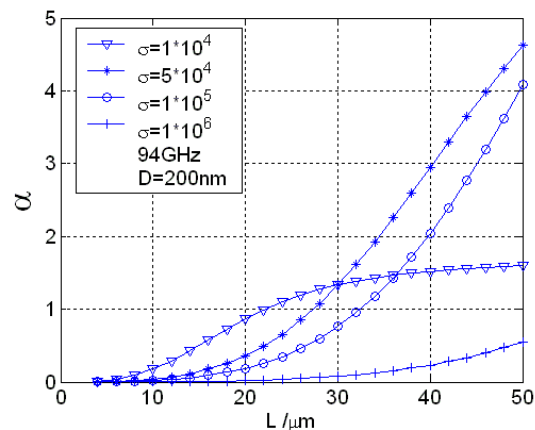


Figure 2 The relationship between mass extinction coefficient and fiber length

The results of Fig.1 and Fig.2 also show that the mass extinction coefficients are related to the conductivity of carbon nanofibers. In order to analyze the influence of the conductivity of carbon nanofibers on the mass extinction coefficient, the mass extinction coefficients of carbon nanofibers

with different sizes are calculated and the relationship between the mass extinction coefficients and the conductivity of carbon nanofibers is shown in figure 3. The results show that the mass extinction coefficients first increase with the increase of conductivity, and then decrease with the increase of conductivity after reaching a maximum value. The optimum conductivity is related to fiber size. If the diameter of the fibers is constant, the longer the fibers are, the greater the optimum conductivity is. The smaller the fiber diameter is, the larger the optimal conductivity is. As shown in Figure 3, for carbon nanofibers with length ranging from 20 μm to 50 μm and diameter ranging from 100nm to 400nm, the conductivity of carbon nanofibers in the range of $1.0 \times 10^4 \text{ S/m} \sim 7.0 \times 10^4 \text{ S/m}$ can achieve better extinction or attenuation effect for 94GHz millimeter wave.

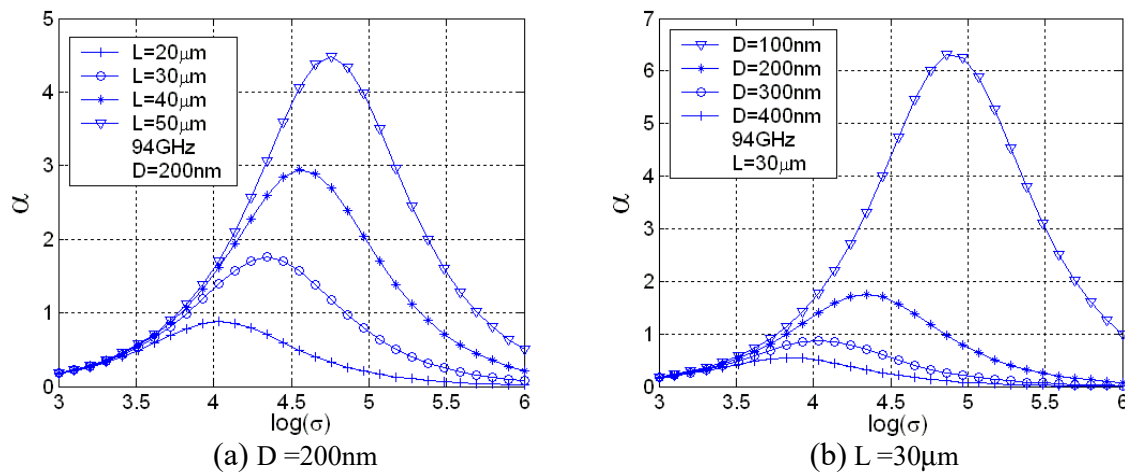


Figure 3 The relationship between mass extinction coefficient and fiber conductivity

4. Transmittance calculation

The attenuation characteristics of electromagnetic wave by carbon nanofibers smoke can be analyzed according to Lambert-Beer law. When the electromagnetic wave with intensity I_0 passes through a smoke screen with distance x (m), its transmission intensity can be expressed as

$$I = I_0 \exp(-\alpha Q x) \quad (11)$$

Where, Q is the mass concentration of smoke (g/m^3).

The transmittance is

$$T = \frac{I}{I_0} = \exp(-\alpha Q x) \quad (12)$$

According to equation (12), the transmittance of 94GHz millimeter wave through carbon nanofibers smoke can be calculated.

Setting: conductivity $\sigma=5 \times 10^4 \text{ S/m}$, diameter $D=200\text{nm}$, length $L = 20\mu\text{m}$, $30\mu\text{m}$, $40\mu\text{m}$ and $50\mu\text{m}$, smoke mass concentration $Q=0.2\text{g/m}^3$. According to the above method and equation (12), the relationship between transmittance T and carbon nanofibers smoke thickness x is calculated as shown in Fig.4.

Settings: $\sigma=5 \times 10^4 \text{ S/m}$, $L = 30\mu\text{m}$, $D = 100\text{nm}$, 200nm , 300nm and 400nm , the smoke thickness $x = 10\text{m}$. The relationship between transmittance T and mass concentration Q of carbon nanofibers smoke is calculated as shown in Fig.5.

The calculation results show that the transmittance decreases with the increase of smoke thickness, and decreases with the increase of smoke mass concentration. When the mass concentration and thickness of carbon nanofibers smoke are constant, the longer the length of carbon nanofibers is, the smaller the diameter is, and the more significant the attenuation effect to 94 GHz millimeter wave is.

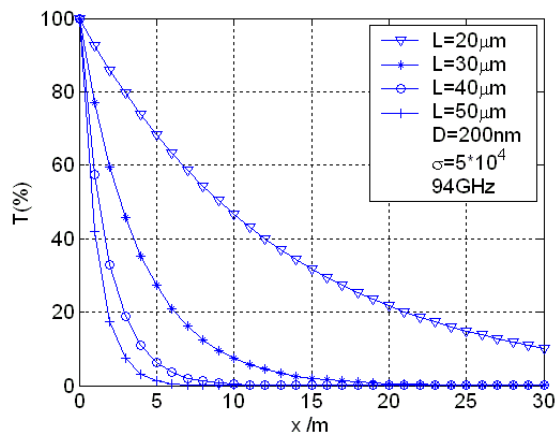


Figure 4 The relationship between transmittance and smoke thickness

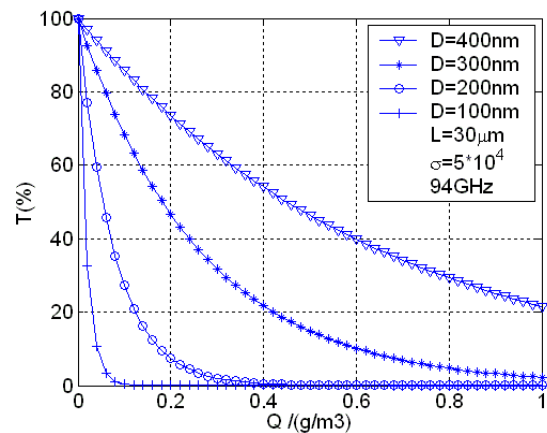


Figure 5 The relationship between transmittance and smoke mass concentration

5. Conclusions

Carbon nanofibers are small in size, light in weight and have good absorbing properties. They are expected to be used as a new generation of millimeter wave smoke jammers. In this paper, the attenuation characteristics of carbon nanofibers to 94GHz millimeter wave are analyzed by using MATLAB programming. The results show that the attenuation characteristics are closely related to the size, conductivity, smoke concentration and thickness of carbon nanofibers. The effective attenuation of 94 GHz millimeter wave can be achieved by choosing appropriate parameters of carbon nanofibers.

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