

The effect of carbon nanofibers conductivity on the extinction properties to millimeter wave

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Abstract. Carbon nanofibers is a new type of quasi one-dimensional carbon materials that has been paid more attention in recent years, and it has good conductivity which is related to the production method and process. To study the extinction properties of carbon nanofibers as interference material to millimeter wave, the integral equation of the carbon nanofibers inductive current is established based on the theory of electromagnetic field and solved by using of the Moment Method, and the formula of extinction cross-section is obtained. The effect of carbon nanofibers conductivity on the extinction capability to millimeter wave is analyzed via programming by Matlab, and the results show that the mass extinction coefficient of carbon nanofibers is closely related to its conductivity. For the millimeter wave with a certain frequency, the greater the ratio of length-to-diameter of carbon nanofibers is, the bigger the optimum electrical conductivity is. And for the carbon nanofibers with a certain size, the higher the millimeter wave frequency is, the bigger the optimum electrical conductivity is. The calculation results provide the theoretical basis for carbon nanofibers to be used as interference material to millimeter wave.

1. Introduction

Carbon nanofibers is a fibrous nano-carbon material that is curled up by layers of graphite. The diameter is approximately 50-500nm, which is between the diameter of carbon nanotubes and typical gas phase grown carbon fibers. Carbon nanofibers have not only the characteristics of carbon fibers in general gas phase, but similar to carbon nanotubes in structure, performance and application, and is characterized by low density, high conductivity, large specific surface area, strong intensity and high modulus ^[1-3]. Now carbon nanofibers has been widely used in aerospace, electromagnetic shielding materials, building materials, polymer additives, energy storage materials, catalyst carriers, anti-static materials, electromagnetic absorption materials and etc ^[4-5]. Compared to carbon nanotubes, carbon nanofibers is more easily to realize industrial production and the cost is lower. At present, there are many ways to prepare carbon nanofibers, mainly including chemical vapor deposition (CVD) ^[6], electro-spinning method ^[7] and etc. The CVD method use low-cost hydrocarbon compounds as raw materials, at a certain temperature, hydrocarbons are thermally decomposed on a metal catalyst to synthesize carbon nanofibers. The CVD method can be divided into matrix method, shower method, gas phase flow catalyst method, and plasma chemical vapor deposition method according to the dispersion state and the catalyst type. Electro-spinning is a method of flowing a charged solution or melt in an electrostatic field and evaporating or solidifying the melt by cooling to obtain a fibrous material. In general, polyacrylonitrile (PAN) is used as a raw material to prepare nanometer PAN raw filaments by using electro-spinning technology. In combination with the traditional carbon fiber manufacturing method, precursor filament is pre-oxidized and carbonized under certain temperature



and protective gas conditions respectively, to obtain carbon nanofibers.

Considering the characteristics of small size, low density and long residence time in the air, carbon nanofibers is expected to be the new generation of passive confrontation materials to millimeter wave. Therefore, it is of great significance to theoretically analyze the extinction properties for carbon nanofibers to millimeter-waves. The electrical conductivity of carbon nanofibers whose value is roughly in the range of 10^4 - 10^6 S/m, and specifically related to the production method and process, is an important parameter affecting the extinction effect [8]. In this paper, the integral equation of the carbon nanofibers induced current is deduced according to the theory of electromagnetic field, and solved by the moment method. The influence of the conductivity of nanofibers on the extinction characteristics to millimeter wave is calculated and analyzed

2. The establishment of integral equation and moment method

The electromagnetic wave is irradiated on any particle, and the distribution of the field inside the particle and the outside scattering field is related to the induced current of the particle. If the induced current distribution is obtained, the scattering and the inside field distributions of particles can be obtained thereby, so that the scattering and absorption characteristics of the particles can be analyzed. For the ideal conductor, a variety of inductive current integral equations have been established. The carbon nanofibers is a well-conducting medium, but the electromagnetic field boundary conditions on its surface are different from those of the ideal conductor. In the following, the integral equation of the unknown induced current of carbon nanofibers is deduced and solved by the moment method^[9-11].

For the fine carbon nanofibers, due to the axial symmetry, the current in the axis can be replaced by the total induced current I , and the length direction is the Z axis. The scattering field generated by this current is ^[12]

$$\vec{E}_s(\vec{r}) = -j\omega\mu \int [1 + \frac{1}{k^2}\nabla^2] I(z') G(\vec{r}, z') dz' \quad (1)$$

where $G(\vec{r}, z') = \frac{\exp(-jk|\vec{r} - \vec{z}'|)}{4\pi|\vec{r} - \vec{z}'|}$ is Green function. The total induced current of the carbon nanofibers affected by the external field is

$$I(z) = \pi a^2 [\sigma + j\omega(\varepsilon - \varepsilon_0)] E_{nei} \quad (2)$$

where the induced current $I(z)$ is unknown, a is the radius of carbon nanofibers, and σ is the electrical conductivity of carbon nanofibers. Thus, the relationship between internal field and carbon nanofibers inductive current can be described as

$$E_{nei} = \frac{I(z)}{\pi a^2 [\sigma + j\omega(\varepsilon - \varepsilon_0)]} \quad (3)$$

The boundary conditions of electromagnetic field are used to get the integral equation of induced current. In the fine fiber boundary surface, the electric fields are continuous along the tangential direction, that is, the electric fields inside and outside the material are equal in the Z direction, and the external field consists of the incident field and the scattered field. The boundary conditions are

$$E_{nei} = E_{iz} + E_{sz}|_{\text{surf}} \quad (4)$$

where E_{iz} and E_{sz} are the axial components of incident field and scattering field respectively.

Substitute equation (1) and (3) into equation (4), then we can get

$$\tau \cdot I(z) + j\omega\mu \int [1 + \frac{1}{k^2} \frac{\partial^2}{\partial z'^2}] I(z') G(z, z') dz' = E_{iz} \quad (5)$$

where $\tau = \{\pi a^2 [\sigma + j\omega(\varepsilon - \varepsilon_0)]\}^{-1}$.

Equation (5) is the integral equation of carbon nanofibers inductive current and can be solved by the Moment Method.

Suppose vertical incidence of a unit amplitude TE plane electromagnetic wave, firstly, divide carbon nanofibers with length L into N segments evenly and each has a length of $\Delta l = L/N$. The n -th segment is denoted as L_n , and the entire integral can be written as the sum of N sub-intervals. The sub-domain representation of inductive current is

$$I = \sum_{n=1}^N I_n p_n \quad n=1, 2, \dots, N \quad (6)$$

where

$$p_n = \begin{cases} 1 & \text{in the } n\text{-th segment } L_n \\ 0 & \text{in other positions} \end{cases} \quad (7)$$

Substitute equation (6) into equation (5), multiply the both ends of the equation by testing functions $\omega_m = \delta(z - z_m)$, then integrate it, and it can be got that

$$\tau \cdot \sum_{n=1}^N I_n \delta_{mn} + j\omega\mu \sum_{n=1}^N I_n \int_{L_n} [1 + \frac{1}{k^2} \frac{\partial^2}{\partial z^2}] G(z_m, z') dz' = E_{iz}(z_m) \quad m=1 \cdots N \quad (8)$$

where function δ_{mn} is 0 when $m \neq n$ and 1 when $m = n$.

According to equation (8), the impedance matrix can be obtained

$$Z(m, n) = \tau \delta_{mn} + j\omega\mu \int_{L_n} [1 + \frac{1}{k^2} \frac{\partial^2}{\partial z^2}] G(z_m, z') dz' \quad m, n = 1, 2, \dots, N \quad (9)$$

After obtaining the impedance matrix, the inductive current can be obtained from the following equation (10)

$$I = E_{iz} / Z \quad (10)$$

After the inductive current I is obtained, the scattering field and the internal field distribution can be obtained by substituting (6) into (1) and (3) respectively.

3. The mass extinction coefficient of carbon nanofibers

According to the definition of scattering cross section, for the incident wave of unit amplitude, the scattering cross section are calculated as

$$C_s = 2\pi \int_0^\pi |\bar{E}_s|^2 r^2 \sin \theta d\theta \quad (11)$$

The absorbing cross section can be expressed as

$$C_a = \int_V k_0 \varepsilon_r'' |\bar{E}_{nei}|^2 dV \quad (12)$$

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

$$C = C_a + C_s \quad (13)$$

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

$$\alpha = \frac{C}{m} \quad (14)$$

where m is the mass of single carbon nanofibers.

4. Numerical calculation results

According to the idea of solving the integral equation by the moment method, program to calculate carbon nanofiber induced current, inner field and scattering field was written by using Matlab, and the influence of the electrical conductivity of carbon nanofibers on the mass extinction coefficient to millimeter wave was analyzed.

Figure 1 depicts the change of mass extinction coefficients along with the wavelength of millimeter wave, the carbon nanofibers length $L = 20\mu\text{m}$, diameter $D = 100\text{nm}$, the conductivity is $1 \times 10^4 \text{ S/m}$, $1 \times 10^5 \text{ S/m}$ and $1 \times 10^6 \text{ S/m}$ respectively. Obviously, when the electrical conductivity of carbon nanofibers is different, the change of mass extinction coefficient with the wavelength of millimeter wave is not the same. The attenuation performance of carbon nanofiber to millimeter wave is closely related to the electrical conductivity. The extinction properties of carbon nanofiber with wavelength of 1-4mm and electrical conductivity of $1 \times 10^5 \text{ S/m}$ are better than that of the other two carbon nanofibers. When the wavelength is greater than 4mm, the extinction performance of carbon nanofibers with electrical conductivity of $1 \times 10^4 \text{ S/m}$ is the best of the three.

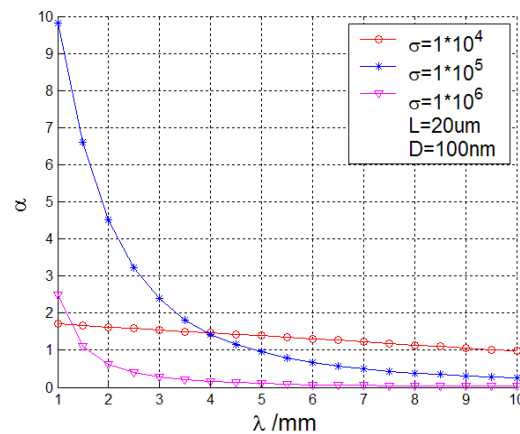
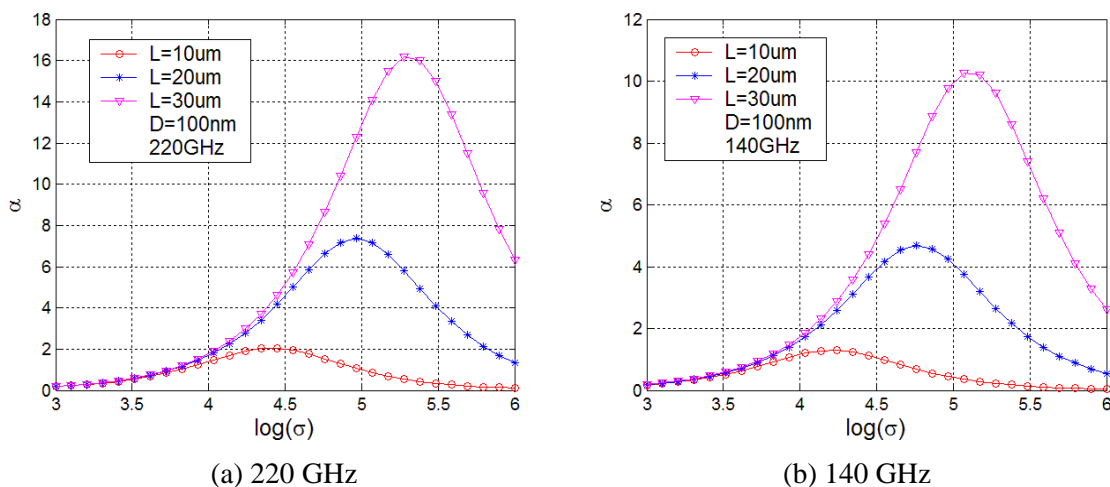
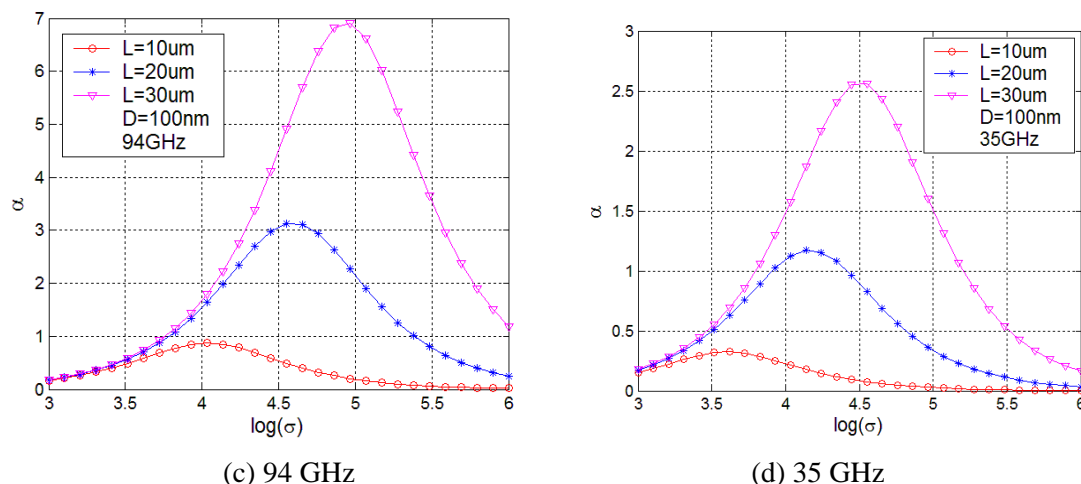


Figure 1 The relationship between mass extinction coefficient and wavelength



(a) 220 GHz

(b) 140 GHz



(c) 94 GHz (d) 35 GHz
Figure 2 The relationship between mass extinction coefficient and conductivity

Figure 2 shows the change of mass extinction coefficient with the electrical conductivity of carbon nanofibers at different millimeter wave atmosphere window (220 GHz, 140 GHz, 94 GHz and 35 GHz) when diameter D is the same but length L is different.

It can be seen that when the fiber diameter is constant, the optimum electrical conductivity is related to the fiber length and frequency. When the millimeter wave frequency (or wavelength) and the fiber diameter are constant, the longer the fiber length is, the greater the optimum electrical conductivity is. When the size of carbon nanofibers is constant, the higher millimeter wave frequency is, the greater corresponding optimum electrical conductivity is.

5. Conclusions

Carbon nanofibers is a new type of absorbing materials and is expected as a new generation of millimeter smoke screen interfering agent. According to the conductive and dielectric properties of carbon nanofibers, the corresponding integral equation of electromagnetic field was established and solved by the moment method. The relationship between the mass extinction coefficient and the electrical conductivity of carbon nanofibers was calculated by Matlab program. The results show that the millimeter wave mass extinction coefficient of nanocarbon fiber is closely related to its conductivity. In order to improve the effect of carbon nanofibers interference millimeter wave, when producing carbon nanofibers interference material, a proper process should be adopted to control the electrical conductivity of carbon nanofibers in the optimal value range.

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