



Microwave Dielectric Characteristics of Single-walled Carbon Nanotubes

Xiaolai Liu & Qinghui Li

Department of Physics and Electronic Science

Beijing University of Chemical Technology

Beijing 100029, China

Donglin Zhao

Education Ministry Key Laboratory of Science and Technology of Controllable Reactions

Institute of Carbon Fiber and Composites

Beijing 100029, China

E-mail: liuxl1@mail.buct.edu.cn

Abstract

In this article, we studied the microwave permittivity of the complex of the single-walled carbon nanotubes and paraffin in 2-18GHz. In the range, the dielectric loss of single-walled carbon nanotubes are higher, and the real part and the imaginary part of the dielectric constant decrease with the increase of frequency, and the dielectric constant possesses the property of dispersion frequency response. The ϵ' , ϵ'' and $\tan\delta$ of the complex of the single-walled carbon nanotubes and paraffin increase with the increase of the content of carbon tubes, and it presents good second-order function relationship with the volume fraction of carbon in certain range. The polarization dispersion dielectric response is the main reason that the single-walled nanotubes absorbs and wastes microwaves.

Keywords: Single-walled carbon nanotubes, Microwave permittivity, Microstructure, Microwave absorption

1. Introduction

Since Iijima found the carbon nanotubes in 1991 (S. Iijima, 1991, P.56), the carbon nanotubes have been broad concerned by people, and it has been the research hotspot in many scientific domains such as chemistry, physics, and material science. There are many methods such as graphite electric arc method (DC electric arc method), catalytic crack method, laser evaporation graphite rod method, pyrolytic polymer method, flame method, ion (electron beam) radiation method, electrolysis method and model carbonization method to be used to prepare nanotubes (G, Ya, Slepyan, 2001, P.121-123, Bachtold A, 2001, P.1317, Tans SJ, 1998, P.49, Wagner HD, 1998, P.188, Planeix JM, 2001, P.1447, Cheng HM, 2001, P.1317, Service RF, 1998, P.940, John W, 2003), and the method which takes Fe, Co, Ni and other metals as activators and catalyze and crack the hydrocarbon to prepare the carbon nanotubes make the industrialization production of carbon nanotubes possible. Various forms and structures of carbon nanotubes make the nanotubes possess many potential applied values, for example, it can be used in the strengthening of materials, one-dimensional quanta lead, semiconductor materials, activator carrier, molecule absorbent, tunnel scanning and the detector of the atom force microscope. The carbon nanotubes have many characters such as small tube diameter and big length-diameter ratio, and the diameter is in tens nanometers, and the axial length of the tube is on the level from micron to centimeter, and it is the thinnest fiber material, and this sort of special structure makes the carbon nanometer possess excellent mechanical performance and special electric performance, and the experiment shows that the Yong modulus of single multiple layers nanotubes averagely are 1.8TPa, and the curve intensity can achieve 14.2GPa (J, A, Roberts, 2004, P.4352-4356), and because the carbon nanotubes are the one-dimensional material with hollow structure, so we can utilize the capillary phenomenon of carbon nanotubes to fill some elements into the interior of the carbon nanotubes and make the one-dimensional quanta line with special performance (K, G, Ong, 2002, P.82, C, Bower, 2002, P.3820, Zhao D L, 2001, P.2471). In a word, the preparation and application of carbon nanotube shave been implemented for a long time, and in recent years, the research about the complex material of carbon nanotubes have been one hotspot of the carbon nanotubes applicaiton, and there are few researches about the microwave permittivity of carbon nanotubes, especial for the single-walled carbon nanotubes and the function relationship between the effective dielectric constant of single-walled carbon nanotubes and the volume fraction of carbon nanotubes. In this article, we study the change rule of the dielectric constant of single walled carbon nanotubes and paraffin complex with the volume fraction and frequency

of carbon nanotubes in 2-18GHz, which will offer references for the application of single-walled carbon nanotubes in the absorbing materials.

2. Experiment

The single-walled carbon nanotubes used in the experiment is made by Shenzhen Nanotech Port Co., Ltd, and the diameter of the single-walled carbon nanotubes are less than 2nm, and length is in 5-15 μ m, and the specific surface area is 450-600m²/g. We use the coaxial line method to measure the dielectric constant of the single-walled carbon nanotubes in the frequency range of 2-18GHz, and the type of the network analyzer is HP8722ES. The preparation process of the dielectric constant testing sample of single-walled carbon nanotubes are that putting the single-walled carbon nanotubes dispersed in the melting paraffin evenly, and casting the liquid compound of paraffin and single-walled carbon nanotubes into the copper loop standard flange, and testing the dielectric constants of the complex with the flange after solidification to eliminate the testing error induced by the gap between sample and flange. And the contents of single-walled carbon nanotubes respectively are 5wt%, 8wt%, 10wt%, 15wt% and 20wt%.

3. Results and discussions

The function between the microwave and the agglomeration matter can be described by the complex dielectric constant ϵ^* ($\epsilon^* = \epsilon' - i\epsilon''$, ϵ' is the real part of the dielectric constant, and ϵ'' is the imaginary part) and the complex electrical conductivity σ^* . And the relationship between the real part $\sigma'(\omega)$ of the electrical conductivity and the imaginary part $\epsilon''(\omega)$ of the complex dielectric constant is $\sigma'(\omega) = \omega \epsilon''(\omega)$, where, ω is the angle frequency of the electromagnetic wave (K, G, Ong, 2002, P.82, C, Bower, 2002, P.3820, Zhao D L, 2001, P.2471, A, K, Jonscher, 1983, P.138, P, Debye, 1945, P.257, E, Mouchon, 1996, P.323, Liu, Xiaolai, 2005, P.721, A, K, Jonscher, 1983, P.13). Most researchers mix the measured samples with the paraffin to test the electromagnetic parameters of the complex (Zhao D L, 2001, P.2471, A, K, Jonscher, 1983, P.138, P, Debye, 1945, P.257, E, Mouchon, 1996, P.323).

Because the specific surface area of the single-walled carbon nanotubes are very large, and it is hard to be compacted, so we can not exactly measure the microwave dielectric constant of the pure single-walled carbon nanotubes. In this article, we studied the change rule of the dielectric character of single-walled carbon nanotube and the paraffin with the content of the carbon nanotubes, and researched the dielectric character of the samples with five different contents (5wt%, 8wt%, 10wt%, 15wt% and 20wt%) in 2~18GHz, and the real part and imaginary part of the dielectric constant of the paraffin used in the experiment were constants, i.e. $\epsilon' = 2.26$ and $\epsilon'' = 0$. Figure 1, Figure 2 and Figure 3 respectively show the change curves of the dielectric constants of the complex with different single-walled carbon nanotubes and paraffin (ϵ' and ϵ'') and the dielectric waste angle tangent ($\text{tg}\delta = \epsilon''/\epsilon'$) with the frequency. We can see that with the increase of the content of single-walled carbon nanotubes, the ϵ' , ϵ'' and $\text{tg}\delta$ of the complex gradually increase, and with the increase of the frequency, ϵ' and ϵ'' gradually decrease, and it possesses obvious frequency response property, which is very beneficial to enhance the absorbing performance of absorbing materials in the wide frequency range.

The research about the complex electromagnetic property is an old and active topic (Liu, 2005, P.721, A, K, Jonscher, 1983, P.13, J, C, M, Garnett, 1904, P.385, J, C, M, Garnett, 1904, P.237, A, H, Sihvola, 1998, P.420, K, Bober, 1997, P.101, G, F, Dionne, 1976, P.1708), and J.C. Maxwell Garnett deduced the famous effective medium formula which was used to solve the complex dielectric constant in 1904, i.e. the Maxwell Garnett formula (A, K, Jonscher, 1983, P.13, J, C, M, Garnett, 1904, P.385). With the development of science and technology, many microwave apparatus, especially for the microwave absorbing materials developing from stealth technology, all need the materials with special electromagnetic property, but single material could not fulfill these special requirements, so we need prepare complex materials to implement these objectives, and though researches try to look for a sort of mathematical theoretical model to compute the microwave electromagnetic parameters of complex materials all along, but they could not establish a sort of general theoretical model (G, F, Dionne, 1976, P.1708).

The effective dielectric function of complex material is generally obtained by experiment and test or the establishment of proper mathematical model, and the later has important function in the material design, but up to now, there is not very satisfactory model, so researchers still try to find the optimal model all along. Bober et al (G, F, Dionne, 1976, P.1708) used Maxwell Garnett formula to respectively compute the complex dielectric constant and complex permeability for the complex materials which are respectively composed by resin with nickel zinc ferrite, mangan zinc ferrite, Sr ferric oxide and graphite in 10GHz, and they found the Maxwell Garnett effective medium formula could approximately compute ϵ' for the complex material of nickel zinc ferrite and resin, but obvious warp would occur in ϵ'' , μ' and μ'' , and ϵ' , ϵ'' , μ' and μ'' all had very large warps in other sorts of complex material. Boner's study result also indicated that the dielectric constant (ϵ' and ϵ'') and permeability (μ' and μ'') of the complex materials which are respectively composed by resin with nickel zinc ferrite, mangan zinc ferrite, Sr ferric oxide and graphite and the volume fractions of ferrite and graphite accorded with the second-order multinomial relationship (ϵ' , $\epsilon'' = Av^2 + Bv + C$). Dionne et al studied the dielectric constants of the complex of rutile ($\epsilon' = 100$), anatase ($\epsilon' = 48$) and paraffin, and found that the warp would occur between measured value with computation value of Maxwell Garnett formula. Above research results indicate the Maxwell Garnett effective medium formula is not fit to compute the dielectric constant and permeability of

the microwave complex materials.

From above discussions, we can see that we should look for other methods to compute the dielectric constant of the complex materials composed by single-walled carbon nanotubes with different materials in the frequency band of microwave. Our research indicated that the dielectric constant measured value of the complex materials with different single-walled carbon nanotubes contents had very good fitting relationship with the volume fraction of nanometer powder, and ϵ' and ϵ'' with the volume fraction of nanometer powder accord with the second-order multinomial relationship (ϵ' , $\epsilon''=Av^2+Bv+C$). Figure 4 and Figure 5 respectively are the second-order function curves of ϵ' and ϵ'' which are obtained by the fitting of dielectric constant measured value in 10GHz for the complex of single-walled carbon nanotubes with paraffin with the volume fraction of nanometer powder (v). From the figures, we can see that $\epsilon'=-39.444v^2+214.531v-7.717$, $r^2=0.9999$, $\epsilon''=2049.436v^2-283.591v+11.011$, $r^2=0.9929$, and they possess very good fitting relationship.

The researches also indicate that when the content of single-walled carbon nanotubes are in 5wt%-20wt%, and in the frequency range from 2GHz to 18GHz, for different frequency testing sites, good second-order function relationship among ϵ' , ϵ'' and v , and the coefficients A, B and C are different with the change of frequency. This research result is very important for the optimal design utilizing single-walled carbon nanotubes and their polymer complex for the single narrow frequency, multiple frequencies and wide frequency absorbing wave.

In the single-walled carbon nanotubes give priority to the sp² hybridization structure with carbon atom hexagonal close array, and the hybridization orbit presents electric moment, and the π electron bond energy is small, and its combination force with atom is weak, and the effective quality is small and it presents high speed move and super polarization property, and in the alternation electric field function of microwave, the turning polarization of electric moment forms, and with the increase of frequency, the turning polarization of electric moment gradually trails the change of the exterior field, so this sort of polarization will decrease with the increase of frequency. In the turning process of electric moment, the energy loss will occur because of the non-elasticity mutual function with surrounding particles, and the move will trail the electric field, so the polarization dispersion dielectric response is the main reason that the single-walled nanotubes absorb and waste microwaves.

4. Conclusions

(1) The dielectric loss of single-walled carbon nanotubes are higher in the microwave frequency range of 2-18GHz, and the real part and the imaginary part of the dielectric constant will decrease with the increase of the frequency, and the dielectric loss angle tangent increases with the increase of frequency, and it possesses the property of polarization dispersion dielectric response.

(2) In the single-walled carbon nanotubes give priority to the sp² hybridization structure with carbon atom hexagonal close array, and the hybridization orbit presents electric moment, and the π electron bond energy is small, and its combination force with atom is weak, and the effective quality is small and it presents high speed move and super polarization property, and in the alternation electric field function of microwave, the turning polarization of electric moment forms, and the polarization dispersion dielectric response is the main reason that the single-walled nanotubes absorb and waste microwaves.

(3) In the microwave frequency range of 2-18GHz, the ϵ' and ϵ'' of the complex of single-walled carbon nanotubes with paraffin have significant independence relationship with the content of single-walled carbon nanotubes, and in the 5%-15% of the single-walled carbon nanotube content, the ϵ' and ϵ'' have good second-order function fitting relationship with the volume fraction of single-walled carbon nanotube, i.e. ϵ' , $\epsilon''=Av^2+Bv+C$.

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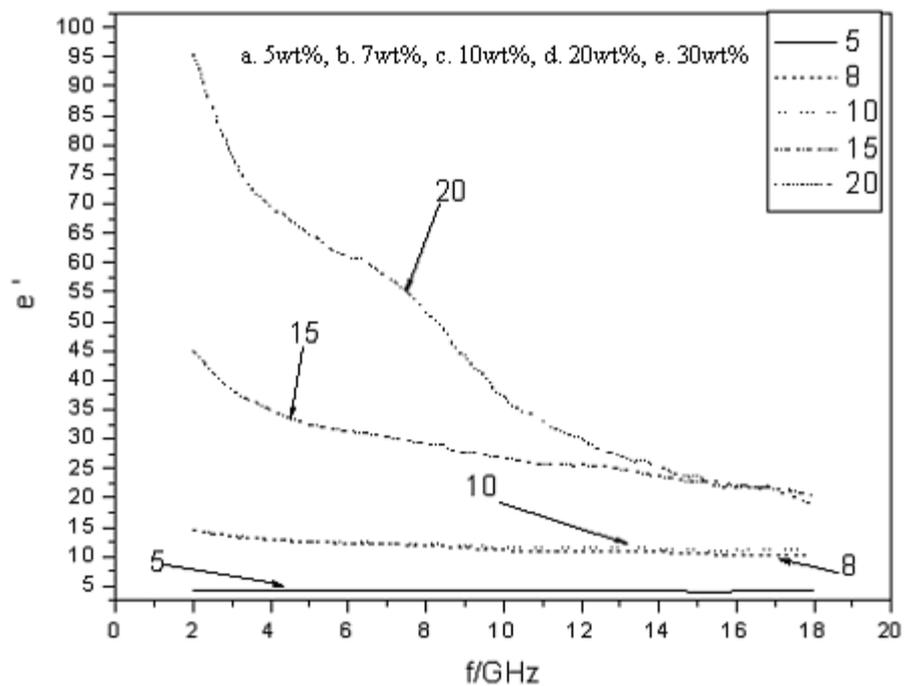


Figure 1. Relationship between ϵ' and frequency

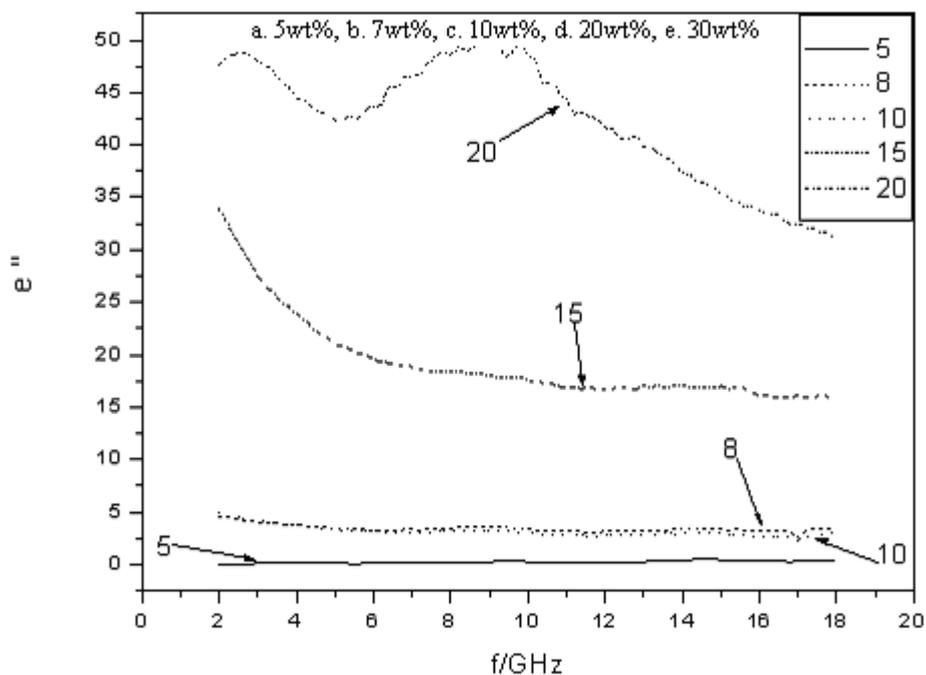


Figure 2. Relationship between ϵ'' and frequency

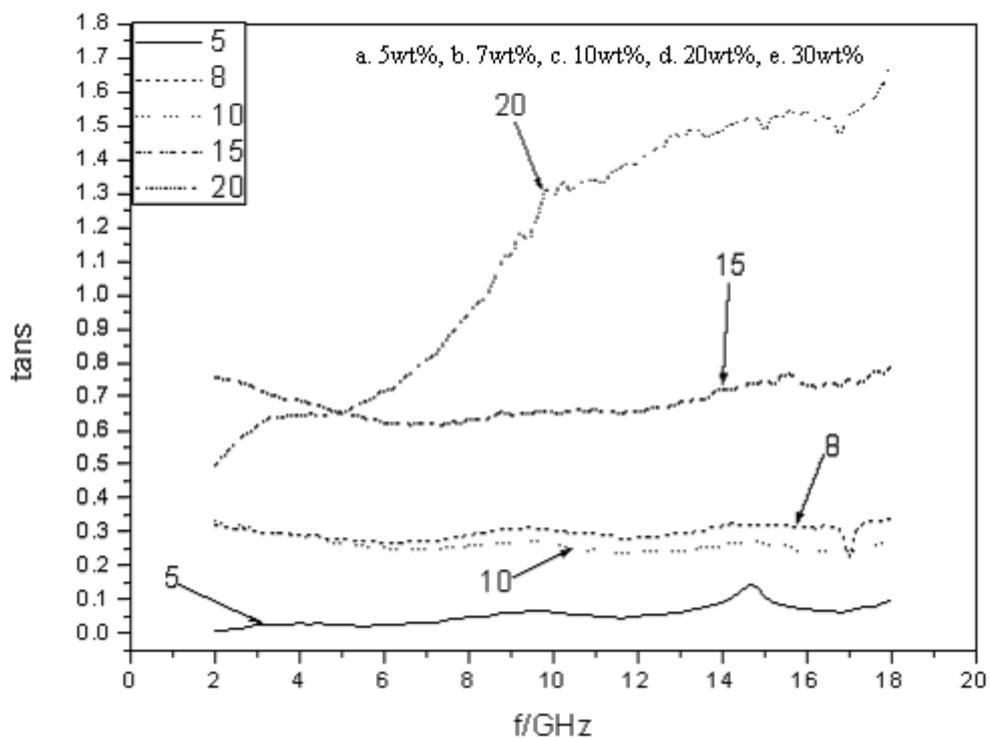


Figure 3. Relationship between $\text{tg}\delta$ and frequency

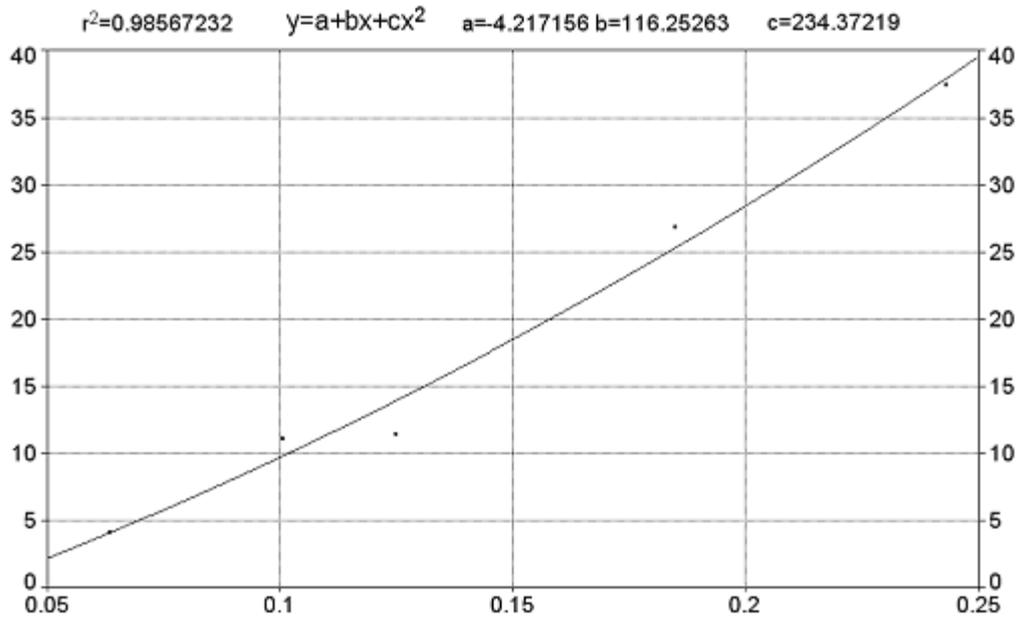


Figure 4. Relationship between ϵ' in 10GHz and nanometer power volume fraction (v)

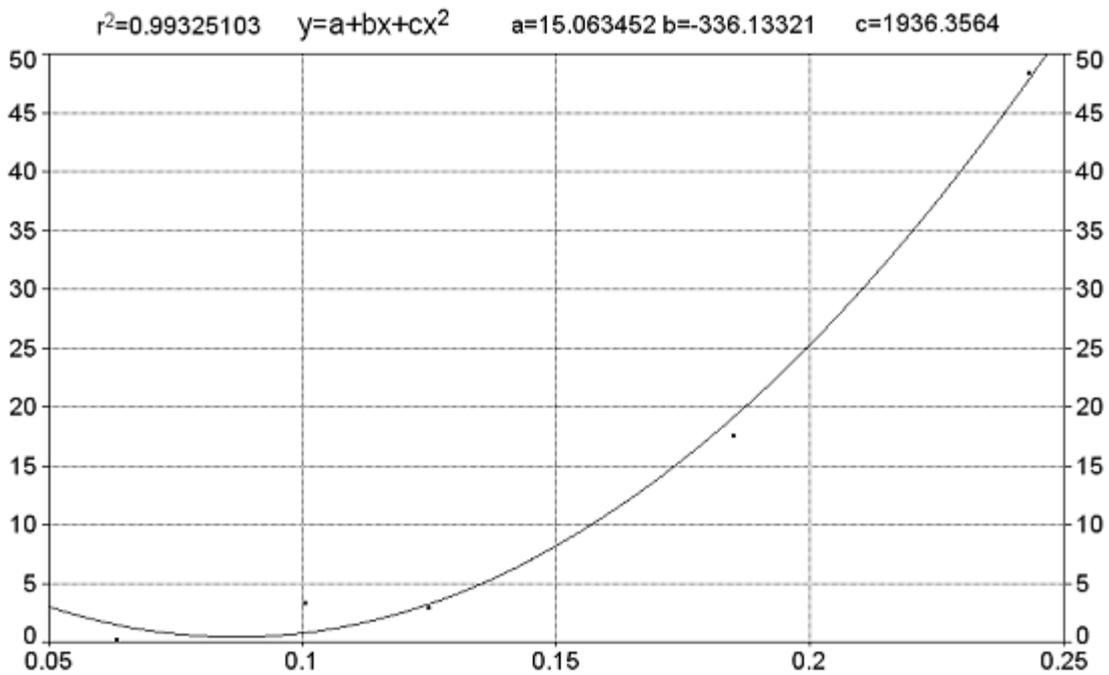


Figure 5. Relationship between ϵ'' in 10GHz and nanometer power volume fraction (v)