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Electromagnetic Characteristics of Carbon Nanotube Based Antennas

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Abstract

We have studied electromagnetic characteristics of carbon nanotube based antennas in different frequency regimes ranging from the microwave to visible. Analysis of the physical characteristics of carbon nanotube based integrated circuit elements, such as antennas, must follow the general principles of electrodynamics and must account for the peculiar dispersion properties of electrons in carbon nanotubes. A key element of the analysis is the formulation of the effective boundary conditions for electromagnetic field on the carbon nanotube surface. We have incorporated the presence of intershell tunneling in the effective boundary conditions, showing thereby that tunneling alters the effective boundary conditions significantly from the effective boundary conditions presented previously. In order to incorporate intershell tunneling in the effective boundary conditions, we have adopted a microscopic approach. We observed that intershell tunneling qualitatively changed the form of effective boundary conditions in a doublewall carbon nanotube in comparison to single wall carbon nanotubes. The surface current densities and the axial component of the electric field on the surfaces of different shells get coupled, which effect leaded to a generalized susceptibility that contained the mutual surface conductivities of both shells. The mutual surface condivities are caused by the tunneling. The existence of mutual condivities leaded to the appearance of electrostatic longitudinal waves in the spectra of a double wall carbon nanotube. Different types of guided waves in the double wall carbon nanotube arise from intershell tunneling. The dispersion characteristics of asymmetric like waves are strongly affected in the wide frequency range by intershell tunneling.

Keywords: Electromagnetic, Carbon nanotube, Antenna, Dispersion, Tunneling, Intershell, Microscopic, Conductivity.

1. INTRODUCTION

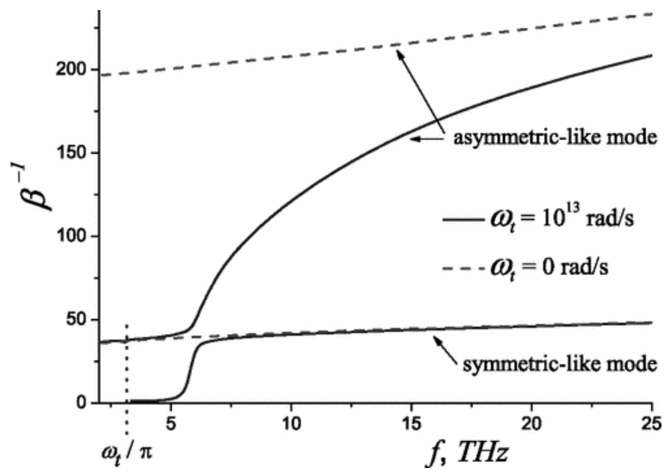
Slepyan et al [1] and Rebczynski et al [2] studied and used carbon nanotubes to fabricate several different integrated circuit elements and electromagnetic devices such as transmission lines, interconnects and nano antennas [3]. The fabrications of a carbon nanotubes based amplitude modulater/ demodulator [4] and a fully intregarated radio receiver [5] have been reported. Hanson [6] showed that carbon nanotube morphology has been demonstrated to play a crucial role as evinced by reported research on single walled carbon nanotubes. Burke et al [7] showed nearly 1 cm long are dimensional chains of electrically connected single wall carbon nanotubes and planar periodic structures of single wall carbon nanotubes, carbon nanotube bundles and carbon nanotube arrays. Hansan [8] presented that metal core can be modeled as a solid cylinder with surface conductivity $\sigma_0 = \frac{\sigma met R_0}{2}$, where σmet is the bulk volumetric conductivity of the metal. R_0 has to be higher than a critical value R_{cr}, which corresponds to the crystalline nanocrystalline transition in metals and separates the quasibulk behavior $R_0 > R_{cr}$ from the quasi-molecular behavior $R_0 < R_{cr}$ of a nanowire. Johnson et al [9] considered the propagation of surface Plasmon waves in an multiwall carbon nanotube with a gold core. The bulk volumetric conductivity σmet of gold was taken to follow the Drude model with different parameters. Wang et al [10] studied that the skin depth of gold in the visible regime is higher than 30nm. The value of $R_{cr} = 1.5\text{nm}$ for gold was found with first principles calculations. Chin et al [11] studied experimentally the absorption and scattering characteristics of an electrically thick multiwall carbon nanotube in the regime of optical transitions depend only on the frequency. Lakhtakia [12] studied and found that the overlaping of a large number of resonances of the surface conductivities of the different shells leaded to a smooth frequency dependence of σ_T. Such an effect is analogous to inhomogeneous broadening is an ensemble of all different harmonic oscillators. We have reported our work on the performance of multiwall carbon nanotubes as antennas.

2. METHOD

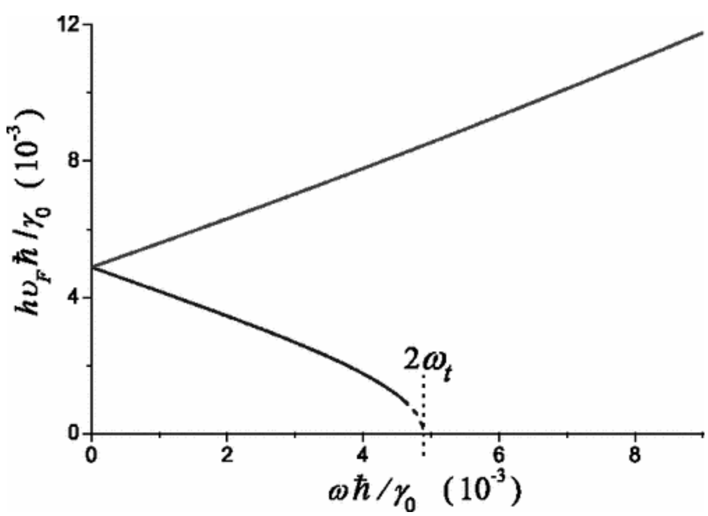
We have considered and incorporated intershell tunneling in carbon nanotube electrodynamics. We have also considered intershell tunneling in double wall carbon nanotubes, the generalization for an multiwall carbon nanotube with three and more shells thereafter being simple. We have chosen double wall carbon nanotube consisted of two infinitely long conducting, coaxial cylindrical shells with cross sectional radii R_2 and $R_1\left(R_2 > R_1\right)$. Both shells are assumed to be conducting low frequency being caused mainly by electrons with energy near the Fermi level. We calculated the axial surface current density in each shell when the double wall carbon nanotube was illuminated by a time harmonic electromagnetic field. Electron transport on each shell can be described by the tightbinding approximation, taking into account the transverse quantization of the motion of charge carriers and the hexagonal structure of the graphene lattice. The influence of the coulomb interaction on the charge carrier motion was neglected.

3. RESULTS AND DISCUSSION

The radiation characteristics of an multiwall carbon nanotube was determined by its waveguiding properties, the dispersion equation of azimuthally symmetric guided wave propagation of an infinitely long double wall carbon nanotube was derived. We formulated a numerical solution of the boundary value problem for scattering by a finite length multiwall carbon nanotube by exploiting an integral equation technique. Our approach was established in antenna theory and has been successfully applied to single wall carbon nanotube antennas and almost circular bundles closely packed single wall carbon nanotube. Numerical results for guided wave parameters and the scattering properties of multiwall carbon nanotube in a wide frequency range from the terahertz to the visible regimes were studied and found in good agreement with previously observed values. Graph (1) shows that asymmetric like mode is more retarded than symmetric like mode. For both modes the retardation sufficiently decreases in the range of $\omega \equiv 2\omega_t$. For comparison, the dispersion curves are also shown when inter shell tunneling is ignored $(\omega_t = 0)$ by setting $\sigma_{pq} = \delta_{pq}\sigma_p$. Intershell tunneling very slightly affects the symmetric like mode, except in the immediate vicinity of tunneling resonance $\omega \cong 2\omega_t$. The vicinity of tunnel resonance $\omega \cong 2\omega_t$ for one of the branches is marked by the dashed line in graph (2). In that vincinity, the applicability condition of electrostatic approximation *h/k* breakes down for this branch and a more rigorous analysis is required. At $\omega = 0$ both branches intersect at a finite value of *h*. Thus intershell tunneling qualitatively changes the character of coulomb screening in a double wall carbon nanotube, the coulomb potential of a point charge, placed at the centre of the double wall carbon nanotube varies as $\cos hz$. This effect is analogous to the Kohn anomaly in metals and degenerate plasma but the singularity is stronger pole. This is due to low dimensional nature of charge motion in double wall carbon nanotube. Most multiwall carbon nanotube of large outer cross sectional diameter nearly 50-300 nm do not possess a coaxially layered morphology and also contain a lot of defects



Graph 1: Frequency dependence of the inverse slow-wave coefficient $\beta^{-1} = h/k$ for guided-wave modes in a DWCNT with (9,0) and (18,0) shells; $\omega_t = 10^{13}$ rad s^{-1}. The solid lines show results with intershell tunneling; the dashed lines without.



Graph 2: Frequency dependence of the guide wave number h in the electrostatic approximation. $\gamma_0 \approx 2.7$eV is the overlap integral

4. CONCLUSION

When modeling the electromagnetic properties of an multiwall carbon nanotube is the intershell interaction leading to intershell electron tunneling or hopping. Results showed a strong dependence on the intrinsic symmetries of the shells, which dictates selection rules for the elements of the tunneling matrix as determined by the conservation laws for energy and momentum. Two incommensurate shells interact differently than two commensurate cells. The Fermi momenta of two incommensurate shells do not coincide within the first Brillouin zone and therefore the intershell tunneling vanishes. Longitudinal electrostatic waves exist in double wall carbon nanotubes due to intershell tunneling. Slightly attenuated guided waves and antenna resonances due to edge effect exist for not too thick multiwall carbon nanotubes in the far infrared and mid infrared regimes. Interband transitions retard the propagation of guided waves and have a deleterious effect on the performance of a finite length multiwall carbon nanotube as a nanoantenna. The obtained results were found in good agreement with previous experimental and theoretical results.

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