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Surface Wave Propagation on Carbon Nanotube Bundle and Characteristics by High Attenuation

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ABSTRACT We have studied the surface wave propagation on carbon nanotube bundle and its characteristics by high attenuation. The slow wave propagation along conducting carbon nanotubes and the high conductivity compared with metallic conductors like copper made these structures for high frequency applications. The property reduced the size of antenna and passive circuits. It was found that the complex surface wave propagation has a significant attenuation coefficient at lower frequency band. This attenuation coefficient induces highly damping effect which reduces the active part of the dipole length. Thus, dipole lie always below resonance and input impedance be always capacitive. The conductivity and electromagnetic wave interaction of the conducting carbon nanotubes have also important features in comparison with traditional conductors like copper wires of the same size. The quantum capacitances of the order of the electrostatic capacitance of the transmission line. This property has two main effects on electromagnetic wave propagation along the carbon nanotube transmission line, slow wave propagation and high characteristic impedance. The wave propagation on the arms of the dipole is highly attenuated such that the active part of the dipole is such smaller than the physical length of the dipole itself. Thus, the dipole always be a short dipole and could not be resonant in any case. The result shows that the advantage of size reduction combined with surface wave propagation is used only in high frequency bands above 100 GHz. The attenuation coefficient has a moderate effect in the frequency band from 10 to 100 GHz. The resonance mechanism occurred when the incident wave at the feeding point adds constructively with reflected wave from dipole ends. The obtained results were found in good agreement with previously obtained results.

KEYWORDS Surface Wave, Propagation, Carbon Nanotube, Attenuation, Dipole, Resonance, Impedance, Capacitive, Transmission Line, Antenna.

1. INTRODUCTION

Slepyan et al. [1, 2] studied the electromagnetic wave interaction with carbon nanotube. Their study included the dc and ac conductivity of single carbon nanotubes and surface wave and likely wave propagation along these nanotubes. Miyamoto et al. [3] studied the inductive effect due to the chiral structure of the nanotubes. Burke [4] made study for which he used electron fluid model to introduce an equivalent circuit model for carbon nanotube transmission line. He introduced additional kinetic inductance and quantum capacitance effects that presented the a.c. conductivity behavior of carbon nanotube transmission line. Burke et al. [5] presented a detailed study on carbon nanotube dipole antenna based on simple transmission line approximation. They found that the wave velocity on the carbon nanotube transmission line equals nearly the Fermi velocity in carbon nanotube. The wave velocity was slightly affected by the flaring, since it depends only on the variation of the capacitance effect which is sensitive to the log of the distance between the two arms. Hanson [6] presented on integral equation based on the macroscopic surface conductivity of the carbon nanotube instead of the equivalent circuit parameters of the carbon nanotube transmission line. Similar formulations were presented by Huang et al. [7].

Fichtner et al. [8] studies to reduce the characteristic impedance of carbon nanotube transmission line, carbon nanotube bundles were introduced. The carbon nanotube bundle is a set of parallel single wall carbon nanotube. They showed that the slow wave coefficients for azimuthally symmetric guided waves increase with the number of metallic carbon nanotubes in the bundle, tending for thick bundles to unity, which is characteristic of macroscopic metallic wires. There is compromise between reducing the length of the resonant bundle dipole and reducing the resonant input impedance. The surface wave strongly influenced the scattering [9] and radiation properties of a carbon nanotube in the terahertz regime. The first type of interaction arises from the direct coupling of the electronic states in adjacent carbon nanotube due to overlap of their electron wave functions [10]. The overlap is always very small for two reasons (i) the contact area between two adjacent carbon nanotubes is small due to their geometrical curvature, even when the two touch each other and (ii) the orbitals of the carbon atoms strongly overlap only in the plane of a graphene sheet, which is known as Vander Waals form of the inter graphene sheet interaction. The momentum mismatch between the Fermi points of neighboring carbon nanotubes suppressed the inter carbon nanotube tunneling and leaded to strong localization of electronic eigen states on individual carbon nanotubes. The second type of interaction is electrodynamic coupling in which coulomb interactions in carbon nanotube are modified by the dielectric screening induced by the adjacent carbon nanotubes. Such dielectric screening induced by the adjacent carbon nanotubes. Such dielectric screening has a significant effect in one dimensional structure such as single wall carbon nanotubes.

Dletz et al. [11] studied the boundaries of wave guides and nanowires have drastic influence on their coherent scattering properties. Designing the boundary profile is a promising approach for transmission and band gap energies with many applications. By performing and experimental study of microwave transmission through rough waveguides they demonstrated that a proposed surface scattering theory be employed to predict the measured transmission properties from the boundary profiles and vice - versa. They demonstrated the nontrivial effects of this scattering mechanism by mode resolved microwave measurements and numerical simulation. The effects induced by surface scattering often are the key for the scattering of underwater waves at metal materials [12]. The transmission properties of a system from a given rough boundary profile, numerical calculations help to overcome these deficiencies of existing analytical methods [13].

Francico et al. [14] theoretically explored the possibility of reducing propagation loss in metal insulator metal waveguide using mode combinations to achieve wall, avoiding field distributions along a certain propagation length. Robert Filter et al. [15] presented an analytical approach was provided for describing the resonance properties of optical nanoantennas made of a stack of homogeneous disks. They calculated analytically the phase accumulation of surface Plasmon polaritons across the resonator at additional contribution from the complex reflection coefficient at the antenna termination. Eigen modes of various nanoantennas have been measured by different means [16-17]. The problematic in further advancing the field is the lack of analytical insight into the scaling behavior of optical nanoantennas to carefully design them for a desired application [18-20].

Qiong et al. [21] studied a wave guide quantum electrodynamic system with a rectangular wave guide and two level systems inside, where the transverse magnetic mode with quantum channels of guided photon. It was found that the loss of photons from the TM_{11} channel into the others overcome by certain coherent super position of TM_{mn} channels, which is named the controllable channel as the photons in the controllable channel perfectly reflected or transmitted by the two level systems. A dark state emerged when the photon was incident from any of the scattering channels orthogonal to the controllable channel. A hybrid system consisting of a one - dimensional waveguide coupled to a two level system has been extensively studies for physical implementation of the quantum mode acting as a quantum switch. This functional hybrid system realized in circuit quantum electrodynamics systems [22, 23].

Mikki and Kishki [24] presented a microscopic model to derive Greens's function that represented the interaction of electromagnetic waves with single wall carbon nanotube based on the potential at each atom that the resulting formulation.

Chiarillo et al. [25] showed that kinetic inductance was found to be much larger than the traditional magneto static inductance of transmission line. The quantum capacitance is nearly of the same order of the electrostatic capacitance of the transmission line. This property has two main effects on electromagnetic wave propagation along the carbon nanotube transmission line, slow wave propagation and high characteristic impedance.

Kumar and Ranjan [26] studied transmission through surface disordered waveguides in general and a solid. The results showed that desired transmission properties on a waveguide through the roughness of its boundaries have been obtained. The surface scattering approach predicted that how mode specific scattering lengths in waveguides depended on the details of system of surface roughness. It was shown previously that was neglected square gradient scattering mechanism and predicted that this new scattering mechanism has to be considered together with conventional amplitude scattering mechanism. They have found that an observed shift of the amplitude scattering was attributed to the non-vanishing disorder length. They also found that short wave lengths exhibited effects for system with long range correlations leading to drastic changes in their transmission properties.

Sattar and Kumar [27] derived expressions that generalized the impedance concept for wave guiding devices from the microwave frequency regime to optics and plasmonic. Their expressions were based on electromagnetic eigen modes that excited at the interface of a structure. Impedance in electromagnetic wave theory is the ratio of the electric and magnetic field strength. They found that applicability of simple circuit parameters the impedance was beyond any point. The impedance was overlap of eigen modes.

2. METHOD

The conductivity of carbon nanotube depends on its chirality. The conductivity is divided into two parts, (i) intraband and (ii) interband conductivities. Interband transitions have more significance in optical frequencies. The analysis is mainly depending on intraband conductivity of an armchair carbon nanotube which has been approximated for small armchair carbon nanotube when vector indices$m \leq 50$, thus

$$\sigma_{zz}^{cn} \approx -j\frac{2e^2 v_F}{2\pi^2 \hbar a(\omega - j\upsilon)}$$

where $\upsilon_F \approx 9.71 \times 10^5 \mathrm{m/s}$ is the Fermi velocity of carbon nanotube, $\upsilon = 3$ps : ω is the operating frequency, e is the electron charge, ħ is the reduced plank's constant. For a carbon nanotube bundle composed of N identical tubes arranged as a cylindrical shele of radius R, the effective axial surface conductivity of this shell has been approximated as

$$\sigma_{zz}^{b} \approx \frac{N\sigma_{zz}^{cn} a}{R}$$

The integration equation representing electromagnetic wave interaction with carbon nanotube was derived by Hanson. The basic idea of integral equation representation for carbon nanotube is based on Hallen's integral equation with adding the effect of surface conductivity as

$$-\int_{-L}^{L}\left(\frac{e^{-jk_o\sqrt{(z-z')^2+R^2}}}{\sqrt{(z-z')^2+R^2}} + \frac{1}{Z_o\sigma R}e^{-jk_o|z-z'|}\right)I(z')dz'$$
$$= C\cos k_0 z - j\frac{4\pi\omega\varepsilon_0}{2k_0}sin.\, k_0|z-z_0|$$

Where R is the radius of the dipole, $R = a$for single nanotube and σ is the effective surface conductivity of the dipole,z_0 is the location of the feeding point, C is a constant that is determined to satisfy the current vanishing at the edges of the dipole and L is the half length of the dipole. To study electromagnetic wave interaction with carbon nanotube bundle, have to study guiding wave properties of the structure. The effective conductivity lies only on the axial direction; the surface wave component is mainly transverse magnetic wave. The total field is represented in terms of the axial transverse magnetic Hertzian potential $\prod_e$ as

$$\vec{E} = \nabla(\nabla \cdot \textstyle\prod_e) + k_0^2 \prod_e$$
$$\vec{H} = j\omega\varepsilon_0 \nabla \times \textstyle\prod_e.$$

where transverse magnetic Hertzian potential is determined by solving the wave equation

$$\nabla^2\prod_e + k_0^2\prod_e = 0$$

for cylindrical configuration in the case of carbon nanotube, the general solution of wave equation is Bessel function. The field inside the cylinder is finite in the range $0 \leq \rho \leq R$. The field in the region is represented by Bessel function of first kind. The field outside the cylinder is finite at $\rho = R$ and is exponentially decaying as $\rho > R$. The field in this region is represented by Hankel function of second kind. The general solution of the transverse magnetic Hertzian potential in carbon nanotube bundle is represented as

$$H_e = A\vec{a}_z \begin{Bmatrix} J_n(\kappa\rho)H_n^{(2)}(\kappa R) \\ J_n(\kappa R)H_n^{(2)}(\kappa\rho) \end{Bmatrix} e^{-j\gamma z}e^{-jn\phi} \begin{matrix} \rho \leq R \\ \rho \geq R \end{matrix}$$

By using this Hertzian potential and applying the boundary condition

$$J_z = \sigma_{zz}E_z(R) = -\lim_{\delta\to 0}\left[H_\phi(R+\delta) - H_\phi(R-\delta)\right]$$

The dispersion equation for surface wave propagation on a carbon nanotube is given by

$$\left(\frac{\kappa}{\kappa_0}\right)^2 J_n(\kappa R)H_n^2(\kappa R) = \frac{2}{\pi\sigma_{zz}Z_0k_0R} \text{ where } Im(\kappa) \leq 0.$$

the longitudinal propagation is given by

$$\gamma = \sqrt{k_0^2 - \kappa^2}$$

where $Im(\gamma) \leq 0$.

3. RESULTS AND DISCUSSION

Figure (1) shows the input impedance of a dipole of a carbon nanotube bundle for different values of N. It was found that the first resonance of the configuration was taken and that corresponded to a half guided wave length dipole for the case $N = 8$ occurred nearly at 280 GHz and the resonant impedance was nearly 2100 Ohms. Increasing the number of nanotubes in the bundle decreased the total surface impedance of the dipole. This has two effects, increasing the resonant frequency for a specific length and decreasing the resonant impedance in the case where N is increased to twenty. In this the first resonance frequency was found 404 Hz and the resonance impedance was found 840 ohms. The scale reduction factor was nearly 0.081. For hundred nanotube bundle of the same length the resonant frequency was 740 GHz and the resonance impedance was 174 ohms and scale reduction were nearly 0.15. Figure (2) shows that there is no resonance. We have found that carbon nanotube did not introduce the same properties in another frequency band. It was also found that the input impedance of antenna at 10 to 1000 GHz band was always capacitive load. Figure (3) shows that when the length of te dipole was 3000 μm, the input impedances of dipole antenna for N=8 and 100 were obtained. The real part of impedance was monotonically decreased with increasing frequency. Open circuit termination introduced a standing wave pattern on this transmission line in free space. In the case of perfectly conducting line in free space propagation constant was same as free space. The resonance of the dipole occurred when the standing wave pattern on the arm of the dipole introduced peak current at the feeding point of the dipole. The first current peak occurred when the length of the flared part equals nearly one fourth of the propagation wave length. Figure (4) shows the calculated $\frac{v}{c}$ for a carbon nanotube bundle transmission above a ground plane as a function of the number of nanotubes in the bundle. The obtained results were found in good agreement with previously obtained results of theoretical and experimental works.

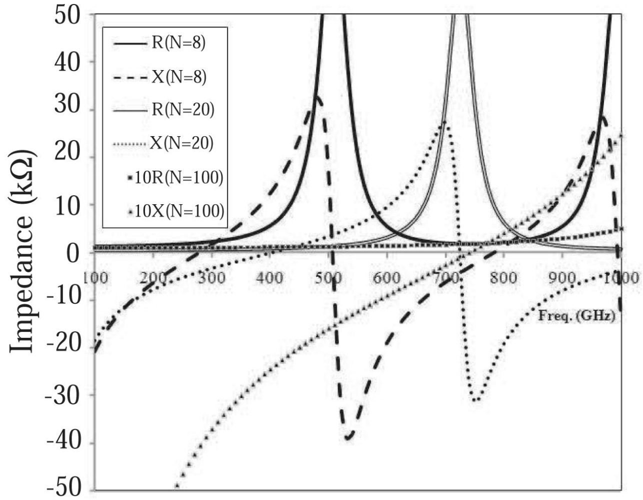

Figure 1: Input impedance of bundle dipoles of L=30μm.

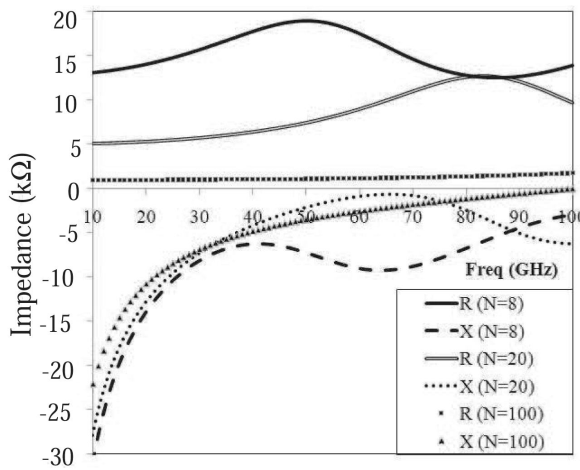

Figure 2: Input impedance of bundle dipoles of L=300μm.

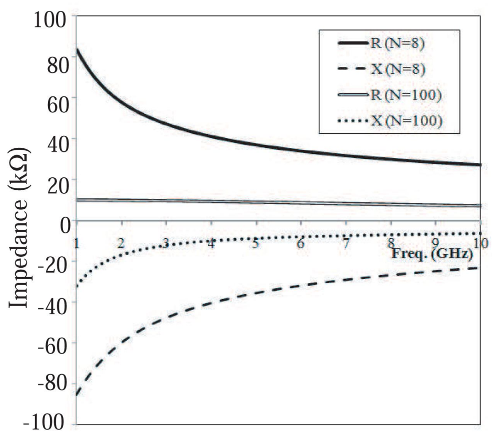

Figure 3: Input impedance of bundle dipoles of L=3000μm.

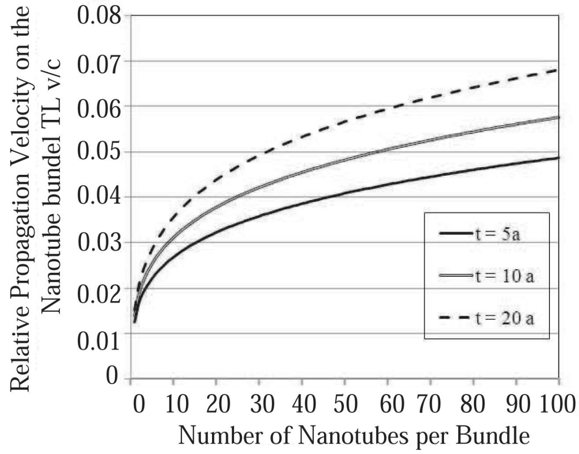

Figure 4: Wave velocity compared with free space wave propagation of a quasi- TEM TL carbon nanotube bundle above a PEC ground plane as a function of N.

4. CONCLUSION

We have studied the surface wave propagation on carbon nanotube bundle and its characteristics by taking in to account high attenuation. We have introduced the physical interpretation of the property based on the relation between the resonance frequency and the surface wave propagation constant on a carbon nanotube. This surface wave propagation was found to be characterized by high attenuation coefficient at low frequency bands. This attenuation coefficient introduced highly damped effect which reduced the active part of the dipole length. The dipole was below resonance in this case and input impedance was capacitive. It was also found that the lowest frequency is suitable for a carbon nanotube antenna.

The result showed the relation between the resonant dipole length and the surface wave velocity on its arms. By studying the surface wave complex wave propagation constant, the attenuation coefficient increased by decreasing the operating frequency. The effect of this attenuation coefficient is negligible in the frequency range from 100 to 1000 GHz. The behavior of the input impedance of the dipole antenna is nearly the same of traditional dipole antenna with scaling reduction factor due to the slow surface wave velocity. This attenuation coefficient has a moderate effect in the frequency band from 10 to 100 GHz. The reflected wave does not add completely at the feeding pint which indicated that the inductive effect due to the delayed reflected signal did not compensate completely the capacitive effect of the dipole arm. We have found that the advantage of size reduction combined with surface wave propagation has been used in high frequency bands above 100 GHz. The obtained results were found in good agreement with previously obtained results of different investigators.

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