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Carbon nanotube antennas analysis and applications: review

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Abstract. Carbon nanotube characterized by additional inductive effect as compared with the traditional conductors like copper wires of the same size. Consequently, carbon nanotubes have high characteristic impedance and slow wave propagation in comparison with traditional conductors. Due to these characteristics, carbon nanotubes can be used as antenna. In view of this, we describe and review the present research progress on carbon nanotube antennas. We present different analysis models and results which are developed to investigate the characteristics of CNT antennas. Then we conclude by summarizing the characteristics of CNT antennas and specifying the operating frequency limit.

Keywords: carbon nanotubes; RF circuit model; dynamic conductivity of SWCNT dipole antennas; optical antenna

1. Introduction

Recently, there has been an increasing interest in the applications of nanotechnology which tend to develop new generation of materials and devices that can handle the growing demands of industry (Poole and Owens 2003). Carbon nanotubes (CNTs) are one of the most commonly used building blocks of nanotechnology (Merkoci 2006). CNTs can be considered as a rolled graphene sheet and are classified according to the number of rolls to: (i) single wall (SWCNT) (ii) multi-wall (MWCNT). Also, they are classified according to the way of rolling and the axis around which the graphene sheet is rolled to chiral and non-chiral nanotubes (Saito *et al.* 2003). Since the discovery of CNTs (Iijima 1991), they have attracted the attention of both physicists and engineers because of their unique interesting properties. Due to these unique properties nanotubes have great potential applications in nanoscale electronic devices such as a field effect transistor (Guo *et al.* 2002, 2003), single electron transistor (Postma *et al.* 2001), and nanoscale p-n junction (Zhou *et al.* 2004). In addition, CNTs are becoming promising candidates in many important applications such as atomic force microscope tips (Cheung *et al*. 2000), field emitters (De Heer *et al*. 1995) and chemical sensors.

Burke and coworker (Burke 2004 a, b) have been able to synthesize and electrically contact the

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single walled carbon nanotubes (SWCNT) up to 1 cm in length. These tubes are comparable in length to the wavelength of microwaves in free space. This motivated some work to study the interaction of microwaves with nanotubes and exploration of their properties as antennas. CNT antenna can be one of the potential solutions to the problem of electrical contact from nanoelectronic devices to the macroscopic world, without giving up on the potential circuit density achievable with nanoelectronics. Also, CNTs can be a candidate for the metallic structure of optical antennas.

Since the nanotubes are one dimensional quantum wires, their properties as dipole antenna need to be recognized. Recently, there has been some activity in this area and some work has been done to gauge the suitability of carbon nanotubes for antenna applications. This paper gives a review of the most of the work developed to study the properties of CNT as nano-antenna. Carbon nano-antennas have several applications such as on-chip AC-coupling, replacement for CCD imaging chips (in current optical camera), chemical/biological sensors (Burke *et al.* 2006). Also, CNTs can be a candidate for the metallic structure of optical antennas and can be used to provide highly efficient solar cells. In view of this, in this article we will introduce a review of the present research progress on carbon nanotube antennas. First, a review of CNT construction and basic parameters is introduced. Then the rest of the paper reviews some work developed to study the characteristics of CNTs as antennas at different frequency ranges and finally, a conclusion is drawn.

2. Carbon nanotube construction and basic properties

Carbon nanotubes (CNTs) are molecular-scale tubes of graphitic carbon and can be considered as the stiffest and strongest fibers known, and have remarkable electronic properties and many other unique characteristics. For these reasons they have attracted huge scientific and industrial interest. CNTs can be grouped into two classifications based upon the number of layers of graphitic carbon that comprise their sidewalls. Tubes consisting of one single layer are called single-wall CNTs (SWNTs) and those having more than one layer of carbon are referred to as multi-wall CNTs (MWNTs). CNTs of both types are of considerable interest depending upon the situation and application. Depending on the CNT chirality (degree of twist) and diameter, a CNT can be either metallic or semiconducting. The band gap of semiconducting nanotubes can be "tuned" by adjusting the diameter of the nanotube; the larger the diameter, the smaller the band gap. Fig. 1 shows the structure of graphite at the atomic level where the apexes of hexagons denote the location of carbon atoms and the lines depict carbon–carbon bonds (Saito *et al.* 2003). Lattice basis vectors are a_1 and a_2, as shown, and the relative position vector is $R = ma_1 + na_2$, where m, n are integers. A carbon nanotube can be formed by wrapping the graphene sheet into a cylinder. The cylinder can be formed by wrapping the she*et al*ong any preferred axis. In the case of wrapping the cylinder around ζ and η axis the resulting tubes are zigzag and armchair, respectively. If the cylinder wrapped about another axis neither ζ nor η, the resulting nanotube is called a chiral. Thus CNT can be characterized by the dual index (m, n), where (m, 0) for zigzag CNTs, (m, m) for armchair CNTs and (m, n), $0 < n \neq m$, for chiral nanotubes. Depending on n, m the cross-sectional radius of a carbon nanotube can be given by (Saito *et al.* 2003)

$$a = \frac{\sqrt{3}}{2\pi} b\sqrt{m^2 + mn + n^2} \tag{1}$$

where b = 0.142 nm is the inter-atomic distance in graphene.

Electrically, carbon nanotubes can exhibit ballistic transport (Javey *et al*. 2003) over at least micrometer lengths. In the case of ballistic transport the resistance of the tube is independent of the length. So, the electronic properties of carbon nanotube depend on the diameter of the nanotubes and consequently the (n,m) indices (Saito *et al.* 2003, Dresselhaus *et al.* 2001). The (n, m) indices determine the metallic or semiconducting behavior of the nanotubes. For example, Zigzag SWCNTs with $m = 3q$ where q is an integer are metallic and armchair CNTs are always metallic (they exhibit no energy band gap).

With recent advances in techniques for synthesizing carbon nanotubes it's now possible to make carbon nanotube with length up to 4.0 cm long with outstanding electrical properties (Kim *et al*. 2002, Huang *et al*. 2003, 2004 , Zheng *et al*. 2004, Durkop *et al*. 2004), which is important for antenna applications.

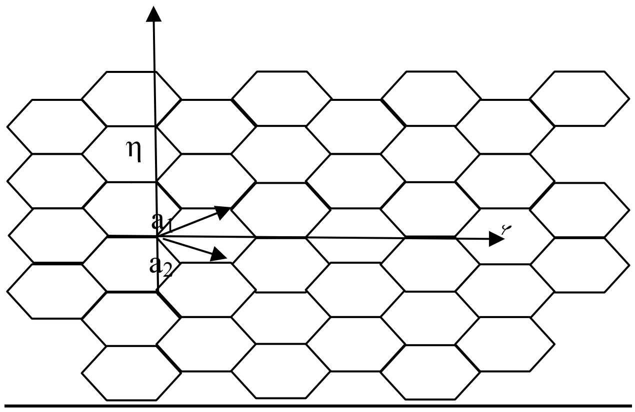


Fig. 1 Atomic structure of grapheme sheet

2.1 Radio-Frequency (RF) circuit model of SWCNT

In this section we will give a brief description of the RF circuit model of SWCNT. (Burke 2004a, b) considered in some detail the electrical properties of a SWCNT above a ground plane. They found that besides the electrostatic capacitance and magnetic inductance, there were two additional distributed circuit elements to be considered: the quantum capacitance and the kinetic inductance. And the (quantum) capacitance per unit length can be considered as follows

$$C_Q = \frac{2e^2}{h\upsilon_F} \tag{2}$$

where e is the electron charge, h is the Plank's constant and υ_F is the Fermi velocity for graphene ($v_F = 8(10)^5$m/s). The kinetic inductance can be given by the following formula

$$L_k = \frac{h}{2e^2\upsilon_F} \tag{3}$$

And by applying the values of e, h and v_F to Eqs. (2), (3) the numerical value of quantum capacitance and kinetic inductance are: $C_Q = 100aF/\mu m$ and $L_k = 16nH/\mu m$.

The circuit model for carbon nanotubes is more complicated, since each nanotube has four channels (two spin up and two spin down), each with its own kinetic inductance and quantum capacitance. For the differential mode excitations, the effective circuit model is modified. There are two spin orientations and two band structure channels that can propagate current, i.e., 4 (1d) quantum channels in parallel. Therefore, the kinetic inductance is 4 times lower than the one channel case, and the quantum capacitance is 4 times higher than the one-channel case. The effective circuit diagram that takes this into account is given in Fig. 2.

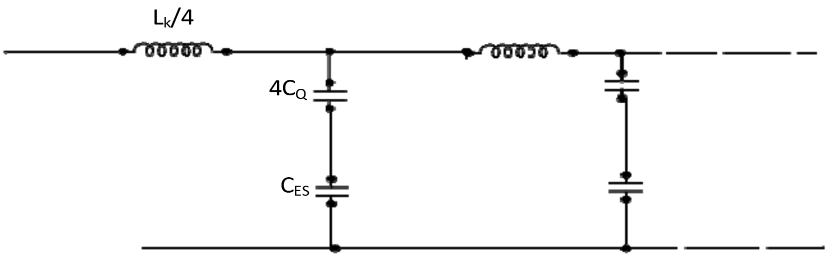


Fig. 2 Effective circuit diagram for SWCNT (C_{ES} represents the electrostatic capacitance between the tube and ground plane)

2.2 Dynamic conductivity of SWCNT

The conductivity of CNTs depends mainly on its chirality. This conductivity is divided into two parts; intraband and interband conductivities (Maffuci *et al*. 2008). Analytical expressions for the axial dynamic conductivity of CNTs were derived by (Maksimenko *et al*. 1999). On the other hand, the conductivity was derived starting with Boltzmann's equation (Roglski and Palmer 2000, Kittel 1986). The Boltzmann's equation can be applied in the case of a -z directed electric field (E_z) and the resulting current flow solely in the direction under the relaxation-time approximation as follows

$$\frac{\partial f}{\partial t} + eE_z \frac{\partial f}{\partial p_z} + \upsilon_z \frac{\partial f}{\partial z} = \nu[f_0(p) - f(p,z,t)] \tag{4}$$

where f is the electron's distribution function, $\mathbf{p}$ is the electron's two-dimensional quasi-momentum tangential to the CNT surface, p_z is the projection of $\mathbf{p}$ on the axis of the CNT, $v_z = \partial\varepsilon/\partial p_z$, $\varepsilon = \varepsilon(p)$ is the electron energy with respect to the Fermi level, and ν is the relaxation frequency. The chemical potential of graphite being null-valued, so the Fermi equilibrium distribution function is

$$f_o(p) = \left(1 + e^{\frac{\varepsilon(p) - E_F}{K_B T}}\right)^{-1} \tag{5}$$

where E_F is the Fermi energy, K_E is the Boltzmann constant and T is the temperature. Using the semiclassical approximation and neglecting the interband transition the axial conductivity for the CNT can be given by

$$\sigma_{zz}(\omega) = j\frac{2e^2}{(2\pi\hbar)^2}\iint \frac{\partial f_0}{\partial p_z}\frac{\upsilon_z}{\omega - j\nu}d^2p \tag{6}$$

where ω, is the angular frequency of the exciting electromagnetic field.

At optical frequencies, another approach is used to develop an expression for the axial conductivity (Maksimenko *et al.* 1999). This approach is based on quantum-mechanical treatment of effective permittivity of a CN-based composite material, as reported by Tasaki *et al.* (1998) and Lin *et al.* (1994). The deduced form of SWCNT axial conductivity of optical frequency is given by:

$$\sigma_{cn}(\omega) = \frac{je^2\omega}{\pi^2\hbar a}\left\{\frac{1}{\omega(\omega - j\nu)}\sum_{s=1}^{m}\int_{1st\,\mathrm{BZ}}\frac{\partial F_c}{\partial p_z}\frac{\partial \varepsilon_c}{\partial p_z}dp_z \right.$$
$$\left. + 2\sum_{\mathrm{s=1}}^{\mathrm{m}}\int_{\mathrm{1st\,Bz}}\varepsilon_{\mathrm{c}}\left|R_{\upsilon c}\right|^2\frac{F_c - F_\upsilon}{\hbar^2\omega(\omega - j\nu) - 4\varepsilon_c^2}dp_z\right\}$$

where $F_{c,\upsilon}$ is the equilibrium Fermi distribution function:

$$F_{c,\upsilon} = (1 + e^{\left[(\varepsilon_{c,\upsilon} - \mu_{ch})/k_BT\right]})^{-1}$$

where μ_{ch} is the chemical potential in graphite (μ_{ch} = 0) and the electro dispersion for armchair CNT $\varepsilon_{c,\upsilon}(p_z, s)$ is

$$\varepsilon_{c,\upsilon}(p_z, s) = \pm\gamma_0\sqrt{1 + 4\cos\left(\frac{\pi s}{m}\right)\cos\left(\frac{d}{\sqrt{3}}p_z\right) + 4\cos^2\left(\frac{d}{\sqrt{3}}p_z\right)}$$

and the matrix elements for armchair CNT $R_{\upsilon c}(p_z, s)$ is

$$R_{\upsilon c}(p_z, s) = -\frac{\sqrt{3}b\gamma_0^2}{2\varepsilon_c^2(p_z, s)}\sin\left(\frac{d}{\sqrt{3}}p_z\right)\sin\left(\frac{\pi s}{m}\right)$$

where s = 1, 2, m accounts for the quantized momentum in the circumferential direction , γ_0 is a constant (2.5 - 3.1 eV), (Hao and Hanson 2006), $d = 3b/2\hbar$ and $\hbar$ is the reduced Planck's constant.

3. Carbon nanotube as a dipole antenna

One possible solution to the complications caused by interconnecting nanodevices between each other or the outside world involves the use of nanowires or nanotubes. The nanotubes and wires may be used in place of wider metal lines to connect device to another device or may act as antennas (Burke *et al.* 2006). Consequently, in this section we will give a review of the methods used to study the properties of CNTs as nano-antenna. Operation of CNTs as antennas has been predicted and discussed in (Wang *et al*. 2004, Burke *et al*. 2006, Hanson 2005, 2006, Hao *et al*. 2006, Huang *et al*. 2008, Attiya 2009).

Burke *et al*. (2006) have studied theoretically CNT antenna through a transmission line model. And other groups (Hanson 2005, 2006, Hao and Hanson 2006, Huang *et al*. 2008) investigated the analysis of dipole antennas formed by CNTs using Hallen type integral equation. On the other hand, Hanson has performed an experimental study of CNT antenna in THz and optical range (Hanson 2006).

3.1 Carbon nanotube antenna analysis based on transmission line model

In this method, the dipole antenna is represented by transmission line consists of two parallel conductors as shown in Fig. 3. The transmission line parameters, inductance (L), capacitance (C), and resistance (R), are determined for the transmission line, based on the line geometry and materials. Then the quantities such as propagation constant, phase velocity and characteristic impedance are determined.

In the case of the transmission line is SWCNT; as described in section 2.1 it has two additional distributed circuit elements to be considered: the quantum capacitance and the kinetic inductance. Accordingly, a circuit model for two parallel carbon nanotubes transmission line was introduced by Burke (2004b). By simple application of Kirchoff's laws to the circuit shown in Fig. 4, a differential equation for the differential voltage was obtained as following

$$\frac{\partial^2 V_D}{\partial x^2} - \gamma_p^2 = 0 \tag{8}$$

where $\gamma_p^2 \equiv 2(R + i\omega L_k/4)(i\omega C_{Total})$ and $_p$ is the propagation constant.

One result of this model is that, the wave velocity of this system is about 100 times smaller than the speed of light.

Also, an expression for the current distribution on the CNT dipole antenna was developed using the transmission line equations and quantitatively including the effect of resistance along the tube length (taking the arbitrary losses into account). The current in the active region of the antenna was written as

$$\mathrm{I(z)} = \begin{cases} \dfrac{\mathrm{V_0^+}}{\mathrm{Z_C}} \sinh\left[\gamma_p (l/2 - z)\right] & 0 < \mathrm{z} < \mathrm{l/2} \\ \dfrac{\mathrm{V_0^+}}{\mathrm{Z_C}} \sinh\left[\gamma_p (l/2 + z)\right] & 0 > \mathrm{z} > -\mathrm{l/2} \end{cases} \tag{9}$$

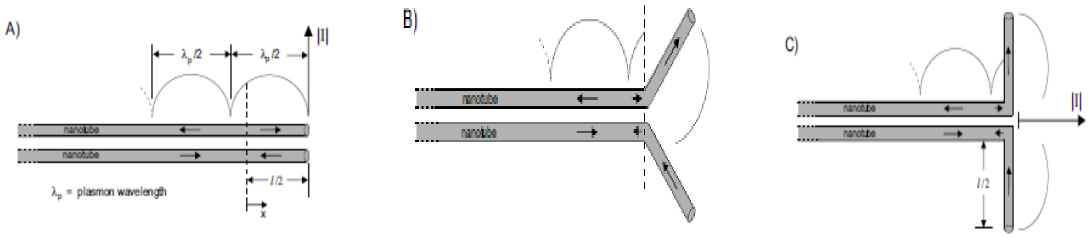


Fig. 3 Two parallel transmission lines represent the dipole antenna

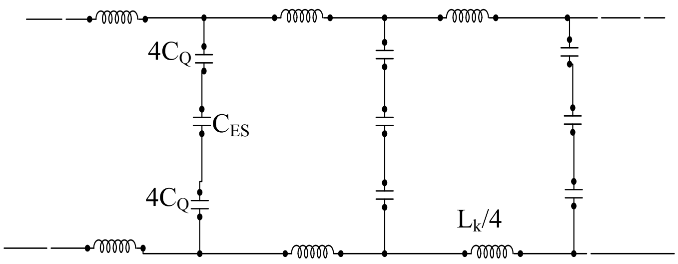


Fig. 4 RF circuit model for two-nanotube transmission line

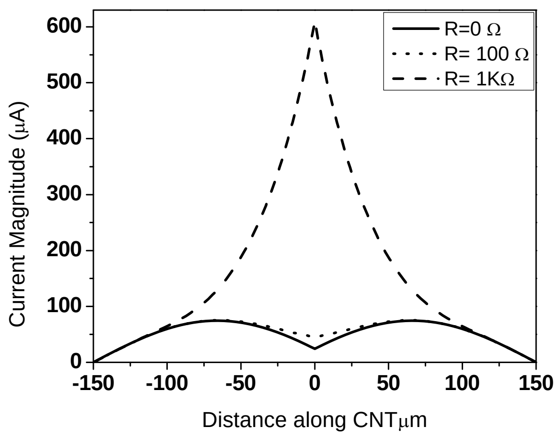


Fig. 5 Current distribution for 1V, 10GHz excitation on a 300 *μm* antenna

These equations describe the nanotube antenna current distribution for arbitrary loss, neglecting the radiation resistance, where V_0^+ is the potential at input terminal and Z_C is the characteristic impedance of the nanotube transmission line. Fig. 5 represents a plot of the magnitude of the AC current as a function of position for various values of *R* for 10GHz frequency and 300 μm long nanotube antennas. Once the current distribution is known, it is straightforward to determine the radiated fields and other antenna parameters (Balanis 2005).

From the analysis and results of Burke *et al.* (2006), it is found that; one advantage of nanotube antenna is that it can serve as excellent impedance matching circuit to get from free space to high impedance devices, but the main disadvantage is the low efficiency. On the other hand, Burke *et al.* have focused on the far field and near field radiation properties of nanotubes. They found that nanotubes act as better antennas when used in the near field rather than the far field because the mutual impedance found is larger than self impedance.

Also in the study of near field properties, an integral equation which would allow for a full numerical calculation for the current distribution on nanotube antenna was derived by Burke *et al.* (2006). The obtained integral equation was on the form

$$\frac{\mu}{4\pi}\int_{-l/2}^{l/2}\frac{I_{z1}e^{-kr}}{r}dz1 = C_1\cos(kz) + \frac{V_T}{2}\sin(k|z|) + \frac{i(R+i\omega L_k/4)}{c}\int_0^z I(s)\sin(k(z-s))ds \tag{10}$$

where I is the current distribution along the nanotube, r is a point on the surface of the nanotube, C_1 is constant, which will be determined during the solution, V_T is the terminal voltage, k is the wave number, R is the distributed resistance, L_k is kinetic inductance and c is the total capacitance. It is worth to mention that Eq. (10) is similar to Hallen integral equation with the exception of kinetic inductance and distributed resistance term.

3.2 Carbon nanotube antenna analysis based on the solution of Hallen type integral equation

3.2.1 Finite-length dipole antennas formed by carbon nanotubes

Hanson (2005) investigated the fundamental properties of a finite length dipole antennas formed by carbon nanotubes using a Hallén's-type integral equation. The input impedance, current profile, and efficiency were presented and compared to ordinary metallic antennas of the same size and shape. To investigate the current distribution and consequent all other antenna parameters, Hanson followed the following steps:

First, he followed the previous work by Maksimenko *et al*. (1999) to determine conductivity of CNT which had been provided in section 2.2, Eq. (4)

Second, used Ohm's law to obtain the integral equation for current density along the tube

$$J_z(z,\omega) = \sigma(\omega)E_z(z,\omega) \tag{11}$$

where $\sigma(\omega)$ is the conductivity of carbon nanotube and J_z is a surface current density (A/m).

Third, continues his formulation using standard antenna analysis (Balanis 2005).

The obtained integral equation form for current was

$$\left(k^2 + \frac{\partial^2}{\partial z^2}\right)\int_{-L}^{L} K(z-z')I(z')dz' = j4\pi\omega\varepsilon\left(Z_i I(z) - E_z^i(z)\right) \tag{12}$$

which σ is in the form of Pocklington integral equation. In Eq. (12) $E_z^i(z)$ is the z component of the incident (source) field, a is the wire antenna radius, σ is the conductance of the carbon nanotube, ε is the permittivity of the surrounding medium, k is the wave number, the kernel

$$K(z-z') = \frac{e^{-jk\sqrt{(z-z')^2+a^2}}}{\sqrt{(z-z')^2+a^2}} \quad \text{and} \quad Z_i = \frac{1}{2\pi a\sigma} \tag{13}$$

The current distribution was obtained by converting Pocklington equation into Hallen integral equation. Balanis (2005), and then obtained equation is solved numerically assuming a slice-gap source of unit voltage.

The investigations by Hanson (2005) showed that CNT antennas exhibit plasmon resonances above a sufficient frequency. In addition, CNT antennas have high input impedances (which is probably beneficial for connecting to nano-electronic circuits) and exhibit very low efficiencies.

3.2.2 Infinitely-long carbon nanotube antenna excited by a gap generator

Hanson (2006) considered an infinite antenna to investigate the basic properties of CNT antennas. In this study he was removing the length dependent current resonance, leaving only the tube radius and the frequency of operation as parameters. So, the CN was modeled as an infinitely thin conducting tube having radius a and sheet conductance σ_{cn}(S).

As stated before, once the current distribution along the antenna is obtained, all other antenna parameters can be determined. Hanson (2006) extended his previous work to find an integral equation for the current distribution along the infinitely long CNT antenna. He started with developing an expression for the semi-classical CN conductance which provided in section 2.2.

For small radius metallic CNs σ_{cn}(S) as a function of frequency (ω), is approximated to

$$\sigma_{cn}(\omega) = \sigma_{zz}(\omega) \cong -j\frac{2e^2\upsilon_F}{\pi^2\hbar a(\omega - j\nu)} \tag{14}$$

And then, the integral equation for surface current density (A/m) can be obtained from Ohm's law (11). By expressing the electric field as the sum of an impressed field, then the field due to the resulting current leads to the standard Pocklington integral equation (Balanis 2005).

$$\left(k^2 + \frac{\partial^2}{\partial z^2}\right)\int_{-\infty}^{\infty} K(z-z')I(z')dz' = \left(j4\pi\omega\varepsilon Z_{cn}I(z) - j4\pi\omega\varepsilon E_z^i(z)\right) \tag{15}$$

Where $Z_{cn} = \dfrac{1}{2\pi a\sigma_{cn}}$ and $K(z-z') = \dfrac{1}{2\pi}\displaystyle\int_{-\pi}^{\pi}\frac{\exp(-jk\sqrt{(z-z')^2 + 4a^2\sin^2(\phi/2)})}{\sqrt{(z-z')^2 + 4a^2\sin^2(\phi/2)}}d\phi$

The previous integral equation for the current along the infinitely long CNT antenna was solved using Fourier transform methods (Jones 1994)

The main results obtained from the investigation made by Hanson (2006) revealed that:

- The real part of the propagation constant for CNT is much larger than the solid and tubular metallic conductors with similar size, and therefore the wave is slower on a CNT antenna.
- Losses on nanometer radius tubes (both copper cylinder and CNT) can be quite high, due to the extremely small radius values. However, CNTs are relatively better conductors than (bulk approximated) copper. Thus, CNTs may be an appropriate choice as an antenna or interconnect as a part of nanoelectronic circuit.
- The current distribution obtained, gives the same results as that obtained from a MOM solution for a finite CNT dipole having total length 800 μm, a = 2.712 nm, f = 100GHz and V_o = 1V, which had been calculated by Hanson (2005).

3.3 Carbon nanotube as optical antenna

Optical antennas are an emerging concept in physical optics. Similar to radio wave and microwave antennas, the purpose of optical antennas is to convert the energy of free propagating radiation to localized energy, and vice versa. The metal nanostructures behave as strongly coupled plasmas at optical frequencies consequently, become a strong candidate for optical antenna.

The absence of optical antennas in technological applications is primarily associated with their small scale. Antennas have characteristic dimensions of the order of a wavelength of light, demanding fabrication accuracies better than 10 nm. The advent of nanoscience and nanotechnology provides access to this length scale with the use of novel top-down nanofabrication tools (e.g., focused ion beam milling and electron-beam lithography) and bottom-up self-assembly schemes. The fabrication of optical antenna structures is an emerging opportunity for novel optoelectronic devices.

In recent years, some work was developed to study the properties of CNTs as optical antennas. Wang *et al.* (2004) presented the optical measurements of periodic and random arrays of (MWCNTs) and found that the response is consistent with conventional radio antenna theory. This was done experimentally through measuring the interaction of MWCNT arrays with visible light and studying both the polarization and the antenna length effects on the received signal.

The main results from the experimental study of Wang et al. are:

- First, each nanotube acts as antenna reradiating light with the electric field E, polarized in the plane parallel to the antenna. A polarizer, with its axis of polarization rotated by an angle θ to this plane, transmits radiation with a projected electric field $E' = E\cos(\theta)$.
- Second, the antenna length effect maximizes the response when the antenna length is a proper multiple of the half wavelength of the radiation.

Hao *et al*. (2006) have investigated the characteristics of armchair CNT antennas in the infrared and optical regime via an analytical technique. Their analyses were based on a classical electromagnetic Hallen's type integral equation (IE) and an axial quantum mechanical conductance function of the tube. As stated previously, the current on the carbon nanotube satisfies Pocklington equation (Jones 1994), and it is given by Eq. (12). The difference is that, the conductance in Eq. (12) is substituted by the quantum conductance function Eq. (7) that was developed by Maksimenko (1999), and is based on a π electron tight binding (TB) model, which has been widely used and includes optical interband transitions as presented in section 2.2 Eq. (7). Then the integral equation obtained for current distribution along the CNT dipole antenna was solved numerically.

The main results from the analysis and results obtained by Hao *et al*. are:

- The interband transitions of carriers cause spikes in the conductivity in the optical range, and this leads to similar behavior in the antenna's properties.
- The study of finite length CNT dipole antenna showed that the antenna exhibits relatively sharp current resonances in the lower THz band according to the velocity factor.
- Resonances occur approximately in the frequency range of ($v/2\pi < f < \upsilon_F/2\pi a$). In this range, resonances like input impedances are found, similar to an ordinary metallic dipole antenna. Outside this range, current is strongly attenuated, such that length dependent resonances do not form.
- CNT dipoles have high input impedances, which may be beneficial for connecting to nano electronic circuits, and exhibit very low efficiencies due to their extremely small radius.
- The CNT dipole field pattern is same as that for a short metallic dipole (E_θ, H_φ α $\sin(\theta)$) and the directivity equals 1.5.

3.4 Carbon nanotube bundle dipole antennas

The previous study, however, has shown that the radiation efficiency of a single-walled carbon nanotube (SWCNT) antenna is very low, which is mainly attributed to the strong retarded surface wave that reduces the radiation resistance. On the other hand, the problem of impedance mismatch is significant if a single CNT is used to build an antenna because its characteristic impedance (10-100 kΩ) is extremely large compared to the normal feeding line (50Ω). Hence, CNT bundles have been proposed to mitigate these problems. Huang *et al*. (2009) theoretically investigated the radiation characteristics of single-walled carbon nanotube (SWCNT) as bundle dipole antennas. Their work based on the distributed circuit parameters and the model of a SWCNT, where the cross section of bundles can be in a circular and a rectangular geometry. The current distributions in such novel antennas are predicted to investigate the effects of bundle cross-sectional size, tube diameter, tube length, and operating frequency.

The geometries of two SWCNT bundle dipole antennas are plotted in Figs. 6 (a)-(c), in which each SWCNT is supposed to be metallic, and the bundle cross sections are built in a circular and a rectangular pattern, respectively. For both dipole antennas, each bundle length is denoted by L. In Fig. 6, the diameter d of each SWCNT is expressed as $d = 2a$, where a is the cross-sectional radius of a carbon nanotube.

The separation between two adjacent tubes is given by (d + 0.34 nm). Therefore, the tube number in the bundle is determined as the bundle radius (R) and the separation (d + 0.34 nm). Also, as the height (H) and width (W) of the rectangular cross section of the bundle are given, the tube number (N) is also determined.

Huang *et al*. (2009) followed the same method used by Hanson (2005), which discussed in section 3.2, to determine the current distribution along the CNT bundle dipole antenna. First, they derived the integral equation for the current distribution along the bundle. They considered only the currents along the outermost tubes in the bundle contribute to the far-zone radiation, while the radiation of inner tubes in the bundle is shielded by the outer tubes. That's because all SWNTs in the circular and rectangular bundles are densely packed together. Then, if the number of outmost tubes is N outermost, then according to Ohm's law

$$\frac{2I_z}{N_{outermost}\pi d\sigma_{cn}} = E_z^s(z) + E_z^i(z) \tag{16}$$

where, d is the nanotube diameter, E_z^s is the scattered field and E_z^i is the impressed field.

Similar to G.W. Hanson work, an integral equation can be derived as

$$\int_{-L}^{L} \left(\frac{e^{-jkr}}{r} + \frac{4\varepsilon_o\omega}{N_{outermost}\pi d\sigma_{cn}} \frac{e^{-jk|z-z'|}}{k}\right) I(z')dz' = B_1\cos(kz) + B_2\sin(kz) - \frac{j2\pi\varepsilon_o\omega}{k}\sin k|z| \tag{17}$$

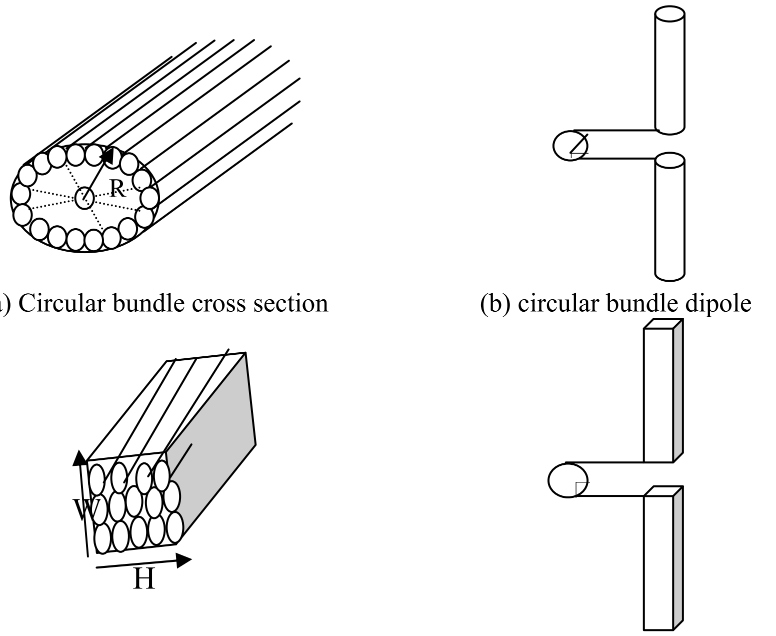
B_1 and B_2 are constants that will be determined during the solution.

Then the previous equation was solved, as done by Hanson, using the method of moments (MoM) and the current distribution along the bundle was obtained. Based on the current distribution obtained using the MoM, the radiated electric field in the far-field region, denoted by E_θ, can be calculated as follows

$$E_\theta = -j\eta_o \frac{ke^{jkr}}{4\pi r}\sin\theta\left[\int_{-L}^{L} I(z)e^{-jkz\cos\theta}dz\right] \tag{18}$$

η_0 is the free space impedance. And hence all other antenna parameters can be obtained.

The important results obtained by Huang *et al*. are:- (1) The efficiency of a bundle antenna was found to be 30-40 dB higher than that of a single SWCNT dipole antenna. (2) All performance indicators of the bundle dipole antenna depend on the SWCNT diameter, the number of tubes included in the bundle, bundle length, as well as operating frequency. Attiya (2009) discussed the lower frequency limit of using CNT bundles as dipole antennas. Attiya followed up the analysis that was discussed by Hanson (2005). And found that to obtain both resonance and size reduction, the lowest frequency that can be suitable for a CNT antenna is nearly 100 GHz.



(a) Circular bundle cross section (b) circular bundle dipole

(c) Rectangular bundle cross section (d) Rectangular bundle dipole

Fig. 6 Schematic of a circular and a rectangular SWCNT bundle dipole antenna excited by a slice-gap source of unit voltage

3.5 CNT based materials for antenna applications

Extensive research has been carried out in recent years to fabricate antenna with CNT and conductive polymer inks instead of metallic conductors. Some recent studies have been reviewed in this section. Dragoman *et al.* (2009) prepared different conductive inks based on DWCNT to develop the tunable impedance on a paper using inkjet printing technology. On the hand, (Yang *et al*. 2004) have been used the inkjet printing to develop a sensor integrated with RFID on the same paper. The sensor was made of SWCNT film which has the affinity for gas molecules. In turn; the absorption of gas molecules changes the conductivity of the SWCNT thin film and hence, the reflected power to the reader of RFID to realize gas sensing.

In 2010 CNTs had been used to develop flexible E-textile conductors on polymer–ceramic composites. Bayram *et al*. (2010) have produced CNT coated E-textile to overcome the challenges found during printing antenna on polymer composites. The E-textile was fabricated by simple dyeing of cotton textile with SWNT dye and Au layers were sputtered to reduce the sheet resistance of the E-textile. The produced conductive sheet has a good adhesion to polymer composites and it is very effective in case of conformal antenna. The other conductive sheet was produced by Zhou *et al*. (2010) through implanting vertical aligned MWCNT in the surface of the polymer, in a similar way as body hair, in much higher density. The conductivity of the printed sheet can be controlled through controlling the length and density of CNTs. This conductive polymer was used to fabricate two conformal antennas. The results ascertained the suitability of using this conductive polymer in conformal antennas. Mehdipour *et al*. (2010) used MWCNT to enhance the conductivity of reinforced continuous carbon fiber (RCCF) composite which is a good replace for metal due to its low cost, ease of fabrication and high oxidation stability. The performance of this composite was investigated for wireless and ultra wideband antenna applications. The results showed that antenna gain and read range of RFID tag antenna can be controlled by changing the conductivity of composite, which is not possible for materials with fixed conductivity such as copper. Mehdipour *et al*. (2011, 2012), used thin film made of SWCNTs (bucky papers) to develop a low profile wideband microstrip-fed monopole antenna operating over 24 to 34 GHz. Measurements and numerical simulations done Mehdipour and coworkers showed that, the bandwidth of CNT composite antenna is wider than that of copper antenna, CNT antenna is less affected by nearby objects than is the copper antenna and CNT antenna shows low dispersion characteristics. On the other hand, CNT antenna has lower efficiency than copper antenna because the Ohmic losses of composite material are higher than that of the metal.

4. Conclusions

This paper presented a review of some work that had been done to study the properties of CNT dipole antennas. The work considered here presented different methods of analysis to obtain current distribution along CNT antennas and their properties in radio, optical and IR range of frequencies.

There are some common results obtained from different works, they are:

- CNT dipoles have high input impedances, which may be beneficial for connecting to nano electronic circuits and serve as an excellent impedance matching circuit to get from free space to high impedance devices.
- CNT dipoles exhibit very low efficiencies.
- For radius values of the order of nanometers, CNTs exhibit significantly less loss than cylindrical copper antennas having the same dimensions.
- The wavelength of the excitation current is much smaller than the wavelength of the far field radiation.
- CNT antennas exhibit longitudinal current resonances within a certain frequency range (encompassing GHz and lower THz frequencies), and are strongly damped outside of this range.
- Using a bundle of SWNTs as a dipole antenna increases the efficiency of CNT antenna.
- The lowest frequency that can be suitable for a CNT antenna is nearly 100 GHz to obtain both of resonance and size reduction.

References

Attiya, A.M. (2009), "Lower frequency limit of carbon nanotube antenna", *Progress In Electromagnetics*

Research, PIER, **94**, 419-433
Balanis, C.A. (2005), *Antenna Theory: Analysis and Design*, Wiley, New York.
Bayram, Y., Zhou, Y., Shim, B.S., Xu, S., Zhu, J., Kotov, N.A. and Volakis, J.L. (2010), "E-textile conductors and polymer composites for conformal lightweight antennas", *IEEE Transactions on Antennas and Propagation*, **58**, 2732-2736
Burke, P.J. (2004a), "Luttinger liquid theory as a model of the gigahertz electrical properties of carbon nanotubes", *IEEE Transactions on Nanotechnology*, **1**(3), 129-144 (2002) and Erratum 3 (2)331-331.
Burke, P.J. (2004b), "An Rf circuit model for carbon nanotubes", *IEEE Transactions on Nanotechnology*, **2**(1), 55-58(2003) and Erratum, 3 (2)331-331.
Burke, P.J., Li, S. and Yu, Z. (2006), "Quantitative theory of nano wire and nanotube antenna performance", *IEEETrans. Nanotechnol*., **5**(4), 76-81.
Cheung, C.L., Hafner, J.F. and Leiber, C.M. (2000), "Carbon nanotube atomic force microscopy tips: direct growth by chemical vapor deposition and application to high-resolution imaging", *Proc. Natl. Acad. Sci.,* **97**, 3809-3813.
De Heer, W.A., Chatelain, A. and Ugarte, D. (1995), "A carbon nanotube field-emission electron source," *Science*, **270**, 1179-1180.
Dragoman, M., Dragoman, D., Al Ahmad, M., Plana, R. and Flahaut, E. (2009), "RF devices written with carbon nanotube ink on paper", *European Microwave Conference*, 575-577.
Dresselhaus, M., Dresselhaus, G. and Avouris, P. (2001), *Carbon Nanotubes: Synthesis, Structure, Properties, and Applications*, Springer Verlag, Berlin,Germany.
Durkop, T., Getty, S.A., Cobas, E. and Fuhrer, M.S. (2004), "Extraordinary mobility in semiconducting carbon nanotubes", *Nano Letters*, **4**(1), 35-39.
Guo, J., Lundstrom, M. and Datta, S. (2002), "Performance projections for ballistic carbon nanotube field-effect transistors", *Applied Physics Letters*, **80**, 3192-3194.
Hanson, G.W. (2005), "Fundamental transmitting properties of carbon nanotube antennas", *IEEE Trans. Antennas Propagate*, **53**(11), 426-3435.
Hanson, G.W. (2006), "Current on an infinitely-long carbon nanotube antenna excited by a gap generator," *IEEE Trans. Antennas Propagate*, **54**, 76-81.
Hao, J. and Hanson, G.W. (2006), "Infrared and optical properties of carbon nanotube dipole antennas", *IEEE Transaction on Nanotechnology*, **5**(6), 766-775.
Huang, S.M., Cai, X.Y., Du, C.S. and Liu, J. (2003), "Oriented long single walled carbon nanotubes on substrates from floating catalysts", *Journal of Physical Chemistry B*, **107**(48), 13251-13254.
Huang, S.M., Cai, X.Y. and Liu, J. (2003), "Growth of millimeter-long and horizontally aligned single-walled carbon nanotubes on flat substrates", *Journal of the American Chemical Society*, **125**(19), 5636-5637.
Huang, S.M., Maynor, B., Cai, X.Y. and Liu, J. (2003), "Ultralong, well-aligned single walled carbon nanotube architectures on surfaces", *Advanced Materials*, **15**(19), 1651-1655.
Huang, S.M., Woodson, M., Smalley, R. and Liu, J. (2004), "Growth mechanism of oriented long single walled carbon nanotubes using 'fast-heating'chemical vapor deposition process", *Nano Letters*, **4**(6), 1025-1028.
Huang, Y., Yin, W.Y. and Lui, Q.H. (2008), "Performance Prediction of carbon nanotube bundle dipole antennas", *IEEE Trans. Nanotechnology*, **7**, 331- 337.
Iijima, S. (1991), "Helical microtubules of graphitic carbon", *Nature*, **354**, 56-58.
Javey, A., Guo, J., Wang, Q., Lundstrom, M. and Dai, H.J. (2003), "Ballistic carbon nanotube field-effect transistors", *Nature*, **424**, 654-657.
Jones, D.S. (1994), *Methods in Electromagnetic Wave Propagation*, IEEE Press, Wiley, New York.
Kim, W., Choi, H.C., Shim, M., Li, Y.M., Wang, D.W. and Dai H.J. (2002), "Synthesis of ultra long and high percentage of semi conducting single-walled carbon nanotubes", *Nano Letters*, **2**(7), 703-708.
Kittel, C. (1986), *Introduction to Solid State Physics*, 6th Edition, Wiley , New York.
Lin, M.F. and Shung, K.W.K. (1994), "Plasmons and optical properties of carbon nanotubes", *Phys. Rev. B*, 50, 17744-17747.

Maffuci, A., Miano, G., Rubinacci, G., Tamburrino, A. and Villone, F. (2008), "Plasmonic, carbon nanotube and conventional nano-interconnects: a comparison of propagation properties", *12th IEEE workshop on signal propagation on interconnects*, SPI.

Maksimenko, S.A., Slepyan, G.Y., Lakhtakia, A., Yevtushenko, O. and Gusakov, A.V. (1999), "Electrodynamics of carbon nanotubes: dynamic conductivity, impedance boundary conditions, and surface wave propagation", *Phys. Rev. B*, **60**, 17136-17149.

Mehdipour, A., Sebak, A.R., Trueman, C.W., Rosca, I.D. and Hoa, S.V. (2010), "Reinforced continuous carbon-fiber composites using multi-wall carbon nanotubes for wideband antenna applications", *IEEE Transactions on Antennas and Propagation*, **58**, 2451-2456.

Mehdipour, A., Rosca, I., Seba,k A., Trueman, C. and Hoa, S., (2011), "Carbon nanotube composites for wideband millimeter- wave antenna applications", *IEEE Transactions on Antennas and Propagation*, **59**, 3572 -3578.

Mehdipour, A., Sebak, A., Trueman, C.W., Rosca, I.D. and Hoa, S.V. (2012), "Conductive carbon fiber composite materials for antenna and microwave applications", NRSC.

Merkoci, A. (2006), "Carbon nanotubes in analytical sciences", *Microchim. Acta,* **152**, 157-174

Poole, C.P and Owens, F.J. (2003), *Introduction to Nanotechnology*, Wiley Interscience.

Postma, H.W.C., Teepen, T., Yao, Z., Grifoni, M. and Dekker, C. (2001), "Carbon nanotube single-electron transistors at room temperature", *Science*, **293**, 76-79.

Roglski, M.S. and Palmer, S.B. (2000), *Solid State Physics*, Gordon and Breach, Australia.

Saito, R., Dresselhaus, G. and Dresselhaus, M.S. (2003), *Physical Properties of Carbon Nanotubes,* Imperial College Press, London, U.K.

Tasaki, S., Maekawa, K. and Yamabe, T. (1998), "π-band contribution to the optical properties of carbon nanotubes: effects of chirality", *Phys. Rev. B*, **57**, 9301-9318.

Wang, Y., Kempa, K., Kimball, B., Carlson, J.B., Benham, G., Li, W.Z., Kempa, T. and Rybczynski, J. (2004), "Receiving and transmitting light-like radio waves: antenna effect in arrays of aligned carbon nanotubes", *App. Phys. Lett.*, **85**(13), 2607-2609

Yang, L., Zhang, R., Staiculescu, D., Wong, C.P. and Tentzeris, M.M. (2009), "A novel conformal RFID-enabled module utilizing inkjet-printed antennas and carbon nanotubes for gas-detection applications", *IEEE Antennas and Wireless Propagation Letters*, **8**, 653-656.

Yu, Z., Li, S. and Burke, P.J. (2004a), "Synthesis of aligned arrays of millimeter long, straight single walled carbon nanotubes", *Chemistry Mater.*, **16**(18) 3414-3416.

Zheng, L.X., O'Connell, M.J., Doorn, S.K., Liao, X.Z., Zhao, Y.H., Akhadov, E.A., Hoffbauer, M.A., Roop, B.J., Jia, Q.X., Dye, R.C., Peterson, D.E., Huang, S.M., Liu, J. and Zhu, Y.T. (2004), "Ultralong single-wall carbon nanotubes", *Nat. Mater.*, **3**, 673.

Zhou, Y., Bayram, Y., Du, F., Dai, L. and Volakis, J.L. (2010), "Polymer-carbon nanotube sheets for conformal load bearing antennas", *IEEE Transactions on Antennas and Propagation*, **58**, 2169-2175.

Zhou, Y., Gaur, A., Hur, S.H., Kocabas, C., Meitl, M.A., Shim, M. and Rogers, J.A. (2004), "p-Channel, n-channel thin film transistors and p-n diodes based on single wall carbon nanotube networks", *Nano Letters*, **4**, 2031.

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