Electromagnetic Modeling of Antenna Array Based on Circular Carbon Nanotubes Bundle

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Abstract— A novel antenna array structure, formed by carbon nanotube bundle is proposed. The geometric structure and radiation characteristics have been investigated using a proposed integral equations system. This equations system is numerically solved using the moments method. The dependence of the radiation performance, upon geometrical parameters, e.g., nanotube length and number and the coupling distance is accurately discussed. Some illustrative numerical results have been presented to discuss the radiation performance of carbon nanotube antenna array for different coupling distances.

1. INTRODUCTION

Carbon nanotubes (CNT) are considered as one of the carbon's allotropes, formed by a rolled-up sheet of graphene. They were discovered by Ijima in 1991 [1]. Because the crystal structure of SWCNT is strongly related to that of graphene, the CNT are typically identified using graphene's lattice vectors [3]. In previous modeling works [4], CNT was considered as an antenna, but its potential performances have never been discussed. Recently, SWCNTs are synthesized with a length near to the microwave in free space, and by the way, this motivation leads to explore their properties as antenna. In the range of centimeter and millimeter applications, CNT antennas are originally proposed by Burke [5]. In [5], CNT dipole antennas are modeled using the transmission line approach, so the following transmission line parameters; kinetic inductance L_K, quantum capacitance C_Q and quantum resistance R are determined using the electrons fluid model.

Another common approach is to simulate electromagnetic wave propagation along CNT based on these electrodynamics properties [6]. This approach presents a macroscopic view for interactions of high frequency electromagnetic field with CNTs. However, the radiation efficiency of CNT antenna is very low, as a result of the slow wave surface which decreases the radiation resistance [7]. In addition, the CNT antennas are very resistive structures so the problem of impedance mismatch is strongly posed. In fact, the characteristic impedance of the CNT antenna (10–100 kΩ) is greater than each of the feeding line (50 Ω). To solve this problem the CNT bundle has been proposed and studied based on effective axial surface conductivity for low coupling distances [7–9]. In terahertz and infrared frequency range, the radiation characteristics of CNT dipole antenna arrays have been investigated by the CST MICROWAVE STUDIO simulator. It found that, $N \times N$ antennas array have a higher radiation efficiency than single CNT dipole antenna [10, 11]. In our previous works, we have proposed a general formulation based on a integral equations system which aimed at studying the coupled CNT dipole antenna. This formulation allowed a rigorously investigation of the antennas interaction for any coupling distance [13].

In this paper we propose a novel antenna array structure formed by carbon nanotube bundle. The numerical results shows that, we can obtain a higher antenna directivity with important reduction of the input impedance compared to the single CNT antenna.

2. MATHEMATIC FORMULATION

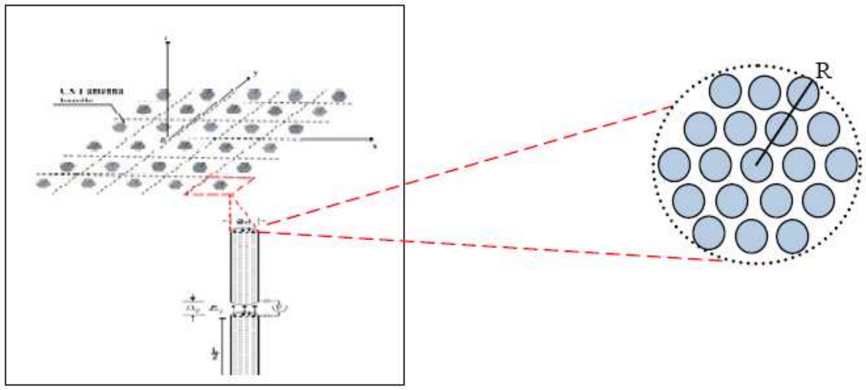
Figure 1(a) shows the antenna array structure made of $N \times N$ carbon nanotube bundles. The unit element is formed by a strongly coupled CNT, as a half wavelength dipole antenna with effective quantum mechanical conductivity σ.

2.1. Antenna Bundle

Dynamic conductivity of CNT can be calculated using the Boltzmann kinetic equation. For a small radius of CNT, the dynamic conductivity is given by [6]:

$$\sigma_{cn}(w) = \sigma_{zz}(w) \simeq -j\frac{2e^2 v_F}{\pi^2 \hbar a(w - j\nu)} \tag{1}$$

where e is the electron charge, ν is the relaxation electron frequency for CNT (equal to $3 \cdot 10^{-12}\,\mathrm{s}^{-1}$), a is the CNT radius, $\hbar$ the reduced Planck constant and here we use the Fermi velocity as $v_F = 9, 71.105\,\mathrm{ms}^{-1}$.



(a) (b)

Figure 1: (a) CNT antenna array formed by $N \times N$ antenna bundle, (b) schematic structure of SWCNT bundle.

In the case of low inter-tubes distances, the array elements are strongly coupled, and the CNT bundle is considered as a single antenna with radius R, length L and effective surface conductivity σ [8]. As shown in Figure 1(b), the antenna bundle is formed by N metallic CNT with radius a, which are parallely connected at their centers by a delta gap source with unit voltage. The effective surface conductivity is expressed as:

$$\sigma \simeq \frac{N\sigma_{cn}(w)a}{R} \tag{2}$$

The electromagnetic wave interaction between CNT antennas is modeled by the integral equation like the analysis of the single antenna. The main idea is to use the integral equation of single CNT antenna based on Hallen's integral equation, with a slight modification to include the surface conductivity of the bundle [8].

$$\left(k^2 + \frac{\partial^2}{\partial z^2}\right) \int_{-h}^{h} \left(\frac{e^{-jk\sqrt{(z-z')^2+a^2}}}{\sqrt{(z-z')^2+a^2}} + \frac{w\varepsilon}{a\sigma} \frac{e^{-jk|z-z'|}}{k} \right) I(z')dz' = -j4\pi w\varepsilon E_z^{in}(z) \tag{3}$$

This integral equation can be solved numerically using the MoM method to obtains the current distribution and deduce later the input impedance and the antenna radiation pattern.

2.2. Coupled Antennas

Considering N identical parallel CNT bundle as dipole antennas center-driven by N generators $V_{1,2,\ldots,N}$ and separated by the distance d. $I_{1,2,\ldots,N}(z)$ are the induced currents on the dipoles antennas.

On the surfaces of each dipole antenna, the electrical field is writing as [13]:

$$\begin{cases} E_{11}^d + E_{21}^d + E_{31}^d + \ldots + E_{N1}^d + E_1^{in} = Z_s I_1 \\ E_{12}^d + E_{22}^d + E_{32}^d + \ldots + E_{N2}^d + E_2^{in} = Z_s I_2 \\ \vdots \\ E_{1N}^d + E_{2N}^d + E_{3N}^d + \ldots + E_{NN}^d + E_N^{in} = Z_s I_N \end{cases} \tag{4}$$

where Z_s is the surface impedance per unit length of a SWCNT and E_{pq} is the z-component of the electric field on the antenna p induced by the current on the antenna q [13]:

$$E_{pq}(z) = \left(\frac{\partial^2}{\partial z^2} + k^2\right) \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{e^{-jkR_{pq}}}{R_{pq}} I_q\left(z'\right) dz' =_{pq} I_q \tag{5}$$

Using the MoM method, we covert this integral equations system in a matrix form and we deduce the unknown current distribution for each dipole antenna:

$$\begin{bmatrix} \left[\left\langle g_{1n}, \left(\widehat{G}_{11} - Z_s\right) f_{1m} \right\rangle\right] & \dots & \left[\left\langle g_{1n}, \widehat{G}_{N1} f_{1m} \right\rangle\right] \\ \dots & \ddots & \vdots \\ \left[\left\langle g_{Nn}, \widehat{G}_{1N} f_{Nm} \right\rangle\right] & \dots & \left[\left\langle g_{nN}, \left(\widehat{G}_{NN} - Z_s\right) f_{Nm} \right\rangle\right] \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_N \end{bmatrix} = - \begin{bmatrix} \left[\left\langle g_{1n}, E_1^{in} \right\rangle\right] \\ \vdots \\ \left[\left\langle g_{Nn}, E_N^{in} \right\rangle\right] \end{bmatrix} \quad (6)$$

3. NUMERICAL RESULTS

We present some illustrative numerical results for antenna array formed by five CNT bundle with length $L = 20\,\mu\text{m}$. Figure 2(a) shows the input impedance of a CNT bundle for different values of N. For $N = 5$, the first resonance occurs nearly at the frequency $f = 430\,\text{GHz}$ for a resonance impedance equal to $1645\,\Omega$. If we compare this results to the conventional half-wavelength dipole antenna, CNT dipole antenna has an important scale reduction factor of 0.057. For $N = 20$, the resonance frequency is nearly to $f = 600\,\text{GHz}$ and the resonance impedance is about $687\,\Omega$. Therefore, the scale reduction factor reaches a value of 0.08. It can be noted that the antenna bundle formed by $N = 120$ carbon nanotubes, does not resonate for this frequency range. So, for a fixed CNT length and radius, the input impedance is inversely proportional to the CNT number. If the CNT number increases, the resonance frequency shifts to the high values.

Next obtained results are shown for antenna array structure formed by five identical CNT antennas bundle distributed as shown in Figure 2(b). Only the antenna (1) is excited.

We present in Figure 3 the current distribution along each dipole antenna. It should be noted that, for a coupling distance $d = 0.1\lambda_p$, the excited antenna generate a current distribution more greater than each of the unexcited antenna. Furthermore, the current distribution of each antenna is approximately a half sinusoid for an operating frequency $f = 150\,\text{GHz}$ and antenna length $L = 20\,\mu\text{m}$ which corresponds to the first resonance. If the coupling distance increase ($d = 0.5\lambda_p$), all the antenna current distributions keeps the same shape with lowering of the magnitude (Figure 3(b)). Figure 4 shows the Antenna array radiation pattern obtained for different coupling distances at the operating frequency $f = 150\,\text{GHz}$. from this results we can note that, the antenna directivity

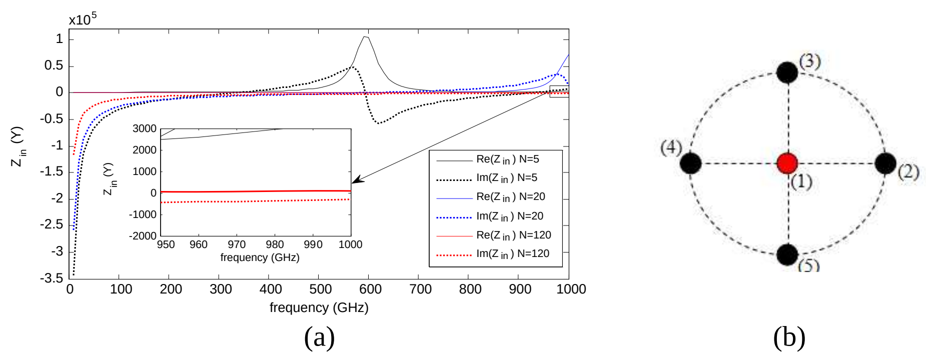


Figure 2: (a) Input impedance of CNT antenna bundle as a function of the frequency for different number of carbon nanotube, (b) five antennas array structure.

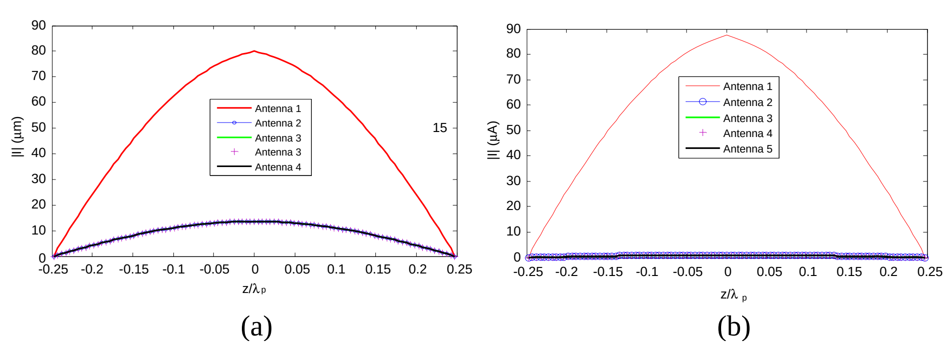


Figure 3: Current distribution along each dipole antenna bundle at the operating frequency $f = 150\,\text{GHz}$. (a) the coupling distance $d = 0.1\lambda_p$, (b) the coupling distance $d = 0.5\lambda_p$.

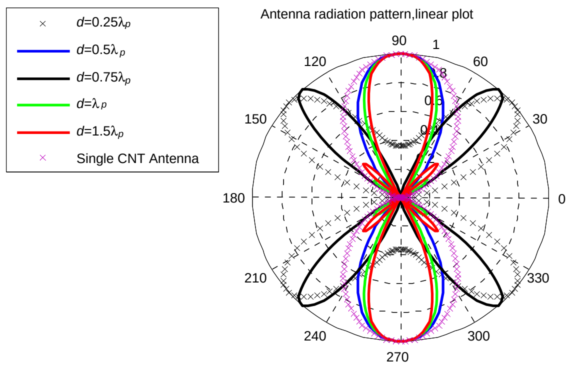


Figure 4: Antenna array radiation pattern obtained for different coupling distances at the operating frequency $f = 150\,\text{GHz}$.

is significantly depends on the antenna separate distance. In fact, for a coupling distances that are greater than λ_p we observe a high directivity compared to the single CNT antenna.

4. CONCLUSION

The geometric structure and the radiation properties of the antenna formed by a CNT bundle have been studied by a proposed integral equations system. Obtained results show that, to obtain a high directivity and radiation efficiency, we can increase the array elements number with optimization of inter-elements distances and CNT length.

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