Electromagnetic Radiation from Carbon Nanotube at Terahertz Frequency

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***Abstract*-The feasibility of terahertz wave radiation emitted form carbon nanotube has been studied based on the simple tight-binding theory. The properties of terahertz wave and the current distribution on carbon nanotube have been characterized. The radiation efficiency of carbon nanotube bundles has been compared with that of single walled carbon nanotube. The result shows the efficiency of single walled carbon nanobue bundle dipole antennas is much higher than that of a single walled carbon nanotue dipole antenna.**

I. INTRODUCTION

Terahertz (THz) technology is important in many fields of science and engineering. One of main limitations of existing basis research, new initiatives and advanced technology development in the THz range is the THz wave emitters [1-4]. Though the generation of THz radiation by optical rectification or photoconductive switching has been extensively studied using ultra-short laser pulse[5], the peak electric fields of THz wave are generally much smaller than that generated by the biased emitters. Therefore, there is a need to develop a new THz emitter that can be expediently embedded into the material and can generate THz radiation for the ultra-wideband applications.

The applications of nanoscale materials and devices, however, are opening up opportunities to significantly improve the development of THz technology and enhance THz system performance. There is a great potential for a synergy between THz technology and nanoscience and nanotechnology which is a rapidly growing area of research. The reason for this is that electrons in solids travel hundreds of times slower than light, and therefore electron dynamics in nanostructures typically fall in the THz frequency region[6-9].

One of the latest trends in THz region is to use carbon nanotubes as an excellent candidate of high frequency devices because of their unique band structure leading to ballistic electron motion over micrometer mean free path.

In this paper, we propose an alternative scheme for generating THz radiation from carbon nanotubes as an antenna.

Carbon nanotubes are formed from the two dimensional graphite layer which has hexagonal lattice structure. A single walled carbon nanotube (SWNT) can be viewed as a seamless cylinder obtained by rolling up a piece of two-dimensional grapheme sheet (Fig.1). A multi-walled carbon nanotube (MWNT) is made out of several concentric grapheme cylinders. The structure of a SWNT is uniquely characterized by the chiral vector

$$\boldsymbol{C}_h = n\boldsymbol{a}_1 + m\boldsymbol{a}_2 \tag{1}$$

where $\boldsymbol{a}_1$ and $\boldsymbol{a}_2$ are the grapheme lattice vectors and n, m are integers. Both the theory calculations and scanning tunneling microscopy (STM) measurements indicate that the vector $\boldsymbol{C}_h$ determines the diameter (d) and chiral angle (θ) of a SWNT, d and θ is given by

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

and

$$\theta = \tan^{-1}\left(\frac{\sqrt{3}m}{2n+m}\right) \tag{3}$$

where b = 0.142nm is the nearest neighbor carbon atom distance. The (n, m) indices determine the three types of SWNT: zig-zag (n, m = 0), armchair ($n = m$) and helical ($n \neq m$) SWNT. A SWNT can be semiconducting with a distinct bandgap, or it can be metallic with no bandgap determined by the diameter and helicity of nanotube. The armchair (n, n) SWNTs are metallic with band crossings at $\mathbf{k} = \pm 2/3$ of the one-dimensional Brilluoin zone. The zig-zag (n, 0) SWNTs have two distinct types of behavior: the tubes will be metals when $n/3$ is an integer, and otherwise semicondutors. The helical SWNTs are metallic when $(2n + m)/3$ is an integer, otherwise semiconducting.

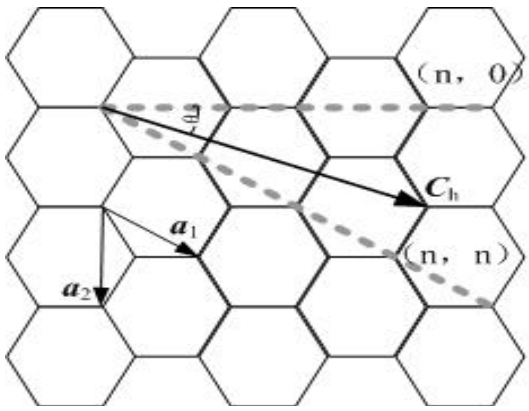

Fig.1 Schematic of a two-dimensional graphene sheet illustrates lattice vectors and the chiral vector.

Semiconducting SWNTs are being extensively studied as the future channel material for ultrahigh performance and scaled field-effect transistors and are expected to be the successors of silicon transistors. Metallic SWNTs have been identified as possible interconnect material of future technology generations and the heir to aluminum and copper interconnects. Leading theoreticians, as well as experimentalists, have started research in earnest to understand the transport mechanism and the conducting properties of metallic SWNTs. It has been demonstrated that the ballistic transport can be achieved in SWNTs, and very high current densities have been noted with very little performance degradation.

The synthesized SWNT bundles consisting of several hundred SWNT arranged in two-dimensional triangular lattice[10]. The individual tubes in the bundle are attracted to their nearest neighbors via the van der Waals interactions, with typical distance between the tubes being comparable to the interplanar distance of graphite which is 0.34nm.

In this paper, we propose an alternative scheme for generating THz radiation from carbon nanotubes as an antenna.

II. Theory of Carbon Nanotube Generating THz Radiation

A SWNT is defined by a cylindrical graphene sheet with a diameter of about 0.4-10nm, though most of the observed SWNTs have diameters d < 5 nm. The electronic energy spectrum of carbon nanotubes is therefore determined by the energy spectrum $E_g(k)$ of a two-dimensional graphene sheet, which can be described by the equation

$$E_g(k) = \pm\gamma_0[1 + 4\cos(\frac{\sqrt{3}a}{2}k_x)\cos(\frac{a}{2}k_y) + 4\cos^2(\frac{a}{2}k_y)]^{1/2} \quad (4)$$

where $a = \sqrt{3}b$. To obtain the electronic structure of SWNTs, we express k_x and k_y by the periodic boundary condition

$$\boldsymbol{k}\cdot\boldsymbol{C}_h = k_x C_x + k_y C_y = 2\pi p \text{ (}p\text{ is an integer)} \quad (5)$$

and substitute Eq.(5) in Eq.(4), thus yielding

$$E^{\pm}_{\mathrm{CNT}}(kl) = \pm\gamma_0[1 + 4\cos(\frac{a}{2}k_{\mathrm{k,l}})\cos\left(\frac{(2n+m)a}{2m}k_{\mathrm{k,l}} - \frac{2\pi}{m}l\right) + 4\cos^2(\frac{a}{2}k_{\mathrm{k,l}})]^{1/2} \quad (6)$$

where

$$k_{\mathrm{k,l}} = k\frac{\sqrt{3}am}{2C_{\mathrm{h}}} + l\frac{\pi a(2n+m)}{C_{\mathrm{h}}^2} \ (l = 0, 1, 2 \ldots). \quad (7)$$

In the case of metallic armchair (n, n) tubes, the expression for the electronic energy spectrum is obtained as following

$$E^{\pm}_{\mathrm{CNT}}(kl) = \pm\gamma_0[1 + 4\cos(\frac{a}{4}k + \frac{\pi}{2n}l)\cos\left(\frac{3a}{4}k - \frac{\pi}{2n}l\right) + 4\cos^2(\frac{a}{4}k + \frac{\pi}{2n}l)]^{1/2} \quad (8)$$

We will now discuss essential aspects of the metallic nanotube band structure that are necessary to understand their generation of electromagnetic wave in terahertz region. The band structure of a single walled armchair metallic nanotube is shown in Fig. 2. The band structure shows various subbands arising from quantization of the wave vector around the circumference of the nanotube.

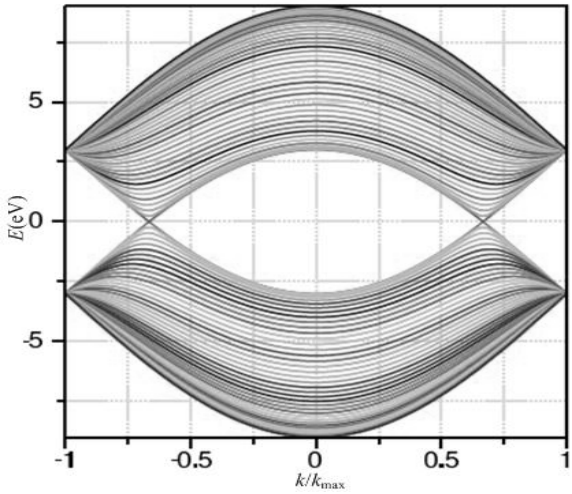

Fig.2 Electron energy structure of armchair nanotube

When the high enough electric field is applied on the carbon nanotube axis, on the one hand, the energy of an electron below the Fermi level will increases and the electron will move along the heavy line shown in Fig. 3. Once the

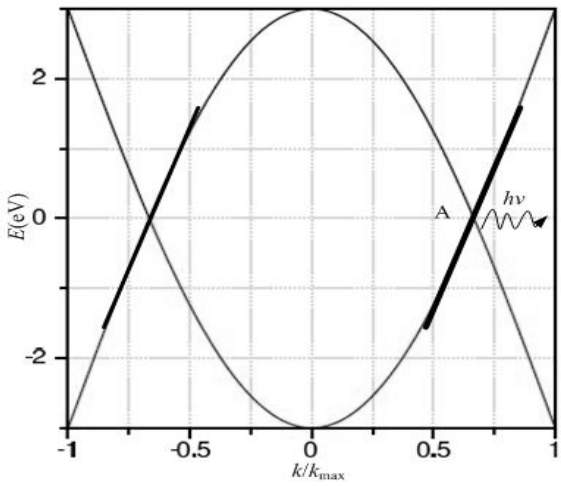

Fig.3 The diagram of inverse population resulting in terahertz radiation

electron exceeds the state 'A', the inverse population is achieved, and this inversion leads to the generation of electromagnetic wave corresponding to optical transitions from high energy state to low energy state. On the other hand, at high biases, accelerated electrons gain enough energy to emit optical or zone-boundary phonons. The energy of optical and zone-boundary phonons is about 0.2 eV and 0.16 eV, corresponding to the frequency of about 50 THz and 40THz, respectively. This implies that the phenomenon under consideration can lead to the radiation of electromagnetic waves in a board range up to terahertz frequencies. Therefore,

the above discussion can be used for creating a terahertz source with carbon nanotube as antenna.

III. Model of SWNT Antenna

Since carbon nanotubes can be grown having length on the order of a centimeter, and exhibiting unique electric properties, they can be regarded as nanotube antenna in recent year. A carbon nanotubes dipole antenna having large aspect ratio *L/R*, can be regarded as a sufficiently thin tube. Therefore, the transverse current can be neglected, and just only the longitudinal current $I_z(z)$ distributes on the canbon nanotubes. The axial component $A_z(z)$ of the magnetic vector potential $\boldsymbol{A}$ on the surface of a carbon nanotubes antenna that has the surface impedance per unit length z^i and the total tangential current $I_z(z)$ satisfies the one-dimensional Pocklington's integral equation

$$\left(\frac{d^2}{dz^2}+k_0^2\right)A_z(z)=\mathrm{j}\frac{k_0^2}{\omega}\left[z^i I_z(z)-E_z^i(z)\right] \tag{9}$$

where

$$z^i=\frac{1}{2\pi R\sigma_{\mathrm{CN}}^z} \tag{10}$$

is the nanotube's surface impedance, k_0 is free-space wave number, ω is the argue frequency, and $E^i_z(z)$ is incident electric field, σ_{CN}^Z is the quantum conductance of the carbon nanotube

$$\sigma_{CN}^z=-j\frac{2e^2\upsilon_F}{\pi^2\hbar R(\omega-j\nu)} \tag{11}$$

where υ_F is the Fermi velocity for a carbon nanotube, $\hbar$ is the Planck constant, and ν is the relaxation frequency. The vector potential on the surface of carbon nanotube antenna is given approximately by

$$A_z(z)=\mu_0\int_{-L/2}^{+L/2}I_z(z')K(z,z')dz' \tag{12}$$

where μ_0 is the permeability of free space, z and z' represent the observation point and the source point, respectively, and

$$K(z,z')\approx\frac{1}{4\pi}\frac{e^{-\mathrm{j}k_0\sqrt{R^2+(z-z')^2}}}{\sqrt{R^2+(z-z')^2}}. \tag{13}$$

We substitute Eq. (10)-(13) in Eq. (9) and the result is

$$\left(\frac{d^2}{dz^2}+k_0^2\right)\int_{-L/2}^{+L/2}I_z(z')\frac{e^{-jk_0\sqrt{R^2+(z-z')^2}}}{\sqrt{R^2+(z-z')^2}}dz'$$
$$=j\frac{4\pi k_0^2}{\mu_0\omega}\left[z^i I_z(z')-E_z^i(z')\right]. \tag{14}$$

The above integral equation is solved using the MoM. Once the current distribution is known, it is straightforward to calculate the other radiated characteristics.

IV. Results

Since carbon nanotubes can be grown having lengths on the order of 0.4 cm, and having unique electric behaviors, it is reasonable to consider them for millimeter wave and sub-millimeter wave antenna.

Figure 4-5 show the current distribution on the L = 100 nm carbon nanotube at the first and second resonant frequencies, F = 6.2 THz, and F = 22.6 THz. As can be seen from figure 4, the current is approximately a half-sinusoid.

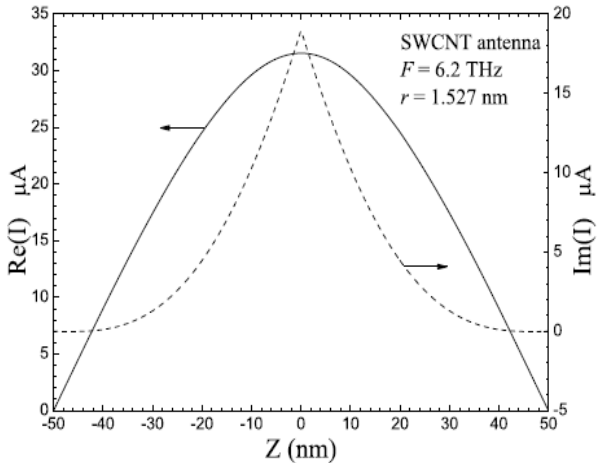

Fig.4 Current distribution on a carbon nanotube (n =39, m=0)

In Fig. 5, the current profiles on the same size nanotube vary in the standing waveform.

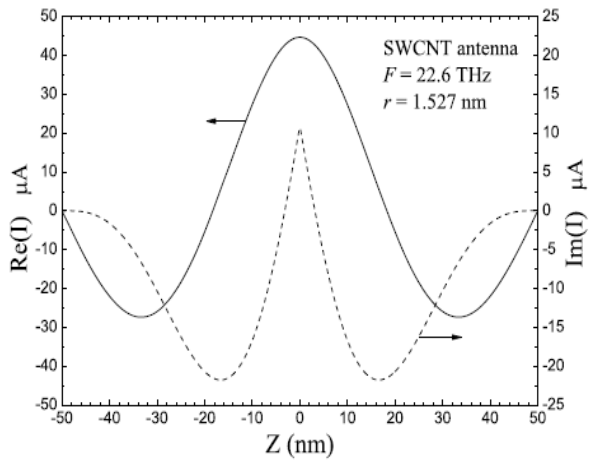

Fig.5 Current distribution on a carbon nanotube (n =39, m=0)

Figure 6 shows a typical transient THz electric field waveform observed in the direction parallel to the dipole antenna with a length of L = 0.5λ at r = (5, 0, 0) μm. The first main positive and negative peaks of pulse have full width at half maxima of 59 fs and 56 fs, respectively. One can note that THz pulse has a delay of about 164 fs, and that the THz signal shows several peaks corresponding to multiple THz reflections in the antenna. The maximum peak of THz field is up to 2.66 kV/cm. Figure 6(b) shows a transient far field THz pulse in the direction at r = (10, 0, 0) μm. Note that there is a delay of approximately 181 fs because of the propagation of the fields from the antenna edges to a probing point in the far field. The

initial negative peak with a width of 56 fs is followed by a high peak pulse which persists for about 0.16 ps. As depicted in Fig. 6(b), the maximum peak of THz field is 1.26kV/cm. Some weaker oscillations can be obviously seen for longer delays and the average oscillation period of THz pulse is roughly 0.13 ps, which can be resulted from current multiple reflections in the CNT antenna.

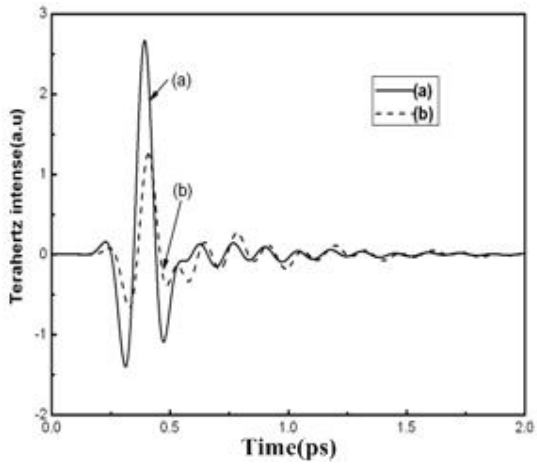

Fig.6 (**a**) THz pulse in a position to the parallel direction with the antenna of $L = 0.5\lambda$ at $r = (5, 0, 0)$ μm. (**b**) THz pulse at $r = (10, 0, 0)$ μm.

Figure 7 shows the efficiency of a SWNT antenna and various SWNT bundles antennas in the THz band. Admittedly, one can see that the efficiency of the SWNT antenna is very

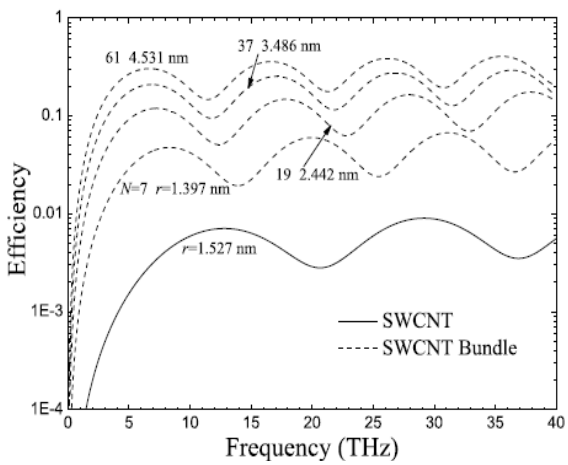

Fig.7 Efficiency of carbon nanotube antenna

low on account of its extremely small radius and large ohmic resistance and the strong retarded surface wave that reduces the radiation resistance, compared with traditional macroscopic dipole antennas. In addition, the problem of impedance mismatch is also obvious. This makes the use of individual SWNT as an antenna unlikely in conventional antenna, and requires parallel/bundle nanotubes for realistic application. As can be seen from Fig.7, the efficiency of the SWNT bundle dipole antennas is much higher than that of a SWNT dipole antenna. Especially, the efficiency of the bundle antenna of N=61 approaches that of the normal macroscopic antenna. Thus, the SWNT bundles as the potential candidate for applications of nano-electronic devices are very promising to replace conventional dipole antenna as new source candidates of terahertz radiation.

V. CONCLUSION

In this paper, we have presented carbon nanotube as antenna for generating terahertz radiation. It is fundamental science study showing that the metallic carbon nanotube can emit the terahertz radiation when the electric field is applied to it. The model of carbon nanotube antenna has been established, and the current distribution and radiation efficiency have been analyzed. The results show that SWNT can radiate terahertz wave, and demonstrate that the efficiency of CNT bundle antenna is higher than that of SWNT antenna.

ACKNOWLEDGMENT

The work is supported by the National Natural Science Foundation of China (60971064), the Open Project Program of State Key Laboratory of Millimeter Wave of China (K201006), the Science and Technology on Electromagnetic Environment Laboratory, the special funds projects for technological and innovative talent of Harbin City (2010RFXXG010), the Ph.D. Programs Foundation of Ministry of Education of China (No.20092302110030), the Research Foundation of Education Bureau of Heilongjiang Province (11531055) and Youth Foundation of Harbin University of Science and Technology (2009YF025).

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