Radiation Efficiency Assessment of Bundled Carbon Nanotube Antenna at Terahertz frequency range

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Abstract

The radiation efficiency of bundled carbon nanotubes (BCNTs) for the fabrication of antennas in the terahertz frequency range is evaluated. The performance is compared against thin gold film, which is conventionally used for antenna fabrication. The macroscopic behavior of BCNTs is modeled by an anisotropic thin resistive sheet model and its surface resistivity is extracted from the theoretical distributed circuit model of a single wall carbon nanotube (SWNT). Also, a thin gold layer in terahertz band is characterized by the Drude-Smith model which calculates the theoretical conductivity of fabricated thin gold in optical frequency. Conventional half-wave strip antennas are designed to resonate from 1 THz to 50 THz and the method of moments (MoM) and the mixed potential integral equation (MPIE) techniques are utilized to calculate radiation efficiencies of the resonant strip antennas composed of BCNTs and thin gold film. The numerical simulation result shows that the radiation efficiency of a BCNT antenna is consistently lower than the efficiency of a gold film antenna in cases of BCNT equivalent density values up to 10^4 [CNTs/μm]. However, if equivalent density values above 10^4 [CNTs/μm] could ever be achieved, which are approximately three order of magnitude higher than the currently realizable density (10 [CNTs/μm]), BCNTs would outperform thin gold film at frequencies above 1 THz.

1. Introduction

Carbon nanotube (CNT) has been introduced as an alternative material to metal for antenna radiators and transmission lines in high frequencies. Single-wall carbon nanotube (SWNT) shows a superior value of the intrinsic conductivity compared to copper in DC. However its resistance per unit length is very high due to its very small radius (on the orders of a few nanometers) [1]. This high resistance causes high mismatch of CNT-based system to conventional 50 Ω transmission line in RF application. To overcome this limitation of SWNTs for an efficient transmission line and antenna radiator, the bundled CNTs (BCNTs) has been suggested [2]. In laboratory measurements up to 50 GHz, it was shown that the impedance of BCNTs is simply equal to component value of discrete circuit element of SWNT divided by its number density [CNTs/μm] [2]. By assuming the scalability of SWNTs in its bundled structure, this paper employed the distributed circuit model of SWNT in theory [3], the series kinetic inductance per unit length of 16nH/μm and the resistance per unit length of 6.5kΩ/μm. Also, the current fabrication technology produces BCNTs where horizontally aligned SWNTs arrays are grown with number densities of 10 ~ 30 [CNTs/μm], the number of SWNTs in unit width along a direction perpendicular to SWNTs axis [4, 5].

The application of SWNTs as an antenna radiator at terahertz frequencies can be viable, due to a high quality factor (~100) of this RL series circuit of SWNT at frequencies higher than 6.5 THz. Also, this high Q factor at terahertz frequencies is preserved in the bundled structure because SWNTs in the bundle are connected in parallel. One dimensional transport of electrons along SWNT indicates that the concept of skin depth for the conventional conductor is not applicable to SWNTs, so the high conductivity of SWNTs is obtained even though the thickness of BCNTs is very small compared to the wavelength of terahertz band. On the other hand, the surface resistivity of general conductors increases with frequency due to skin depth effect. Thus, it is expected that BCNT antenna should surpass metallic antenna in terms of radiation efficiency at a particular frequency in terahertz band. To apply high frequency properties of metal (the thin gold film in this paper) to the numerical simulation, the Drude-Smith model is utilized [6]. In this paper, an anisotropic resistive sheet model to represent BCNTs electromagnetically is presented. Then, a numerical simulation using method of moments (MoM) is developed to calculate radiation efficiencies of resonant strip antennas fabricated with BCNTs and thin gold film. The radiation efficiencies are compared as a function of frequency and number density of BCNTs to find a crossover frequency where BCNT antenna outperforms the thin gold film antenna.

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3. Anisotropic Resistive Sheet Model of Bundled Carbon Nanotube

In a BCNT, the electrons in each single SWNT predominantly pass along the tube axis while there is also a small amount of movement in the transverse direction, which indicates that electrons can jump to adjacent SWNTs. Even though this microscopic electron transport occurs randomly, the reported experiments, which have verified the scalability of inductance element of SWNT in its bundled structure [2], indicate that the overall current flow along the bundle can be assumed to be axial. Thus, to examine the electromagnetic properties of SWNTs aligned in a planar structure, an anisotropic macroscopic model is proposed. Since the thickness of a BCNT layer (~10nm) is much thinner than the wavelength up to optical frequencies, such material can be explained by a thin resistive sheet model. The general boundary conditions for the thin resistive sheet are shown in (1) where $\hat{n}$ is the unit vector normal to the resistive sheet drawn at the upward (positive) side of the sheet and $[..]_-^+$ denotes the discontinuity across the sheet. Fig. 1 shows the proposed geometry of a strip dipole antenna constructed from strands of SWNTs. Each SWNT in the bundle is equivalent to series inductance (L_k) and resistance (R_{CNT}) and is connected in parallel inside its bundle. Since SWNT is aligned along x-axis, only the x-directed electric field can excite the current on the surface. In the rectangular segment indicated by Δ and δ in Fig. 1, the surface resistivity along x-axis is derived as shown in (2) by dividing voltage across Δ with the current flowing through δ. The number density (N) represents the number of SWNTs in unit width. The x-directed surface resistivity (R_x) of BCNTs is proportional to the resistance and kinetic inductance of SWNT and is inversely proportional to number density of SWNTs. This one directional current flow causes the anisotropic property of BCNTs and results in $\overline{\overline{R}}$, a complex surface resistivity dyad as shown in (3). The boundary condition (1) is implemented in a MoM code developed for antenna simulations.

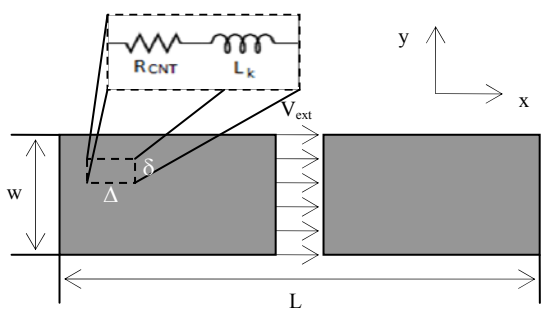

Figure. 1: Geometry of a strip antenna made up of BCNTs.

$$\left[\hat{n}\times\overline{E}\right]_-^+ = 0,\ \ \hat{n}\times\left(\hat{n}\times\overline{E}\right) = -\overline{\overline{R}}\cdot\overline{J} \qquad (1)$$

$$\text{where } \overline{J} = \left[\hat{n}\times\overline{E}\right]_-^+$$

$$R_x = \frac{R_{CNT} + j\omega L_K}{N} \qquad (2)$$

$$\text{where } R_{CNT} = 6.5\,k\Omega/\mu m,\ L_K = 16nH/\mu m$$

$$\overline{\overline{R}} = \begin{bmatrix} R_x & 0 \\ 0 & R_\infty \end{bmatrix} \qquad (3)$$

4. Strip Dipole Antenna Simulation

To evaluate the performance of the antenna made up of BCNTs and thin gold film, the length (L) of strip dipole antenna in Fig. 1 is designed to get a fundamental resonance over the frequency range of 1 THz to 40 THz. The physical length of each CNT antenna always turns out to be less than the half of the fundamental resonant wavelength. The ratio depends on number density of SWNT (N) and the kinetic inductance of its equivalent circuit. The width (w) is chosen to be L/6 and antenna feed gap is set to λ/100. Fig. 2 and 3 are obtained from MoM simulations for BCNT and thin gold film antennas. Fig. 2 shows the normalized antenna length (2L/λ) at the first resonance for different BCNT number densities and also for the thin gold film antenna. Fig. 3 shows the radiation resistance of the antennas at their resonant frequencies. Each point in the figures is calculated from an antenna design which has a specific length (L) and a material property. As shown in Fig. 2, when BCNT density is low, the resonant frequency happens at frequencies where 2L/λ is less than one. This is due to the fact that series kinetic inductance lowers the resonant frequency. Otherwise, as the number density increases, the series inductance is lowered to a point that effective inductance becomes very small. Fig. 3 shows that the BCNT antenna radiation resistance decreases with frequency. Otherwise, the thin gold film antenna radiation resistance is almost constant or slightly increases with frequency.

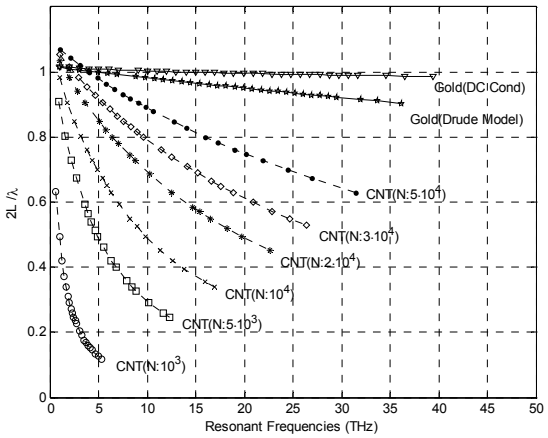

Figure. 2: Normalized antenna length (2L/λ) versus resonant frequencies.

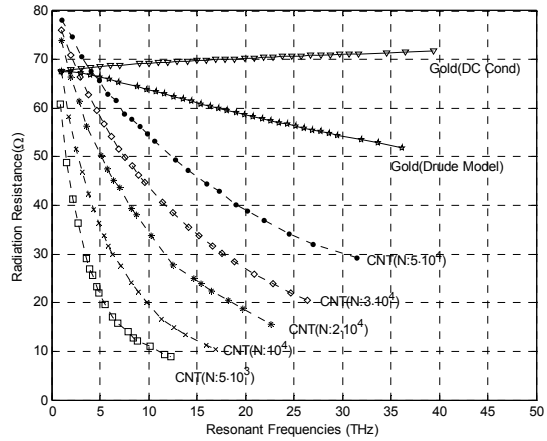

Figure. 3: Radiation resistance of strip antenna made of BCNT antenna and thin gold film versus resonant frequencies.

The radiation and antenna efficiency at the resonant frequencies for BCNT and thin gold antennas are calculated. Fig. 4 shows the antenna efficiency of BCNT and thin gold antennas without considering input mismatch to 50 Ω feeding transmission line while Fig. 5 shows the radiation efficiency which accounts for the input reflection to 50 Ω line. The radiation efficiency of BCNT antenna significantly drops compared to the antenna efficiency due to a very small input resistance at terahertz frequencies. As shown in both figures, the BCNT antenna with a number density lower than 10^3 [CNTs/μm] does not show efficient radiation efficiency. Also, the gold thin film antenna designed by the Drude model shows a more gradual efficiency drops compared to that of DC gold in terahertz frequencies. To evaluate BCNTs as terahertz antenna applications, the efficiency of BCNT antenna should be compared with the efficiency of a conventional thin gold film antenna. Fig. 4 and 5 indicate that a number density of BCNTs should be approximately $2{\cdot}10^4$ [CNTs/μm] to outperform thin gold film. The radiation efficiency in Fig. 5(b) shows that when the number density (N) is $2{\cdot}10^4$ [CNTs/μm], the radiation efficiency of CNT antenna outperforms thin gold film up to 4 THz. Specifically with number densities of $2{\cdot}10^4$, $3{\cdot}10^4$, and $5{\cdot}10^4$ [CNTs/μm], the radiation efficiency of BCNT antennas outperforms thin gold film at frequencies up to approximately 10 THz, 16 THz, and 30 THz, respectively. The big mismatch caused by a small input resistance of BCNT antenna compared to 50 Ω at high frequencies makes its radiation efficiency lower than the efficiency of thin gold film antenna.

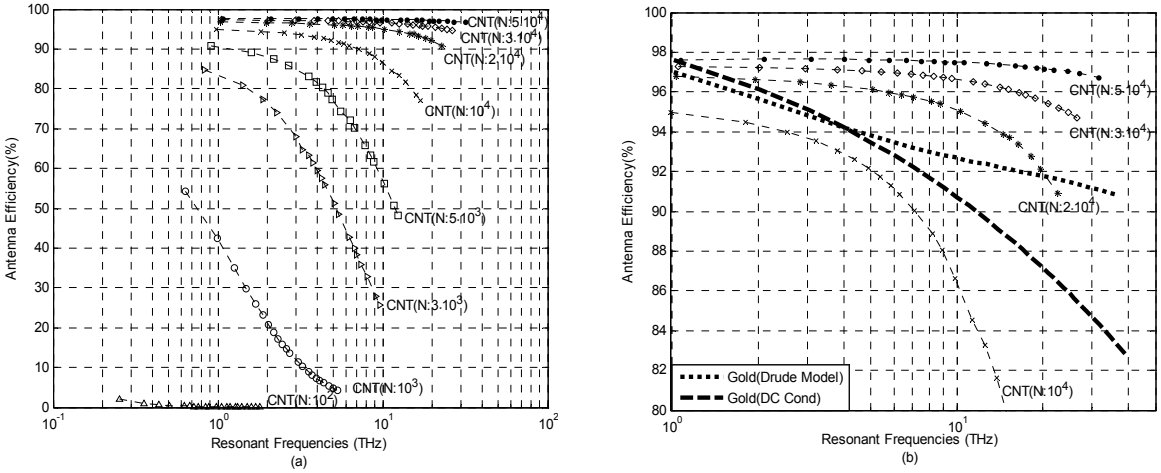

Figure. 4: Antenna efficiency of strip dipole antenna of BCNTs (N: CNTs/μm) and thin gold film.

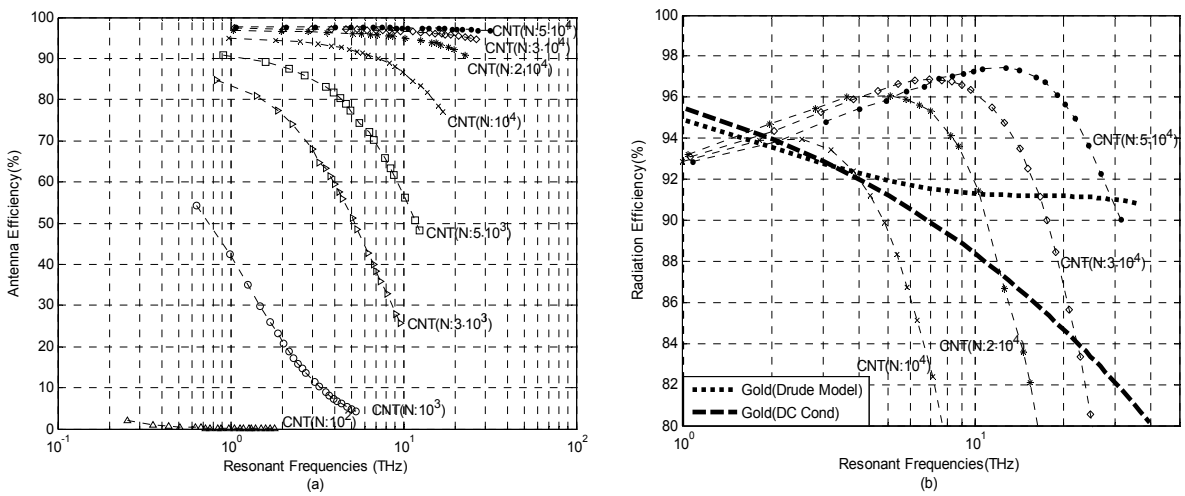

Figure. 5: Radiation efficiency (with 50 Ω matching) of strip dipole antenna of BCNTs (N: CNTs/μm) and thin gold film.

5. Conclusion

By using scalability of equivalent circuit of SWNT in its bundle structure, a nano-sized material, BCNTs is modeled by the anisotropic thin resistive sheet in terahertz frequency range. The strip antenna consists of BCNTs is simulated by a MoM code where the anisotropic surface resistivity of BCNTs is implemented in the boundary condition. The results show that the BCNT antennas where the density of SWNT lower than 10^3 [CNTs/μm] do not show effective radiation efficiency in terahertz frequencies. To be an efficient radiator, the number density of the BCNTs should be higher than approximately 10^4 [CNTs/μm], which indicates the necessity of more densely aligned CNTs in the fabrication process. Thus, BCNTs as an efficient antenna radiator in terahertz region should have a density of approximately thousands of times higher than the currently realizable density, 10 [CNTs/μm] inside the bundled structure.

6. References

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