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Carbon Nanotubes Composite Materials for Dipole Antennas at Terahertz Range

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Abstract—This paper aims to present two types of carbon nanotubes composite materials (CNTs-composite) for antenna applications within terahertz (THz) frequency band. These composite materials consist of CNTs coated by copper and silver, separately, to construct CNTs-copper and CNTs-silver composite materials, respectively. The comparisons between the dipole antennas of these structure materials with CNTs dipole antenna and copper dipole antenna are presented to exhibit performance evaluation of the presented new dipole antennas. The mathematical modeling of CNTs-composite material is presented in this paper. The results obtained from the comparisons CNTs-copper and CNTs-silver dipole antennas are presented based on S_{11} parameters, gain and efficiency.

1. INTRODUCTION

The field of THz technology has been growing dramatically over the past few years [1]. From the electrical stand point, CNTs have high electrical properties which make them distinguished from other materials. CNTs have several forms of structures derived from an original graphene sheet and are classified into single-walled carbon nanotube (SWCNT) and multi-walled carbon nanotube (MWCNT) based on their structures [2, 3]. A lot of researchers assumed that CNTs antennas technology will be at the frontier of scientific research for next decades, especially in wireless communication technology. This assumption was presented, based on the idea that CNTs can radiate as a small nano-dipole antenna when it is electromagnetically excited [4–6]. With nanometer length of CNTs dipole antenna, the electromagnetic (EM) radiation from this antenna is expected to cover a range within terahertz and optical frequency [7]. SWCNT was presented as a theoretical study to characterize the THz antenna based on combining the Boltzmann transport equation and Maxwell's equations with boundary conditions of the electron distribution function [8].

CNTs antenna can be a novel solution to reduce the gap of communication between the microscopic world and nanotechnology devices. It would also be advantageous to the applications requiring a wireless connection with the nano-scale devices like nano-sensors [9]. SWCNTs-dipole antenna is one of the most potential CNTs antennas in the nanotechnology antenna field, especially for the infrared (IR) and terahertz (THz) frequency ranges [2, 10, 11]. For the purpose of comparison of the SWCNT dipole antenna with metal dipole antenna, it is beneficial to implement a comparison of these antennas with same size and shape [2].

The CNTs-composite material is a promising nano material for different applications, where CNTs are coated by other materials to modify the CNTs structure properties and to construct the CNTs-composite material structure [12–15]. Therefore, these approaches make the CNTs-composite material

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become materials with much more potential for various applications that have been explored in recent years.

This paper proposes CNTs-composite materials consist of CNTs coated by a thin layer of copper and silver separately for the first time, for THz frequency band, where the SWCNT is a specific structure of CNTs utilized in this work. The mathematical model of the presented structures is derived based on the mixture rule, for a simple parallel model of the radial interface of coating material and SWCNT. The comparisons between the dipole antennas of these material structures with CNTs and copper dipole antennas are presented to exhibit the enhancement of performance for the proposed dipole antennas.

2. METHODOLOGY

In this paper, a new material structure (NMS) is presented to design a dipole antenna for wireless antenna applications at THz frequency band and fulfill the required enhancement for the antenna properties. The effective model approach will be used for modelling the NMS.

2.1. Structure of Proposed Composite Material

Researchers have attempted to produce new materials necessary for designing antennas for the future technology. There is an urgent demand for designing and implementing antennas based on new material structures with remarkable properties. To achieve this aim, this work proposes a new material structure based on CNTs material (SWCNTs), due to their rare properties, through the integration of CNTs material with other materials. The CNTs-composite material consists of SWCNT coated by a thin layer of copper to construct (SWCNT-copper) material and SWCNT coated by silver to construct (SWCNT-silver) material. The main structure of CNTs-composite material (NMS) is illustrated in Figure 1 and Figure 2.

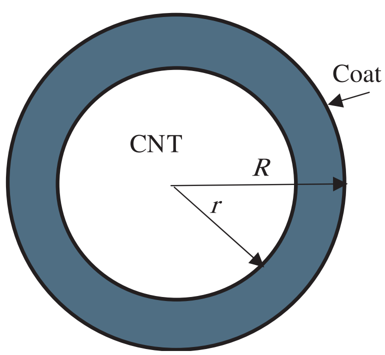

Figure 1. Structure of CNTs-composite material.

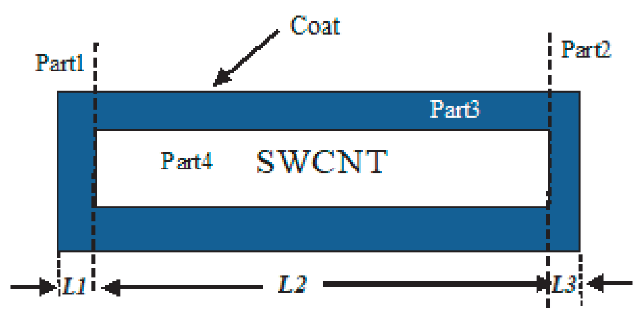

Figure 2. Schematic of CNTs-composite material.

The dependence of the CNTs-composite material properties on SWCNT-composite length, diameter, and type of coating material has been taken into considerations when designing and implementing the dipole antennas of NMS.

In this structure, assume that $L_1 = L_3$, which means that the two terminals at the end of composite tube have the same dimensions with respect to the length of SWCNT. The electrical conductivity of NMS consists of four parts, which are Part1 & Part2 representing the coating material at the two ends of composite tube; Part3 represents the coating material over the SWCNT; Part4 represents the SWCNT material.

2.2. Mathematical Analysis of SWCNT-Composite Material

The electrical conductivity is an important property of the NMS (SWCNT-composite material). Similarly, the influences of the SWCNT and layer of coated material are related significantly with the electrical conductivity of the NMS. Therefore, the estimation of this property for the new structure or any other similar structures is very crucial for modelling and EM simulation in the CST (MWS). In this mathematical modelling approach, the electrical conductivity of the new structure (SWCNT coated by other material) is denoted by (σ_{NMS}). Meanwhile, the conductivity of coating material is denoted by (σ_{coat}).

The mathematical model of proposed structure (NMS) is derived based on the mixture rule, for a simple parallel model of the radial interface of coating material and SWCNT. Therefore, the electrical conductivity of this structure is derived to obtain the general formula of the electrical conductivity of NMS presented as follows:

$$A_{\mathrm{NMS}}\sigma_{\mathrm{NMS}} = C_{\mathrm{SWCNT}}L_2\sigma_{\mathrm{SWCNT}} + A_{\mathrm{Coat}}L_2\sigma_{\mathrm{Coat}} + 2A_{\mathrm{tip}}L_1\sigma_{\mathrm{Coat}} \tag{1}$$

where, (A_{NMS}) represents the cross-sectional area of SWCNTs-composite structure, (C_{SWCNT}) the cross-section area of individual SWCNT (circumference of SWCNT), (A_{Coat}) the radial cross-sectional area of coating material, and (σ_{SWCNT}) the electrical conductivity of SWCNT [2]. Then, the final expression of this conductivity is presented as follows:

$$\pi R^2\sigma_{\mathrm{NMS}}(w) = \left(2\pi R^2 L_1 + \pi\left(R^2 - r^2\right)L_2\right)\sigma_{\mathrm{Coat}} + 2\pi r L_2\sigma_{\mathrm{SWCNYT}} \tag{2}$$

$$\sigma_{\mathrm{NMS}}(w) = \frac{1}{R^2}\left[\left(2R^2 L_1 + \left(R^2 - r^2\right)L_2\right)\sigma_{\mathrm{Coat}} + 2rL_2\sigma_{\mathrm{SWCNT}}\right] \tag{3}$$

$$\sigma_{\mathrm{NMS}}(w) = \frac{1}{R^2}\left[\left(2R^2 L_1 + \left(R^2 - r^2\right)L_2\right)\sigma_{\mathrm{Coat}} + \left(-j\frac{4e^2V_fL_2}{\pi^2 h(w-jv)}\right)\right] \tag{4}$$

$$\sigma_{\mathrm{NMS}}(w) = \frac{1}{R^2}\left[\left(2R^2 L_1 + \left(R^2 - r^2\right)L_3\right)\sigma_{\mathrm{Coat}} + L_3\left(\frac{4e^2V_fv}{\pi^2 h\left(w^2+v^2\right)} - j\frac{4e^2V_fw}{\pi^2 h\left(w^2+v^2\right)}\right)\right] \tag{5}$$

where r is the radius of SWCNT, e the electron charge, h the reduced Plank's constant ($h = 1.05457266 \times 10^{-34}\,\mathrm{J}\cdot\mathrm{s}$), t the average thickness of coating layer, V_f the Fermi velocity of CNT ($V_f = 9.71 \times 10^5\,\mathrm{m/s}$), v the estimated phenomenological relaxation frequency ($v = \frac{6T}{r}$), when T is temperature in kelvin, so $F_v = v/2\pi$, and w the angular frequency.

For the purpose of EM modelling and simulation, plasma frequency (W_{NMS}) is an important parameter of the NMS that must be estimated in this mathematical modeling approach.

$$W_{\mathrm{NMS}} = \frac{e}{\pi R}\left[\frac{4V_f + \pi^2 hD}{h\varepsilon^o}\right]^{1/2} \tag{6}$$

$$D = \left(\frac{\left(R^2 - r^2\right)v\sigma_{\mathrm{Coat}}}{e^2}\right) \tag{7}$$

The relative complex permittivity of the NMS is derived, based on the material parameters reported in this mathematical modeling approach and the general mathematical relation between the complex permittivity and plasma frequency.

$$\varepsilon'_{\mathrm{NMS}} = 1 - \frac{w^2_{P,\mathrm{NMS}}}{w^2 + v^2} \tag{8}$$

$$\varepsilon''_{NMS} = \frac{vw^2_{P,\mathrm{NMS}}}{w^3 + wv^2} \tag{9}$$

where $\varepsilon'_{\mathrm{NMS}}$ and $\varepsilon''_{\mathrm{NMS}}$ represent the real and imaginary parts of the relative complex permittivity of the NMS. From the above mathematical representation and analysis for the NMS, one can conclude that the effective conductivity, relative complex permittivity, and plasma frequency are affected by several parameters such as the conductivity of coating material (σ_{Coat}) and average thickness of coating layer (t). In another context, the EM behavior of these structures will be changed corresponding to the change of these parameters.

2.3. Simulation Modelling Approach of New Material Structure

In modern research of antenna applications, the investigation of electromagnetic properties is very important to present new materials for designing and implementing the modern antennas. This work relies on the EM representation approach to represent the CNTs-composite material structure based on its major parameters that have been extracted for the purpose of EM simulation. This model is inherently limited to the case of SWCNT-composite material structure. These parameters have been employed to represent the NMS by equivalent bulk material into CST (MWS). The main objective of this modelling approach is to enable simple and efficient EM analysis for the NMS using the CST (MWS). Therefore, the material parameters of NMS have been set in the CST (MWS) to design and implement the dipole antennas of NMS to estimate the antenna parameters of NMS.

3. SIMULATION RESULTS AND DISCUSSIONS

This section presents the simulation results of the proposed material structure NMS (SWCNT-copper) and (SWCNT-silver) according to their material parameters through CST (MWS).

The behaviour of electrical conductivity of the NMS dipole antennas are presented to explain the dependency of the behaviour of this structure on different parameters such as length of SWCNT, radius of SWCNT, type of coating material and average thickness of coating layer. In these simulation results, the length of coating material at two terminals of the tube is $L_1 = L_3 = 0.005L_2$. Figure 3(a) presents the dependency of conductivity of the NMS on the frequency at antenna length $L = 10\,\mu\text{m}$, radius of SWCNT $r = 2.71\,\text{nm}$, and average thickness layer of coating material $t = 2\,\text{nm}$. At the same dimensions with SWCNT length $L = 40\,\mu\text{m}$, Figure 3(b) presents the dependency of conductivity of the NMS on the frequency. Figure 4, presents the dependency of conductivity of the NMS on the frequency based on antenna length $L = 10\,\mu\text{m}$, radius of SWCNT $r = 6.77\,\text{nm}$ and average thickness layer of coating material $t = 2\,\text{nm}$. Meanwhile, the dependency of conductivity of NMS on the frequency based on antenna length $L = 10\,\mu\text{m}$, radius of SWCNT $r = 2.71\,\text{nm}$ with average thickness layers of coating material $t = 5\,\text{nm}$ and $t = 2\,\text{nm}$ is presented in Figure 5 and Figure 6, respectively.

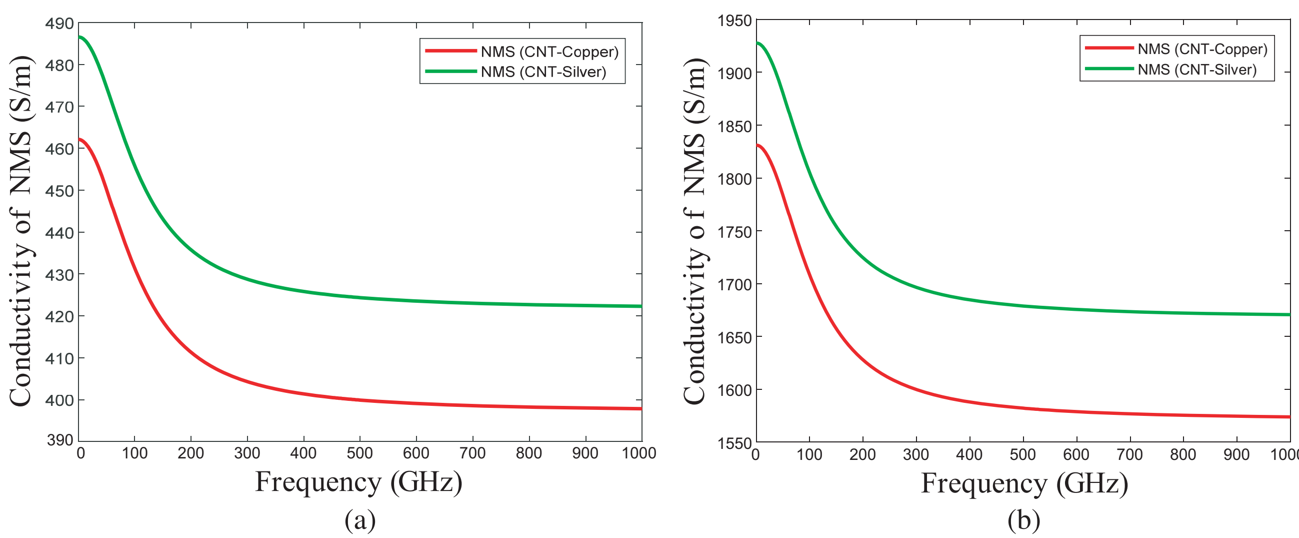

Figure 3. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver), radius $r = 2.71\,\text{nm}$, average thickness layer of coating material $t = 2\,\text{nm}$, and (a) at antenna length $L = 10\,\mu\text{m}$, (b) at antenna length $L = 40\,\mu\text{m}$.

As illustrated in these results, the conductivity is inversely proportional to the radius of SWCNT based on Figures 4&5 and proportional to the length of SWCNT based on Figure 3, and the average thickness of coating layer based on Figure 5 and Figure 6. The EM simulation results of the NMS (SWCNTs-copper) and NMS (SWCNTs-silver) dipole antennas are presented in this section based on different antenna lengths L and average thickness of coating layer (t) between 2 and 5 nm. The main parameters of the NMSs are mathematically derived and inserted into the CST (MWS), Drude dispersion

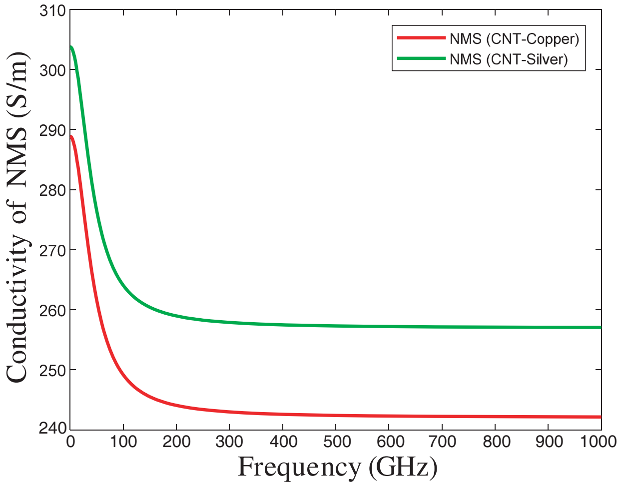

Figure 4. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver), radius $r = 6.77\,\text{nm}$, average thickness layer of coating material $t = 2\,\text{nm}$, and at antenna length $L = 10\,\mu\text{m}$.

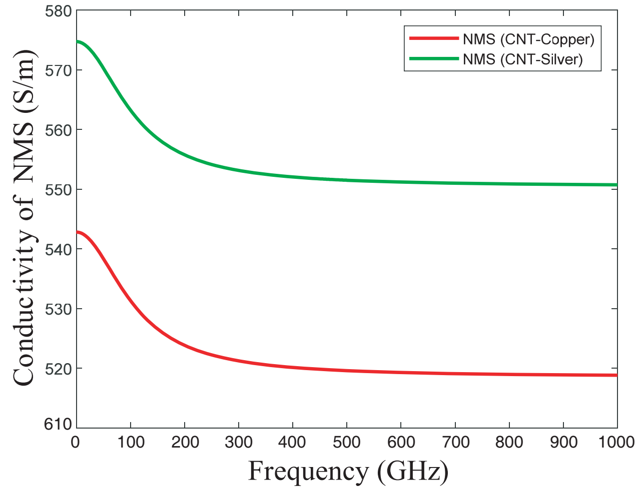

Figure 5. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver), radius $r = 2.71\,\text{nm}$, average thickness layer of coating material $t = 5\,\text{nm}$, and at antenna length $L = 10\,\mu\text{m}$.

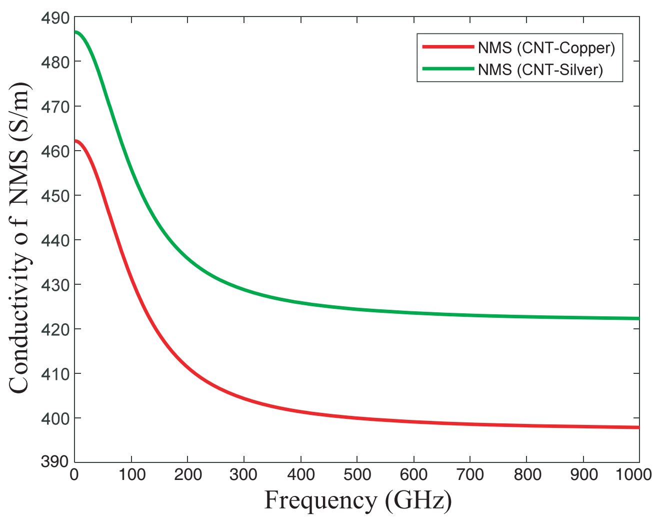

Figure 6. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver), radius $r = 2.71\,\text{nm}$, average thickness layer of coating material $t = 2\,\text{nm}$, and at antenna length $L = 10\,\mu\text{m}$.

method as a new normal material, in order to represent these structures in the CST (MWS). The dipole antenna of both structures of NMSs are designed and implemented to estimate their EM properties.

Figure 7, illustrates the simulation results of S_{11} parameter of the NMS (SWCNT-copper and SWCNT-silver) dipole antennas with SWCNT radius $r = 2.71\,\text{nm}$, average thickness of coating layer $t = 2\,\text{nm}$, and total antenna length $L = 10$, 20, 30, and $40\,\mu\text{m}$.

The comparisons of simulation results for the SWCNT-copper and SWCNT-silver dipole antennas with CNT dipole antenna (SWCNT dipole antenna) have been presented based on the similarity of dimensions of these dipole antennas. For this purpose, the simulation modeling approach of SWCNT, presented in our previous work [4, 6], is utilized to design and simulate the SWCNT dipole antenna into CST (MWS). The simulation results of SWCNT dipole antenna are illustrated in Figure 8, with different dipole antenna lengths.

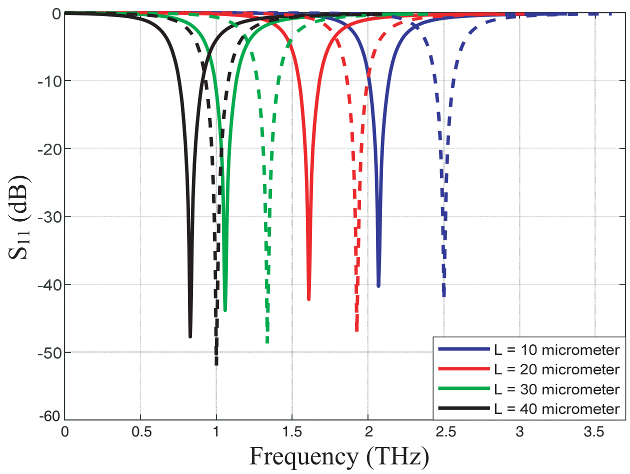

Figure 7. Simulation results of S_{11} parameters of equivalent NMS (SWCNT-copper as solid line) and (SWCNT-silver as dotted line) dipole antennas, where $r = 2.71\,\text{nm}$, $t = 2\,\text{nm}$, and antenna length $L = 10$, 20, 30, and 40 μm.

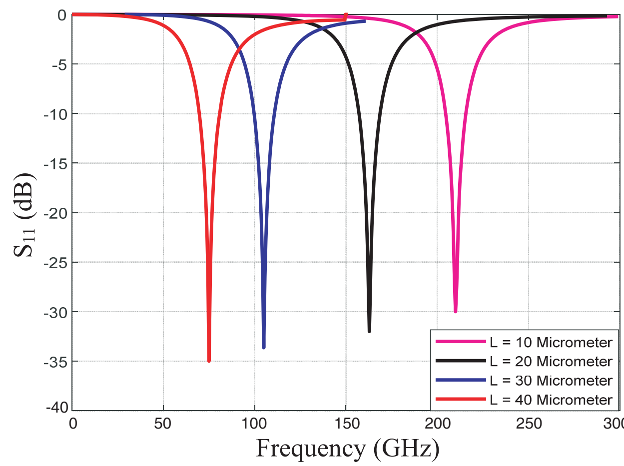

Figure 8. Simulation results of S_{11} parameters of equivalent SWCNT dipole antennas, where $r = 2.71\,\text{nm}$ and antenna length $L = 10$, 20, 30, and 40 μm.

According to the antenna performance, scientific comparisons for SWCNT-copper and SWCNT-silver dipole antennas with original (CNT dipole antenna) SWCNT dipole antenna are implemented based on the similarity of dimensions of these dipole antennas. These comparisons are implemented to clarify the advantages of these new material structures over the pure CNTs (SWCNTs) dipole antenna. Table 1 and Table 2 show the results of these comparisons.

As can be seen in Figure 7 and Figure 8 with Table 1 and Table 2, the NMS (SWCNT-copper) and (SWCNT-silver) resonate at 1.6 THz and 1.8 THz, respectively at antenna length $L = 20$ μm. Also,

Table 1. Summary of comparison results for SWCNT and NMS (SWCNT-copper) dipole antenna.

L (μm)	SWCNT dipole antenna				NMS (SWCNT-Copper) (after coating)			
	Fr (GHz)	Directivity (dBi)	Gain	Efficiency	Fr (THz)	Directivity (dBi)	Gain	Efficiency
10	210	1.96	9.61×10^{-5}	6.11×10^{-5}	2.1	1.92	7.5×10^{-2}	6.33×10^{-2}
20	162	2.05	9.89×10^{-5}	6.18×10^{-5}	1.6	2.10	6.47×10^{-2}	5.68×10^{-2}
30	105	2.21	1.07×10^{-4}	6.40^{-5}	1.1	1.95	7.4×10^{-2}	7.1×10^{-2}
40	76	2.14	1.10×10^{-4}	6.74×10^{-5}	0.8	1.94	8.2×10^{-2}	7.5×10^{-2}

Table 2. Summary of comparison results for SWCNT and NMS (SWCNT-silver) dipole antenna.

L (μm)	SWCNT dipole antenna				NMS (SWCNT-silver) (after coating)			
	Fr (GHz)	Directivity (dBi)	Gain	Efficiency	Fr (THz)	Directivity (dBi)	Gain	Efficiency
10	210	1.96	9.61×10^{-5}	6.11×10^{-5}	2.5	1.95	4.85×10^{-2}	4.2×10^{-2}
20	162	2.05	9.89×10^{-5}	6.18×10^{-5}	1.9	1.93	5.23×10^{-2}	4.75×10^{-2}
30	105	2.21	1.07×10^{-4}	6.44×10^{-5}	1.3	1.94	6.33×10^{-2}	5.9×10^{-2}
40	76	2.14	1.10×10^{-4}	6.74×10^{-5}	1.0	1.92	7.42×10^{-2}	6.85×10^{-2}

the NMS (SWCNT-silver) has a resonant frequency higher than NMS (SWCNT-copper) and SWCNT dipole antennas with the same shape, length and size. These differences of resonant frequencies are due to different properties of their material structures, as well as different properties of the electrical conductivity of these structures as illustrated in Figure 3, Figure 4, Figure 5 and Figure 6.

Also, the bandwidth of SWCNT dipole antenna is 11.551 GHz in resonant frequency 162 GHz, and the bandwidth of NMS (SWCNT-copper) dipole antenna is 0.15THz in resonant frequency 1.6 THz, at antenna length 20 μm. From these results, the NMS (SWCNT-copper) and (SWCNT-silver) is suitable for THz frequency range.

On the bases of these comparisons, the advantages of the new structures are shifting up the resonant frequency and increasing the bandwidth of their dipole antennas compared with the dipole antenna of SWCNT. Enhancements the gain and efficiency of the NMS dipole antenna are compared with SWCNT dipole antenna, as well as enhancement the S_{11} parameters of the NMS dipole antenna.

On the other hand, to explain the advantage of the NMS over copper material, the scientific comparison is implemented for these materials based on the same dimensions of dipole antennas. Therefore, the dipole antenna of copper material is designed and implemented using CST (MWS). The copper dipole antenna is designed with antenna lengths ($DL = 10$, 20, 30, and 40 μm) and radius ($rcu = 4.71$ nm). The simulation result of copper dipole antenna is illustrated in Figure 9. In this figure, the copper dipole antenna shows no resonant frequency which is in agreement with the finding demonstrated by [2]. On the bases of the NMS dipole antennas results presented in Figure 7, the NMS can be considered as a good material structure for designing dipole antennas at nanoscale and microscale dimensions. This is a very important advantage for the NMS over copper material at these scales of dimensions.

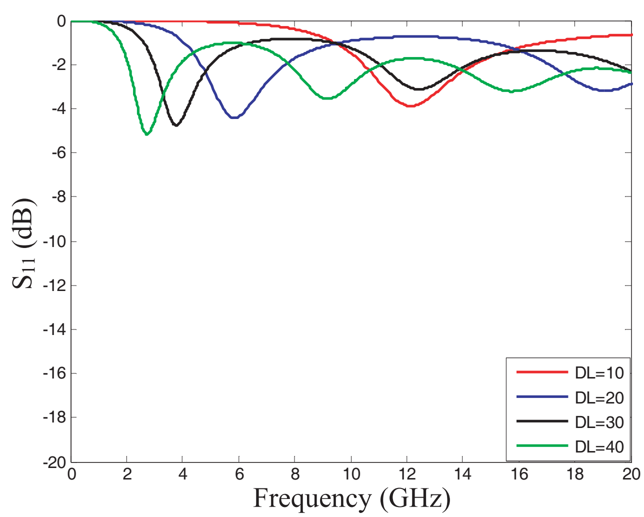

Figure 9. Simulation results of S_{11} parameters of Copper dipole antenna where, $rcu = 4.71$ nm, and the antenna length ($DL = 10$, 20, 30, and 40 μm.

4. CONCLUSIONS

In this work, the new material structure NMS, which is SWCNTs coated by a thin layer of a copper and silver material, respectively, is presented. The main purpose of this structure is to design a dipole antenna with two different structures (SWCNT-copper) and (SWCNT-sliver).

The NMS (SWCNT-copper) and (SWCNT-sliver) are proposed to design dipole antennas with the enhancement of antenna parameters such as S_{11} parameter, gain, efficiency, bandwidth, and other parameters compared with the original SWCNTs dipole antenna and copper dipole antenna. All these enhanced antenna parameters are shown and elucidated in this work. Finally, on the bases of the results presented in this work, the NMS (SWCNT-copper) dipole antenna has better gain and efficiency than other dipole antennas.

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