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Bandwidth Optimization of Single-walled Carbon Nanotube Dipole Antenna at GHz Frequency Regime

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***Abstract*— *This paper presents two different materials-based carbon nanotube composite (CNT-composite) material for antenna applications. These materials are single-walled CNT SWCNT and single-walled CNT composite material SWCNT-composite. The SWCNT are coated by a thin layer of (graphite, silver, or copper) material to construct new Nano-materials. Scientific and mathematical modeling approaches are presented in order to estimate the electromagnetic properties of these materials into CST (MWS) software package. For the purpose of supporting these modeling approaches, the required mathematical analysis is presented and discussed. The dipole antenna configuration will be utilized to estimate the electromagnetic properties of the SWCNT-composite a material. The results of this work showed the enhancement in the electromagnetic properties of the SWCNT-composite materials compared with the SWCNT material, respectively. The bandwidth and fractional bandwidth are the main enhance parameters that will be focused in this work.*

***Keywords*— Bandwidth Optimization, MWS, SWCNT.**

I. INTRODUCTION

The field of THz technology and applications has been growing significantly over the bygone years [1-2]. From the electrical stand point, the CNTs have high electrical properties which make them distinguished from other materials. The CNTs have several forms of structures derived from an original graphene sheet. The CNTs are classified into single-walled carbon nanotube (SWCNT) and multi-walled carbon nanotube (MWCNT) based on their structures [3-4]. A lot of researchers assumed that the CNTs antennas technology will be at the frontier of scientific research for the next decades, especially in the wireless communication nanotechnology. This assumption was presented, based on the idea that the CNTs can radiate as a small nano-dipole antenna when it is electromagnetically excited [5-7]. With the nanometer length of CNTs dipole antenna, the electromagnetic (EM) radiation from this antenna is expected to cover a range within terahertz and optical frequency [8]. The SWCNT was presented as a theoretical study to characterize the THz antenna based on combined the Boltzmann transport equation and Maxwell's equations with boundary conditions of the electron distribution function [9-10].

The CNTs antenna can be a novel solution to reduce the gap of communication between the microscopic world and the nanotechnology devices. It would also be advantageous to the applications which required a wireless connection with the nano-scale devices like nano-sensors

[9]. The 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, 10-14]. For the purpose of comparison the SWCNT dipole antenna with metal dipole antenna results, it is benefit 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, the CNTs are coated by other materials to modify the CNTs structure properties and to construct the CNTs-composite material structure [15-18]. Therefore, these approaches make the CNTs-composite material becomes much more potential materials for various applications that have been explored in recent years.

This paper proposes the 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 the specific structure of CNTs utilized in this work. The mathematical model of 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 evaluation for the proposed dipole antennas.

II. METHODOLOGY

In this paper, a new material structure (NMS) is presented to design 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.

1.1 Structure of proposed composite material

The researchers have attempted to produce new materials, which are necessary for designing antennas for the future technology. There is an urgent demand to design and implement the antennas based on new material structure has remarkable properties. To achieve this aim, this work proposed 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.

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

In this structure, assume that the $L_1 = L_3$, that means 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 represent the coating material at the two ends of composite tube, Part3 represents the coating material over the SWCNT and Part4 represents the SWCNT material

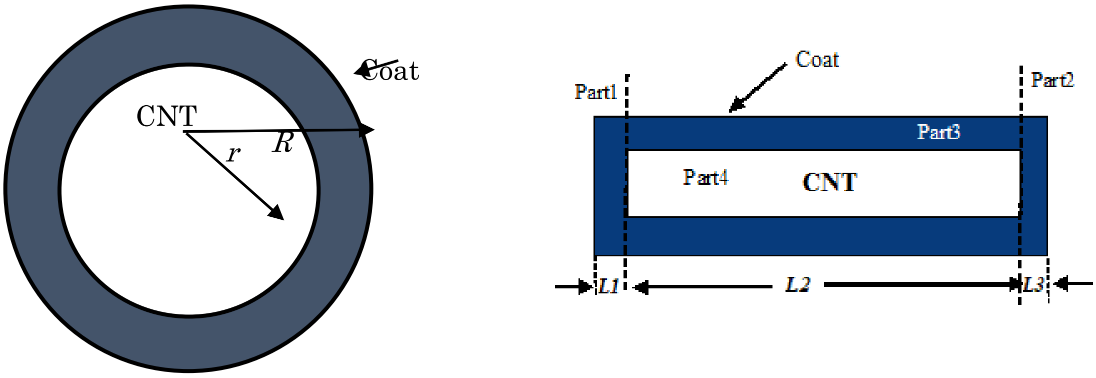


Fig.1. Structure of CNTs-composite material.

1.2 Mathematical Analysis of SWCNT-composite Material

The electrical conductivity is the 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 structure 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 has been derived to obtain the general formula of the electrical conductivity of NMS that was presented as follows:

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

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

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

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

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

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

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

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

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

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

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.

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

$$\varepsilon''_{NMS} = \frac{v\;\; w^2_{P,NMS}}{w^3 + w v^2} \tag{9}$$

Where, ε'_{NMS} and ε''_{NMS} represents the real part and imaginary part 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.

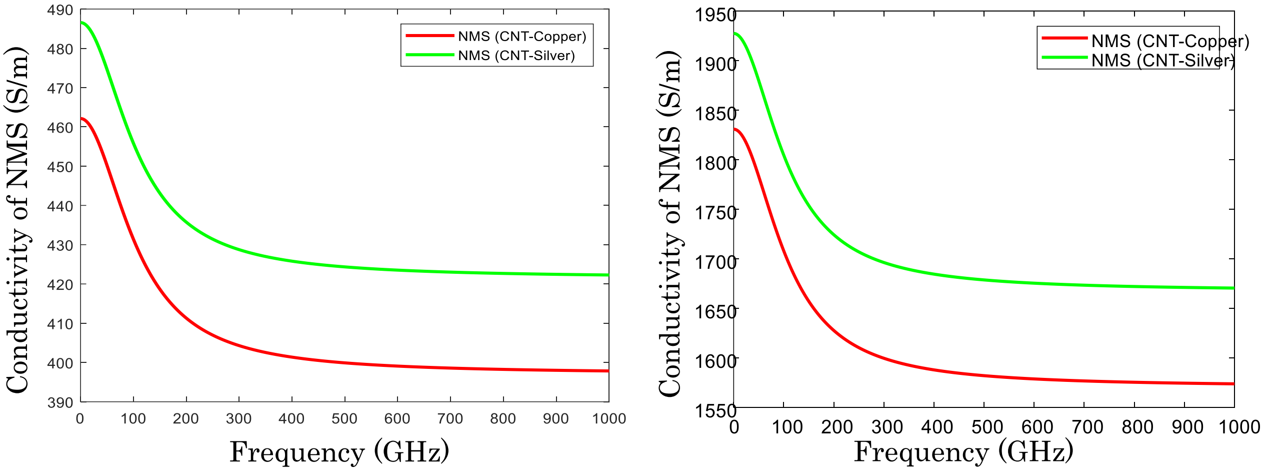
2.3 Simulation Modelling Approach of New Material Structure

In modern research of antenna applications, the investigation of electromagnetic properties is very important to candidate the materials to design and implement the modernist antennas. This work relies on the EM representation approach to represent the CNTs-composite material structure based on their 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.

III. 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 the 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 the two terminals of tube is $L_1 = L_3 = 0.005\ L_2$**.** Figure (3-a) presents the dependency of conductivity of the NMS on the frequency at SWCNT length L = 10 µm, radius of SWCNT is r = 2.71 nm and the average thickness layer of coating material is t = 2nm. At the same dimensions with SWCNT length L = 40 µm**,** Figure (3-b) present the dependency of conductivity of the NMS on the frequency. Figure 4, present the dependency of conductivity of the NMS on the frequency based on SWCNT length L = 10 µm, radius of SWCNT is r = 6.77 nm and the average thickness layer of coating material is t = 2nm. Meanwhile, the dependency of conductivity of NMS on the frequency based on SWCNT length L = 10 µm, radius of SWCNT is r = 2.71 nm and the average thickness layer of coating material are t = 5 nm and t = 2 nm have been presented in Figure 5 and Figure 6, respectively.



(a) (b)

Fig.3. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver) radius r= 2.71 nm, average thickness layer of coating material is t=2nm, and (a) at antenna length L = 10 µm (b) at antenna length L = 40 µm.

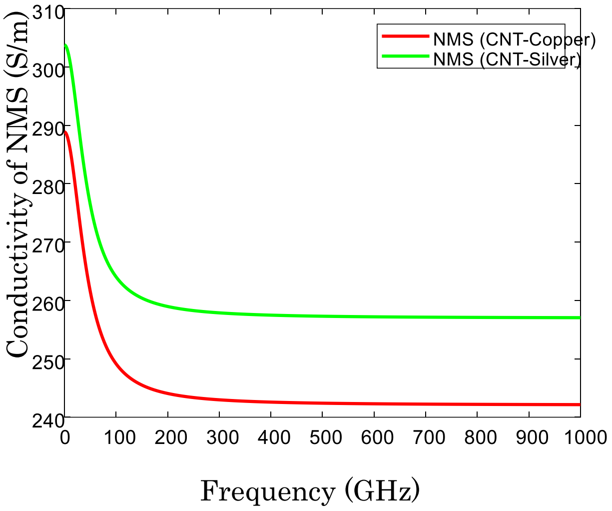


Figure 4. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver) radius r= 6.77 nm, average thickness layer of coating material is t=2nm, and at antenna length L = 10 µm.

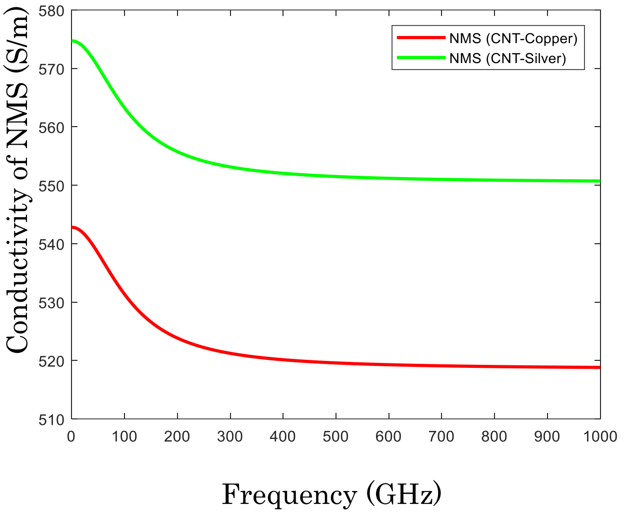


Figure 5. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver) radius r = 2.71 nm, average thickness layer of coating material is t=5nm, and at antenna length L = 10 µm.

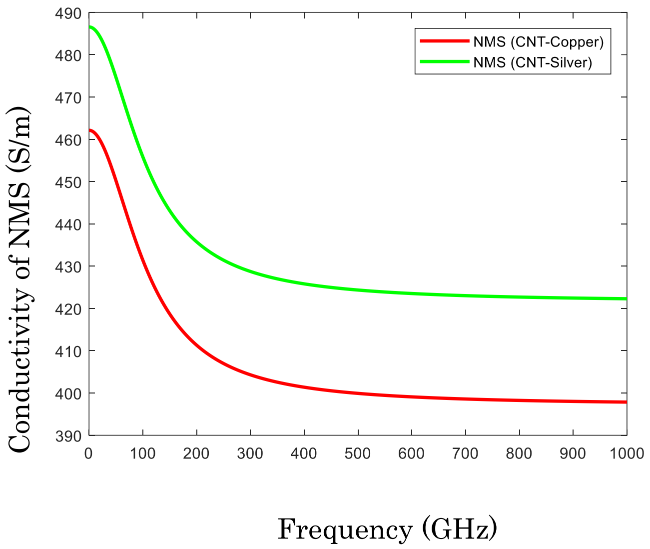


Fig.6. Simulation results of conductivity of NMS (SWCNT-copper and SWCNT-silver) radius r = 2.71 nm, average thickness layer of coating material is t=2nm, and at antenna length L = 10 µm.

As illustrated in these results, the conductivity has been 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 an average thickness of coating layer (t) is between 2 to 5nm. The main parameters of the NMSs were mathematically derived and inserted into the CST (MWS), Drude dispersion method as a new normal material, in order to represent these structures in the CST (MWS). The dipole antenna of both structures of the 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 nm, average thickness of coating layer t = 2 nm, and total antenna length L = 10, 20, 30, and 40µm.

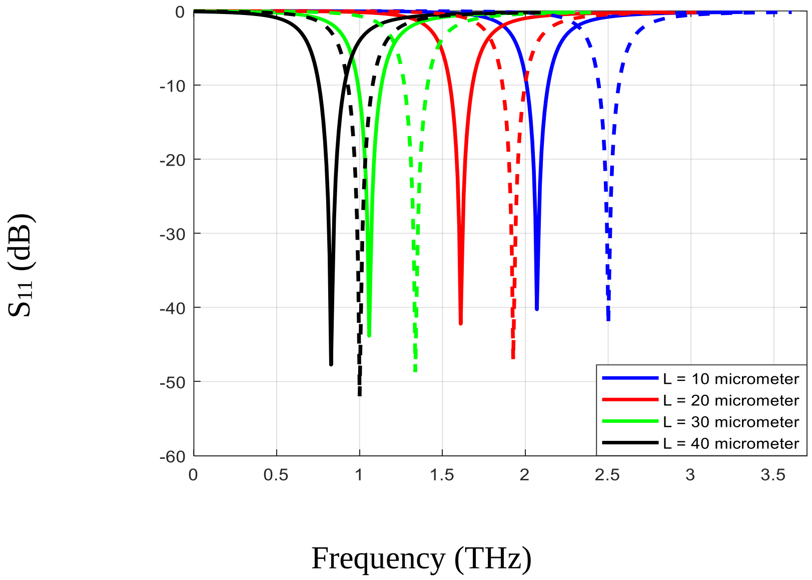


Fig. 7. Simulation results of S11 parameters of equivalent NMS (SWCNT-copper as solid line) and (SWCNT-silver as dotted line) dipole antennas where, r = 2.71 nm, t = 2 nm, and the antenna length L= 10, 20, 30, and 40 µm.

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], has been 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 length.

According to the antenna performance, the scientific comparisons for SWCNT-copper and SWCNT-silver dipole antennas with original (CNT dipole antenna) SWCNT dipole antenna have been 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 are present the results of these comparisons.

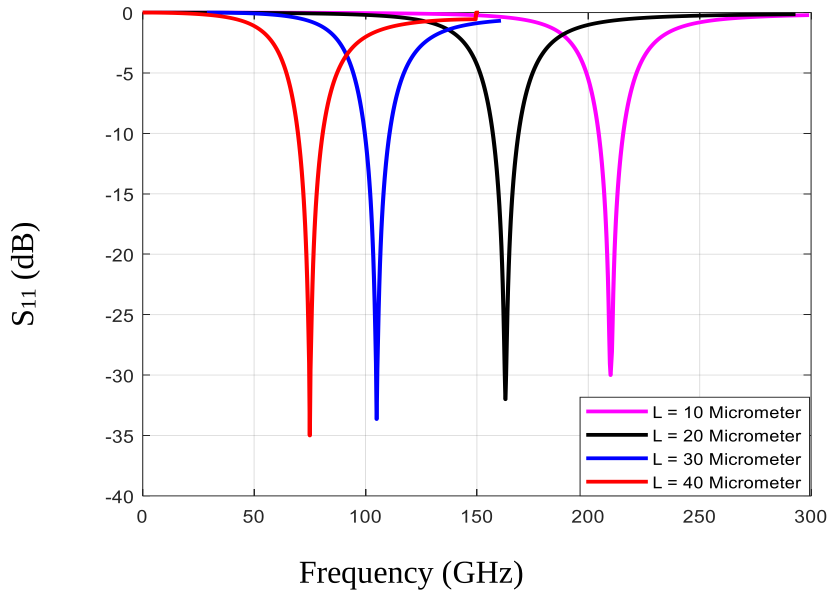


Fig.8. Simulation results of S11 parameters of equivalent SWCNT dipole antennas Where, r = 2.71 nm, and the antenna length (L= 10, 20, 30, and 40 µm.

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}	6.44×10^{-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	$5.23\times10\text{-}^{2}$	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}

As can be seen in Figure 7 and Figure 8 with Tables 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, the NMS (SWCNT-silver) has a resonant frequency higher than NMS (SWCNT-copper) and SWCNT dipole antennas at the same shape, lengths and size. These differences of resonant frequencies were due to the different properties of their material structures, as well as due to the 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 was 11.551GHz in resonant frequency 162 GHz and the bandwidth of NMS (SWCNT-copper) dipole antenna was 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 increased the bandwidth of their dipole antenna compared with the dipole antenna of SWCNT. Additionally, the gain and efficiency for the NMS dipole antenna are enhances compare with SWCNT dipole antenna, as well as enhancement the S_{11} parameters behavior.

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 was 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 that presented in Figure (7), the NMS can be considered as a good material structure for designing dipole antennas at nanoscale and microscale dimensions. This very important advantage for the NMS over copper material at these scales dimensions.

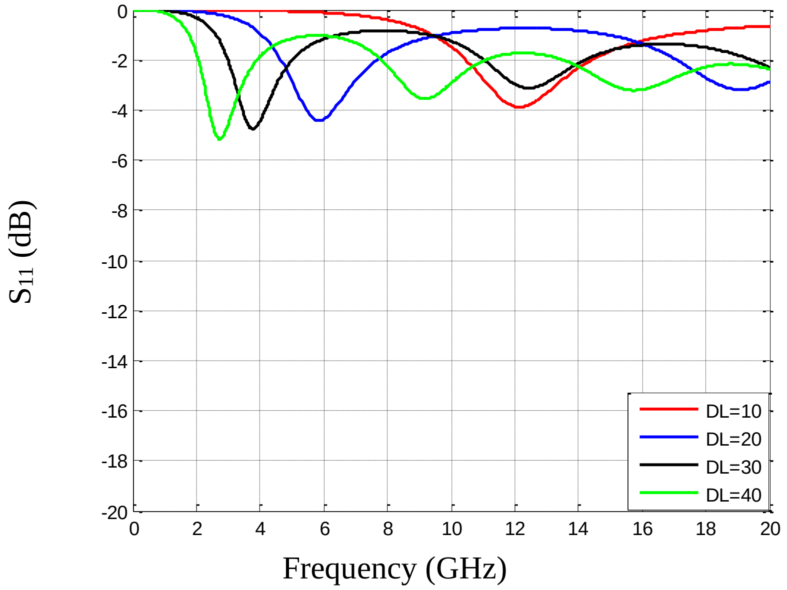


Fig.9. Simulation results of S11 parameters of Copper dipole antenna where, rcu = 4.71 nm, and the antenna length (DL= 10, 20, 30, and 40 µm.

IV. CONCLUSIONS

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

The NMS (SWCNT-copper) and (SWCNT-sliver) are proposed to design the 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 of other dipole antennas.

REFERENCES

[1] A. Redo-Sanchez and X.-C. Zhang, "Terahertz Science and Technology Trends", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, issu: 2, 2008, pp. 260-269.

[2] E. Th. Papaioannou, and R. Beigang, "THz spintronic emitters: a review on achievements and future challenges", Nanophotonics, vol. 10, no. 4, pp. 1243–1257, 2021.

[3] G. W. Hanson, "Fundamental Transmitting Properties of Carbon Nanotube Antennas", *IEEE Transactions on Antennas and Propagation*, vol. 5, no. 11, 2005, pp. 3426-3435.

[4] G. W. Hanson & J. A. Berres, "Multiwall Carbon Nanotubes at RF-THz Frequencies: Scattering, Shielding, Effective Conductivity and Power Dissipation", *IEEE Transactions on Antenna and Propagation*, vol. 59, no.8, 2011, pp. 3098-3103.

[5] Yaseen N. Jurn, Mohd F. Malek & and Hasliza A. Rahim, "Mathematical Analysis and Modeling of Single-Walled Carbon Nanotube Composite Material for Antenna Applications*", Progress in Electromagnetics Research M*, vol. 45, 2016, pp. 59–71.

[6] Yaseen N. Jurn, Mohd F. Malek, Wei-Wen Liu & Haider K. Hoomod, "Investigation of Single-Wall Carbon Nanotubes At THz Antenna", *2nd International Conference on Electronic Design (ICED),*2014, pp. 415-420.

[7] Yaseen N. Jurn, Mohd F. Malek & and Hasliza A. Rahim, "Performance Assessment of the Simulation Modeling Approach of SWCNT at THz and GHz Antenna Applications", *IEEE 12th Malaysia International Conference on Communications (MICC),* 2015, pp.

246-251.

[8] G. W Hanson, & J. Hao, “Infrared and Optical Properties of Carbon Nanotube Dipole Antennas”, *IEEE Transactions on Nanotechnology*, vol. 5, no. 6, 2006, pp.766-775.

[9] Mo Zhao, M. Yu, & H. Robert Blick, “Wavenumber-Domain Theory of Terahertz Single-Walled Carbon Nanotube Antenna”, *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 18, no. 1, 2012, pp. 166-175.

[10] Yaseen N. Jurn, Sawsen A. Mahmood, and Imad Q. Habeeb, “Performance Prediction of Bundle Double-Walled Carbon Nanotube-Composite Materials for Dipole Antennas at Terahertz Frequency Range”, PIERM, vol. 88, pp. 179-189, 2020.

[11] P. J Burke, C. Rutherglen & Z. YU, “Single-walled Carbon Nanotubes: Applications in High Frequency Electronics”, *International Journal of High Speed Electronics and Systems*, vol. 16, no. 4, 2006, pp. 977-990.

[12] Muna Hajjyahya, Maen Ishtaiwi, Jeelan Sayyed, and Ayyam Saddouq," Design of Carbon Nanotube Antenna in Nanoscale Range ", Open Journal of Antennas and Propagation, Vol.9 No.4, December 2021.

[13] G. W Hanson, “Current on an Infinitely-Long Carbon Nanotube Antenna Excited by a Gap Generator”, *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 1, 2006, pp. 76-81.

[14] G. W. Hanson, “Radiation Efficiency of Nanoradius Dipole Antennas in the Microwave and Far-Infrared Regime”, *IEEE Antennas and Propagation Magazine*, vol.50, no. 3, 2008, pp. 66-77.

[15] Y. Su, H. Wei, Z. Yang, & Y. Zhang, “Highly compressible carbon nanowires synthesized by coating single-walled carbon nanotubes”, *Carbon*, vol. 49, issue 6, 2011, pp. 3579-3584.

[16] Y. Peng & Q. Chen, “Fabrication of Copper/MWCNT Hybrid Nanowires Using Electroless Copper Deposition Activated with Silver Nitrate”, *Journal of The Electrochemical Society*, vol. 159, issue 5, 2012, pp. 72-77.

[17] Yaseen Naser Jurn, MF Malek, Wei-Wen Liu, Haider K Hoomod, Amal Abbas Kadhim, “coating methods of carbon nanotubes and their potential applications”, *2014 IEEE International Conference on Control System, Computing and Engineering*, 2014, pp. 118-123.

[18] Yaseen Naser Jurn, Mohamed Fareq Abdul Malek, Hasliza A Rahim, “Carbon Nanotubes Composite Materials for Dipole Antennas at Terahertz Range”, *Progress In Electromagnetics Research M*, vol. 66, 2018, pp.11-18.