An-Najah National University

Faculty of Graduate Studies

Carbon Nanotube-Composite Material for Dipole Antenna at Terahertz Range, Analysis, Properties, Efficiency and Performance

By

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Dedication

I dedicate my dissertation to my great loving mother and to my father's soul, with my special feeling of gratitude to them, whose words encourage and support me throughout my study. To my loving supporter who keeps saying 'I am proud of you', Ayyam. To my brothers and sisters, and all my family. To Dr. Muna hajj yahya who paved my way of science and knowledge, all my distinguished teachers.

Jeelan Tareq Sayyed

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Jeelan Tareq Sayyed

الإقرار

أنا الموقعة أدناه مقدمة الرسالة التي تحمل عنوان

Carbon Nanotube-Composite Material for Dipole Antenna at Terahertz Range, Analysis, Properties, Efficiency and Performance

أقر بأن ما اشتملت عليه هذه الرسالة انما هي نتاج جهدي الخاص، باستثناء ما تم الاشارة اليه حيثما ورد، وأن هذه الرسالة ككل أو أي جزء منها لم يقدم لينال أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة تعليمية أو بحثية اخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work and has not been submitted elsewhere for any other degree or qualification.

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Date: **التاريخ:2021/6/23**

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List of Abbreviations

CNTs	Carbon Nanotube
SWCNTs	Single Wall Carbon Nanotube
MWCNT	Multi Wall Carbon Nanotube
DWCNT	Double Wall Carbon Nanotube
THz	Terahertz
MoM	Method of Moments
HFSS	High Frequency structure Simulator
CST	Computer Simulation Technology
EM	Electromagnetic
HIE	Hallén's- type integral equation
IR	Infrared Radiation
VSWR	Voltage Standing Wave Ratio
SNR	Single-to-Noise Ratio
S-Parameter	Scattering Parameter
NMS	Nano Material Structure
NM	Nano Meter
EBM	Equivalent Bulk Model
$\boldsymbol{\eta}$	Antenna efficiency
$\boldsymbol{p_{rad}}$	Radiated power
$\boldsymbol{p_{in}}$	Input power
$\boldsymbol{\Gamma}$	Reflection coefficient
$\boldsymbol{\sigma_c}$	Complex conductivity
$\boldsymbol{\sigma_{SWCNT}}$	Conductivity of hollow cylinder of Carbon Nanotube
$\mathbf{V_f}$	Fermi velocity
j	Imaginary number
h	Plank’s constant
π	Pi
r	Radius of SWCNTs
ω	Angular frequency
v	Relaxation frequency
$\boldsymbol{\varepsilon_c}$	Complex permittivity
$\boldsymbol{\varepsilon_{rel}}$	Relative permittivity
$\mathbf{w_p}$	Plasma frequency
$\boldsymbol{\sigma_{coat}}$	Conductivity of coating layer
A	Average radial cross section area
P	Circumference cross section area
t	Thickness of the coating layer
T	Room temperature

$\mathbf{v_{composite}}$	Phenomenological relaxation frequency
$\mathbf{N_{coat}^{D}}$	No. of electron per m^3 of coating material
$\mathbf{m_e}$	electron mass
$\boldsymbol{\rho}$	$the\ resistivity\ of\ the\ coated\ material$
$\boldsymbol{\tau}_{\mathbf{relaxation}}$	$time\ of\ coating\ material$
$\boldsymbol{\sigma}_{\mathbf{r}}$	Real part of effective conductivity
$\boldsymbol{\sigma}_{\mathbf{i}}$	Imaginary part of effective conductivity
$\boldsymbol{\varepsilon}_{\mathbf{c}}$	Complex permittivity
$\boldsymbol{\varepsilon}_{\mathbf{c}}'$	Real part of complex permittivity
$\boldsymbol{\varepsilon}_{\mathbf{c}}''$	Imaginary part of complex permittivity

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Abstract

Carbon nanotubes (CNTs) are very interesting material for nano devices for their uncommon mechanical and electrical properties. They may be metallic or semiconducting, depending on their geometry. It has been examined for a wide range of applications including the possibility of building antennas in the nanometer scale. Many studies have been carried out to solve the problems associated with the CNTs antennas. The limitations on the adopted numerical analysis methods such as method of moments (MoM) and the inefficient assumption concerning the conductivity of CNTs materials don't give an adequate solution.

In this thesis, complex permittivity approach have been considered to define the characteristics of various terahertz antenna configurations formed by metallic CNTs materials after modeling its conductivity accurately. Complex conductivity that depends on frequency is taken into account of the CNTs material in the investigation of these advanced antennas. CNTs-composite materials have been proposed that consist of CNTs coated by a thin layer of aluminum, or copper, for THz frequency band, where the single wall carbon nanotubes (SWCNTs) is a specific structure of CNTs utilized in this work.

The CNTs-composite material is a promising nano material for different applications, where CNTs are coated by other materials to modify its structure to be more effective for various applications that have been explored in recent years. The idea of using copper or aluminum in coating dipole antennas have been applied in this thesis to exhibit the enhancement of performance for the proposed dipole antennas.

The radiation characteristics of various configurations of coating and non-coating CNTs dipole antenna is investigated using the concept of the effective conductivity of carbon nanotube (CNTs) material. It takes into account the frequency dependent complex permittivity of the CNTs material and gives way to a virtual CNTs dipole suitable for adaptation in conventional antenna theory and in commercial electromagnetic software solvers. Simulation results related to SWCNTs dipole antennas are presented using CST software package or HFSS to show the effect of parameters on antenna performance.

HFSS (high frequency structure simulator) and CST (computer simulation technology) both simulation program have been used to simulate the same prototype. Firstly, complex permittivity as a function of frequency have been calculated by using a matlab code, then the complex conductivity of CNTs have been obtained, after that the modeling have been done to get the efficiency measurement of CNTs.

CHAPTER ONE

INTRODUCTION

CNTs have been investigated as antennas in various areas-communications between nano devices and macroscopic world, nano interconnect, fiber communication, aircraft and space communication systems.

Carbon nanotubes are tubular structures typically of nanometer diameter and many microns in length. They are unusual because of their very small diameters, which can be as small as 0.4 nm and contain only 10 atoms around the circumference, and because the tubes can be only one atom in thickness. The aspect ratio (length/diameter) can be very large. This aspect ratio can be accepted when one talks about the CNTs application in antenna field. Therefore it is necessary to study the electromagnetic properties of this material.

CNTs have high electrical properties which make them distinguished from other materials. 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. 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. SWCNTs where 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.

The performance of CNTs dipole antennas has been investigated using comprehensive numerical techniques.

- Classical Hallén's- type integral equation (HIE), based on a quantum mechanical conductivity investigated by Hanson [1].
- The model for electromagnetic scattering from infinite planar arrays of finite-length metallic CNTs, and isolated nanotubes, in the lower infrared radiation (IR) bands presented by Hao and Hanson [1].
- Studying the current on an infinitely long CNTs antenna fed by a delta-gap source using Fourier transform technique by Hanson [1].

In this thesis, a virtual CNTs model is developed to be used with commercial software packages to deduce the performance of various CNTs antenna configurations. There are several methods for the investigation of the properties of the CNTs antenna.

- The transmission line method assumes the SWCNTs antenna as a flared transmission line. The parameters of a transmission line are generalized to the SWCNTs antenna. This method is capable of simple understanding of the effect of plasmon wavelength in CNTs properties which is attributed to the existing kinetic inductance and quantum capacitance.
- Another method considers the SWCNTs as a tubed cylinder with a longitudinal current only and the MoM is applied as a solver for the Maxwell's equations.

- Complex permittivity approach have been adopted to know the constitutive parameters of the antenna material.

In this thesis the complex permittivity approach has been adopted to know the constitutive parameters of the antenna material that will be modeled to become ready for the simulation.

1.1 CARBON NANOTUBES

1.1.1 Structure and Types of Carbon Nanotubes

CNTs have developed into independent research field since their discoveries by Iijima in 1991. They are well known for their distinctive seamlessness cylindrical structure with nano-scale diameters.

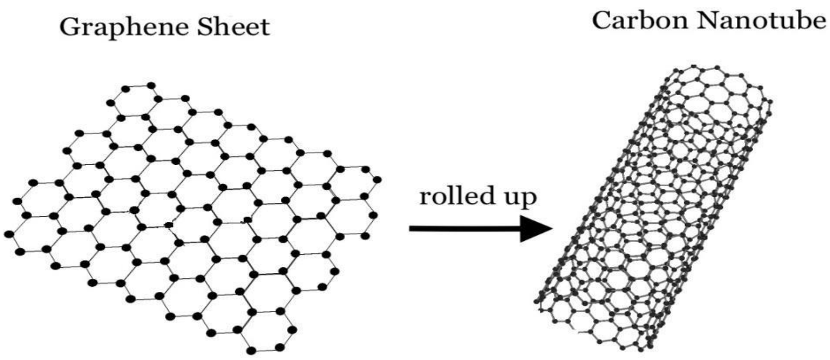


Figure 1.1: Sheet of graphene rolled up to form SWCNTs [33].

CNTs are generated by rolling up of graphene sheet into a cylinder. Depending on the number of rolled-up CNTs have been classified as single-walled (SWCNTs), double-walled, (DWNTs), and multiwall CNTs (MWNTs) As shown in Figure 1.2.2.

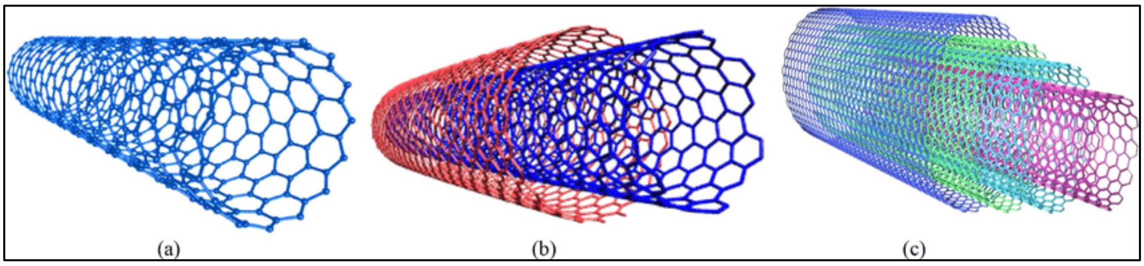


Figure. 1.2: Basic structure of a single-walled (a), double-walled (b), and multi-walled CNTs (c) [34].

1.1.2 Carbon Nanotubes Properties and Applications.

Its unique structure leads to remarkable characteristics, such as a large surface area, high aspect ratios, low densities, high mechanical and tensile strengths, High electrical and thermal conductivity, strong photo-luminescence that can be summarized in figure 1.2.3 below.

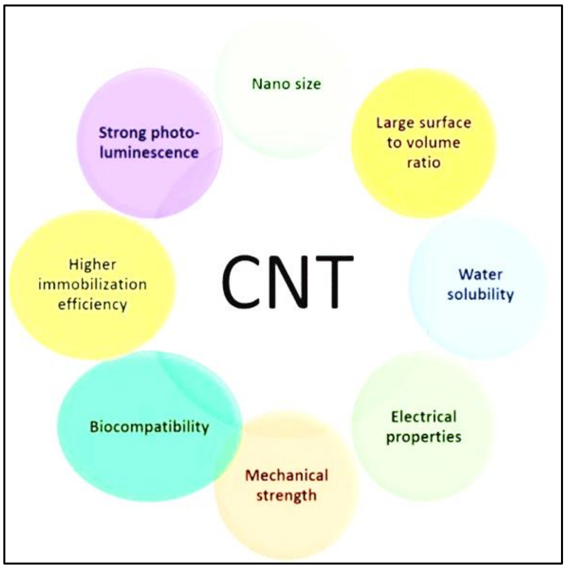


Figure 1.3: Properties of carbon nanotube antenna [35].

1.2 ANTENNA

Antenna is a device that electromagnetic waves have been transmitted and received in a specific direction. Some of the antennas are used to transmit and receive signals from all directions. A good antenna should be efficient for power transmitting and receiving. Also, the resonance frequency range of an antenna should be desirable. In order to be able to design an antenna with high functionality, one should know the basic fundamental properties of the antenna which are given below.

Antenna reciprocity is electrical and magnetic properties of the antenna. These properties include radiation pattern, gain, beam width, bandwidth, antenna efficiency, $S-$ parameters, input impedance and voltage standing wave ratio (VSWR) have been mentioned below.

Radiation Pattern

Defined as energy radiated by the antenna as a function of space coordinates. The radiation pattern is determined as a function of the directional coordinates in the far-field region.

Directivity

Defined as the radiation intensity from the antenna in a given direction divided by the radiation intensity averaged over all directions [4]. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π.

$$Directivity = \frac{radiation\ intensity}{total\ power\ radiated/4\pi} \tag{1.1}$$

Gain and Antenna efficiency

Gain is defined as the product of efficiency times the directivity overall directions [4].

$$Gain = directivity * efficiency \tag{1.2}$$

Antenna efficiency is defined as the ratio of radiated power over input power [4].

$$\eta = \frac{p_{rad}}{p_{in}} \tag{1.3}$$

Scattering parameter (S-parameters)

The most commonly used parameter regarding antenna is S_{11}. S_{11} shows how much power is reflected from the antenna and is known as reflection coefficient or return loss. If S_{11} = 0 dB, then all the power is reflected from the antenna and nothing is radiated. As S_{11} have small value in minus antenna efficiency becomes better.

VSWR (Voltage Standing Wave Ratio)

VSWR stands for Voltage Standing Wave Ratio and also known as Standing Wave Ratio (SWR) [4]. It is defined by the reflection coefficient as how much power reflected back from the antenna. It can be defined mathematically by the reflection coefficient (S_{11}) as below

$$VSWR = \frac{1-|s_{11}|}{1+|s_{11}|} \tag{1.4}$$

Impedance Matching

The impedance matching is an important property of a transmission line and in microwave communication link. Impedance matching network is taking placed between the load impedance (antenna) and a transmission line (feed point) which in our case is between the antenna and the feeding line. It should be lossless to avoid power loss in it.

Importance of impedance matching or tuning can be summarized as the power loss due to the reflection in the feed line is minimized. In addition to reduce the amplitude and phase errors, Impedance matching network will improve the single-to-noise ratio (SNR) of the components like antenna and low-noise amplifier of the system.

1.3 SINGLE WALL CARBON NANOTUBES DIPOLE ANTENNA

CNTs have been investigated for a wide array of applications including the possibility of building novel antennas in the nanometer scale. In this thesis the characteristics of various antenna configurations formed by metallic CNTs materials after modeling its conductivity accurately have been investigated.

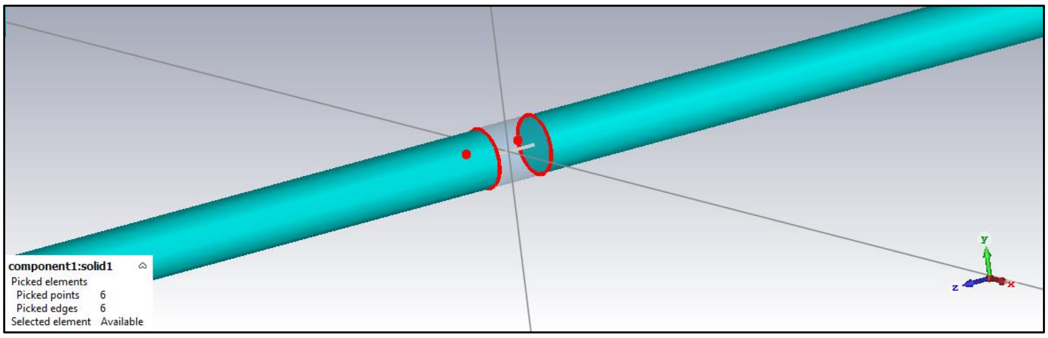


Figure1.4: SWCNTs dipole antenna.

The implementation of complex permittivity approach model can be used to predict the electromagnetic properties of the CNTs antennas. Quantitative predictions of the performance of CNTs antenna dipoles, including input impedance, reflection coefficient, gain, and efficiency, are presented as a function of frequency.

1.4 Composite Materials for Single Wall Carbon Nanotubes Dipole Antenna

New material structure (NMS) is presented to enhance antenna properties consist of SWCNTs dipole antenna coated by thin layer (in nm scale) of several materials separately as aluminum or copper.

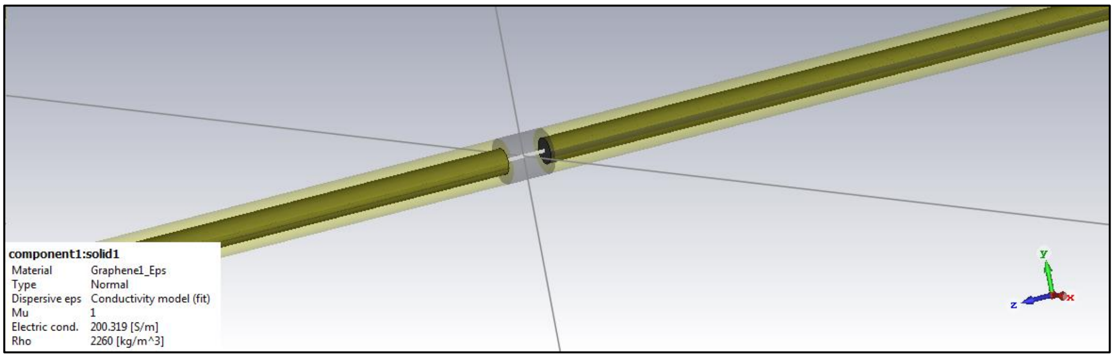


Figure1.5: Structure of SWCNTs-composite material (SWCNTs coated by another material).

The simulation of the equivalent modeling approach for SWCNTs-composite material is illustrated. The study of their EM properties is very important to offer a new material for antenna design at different applications. In order to predict the EM behavior of the SWCNTs-composite material, the important parameters of this material have been extracted.

Hence, these parameters are utilized to represent the equivalent modeling approach of SWCNTs composite material in the 3D EM computer simulation technology (CST). Where, this equivalent model is equivalent bulk material (EBM). The EBM model has the same properties of SWCNTs composite material such as, effective conductivity, complex permittivity, plasma frequency, and relaxation frequency. Therefore, by inserting these material parameters in the available 3D EM simulation software packages, the EBM model can be designed and implemented.

1.5 Litreture Review

The trails of having dipole antenna with efficiency higher than the copper one have been made by researcher in recent years. The idea of using carbon nanotube as a single wall is a new way to developed the dipole antenna and have small size light weight prototype. But the values of efficiency does not reach the desired goal. Because of this the idea of coating SWCNTs have been studied. The idea in this thesis to use new metal in coating SWCNTs and compare the value that we have in those in last three years. The efficiency of SWCNTs-coated and non-coated dipole antennas as a function of frequency are founded at different rang of length and constant radius. The result shows new values of efficiency for coated carbon nanotube dipole antenna, it is about 59% in the case of zero loss and 77% in the case of loss due to miss matching impedance. Compering the values that we have 59% with latest research that has been published about 40%, we obtain new percent of efficiency.

Sh.G. El-sherbiny, S. Wageh, S.M. Elhalafawy and A.A. Sharshar[1],studied Carbon nanotube antennas analysis and applications. Y. N. Jurn, S. A. Mahmood, and I. Q. Habeeb[9], investigate the Performance Prediction of Bundle Double-Walled Carbon Nanotube-Composite Materials for Dipole

Antennas at Terahertz Frequency Range. They found that the coated DWCNT by a thin layer jacket of graphite material leads to decreasing the resonant frequency, while the coated DWCNT by a thin jacket layer of copper leads to increasing the resonant frequency. Y. N. Jurn, M. F. Malek, W.W. Liu, H, K. Hoomod[19] Investigate single-wall carbon nanotubes at THz antenna. Y. N. Jurn, M. F. Malek, H. A. Rahim[23], study the Mathematical analysis and modeling of single walled carbon nanotube composite material for antenna applications. S. Islam, K. Shafaet -Uz-Zaman [35], studied the Performance Analysis between SWCNTs and Copper Antennas in High Frequency Region.

1.6 Research Objectives

The main goals of this research project can be summarized as follows:

1. Obtain CNTs dipoles antenna coating by thin layer of different material exhibit very high efficiencies using terahertz frequency band taking into account the frequency dependent complex conductivity of the CNTs material.
2. Obtain the efficiency for antennas using electromagnetic methods and compare it with copper.

CHAPTER TWO

MATHMATICAL ANALYSIS & MODELING STEPS

The performance of SWCNTs dipole antennas has been investigated by using comprehensive numerical techniques. In this thesis, a virtual CNTs model is developed to be used with commercial software packages to deduce the performance of various CNTs antenna configurations.

First step of modeling SWCNTs to create CNTs on software package (CST or HFSS), the method of defining SWCNTs by using complex permittivity approach in two ways either by Discrete values of $\varepsilon_c'$and ε_c'' tabulated in dielectric dispersion fit window and computed using MATLAB codes, or by Drude dispersion model have been discussed.

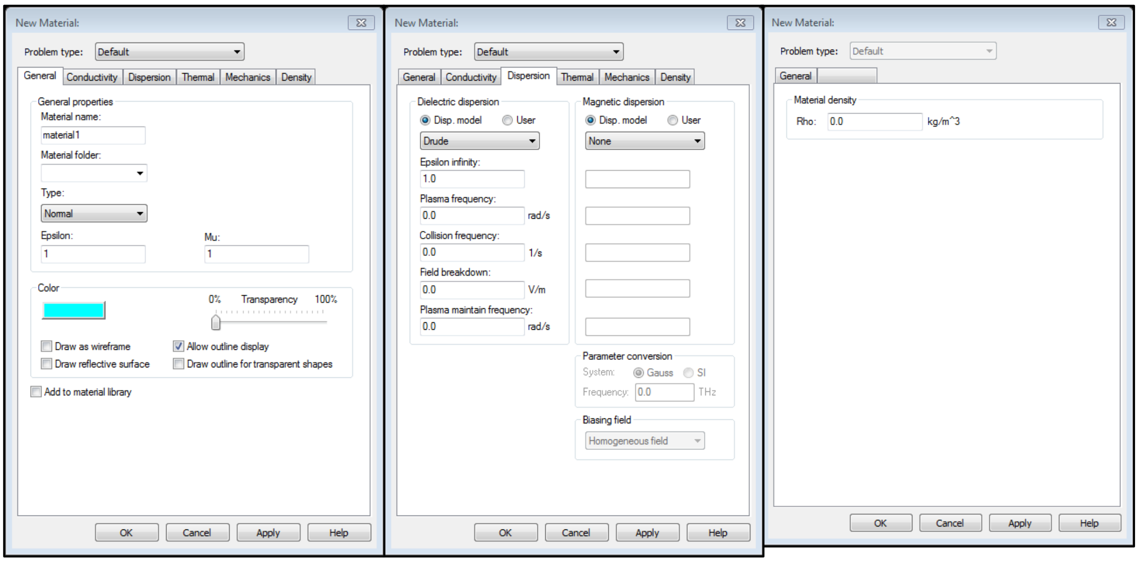


Figure 2.1.1: Drude dispersion model in defining SWCNTs at CST.

The idea of coating material had been suggested through EBM (equivalent bulk model) To improve antennas efficiency. EBM supposed to treat

SWCNTs and the coating material as on bulk cylinder with effective complex conductivity and permittivity by using drude dispersion model.

2.1 DRUDE DISPERSION MODEL

Mathematical dispersion formulas in Drude Dispersion model have been used to evaluate the material's optical properties by adjusting specific set parameters. Drude' model is based on the kinetic theory of electrons in a metal which assumes that the material have motionless positive ion and non-interacting electron gas using classical mechanical theory of free electron to explain the transport properties of conduction electrons in metals, conductive oxides, and semiconductors.

In Drude Dispersion model for dealing with the complex permittivity approach using CST software package, CNTs material has been defined as new material with normal type, from the windows of defining CNTs, dispersion Drude model was picked. The value of epsilon infinity is one for all types of CNTs the value of plasma frequency for SWCNTs antenna without coating and with coating material is computed from equations

$$w_p = \frac{2e}{\pi r}\sqrt{\frac{V_f}{\varepsilon_0 \hbar}} \tag{2.1}$$

$$w_p = \frac{e}{\pi(r+t)}\left[\frac{4V_f + \pi^2 \hbar M}{\hbar \varepsilon_0}\right]^{1/2} \tag{2.2}$$

Where, V_f is the Fermi velocity for CNTs, r is the radius of CNTs and t is the thickness of coating layer, $M = (\frac{(R^2 - r^2) v \sigma_{coat}}{e^2})$, σ_{coat} is the conductivity of coating layer [7].

And the collision frequency is considered as the same value of the relaxation frequency for SWCNTs antenna without coating and with coating material computed from equations

$$\nu = \frac{6T}{r} \tag{2.3}$$

$$\nu = \frac{6T}{r+t} \tag{2.4}$$

2.2 Modiling of Antenna Parameters

Antenna configurations formed by CNTs materials

The characteristics of various terahertz antenna have been investigated by apply Maxwell's equations simply to predict the electromagnetic properties of the CNTs antennas as reflection coefficient, gain, and efficiency, presented as a function of frequency.

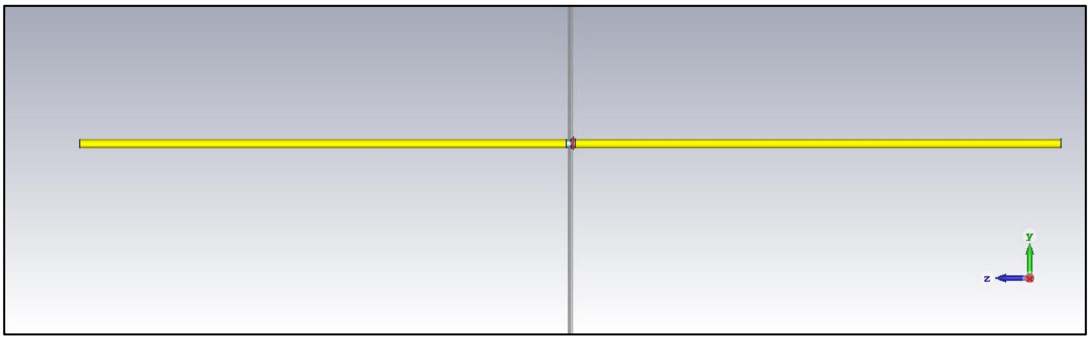


Figure 2.2.1: SWCNTs dipole antenna.

To simulate SWCNTs dipole antenna, its parameter is very important part to have effective efficiency antenna, such as its length to radius ratio, input impedance, radius, and metal contacts at feeding points.

2.2.1 Length to radius ratio

For different scales of antenna, the length to radius ratio $\frac{L}{r}$ is very high as

$$L = 10\ \mu m, r = 2.71\ nm, \frac{L}{r} = \frac{10*10^{-6}}{2.71*10^{-9}} = \frac{1000000}{271}$$

$$L = 20\ \mu m, r = 2.71\ nm, \frac{L}{r} = \frac{20*10^{-6}}{2.71*10^{-9}} = \frac{2000000}{271}$$

$$L = 30\ \mu m, r = 2.71\ nm, \frac{L}{r} = \frac{30*10^{-6}}{2.71*10^{-9}} = \frac{3000000}{271}$$

$$L = 40\ \mu m, r = 2.71\ nm, \frac{L}{r} = \frac{40*10^{-6}}{2.71*10^{-9}} = \frac{4000000}{271}$$

The electrical conductivity of CNTs has been increased with high length to radius ratio leading to high efficiency carbon nanotubes. In addition of increasing electrical conductivity, mechanical properties of CNTs have been affected certainly.

2.2.2 Matching impedance of antenna model

Antenna **impedance** is how much circuit impedes the current flow in the antenna. The power radiated away or absorbed within the antenna are represented the real part of the antenna impedance. The power stored in the near field of the antenna is the imaginary part of the impedance.

The mathematical analysis of the SWCNTs structure needed to characterized dipole antenna by a high input impedance. To simplify the mathematical calculation, the standard fixed impedance for antenna in micro scale was (*Ro* = 50Ω), whereas this value was approximate to (*Ro* = 12.9 k Ω) for nano scale. In this thesis matching impedance is very important point to have accurate result, the surface impedance is considered as input impedance for dipole antenna.

Input impedance for non- coating SWCNTs dipole antenna:

$$Z_{in} = Rq + jw\zeta \quad (2.5)$$

Where, Rq is the quantum resistance and ζ is the inductance[23].

$$Rq = \frac{3\pi hLT}{2re^2V_f} \quad (2.6)$$

$$\zeta = \frac{\pi hL}{4e^2V_f} \quad (2.7)$$

Where, L is the length of the antenna, V_f is the Fermi velocity of the CNTs[23].

For SWCNTs-composite structure, one can find the quantum parameters as given by:

$$Rq = \frac{\pi hLv_{comp}}{4te^2V_f} \quad (2.8)$$

$$\zeta = \frac{\pi hL}{4te^2V_f} \quad (2.9)$$

Where, v_{comp} is the phenomenological relaxation frequency of SWCNT-composite material[23].

Matching issue between antennas and the feeding source (discreet port) is one of the main problems of SWCNTs dipole antenna and SWCNTs-composite dipole antenna. This matching approach depends on changing the Normalized Fixed Impedance (NFI) of S_{11} parameter to balance the effectiveness of the input impedance of these dipole antennas with the internal impedance of the feeding source. The NFI is selected based on calculating the value of impedance for SWCNTs or for SWCNTs-composite dipole antenna. This value is needed to realize the matching between feeding source and dipole antenna (load). In another context, it represents a starting value to obtain an ideal value of matching impedance between source and (SWCNTs or SWCNTs-composite) dipole antenna to obtain the exact result of s_{11} parameter. Indeed, the simple matching approach presented above is implemented for designing the SWCNTs dipole antenna and SWCNTs-composite dipole antenna. Similarly, this matching process benefits the achievement of the matching situation for different nano electronic antennas.

2.3 Comparison Between Swcnts Coated by Several Metal

Varied material used to coat SWCNTs each one have its efficiency and scattering parameter. The difference in its efficiency led to classify it as below, SWCNTs- Copper dipole antenna, SWCNTs- Aluminum dipole antenna. The values of different parameters for SWCNTs dipole antenna coated by above materials will be discussed in details.

Copper dipole antenna does not offer reliable efficiency when it is transmitted or detected very high frequency signal because of skin effect. The efficiency is very low for copper dipole antenna that is known as good conductor at terahertz frequency. In the other hand, SWCNT dipole antenna is transmitted and detected high frequency signal with high efficiency (SWCNT does not have any skin effect). It offers better conductivity at terahertz frequency because all volume of CNTs can be used or conduction.

2.4 Computer Simulation Technology

Computer Simulation Technology is powerful numerical full electromagnetic simulator. Maxwell’s equations can be solved numerically inside the structure to make it more simple. The behaviors of electric and magnetic fields within the structure in either time or frequency domain have been contained in CST.

Four different simulation techniques have been established at CST. First, transient solver, then frequency domain solver, also integral equation solver, last one is eigen mode solver.

Most proper technique for antenna is the transient solver. This solver is remarkably efficient for most kinds of high frequency applications such as connectors, transmission lines, filters, and antenna. The first step is to create a cylinder by select the cylinder creation tool from the main menu:

Objects →Basic Shapes →Cylinder.

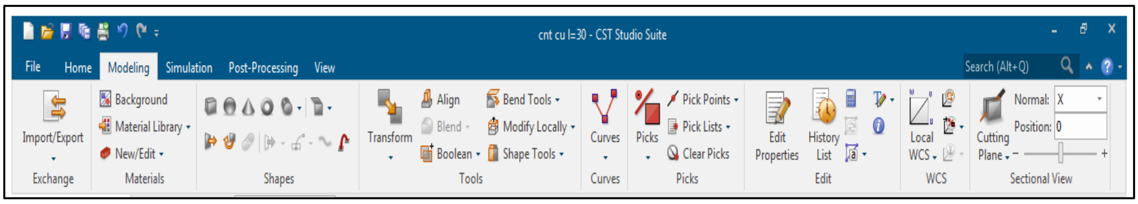


Figure 2.4.1: Main menu at CST, modeling part.

Then Set up the radius, length and type of material that have been defined in previous section.

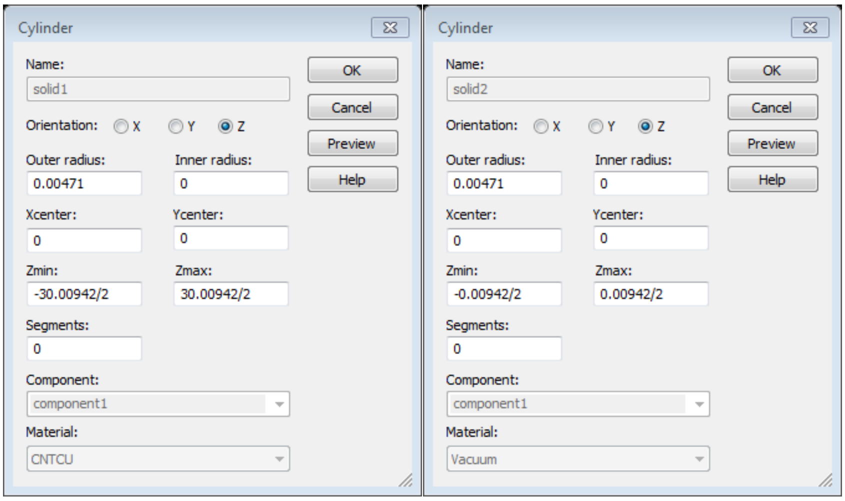


Figure 2.4.2: Windows to create solid cylinder (antenna arms and gap between them) at CST.

After that configuration of port between two CNTs cylinder have been made by Selected simulation option from menu bar → discret port.

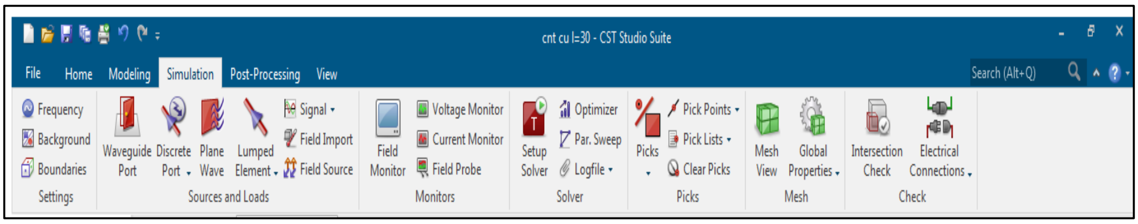


Figure 2.4.3: Main menu at CST, simulation part.

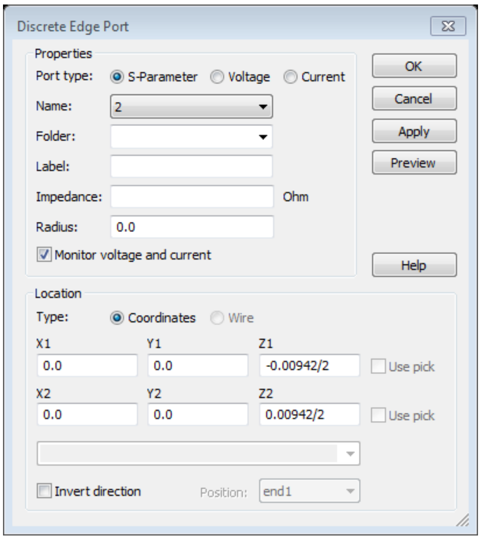


Figure 2.4.4: Discrete edge port window.

Mesh configuration is configured probably fitted with the length of antenna. Cell per max model box edge and cell per unit length can be Inserted as 15 refered to antenna length.

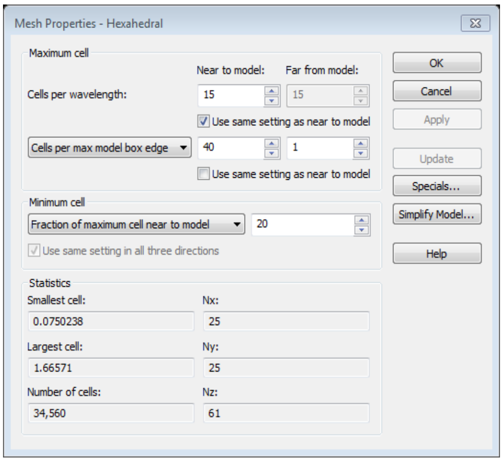


Figure 2.4.5: Mesh properties window.

Far-Field monitor can be chosen at spesifice resonance frequancy.

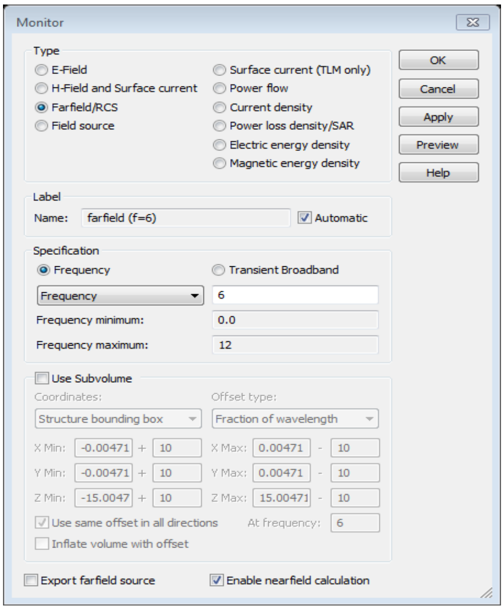


Figure 2.4.6: Mesh properties window.

In simulation part, time domain simulator have been selected, the accuracy equale -40 (dB), and adjusting normalized fixed impedance.

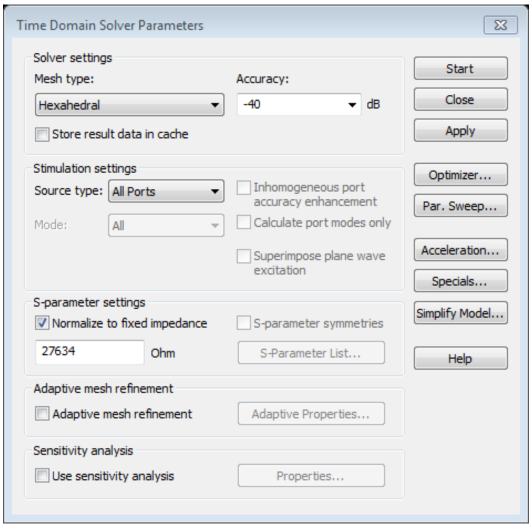


Figure 2.4.7: Time domain solver parameter window.

CHAPTER THREE

RESULTS & DISCUSSION

In this chapter values of efficiency, scattering parameter, gain, and other parameters for coating and non-coating SWCNTs will be investigated starting with:

3.1 Defining CNTs on simulation package.

- Effective conductivity.
- Modeling of SWCNTs using complex permittivity approaches.
- Effective permittivity charts after defining CNTs at CST

3.1 Matching impedance in discrete port.

3.2 Efficiency.

3.3 Scattering parameter S_{11}.

3.4 VSWR.

3.5 SWCNTs dipole antenna with metal contact and without.

3.6 Results after get rid of antenna loss due to impedance mismatch.

The parameters that have been used in our calculations is given in table 3.1 below:

Table 3.1: Numerical parameter used in calculation [35].

Density of Al (Kg/m^3)	2700
Density of CNTs (Kg/m^3)	2260
Density of Cu (Kg/m^3)	8960
Room temperature (K)	300
ε_0 ($C^2/N.m^2$)	$8.85 * 10^{-12}$
$m_e(Kg)$	$9.11 * 10^{-31}$
e (c)	$1.6 * 10^{-19}$

ħ(J.s)	$1.054 * 10^{-34}$
V_f(m/s)	$9.71 * 10^{5}$
C(m/s)	$3 * 10^{8}$
N_{coat}^{D} Al	$6.02 * 10^{28}$
N_{coat}^{D} Cu	$8.5 * 10^{28}$
$\tau_{relaxation}$ Al	$2.173 * 10^{-14}$
$\tau_{relaxation}$ Cu	$2.78 * 10^{-14}$
$\tau_{relaxation}$ CNTs	$2.27 * 10^{-17}$
$V_f\ Al$(m/s)	$2.02 * 10^{6}$
$V_f\ Cu$(m/s)	$1.57 * 10^{6}$
$V_f\ CNT$(m/s)	$0.971 * 10^{6}$

3.1 Defining Cnts at Simulation Package.

3.1.1 Effective conductivity of SWCNTs

The unit of CNTs conductivity σ_{SWCNT} is measured in Siemens (S), but the conductivity σ_c in Maxwell's equations is measured in (S/m). CNTs considered as longitudinal geometry and the derivation of the conductivity is based on. This fact is because of difference in the geometry of the CNTs. In contrast, the metal wires are usually assumed to be a bulk and the physical geometry is assumed to be a transverse then the unit of the conductivity appears to be (S/m). To solve this problem, the CNTs is considered here as having an equivalent cylinder with the effective parameters in order to manipulate it.

The mathematical model of the effective conductivity of coating and non-coating SWCNTs dipole antenna can be derived as shown below:

Non-coating SWCNTs dipole antenna:

$$\sigma_c(w) = \left(\frac{2}{r}\right)\sigma_{SWCNT} = -j\,\frac{4e^2V_f}{\pi^2 hr^2(\omega - jv)} \qquad (3.1)$$

$$\sigma_{SWCNT}(w) = -j\,\frac{2e^2V_f}{\pi^2 hr(\omega - jv)} \tag{3.2}$$

Where, σ_c is the conductivity of equivalent bulk cylinder of CNTs.

$$\sigma_{SWCNT} = \sigma_r(w) + j\sigma_i(w) \tag{3.3}$$

$$\sigma_r(w) = \frac{2e^2V_f}{\pi^2 hr}\frac{\nu}{w^2+\nu^2} \tag{3.4}$$

$$\sigma_i(w) = -j\,\frac{2e^2V_f}{\pi^2 hr}\frac{w}{w^2+\nu^2} \tag{3.5}$$

Where, $\sigma_r(w)$ is the real part of conductivity and $\sigma_i(w)$ is the imaginary part of conductivity [23].

Coating SWCNTs dipole antenna:

$$\sigma_{composite} = \sum_{j=1}^{k} m_j\,\sigma_{nj} \tag{3.6}$$

$$\sigma_{composite} = \sum_{j=1}^{2} m_j\,\sigma_{nj} = m_1\sigma_{1j} + m_2\sigma_{2j} \tag{3.7}$$

Where, k is the number of materials that constructs the composite material. The mj is the volume fraction factor of the jth material, (σ_{1j}) represent the conductivity of SWCNTs (σ_{SWCNT})and (σ_{2j}) represent the conductivity of coating material (σ_{coat})

$$\sigma_{composite} = P\sigma_{SWCNT} + A\sigma_{coat} \tag{3.8}$$

The P represent the circumference of SWCNTs($P_{SWCNT} = 2\,\pi\,r$), and A represent the average radial cross section area of coating layer

$$\sigma_{composite} = \frac{1}{(r+t)^2}\left[-j\,\frac{4e^2V_f}{\pi^2 h(w-jv)} + t^2\sigma_{coat}\right]$$

Where, $v_{composite}$ is the phenomenological relaxation frequency of SWCNTs-composite material.

$$\sigma_{coat} = \frac{e^2N_{coat}^D}{2m_e v_{coat}} \tag{3.10}$$

$$v_{coat} = \frac{1}{\tau_{relaxation}} \tag{3.11}$$

$$w_p = \frac{e}{\pi(r+t)}\left[\frac{4V_f+\pi^2\hbar M}{\hbar\varepsilon_0}\right]^{1/2} \tag{3.12}$$

Where, v_{coat} is the phenomenological relaxation frequency of coating material.

$$\tau_{relaxation} = \frac{m_e}{N^D_{coat}e^2\rho} \tag{3.13}$$

N^D_{coat}:No. of electron per m^3 of coating material.

$\tau_{relaxation} time\ of\ coating\ material$

$\rho\ is\ the\ resistivity\ of\ the\ coated\ material$, r is the radius of CNTs, t is the thickness of coating material, T is the temperature (T=300 K), m_e electron mass (m_e= 9.11*10^{-31} Kg).

Where, e is the electron charge, r the radius of SWCNTs, h the reduced Plank's constant (h = 1.05457266 × 10^{-34} J · s), V_f the Fermi velocity of CNTs (V_f = 9.71 × 10^5 m/s), ν a phenomenological relaxation frequency ($\nu = \frac{6T}{r}$), where (T = 300) is temperature in kelvin, and w is the angular frequency [23].

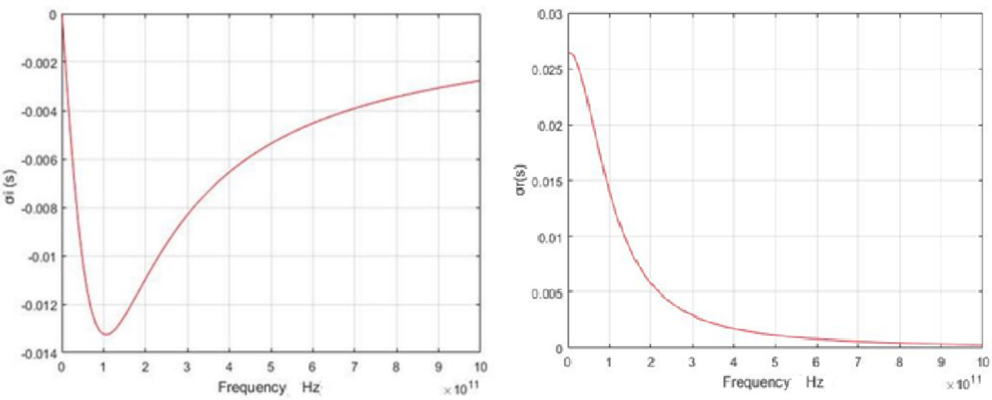


Figure 3.1.1: Conductivity of SWCNTs at T=300 K with radius r=2.71 nm and frequency range 0-1000(GHz).

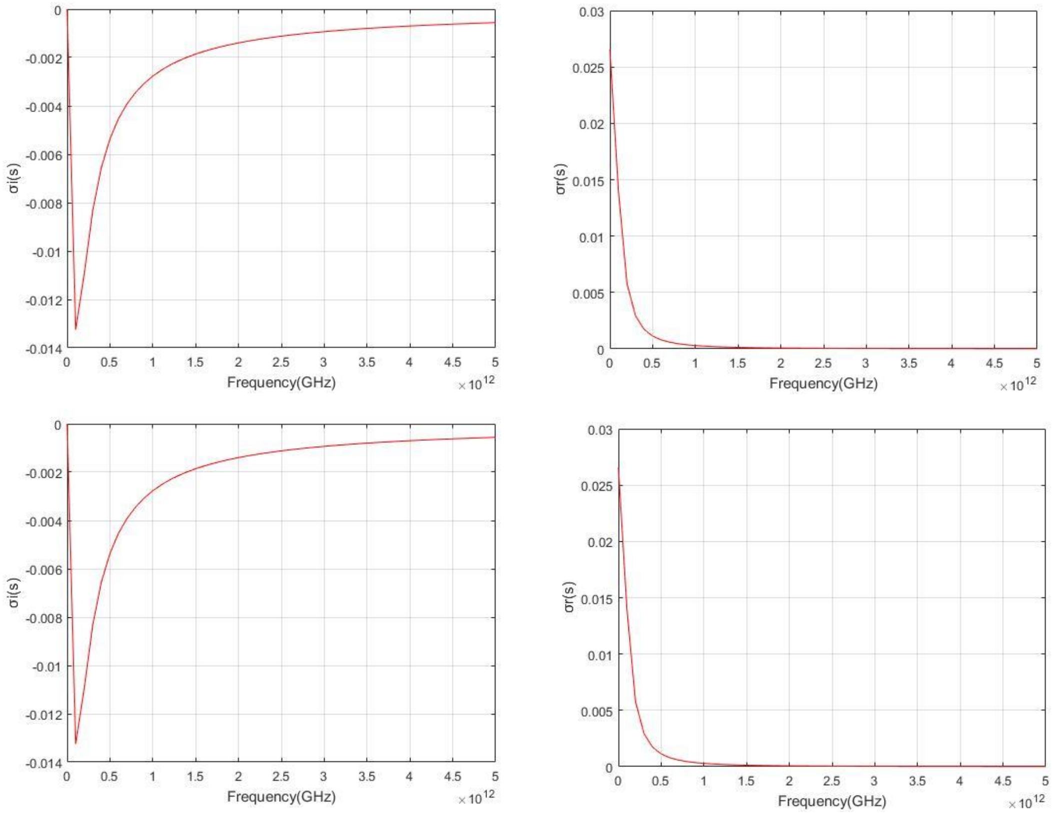


Figure3.1.2: Conductivity of SWCNTs at T=300 K with radius r=2.71 nm and frequency range 0-5000(GHz).

As the frequency increase the real and imaginary part of conductivity increase successively, showing that relationship through MATLAB comparison in figure 3.1.1 and 3.1.2.

3.1.2 Modeling of SWCNTs using complex permittivity approaches

The effective conductivity can be generalized to other quantities known as key parameters in Maxwell's equations, such as permittivity and permeability. In all forms of CNTs, if the relative permeability is considered to be unity, then the argument is about permittivity.

Therefore, one can verify from Maxwell's equations the real and imaginary parts of the relative complex permittivity given by:

$$\varepsilon_c = \varepsilon_c' - j\varepsilon_c'' \tag{3.14}$$

Where ε_c' , ε_c'' the real and imaginary parts of the relative complex permittivity.

Real part of the complex permittivity can be expressed as:

$$\varepsilon_c'(w) = \varepsilon_{rel}(w) + \frac{w_p^2}{w^2+v^2} \tag{3.15}$$

$\varepsilon_{rel}(w)$ is relative permittivity and as $w \to \infty$, $\varepsilon_{rel}(\infty) \to 1$

Where w_p the plasma frequency in CNTs is found to be:

$$w_p = \frac{2e}{\pi r}\sqrt{\frac{V_f}{\varepsilon_0 \hbar}} \tag{3.16}$$

Imaginary part of the relative complex permittivity can be expressed as:

$$\varepsilon_c''(w) = \frac{w_p^2 v}{w(w^2+v^2)} \tag{3.17}$$

Because the CNTs is non-magnetic material, the relative permeability is assumed to be unity such that $\mu = \mu_0$ where μ is the permeability of CNTs and μ_0 is the free space permeability. To deal with the complex permittivity approach using CST software package:

- Set the CNTs material as a new material with normal type and drude dispersion model. The value of epsilon infinity is one for all types of CNTs and plasma frequency is computed from equation (3.18), the collision frequency is considered as the same value of the relaxation frequency $v_{coll} = v = \frac{6T}{r}$.

- Or, Set the CNTs as a new material in CST environment with normal type. Discrete values of $\varepsilon'$and $\varepsilon''$are tabulated in dielectric dispersion fit window and computed using MATLAB.

In this thesis the first method is used through feeding the input data of the plasma and relaxation frequencies when asked by the CST seem healthier. Using Matlab charts of equation (3.17) & (3.19) can be shown:

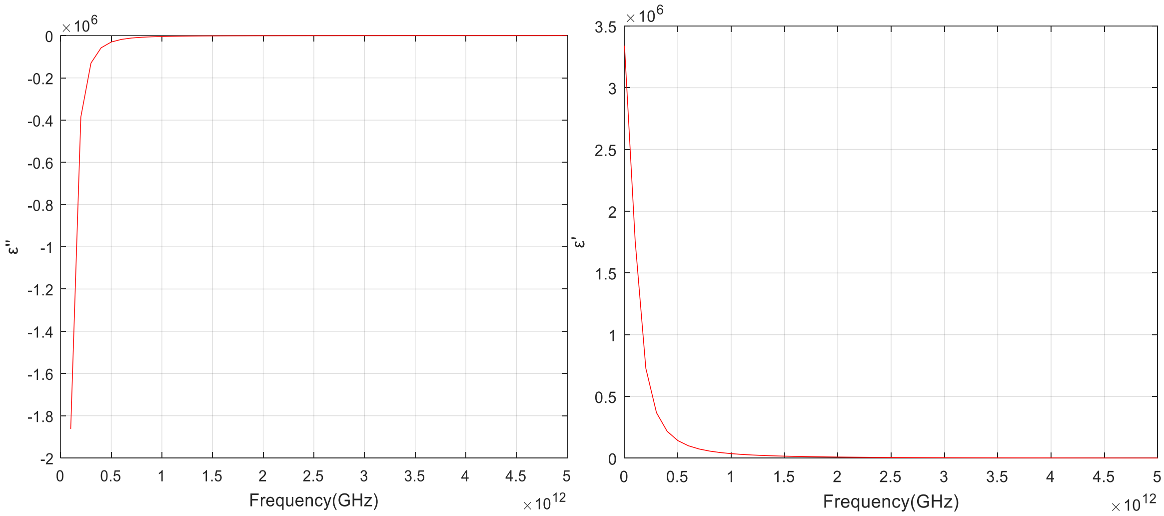


Figure 3.1.3: shows the values of ε_c' and ε_c'' for a SWCNTs having r = 2.71 nm.

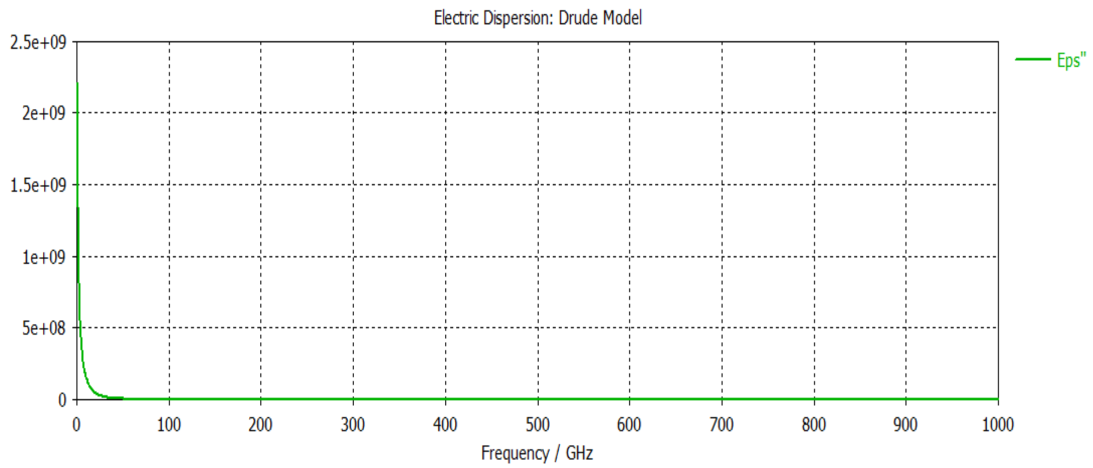
Effective parameters as (plasma frequency and relaxation frequency) have been calculated through equation (3.4) & (3.14) for non-coating and coating SWCNTs dipole antenna. The values of plasma and relaxation frequency can be summarized in table 3.1.1 below. Though Drude dispersion model previous value have been entered in dispersion window to define CNTs.

Table 3.1.1: Plasma and relaxation frequency of SWCNTs- Al and SWCNTs- Cu.

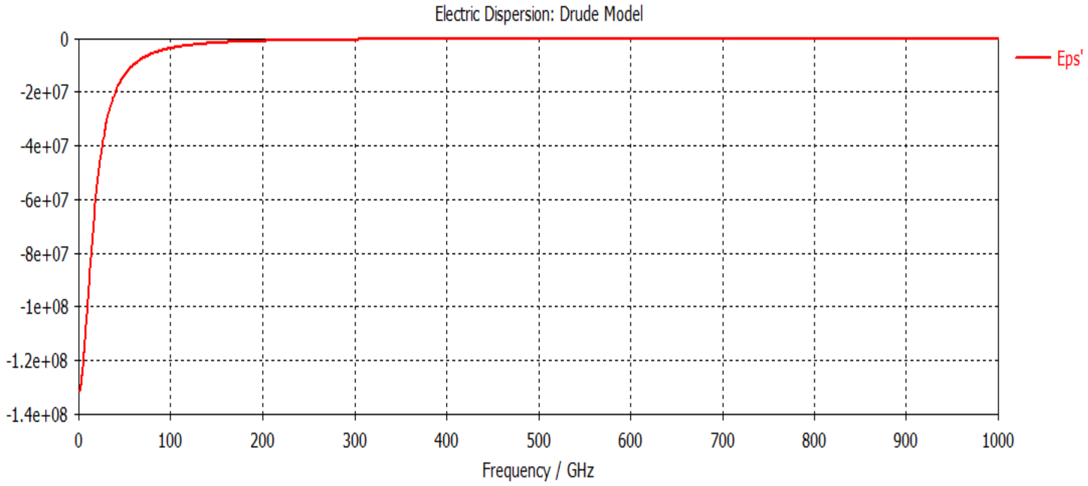
Effective parameters	SWCNTs- Al	SWCNTs- Cu
$w_{p,coating}(rad/s)$	$1.0008 * 10^{15}$	$9.7 * 10^{14}$
$\nu_{rel,coating}(1/s)$	$6.05 * 10^{10}$	$6.05 * 10^{10}$
Effective parameters	**SWCNTs**	
$w_p(rad/s)$	$1.213 * 10^{15}$	
$\nu_{rel}(1/s)$	$6.642 * 10^{11}$	

3.1.3 Effective permittivity charts after defining CNTs at CST

After defining CNTs through dispersion model, charts of real and imaginary part of permittivity have been appeared, or we can have permittivity chart through writing equation of permittivity as code on MATLAB.



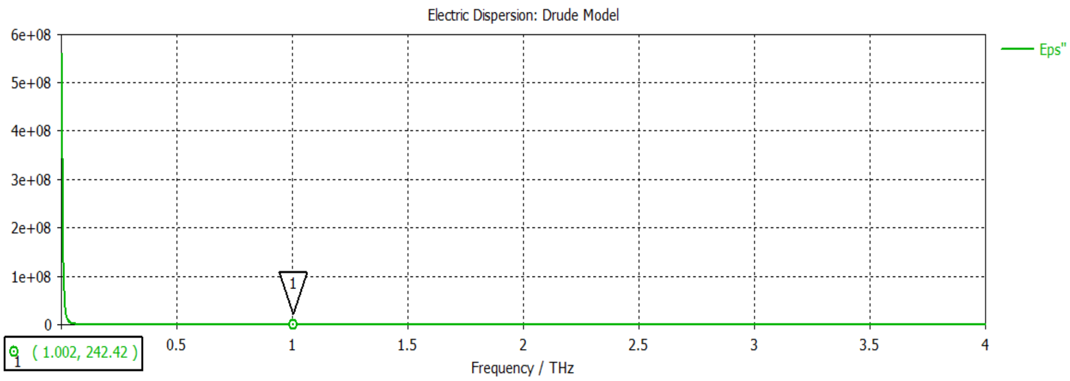
(a)



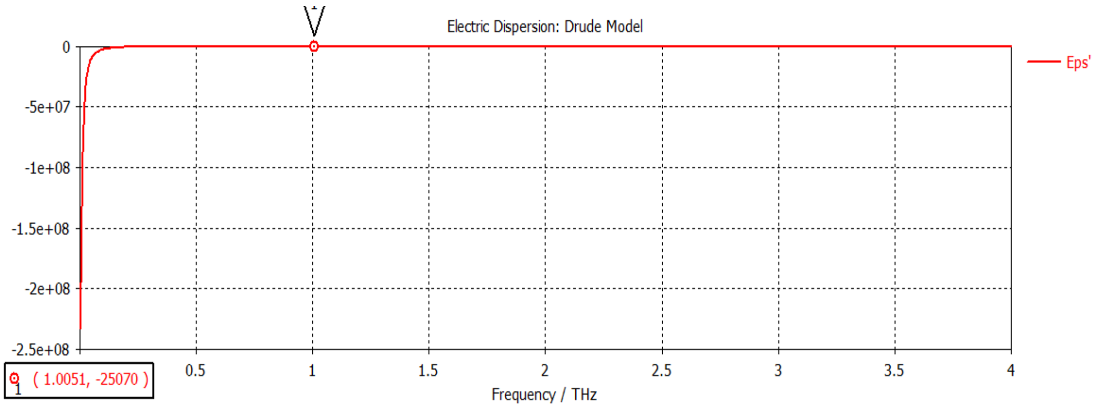
(b)

Figure 3.1.4: Effective complex permittivity (a)Real part of complex permittivity as a function of frequency of SWCNTs dipole antenna of radius r = 2.71 nm, and length L=10µm. (b) Imaginary part of complex permittivity as a function of frequency of SWCNTs dipole antenna of radius r = 2.71 nm, and length L=10µm.

Effective permittivity for SWCNTs- Al dipole antenna real and imaginary part as a function of frequency have been shown in Figure 3.1.5 (a) and Figure 3.1.5 (b). The value of permittivity (real part) had been obtained at almost 1 THz to be 242.42. While imaginary part of permittivity had been obtained in around -25070.



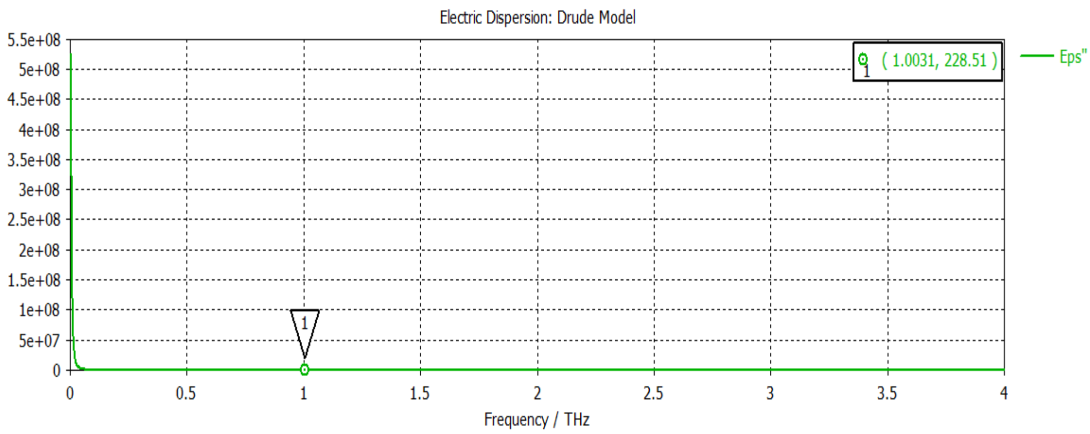
(a)



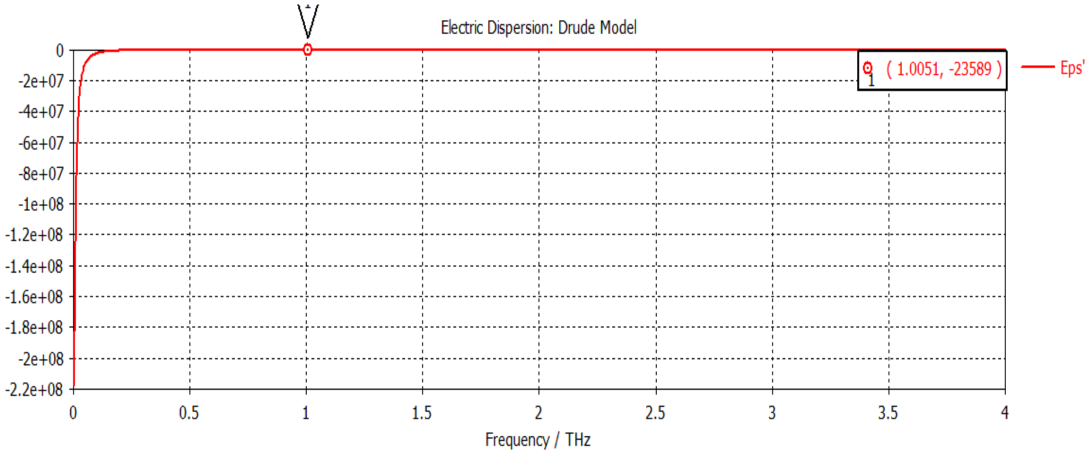
(b)

Figure 3.1.5: Effective complex permittivity (a)Real part of complex permittivity as a function of frequency of SWCNTs dipole antenna coated by Aluminum of radius r = 2.71 nm, thickness 2 nm and length L=10µm. (b) Imaginary part of complex permittivity as a function of frequency of SWCNTs dipole antenna coated by Aluminum of radius r = 2.71 nm, thickness 2 nm and length L=10µm.

Effective permittivity for SWCNTs- Cu dipole antenna real and imaginary part as a function of frequency have been shown in Figure 3.1.6 (a) and Figure 3.1.6(b). That the value of permittivity (real part) at almost 1 THz have been obtained as 228.51. While imaginary part of permittivity is equal to -23589.



(a)



(b)

Figure 3.1.6: Effective complex permittivity (a)Real part of complex permittivity as a function of frequency of SWCNTs dipole antenna coated by Copper of radius r = 2.71 nm, thickness 2 nm and length L=10μm. (b) Imaginary part of complex permittivity as a function of frequency of SWCNTs dipole antenna coated by Copper of radius r = 2.71 nm, thickness 2 nm and length L=10μm.

Through our studied of SWCNTs- composite dipole antenna, the absolute value of permittivity(real and imaginary) at 1 THz is equal for SWCVT-Al 25071.1 and for SWCNTs- Cu is equal to 23590.1, that show us the permittivity of SWCNTs- Al is larger than the copper one, that because the fermi velocity of aluminum $2.02 * 10^6(m/s)$ more than that of copper.

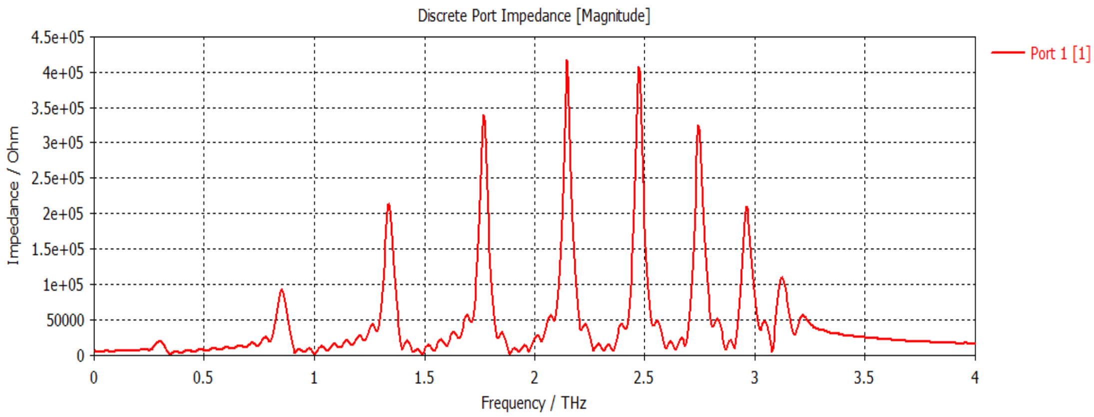
Table 3.1.2: Real and imaginary part of effective permittivity of SWCNTs, SWCNTs- Al and SWCNTs- Cu with L=10μm.

	Real part of permittivity	**Imaginary part of permittivity**
SWCNTs- Al	242.42	-25070
SWCNTs- Cu	228.5	-23589

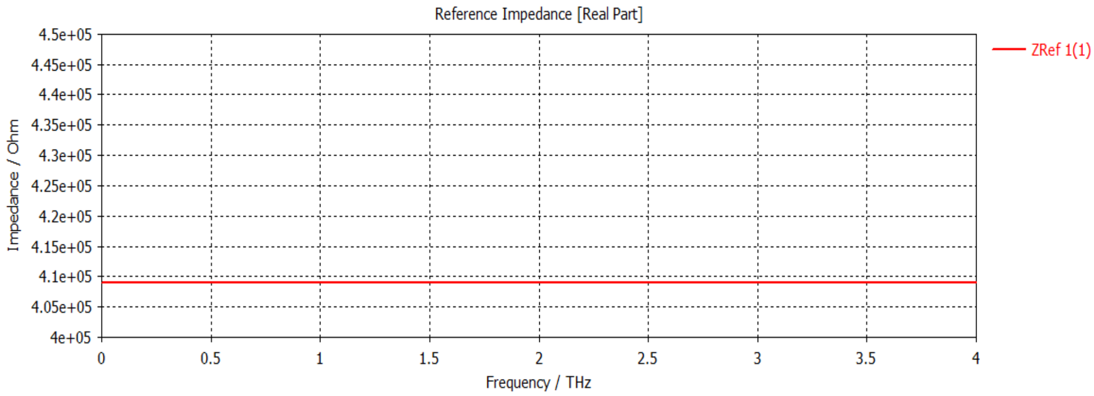
3.2 Matching Impedance in Discret Port

For efficient transfer of energy, the impedance of the antenna, and the transmission line should be the same. In this section the value of impedance for coating and non-coating SWCNTs antenna at different length for aluminum coating and copper coating had been founded by optimization between antenna and port.

Discrete port impedance and antenna impedance should be matched to have efficient antenna without power loss. Figure 3.2.1 (a) give us the value of impedance used in SWCNTs- Al dipole antenna with length equal $10\mu m$ and figure 3.2.1 (b) give us the value of impedance had been used in the port that connect the two arms of antenna and it is equal to $4.09 * 10^5$.

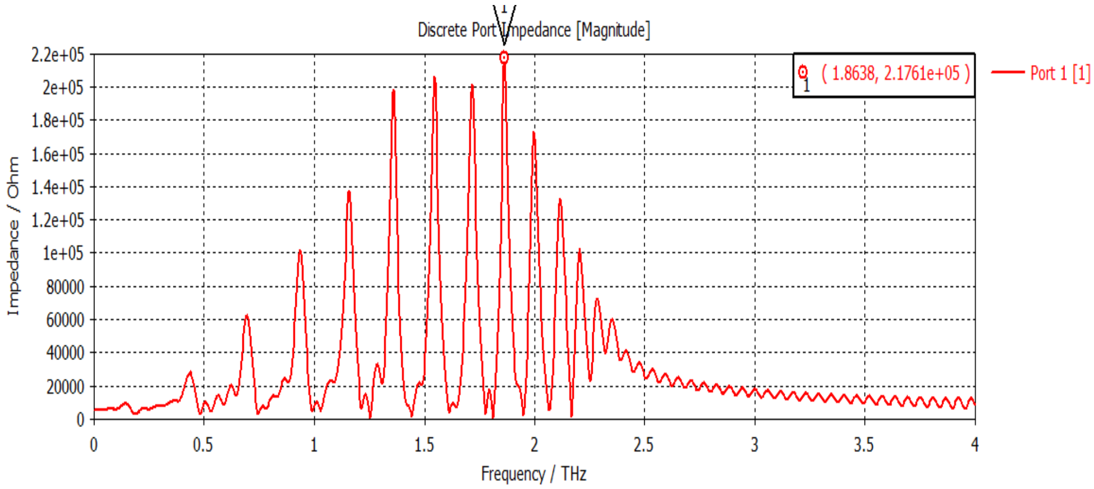


(a)

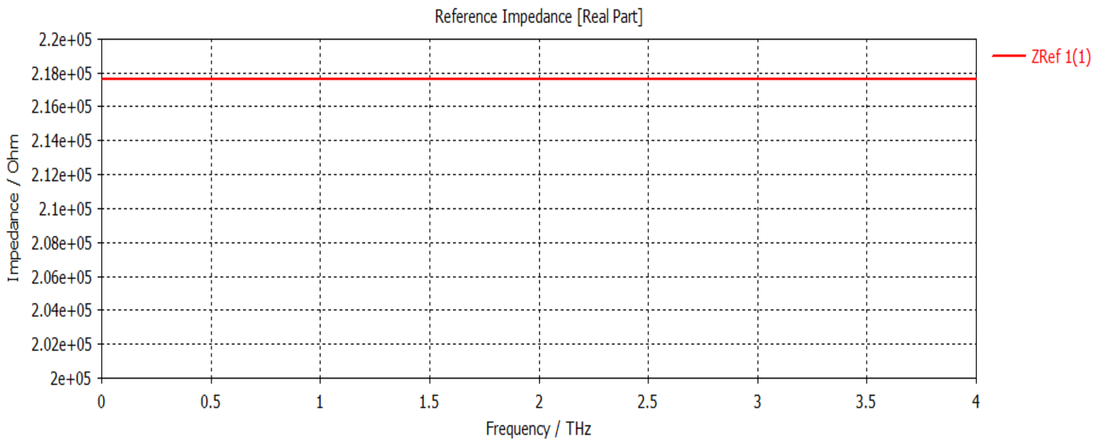


(b)

Figure 3.2.1: Impedance as a function of frequency (a) Impedance used in SWCNTs- Al dipole antenna as a function of frequency with length equal $10\mu m$ and figure 3.2.1 (b) Impedance used in the port that connect the two arms of antenna and it is equal to $4.09 * 10^5 \Omega$.

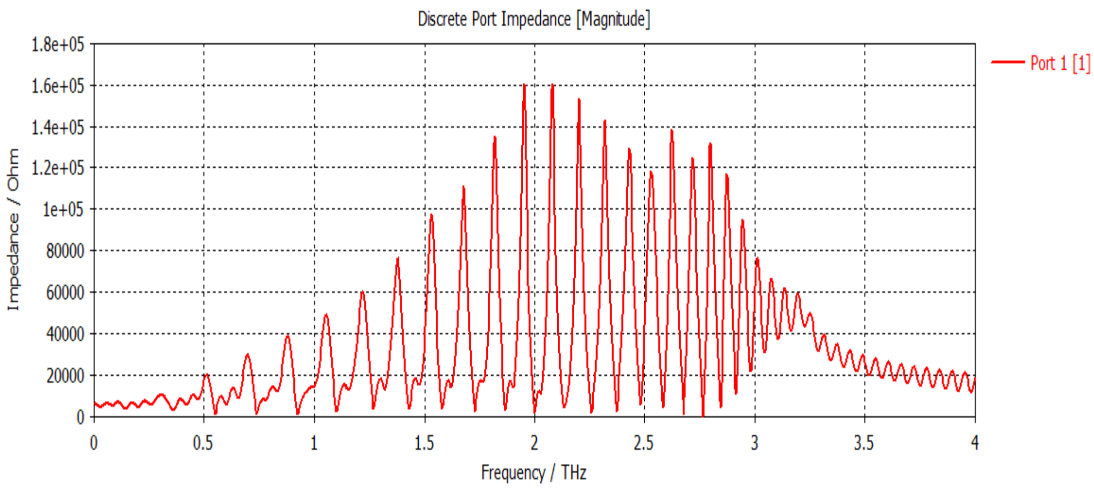


(a)

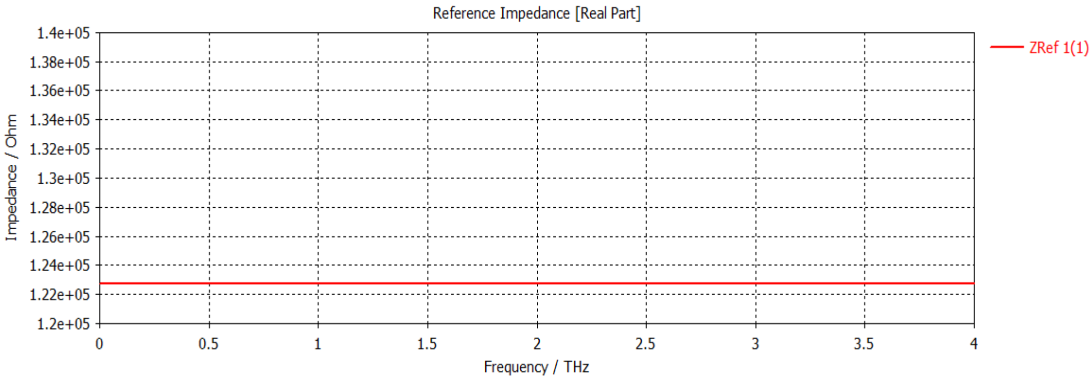


(b)

Figure 3.2.2: Impedance as a function of frequency (a) Impedance used in SWCNTs- Al dipole antenna as a function of frequency with length equal $20\mu m$ and Figure 3.2.2 (b) Impedance used in the port that connect the two arms of antenna and it is equal to $2.1761 * 10^5 \Omega$.

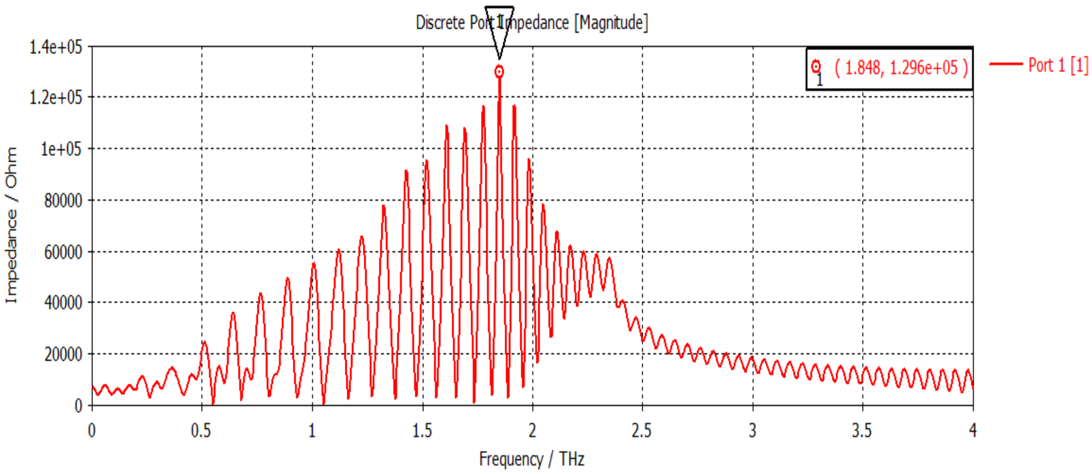


(a)

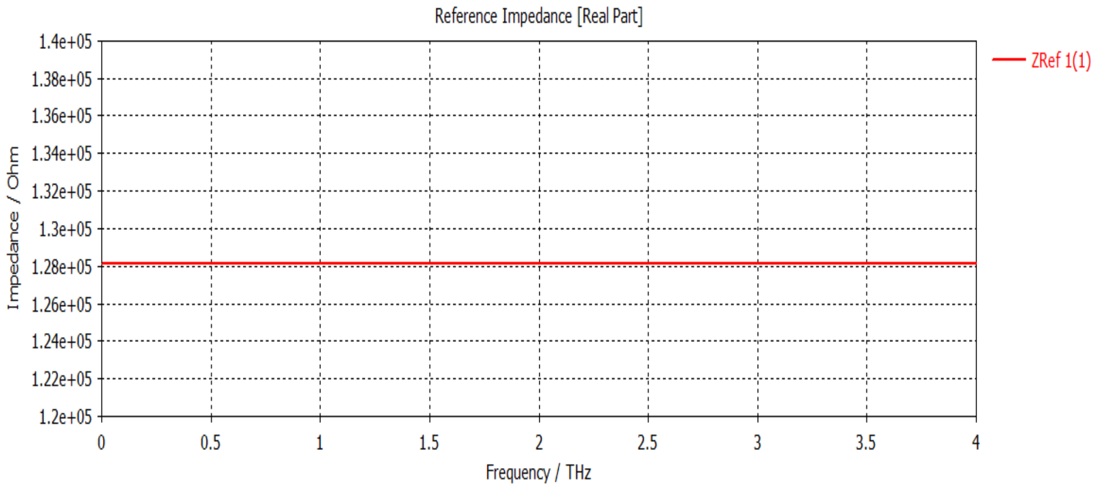


(b)

Figure 3.2.3: Impedance as a function of frequency (a) Impedance used in SWCNTs- Al dipole antenna as a function of frequency with length equal $30\mu m$ and figure 3.2.3 (b) Impedance used in the port that connect the two arms of antenna and it is equal to $1.227 * 10^5 \Omega$.



(a)



(b)

Figure 3.2.4: Impedance as a function of frequency (a) Impedance used in SWCNTs- Al dipole antenna as a function of frequency with length equal $40\mu m$ and Figure 3.2.4 (b) Impedance used in the port that connect the two arms of antenna and it is equal to $1.296 * 10^5 \Omega$.

As the length of coated SWCNTs dipole antenna increase the impedance matched at lower value but still around 10^5.

Table 3.2.1: Matching impedance of SWCNTs and SWCNTs- Al.

SWCNTs dipole antenna length (μm)	**Matching impedance$R_{eq}(\Omega)$**	**SWCNTs-Aluminum Antenna length (μm)**	**Matching impedance $R_{eq}(\Omega)$**
10	22108	10	$4.09 * 10^5$
20	44216	20	$2.176 * 10^5$
30	66324	30	$1.227 * 10^5$
40	88433	40	$1.296 * 10^5$

3.3 EFFICIENCY

Radiation efficiency of SWCNTs antenna had very low values that restricted its application as antenna in the THz regime. SWCNTs-composite material is used to increase the radiation efficiency very significantly in the THz regime. The relation $10\log_{10}(\frac{power\ radiated}{power\ input})$ is used to transfer between (dB) and percent.

In figure 3.3.1 the radiation efficiency of SWCNTs without coating layer for $10\mu m$ length and radius $2.71\ nm$ had been found to be $1.059 * 10^{-2}$, this value is not good compering with antenna with coating layer as shown in figure 3.3.1.

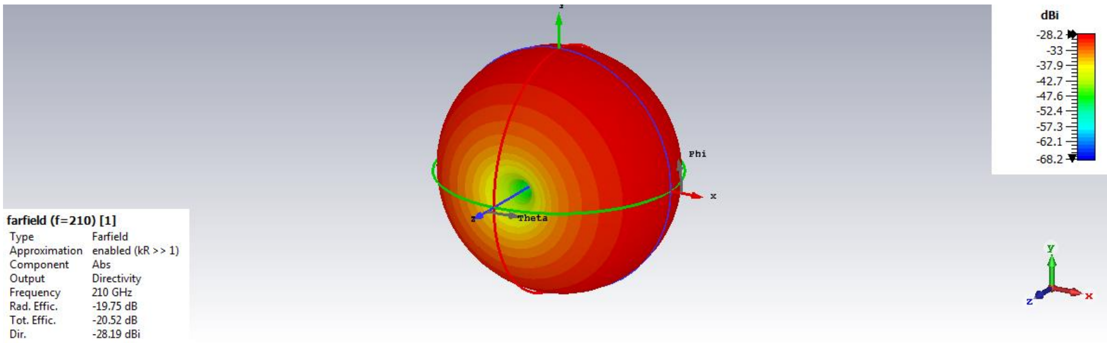
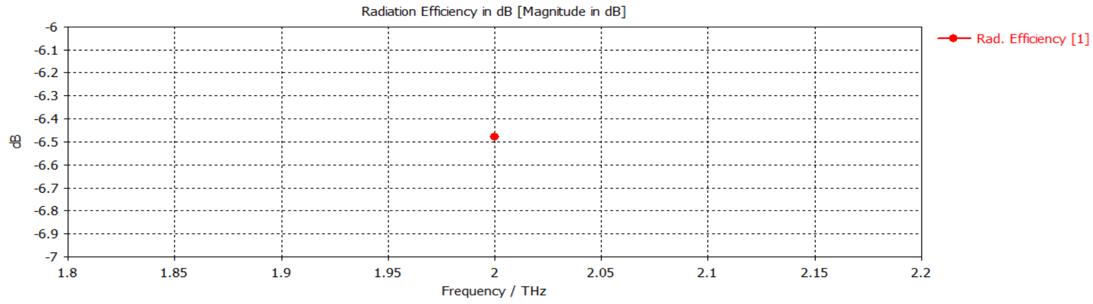


Figure 3.3.1: 3D far field plot and Radiation efficiency of SWCNTs dipole antenna $10\mu m, 2.71\ nm$ radius at 210 GHz**.**

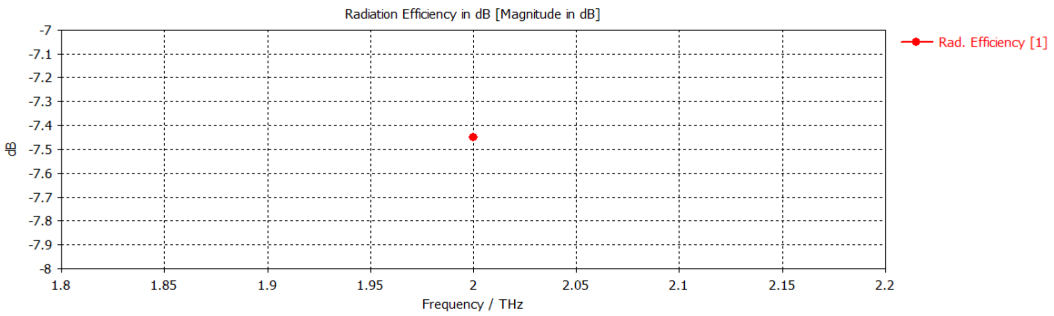
Table 3.3.1: Radiation efficiency of SWCNT dipole antenna at different length.

Length of SWCNTs dipole antenna L(μm)	**Radiation efficiency of SWCNTs**
10	$1.059 * 10^{-2}$
20	$0.3352 * 10^{-2}$
30	$0.2986 * 10^{-3}$
40	$0.2311 * 10^{-3}$

As metal had been used to coat antenna the efficiency increased rapidly as shown in figure 3.3.2. Aluminum has been used to coat SWCNTs dipole antenna.



(a)



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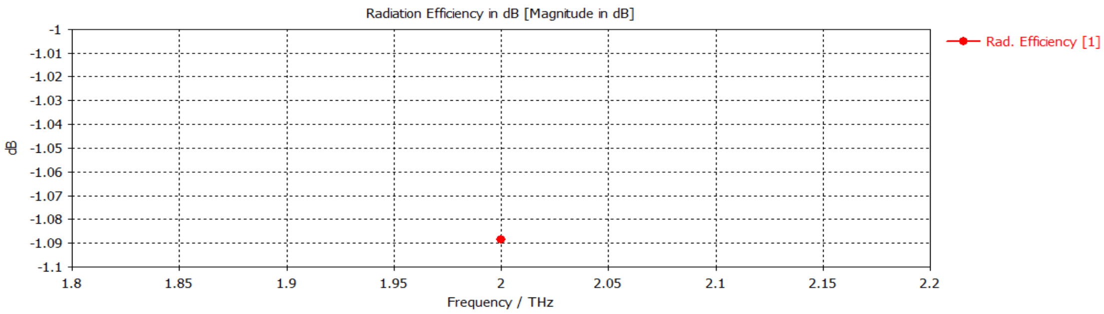
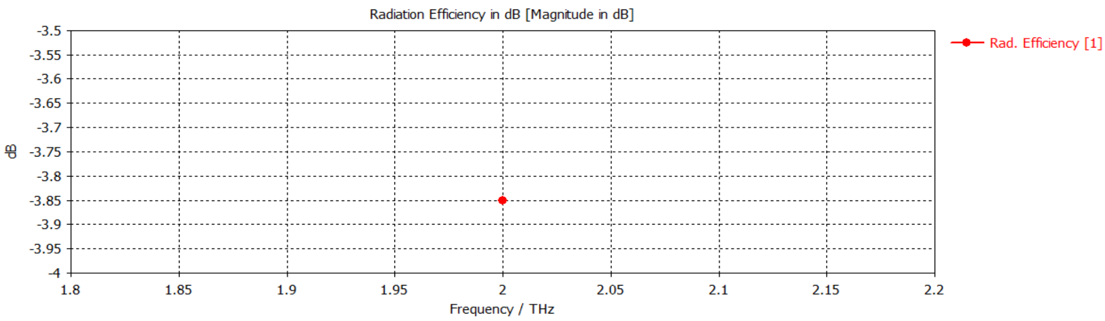


(c)



(d)

Figure 3.3.2: Radiation efficiency of SWCNTs- Al dipole antenna as a function of frequency in terahertz range ,L=$10, 20, 30, 40\mu m$, r= 2.71 nm, t= 2 nm.

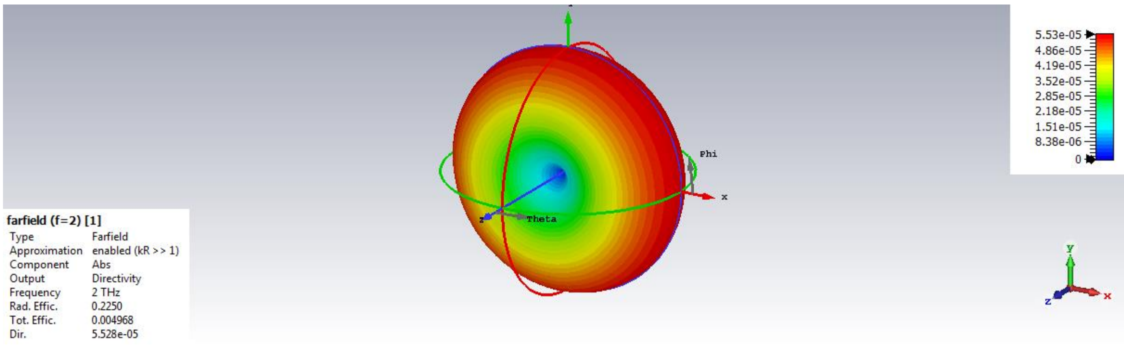
The radiation efficiencies in figure 3.3.2 (a), (b), (c), (d), have been considered at verious lengths, the most probable length that have the highest radiation effiecincy value at figure 3.3.2 (c) around 77%. The radiation efficiency of antenna affected by the length of antenna directly.

In table 3.3.2 the value of radiation efficiency have been summarized at four antenna lengths. The most probaple length that the antenna radiated and transmettied wave effectively at 30 μm.

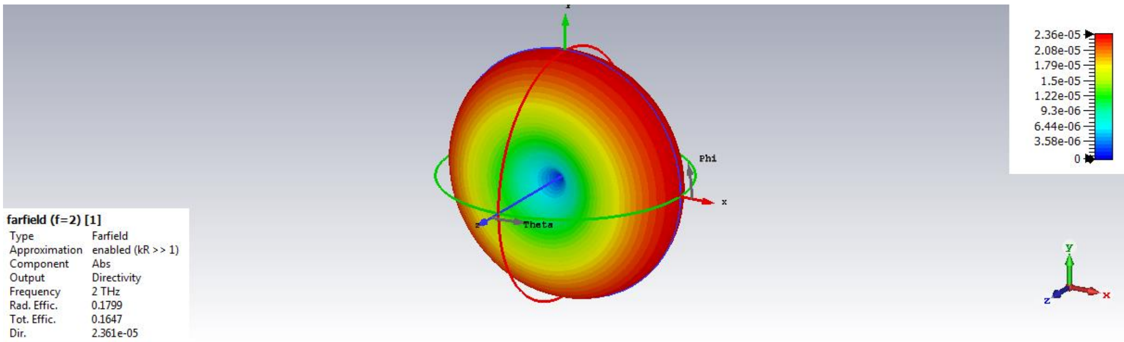
Table 3.3.2: Length of SWCNTs- Al dipole antenna in (μm) against radiation efficiency at each length at different resonance frequency.

Length of SWCNTs- Al dipole antenna L(μm)	**Radiation efficiency of SWCNTs- Al**
10	0.225
20	0.1799
30	0.77
40	0.4119

In figure 3.3.3 the total efficiency have been obtained from 3D far field plots at four different length. From the results below the values of total efficiency was very small because of mismatch in reserved waves that the antenna transmitted. To get rid the mismatch, transformer circuit could be built to reserve all the transmitted wave.



(a)



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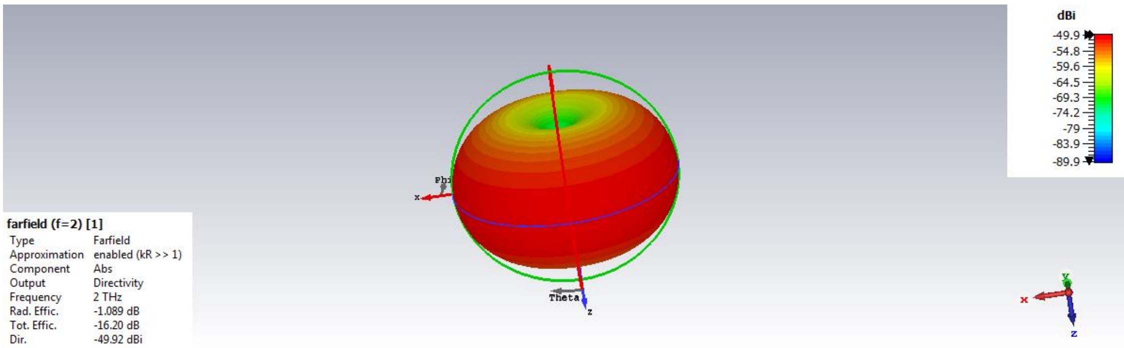
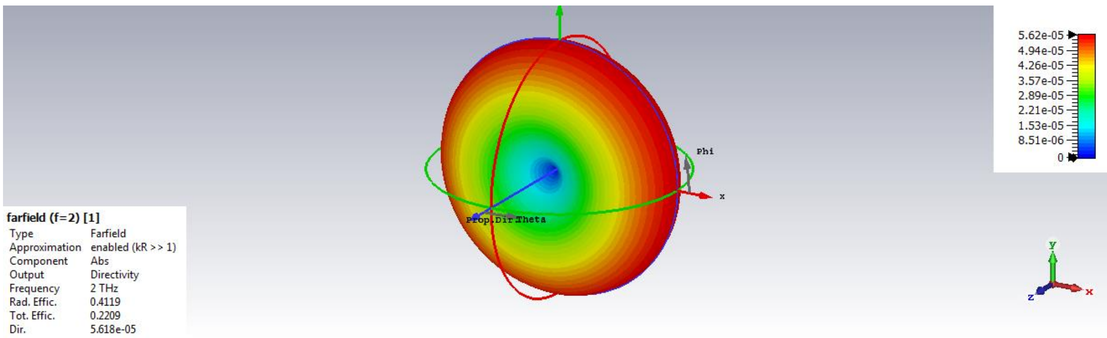
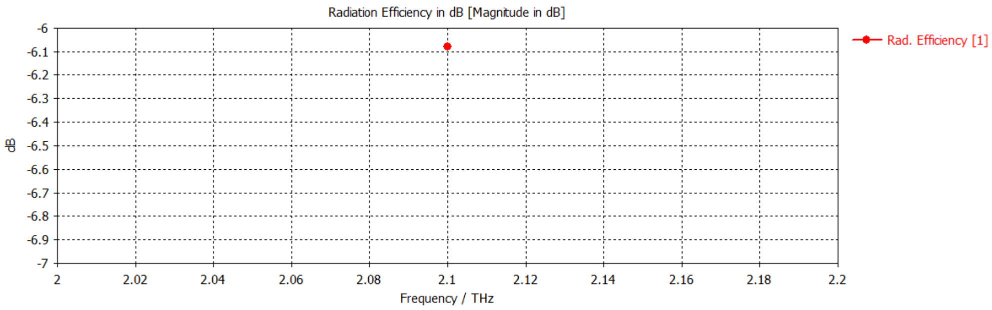


(c)

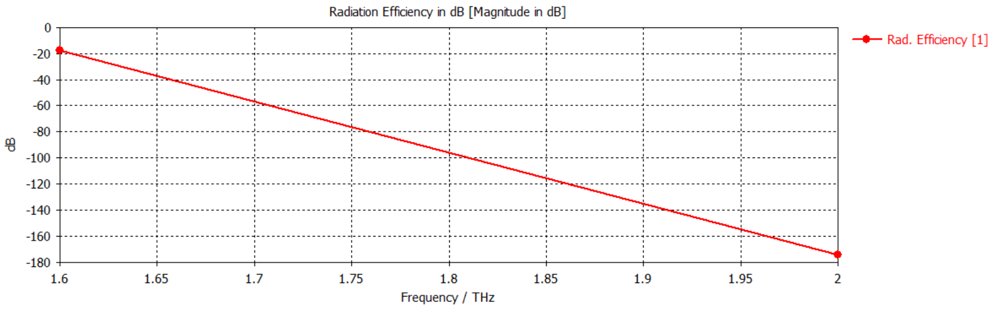


(d)

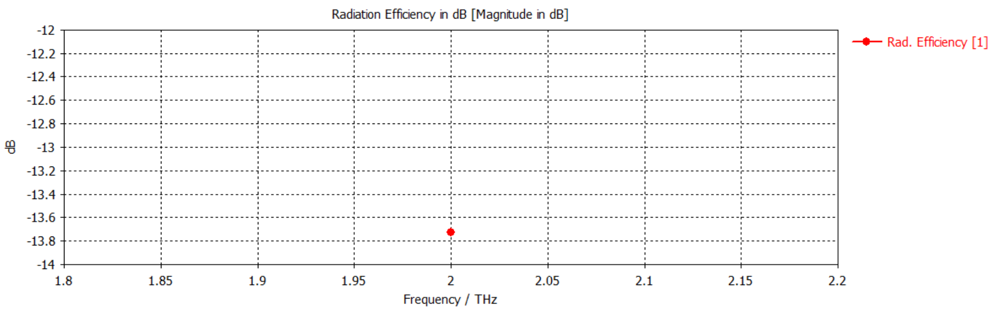
Figure 3.3.3: 3D far field plot at L= 10,20,30,40 μm in (a), (b), (c), (d).



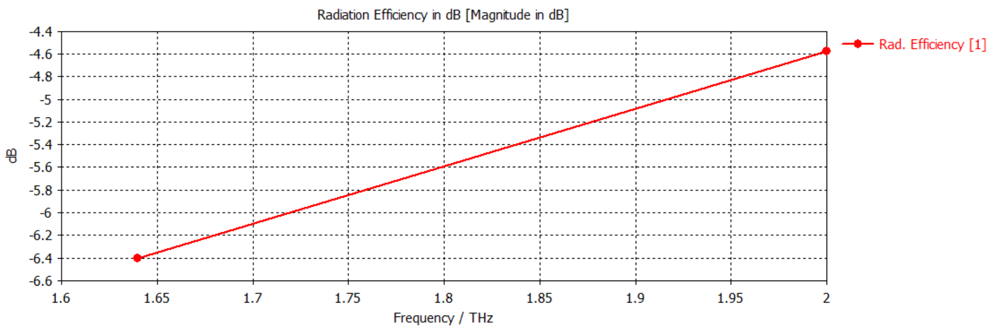
(a)



(b)

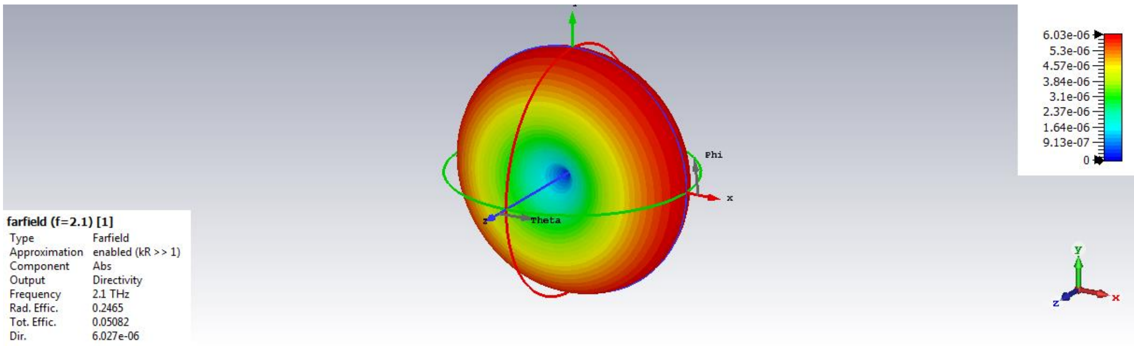


(c)

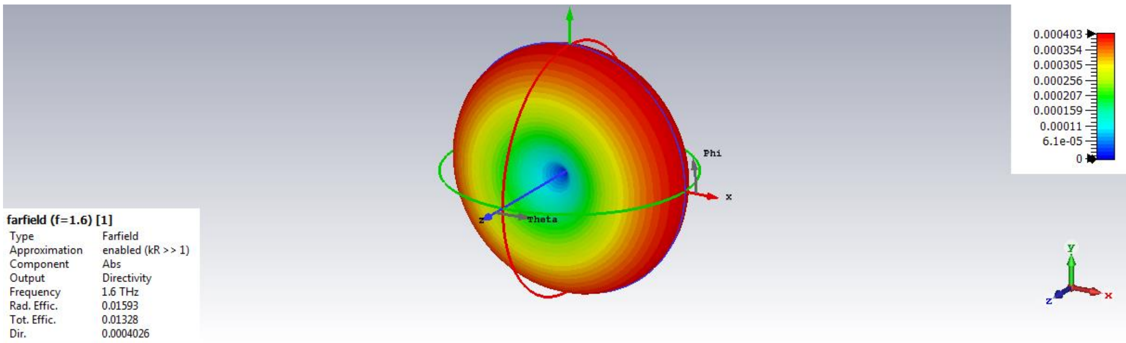


(d)

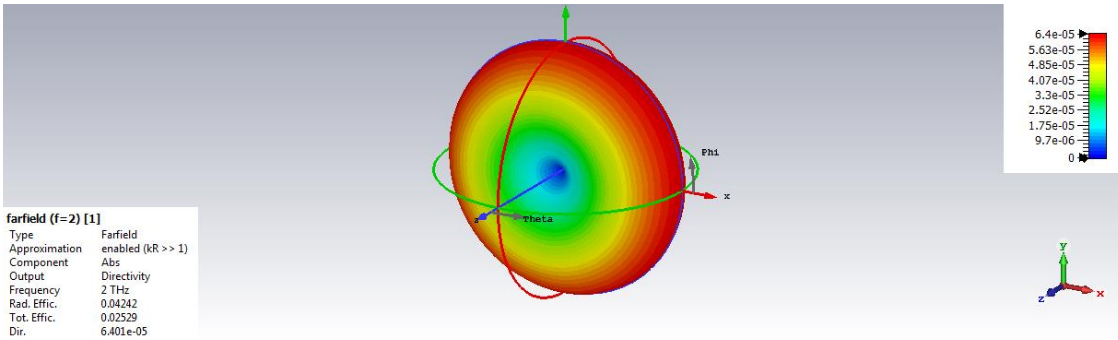
Figure 3.3.4: Radiation efficiency of SWCNTs- Cu dipole antenna as a function of frequency in terahertz range, L=10, 20, 30, 40 μm, r= 2.71 nm, t= 2 nm as in (a), (b), (c), (d).



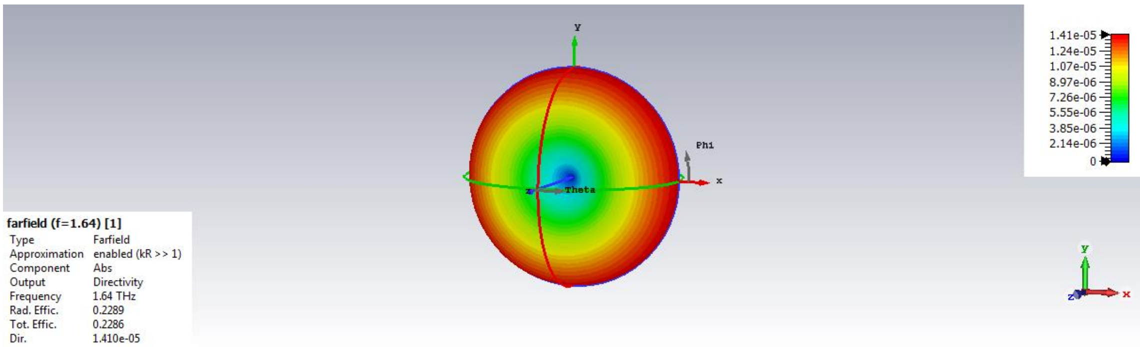
(a)



(b)



(c)



(d)

Figure 3.3.5: 3D far field plot.

In figure 3.3.4 (a), (b), (c), (d), the values of radiation efficiency have been obtained at four different length for SWCNT- Cu dipole antenna. And at 10 μm it had the highest value between other length means that 10 μm is the most probable length.

Table 3.3.3: Radiation efficiency of SWCNTs- Cu dipole antenna at several lengths.

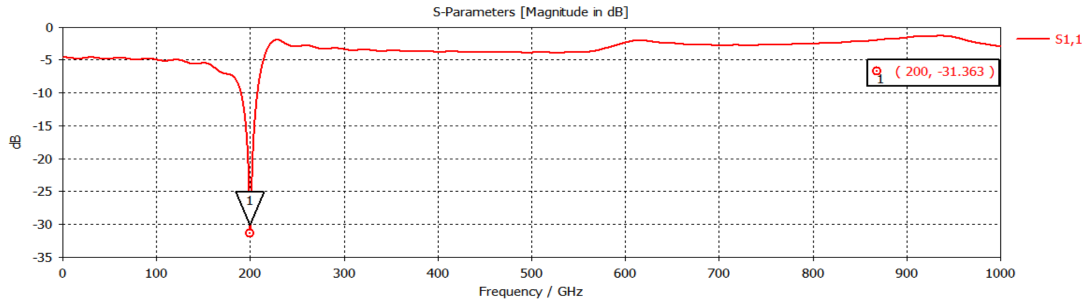
Length of SWCNTs-Cu dipole antenna L(μm)	**Radiation efficiency of SWCNTs-Cu**
10	0.2465
20	0.01593
30	0.04242
40	0.2289

Through table 3.3.1, 3.3.2 and 3.3.3 have shown the radiation efficiency of SWCNTs, SWCNTs- Al, SWCNTs-Cu dipole antenna with different length and constant radius equal to 2.71 nm. We conclude that the efficiency have its highest value at length SWCNTs- Al equal 30 μm in SWCNTs- Al, and 10 μm in SWCNTs-Cu.

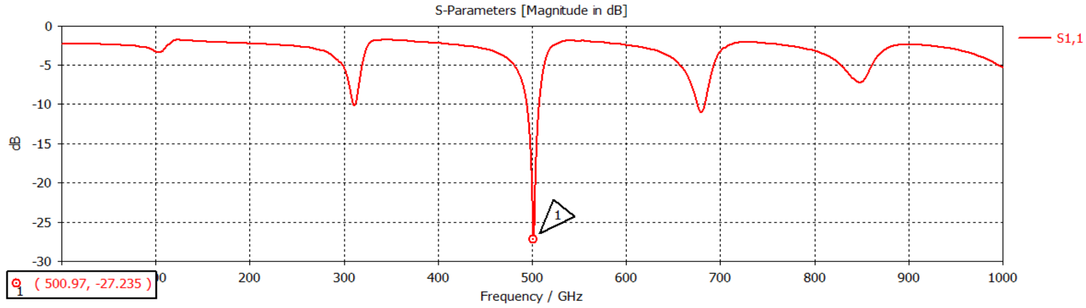
The radiation efficiency of coated SWCNTs dipole antenna is larger than the SWCNTs dipole antenna without coating layer. Also the antenna with 30 μm length have the highest value of efficiency, this means that it is the most probable length for designing antenna.

3.4 Scattering parameter.

Scattering parameter shows how much power is reflected from the antenna. Figures 3.4.1 (a), (b), (c), (d), have been shown the scattering parameter of SWCNTs with length $10, 20, 30, 40\ \mu m$.



(a)



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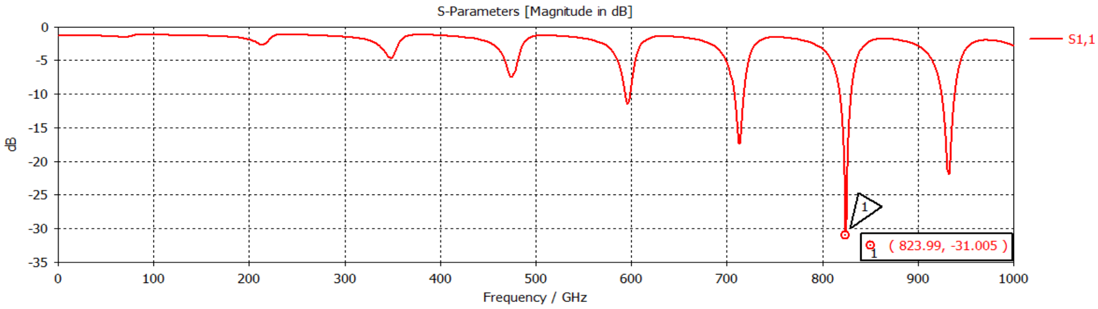
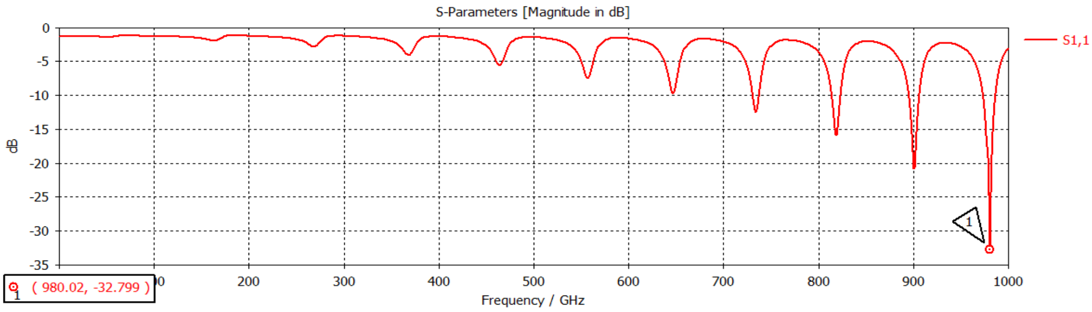


(c)



(d)

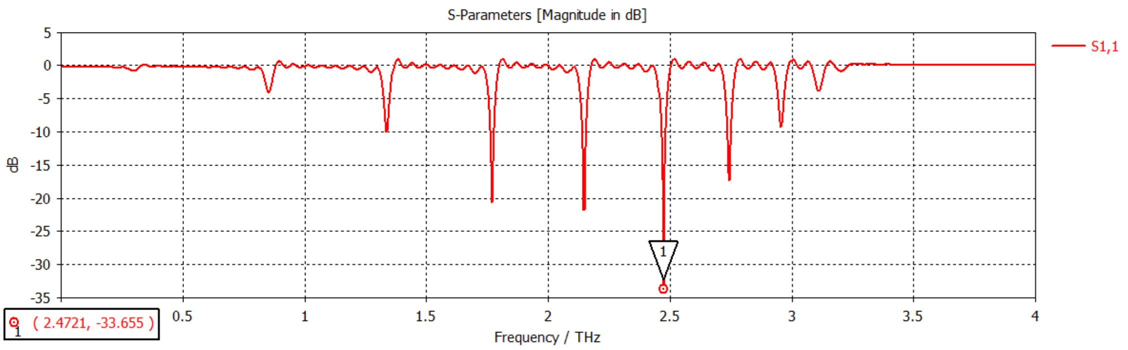
Figure 3.4.1: Simulation result of s_{11} in decibel as a function of frequency for SWCNTs dipole antenna, where length L=10, 20, 30, 40 μm and radius 2.71 nm.

In figure 3.4.1 (a), (b), (c), (d), scattering parameter values have been summarized in table 3.4.1 at progressively resonance frequency as below:

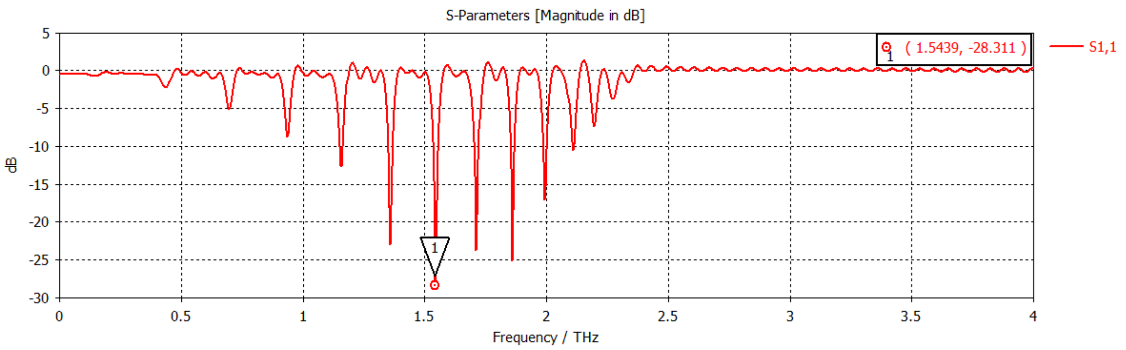
Table 3.4.1: Scattering parameter of SWCNTs as a function of frequency of dipole antenna at several length.

Length of SWCNTs dipole antenna L(μm)	Scattering parameter of SWCNTs(dB)	Frequency (GHz)
10	-31.363	200
20	-27.235	500.97
30	-31.005	823.99
40	-32.671	980.02

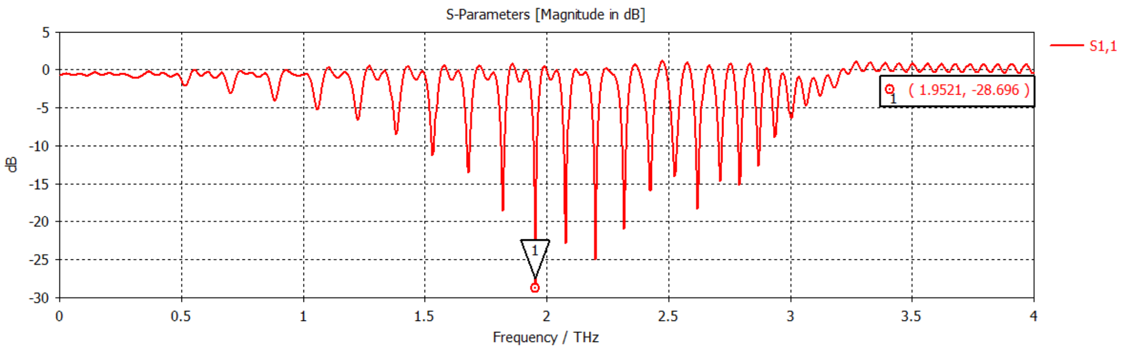
After coating SWCNTs dipole antenna with aluminum the scattering parameter values have been obtained in figure 3.4.2 (a), (b), (c), (d).



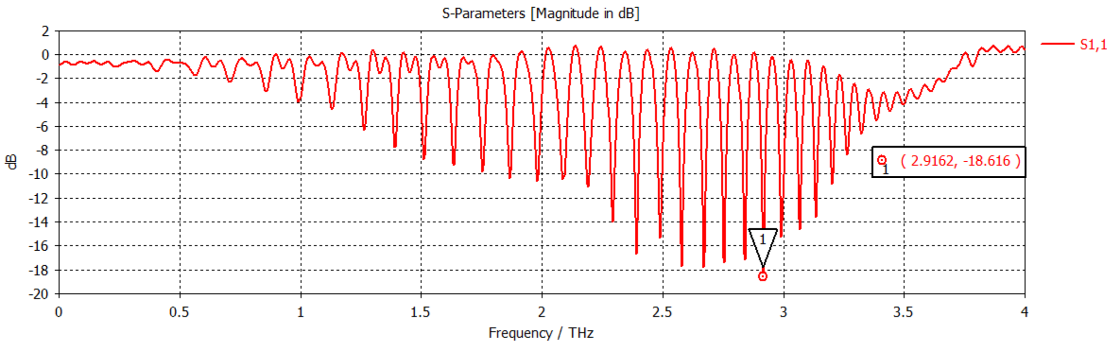
(a)



(b)



(c)



(d)

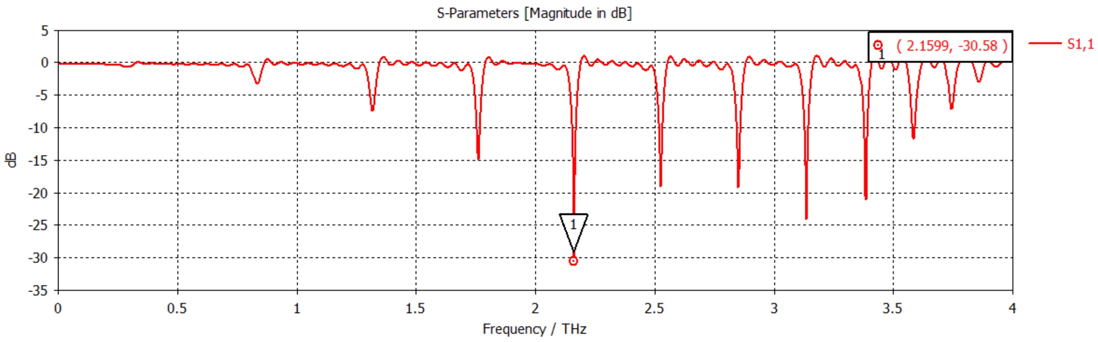
Figure 3.4.2: Simulation result of s_{11} in decibel as a function of frequency for SWCNTs-Al dipole antenna, where length $10, 20, 30, 40\ \mu m$ and radius 2.71 nm, thickness of coating layer 2 nm.

Scattering parameters represented how much wave was scattered, and as the values of it have been decreased as the efficiency of antennas have been increased.

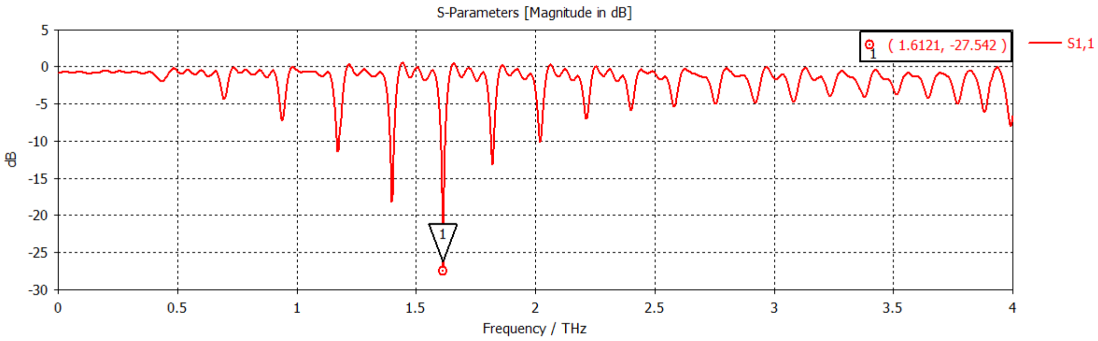
Table 3.4.2: Scattering parameter of SWCNTs-Al dipole antenna at several length.

Length of SWCNTs- Al dipole antenna L(μm)	**Scattering parameter of SWCNTs- Al(dB)**	**Frequency (THz)**
10	-33.655	2.47
20	-28.311	1.54
30	-28.696	1.95
40	-18.616	2.91

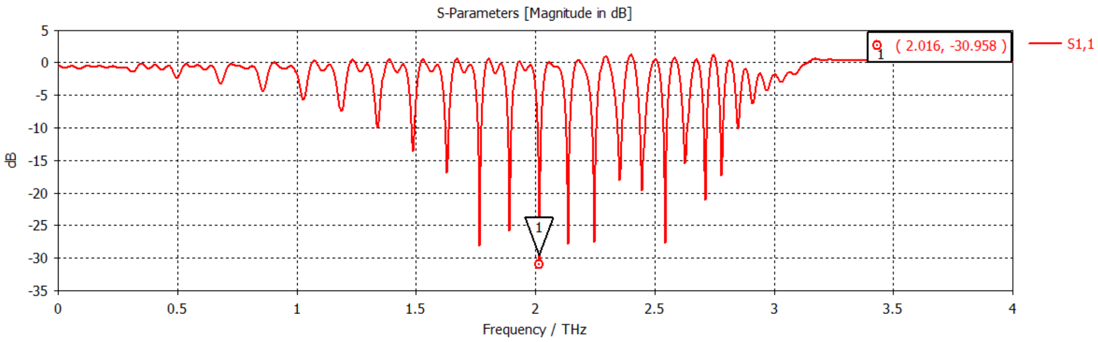
In figure 3.4.3 (a) that the scattering parameter of SWCNTs- Cu with length 10 μm, radius 2.71 nm, thickness of coating layer 2 nm is equal to -30.53(dB) at 2.1599 THz.



(a)



(b)



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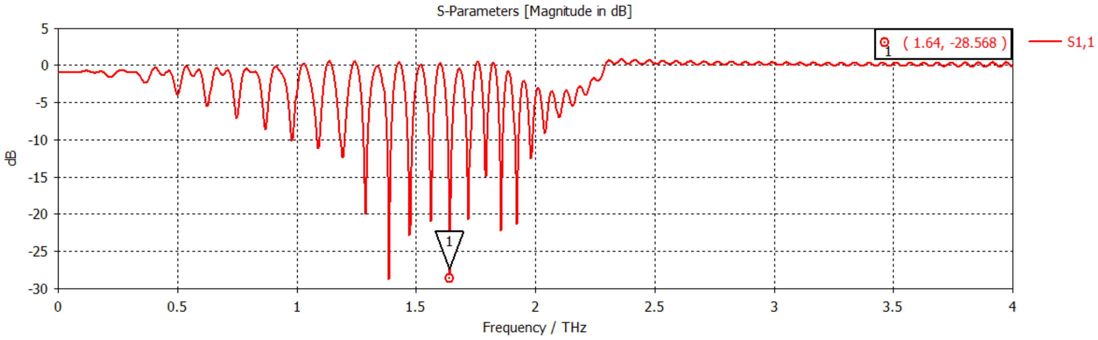


(d)

Figure 3.4.3: Simulation result of s_{11} in decibel as a function of frequency for SWCNTs-Cu dipole antenna $10, 20, 30, 40$ μm and radius 2.71 nm, thickness of coating layer 2 nm.

In figure 3.4.3 (a), (b), (c), (d), the scattering parameter of SWCNTs- Cu dipole antenna have been founded for antenna length $10, 20, 30. 40$ μm, radius 2.71 nm, thickness of coating layer 2 nm. Scattering parameter represent how much power scattered at specific length. In each antennas length we have obtained percent of scattered power depended on the design we have been built.

Table 3.4.3: Scattering parameter of SWCNTs-Cu dipole antenna at several length.

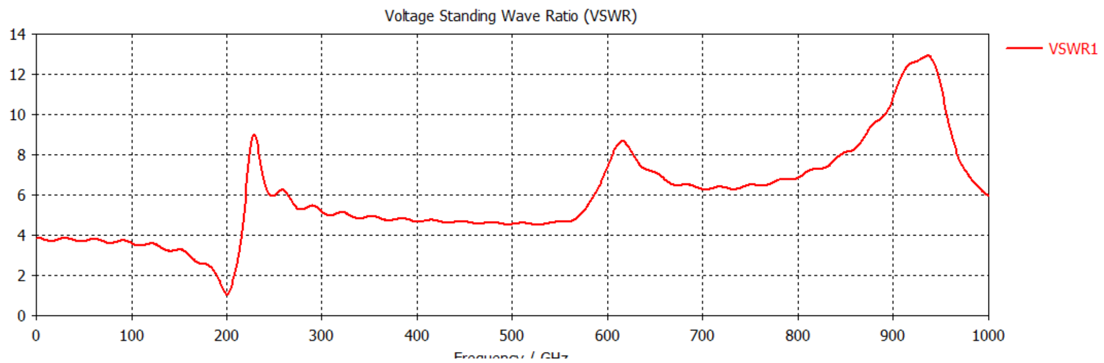
Length of SWCNTs-Cu dipole antenna L(μm)	**Scattering parameter of SWCNTs- Cu(dB)**	**Resonance frequency(THz)**
10	-30.53	2.15
20	-27.542	1.61
30	-30.985	2.01
40	-28.568	1.64

3.5 VSWR

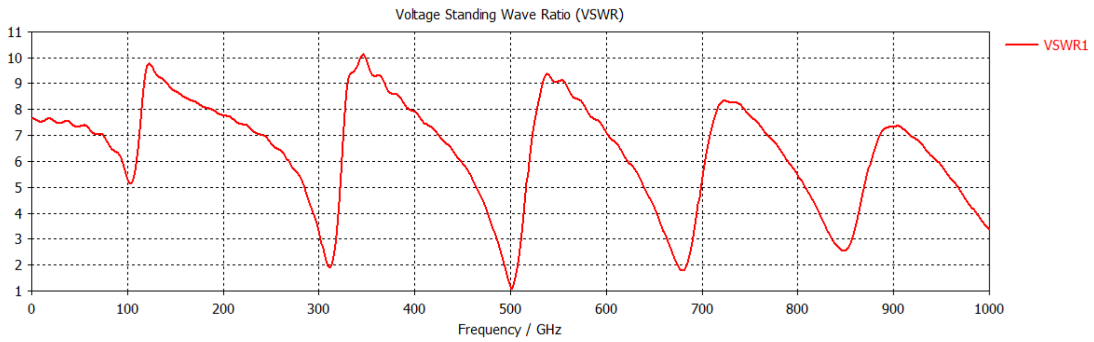
A common measure of how well matched the antenna to the transmission line is known as the Voltage Standing Wave Ratio (VSWR). VSWR is a real number that is always greater than or equal to 1. When VSWR is equal to 1, means that there is no mismatch loss (the antenna is perfectly matched). Higher values of VSWR indicate more mismatch loss. In this part figures representing VSWR at different length and frequencies:

$VSWR$ for SWCNTs dipole antenna without coating L=$10, 20, 30, 40\ \mu m$ and radius equal 2.71 nm represented in figure 3.5.1(a), (b), (c), (d), as a function of frequency.

The value of VSWR have been obtained in figure 3.5.1 (a) to be one at frequency almost 200 GHz, that means at this value of frequency there is no mismatch loss. Sequentially, in figure 3.5.1 (b), (c), (d), the resonance frequency that have VSWR almost one is equal to 500, 940, 990 GHz.



(a)



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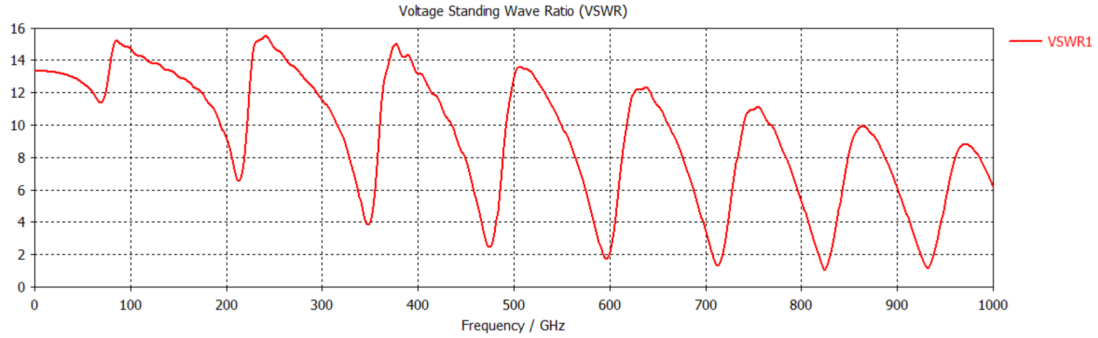
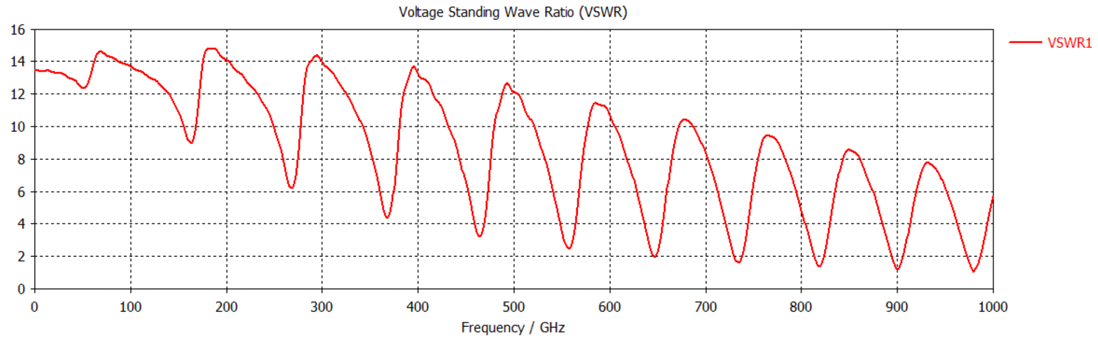


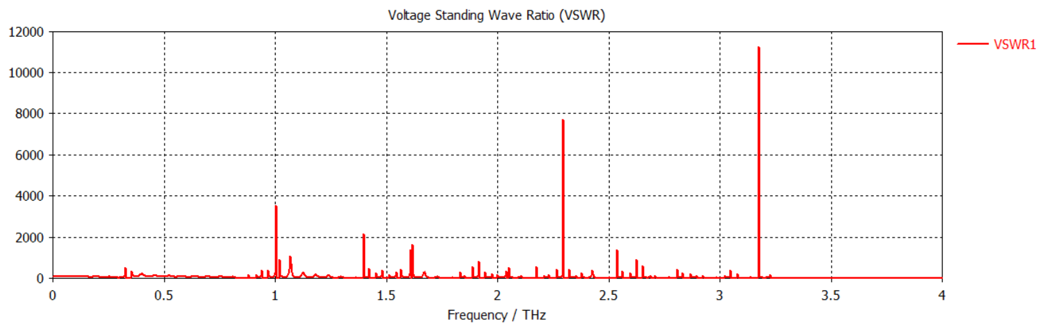
(c)



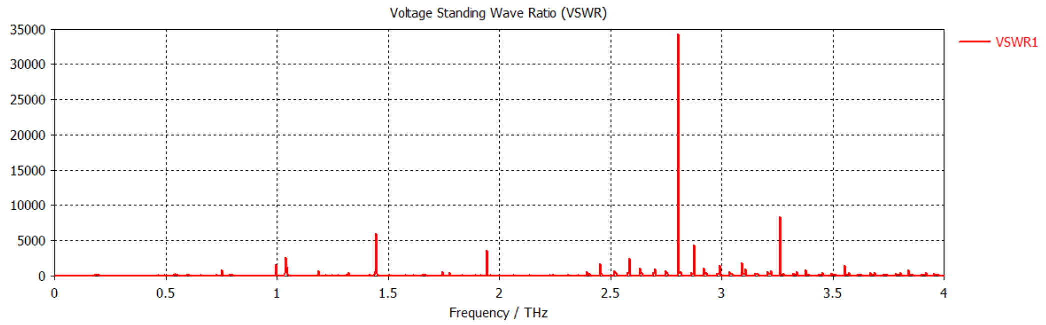
(d)

Figure 3.5.1: VSWR as a function of frequency of SWCNTs dipole antenna, L=$10, 20, 30, 40\ \mu m$ and radius equal 2.71 nm.

After coating SWCNTs with aluminum VSWR is equal to one at frequencies 2.47, 1.54, 1.95, 2.91 THz appear in figure 3.5.2 (a), (b), (c), (d), L=$\mathbf{10, 20, 30, 40}\ \boldsymbol{\mu m}$



(a)



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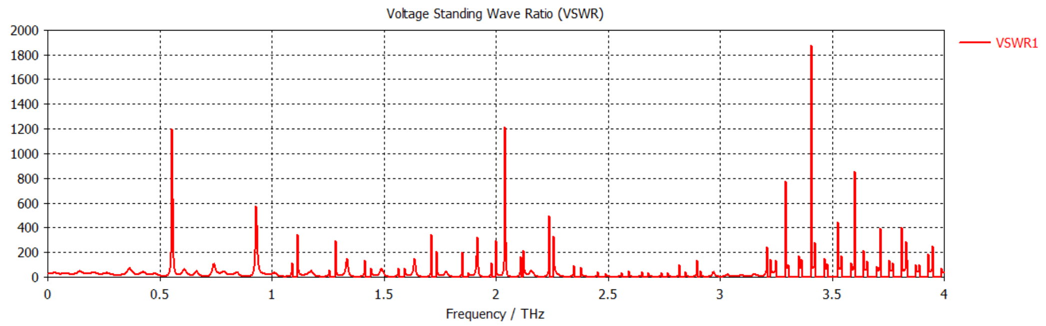
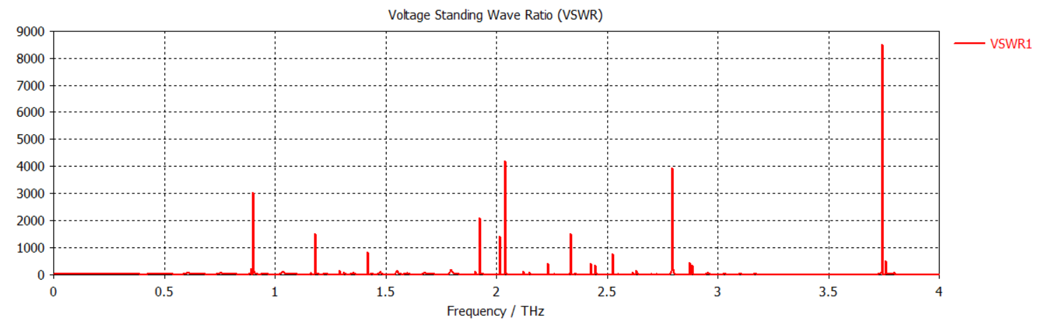


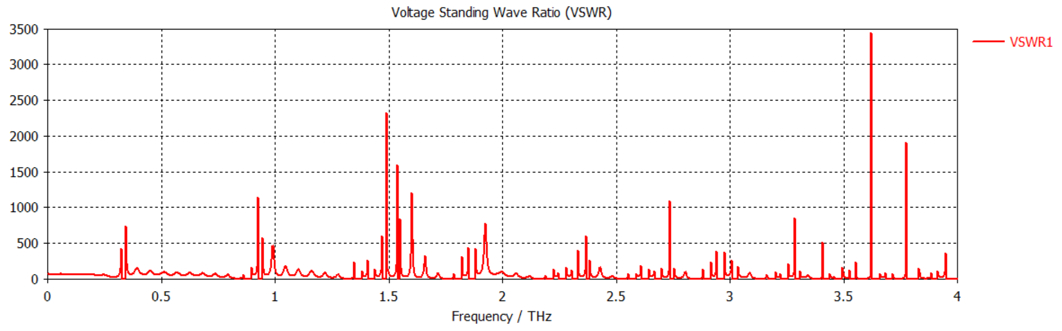
(c)



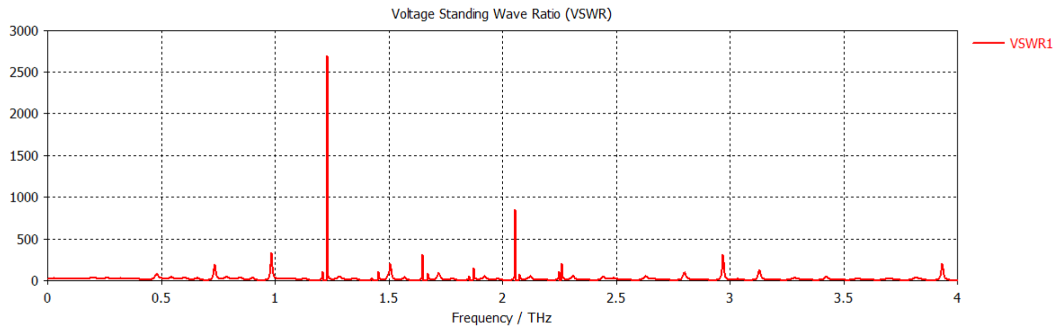
(d)

Figure 3.5.2: Simulation results of VSWR as a function of frequency of SWCNTs- Al dipole antenna, where L=$10, 20, 30, 40$ μm and radius equal 2.71 nm.

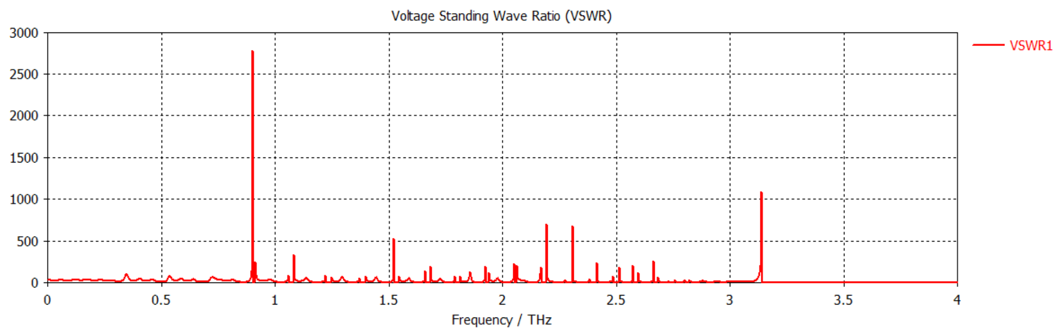
By repetition for SWCNT- Cu dipole antenna, the value of VSWR have been obtained in figure 3.5.3 (a), (b), (c), (d) to be one at frequencies equal to 2.15, 1.6, 2, 1.64 THz.



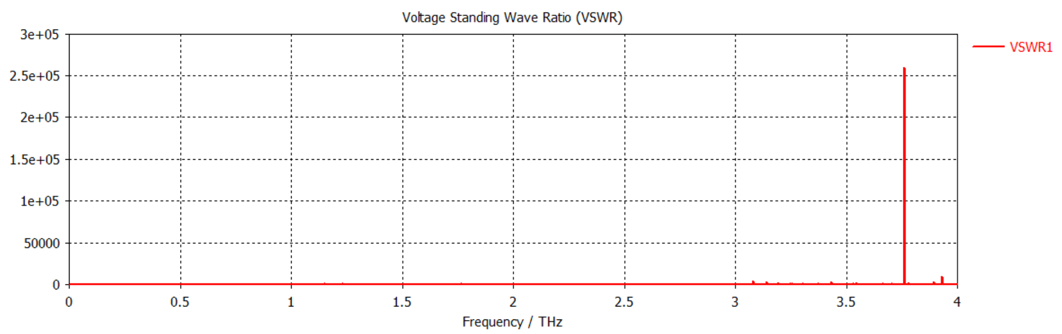
(a)



(b)



(c)



(d)

Figure 3.5.3: Simulation results of VSWR as a function of frequency for SWCNTs- Cu dipole antenna, where L=10, 20, 30, 40 μm and radius equal 2.71 nm.

3.6 Swcnts Dipole Antenna with Metal Contact and Without

One of the main problems of CNTs antenna was the contact of this type of antenna with the external world. We try to make it more easy efficient connection by using metal contact between SWCNTs and the two edges of the port as an interface without affect the properties of SWCNTs.

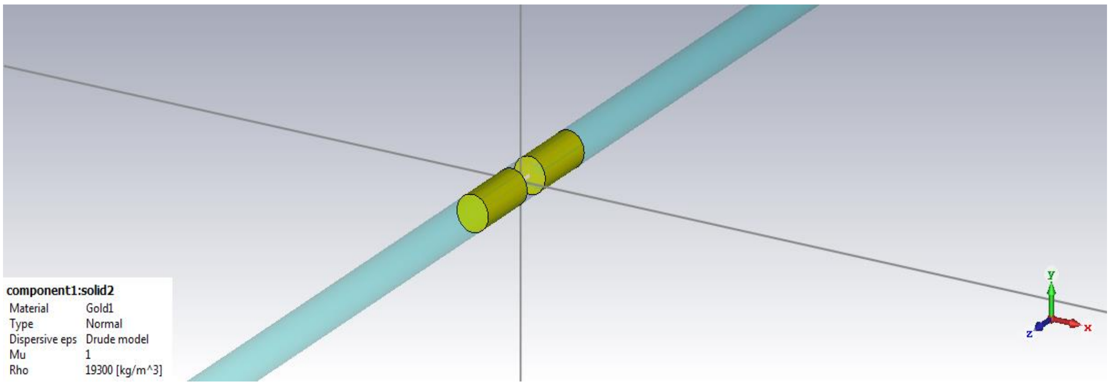
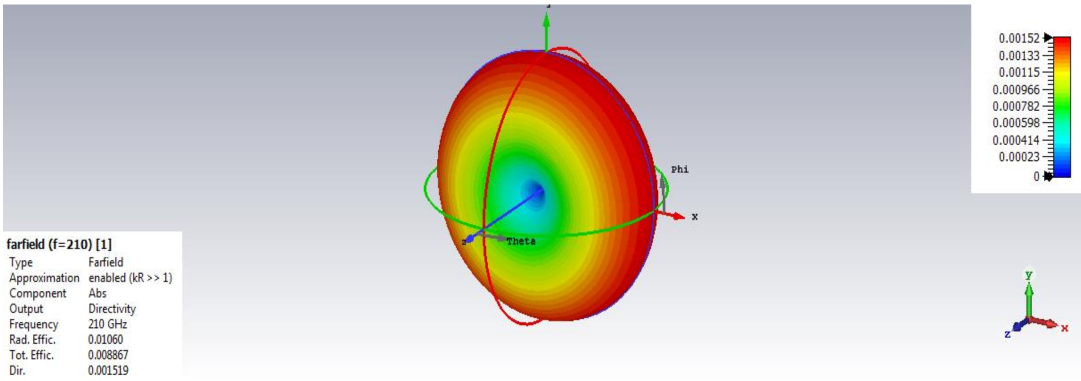
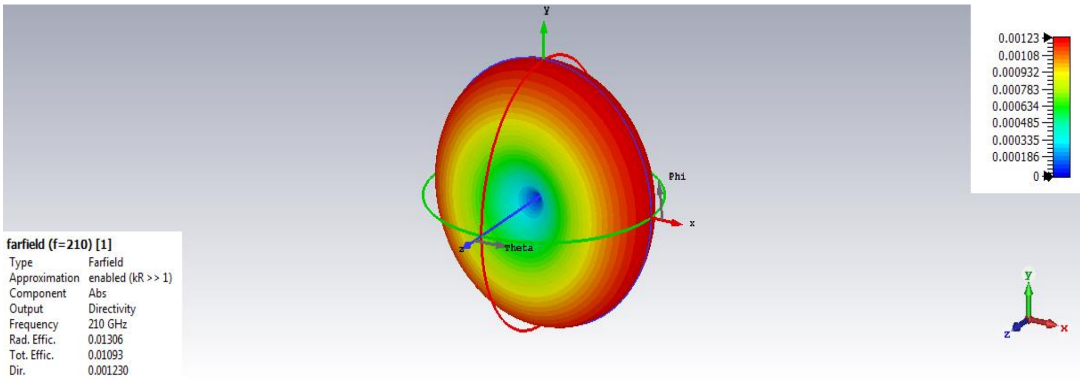


Figure 3.6.1: 3D Model of SWCNTs dipole antenna with gold metal contact.

In figure 3.6.2(a) radiation efficiency of SWCNTs dipole antenna without metal contact is shown with length 10 μm, and radius 2.71 nm. In figure 3.6.2(b) radiation efficiency of SWCNTs dipole antenna with gold metal contact its length 10 μm, and radius 2.71 nm. It seems that the radiation efficiency in part (b)$1.306 * 10^{-2}$ is more than in (a) $1.06 * 10^{-2}$that means the metal contact affect radiation efficiency of SWCNTs.



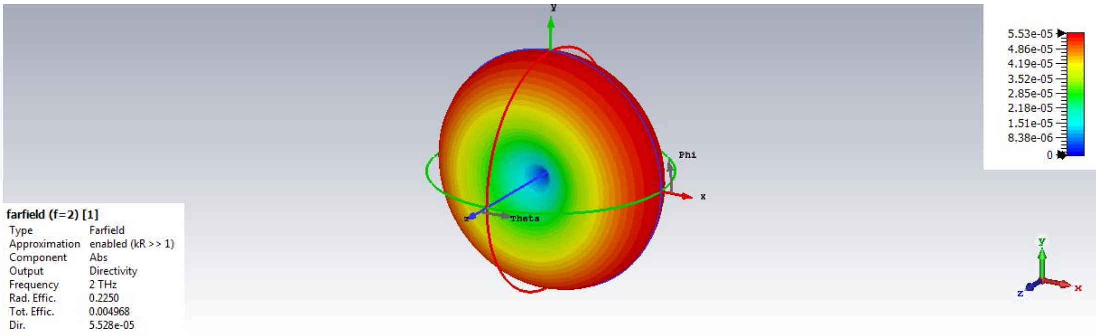
(a)



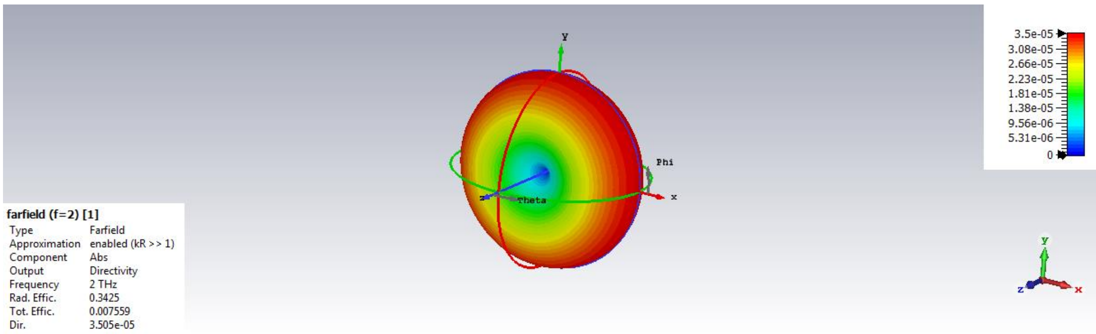
(b)

Figure 3.6.2: (a)3D far field plot of Radiation efficiency of SWCNTs dipole antenna as a function of frequency without metal contact with length 10 μm, and radius 2.71 nm. (b) (a) 3D far field plot of radiation efficiency of SWCNTs dipole antenna as a function of frequency with gold metal contact its length 10 μm, and radius 2.71 nm.

In figure 3.6.3(a) that the radiation efficiency of SWCNTs-Al dipole antenna without metal contact length 10 μm, and radius 2.71 nm is obtained to be 0.2250. In figure 3.6.3(b) the radiation efficiency of SWCNTs dipole antenna with gold metal contact, length 10 μm, and radius 2.71 nm is obtained to be 0.3425. It seems that the radiation efficiency in part (b) is more than in (a) that means the metal contact affect radiation efficiency of SWCNTs.



(a)



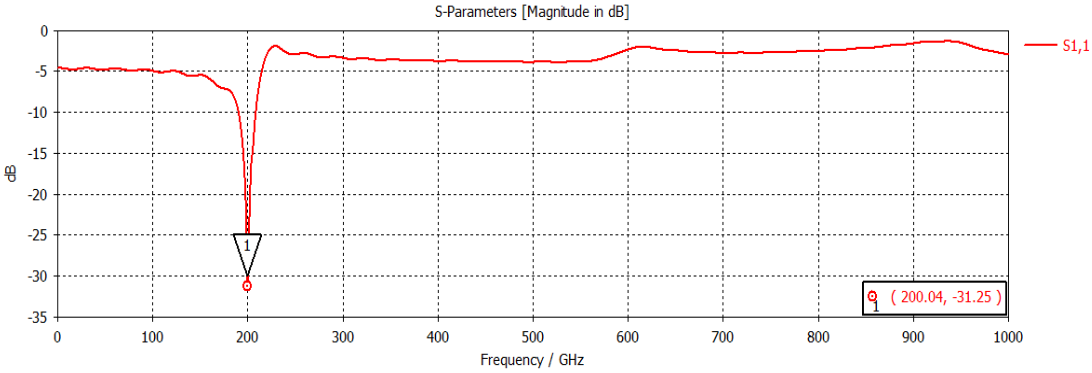
(b)

Figure 3.6.3: (a) 3D far field plot of Radiation efficiency of SWCNTs- Al dipole antenna as a function of frequency without metal contact with length 10 μm, and radius 2.71 nm. (b) 3D far field plot of radiation efficiency of SWCNTs- Al dipole antenna as a function of frequency with gold metal contact, where L= 10 μm, and radius 2.71 nm.

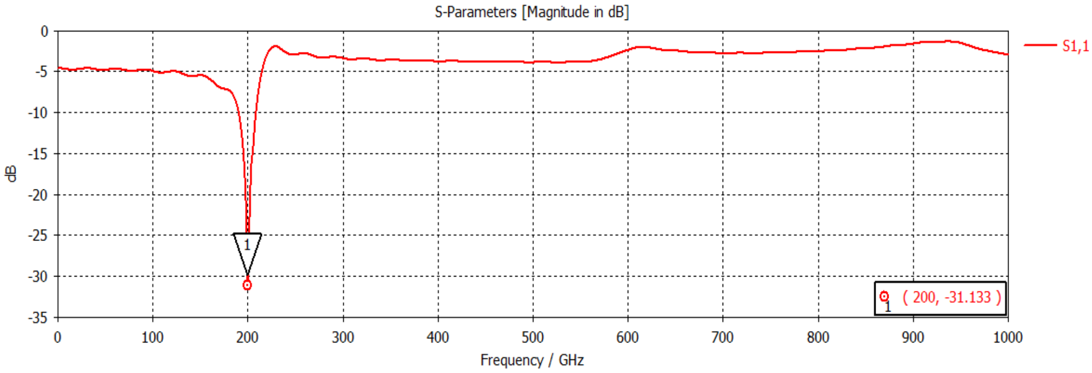
Table 3.6.1: Radiation efficiency of SWCNTs dipole antenna and SWCNTs_ Al dipole antenna with and without metal contact, with length 10 μm and radius 2.71 nm.

	SWCNTs dipole antenna without metal contact	**SWCNTs dipole antenna with metal contact**
Radiation efficiency	$1.06 * 10^{-2}$	$1.306 * 10^{-2}$
	SWCNTs-Al dipole antenna without metal contact	**SWCNTs-Al dipole antenna with metal contact**
Radiation efficiency	0.2250	0.3425

Scattering parameter of SWCNTs dipole antenna have been affected with metal contact as in figure 3.6.4(a) the scattering parameter is equal to -31.25 more than the scattering parameter without metal contact -31.33 in figure 3.6.4(b).



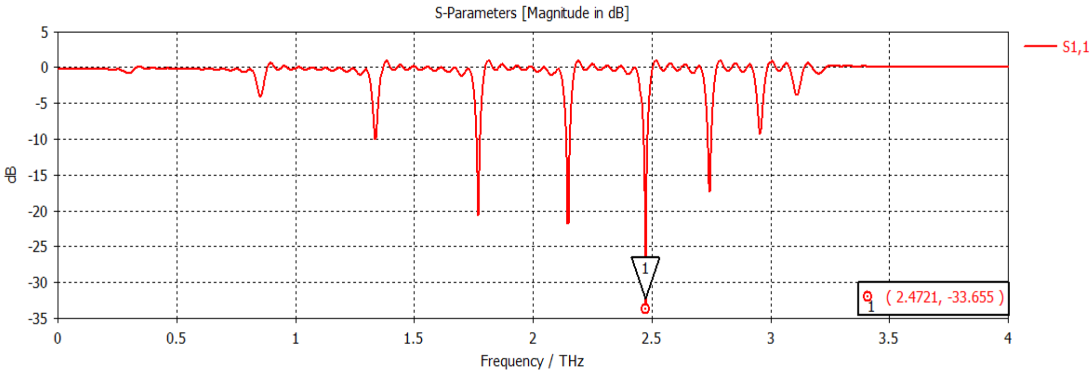
(a)



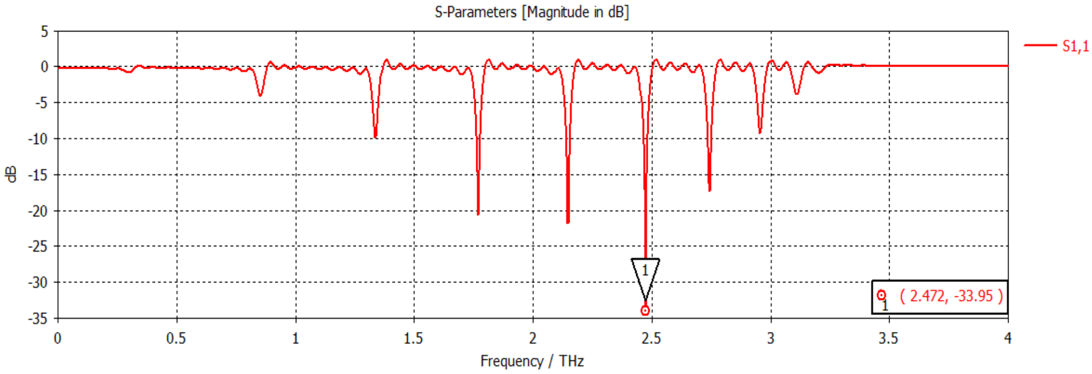
(b)

Figure 3.6.4: (a) Scattering parameter as a function of frequency of SWCNTs dipole antenna without metal contact (b) Scattering parameter of SWCNTs dipole antenna with metal contact as a function of frequency**.**

Metal contact of SWCNTs- Al dipole antenna also affect the scattering parameter as in figure 3.6.5(a) the scattering parameter is equal to -33.95 more than the scattering parameter without metal contact -33.665 in figure 3.6.5(b).



(a)



(b)

Figure 3.6.5: (a) Scattering parameter as a function of frequency of SWCNTs-Al dipole antenna without metal contact (b) Scattering parameter of SWCNTs-Al dipole antenna with metal contact as a function of frequency.

Table 3.6.2: Scattering parameter of SWCNTs dipole antenna against SWCNTs_ Al dipole antenna against SWCNTs-Cu dipole antenna, with length 10 μm and radius 2.71 nm.

	SWCNTs dipole antenna without metal contact	**SWCNTs dipole antenna with metal contact**
Scattering parameter	-31.25	-31.133
	SWCNTs-Al dipole antenna without metal contact	**SWCNTs-Al dipole antenna with metal contact**
Scattering parameter	-33.665	-33.95

3.7 RESULTS AFTER GET RID OF ANTENNA LOSS DUE TO IMPEDANCE MISMATCH

In previous sections, the designed prototype radiated EM waves in very high level, appeared from the value of radiation efficiency. From observed results that have been checked carefully, there is loss due to mismatch between transmitter and receiver.

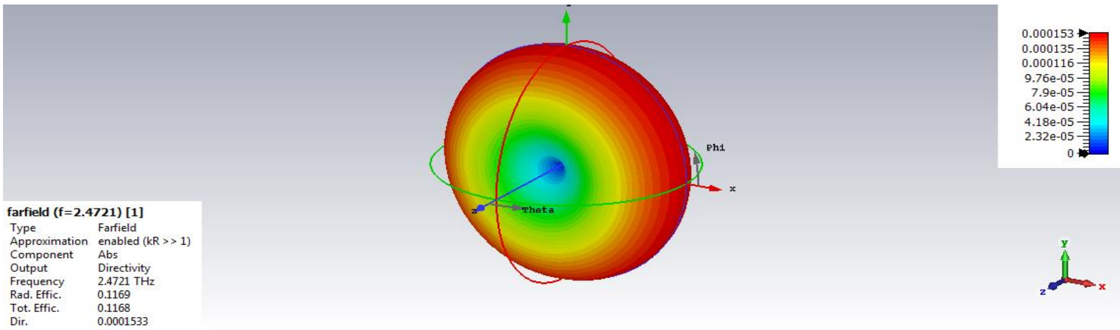
To get out from this problem there is several way by editing our antenna through using transformer or tuning stub or adding a slot. In this thesis through simulation package program that have been used, we headed towards matching the impedance by trails.

Our results obtained is larger than any results in pervious papers in 2019 and 2020.

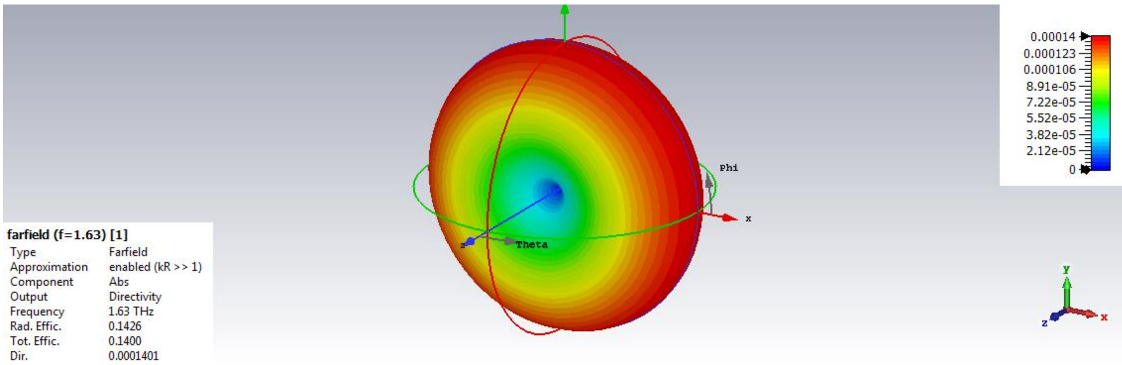
3.7.1 Efficiency

Starting with SWCNTs- Al, in figure 3.7.1 radiation efficiencies value was founded for antennas length$10, 20, 30, 40\ \mu m$ and radius $2.71\ nm$ at resonance frequency 2.472, 1.63, 0.132, 0.8 THz.

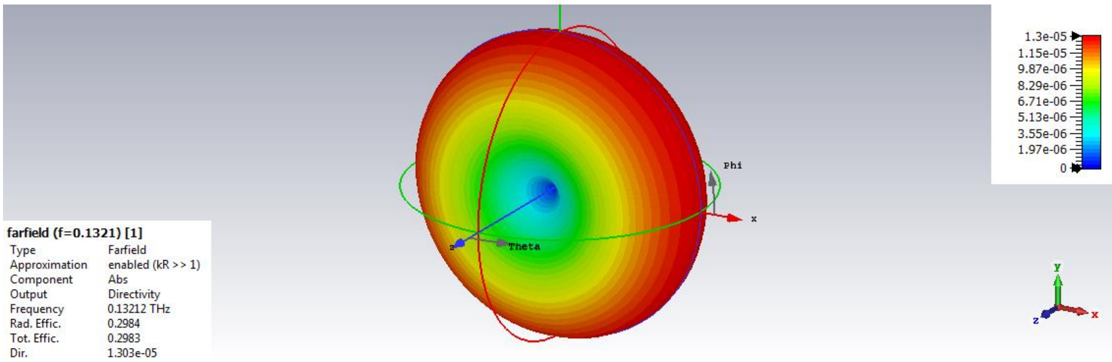
The radiation efficiency is equal to 0.1169 , 0.1426, 0.2984, 0.3844 and equal almost to the total radiated power, means that there is no loss occur.


0.000153
0.000135
0.000116
9.76e-05
7.9e-05
6.04e-05
4.18e-05
2.32e-05
0
Phi
x
Theta
z
y
farfield (f=2.4721) [1]
Type Farfield
Approximation enabled (kR >> 1)
Component Abs
Output Directivity
Frequency 2.4721 THz
Rad. Effic. 0.1169
Tot. Effic. 0.1168
Dir. 0.0001533

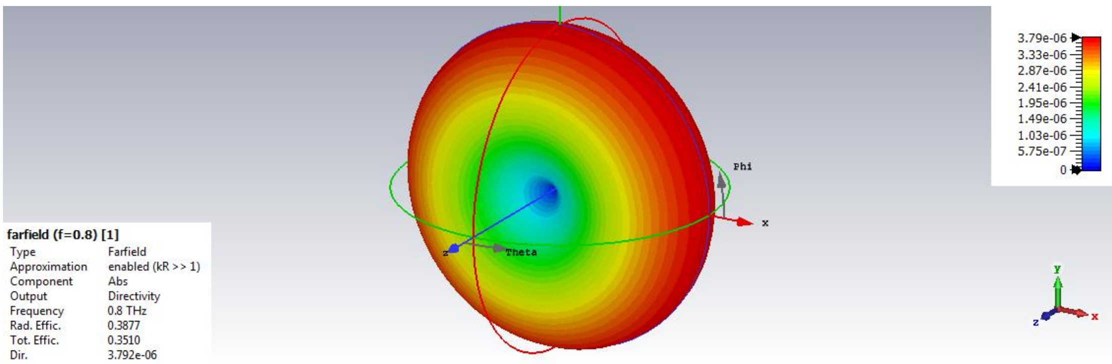
(a)


0.00014
0.000123
0.000106
8.91e-05
7.22e-05
5.52e-05
3.82e-05
2.12e-05
0
Phi
x
Theta
z
y
farfield (f=1.63) [1]
Type Farfield
Approximation enabled (kR >> 1)
Component Abs
Output Directivity
Frequency 1.63 THz
Rad. Effic. 0.1426
Tot. Effic. 0.1400
Dir. 0.0001401

(b)


1.3e-05
1.15e-05
9.87e-06
8.29e-06
6.71e-06
5.13e-06
3.55e-06
1.97e-06
0
Phi
x
Theta
z
y
farfield (f=0.1321) [1]
Type Farfield
Approximation enabled (kR >> 1)
Component Abs
Output Directivity
Frequency 0.13212 THz
Rad. Effic. 0.2984
Tot. Effic. 0.2983
Dir. 1.303e-05

(c)


3.79e-06
3.33e-06
2.87e-06
2.41e-06
1.95e-06
1.49e-06
1.03e-06
5.75e-07
0
Phi
x
Theta
z
y
farfield (f=0.8) [1]
Type Farfield
Approximation enabled (kR >> 1)
Component Abs
Output Directivity
Frequency 0.8 THz
Rad. Effic. 0.3877
Tot. Effic. 0.3510
Dir. 3.792e-06

(d)

Figure 3.7.1: 3D far field plot of SWCNTs- Al dipole antenna with lengths $\mathbf{10, 20, 30, 40\mu m}$ length and radius $\mathbf{2.71\ nm}$.

The highest value of radiation efficiency has been obtained at $40\mu m$ length, and it is about 38%.

In table 3.7.1 the value of radiation and total efficiency was shown at five antennas lengths. The highest value of antenna efficiency at 40 μm and it is equal to 38.4% for SWCNTs- Al dipole antenna.

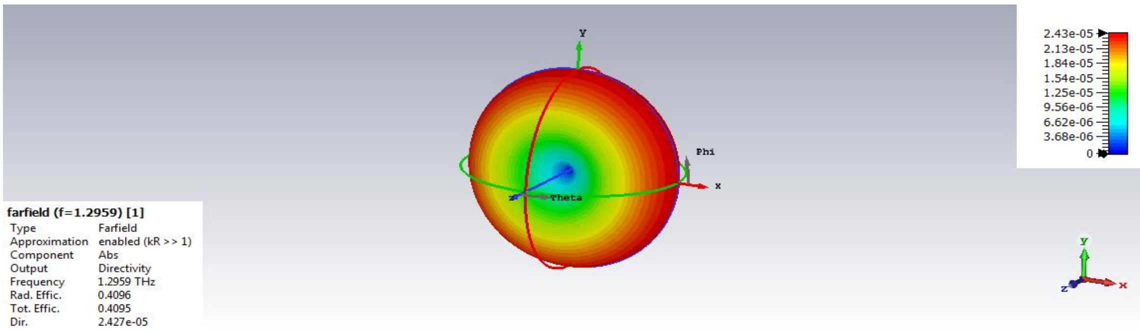
Table 3.7.1: Radiation efficiency and total efficiency of SWCNTs- Al dipole antenna at various resonance frequencies for $\mathbf{10, 20, 30, 40\mu m}$ length.

Length (μm)	Resonance freq.(THz)	Radiation efficiency	Total efficiency	Loss (M)
10	2.472	0.1169	0.1168	0.99
20	1.63	0.1426	0.1400	0.98
30	0.132	0.2984	0.2983	0.99
40	0.8	0.3844	0.3510	0.91

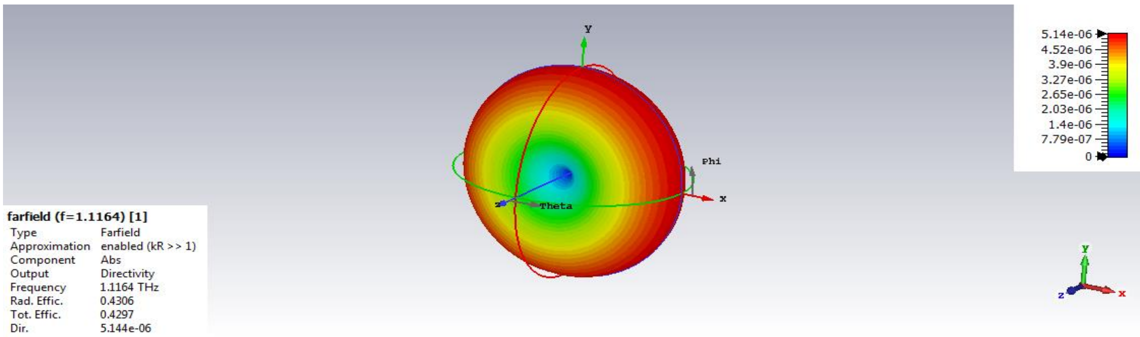
Table 3.7.2: Simulation results of S_{11} for SWCNTs- Al dipole antenna at various resonance frequency where L=$\mathbf{10, 20, 30, 40\mu m}$.

Length (μm)	Resonance freq.(THz)	Scattering parameter
10	2.472	-33.69
20	1.63	-36.31
30	0.132	-37.334
40	0.8	-10.24

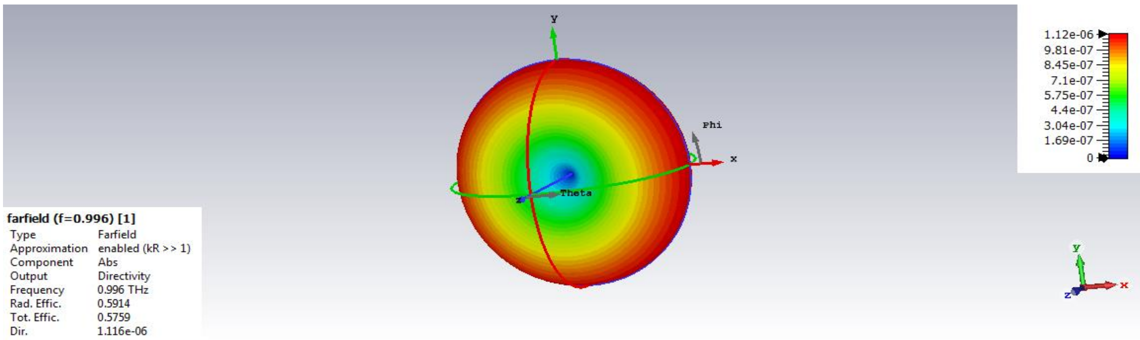
In figure 3.7.6 the radiation efficiency in 3D far field plot of SWCNTs- Cu dipole antenna, is equal to 0.4096,0.4306, 0.5914, 0.4894 at antennas lengths equal to $10, 20, 30, 40\mu m$, and radius 2.71 nm with copper layer of thickness 2 nm.



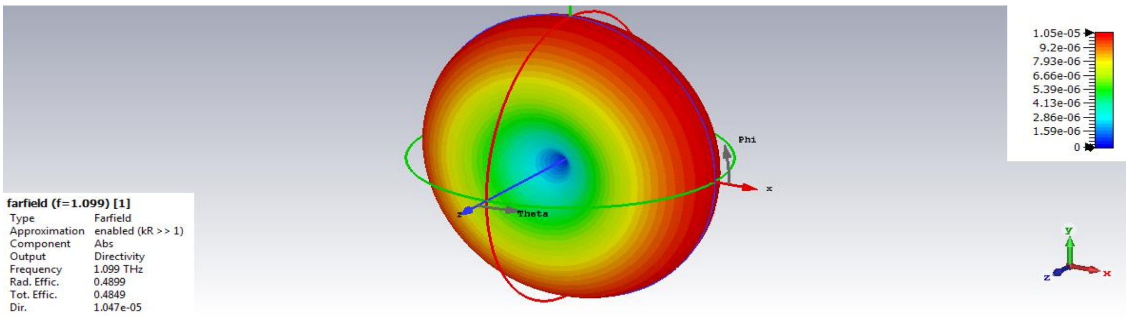
(a)



(b)



(c)



(d)

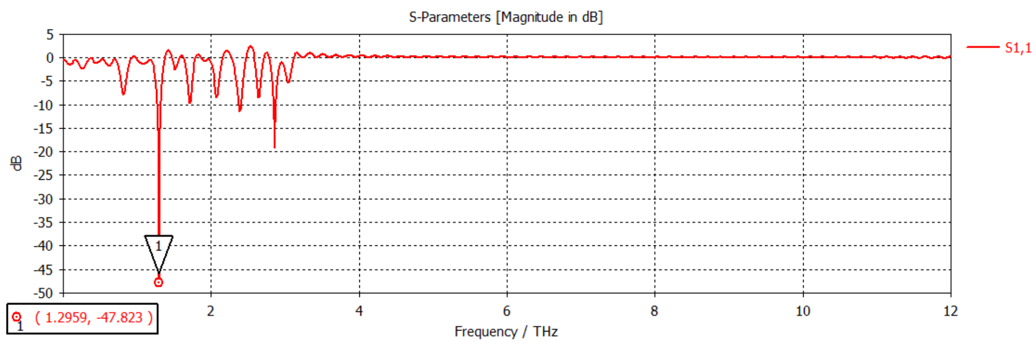
Figure 3.7.2: 3D far field plot of SWCNTs- Cu dipole antenna, where L=$10, 20, 30, 40\mu m$ and radius 2.71 nm, thickness layer 2 nm of copper.

The highest value of radiation efficiency have been obtained in this thesis at 30 μm length, and its equal to 59.14%.

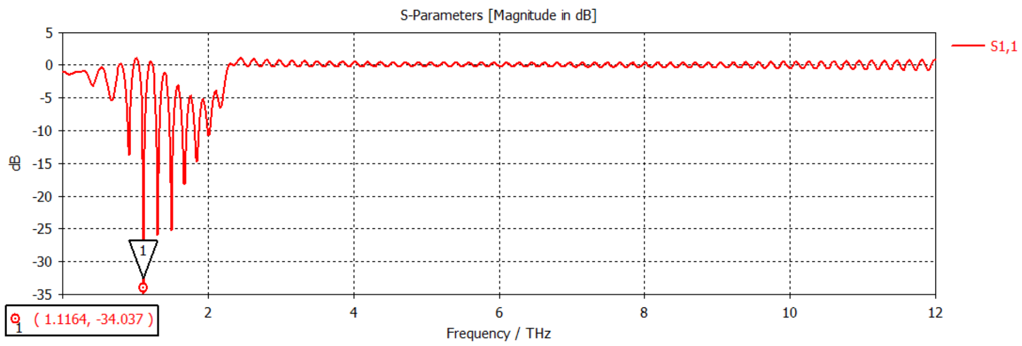
Table 3.7.3: Radiation efficiency and total efficiency at various resonance frequency for $\mathbf{10, 20, 30, 40}\boldsymbol{\mu m}$ length of SWCNTs- Cu dipole antenna.

Length (μm)	Resonance freq.(THz)	Radiation efficiency	Total efficiency	Loss (M)
10	1.2959	0.4096	0.4095	0.9997
20	1.1164	0.4306	0.4297	0.9979
30	0.996	0.5914	0.5759	0.9737
40	1.099	0.4894	0.4849	0

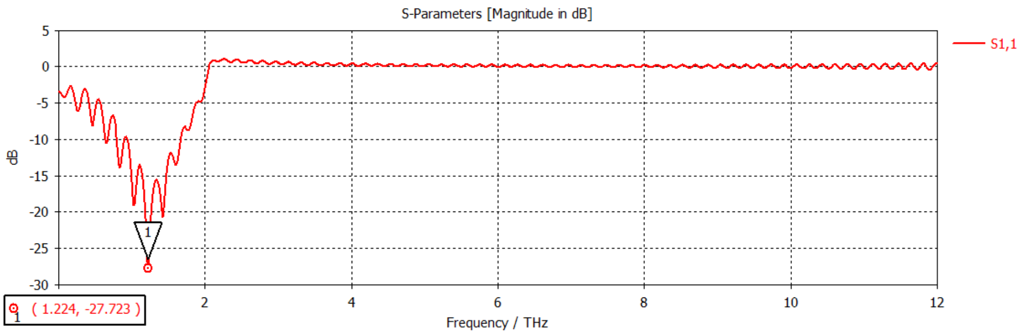
Figure 3.7.7(a), (b), (c), (d), represented scattering parameter as a function of frequency of SWCNTs- Cu dipole antenna with length $10, 20, 30, 40$ μm and radius 2.71 nm, thickness layer 2 nm of copper.



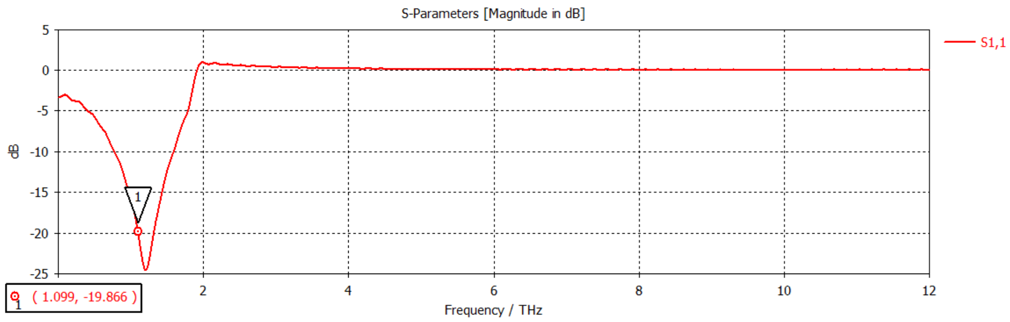
(a)



(b)



(c)



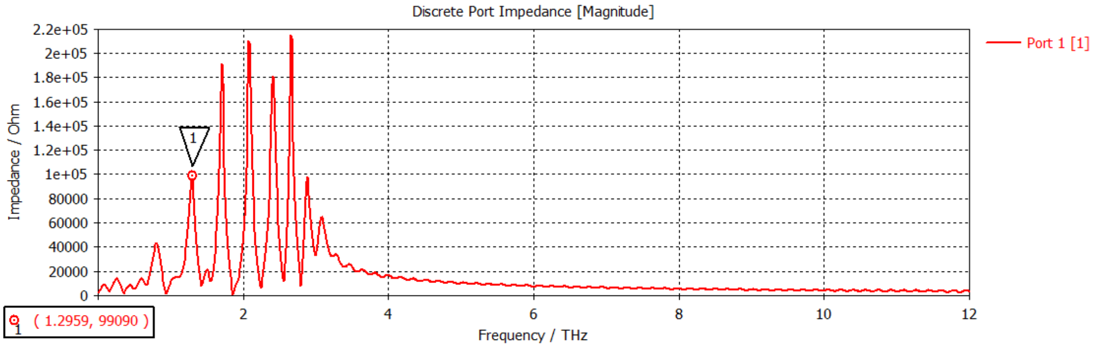
(d)

Figure 3.7.3: Scattering parameter of SWCNTs- Cu dipole antenna as a function of frequency, where L= $10, 20, 30, 40\mu m$ and radius 2.71 nm, thickness layer 2 nm of copper.

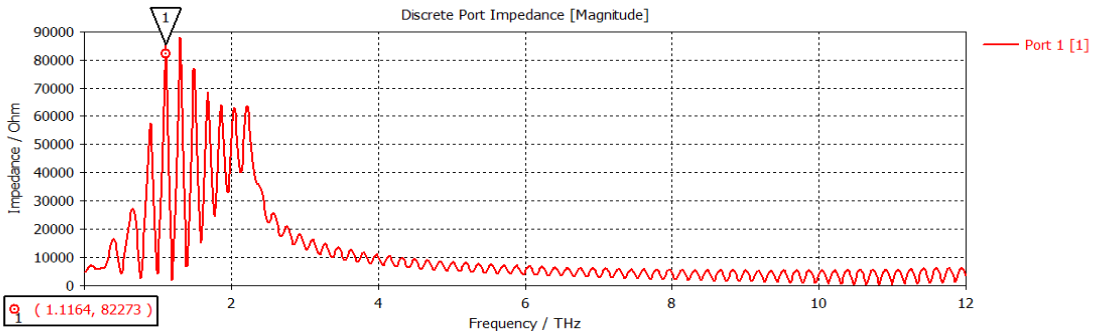
Table 3.7.4: Scattering parameter at various resonance frequency for $10, 20, 30, 40\mu m$ length of SWCNTs- Cu dipole antenna.

Length (μm)	**Resonance freq.(THz)**	**Scattering parameter**
10	1.2959	-47.823
20	1.1164	-34.037
30	0.996	-27.723
40	1.099	-25

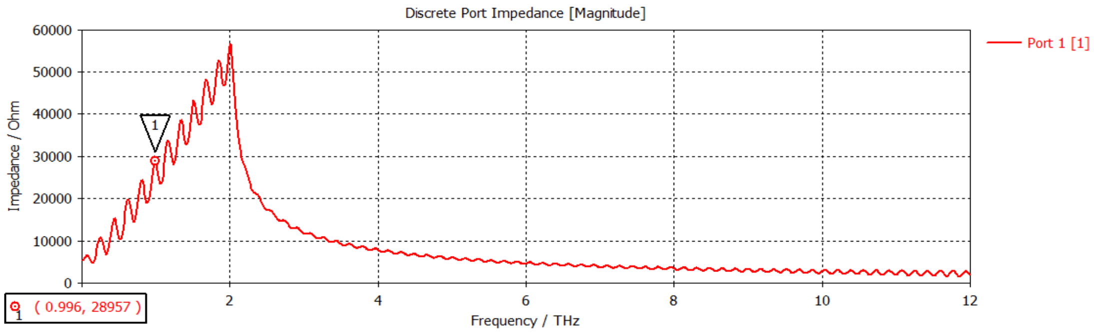
Matching impedance have founded in figure 3.7.4 as a function of frequency with values 99090, 89345, 28957, 31084 Ω fo SWCNTs- Cu dipole antenna with length $10, 20, 30, 40$ μm and radius 2.71 nm, thickness layer 2 nm of copper.



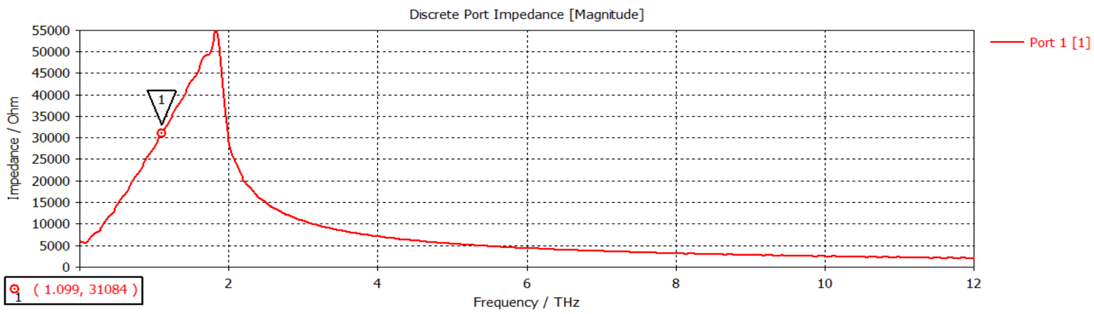
(a)



(b)



(c)



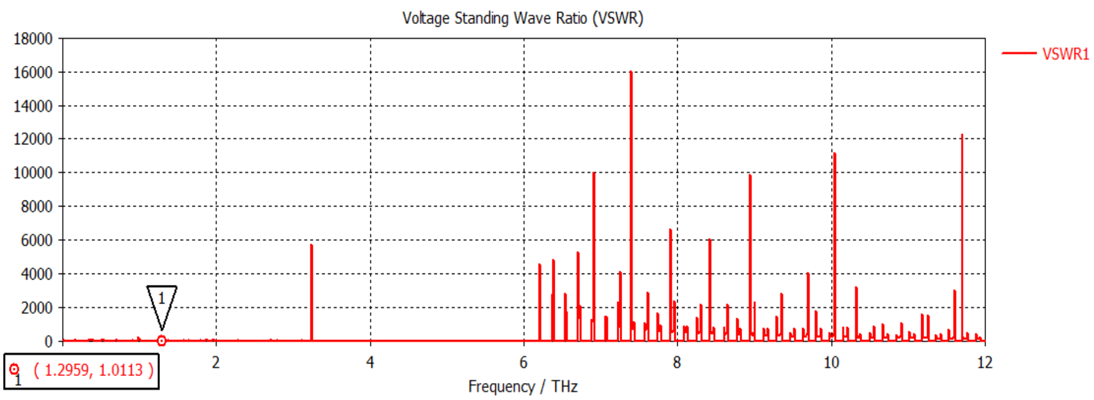
(d)

Figure 3.7.4: Impedance in Ω as a function of frequency of SWCNTs- Cu dipole antenna where L=$10, 20, 30, 40\mu m$ and radius 2.71 nm, thickness layer 2 nm of copper.

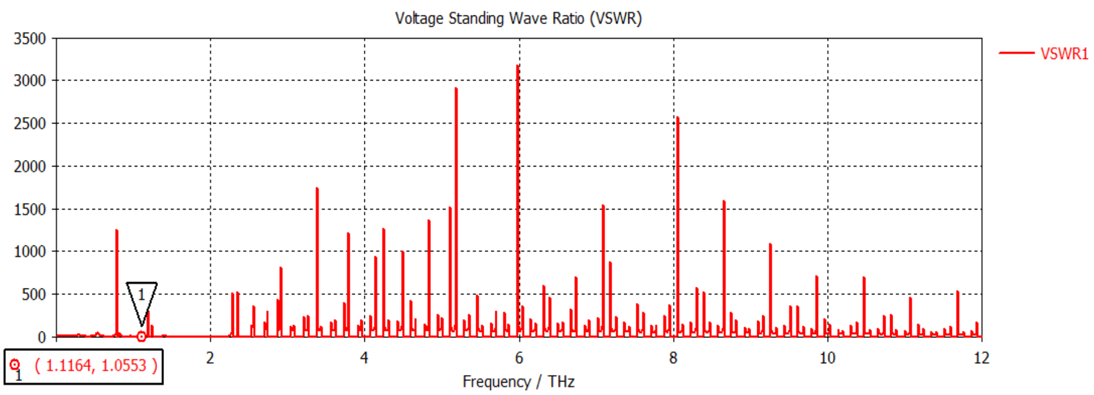
Table 3.7.5: Matching impedance at various resonance frequency for $10, 20, 30, 40\ \mu m$ length of SWCNTs- Cu dipole antenna.

Length (μm)	Resonance freq.(THz)	Impedance
10	1.2959	98345
20	1.1164	83379
30	0.996	27634
40	1.099	31084

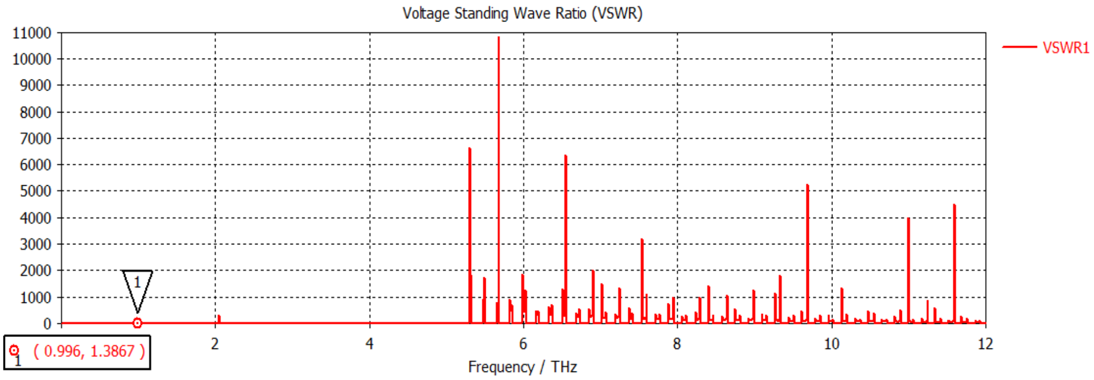
In figure 3.7.5 voltage standing wave ratio was shown as a function of frequency that represented a common measure of how well matched the antenna to the transmission line it is almost equal to 1 of SWCNTs- Cu dipole antenna with length $10, 20, 30, 40\ \mu m$ and radius 2.71 nm, thickness layer 2 nm of copper.



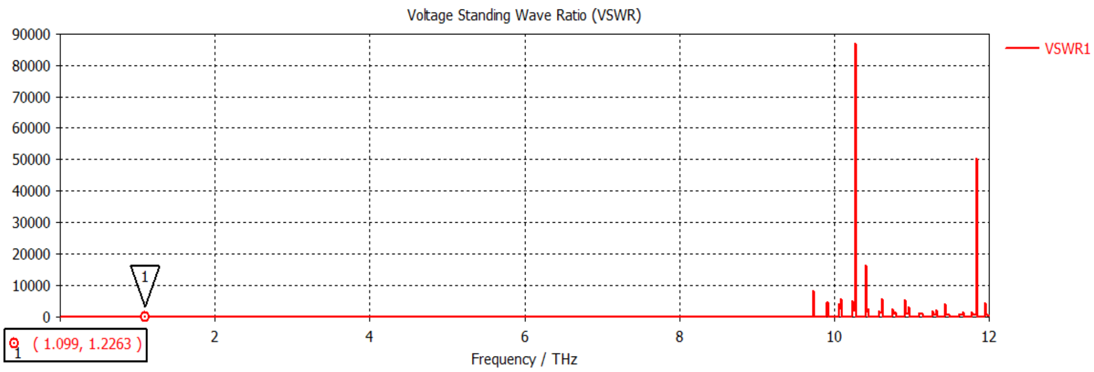
(a)



(b)



(c)



(d)

Figure 3.7.5: VSWR as a function of frequency of SWCNTs- Cu dipole antenna with length $10\mu m$ and radius 2.71 nm, thickness layer 2 nm of copper.

Table 3.7.6: VSWR at various resonance frequency for $10, 20, 30, 40, 50\mu m$ length of SWCNTs- Cu dipole antenna.

Length (μm)	**Resonance freq.(THz)**	**VSWR**
10	1.2959	1.0113
20	1.1164	1.0553
30	0.996	1.2867
40	1.099	1.226

Chapter Four

Conclusion

In this thesis, the efficiency of SWCNTs-coated and non-coated dipole antennas as a function of frequency are founded at different rang of length and constant radius. The result shows new values of efficiency for coated carbon nanotube dipole antenna, it is about 59% in the case of zero loss and 77% in the case of loss due to miss matching impedance. Compering the values that we have 59% with latest research that has been published about 40%, we obtain new percent of efficiency.

We have simulated four length of SWCNTs dipole antenna, and four other after coating the dipole antenna with copper once and aluminum again, using simulation package program (CST). First trails are with some loss in power treated by using transformer or tuning stub or adding a slot in the exterior design. In our case using virtual simulating program, we tried to get matching between the antenna and receiver by entering trails of impedance value and have the best result in each length. Although we get full matching in impedance, the efficiencies value decrease a little bit, but it still better than the one in previous research.

The comparison between the coated and non-coated dipole antenna once by copper and other by aluminum are represented at four lengths antenna. We see that the most probable length is $30\mu m$. Also the values of scattering parameter as a function of frequency in each case are founded. It seems that its decrease as length increase in most cases.

We also compare between the SWCNTs coated by copper and SWCNTs coated by aluminum. The results show that the SWCNTs coated by copper

The first steps in this work, is to define the rolled sheet of graphene at CST. From this step we compute the value of permittivity by using matlab codes, repeating this step again in the coating part by calculating the value of plasma and relaxation frequency then defining the permittivity of the carbon nanotube at CST.

Matlab codes.

Real part of conductivity.

```
clear;

% Input values

f = input('Frequency: ');

fprintf('\n'); % empty line between input and output values

% Constants

w = 2.*pi.*f; % angular frequency

segma = 11.68e21./(w.^2 + 4.4e23);

fprintf('OUTPUT: \n');

disp('segma');

% Print output to the screen

fprintf('segma = %f \n',segma);

plot(f,segma,'r')

grid on
```

Imaginary part of conductivity.

```
clear;

% Input values

f = input('Frequency: ');

fprintf('\n'); % empty line between input and output values

% Constants

w = 2.*pi.*f; % angular frequency

segmai = -1.76e10.*w./(w.^2 + 4.4e23);
```

```
fprintf('OUTPUT: \n');
disp('segmai');
% Print output to the screen
fprintf('segmai = %f \n',segmai);
plot(f,segmai,'r')
grid on
```

Real part of permittivity.

```
clear;
% Input values
f = input('Frequency: ');
fprintf('\n'); % empty line between input and output values
% Constants
w = 2.*pi.*f; % angular frequency
epsr = 1+(1.47e30./(w.^2 + 4.4e23));
fprintf('OUTPUT: \n');
disp('epsr');
% Print output to the screen
fprintf('epsr = %f \n',epsr);
plot(f,epsr,'r')
grid on
```

Imaginary part of permittivity.

```
clear;

% Input values

f = input('Frequency: ');

fprintf('\n'); % empty line between input and output values

% Constants

w = 2.*pi.*f; % angular frequency

epsi = - 9.769e41./(w.*(w.^2 + 4.4e23));

fprintf('OUTPUT: \n');

disp('epsi');

% Print output to the screen

fprintf('epsi = %f \n',epsi);

plot(f,epsi,'r')

grid on
```

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جامعة النجاح الوطنية
كلية الدراسات العليا

الأنابيب الكربونية المركبة والمغطاة الخاصة بالهوائي ثنائي القطب في حدود ترددات التيراهيرتز، دراسة خصائصها وأدائها وكفائتها

اعداد
جيلان طارق السيد

اشراف
د. منى الحاج يحيى
د. معن شتيوي

قدمت هذه الأطروحة استكمال لمتطلبات الحصول على درجة الماجستير في الفيزياء، بكلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس – فلسطين
2021

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الملخص

في هذه الأطروحة، تم ايجاد كفاءة الهوائيات ثنائية القطب المطلية وغير المطلية المكونة من SWCNT كدالة للتردد في مدى مختلف من الطول ونصف القطر الثابت. تُظهر النتيجة قيمًا جديدة للكفاءة لهوائي الأنابيب النانوية الكربونية المطلية ، وهي حوالي 59٪ في حالة تطابق المقاومة بين الهوائي و مصدر مزود الجهد و 77٪ في حالة الخسارة بسبب عدم وجود مقاومة مطابقة. بمقارنة القيم التي لدينا 59٪ مع أحدث الأبحاث التي تم نشرها حوالي 40٪ ، نحصل على نسبة جديدة من الكفاءة.

لقد قمنا بمحاكاة أربعة أطوال لهوائي ثنائي القطب SWCNTs ، وأربعة أخرى بعد طلاء الهوائي ثنائي القطب بالنحاس مرة واحدة والألمنيوم مرة أخرى ، باستخدام برنامج حزمة المحاكاة (CST). يتم معالجة المسارات الأولى مع بعض فقدان الطاقة باستخدام المحول أو كعب الضبط أو إضافة فتحة في التصميم الخارجي. و في حالتنا باستخدام برنامج محاكاة افتراضي ، حاولنا الحصول على مطابقة بين الهوائي والمستقبل عن طريق إدخال مسارات ذات قيمة مقاومة والحصول على أفضل نتيجة في كل طول. على الرغم من أننا نحصل على مطابقة كاملة في المقاومة ، فإن قيمة الكفاءات تنخفض قليلاً ، لكنها لا تزال أفضل من تلك الموجودة في البحث السابق.

يتم تمثيل المقارنة بين هوائي ثنائي القطب المطلي وغير المطلي مرة واحدة بالنحاس والألومنيوم بأربعة أطوال. نرى أن الطول الأكثر احتمالًا هو 30 ميكرومتر. كما تم تحديد قيم معامل التشتت كدالة للتردد في كل حالة. ويبدو أن تناقصه مع زيادة الطول في أغلب الأحوال.