Dual Band Cylindrical DRA with Carbon Nano Tube

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Abstract - *This paper presents the design of a CNT based cylindrical Dielectric Resonator Antenna (DRA) coupled to narrow slot aperture that is fed by coaxial line. The fundamental TE_{11} mode and higher-order TE_{13} mode are excited with their resonant frequencies respectively. These frequencies can be controlled by changing the DRA dimensions. A dielectric resonator with high permittivity is used to miniaturize the global structure. The proposed antenna is designed to have dual band operation suitable for both L & S band applications. The return loss, radiation pattern and gain of the proposed antenna are evaluated. Reasonable agreement between simulation and experimental results is obtained.*

Key Words: ***DRA, MW, CNT, Dual Band DRA, Cylindrical DRA, Wide Bandwidth DRA.***

1. INTRODUCTION

With the increasing demand for high performance communication networks and the proliferation of mobile devices, significant advances in antenna design are essential in order to meet tomorrow's requirements. In recent years, the rising developments of the wireless communication industry have pushed antenna technology for increased performance, while being limited to an ever decreasing footprint. Such design constraints have forced antenna designers to multi band antennas. In the last decade, the attempts have been made to design Cylindrical DRAs using the dielectric resonator (DR). Dielectric resonator antenna (DRA) [1] [2] has been of interest due to their low loss, high permittivity, light weight and ease of excitation. In addition, wide bandwidth, and high radiation efficiency are inherent advantages of DRAs. Deferent shapes of DRAs such as cylindrical, hemispherical, elliptical, pyramidal, rectangular, and triangular have been presented in the literature. The rectangular-shaped DRAs over practical advantages over cylindrical and hemispherical ones in that they are easier to fabricate and have more design flexibility [3]. Various dual mode DRAs have been studied in recent years. For example, two DRA elements resonating at two different frequencies were combined to give a Cylindrical DRA [4]. The resonant mode of the feeding slot was also utilized to widen the bandwidth [5]. Recently, a higher-order mode of a DRA was used to increase the bandwidth [6] or to design a dual band DRA [7]. This higher-order-mode design approach has two major advantages. First, it requires no additional DRA and second, it facilitates the matching of the Cylindrical DRA.

1.1 BASICS OF LINEAR ELEMENTS IN THE NANO METRIC SCALE

Size reduction toward nano metric scale changes the electromagnetic properties of the conducting elements. When a wire is fabricated whose cross-sectional dimension is comparable to the quantum mechanical (Fermi) wavelength of the electron, the wire forms essentially a single-mode waveguide for the electron waves. Then, in a one-dimensional conductor such as a nanotube, the electrons are only free to move along the length of the wire, and not in the transverse direction. Therefore the current distribution is effectively one-dimensional. In addition to the electron transport occurring in only one dimension, we also have two more important effects, large resistance and large inductance. While copper is typically used in applications where high conductivity is required, it does not maintain its bulk conductivity when scaled to nanometer dimensions [12]. In contrast, nanotubes have better conductivity than copper when scaled to their diameter. It has recently been [13] that the dc resistance per unit length of a single-walled carbon nanotube at room temperature is about 6 kΩ/μm. A copper wire with the same diameter (1.5 nm) would have an even higher resistance per unit length. This resistance per unit length is quite large compared to the characteristic impedance of free space, as well as typical radiation resistances in traditional antennas. Therefore, it cannot be neglected. Recently it has been proven that the ac and dc resistances are the same for a nanotube up to about 10 GHz [14]. However, these high impedances could be significantly reduced towards the 50 Ω if instead of resistive contact between the CNT and the dielectric substrate a capacitive contact is used [18]. This means that between the metallic contact and CNT a thin dielectric is introduced. This particular configuration of the contact i.e. metal/dielectric/nanotube means that in parallel with the 6.5 kΩ resistance will be a capacitor with the overall effect of reducing the impedance of the CNT. Thus, the nano T/R module could work at impedance which is nearly of 50 Ω conferring compatibility with existing wireless systems.

1.2 Nano-Antennas

It ensues from these electrical properties of the nano-tube the theoretical behavior of a nano-tube antenna. These characteristics are the same ones we acknowledge for a macro antenna but with very different values. The first and most apparent change in characteristics is the wave propagation velocity and the resonance velocity. In a macro model, the resonance wave velocity is equal to the speed of light, in a nanotube antenna it goes otherwise. As was stated earlier, the wave propagation velocity in a nanotube transmission line is already 0,02 c, when used as a resonant dipole, the wave resonance in the nanotube can be associated with Plasmon's by the transmission line developed in [2] , where the propagation velocity of the antenna was found to be vp = 3vF = 0.01 c 1 . Yet this is only a theoretical rough approximation of the reality. Further calculation and experiment give value around 0.015 c and 0.017 c.

1.3 CNT material properties for antenna applications

For antenna design prospects, specific material electromagnetic properties must be identified such as conductivity, permittivity and associated propagation constant of a microwave signal transmitted through this nano material. Multiphysics and multiscale modelling procedures are then accessible from Carbon nanotubes are becoming an extraordinary nano material for antenna design, thanks its atomic structure and spatial geometry. For radiation properties purpose, some antenna parameters must be strongly considered from material point of view such as:

- Linear inductance/capacitance in order to define the efficient dimension of a LC resonant cell - Dynamic permittivity which allows the definition of plasma resonance.

- Band diagram and work function definition in a metallic behavior to identify efficient contact type with microwave electrode access to match input impedance. Different modelling tools using electrical or electromagnetic properties of individual Carbon nanotubes have been studied in order to predict radiation properties of unique or bundle of CNTs. This part summarizes all accessible modelling tools for CNT-based antenna design. From material point of view, CNT-based nano antennas design activity needs to take into account SW/MW CNTs electrical characteristics in order to fulfill radiative behavior predictions in microwave frequency domain. In this project, three modeling procedures, implemented in existing commercial microwave circuit design HFSS, are reported:

- Individual electrical modeling which can be developed in commercial analytical/electrical HFSS.

- Electromagnetic modeling as a bulk material defined by its electromagnetic parameters to achieved a completed 3D definition of radiative elements [8].

- A Transmission-line equivalent model represented by its linear resistance, inductance, capacitance and conductance parameters

- A metamaterial approach for dimensions and density influence effect on electromagnetic properties.

1.4 Material parameters considerations for antenna design

From theoretical results, specific material optimization work must be undertaken in order to match as close as possible to:

- A resonant input impedance with highest resistance and near zero reactance value at frequency of emission

- The highest far-field emission gain - A near zero input reflection coefficient for impedance circuit matching to 50 Ohms.

Table (1) Material Properties.

Material	Young's modulus (GPa)	Tensile Strength (GPa)	Density (g/cm3)
Single Wall Nanotube	**1054**	**150**	**N/A**
Multi Wall Nanotube	**1200**	**150**	**2.6**
Steel	**208**	**0.4**	**7.8**
Epoxy	**3.5**	**0.004**	**1.25**
Wood	**16**	**0.008**	**0.6**

1.5 CNT-Based Antenna Topologies

This activity report summarizes CNT-based antenna design work relying on use of 3D FDTD parametric electromagnetic analysis from HFSS commercial software. The main scientific objective is to validate theoretical results on exceptional sub-wavelength radiation of such antenna topology with CNT material, by electromagnetic simulations. Free space (monopole/dipole) and integrated on usual substrate (quartz, Si) CNT-based antenna topologies have been investigated in order to validate potential antenna miniaturization by this innovative material thanks to the existence of a negative imaginary conductivity leading to high inductive behavior compared to classical metals in microwave domain. In coordination with NANO RF partnership available technological platforms to CNT growth, vertically aligned MW CNT arrays organized in cylindrical bundles were considered in order to define a hollow wire-like dipole/monopole, into two electromagnetic environments such as:

- Free space environment

- Integrated technology CNT-based antenna design optimizations are executed on microwave performances such as resonant frequency / frequency bandwidth, input impedance and E and H-plane radiation patterns. CNT-based radiating part is modeled by an exotic conductive tube with specific impedance and diameter defining then the vertical MW metallic CNT bundle.

Zs complex value can be easily tuned through parametric simulations in order to achieve targeted microwave performances.

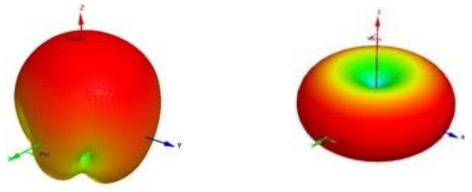
$$Z_s = \frac{1}{2\pi . r . \sigma_{zz}} = R_s + jL_s\omega$$

For miniaturization purpose, this statement becomes crucial to shorten drastically the operational Dipole/monopole length which must be typically equal to the wavelength λ over 2 or 4 respectively in the case of a classical metallic wire.

1.6 CNT Cylindrical Dra

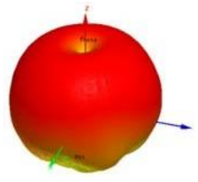
The cylindrical DR offers three fundamental modes, denoted as $\text{HEM}_{11\delta}$, $\text{TM}_{01\delta}$ and$\text{TE}_{01\delta}$. These modes can be excited within a single CNT based cylindrical DR element, which makes it a suitable potential candidate for multiband, multifunction or diversity applications [9, 5, and 3]. In some cases, the cylindrical DR is modified to an annular shape to increase the number of degrees of freedom and achieve enhanced performance, for example, increasing bandwidth, improving coupling or shifting resonant frequency. Field distribution, resonant frequency and Q-factor of fundamental modes.

The field distributions of the HEM11δ, TM01δ and TE01δ modes of a cylindrical DR are sketched in Fig. 1 (adapted from [9]). The HEM11δ and TE01δ modes have been widely used to radiate broadside and Omni-directional radiation patterns, as shown in Fig. 1 (a) and (b), respectively. The TE01δ mode has traditionally been used in filters or oscillators in circuit applications due to its intrinsically high Q-factor. The concept of using TE01δ mode as a radiating-mode is validated through demonstration of a horizontally polarized DRA.



(a) HEM11δ mode

(b) TM01δ mode



(c)TE01δ

Figure1. Radiation patterns of three fundamental modes of a cylindrical DR.

Unlike in the case of the rectangular DR, there is no exact solution for the resonant modes of the cylindrical DR. The approximate approaches of deriving the field for a CNT based cylindrical DR are omitted here and the interested reader is referred to the literature, e.g. [7, 8], for detailed expressions. The equations of the resonant frequency and Q-factor of the HEM11δ, TM01δ and TE01δ Modes are based on extensive numerical simulations and the closed-form expressions describing the dependence for different geometrical parameters are approximated subsequently by curve fittings. Different literature sources[7, 6, and 8] provide different formulas to calculate the resonant frequency and Q-factor, but generally these formulas give similar results with good approximation. The equations from [10] are given below, where $k_0 = 2\pi\ f_0/c$ denotes the free space wave number corresponding to the resonant frequency $f_0$and c is the velocity of light in free space. Here, x is equal to a/h, where *'a' and 'h'* are cylindrical DR radius and height, respectively. The modes are as follows:

The $\text{HEM}_{11\delta}$mode

$$k_0 a = \frac{6.324}{\sqrt{\varepsilon_r + 2}} \left\{ 0.27 + 0.36\frac{x}{2} - 0.02\left(\frac{x}{2}\right)^2 \right\}$$

$$Q = |0.01007\varepsilon_r^{1.3} x \left\{ 1 + 100e^{-2.05(x/2 - x^2/80)} \right\}$$

The $\text{TM}_{01\delta}$mode

$$k_0 a = \frac{\sqrt{3.83^2 + (\pi x/2)^2}}{\sqrt{\varepsilon_r + 2}}$$

$$Q = 0.008721\varepsilon_r^{0.888413} e^{0.0397475\varepsilon_r} \left\{ 1 - (0.3 - 0.2x)\left(\frac{38 - \varepsilon_r}{28}\right) \right\} \left\{ 9.498186x + 2058.33x^{4.322261} e^{-3.50099x} \right\}$$

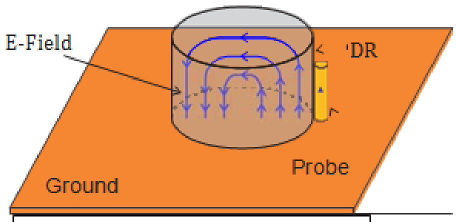
The $\text{TE}_{01\delta}$mode

$$k_0 a = \frac{2.327}{\sqrt{\varepsilon_r + 1}} (1 + 0.2123x - 0.00898x^2)$$

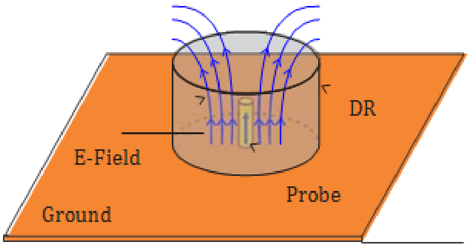
$$Q = 0.078192\varepsilon_r^{1.27} \left(1 + \frac{17.31}{x} - \frac{21.57}{x^2} + \frac{10.86}{x^3} - \frac{1.98}{x^4} \right)$$

1.7. Coaxial Probe

The coaxial probe provides a simple way to couple energy to a CNT based cylindrical DR without using a bulky feeding network. To achieve maximum coupling, the probe should be located at the place with the maximum electric field intensity. According to the field distribution in Fig.2 (a) & (b), the maximum electric field intensity of the $\text{HEM}_{11\delta}$ and $\text{TM}_{01\delta}$ mode are located at the periphery and center of the CNT based cylindrical DR, respectively. Therefore, to excite either mode, the probe should be correspondingly placed at the periphery or center, as shown in Fig. 2. The impedance can be matched by optimizing the height and the radius of the probe. To excite the $TM_{01\delta}$ mode, the center of the cylinder has to be removed to hold the probe, which increases the manufacture difficulty. This can be avoided by using slot aperture or coplanar waveguide, as shown in the following sections.



(b)TM01δ mode



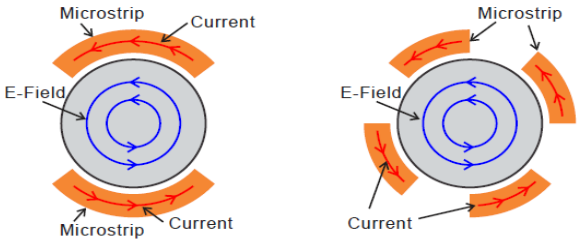
(b)TM01δ mode

Figure2. Probe coupling to a CNT based cylindrical DR.

1.8 VSWR Reduction Method

The TE01δ mode is usually utilized in filters and oscillators design due to its intrinsically high quality (Q) factor. The TE01δ mode can be excited by most available transmission line types, such as coaxial probe, cylindrical line, waveguide, and image guide. In order to achieve the maximum power coupling between resonator and transmission line, the impedance of the resonator and feeding must be matched at the resonance frequency.

The magnetic field distribution of TE01δ mode is equivalent to a magnetic dipole along the axis of the cylinder at the center of DR, as shown in Fig. 3 (a). Inspired by this fact, we propose to use the TE01δ mode to radiate horizontally polarized Omni-directional patterns. An air gap between the cylindrical DR and substrate is introduced to lower the Q-factor and thus increase the impedance bandwidth. Due to the symmetrical field distribution of the TE01δ mode, a balanced coupling method described in [6] is utilized to obtain a symmetrical feeding, as shown in Fig. 3 (a). The balanced coupling method is formed by placing two arc-shaped cylindrical lines on each side of the DR. A bandwidth of 5.6% around the center frequency of 3.9 GHz is achieved by further optimizing the shape of the cylindrical lines [4]. To create a more uniform current loop distribution, four arc-shaped cylindrical lines are utilized to design a horizontally and vertically polarized Omni-directional DRA.



(a)Two arc-shaped Cylindrical lines (b) Four arc-shaped Cylindrical lines

Figure 3. A balanced coupling method to excite the TE01δ mode in a cylindrical DR.

1.9 Quality Factor

Quality or Q-factor is a measure of the ability of the DR to store microwave energy with minimal signal loss. The inherent Q-factor of a DR solely depends on the loss factor of the dielectric material. But in practical applications, the resonator is always associated with metallic parts, in the form of shields or ground planes. In general, the loaded Q-factor of a resonant cavity can be defined as the ratio of the stored energy to the dissipated power

$$Q_L = \frac{\textit{Stored Energy}}{\textit{Dissipated Power}} = \frac{2\omega_o E_s}{P_{dis}}$$

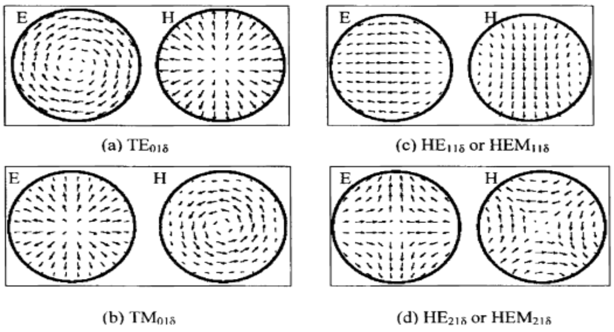


Figure 4: Field distributions inside a cylindrical DR.

2. Result and Simulation

An antenna prototype was fabricated using FR4 substrate as shown in Figures. Illustrate the measured and simulated return loss of the Microwave range antenna, which is plotted together with the simulated results for comparison purpose and reasonable agreement between them, is observed. The measured resonant frequencies of the lower and upper bands are 1.80 GHz and 2.43 GHz respectively, which agree very well with the HFSS simulated frequencies of f1 = 1.82 GHz (0.025 % error) and f2 = 2.4 GHz (1.25 % error) . The measured bandwidths of the lower and upper bands are 8.3 % (1.72 - 1.87 GHz) and 3.7 % (2.39 - 2.48 GHz), respectively, covering the entire DCS and (C, K, KU) bands. Figure 7 shows the maximum measured gain versus frequency for the proposed antenna. The curve exhibits two peaks VSWR of -59dBi and -50dBi at 1.8 GHz and 2.4 GHz respectively. Figures show the measured radiation patterns of the proposed DRA at the two TE_{111} and TE_{113} mode frequencies. The figure, reveals that the two resonant modes exhibit broadside radiation patterns and are very similar to each other, which is desirable. For each resonant mode, the co-polarization field are stronger than the cross-polarized counterparts by more than 20 dB in the broadside direction (θ° = 0). A good asymmetry radiation pattern in the two plans E and H is observed. However, an asymmetry in the H plane TE_{111} mode pattern is remarked at 70°. This shows that the effect of the matching slot on radiation field is not significant.

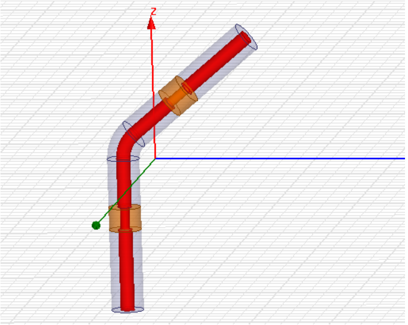


Fig (5) Design of Cylindrical CNT based DRA

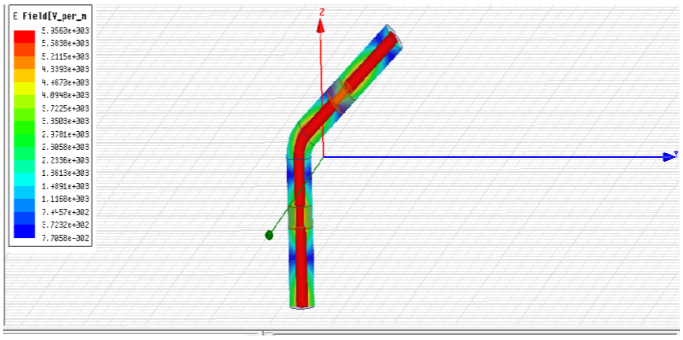


Fig (6) E Field Cylindrical DR NANO TUBE CNT with Cylindrical Feeder DRA.

Fig (7) Polar plot E Field cylindrical NANO Tube CNT with cylindrical DR Feeder DRA.

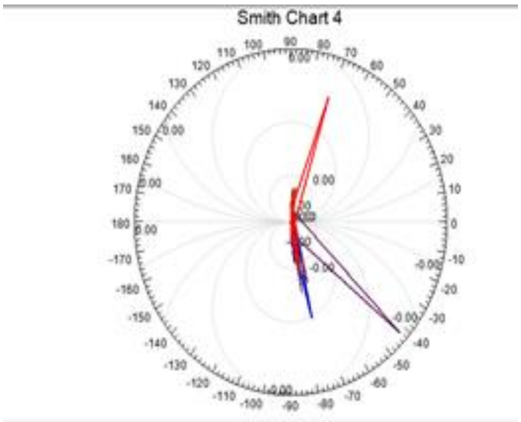


Fig (8) Smith Chart Cylindrical NANO Tube CNT with Cylindrical Feeder DRA.

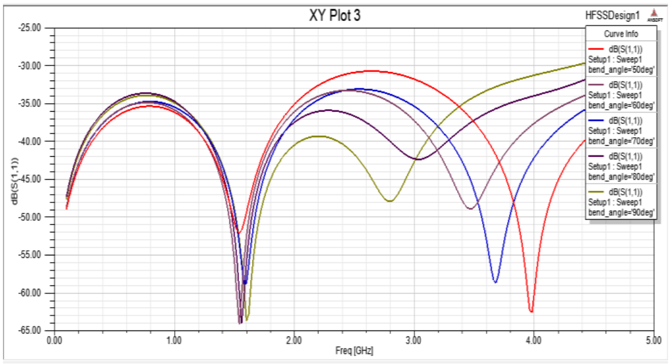


Fig (9). Measured and simulated Return Loss.

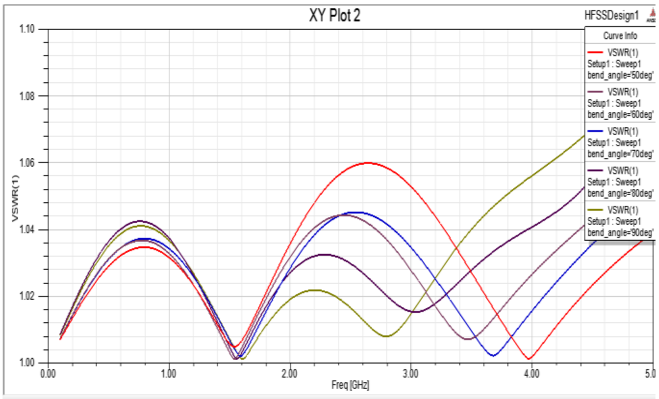


Fig (10) VSWR v/s Frequency.

3. Conclusions

The research work in this thesis includes two major aspects related to the dielectric resonator antennas (DRAs): The first part of the thesis describes multifunction and diversity DRA implemented using a single dielectric resonator (DR), while the second part of the thesis extends DRA research from microwave to the visible spectrum. These two aspects are respectively based on two attractive features of DRAs,

•Various resonant modes can exist in a DR volume and each mode is related to different radiation characteristics. The orthogonality of field distribution for the fundamental modes builds the basis for realization of low coupling multi-mode design. The resonance frequency and bandwidth of selected orthogonal modes can be designed to satisfy the desired requirements by optimizing the DR geometry and the configuration of the feeding network.

•The high radiation efficiency of DRA has been experimentally proved in the millimeter wave (MMW) frequency region due to the absence of the inherent conductor losses in DR. This motivates further scaling towards optical frequencies, and suggests favorable performance when compared to metallic optical antennas.

Apart from these two features, other advantages of DRAs, including small size, light weight, low cost, coupling to most transmission lines and design flexibility, allow for a wide range of designs to satisfy specified requirements.

In light of these features, various DRAs have been proposed in the literature with enhanced performance in terms of bandwidth, gain, radiation efficiency and functionality. It is noted that a deep and thoughtful understanding of resonance frequency, excited modes, and impedance bandwidth and radiation characteristics is generally required to create novel advanced designs. As basis for this understanding, the canonical DRA geometries, including hemisphere, rectangle and cylinder, are the fundamental building blocks for all other advanced DRA geometries.

A compact CNT based cylindrical dielectric resonator antenna fed by a coaxial line has been proposed and measured. The designed prototype has a dual-band operation suitable for both DCS (1710 - 1880MHz) and Microwave (2400 - 2484MHz) applications. The compact CNT based cylindrical directional antenna achieves a desirable directional radiation pattern with a VSWR of -59 dBi for the 1.8 GHz band and -50dBi for the 2.4 GHz band. It has a small size which satisfies the new communication system requirements.

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