Optimization of microstrip patch antenna's bandwidth using fabricated multiwall carbon nanotubes-Al$_2$O$_3$-ceramic composite substrate

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Abstract- The choice of substrate material is very important in Microstrip Patch Antenna (MPA) fabrication for efficient bandwidth realization. However, tolerance control of the substrate properties is a challenge. In this paper, Multiwall Carbon Nanotubes (MWCNTs) have been synthesized, characterized, and used to develop MWCNTs-Al$_2$O$_3$-Ceramic composite substrates for Rectangular Microstrip Patch Antenna (RMPA) bandwidth optimization. The realized composite substrates (9.1wt%MWCNTs, 11.1wt%MWCNTs, 13.04wt%MWCNTs, 14.89wt%MWCNTs, and 16.67wt%MWCNTs) showed good qualities of dielectric, electric, and magnetic properties suitable for RMPA bandwidth optimization than conventional Al$_2$O$_3$-Ceramic substrate at higher microwave and millimeter frequency bands.

1. Introduction
Microstrip Antenna was initially proposed by G. A Deschamps in the year 1953 but came into existence in the 1970s when Robert E. Munson developed it using a low substrate [1]. They are becoming increasingly useful because they can be printed on circuit boards and have become widespread within the mobile phone market [2], and [3]. Patch Antennas are low profile, low–gain, low power, and narrow–bandwidth antennas that are usually formed on a dielectric material also known as substrate [4]. The choice of substrate material is very important in Microstrip Patch Antenna (MPA) fabrication. The substrate ought to be chosen carefully to maximize bandwidth and efficiency since decrease in thickness of the substrate will result to drastic increase in conductor and dielectric losses thereby restricting the efficiency while higher values of dielectric constant will lead to tiny patch with reduced bandwidth and eventually make fabrication more difficult [4] and [5]. Moreover, tolerance control of the dielectric constant remains a problem for accurate design particularly at higher microwave frequencies [6]. Meanwhile, the extraordinary characteristics, specific properties, and potentials of Multiwall Carbon Nanotubes (MWCNTs) has made it useful in the design of broadband absorbing materials at microwave band [7].
Therefore, this paper is focused on the fabrication of Multiwall Carbon Nanotubes-Ceramic composite (MWCNTs-Al₂O₃-Ceramic) as a substrate for Microstrip Patch Antennas’ bandwidth optimization.

2. Basic Microstrip Patch Antenna Structure
Primarily the design of the MPA consists of the radiating elements, substrates, feeder, and ground plane [1]. Antenna substrate materials are supporting materials that need to give mechanical support to the antenna and have an influence on the performance. Substrates used in MPA varies from $2.2 \leq \varepsilon_r \leq 12$ [1], examples are Ceramic (Al₂O₃), RT Duroid 5880, and FR-4. The surface and interface characteristics of the substrate drastically influence the performance of the antenna [6].

3. Production of Multiwall Carbon Nanotubes
Six grams of Ferrocene Fe (C₅H₅)₂ was dispersed in acetone and methanol, sonicated for one hour, preheated at 120°C, and co-evaporated into a tube furnace of the chemical vapor deposition (CVD) machine for the production of the MWCNTs. It has been reported in literature that CNT produced at best conditions using acetone have little structural imperfections than those produced using polypropene [8]. The tube furnace of the CVD machine was initially pumped down to a vacuum level and filled with argon to a higher pressure and heated up to 100°C. At a temperature higher than 900°C the mixture of ferrocene, acetone and methanol decomposed completely in the furnace. The MWCNTs forms from the reactive hydrocarbon nucleate and grow with the carbon atom of the ferrocene on support placed at the center of the furnace. After cooling, MWCNTs films of different diameters were grown and the process repeated at different temperatures of 1000°C, 1100°C to an optimized temperature of 1200°C and 25grams of different diameters of the MWCNTs were produced.

The synthesized MWCNTs were purified by adding them to H₂SO₄ and sonicated for 5hours at 75°C to separate the MWCNTs from the metallic catalyst and amorphous carbons. Thereafter, it was dispersed in the aqueous solution by the sonication process. Proper dispersion becomes necessary to retain the electronic characteristics of the MWCNTs [9]. After the temperature cools, the sample obtained was dispersed in methanol for functionalization at room temperature, rinsed off and oven-dried for 12 hours and the final sample obtained were characterized using FESEM, XRD, RAMAN spectroscopy and EDX to obtain the morphology, structural, defect density, surface composition and elemental characteristics of the MWCNTs. The results obtained are as shown in figure 1.
Figure 1: (a) FESEM morphology image result (b) XRD structural pattern result (c) Raman Spectroscopy result (d) Elemental composition result obtained from EDX

The results obtained from figure 1(a) to 1(d) show that higher quality yield of the MWCNTs was produced with little impurities and negligible defects.

4. Fabrication of MWCNTs-Al2O3-Ceramic Composite Substrates

100 grams of Al2O3-Ceramic powder was divided into five portions and doped proportionately with 9.1 wt% (2.0 g), 11.1 wt% (2.5 g), 13.04 wt% (3.0 g), 14.89 wt% (3.5 g) and 16.67 wt% (4.0 g) of the MWCNTs and molded to the desired shapes to form MWCNTs-Al2O3-Ceramic composite substrates.

Figure 2: Molded samples of the MWCNTs-Al2O3-ceramic composite Substrates
5. Properties Measurements of the MWCNTs-Al2O3-Ceramic Composite Substrates

The determination of the electromagnetic properties of materials is an important feature of many applications in the design of broadband absorbing materials at microwave bands [8] and [10]. Hence, the MWCNTs-Al2O3-Ceramic composite substrates properties such as relative permittivity, relative permeability, dielectric loss tangent, magnetic loss tangent and conductivity were obtained at microwave frequency band of 8.2GHz-12.4GHz using Rectangular Waveguide Transmission/Reflection device connected to Keysight Network Analyzer.

The Phase velocity delay in the Rectangular Waveguide Transmission/Reflection device with a sample of the MWCNTs-Al2O3-Ceramic composite substrate of thickness (d) is given by [11] as;

\[ T = e^{-jkd} = e^{-\gamma d} \]  

In the presence and absence of the sample the reflection coefficient at the first front end between the transmission lines was obtained using equation (2) given by [11] as;

\[ \Gamma = \frac{Z_1 - Z_0}{Z_1 + Z_0} \]  

\( Z_0 \) is transmission line characteristic impedance in absence of the sample and \( Z_1 \) is transmission line characteristic impedance in the presence of the sample.

It propagation constant was deduced from equation (3) given by [11] as;

\[ \gamma = jk = \frac{1}{d} (-\ln (|\Gamma|) - j\phi + j2\pi n) \]  

Since the propagation constant can be estimated using equation (3). The electrical permittivity and magnetic permeability of each fabricated sample was deduced [11] as follow;

\[ \varepsilon^* = \frac{\varepsilon}{\varepsilon_0} \left( \frac{1 - i\gamma}{1 + i\gamma} \right) n = 0 \]  

\[ \mu^* = \frac{\mu}{\mu_0} \left( \frac{1 - i\gamma}{1 + i\gamma} \right) n = 0 \]  

Then in the waveguide environment the magnetic permeability of each fabricated sample was estimated from the equivalent circuit of waveguide transmission line given by [12] as;

\[ \mu^* = \frac{\sqrt{\kappa_0^2 - \kappa_f^2}}{\omega \mu_0} \]  

\( \kappa_0 \) and \( \kappa_f \) are the propagation constant in free space and the constant wave number of the waveguide respectively, Dielectric relative permeability of each fabricated sample was derived from the propagation constant by [11] as;

\[ \varepsilon_r = \frac{\kappa^2 + \kappa_f^2}{\kappa_0^2 \mu^*} \]  

The bulk conductivity (s/m) of each fabricated sample was deduced from permittivity as given by [13]as;

\[ \sigma = 2\omega \varepsilon_0 \varepsilon_r^* \]
The dielectric loss tangent and magnetic loss tangent of each fabricated sample were deduced from measurement values using equation 8 and 9 given by [13] as;

$$\tan\delta_E = \frac{\sigma}{\omega\varepsilon_0\varepsilon_r} = \frac{\varepsilon_r}{\varepsilon_r^{'}}$$ (8)

$$\tan\delta_\mu = \frac{\sigma}{\omega\mu_0\mu_r} = \frac{\mu_r}{\mu_r^{'}}$$ (9)

Figures 3a, 3b, 3c, 3d and 3e show the results of measured real relative permittivity, real relative permeability, bulk conductivity, dielectric loss tangent, and magnetic loss tangent of the MWCNTs-Al2O3-Ceramic composite substrates obtained from the transmission/reflection device. It was observed that the real relative permittivity of all the fabricated samples decreases proportionately with an increase in the frequency range of 8.2 GHz-12.4 GHz. Real permeability increases with an increase in frequency. The results of the bulk conductivity of the samples doped with 11.1wt% and 16.67wt% show that they are purely dielectric composite substrates while the samples doped with 9.1wt%, 13.04wt% and 14.89wt% are conductors. The results of the fabricated MWCNTs-Al2O3-Ceramic composite substrates also show low values of dielectric loss tangent and magnetic loss tangent.
Figure 3: (a) Relative Permittivity result (b) Relative Permeability Result (c) Bulk conductivity (d) Dielectric loss tangent and (e) Magnetic loss tangent.

6. Optimization of Rectangular Microstrip Patch Antenna's Bandwidth

The parameters obtained from the T/R device were added to the High-Frequency Structure Simulator (HFSS) material’s library for simulation and optimization of rectangular microstrip patch antenna's bandwidth at the frequency range of 8.2GHz-12.4GHz and the result are shown in figures 4a and 4b.
Figure 4: (a) Comparison of the bandwidth of the fabricated MWCNTs-Al₂O₃-Ceramic composite substrates with Al₂O₃-Ceramic substrate (b) Resonating frequency comparison.

Figure 4a shows that all the fabricated MWCNTs-Al₂O₃-Ceramic composite substrates give higher bandwidth than the Al₂O₃-Ceramic substrate over the frequency range of 8.2 GHz -12.4 GHz which implies that MWCNTs can be used to form a composite with other ceramic to optimize rectangular patch antenna bandwidth. Figure 4b shows that the fact that an antenna resonates at higher frequency does not guarantee higher bandwidth in every scenario.

7. Conclusion
In this research work, MWCNTs have been used at different concentrations to fabricate MWCNTs-Al₂O₃-Ceramic composite substrates for patch antenna bandwidth optimization. The fabricated composite substrates demonstrated some similar and varying dielectric, electric, and magnetic properties. The simulation results showed that the substrates fabricated with MWCNTs-Al₂O₃-Ceramic composite have higher bandwidths when used to simulate Rectangular Microstrip Patch Antennas than that of the existing Al₂O₃-Ceramic substrates. Hence, MWCNTs-Al₂O₃-Ceramic composite substrates can be produced en mass on an industrial scale as substrates for Microstrip Patch Antennas design and construction at higher microwave frequency bands.
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