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Multiwalled carbon nanotube-based patch antenna for bandwidth enhancement

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ABSTRACT

A novel carbon nanotube (CNT)-based rectangular microstrip antenna for wide impedance bandwidth applications has been designed and developed. The copper patch commonly placed on the substrate in a conventional rectangular microstrip antenna is replaced with a CNT patch prepared using spin coating. The MWCNT patch antenna was fabricated by spin coating method and it exhibits an increased impedance bandwidth of 20%. The enhancement of the impedance bandwidth does not affect the broadside radiation characteristics. The carbon nanotubes are highly conductive nanomaterial. Due to this unique property, each nanotube present on the surface resonates electromagnetic waves individually and influences the enhancement in the bandwidth. The simple design and fabrication of the proposed antenna can be employed for synthetic aperture radar applications.

1. Introduction

Carbon nanotubes (CNTs), experimentally discovered in the early 1990s by Iijima, are among the most commonly investigated building blocks in nanotechnology [1]. They have been used in several research fields to utilize their unique physical properties. The AC conductivity and electromagnetic wave interactions of conductive CNTs are superior to those of traditional conductors, such as copper, of the same size. Recently, several studies investigating the possibility of using multiwalled CNTs (MWCNTs) as patch antennas [2–4] have been reported based on different numerical analysis and modelling approaches [5–10]. CNTs are particularly attractive in nanoscale electronic applications because they show excellent mechanical, electrical, and thermal properties [1,2]. The use of MWCNT-based antennas in low-power communication devices, such as synthetic aperture radar (SAR), in harsh chemical and gas environments is of particular interest because antennas using conventional copper patches can become oxidized in such environments [5,11–15].

MWCNT thin-film patch antennas have been fabricated by using dispersed MWCNT solution. However, obtaining stable MWCNT dispersions is difficult because of the different forces present within the MWCNT bundles. At the nanoscale, van der waals interactions may significantly hinder the stability of CNT dispersions. Recently, many methods have been developed for dispersing CNT in ethanol by employing various chemical and mechanical modifications. Some unique nature of CNT thin film, such as ultra-thin thickness and soft nanoporous structure, have made the measurement process challenging. Therefore, obtaining accurate measurements of thickness of CNT thin films to evaluate the properties of the nanocomposites is critical [16]. These MWCNT-solution based thin film can be applied in several applications such as interconnections, microelectronic chips, transmission lines, and radio-frequency identification (RFID) microstrip patch antennas [4].

Bandwidth enhancement is a major requirement for the practical application of microstrip patch antennas. The challenges encountered in the development of nanomaterial-based radio frequency (RF) antennas are associated with the determination of the material resonance at lower frequencies and the formation of reliable electrical contacts with the nanomaterials to determine their performance; examining the RF response is also very challenging. These challenges impede the determination of the radiating properties of nanomaterials, and the RF applications of materials such as metallic nanofilms have not yet been investigated. Nanostructured MWCNTs exhibit several desirable electromagnetic and mechanical properties suitable for the design and development of microstrip patch antennas [5]. A highly uniform current distribution can be achieved using CNT-based antennas compared to those of traditional antennas comprising conventional metallic and dielectric materials, thereby enabling

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the production of an antenna with a greater bandwidth [19]. The MWCNT microstrip patch antenna exhibited the highest possible impedance bandwidth in the X-band frequency range.

In this study, we experimentally characterize the CNT-based patch antenna in which the radiating patch is composed entirely of MWCNT nanofilm. We discuss the design and fabrication of these structures and the properties of the obtained antenna. Three key issues are addressed: determining the best MWCNT formulation, investigating fabrication methods for MWCNT antennas, and testing the performances of the fabricated MWCNT antennas. We characterize the MWCNT antenna performance using a network analyser and an anechoic chamber.

2. Experimental

2.1. Materials

MWCNTs (CAS No 698849), sodium dodecyl sulphate (SDS), and ethanol were supplied by Sigma Aldrich. The ultrasonicator was supplied by Chemilabs, while the centrifuge device and FR4 sheet were supplied by Entuple Technologies.

2.2. MWCNT dispersion

We prepared a stable and homogeneous CNT dispersion by mixing the purified MWCNTs (98%) with an aqueous solution of ethanol in a 1:1 ratio by weight. In the second step, SDS, which exhibits a great capacity in dispersing CNTs in aqueous media, was used as a surfactant [10] to establish good interactions between the CNT walls and ethanol.

In order to obtain a stable good solution, the concentration of the CNTs was fixed as 0.1 mg ml^{-1}. An ultrasonicator was used for dispersing the CNTs. The key parameter employed for obtaining the stable solution was the amplitude of sonication for 8 h in a room-temperature environment i.e., 25 °C. After sonication, a CNT solution with the required viscosity was obtained Fig. 1.

Large CNT aggregates were separated from small aggregates through centrifugation. The ultrasonication and centrifugation cycle was repeated five times until no aggregates remained at the bottom of the vial. The homogeneous stable solution thus obtained was filtered. This solution was used for fabricating a thin film on the FR4 substrate by a spin-coating method Fig. 2.

3. Antenna fabrication and geometry

The microstrip antenna was fabricated using rectangular MWCNT patch. The MWCNT patch size was calculated based on the centre frequency of 10 GHz in the X-band frequency range of 8–12 GHz. The substrate and the ground plane used measured 30 mm × 30 mm. Fig. 3 depicts the antenna geometry. The detailed design parameters used are listed in Table 1.

The antenna was fabricated on an FR4 substrate with the relative permittivity of 4.4. Rectangular-shaped MWCNT patch geometry was first calculated theoretically for 10 GHz centre frequency over 8 GHz–12 GHz range. These antenna design parameters were transferred to the mask on the top of the FR4 substrate by laser lithography. Then, the MWCNT solution was coated on FR4 substrate with optimized spinning speed of 3000 rpm - 60 s in spin coating device. A Subminiature version A (SMA) connector was soldered to the copper microstrip feed line. The fabricated MWCNT patch antenna is shown in Fig. 3.

4. Results and discussion

4.1. CNT electrical conductivity

Conductivity measurement is an essential test when characterizing of MWCNT material. The conductivity of a material is highly sensitive to variations by factors such as temperature, humidity, and thickness; therefore, the stability of these parameters is important for providing repeatable evaluations of the material properties.

To measure the electrical conductivity of MWCNT material, two probes provide the current path and another two determine the voltage. This configuration is the so-called four-point probe measurement. The four-point probe approach provides more reliable test results compared to the conventional two-point probe

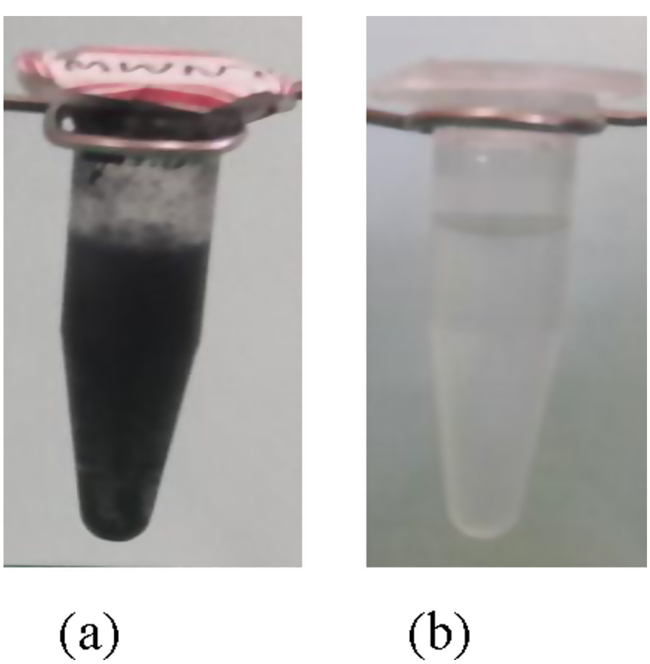

Fig. 1. (a) Solution of MWCNT, (b) Aqueous solution of ethanol with SDS.

Fig. 2. Spin coating device.

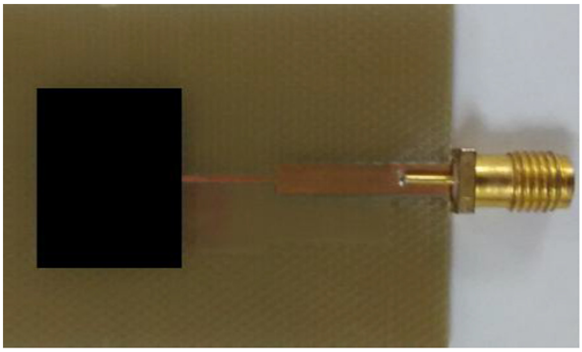

Fig. 3. Fabricated MWCNT patch antenna.

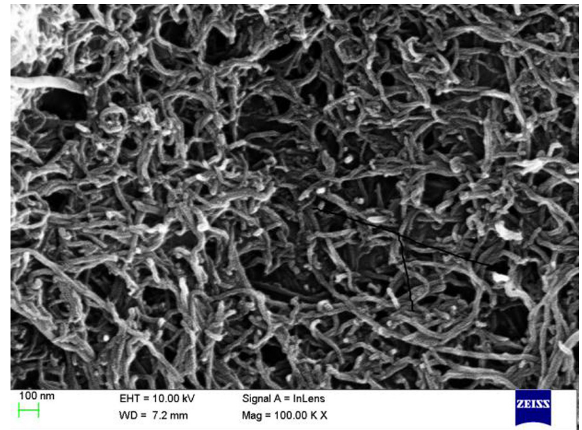

Fig. 5. Scanning Electron Microscopic image of MWCNT.

Table 1
Geometry of the MWCNT patch antenna.

Parameter	Calculated value (mm)	Optimised value (mm)
Width (W) of the patch	6.0	6.2
Length (L) of the patch	9.75	9.0
Feed line width (W_f)	2.5	2.2
Transformer width (W_t)	0.44	0.44
Transformer length (L_t)	2.7	3.6

method. However, careful setup is required to ensure accurate resistance measurements by factoring in equipment calibration, sample structure, sample size and environmental conditions. The conductivity of the MWCNT thin film was measured through DC 4-probe station method using Agilent DC analyzer. The measured conductivity of MWCNT suspended in solvent was found to be 1.8×10^{-3} $S.m^{-1}$ as shown in Fig. 4.

4.2. MWCNT scanning electron micrograph

A scanning electron microscopy (SEM) image of carbon nanotubes grown by arc-discharge is shown in Fig. 5. The web-like structure consists of nanotube bundles. In such a bundle the tubes are packed in a two-dimensional hexagonal lattice with 100 nm dimension. The bundling results from the attractive van-der-waals forces between nanotubes. A group of CNTs can form a randomly oriented CNT mat or super aligned CNT arrays, depending on the density of catalyst and their activities under the same synthesis conditions. Fig. 5 shows SEM image of a MWNT thin sheets array, in which nanotubes are super aligned. The nanotubes within each sheet confine the nearest neighbors and attract the outermost nanotubes to their neighbors via van der waals force, thereby producing oriented growth. As the thickness of the sheet increases, the alignment of the CNTs could be improved due to the crowding effect.

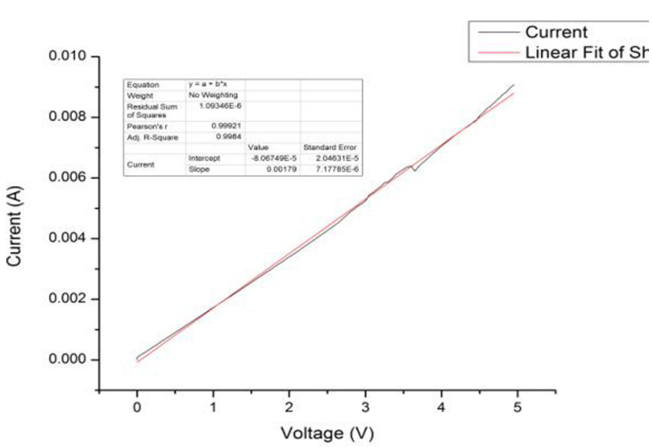

Fig. 4. DC conductivity of MWCNT material.

4.3. Measurement results obtained for the MWCNT patch antenna

The MWCNT patch antenna was characterized to determine the performance. The geometry of the MWCNT patch antenna is shown in Table 1. The results obtained for the reflection coefficient (S11), resonant frequency, and far-field radiation pattern are shown in Figs. 6 and 7 respectively.

The proposed MWCNT antenna was examined using an Agilent E8364B network analyzer to determine the S11 value of the antenna fabricated using MWCNTs on the FR4 substrate.

Since the design frequency of the MWCNT patch antenna is 10 GHz, the impedance bandwidth over return losses of less than −10 dB can be measured from 8.5 to 11 GHz in the X-band frequency range. The plot of the variation of the return loss versus the frequency of the MWCNT-based antenna is shown in Fig. 6. The MWCNTs resonate at the frequency of 10 GHz, which is close to the design frequency of 10 GHz calculated theoretically.

The impedance bandwidth is calculated using following equation:

$$\text{Impedance Bandwidth}\ (\%) = \left[\frac{f_2 - f_1}{f_r}\right] \times 100\%. \quad (1)$$

where f_2 and f_1 are the upper and lower cut-off frequencies of the band, respectively, when its return loss approaches −10 dB, and f_r is the centre frequency between f_1 and f_2. The impedance bandwidth of the MWCNT antenna is 20%, covering the wide band over the 8.5 GHz–11 GHz range.

The MWCNT patch antenna is highly current carrying conductive material [17]. Each nanotubes in the patch acts as a primary resonators resonate electromagnetic waves So, Current flowing along the edges of the patch induces additional resonances, which enhances the fundamental resonance of the radiating element. Thereby enhancing the impedance bandwidth.

To measure the radiation pattern, the MWCNT patch antenna was tested in an anechoic chamber, i.e. the proposed MWCNT patch antenna and a standard isotropic antenna were maintained in the far-field region. In the anechoic chamber, the receiving antenna was maintained in phase with the transmitting isotropic antenna. The power received by the anechoic chamber is measured from −150° to +150° with steps of 10°.

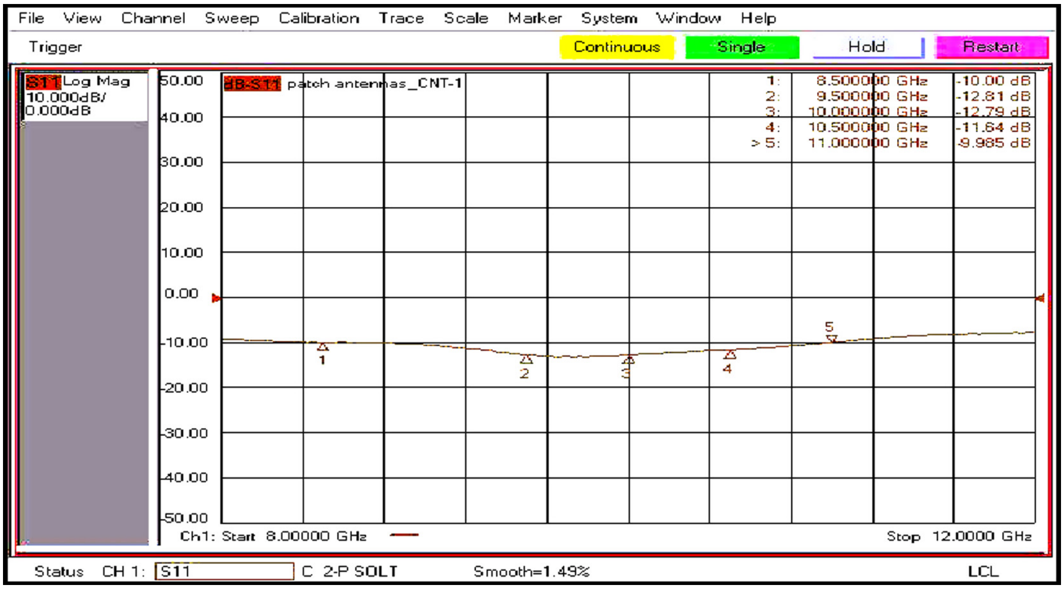

Fig. 6. Measurement of return loss (S11) of the MWCNT patch antenna.

The co-polar radiating patterns of the MWCNT path antenna were measured at the frequency of 10 GHz (Fig. 7). The co-polar patterns are found to be broadsided and linearly polarized. The -3 dB half-power beam width is 109°. Hence, by using the MWCNT patch antenna, the sharpness of the beam is improved compared to the other conventional antennas. This is because the MWCNT patch suppresses the maximum back radiation, thereby sharpening the beam and improving the radiation pattern. The performance comparison of conventional and CNT based antennas are given in Table 2.

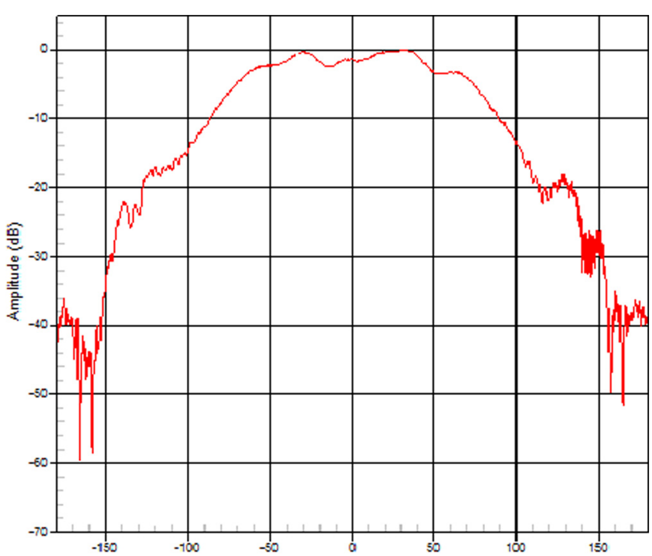

Fig. 7. Measured Radiation pattern of the MWCNT patch antenna.

In our previous reported work, standard patch antenna and MWCNT – nano composite patch antennas were designed and simulated, these three patch antennas had nearly same resonating frequency of 10 GHz. The MWCNT nano composites antennas such as PAni-PTsA with MWCNT composite enhance the bandwidth of 2.84% and PAni-NSA with MWCNT nano composite antenna enhance 3.12% bandwidth compared to the conventional patch antenna. The radiation pattern and antenna gain were almost similar, i.e., 7.3 dB. The above result shows that a suitable design of MWCNT nano composites patterns has favorable effect on the performance enhancement of the antenna [18]. Aidin Mehidipur et al. [19] used single-walled carbon nanotube composite material to fabricate antenna for millimeter-wave applications.

The CNT antenna shows stable gain and radiation patterns over the 24–34 GHz frequency range**.** Moreover, the CNT antenna shows low dispersion characteristics over the frequency range of interest and so may be used for ultra-wideband radios. The antenna performance such as gain can be adjusted by changing the conductivity of composite, while it is not possible for materials with fixed conductivity such as copper.

Taha A Elwi et al. 2010 [4] reported MWCNT patch antennas simulated based on the measured constitutive parameters. The CNT antennas demonstrated a remarkable enhancement in the bandwidth ranging from 2.2% to 5.6% at the first mode, as compared to 1.1% to 3.0% for their identical copper-based counterparts. This is approximately 45% more bandwidth than the antennas with

Table 2
Comparison of standard and CNT based antennas.

Sl. No.	Antennas	Frequency	Gain	Bandwidth	Efficiency	References
1.	Standard copper patch antenna	10 GHz	8.3 dB	2.1%	95%	Previous work [18]
2.	Low RCS antennas PAni-PTsA1 + MWCNT patch antenna	10 GHz	7.9 dB	2.8%	99%	
3.	PAni-NSA + MWNT patch antenna	10 GHz	7.5 dB	3.1%	94.5%	
4.	MWCNT patch antenna	10 GHz	0.81 dB	2.5	25%	Current study
5	SWCNT patch antenna	24–34 GHz	5 dB	12%	98%	Aidin Mehidipur et.al. [19]
6.	MWCNT ink patch antenna	10 GHz	7 dB	2.1%	90%	T. A. Elwi et.al. [4]

copper patches at their corresponding fundamental resonant mode. The MWCNT antennas possess a lower gain compared to their copper counterparts due to the lower conductivity of the patch. Current study reports the MWCNT patch antenna fabricated in spin coating method and it exhibits an increased impedance bandwidth of 20% which is a very appropriate candidate to be employed in synthetic aperture radar applications.

5. Conclusion

The MWCNT-based microstrip antenna was successfully fabricated using a cost-effective spin-coating technique, which can be employed for mass production. Different patch antenna parameters were examined. The antenna exhibits an impedance bandwidth i.e., 20% higher than that of a conventional antenna designed with the same resonant frequency. By using MWCNTs, an antenna with a simple design and easy fabrication can be produced. The same fabrication procedure could be used to mass produce MWCNT patch antennas.

The measurement results indicate that the MWCNT patch antenna exhibits good performance over the bandwidth in the frequency range of 8.5 GHz–11 GHz, showing potential applicability for SAR applications. Antenna performance parameters such as gain can be tuned by controlling the concentration of the material and also high precision geometry, which alters the conductivity in MWCNT material. This cannot be done with conventional conductive materials such as copper.

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