A Dual-Frequency Wearable MWCNT Ink-Based Spiral Microstrip Antenna

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ABSTRACT

In this paper, we present a dual-frequency, square spiral microstrip patch antenna constructed from Multi-Walled Carbon Nanotubes (MWCNT) ink deposited on a thin flexible FR4 substrate using a cold printing process. The proposed antenna operates at 1.2276 GHz for wearable Global Positioning System applications and 2.47 GHz for wearable Multichannel Multipoint Distribution Services. The MWCNT ink, possessing an electrical conductivity of 2.2×10^4 S/m and a relative permittivity of 5-j1, is used as the conductor patch. CST Microwave Studio (CST MWS) was utilized to evaluate the return loss, matching impedance, resonant frequency, bandwidth, and far-field radiation patters. The antenna gain is found to be -12.5 dBi and -4.25 at 1.2276 GHz and 2.47 GHz, respectively. The corresponding gain values when copper is used for the patch are -12.05 dBi and -4.01dBi. Simulations and measurements based on MWCNT ink and copper are presented and compared. An excellent agreement was found between the measured and simulated results.

Keywords: Conductive ink, CST MWS, Square spiral antenna

1 INTRODUCTION

Rapid developments wireless communications coupled with recent progress in material exploration resulted in a growing interest to apply nanostructure materials for microwave devices. The need for developing new materials that provide wireless devices with novel properties, in particular wearable microstrip antennas, is subtle for applications where regular conductors may fail such as mining, fire, chemical or for biological degrading environments. Nanoscale materials are the most promising candidates since they have proven to provide new properties that were not possible for traditional bulk material. Electrically conductive ink based on nanoscale material is one such example. We have developed MWCNTs suspended in an adhesive solvent to create printable ink that dries quickly, adheres homogenously, and possess the characteristics of a good conductor at microwave frequencies. For the last several decades, conductive inks have stimulated the consideration and interest of many researchers due to their wide applications in microelectronics[1]. These materials have numerous advantages over traditional conductive bulk material such as lower mass density and high resistivity against corrosion. Moreover, the electromagnetic constitutive parameters can be controlled by chemical manipulation using different functional groups, density of doping, or mixing with different hosting[2, 3]. The MWCNT ink is painted using an ink jet cold printing process, which provides a low cost manufacturing process to manufacture passive microwave printed circuit boards such as transmission lines and microstrip antennas and is characterized by high resistance against corrosion. In this paper, we present a microstrip square spiral antenna constructed from MWCNT ink for wearable applications. The antenna design is conducted using CST MWS[4]. Measurements and simulation results are presented for both MWCNT and copper patches. The DC electrical conductivity is measured by the four-probe technique, while the permittivity measurement is conducted over the frequency range from 300 kHz to 8.5 GHz using an Agilent 85070B dielectric probe.

2 MATERIAL CHARACTERIZATION

In this section, we present the measured constitutive parameters of the MWCNT ink in terms of electrical conductivity and relative permittivity. The electrical conductivity measurement has been performed using the four-probe technique and it is found in the range of 2.2×10^4 S/m. The measurement of the real and imaginary parts of the complex relative permittivity is conducted using the Agilent 85070B dielectric probe kit and the 300 kHz - 8.5 GHz ENA series Network Analyzer. The measured real and imaginary parts of the relative permittivity are 5±0.1 and 1±0.05, respectively.

3 ANTENNA DESIGN AND CHARACTERIZATION

The CST model for the MWCNT antenna is presented in this section using the measured constitutive parameters presented in Section 2. The thickness of the MWCNT based patch is 0.5 mm. The patch is shaped as a square spiral trace truncated horizontally on a lossy FR4 substrate with a relative permittivity of 2.5, a loss tangent of 0.018, and a thickness of 0.5 mm. A thin copper layer, 35 μm in thickness is used as the ground plane. The 50 Ω feeding point is fixed at X_p = -17.5 mm and Y_p = 17.5 mm from the substrate's center as seen in Fig. 1. The MWCNT patch is positioning at the center of the substrate as shown in Fig. 1.

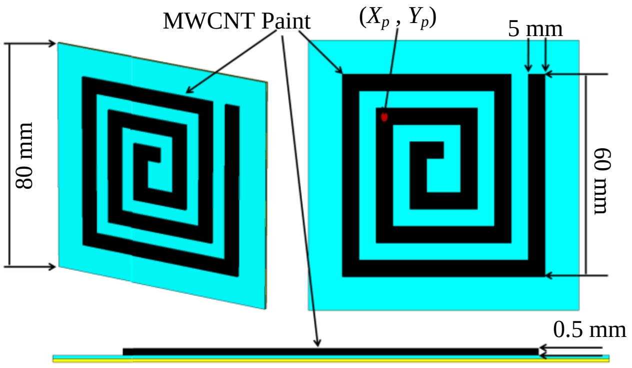

Fig. 1 The numerical model of the square spiral microstrip antenna.

Comparison of the simulated S_{11} spectrum for the MWCNT patch and the copper patch is presented in Fig. 2 (a) and (b). Fig. 2(a) shows that the return loss for the MWCNT patch is -12 dB at 1.2276 GHz, while the return loss for copper is -13 dB at 1.25 GHz. In Fig. 2(b), the MWCNT patch shows a resonance mode at 2.47 GHz with a matching return loss of -27 dB, while the copper antenna is matched with -13 dB at 2.53 GHz. However, the position of the feed has been shifted for the copper patch to the point at X_p = -7.5 mm, Y_p = -7.5 mm to obtain an optimum match to the 50 Ω feeding point. This shift in feeding position is attributted to the electrical conductivity of the MWCNT patch being less than that of copper. The -10 dB bandwidth of the MWCNT patch at both resonating frequency is about 3%, which is higher than the copper patch, which is about 1.9%. This is due to the relatively higher loss of the MWCNT patch. The resonant frequancies for the two modes of the MWCNT patch are shifted by about 45 MHz with respect to the copper patch because of the relative permittivity of the MWCNT patch. In Fig. 2(c) and (d), the absolute gain versus frequency is presented for the MWCNT- and copper- based antennas, for both the first and second modes, respectively. The peak gain of the MWCNT patch is about -12.5 dBi and -4.25 dBi at 1.2276 GHz and 2.47 GHz, respectively, which are compared to the copper case in which the gain is about -12.05 dBi and -4.01 dBi at both 1.25 GHz and 2.53 GHz, respectively. This slight decrease in gain is caused by the conductor and dielectric losses of the MWCNT patch. The radiation patterns for both MWCNT and copper patches at the two operating frequencies are presented in Fig. 3. In Fig. 3(a) and (b), the radiation patterns of both antennas are illustrated in the θ = 0° and 90° planes at 1.2276 GHz for MWCNT patch and 1.25 GHz for copper. The radaition patterns of the MWCNT and copper at 2.47 GHz and 2.53 are presented in the θ = 0° and 90° planes, respectively, in Fig. 3(c) and (d). By inspecting Fig. 3, it is clear that the degradation in conductivity of the MWCNT ink with respect to copper does not significantly affect the shape of the far-field radiation patterns. In Fig. 4, we present the power dispated by the patch due to conductor and dielectric losses at the two resonance modes. In Fig. 4(a) and (b), the conductor and dilectric losses for the MWCNT patch is higher than the conductor losses of copper as presented in Fig. 4(c) and (d). The radiation efficiency at both resonance frequencies of the MWCNT were found to be 2% and 16%, while copper was found about 2.2% and 18%.

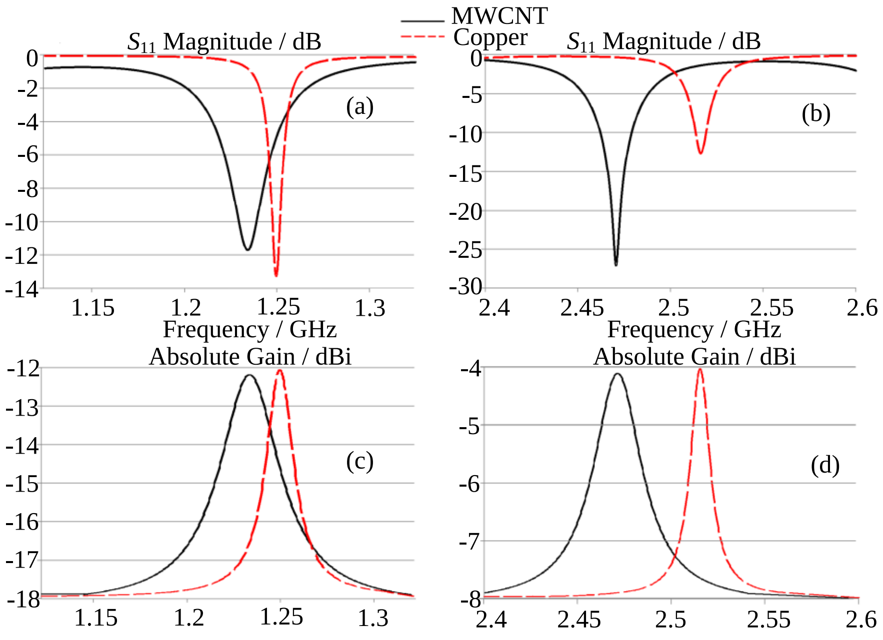

Fig. 2 Numerical results for the MWCNT and copper patches at the targeted frequancies (a) S_{11} versus frequency of MWCNT shows resonance at 1.2276 GHz and copper shows resonance at 1.25 GHz, (b) S_{11} versus frequency of MWCNT shows resonance at 2.47 GHz and copper shows resonance at 2.53 GHz, (c) absolute gain versus frequency of MWCNT shows -12.5 dBi at 1.2276 GHz and copper shows -12.05 at 1.25 GHz, and (d) absolute gain versus frequency of MWCNT shows -4.25 dBi at 2.47 GHz and copper shows -4.01 at 2.53 GHz.

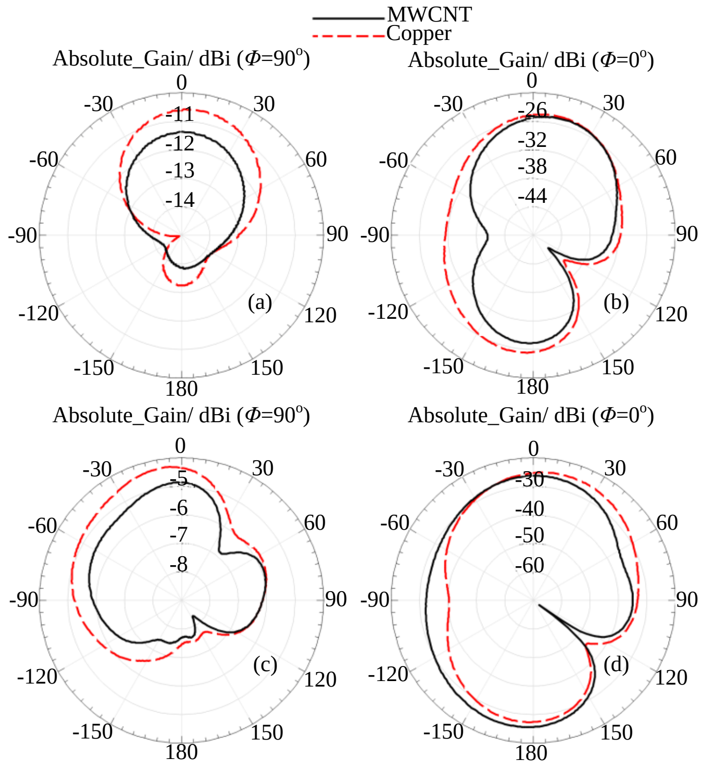

Fig. 3 Radiation patterns for the MWCNT and copper patches at the targeted frequancies (a) radiation patterns at $\theta = 0^o$ of MWCNT at 1.2276 GHz and copper at 1.25 GHz, (b) radiation patterns at $\theta = 90^o$ of MWCNT at 1.2276 GHz and copper at 1.25 GHz, (c) radiation patterns at $\theta = 0^o$ of MWCNT at 2.47 GHz and copper at 2.53 GHz, and (d) radiation patterns at $\theta = 90^o$ of MWCNT at 2.47 GHz and copper at 2.53 GHz.

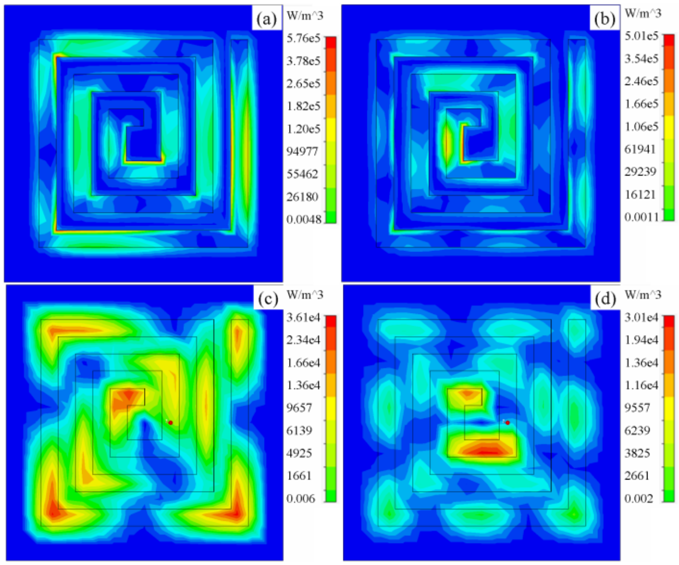

Fig. 4 Power dissipated by the conductor patch (a) at 1.2276 GHz for MWCNT, (b) at 2.47 GHz for MWCNT, (c) at 1.25 GHz for copper, (d) at 2.53 GHz for copper.

4 FABRICATION PROCESS

MWCNTs were synthesized on the Fe-Co/$CaCO_3$ catalyst system by chemical vapor deposition approach using Radio Frequency heating method as presented by Dervishi et. al.[1]. About 100 mg of the catalyst was uniformly spread into a thin layer on a graphite susceptor and placed in the center of a quartz tube with inner diameter of 1 inch. The quartz tube was horizontally positioned at the center of the RF generator. Next, the system was purged with nitrogen at 200 ml/min for 10 minutes, and when the temperature reached around 720 °C, acetylene was introduced at 3.3 ml/min for 30 minutes. The as-produced MWCNTs were purified in one simple step using diluted hydrochloric acid solution and sonication. A conductive ink composition consisting of purified MWCNTs is dispersed in sodium cholate (NaCh) aqueous solution (CNT: sodium cholate 1:1 wt., 5 mg/L). An inkjet printer based on a single inkjet head controlled by a piezoelectric actuation process is involved to drop the MWCNT ink onto a flexible FR4 substrate. The flexible FR4 substrate is treated by oxygen plasma for 2 minutes to increase the hydrophilicity of the polymeric films. The plasma treatment process is carried out at 200 W inside a cylindrical reactor connected to a rotary pump in series with an RF power source vacuumed at 2 × 10^{-3} Torr before introducing oxygen inside the reactor. The MWCNT patch is fed through an N - type female SMA coaxial cable to the 50 Ω matching point by silver paste, which dries at room temperature and adheres easily to the MWCNT structure. Fig. 5(a) shows the manufactured prototype of the MWCNT antenna. The copper patch has been deposited on the FR 4 substrate and the N - type female SMA connector is soldered to the 50 Ω matching point as shown in Fig. 5(b).

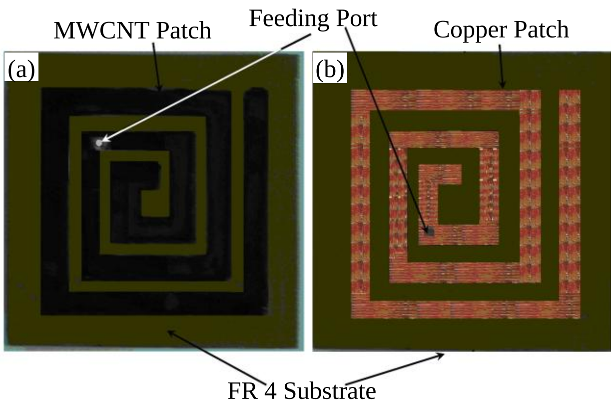

Fig. 5 Front veiw of the MWCNT and copper antennas, (a) MWCNT patch, (b) Copper patch.

5 EXPERIMENTAL MEASUREMENTS

The MWCNT and copper spiral patch antennas are tested and characterized by measuring the resonant frequency, return loss, and bandwidth as shown in Fig. 6 using an Agilent E5071B network analyzer. The -10 dB return loss bandwidth is 3.2% at the two resonant frequencies. On other hand, the copper patch shows a bandwidth of 1.8%, at the two resonant frequencies. The measured simulated results of the S_{11} of both cases and resonance frequencies are presented and compared in Fig. 6; an excellent agreement has been achieved between the measured and simulated results.

6 CONCLUSION

In this paper, we presented a square spiral microstrip antenna based on MWCNT conductive ink with an electrical conductivity of 2.2 × 10^4 S/m and a relative permittivity of 5-j1. The antenna performance is investigated numerically using CST MWS. The MWCNT antenna performance in terms of S_{11} spectrum was validated experimentally. In addition, the identical antenna geometry based on copper has been tested numerically and experimentally. The antenna performance is compared to the copper case and an excellent agreement has been achieved between experimental and simulated results. The comparison pointed out that the bandwidth of the MWCNT patch is about 3%, which is wider than antenna made from copper. The resonant frequencies of the MWCNT patch are shifted by about 45 MHz with respect to the copper patch. The gain and far-field radiation patterns of the MWCNT are found not to be significantly different compared to the copper patch. Finally, the MWCNT antenna offers a larger gain bandwidth product compared to the copper-based antenna.

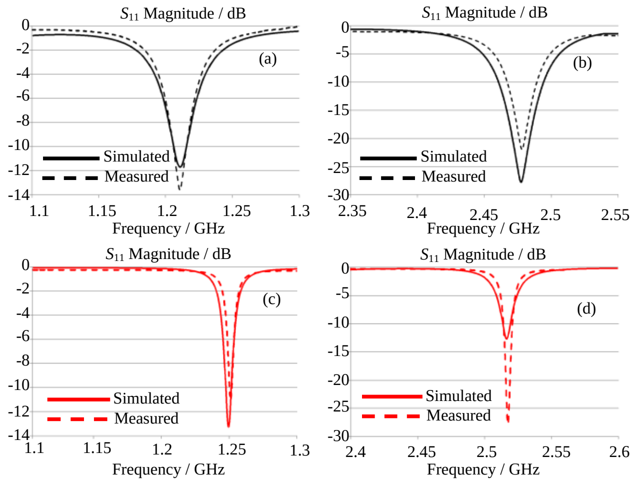

Fig. 6 Measured versus simulated S_{11} spectrum for both the MWCNT and copper patches (a) MWCNT at 1.2276 GHz, (b) MWCNT at 2.47 GHz, (c) copper at 1.25 GHz, and (d) copper at 2.53 GHz.

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Acknowledgments

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