Multifunctional Meshed Carbon Nanotube Thread Patch Antenna

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Abstract—A meshed patch antenna fabricated with carbon nanotube thread is proposed for multiple applications, including communications and chemical/gas sensing. Full wave simulation results of the meshed patch antenna are presented to demonstrate its use as a communications antenna and to predict its performance as a chemical/gas sensor. The patch antenna exhibits a center frequency of 27.85 GHz with a -10 dB bandwidth of 2.1 GHz (7.5%). The patch center frequency shifts approximately 60 MHz in direct response to the change in carbon nanotube permittivity that occurs due to the presence of a reacting gas.

I. INTRODUCTION

Carbon nanotube (CNT) technology has recently emerged as an attrcactive electronic material due to its extremely light weight, durability, and conductive properties. While the application of an individual single-wall nanotube (SWNT) as an antenna has been analytically shown to yield very low radiation efficiency at microwave frequencies [1, 2], it has recently been shown through analysis [3, 4] and measurement [5] that the dominant kinetic inductance and resistance of a CNT can be significantly reduced by fabricating a large number of CNTs into a bundle structure. It has also been predicted through simulations that dipole antennas constructed from CNT bundle structures may exhibit radiation efficiency orders of magnitude higher than that of individual CNTs [6] and that this radiation efficiency increases as the nanotube density with the bundle is increased [7]. Emerging fabrication techniques have made realizable the synthesis of large-scale CNT bundle structures such as threads, ribbons and sheets [8]. By using these CNT threads to produce wireframe antennas and CNT sheets/ribbons to produce planar and waveguide antennas, it may be possible to fabricate antennas with significantly reduced weight and enhanced flexibility, durability and power handling capabilities when compared with antenna structures fabricated out of traditional bulk conductive materials [9].

Additionally, recent research has shown that the permittivity, \( \varepsilon_r \), and conductivity, \( \sigma \), of a CNT is temporarily altered when it is subjected to certain gases, especially oxidizing/reducing gases such as NH\(_3\) (ammonia) and O\(_2\) (oxygen) [10]. This reaction has been exploited as a gas sensor by incorporating a thin layer of either randomly scattered SWNTs [11–14] or aligned multiwall nanotubes (MWNTs) [15] as part of a microwave resonator. The resonator center frequency shifts in direct response to the change in the permittivity of the CNT layer that occurs due to the presence of a reacting gas. While the mechanism by which this permittivity shift occurs has not been conclusively determined, it is generally accepted that this shift arises from charge transfer between the reacting gas molecules and the nanotubes, with the molecules acting as either electron donors or acceptors [16].

All of these unique properties may be exploited in the proposed meshed CNT thread patch antenna to provide a multifunctional communications/gas sensor system that can be fully integrated into a textile substrate.

II. DESIGN

The patch antenna has proven to be quite effective for a variety of applications, including terrestrial and satellite communications systems and various radar electronic scanning arrays due to its low-profile, planar structure, reasonable bandwidth of typically 10-20\%, and excellent gain of typically 7 dBi. Previous research has shown that substituting a meshed conductive structure for the radiating patch and/or ground plane in place of a traditionally used solid conductive structure (e.g. copper patch) yields no significant change to the antenna radiation pattern and moderate losses in gain and bandwidth depending on the density of the mesh [17]. By applying interwoven CNT thread/rope to such a design, it may be possible to construct a patch antenna capable of being easily integrated into a textile material for applications in which weight, flexibility and durability are major concerns.

A basic aperture-coupled microstrip fed patch antenna was designed to provide a layout for the meshed CNT thread patch antenna. The baseline solid metal patch antenna was designed to operate at Ka-band in order to allow for future SATCOM applications and also to keep the patch dimensions small enough for the simulation of the meshed patch antenna, composed of individual CNT threads with \( \mu \text{m} \) radius. The
specific center frequency of the basic solid metal patch design was $f_0 = 30$ GHz, but a downward frequency shift was expected in the final meshed CNT thread antenna due to the meshed thread structure and the dielectric-loading semiconducting CNT spacer threads.

A model of the meshed CNT thread patch antenna is shown in Fig. 1. The antenna consists of a 2.65 x 3.68 mm patch constructed from 50 µm diameter meshed CNT threads residing on a dielectric substrate and fed with aperture coupling by a 50 Ω microstrip feedline ($w = 239$ µm). While the ultimate goal is for this design to be fully embedded in a flexible, body-wearable textile substrate, the substrate used for this initial proof of concept is RT/Duroid 6010 ($\varepsilon_r = 10.2$, $t = 10$ mil) for the feedline layer and RT/Duroid 5870 ($\varepsilon_r = 2.33$, $t = 20$ mil) for the patch layer, with a metallic ground plane and aperture ($l = 1587$ µm, $w = 190$ µm) separating the two layers. In order to achieve multifunctionality, the CNT threads that comprise the meshed patch are alternated between fully conducting thread fabricated from multi-wall nanotubes (MWNTs) and semiconducting threads fabricated using the same technique but with a significant number of defects added, as shown in Fig. 2. The additional defects introduced to the semiconducting threads ensure that the threads exhibit lower conductivity than their conductive thread neighbors (closer to a dielectric buffer) and also provide more locations for reactive gas molecules to donate or accept electrons, thus increasing the likelihood that a reactive gas will cause a noticeable change in the thread permittivity. The threads were spaced $\sim \lambda/67$ apart.

With the conductive CNT threads serving as the meshed patch antenna structure and the semiconducting CNT threads serving as dielectric spacer material with variable permittivity based on the presence of a reacting gas, this meshed CNT thread patch may simultaneously serve as both the radiating antenna for a communications system and as the dielectric loaded resonator for a gas sensor system.

III. RESULTS

A. Patch Antenna Functionality

Based on measured data, the conductive threads were modeled in Ansoft HFSS as rectangular tubes with $\sigma = 1e6$ S/m [18] while the semiconducting threads were modeled as material with estimated $\varepsilon_r = 5$ [14]. It should be noted that this full wave simulation does not account for defects in the CNT walls that may disrupt electron flow and act as a resistive barrier. Also unaccounted for are quantum level effects such as the quantum capacitance and kinetic inductance for the individual CNTs that comprise the threads. Each of these factors will likely increase the total resistance of the CNT thread and thus decrease the overall conductivity. An initial simulation was conducted to predict the change in $f_0$ expected for the meshed CNT thread patch antenna in the presence of a reacting gas. The antenna exhibits a center frequency, $f_0 = 27.85$ GHz, and -10 dB bandwidth of 2.1 GHz. This is a center frequency shift of $\sim 2$ GHz (7 %) and bandwidth reduction of $\sim 400$ MHz (16 %) from the center frequency of 29.6 GHz and -10 dB bandwidth of 2.5 GHz predicted for the baseline solid patch antenna, as shown in Fig. 3. The simulated realized gain for the meshed CNT thread patch antenna is shown in Fig. 4. The peak total realized gain ($\theta = 0^\circ$, $\theta = 90^\circ$) was predicted to drop $\sim 0.46$ dB (7 %) from 6.79 dB to 6.33 dB by substituting the meshed CNT thread patch for the baseline solid copper patch.

Figure 1. Model of meshed carbon nanotube thread patch antenna.

Figure 2. Detailed model of meshed patch antenna fabricated from conductive and semiconducting MWNT nanotube thread.
B. Gas Sensor Functionality

In addition to operating as a radiating antenna for communications applications, the meshed CNT thread patch may also serve as a resonator for a gas sensor system. Previous research has shown through measurement that $\varepsilon_r$ for a thin layer of mainly semiconducting SWNTs increases linearly when in the presence of increasing concentrations of NH$_3$ [15]. The estimated changes in $\varepsilon_r$ from these measurements for NH$_3$ concentrations is an approximate increase from $\varepsilon_r = 5$ to $\varepsilon_r = 5.15$ for 1000 ppm and increases of 0.15 with each additional 3000 ppm. These varying permittivity values were applied to the semiconducting CNT threads in the HFSS model of the meshed CNT thread patch antenna and the resulting shifted $f_0$ was simulated, as shown in Fig. 5. A small, but measurable resonant frequency shift of -60 MHz is predicted to occur as the concentration of NH$_3$ is increased around the meshed patch antenna. This shift in $f_0$ is large enough to measure with the appropriate complementing gas sensor circuitry and small enough to guarantee continuous bandwidth for communications functionality.

IV. Conclusion

A meshed patch antenna fabricated from CNT thread has been investigated to serve as a multifunctional communications system antenna and gas sensor resonator capable of being integrated into a textile substrate. Full-wave electromagnetic simulation results indicate the viability of this design to fill both of these roles. By interweaving conducting CNT thread with semiconducting CNT thread, a meshed patch antenna/resonator is constructed with a 27.85 GHz resonant frequency and bandwidth of ~2.1 GHz. The predicted effect of an increasing presence of NH$_3$ around the meshed CNT thread resonator is an approximately linearly downward shift of -60 MHz. This behavior is expected to carry over to other reactive gases, including NO$_2$ (nitrogen dioxide), O$_2$, N$_2$ and CO$_2$ (carbon dioxide) and will be explored in future research. With the appropriate additional gas sensor circuitry, this design may be used to simultaneously radiate signals as a SATCOM antenna and track the presence of a surrounding reactive gas as a resonator gas sensor.

REFERENCES


Figure 3. Simulated reflection coefficient (S$_{11}$) for meshed carbon nanotube thread patch antenna.

Figure 4. Simulated realized gain (3-D polar plot) for meshed carbon nanotube thread patch antenna.

Figure 5. Simulated change in meshed carbon nanotube thread patch antenna resonant frequency in presence of varying concentrations of NH$_3$ (ammonia) gas.


