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Onion-like carbon and carbon nanotube film antennas

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In this paper, radiating dipole antennas have been fabricated from rolled carbon films, which are typically used for supercapacitor electrodes. Return loss and radiation pattern measurements for onion-like carbon (OLC) and multi-walled carbon nanotubes (MWCNTs) antenna samples are presented and compared to a copper standard. The OLC antenna’s radiation pattern measurements show a peak gain of −1.48 dBi, just less than 3 dB of a copper dipole antenna. Compared to antennas made from MWCNT films, the OLC samples show better radiation performance despite a lower measured conductivity. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4818464]

Carbon based materials are widely used in electronic applications given their various allotropes (e.g., graphene, carbon nanotubes, and diamond), and are capable of being conductors, semi-conductors, or insulators. Carbon nanotubes and other carbon materials have gained popularity in antenna applications in the last 10 years with the literature primarily consisting of modeling the properties of single walled CNT arrays. More recent literature, onion-like carbons (OLCs) (multi-shelled fullerenes) have been studied for applications in THz electromagnetic and microwave shielding. Electrochemical double layer capacitors (EDLCs), or supercapacitors, use the same high surface area carbon materials as electrodes, therefore making the integration of transmitters and receivers with power sources possible while using the same fabrication techniques.

In this work, we demonstrate the fabrication of dipole antennas made from conventional EDLC electrode films of OLC and multi-walled carbon nanotubes (MWCNTs). What makes these materials attractive for immediate use is that many of these carbon materials are commercially available as rolled films and, unlike metals, carbon is resistive to environmental corrosion. The material composition of these antennas allows for obfuscation in sensitive or secure applications or the antennas can be destroyed via incineration, with combustion in air occurring below 800°C. The straightforward fabrication of these devices requires less energy and waste than that of a traditional metal deposition process and allows for the use of a wide variety of substrates, including flexible films and textiles. To date, a variety of flexible EDLCs have been developed that can be paired with flexible and wearable antennas. When combined with the sheer abundance of carbon, this approach is also more environmentally friendly compared to metals.

This study presents data on OLC and MWCNT film dipole antennas tuned to 2.4 GHz, a frequency commonly used in wireless networks such as WiFi, WIMAX, Bluetooth, as well as others. While the carbon antennas do show lower performance than their copper counterparts, the amount of loss, in practice, is small. The carbon antennas are well within the specifications for low-power networks such as Bluetooth, designed to work at received power levels as low as −60 dBm with an error margin of ±6 dBm.

Carbon onions were produced by annealing UD50 nanodiamond detonation powder (supplied by Nanoblox, USA) at 1800°C for 3 h in vacuum ~10−6 Torr. The average particle size is ~5 nm in diameter with inter-particle pores from 3–20 nm. Multi-walled carbon nanotubes were grown from ethylene vapor utilizing an iron catalyst (Arkema, France). Films of carbon were fabricated using traditional processes for supercapacitor electrodes. The active material was first mixed with 5 wt. % polytetrafluoroethylene (PTFE) and ethanol. Heat and stirring was applied to the mixture until ethanol was evaporated. The mixture was then wetted with a small amount of ethanol and worked using a mortar and pestle in order to reshape the spherical PTFE particles into long fibers connecting carbon particles. At a critical point, the mixture is mechanically stable and subsequently rolled into 250 μm films. SEM and TEM images of the OLC and MWCNT films can be seen in Fig. 1. From the SEM images, the films have good continuity at large (Figs. 1a and 1d) and small length scales (Figs. 1b and 1e). TEM images (Figs. 1c and 1f) reveal the shape and structure of the respective particles, with OLC having a spherical shape and MWCNTs having an elongated needle-like structure. Both materials are highly graphitic with their interlayer spacing being ~0.34 nm. The conductivity of each film was measured using the Van der Pauw method with a 4-point probe constructed in-house. A 3.5 mm square sample of the OLC and CNT films was measured at the corners, yielding a conductivity of 1.5 S/cm and 9.0 S/cm, respectively.

A center-fed half-wave (0.5 λ) dipole geometry was selected as the test antenna structure due to its planar rectangular fabrication and well-studied properties. The antenna was designed to have a resonant frequency of 2.4 GHz, as this frequency range allows most available test equipment and possible applications across many wireless networks and fields. Electromagnetic radiation at 2.4 GHz
yields a wavelength of $\lambda = 125$ mm. Therefore, an infinitely thin and ideally conductive half-wave dipole antenna would have a total length of 62.5 mm. Practical dipoles in air, however, will be resonant at a length shorter than $\lambda/2$, due to the complex nature of the input impedance as a function of both antenna geometry and the material properties.\textsuperscript{22}

In typical high-conductivity (metal) dipole applications, the minimum, purely resistive impedance is found at a length of $0.47–0.48\lambda$, at the local minimum in the complex impedance plot (Fig. 2). Therefore, the reference copper dipole antenna has a total length of 59 mm to radiate at 2.4 GHz.

To create the OLC and CNT antennas, the films were first cut into strips, 3 mm in width and 30 mm in length. Two strips were arranged with a 2.5 mm gap between them and attached to borosilicate glass slides (1 mm thick, $\varepsilon = 4.6$) with a small amount of adhesive to form the arms of the dipole structure with an initial total length of 62.5 mm (Fig. 3). A gold-plated SubMiniature version A (SMA) connector was fixed to the glass substrate using hot-melt glue. Silver paint (silver flake in solvent, SPI Supplies) created a conductive bridge from the connector to the carbon films. Both OLC and CNT samples were symmetrically shortened to bring the resonant frequency to approximately 2.4 GHz, while observing the resonance frequency on an Agilent N5230A network analyzer. A final length of 51 mm, or $\sim 0.41\lambda$, was found to be optimal for resonance close to 2.4 GHz for both samples.

The return loss ($S_{11}$) of the carbon film antennas was considered as the initial performance metric, illustrating the amount of power accepted by the antenna rather than reflected back to the source (Fig. 4(a)). The return loss of the sample antennas was measured with an Agilent N5230A vector network analyzer. The copper film dipole exhibits a peak return loss of over 30 dB, however, both carbon antennas have a peak return loss at or below 10 dB. On a linear scale, a return loss of 10 dB equates to $\sim 90\%$ of the incident signal not having returned to the source. To maintain energy conservation, this power must either be radiated from the antenna or lost in another form, such as heat. Though a small amount of heat will be generated in any real, non-ideal system, a measurement of the antenna’s radiation pattern can confirm that power is indeed radiating out from the antenna. This measurement is made by rotating the sample antenna about an axis and measuring the power received by a calibrated stationary receiver antenna. Reflections and outside interference are minimized by performing this procedure within an anechoic chamber. Each material was repeated for three different films, with the data between samples being consistently similar. Data shown are for the measurement with the least noise. Compared to the copper dipole, the shape of the return loss plot for MWCNTs is especially broad, but is in agreement with modeled and measured return
loss patterns for MWCNT ink antennas reported by Elwi et al.\textsuperscript{5}

An antenna’s radiation pattern illustrates both the directionality and magnitude of power radiated from an antenna through the electric field. In three dimensions, an ideal dipole antenna’s radiation pattern is in the shape of a toroid. Experimental measurements were performed in an anechoic chamber by aligning the substrate and dipole arms vertically normal to the receiver antenna and stepping the device through a full rotation in the elevation plane. Measurements sampled from this rotation represent a cross-section of the 3-dimensional toroidal radiation pattern. All experimental radiation measurements (Fig. 4(b)) were made relative to the peak gain of a cylindrical reference dipole with a peak gain at 2.4 GHz of 3.5 dBi. The copper film dipole exhibits a peak gain of 3.37 dBi while the OLC and CNT measurements show peak gains of -1.48 dB and -2.76 dB, respectively. The asymmetrical distortion in the shape of the toroidal radiation pattern is due to imbalanced power delivery to the antennas, as well as from an impedance mismatch with the 50 Ω-matched instrumentation. The asymmetry in the driving signal arises from the different coupling of both the inner and outer conductors of the coaxial cable to the antenna.\textsuperscript{20} A balun can be used to cancel out the impedance differences between the two conductors, yielding a balanced driving signal. The inherent impedance of the carbon samples versus a traditionally used highly conductive metal conductor increases the magnitude of the impedance mismatch, leading to a larger distortion between the lobes of the radiation pattern. Impedance matching can be improved by the use of a matching network containing one of many different types of impedance transformers. This was not, however, a part of this study.

Interestingly, the performance of the OLC antennas regarding peak gain was better than our MWCNT antennas. We speculate that the nature of the carbon structure can play a role in the antenna performance due to effects seen at operating frequencies well out of the DC regime. In particular, the OLC antennas have ~6 times lower DC conductivity, but show a higher peak gain compared to the MWCNT film (OLC: 1.5 S/cm, MWCNT: 9.0 S/cm). Both forms of carbon show a return loss $S_{11}$ that has a wider bandwidth with more than 10 dB of return loss compared to copper. In many applications, antennas are made to perform over a wider bandwidth by adding multiple paths for current distribution, as shown by Evtioushkine.\textsuperscript{23} A great many paths, formed by adjacent carbon structures within the PTFE binder, could be responsible for this increased bandwidth. Similar return loss measurements are seen in poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) polymer antennas which also contain many linked chains of molecules.\textsuperscript{24}

In conclusion, supercapacitor electrode films were used for the fabrication of radiating dipole antennas. The OLC antenna exhibited a lower conductivity and a somewhat poorer return loss than the MWCNT antenna, however, had a higher peak gain. This behavior will be further examined to determine if the physical structure of the OLC makes it more desirable for use in antenna radio- and microwave-frequency applications, and if the effect can be leveraged for higher performance devices. Carbon film antennas represent a promising alternative to traditional metallic antennas while maintaining sufficient antenna performance to be used in modern wireless applications. Carbon film antennas, made from the same material as supercapacitor electrodes, show vast potential for integration into supercapacitor-powered systems. Their flexibility and conformal nature will also extend their application into flexible and wearable wireless systems.

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