Beyond Copper: MR Imaging with Carbon Nanotube Receiver Coils

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Introduction

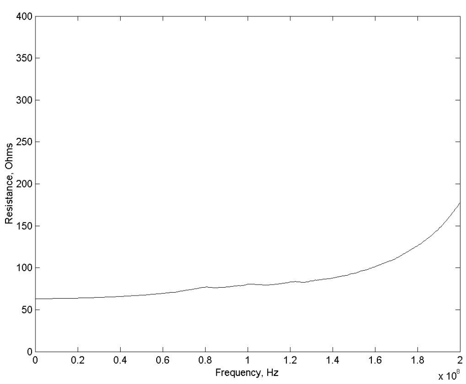
Recent advances in nanotechnology have heralded new processes for fabrication of nanomaterials having macroscopic dimensions. A solid-state process for producing macroscopic sheets made of carbon nanotubes has been reported in [1]. The technological promise of carbon nanotubes includes charge transport with minimal scattering, leading to expectations of large electrical conductivity or low electrical resistance. As is well known, at high frequencies (usually over 10 KHz for practical purposes) metallic conductors display an increasing resistance with frequency due to the skin effect that confines current density to a surface layer of the conductor. In contrast, it was shown in [2] that the skin depth of bulk carbon nanotube material is large. The reduced cross section for electron transport in metals leads to a significantly higher resistance at high frequencies as compared to the DC resistance. Additionally, when formed into a receiver coil device for signal reception purposes, its effective resistance demonstrates further increases due to interactions between current densities in adjacent turns or adjacent portions of conductors, a phenomenon often termed the proximity effect. Typically, this behavior generates constraints on coil imaging performance. Here we describe the first construction of a MR imaging coil made of carbon nanotube conductor that does not display such effects, at least within frequency ranges relevant for medical magnetic resonance imaging, leading directly to prospects of significant enhancements in SNR and image quality.

Materials and Methods

A “carpet” of carbon nanotubes of uniform height was grown in the form of a forest over a catalyzed silicon wafer with a furnace process, as described in [1]. The forest was drawn into a continuous, macroscopic carbon nanotube sheet of width 3 cm. The DC electrical resistance of an individual nanotube sheet was measured to be of the order of 700 ohms per square, as in [1], still quite high in comparison to metallic sheets with the same sheet thickness. In order to reduce the resistance, we formed a layered structure of sheets by winding the sheet on a drum. In this manner we obtained an effective ribbon structure made of a stack of 80 sheets or layers. The stack was densified by ethanol application to obtain a ribbon thickness of approximately 4 microns. The ribbon was 3 cm wide with a length of about 21.5 cm, sufficient to wrap approximately twice around a test tube of diameter 3 cm. Gold-plated copper electrodes were attached to the ends of the ribbon and mounted on a specially built circuit board for electrical characterization to 200 MHz using a Vector Network Analyzer. Next, the ribbon was laid on a 1 mm-thick foam substrate and wrapped twice around a 3 cm diameter test tube to form a coil. Tuning and impedance matching circuitry was built and attached to the coil to produce a resonant circuit tuned to yield close to 50 ohms of impedance with negligible imaginary part at 127.7 MHz, which was suitable for connection of the coil to a 3 Tesla MRI system via a coaxial cable.

Results

With this (parallel) arrangement of nanotube sheets, the single-sheet DC resistance value of 700 ohms/square is expected to translate to a ribbon resistance of 63 ohms, a value confirmed by direct measurement. In contrast to metals, resistance of the layered stack or ribbon composed of nanotube sheets demonstrated only a small dependence on frequency over the 5 – 130 MHz range relevant to commercially available magnetic resonance imaging systems, as shown in Figure 1. The increasing trend in the resistance can be attributed to capacitive effects. The coil was used to initially image a saline solution to confirm a good SNR response. Subsequently a mouse was inserted into the test tube and imaged with the coil.



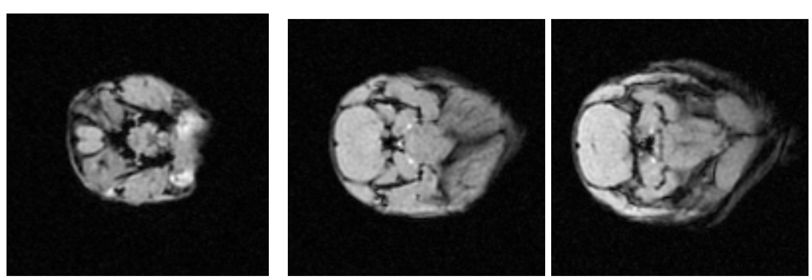


Figure 1: Nanotube ribbon resistance vs. frequency ***Figure 2: Three images at 3T from a mouse head showing the brain at 0.25 mm resolution***

The high resolution (0.25 mm in-plane) images in Figure 2 were obtained at 3T with a standard imaging sequence (SPGR, TE = 6.5 ms, TE = 68 ms, FOV = 6 cm x 6 cm, slice thickness 0.9 mm).

Conclusions

Despite the relatively large resistance of this early prototype coil, excellent image quality was obtained, demonstrating the potential of the nanomaterial for imaging applications. The mouse brain in Figure 2 is only about 3 mm across and sub-millimeter blood vessels can be clearly seen in cross section. Scaling studies suggest that the resistance of the material drops as expected with increasing material cross section for charge transport. Efforts are under way to fabricate material with increased cross section and to enhance electrical conductivity. Coils suitable for human anatomical imaging are under development.

References

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