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High-Performance, Lightweight Coaxial Cable from Carbon Nanotube Conductors

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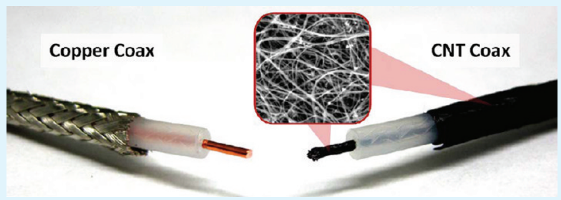
ABSTRACT: Coaxial cables have been constructed with carbon nanotube (CNT) materials serving as both the inner and outer conductors. Treatment of the CNT outer and inner conductors with $KAuBr_4$ was found to significantly reduce the attenuation of these cables, which demonstrates that chemical agents can be used to improve power transmission through CNT networks at high frequencies (150 kHz-3 GHz). For cables constructed with a $KAuBr_4$-treated CNT outer conductor, power attenuation per length approaches parity with cables constructed from metallic conductors at significantly lower weight per length (i.e., 7.1 g/m for CNT designs compared to 38.8 g/m for an RG-58 design). A relationship between the thickness of the CNT outer conductor and the cable attenuation was observed and used to estimate the effective skin depth at high frequency. These results establish reliable, reproducible methods for the construction of coaxial cables from CNT materials that can facilitate further investigation of their performance in high-frequency transmission structures, and highlight a specific opportunity for significant reduction in coaxial cable mass.



KEYWORDS: *carbon nanotubes, lightweight coaxial cable, attenuation, high frequency, chemical treatment, performance enhancement*

1. INTRODUCTION

Bulk carbon nanotube (CNT) structures (e.g., papers, ribbons, and wires) have the potential to replace conventional metallic conductors in a variety of cabling applications, due to their high conductivity, low weight, and resistance to damage by environmental factors.[1] Chemical doping and densification has increased the electrical conductivity of these materials to near parity with metallic conductors, and in some cases exceeding it on a mass-normalized basis (e.g., gold).[2,3] In addition, several other properties of CNT materials, such as their resistance to corrosion and flexure tolerance, make them desirable in a variety of cabling applications.[1,4,5] It has recently been shown that CNT wires can withstand >200 000 flexures and >90 days in hydrochloric acid without an increase in resistance.[1] However, a primary motivation for the adoption of CNT materials into cabling designs is the ability to reduce mass, as CNT structures typically have densities on the order of 1000 kg/m^3,[6] which is significantly lower than most metals (e.g., copper is 8910 kg/m^3). These metrics motivate efforts toward the implementation of CNT materials in power and/or data transmission applications, such as coaxial cabling.

Characterization of the frequency dependent response of CNT materials is essential for integration into transmission structures such as coaxial cable. Investigation of bulk CNT materials at high frequencies has been approached with a number of methods, including the construction of planar waveguide structures, incorporation of CNTs into resonator cavities, the Corbino disk method, and theoretical modeling.[7−13] These efforts have provided valuable new information about these materials, some of which suggests that individual CNTs, CNT bundles, and bulk CNT networks (which are particularly significant to cabling applications) can display less resistance compared to metallic conductors at sufficiently high frequencies.[14] However, results are difficult to interpret due to variability in fabrication methods and modeling of the power dissipation mechanisms. For example, radiative losses in planar waveguides[15] are larger and more difficult to model than coaxial transmission lines. Additionally, control over the characteristic impedance (Z_0) of a transmission line is very important, primarily because it affects power transfer between components (e.g., cables) in series. Differences in Z_0 between components lead to reflective losses, which are independent of the intrinsic response of the materials used in the components, but nevertheless complicate analysis.[16] Control over the characteristic impedance can be difficult in the construction of certain types of transmission lines (e.g., planar waveguides), particularly when implementing novel materials, but is fairly straightforward in coaxial construction. Coaxial cable con-

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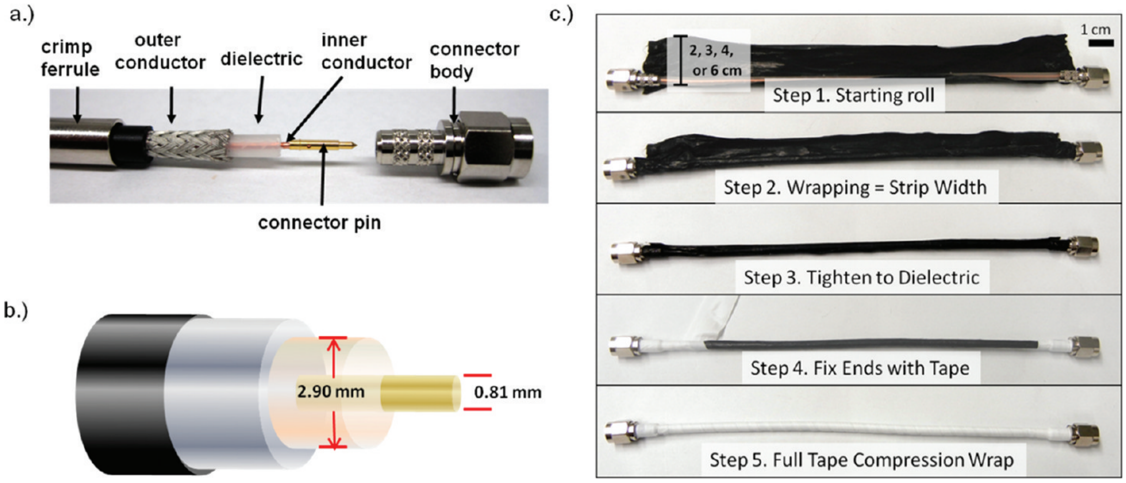

Figure 1. (a) Photograph of a partially disassembled RG-58 cable, illustrating the key components; (b) an illustration of the cross-section of an RG-58 cable, with dielectric and inner conductor diameters designed to give a characteristic impedance of 50 Ω; (c) a series of photographs illustrating the fabrication of cables with a CNT fabric outer conductor.

struction is also throroughly standardized, which facilitates the comparison of materials and improves reproducibility. For these reasons, the construction of coaxial cables with CNT materials has been pursued for characterization of their frequency-dependent response while simultaneously investigating the potential benefits of their integration into form factors that are readily amenable to commercial adoption.

The present work expands upon previous accounts of CNT coaxial cables,[17−19] focusing on the effect of fabrication methods and material modifications on cable performance. It is shown that CNT materials can replace metal as both the inner and outer conductor in a coaxial cable while maintaining performance comparable to those constructed from metal. New methods for the construction of CNT coaxial cables were developed to match with the unique properties of this material. For example, replacing the outer conductor was facilitated by the high flexibility and plasticity of the material (as compared with metallic foils and braids). Compressive tape wrapping of cables constructed with a CNT outer conductor improved performance. Less compression was required to ensure conformality on the dielectric with a CNT fabric than a copper braid. In addition, a recently developed method to densify CNT sheets into drawn CNT wires[2] was found to be effective to prepare wires which were sufficiently uniform and conductive to replace the copper center conductor. Also, chemical treatment of CNT outer and inner conductors with $KAuBr_4$ was observed to improve the performance of cables constructed from them. Thus, this represents the initial demonstration that select chemical treatment can improve power transmission through a CNT network at high frequency. An analysis of the weight of these novel CNT coaxial cables is also provided, and clearly highlights the potential for reduction in cable mass.

2. EXPERIMENTAL SECTION

CNT materials used in this study were provided by Nanocomp Technologies, Inc., which are produced by chemical vapor deposition, using a floating catalyst.[4,17] A standard coaxial cable specification (RG-58) was selected for construction, which allowed for systematic comparisons upon replacement of individual cable components (i.e., the inner and outer conductor) with CNT materials. The cable used was manufactured by Carol Brand and connectors were manufactured by Amphenol. Attenuation of all cables was measured using a vector network analyzer (Agilent E5061B) at room temperature in a two port through configuration after short, open, load, and through calibration on both ports.

Figure 1a shows a section of RG-58 cable which has been partially disassembled. The characteristic impedance of this cable is 50 Ω (ubiquitous in transmission systems[20]), as can be determined from eq 1,[16] given that the outer diameter of the center conductor (d) is 0.81 mm, the dielectric (D) is 2.9 mm (Figure 1b) and the dielectric is polyethylene (PE), with a dielectric constant (ε_r) of 2.25.[21] It is important to note that the characteristic impedance is fairly sensitive to variations in these dimensions, particularly with respect to the inner conductor.

$$Z_0 = \frac{138\ \Omega}{\sqrt{\varepsilon_r}}\log\left(\frac{D}{d}\right) \tag{1}$$

Signal attenuation (i.e., insertion loss) is a critical performance metric for cables, and it is commonly reported for a defined frequency range, normalized to cable length (α/L).[16] Attenuation is reported as the logarithm of power received divided by power supplied to a cable in units of decibels (dB), which is then typically normalized to cable length (eq 2).[16]

$$\frac{\alpha_{\text{cable}}}{L} = \frac{-20\log(\text{power}_{\text{out}}/\text{power}_{\text{in}})}{\text{cable length}} \tag{2}$$

Conductivity measurements were performed using a Keithley 2635 instrument in four wire mode. Leads were equipped with flat copper clips to make contact to the CNT fabrics or wires. CNT fabric thicknesses were measured using a digital micrometer (Cen-Tech) with wide flats and a clutched engagement to minimize compression of the material. Wire diameters were measured with optical microscopy (Nikon Eclipse LV150). Raman analysis of materials was performed with a Jobin Yvon Horriba LabRAM HR Raman microscope, using a 632 nm (1.96 eV) HeNe laser. Calibration of the Raman was performed using a silicon reference at 520.9 cm^{-1}. SEM images were collected using a Hitachi S-900 electron microscope with an operating voltage of 2 kV.

3. RESULTS AND DISCUSSION

Replacement of the Outer Conductor with CNT Fabric. Initial efforts were focused on the incorporation of CNT fabric as an outer conductor to replace a copper braid, which is common in flexible coaxial cables. CNT fabric material was obtained from Nanocomp Technologies, Inc. (Lot: 1986F) and used as received. Electrical conductivity was measured by the four point probe method on strips cut from this material,

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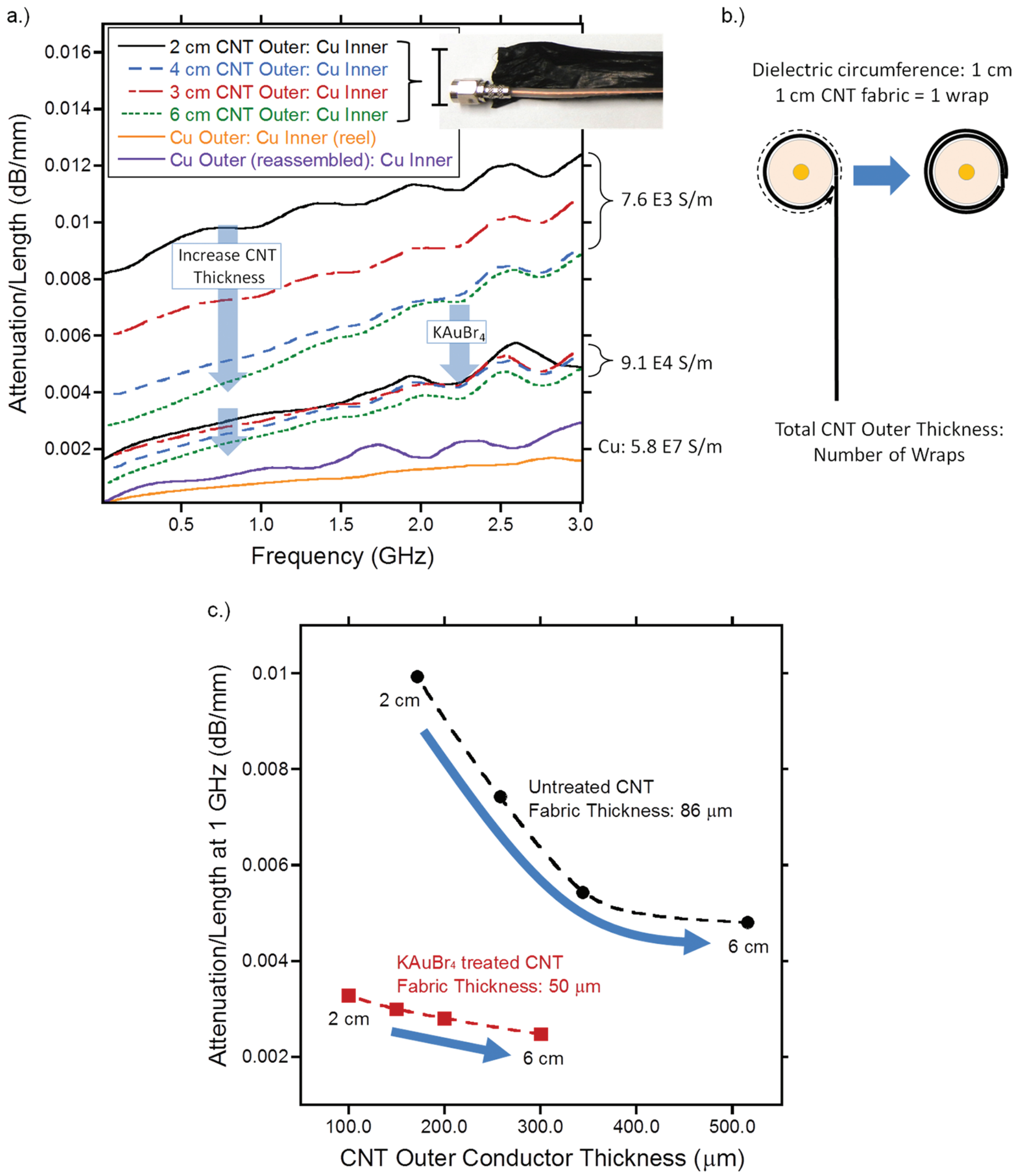

Figure 2. (a) Attenuation/length (dB/mm) vs frequency for cables with CNT fabric outer conductors of increasing thickness, both before and after treatment with $KAuBr_4$. Data are smoothed (10 point average) for clarity. Error < 5%. (b) Schematic illustrating the process of wrapping CNT fabric onto the dielectric. Every 1 cm of fabric creates a complete layer (wrap) of material and increases the total thickness of the outer conductor. (c) Attenuation/length at 1 GHz as a function of total CNT outer conductor thickness before and after treatment with $KAuBr_4$.

prior to their utilization in construction of coaxial cables. The average thickness of the sheet material was measured at 86 ± 9 μm. The average electrical conductivity was measured to be 7.6 ± 0.4 E3 S/m for the as-received material, with variability attributed to thickness. Strips of the as-received CNT material were cut with a length of 18 cm and widths of 2, 3, 4, and 6 cm, where the width in cm corresponds to the number of complete wraps around the dielectric (i.e., every 1 cm = 1 wrap). The product of the number of wraps and sheet thickness of 86 μm yields the total outer conductor thickness, which ranges from ~192–516 μm for this study. A section of dielectric containing a copper center conductor was obtained from a commercial coaxial cable by removing the insulation and outer conductor. The two ends of the copper center conductor were stripped of dielectric and terminated with standard SubMiniature A (SMA) pins and connector bodies. As shown in Figure 1c, the CNT fabric was then wrapped around the dielectric and connector bodies, tightened to the dielectric by rolling, and held in place with a tight spiral wrapping of Teflon tape. Teflon tape was advantageous for its low adhesion to the CNT shielding, which enabled disassembly and reassembly of the cables without damage. Conformality with the dielectric was excellent, due to the flexibility, plasticity, and slight self-adhesion of the CNT material. In comparison, a tinned-copper braid, which is a conventional outer conductor, typically requires a thick, compressive plastic insulation layer to maintain conformality with the dielectric as shown in Figure 1a.

The attenuation of the CNT outer conductor RG-58 cables (with Cu center) were measured as a function of frequency from 150 kHz-3 GHz, and normalized to the conductor length of 18 cm, which was constant for all cables fabricated. Therefore differences in attenuation between cables can be

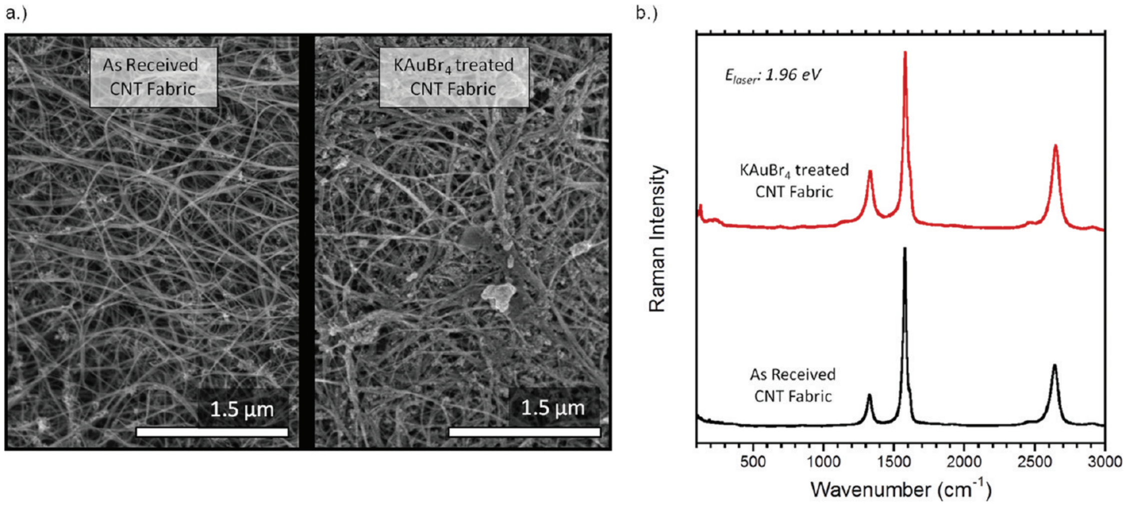

Figure 3. (a) SEM images of CNT fabric material as-received (left) and after treatment with $KAuBr_4$ solution (right). Scale bar: 1.5 μm. (b) Raman spectra of CNT fabric material before and after treatment with $KAuBr_4$ solution at excitation laser energy of 1.96 eV.

attributed to changes in the outer conductor, as dielectric losses are expected to be constant for all cables measured, and radiative losses are expected to be very low in comparison with resistive losses in the conductors.[16] Cables that were assembled with a greater number of wraps (resulting in greater thickness) of CNT fabric were observed to have lower attenuation/length (Figure 2a), with improvement diminishing sharply above 4 full wraps, which corresponds to a layer thickness of ~350 μm of material (Figure 2b). This trend is more clearly observed in Figure 2c, which highlights the change in attenuation/length at 1 GHz as a function of CNT fabric wrap thickness. This response in α/L with increasing outer conductor thickness suggests that there is skin effect behavior in the CNT fabric. In coaxial cables, attenuation caused by the resistance of the conductor is proportional to the amount of current flowing through it. It is established that more than 98% of the alternating current flows through a thickness of 4 skin depths (δ) of the conductor at a given frequency, and increasing material thickness beyond 4δ will have little impact on the cable attenuation.[22] Therefore, from the data at 1 GHz shown in Figure 2c, the effective skin depth of the as-received CNT fabric is ~100 μm, which is consistent with a previous calculation based on measurements of CNT networks.[11]

Cables with CNT fabric outer conductors which were disassembled and reassembled displayed good reproducibility (<5% change in attenuation/length). This suggests that the observed changes in performance with increasing conductor thickness are due to intrinsic changes in the cable and are not likely due to variability in fabrication or testing. Figure 2a also shows the attenuation/length of a commercially assembled RG-58 coaxial cable with conventional copper conductors as well as the same cable after removal and reassembly of the outer conductor with Teflon tape compression. The attenuation/length of the reassembled cable was ~2x greater over the frequency range, which underscores the importance of construction method on cable performance, and highlights the difficulty of ensuring conformality to the dielectric with a metallic outer conductor.

After characterization of the cables with as-received CNT fabric outer conductors, the cables were disassembled, and the CNT fabric strips were treated for 20 min in a 0.025 M aqueous solution of $KAuBr_4$, which has been previously shown to increase the conductivity of CNT materials.[2,23,24] The conductivity of the strips after drying was measured to be 9.1 E4 S/m, which is lower than the best reported values for CNT networks after treatment with gold salts[2,25] and other chemical species (e.g., iodine[3] and copper[26]), but is consistent with a number of reported conductivity values for CNT fabrics.[2,23,27−35] The average thickness of the strips was reduced after drying to 50 ± 10 μm. Analysis with SEM clearly shows the presence of CNTs in the as-received sample, and suggests the introduction of metallic nanoparticles during $KAuBr_4$ treatment, which are suspected to be gold, consistent with previous reports (Figure 3a).[25,36,37] Additionally, the CNTs do not show evidence of significant damage from this treatment, as is further supported by Raman spectroscopy, by virtue of the small change in the intensity of the D-band centered near 1325 cm^{-1}, relative to the G band at 1580 cm^{-1} (Figure 3b). The ratio of the D to G peak intensity (I_D/I_G) for the untreated material was found to be 0.17, whereas I_D/I_G for the $KAuBr_4$ treated material was 0.38. The Raman spectra also lack prominent peak intensity in the region of 100−300 cm^{-1}, as would be expected for SWCNTs,[38] which suggests that the material predominately comprises double and/or multiwalled CNTs.

The $KAuBr_4$-treated fabric strips were reused as outer conductors to assemble coaxial cables. Figure 2a contains the attenuation/length results for the higher conductivity CNT fabrics, and illustrates a significant reduction in attenuation/length compared to the lower conductivity samples. A trend of decreasing attenuation with increasing wrap thickness remains with the higher conductivity CNT fabrics, although this dependence is clearly diminished in comparison to the as-received material. Thus, it has been demonstrated that replacement of metallic outer conductors with CNT fabrics is a reproducible method of coaxial cable fabrication which can provide information about the intrinsic electrical properties of bulk CNT materials at high frequencies.

Replacement of Inner Conductor with CNT Wire. Replacement of the inner conductor with a drawn CNT wire has also been demonstrated. CNT wires were prepared by mechanical densification of rolled strips of the CNT fabric with a drawing die in the presence of a lubricating solvent (water, or 0.025 M aqueous $KAuBr_4$), following a previously described

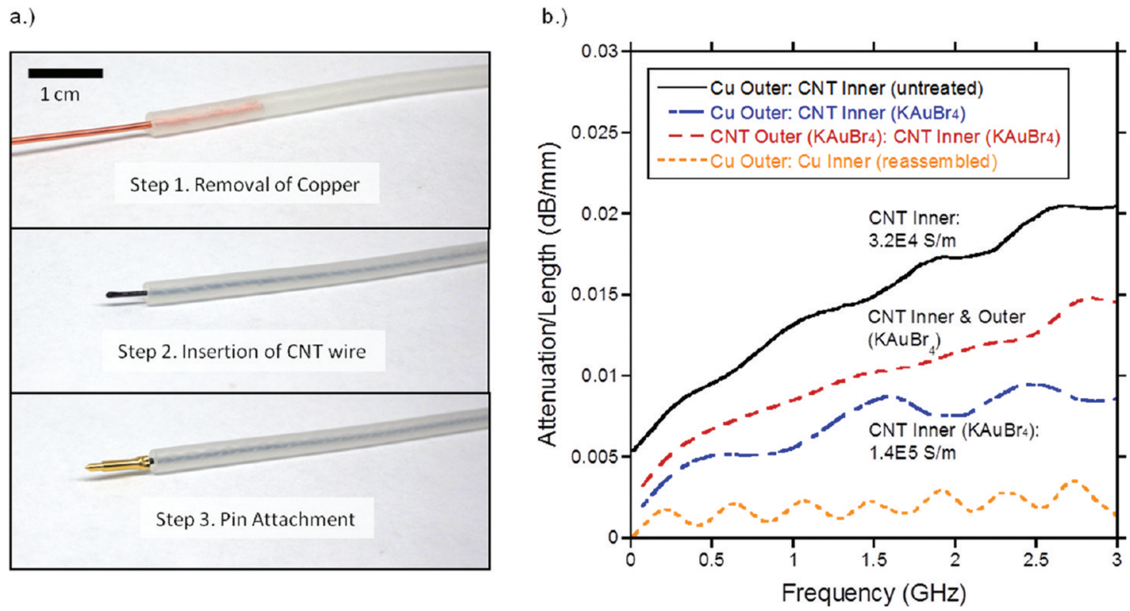

Figure 4. (a) Series of photographs illustrating the construction of coaxial cable with a CNT wire center conductor; (b) plot of attenuation/length vs frequency for three cables constructed with CNT wire center conductors of 0.80 mm diameter, two of which had been doped with $KAuBr_4$ prior to cable construction. One of the cables was also constructed with a $KAuBr_4$ treated CNT fabric outer conductor, whereas the other two were constructed with braided copper outer conductors.

procedure.[2] The center conductor of the commercial RG-58 cable was removed, and a CNT wire (water lubricant) of slightly smaller diameter (0.80 ± 0.05 mm) was then threaded through the empty dielectric. Connector pins were crimped to the CNT wire and cables were assembled with connector bodies and an outer conductor (either tinned-copper braid or treated CNT fabric). Figure 4 illustrates these construction steps and shows the performance of several cables with CNT wire inner conductors. A second CNT wire was prepared from a strip which was treated with 0.025 M $KAuBr_4$ prior to densification and drawn with 0.025 M aqueous $KAuBr_4$ as a lubricating solvent. The final diameter of this wire was also 0.80 ± 0.05 mm. The cable constructed with this wire serving as the center conductor exhibited significantly less attenuation than the cable with the untreated CNT wire center, similar to results with the CNT fabric outer conductor. However, the attenuation of the cables with CNT wire inner conductors is greater than that observed in cables with the outer conductor replaced with CNT fabric. This may be partly due to the process of removing the center conductor, which may alter the dielectric and the smaller diameter of the CNT wires. Figure 4b shows the attenuation/length of a cable after removal of the 20 gauge copper wire center conductor and replacement with a copper wire of slightly smaller diameter (22 gauge). The performance is diminished in comparison to the original cable (Figure 2a), though only slightly. The remaining difference in performance with the CNT center conductors may be due to variations in the diameter of the drawn CNT wires, which were observed by optical microscopy to be (±50 μm), which is greater than that achieved by conventional copper wire drawing (<5 μm). Therefore, future improvements in CNT wire properties (e.g., concentric diameter, length uniformity, and surface conformality) as well as the bulk electrical conductivity should further reduce the attenuation/length of CNT-based coaxial cable. A cable fabricated with both a CNT outer and inner conductor (both treated with $KAuBr_4$) exhibited attenuation/length that was comparable to the sum of the additional attenuation caused by replacement of the conductors independently.

Comparison with Conventional Materials. The measured levels of attenuation/length are approaching compliance for RG-58 and other lightweight cable types such as RG-174. According to specification MIL-C-17, the maximum acceptable level of attenuation/length is 28 dB/100 ft for RG-58 and 45 dB/100 ft for RG-174 at 1 GHz. The cables constructed with 6 cm width of $KAuBr_4$-treated CNT fabric outer conductors were measured to have an attenuation/length value of 0.0025 dB/mm, which is equivalent to 75 dB/100 ft. The remaining gap in performance should be surmountable with additional improvement in electrical conductivity for CNT materials (e.g., via network alignment and densification) as well as improvement in cable construction methods with CNT materials (e.g., improved methods of termination and introduction into the dielectric).

A substantial weight reduction can be achieved if CNT materials are used to fabricate coaxial cables with attenuation/length comparable to metallic construction. For example, the CNT strips that were used to replace the copper braid outer conductor weigh approximately 0.4 g/m at a 6 cm strip width, whereas the copper braid of the RG-58 cable studied weighs more than 12.3 g/m (Table 1). In addition, the outermost insulation which was applied over the copper braid in commercial fabrication weighs more than 16.3 g/m. Thick insulation is required in the case of the copper braid, in order to ensure conformality of the conductor and to protect it from corrosion. It is likely that significantly less insulation material will be required for a CNT fabric owing to the high flexibility and intrinsic corrosion resistance of this material.[1] As shown in Table 1, replacement of the conventional outer conductor and insulation with the CNT outer conductor and Telon tape insulation can reduce the cable mass/length by more than 70% over standard RG-58 designs (11.5 vs 38.8 g/m, respectively). In addition, the CNT outer conductor cable is ~10% lower than a RG-174 cable design (12.5 g/m), which is among the

Table 1. Weight/length Analysis of Coaxial Cable Components Illustrating the Potential Weight Savings from Employing CNT Materials[a]

material (RG-58)	weight/length (g/m)	% commercial (RG-58)[b]
copper wire (20 gauge)[b]	4.6	
copper braid[b]	12.3	
dielectric[b]	5.4	
insulation (commercial)[b]	16.5	
CNT wire[c]	0.2	
CNT wrap[c]	0.4	
insulation (Teflon tape)[c]	1.3	
total (Cu outer, Cu center)	38.8	100.0
total (CNT outer, Cu inner, Teflon insulation)	11.5	29.6
total (CNT outer, CNT inner, Teflon insulation)	7.3	18.8

[a]Error: 0.1 g/m. [b]Measurements made of components from commercial cable. [c]Measurements made of experimental materials.

lowest weight/length coaxial cable types commonly used.[20] Furthermore, if a coaxial cable with both a CNT outer and inner conductor is utilized, it would be transformative in that more than 80% savings by mass could be achieved compared to RG-58 and 40% savings compared to RG-174. The impact of this weight reduction would dramatically affect mobile systems and other weight sensitive applications, such as space-craft, which are costly to launch.

4. CONCLUSION

In summary, it has been demonstrated that CNT materials can be used to fabricate coaxial cables by replacement of the metallic outer and/or inner conductors. Increasing thickness of the outer conductor was observed to improve cable performance by lowering attenuation per length, with little change observed beyond a critical thickness, which is attributed to the skin depth. For the first time, it has been observed that chemical treatment of CNT fabrics with $KAuBr_4$ results in a reduction in the attenuation/length of coaxial cables constructed with these materials, which is attributed to the observed improvement in conductivity. These initial results for CNT coaxial cables are approaching a level of performance which will render them competitive with cables constructed from metallic conductors. Additional benefits like enhanced flexure tolerance and corrosion resistance combined with the reduction in weight/length motivate further development of this technology for cabling applications.

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Notes

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