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Article

From Waste Plastics to Carbon Nanotube Audio Cables

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Abstract: Carbon nanotubes (CNTs) have long been at the forefront of materials research, with applications ranging from composites for increased tensile strength in construction and sports equipment to transistor switches and solar cell electrodes in energy applications. There remains untapped potential still when it comes to energy and data transmission, with our group having previously demonstrated a working ethernet cable composed of CNT fibers. Material composition, electrical resistance, and electrical capacitance all play a strong role in the making of high-quality microphone and headphone cables, and the work herein describes the formation of a proof-of-concept CNT audio cable. Testing was done compared to commercial cables, with frequency response measurements performed for further objective testing. The results show performance is on par with commercial cables, and the CNTs being grown from waste plastics as a carbon source further adds to the value proposition, while also being environmentally friendly.

Keywords: carbon; carbon nanotube; copper; electrical conductor; data transmission; audio cable; frequency response

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1. Introduction

Carbon nanotube (CNT) research has been actively ongoing for the better part of three decades and has been found to exist for even longer than that. There is a lot of potential due to the untapped properties of CNTs, and this has led to their use in various fields ranging from sports equipment and composites in construction and manufacturing to electrical and/or thermal conductors in energy applications, transportation, and even as art pieces and extremely dark paint owing to their high specific surface area and light absorption, accordingly [1–5]. When it comes to electricity transmission, CNTs are often paired with other metals or doped to increase the electrical conductivity, with the current state-of-the art in CNT research yet to wholly replace the likes of copper and aluminum for the electric grid [5].

CNT-based cables show plenty of promise with individual CNT electrical conductivity besting copper, while also having the benefit of lower mass density, owing to the hollow cylindrical nature of the nanotubes [6]. Despite there being several different attempts at making long cables out of individual CNTs [7–13], the primary issue remains that the starting material with the CNTs is generally a mixed bag when it comes to both the general purity being questionable—owing to the presence of contaminants, such as residual catalyst and amorphous carbon—as well as containing a mix of single- and multi-walled CNTs of different chiralities [14,15] to where there is a sliding scale of metallic to semiconducting CNTs in use.

We have previously [16] demonstrated the use of a hybrid CNT/copper cable for data transmission as an ethernet cable, which routinely achieved 100 Mbps throughput on both the uplink and downlink to be classified as meeting CAT5 transmission speeds.

This was made more attractive by the fact the CNTs themselves were produced from the upcycling of waste plastics, including polystyrene [17]. This work describes a similar cable structure but is instead used for audio transmission. The hybrid CNT/Cu audio cable was manufactured with 3.5 mm TRS connector plugs on either end to use with speakers primarily for public outreach, however, they proved to work well in terms of longevity and prolonged sound quality to where we then quantified their characteristics as both headphone and microphone cables.

Measuring the headphone and microphone cable properties was achieved by pairing a set of highly resolving headphones with a set of custom-made artificial ears fitted with IEC711 [18] occluded ear simulators and measuring the frequency response of the headphones with the CNT/Cu cable. First, a control measurement was taken with a commercially available copper-based microphone and headphone cables. This was followed by replacing the commercial headphone cable with our CNT/Cu concept cable while still using the same commercial microphone cable as before to test the CNT/Cu cable as a headphone cable. Next, in order to test the CNT/Cu cable as a microphone cable, it was used to replace the commercial microphone cable with the headphones running off the commercial headphone cable. The electrical resistance of the individual cables and the raw materials were also measured, as was the copper as a control, and the results show the CNT/Cu cables are a viable alternative to commercial copper cables for audio transmission.

2. Experimental Section

2.1. Carbon Nanotube Production

The carbon nanotubes used in this work were produced using floating catalyst chemical vapor deposition (FC-CVD) in a two-zone horizontal furnace liquid injection reactor (LIR), with details described previously [16,17]. In summary, CNTs were grown using various concentrations of polystyrene and toluene. In a typical reaction, polystyrene (C_8H_8)n, with a molecular weight of 6400 (Mn 64,000, Sample#P2444-S, Polymer Source Inc., Dorval, QC, Canada) was added to toluene in concentrations of either 1, 2, and 4 wt% (*w*/*w*) in 1 mL (865 mg) anhydrous toluene (98% ($C_6H_5CH_3$) Sigma Aldrich Dorset, UK)) [16]. This was then mixed and injected into the reactor at 5 mL/h under a gas flow of 1 L/min using a blended carrier gas of composition 5 vol% hydrogen in argon (BOC, Guilford, UK) into a two-zone horizontal furnace (Nanotech Innovations, Oberlin, OH, USA). The first zone, used for catalyst formation and cracking of the carbon source, was set to approximately 225 °C and zone two, employed for CNT growth, was set to approximately 780 °C. The CNTs were grown in a 100 cm long quartz tube with an outer diameter of 38 mm and an inner diameter of 36 mm (Multi-Lab, Newcastle upon Tyne, UK). All reactions were carried out using a needle gauge of 20. All reactions were carried out with a fixed catalyst ratio of ferrocene (5 wt% *w*/*w*) (98% ($C_{10}H_{10}Fe$) Sigma Aldrich (UK)) with respect to the total carbon reactant from both toluene and/or toluene and polystyrene. All materials were used as received without prior cracking or drying and handled as described here [19]. No measured effect from carbothermal reduction due to the aging of the quartz tube was identified [16].

2.2. CNT Characterization

The CNTs produced in analogous experiments described before were confirmed to be multi-walled in nature using high-resolution transmission electron microscopy [16]. For this work, scanning electron microscopy (SEM) was used to better understand the CNT morphology in addition to confirming they are also multi-walled carbon nanotubes (MWCNTs). Some of the CNTs produced were suspended in ethanol and drop cast onto a piece of clean silicon wafer to enable easier imaging. The concentration of the CNTs was accounted to allow for imaging of the CNT ensemble while retaining enough information about the individual CNTs. The SEM (JEOL 7800F FEG, JEOL, Akishima, Tokyo, Japan) was used at an operating voltage of 5 kV or lower and with a working distance of approximately 10 mm. Diameters were measured using ImageJ [20].

Resonant Raman microscopy was performed using a Renishaw inVia™ Raman microscope (Renishaw plc, Miskin, Pontyclun, UK) equipped with 633 nm and 785 nm lasers and a Leica PL Fluortar L50x/0.55 long working distance objective lens. Data acquisition was taken for the CNTs placed as-is on a clean silicon wafer from 100 to 3200 cm^{-1} Raman shift. The laser beam was focused by maximizing the G-peak intensity to confirm the best z-height alignment of the beam between the sample and detector. For each CNT sample, a Raman spectrum was acquired in three separate locations.

2.3. CNT/Cu Audio Cable

Carbon nanotube/copper hybrid cables were prepared using CNT powders firmly packed into the sheath of heat shrink tubing. Copper wire was inserted into the CNT wire ends and compressed to ensure maximum contact of the CNTs with the Cu lead before heat shrinking the outer sheath. Three such individual cables were collectively put together and soldered to commercially available three-pole 3.5 mm stereo jack plugs (RS Components, Corby, UK) on either end, as seen in Figure 1. Two acrylic panels were used for the increased structural integrity of the audio cable, particularly for outreach events, which otherwise do not influence the functionality of the cable itself.

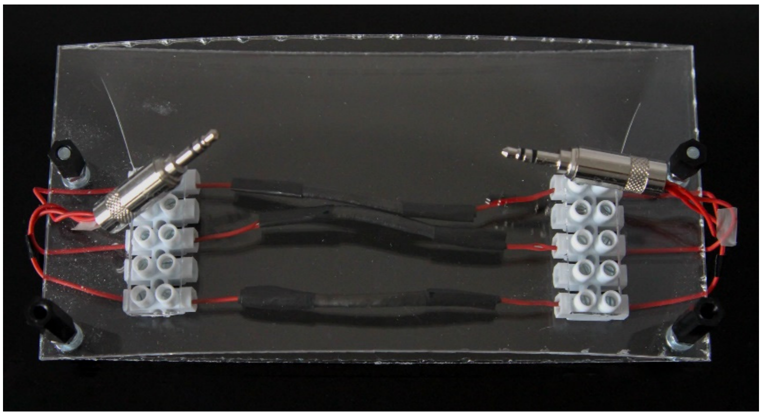

Figure 1. Example CNT/Cu audio cable manufactured using CNTs grown from polystyrene as the carbon source in the middle (black wiring) and copper wiring (red wiring) on either side to complete the circuit from one 3.5 mm stereo jack plug to another.

2.4. CNT/Cu Audio Cable Performance Testing

While originally envisioned to be simply used for public outreach to connect a mobile device to a portable speaker unit [21], it was quickly realized that the use of standard 3.5 mm stereo connectors allowed for more rigorous testing of the same. Towards this end, a set of headphones that used 3.5 mm cable connectors was identified in the form of the HiFiMAN Arya (HiFiMAN Electronics, Tianjin, China). The single CNT/Cu cable allowed connection to one channel at each time, which suffices for the scope of this article. Two such cables can be used with a Y-splitter adapter to use the headphones in stereo. A custom set of artificial ears was manufactured to our specifications with two soft silicone earmolds and two IEC711 occluded ear simulators [18] inside for frequency response measurements from 20 Hz to 20 kHz, to cover the entire range of human hearing. The housing allows for both XLR and 3.5 mm microphone cable connections, as seen in Figure 2.

The headphones were measured using a commercial copper XLR cable as the microphone cable, and the stock headphone cable—also copper-based—as a control experiment before switching with the CNT/Cu cable as either the headphone or microphone cable. Frequency response measurements were performed using a calibrated soundcard for microphone input connected to a laptop, and the headphones were powered from a dedicated digital-to-analog converter and amplifier combination unit (JDS Labs, St. Louis, MI, USA) to eliminate any influence of the laptop's internal audio circuitry. Room EQ Wizard v5.20 was used to generate a sine sweep from 20 Hz to 20 kHz and to measure the frequency response of the headphones. A minimum of three trials were completed per experimental configuration for statistical accuracy.

Figure 2. Custom set of artificial ears manufactured with soft silicone earmolds on either side and two IEC711 occluded ear simulators to measure the frequency response of headphones. There are both XLR and 3.5 mm microphone outputs to aid in the same.

3. Results and Discussion

3.1. CNT Characterization

Given the MWCNTs used in this work were previously described in more detail in both production and characterization [16,17], herein we mostly corroborated that the carbon nanotubes used in the CNT/Cu audio cable were the same as before. SEM imaging showed these are indeed multi-walled carbon nanotubes with some residual catalyst and amorphous carbon present [14,16], with typical morphology seen in Figure 3. This particular sample was of the MWCNTs produced from polystyrene/toluene as the carbon source.

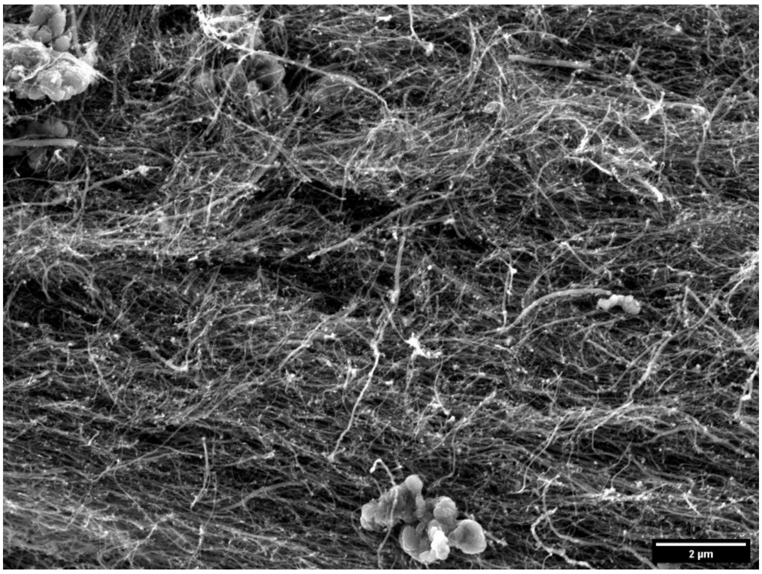

Figure 3. Scanning electron microscopy of MWCNTs produced using polystyrene dissolved in toluene as the carbon source and ferrocene as a source of iron catalyst. Residual catalyst and amorphous carbon impurities are present here, although the vast majority of the product remains CNTs.

The CNTs were not purified and were used as-is with the by-product impurities intact, with the average electrical resistance of the ensemble measured to be between 1.8 and 2.2 Ω for a continuous section of bucky paper prepared from these CNTs, compared to 0.6 and 0.8 Ω for the copper control under the same testing conditions. This proof-of-concept CNT/Cu cable had a measured electrical resistance of 14.4 Ω across the 10 cm length from end to end. There is thus significant contact resistance with the two probes used with the digital multimeter, and further testing is planned with purified samples using more sensitive and accurate 4-point probe measurements in a forthcoming article. More so, the current goal is simply to demonstrate a proof-of-concept CNT/Cu cable for audio transmission.

Resonant Raman spectroscopy confirmed the presence of MWCNTs again, with no radial breathing modes detected at either 633 or 785 nm, as seen in Figure 4, where most CNTs would resonate at. The peak at ~1350 cm^{-1} confirms a disorder D-peak, which is attributed primarily to amorphous carbon [22,23], whereas the taller G-peak at ~1600 cm^{-1} is attributed to graphitic carbon, which in this case would be the CNTs themselves. The G′ (G prime) peak at ~2700 cm^{-1} further indicates the presence of multiple walls, which is to be expected for samples of multi-walled carbon nanotubes. The spectra shown below are averaged over multiple acquisitions and are representative of the CNT ensemble. We also see the relatively higher intensity of the G-peak to the D-peak at 785 nm, which indicates a generally higher quality CNT sample. This is because MWCNTs are more likely to resonant at 785 nm than 633 nm, especially for the larger diameter tubes produced here.

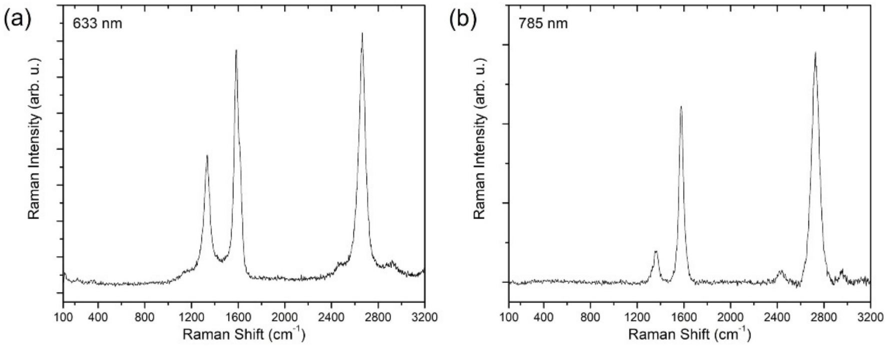

Figure 4. Resonant Raman spectroscopy of MWCNTs was recorded using (**a**) 633 nm and (**b**) 785 nm lasers.

3.2. *CNT/Cu Cable as Headphone Cable*

Figure 5 shows the arrangement of the various cables used in the testing of the CNT/Cu cable as a headphone cable. The control in Figure 5a employed a commercial copper cable going from the XLR microphone input on the artificial ears' setup to a 3.5 mm microphone header on a calibrated soundcard. The soundcard was hooked to the right channel on the artificial ears to measure the frequency response of the right channel of HiFiMAN Arya headphones only. Furthermore, to eliminate the left channel causing any interference, only the right channel of the headphones was plugged into the standalone DAC/amplifier using the stock headphones cable. Once three separate frequency response measurements were collected and averaged, the headphone cable was replaced with the CNT/Cu cable, as seen in Figure 5b.

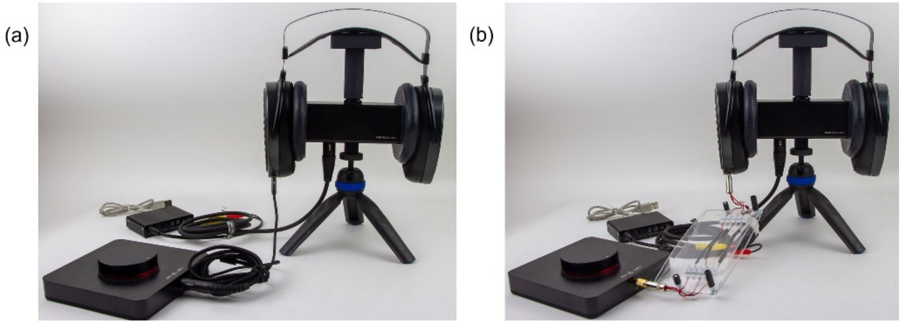

Figure 5. (**a**) Control setup for the frequency response measurement of the HiFiMAN Arya headphones using commercial copper headphone and microphone cables and (**b**) the setup using the CNT/Cu audio cable as the headphone cable along with the same commercial microphone cable.

Figure 6 compares the frequency response of the headphone's right channel as measured with the control setup to that of the CNT/Cu cable. In this case, the commercial microphone cable was common across both tests, and the two responses were seen to match each other within error margins, including the line shape of the plots themselves and the relative SPL intensities at various frequencies. The plots themselves were smoothened to an octave scale of 1/12th in Room EQ Wizard here, and this did not affect the relative comparisons of the two. It must be noted that, because of the higher contact resistance of the CNT/Cu cable, including with the need to add in a 3.5 mm to 6.35 mm adapter to connect to the DAC/amplifier, slightly more power was required to equalize the SPL volume loudness of the headphones with the CNT/Cu audio cable relative to the commercial headphone cable. Once the volume was matched, as in Figure 6, the CNT/Cu audio cable could be an objective replacement for commercial headphone cables.

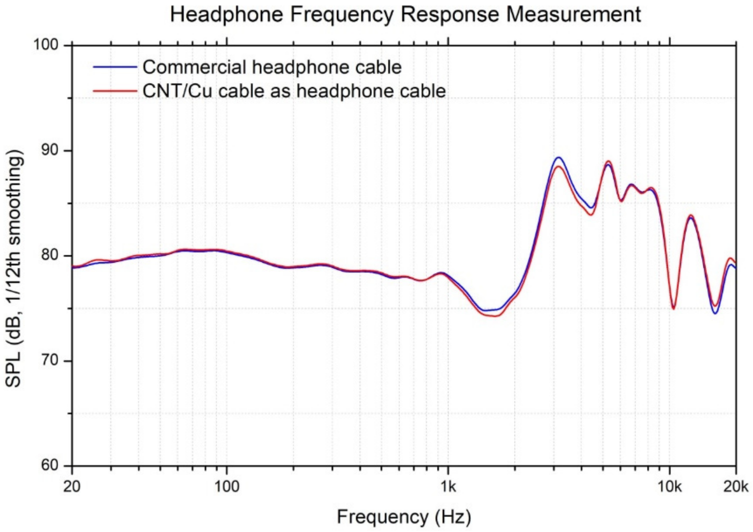

Figure 6. The frequency response of the HiFiMAN Arya headphones (right channel, averaged over three measurements) using a commercial headphone cable compared to the CNT/Cu cable as the headphone cable. Both are within error margins once the volume is matched.

3.3. CNT/Cu Cable as Microphone Cable

In this arrangement, the CNT/Cu audio cable was configured as a microphone cable, and Figure 7 shows the configuration of the various cables used here. The commercial copper headphone cable which is provided with the headphones is common to both, meaning the control test setup here was the same as the control in the previous testing scenario. What changed was the replacement of the commercial microphone cable in Figure 7a to the CNT/Cu cable in Figure 7b. The 3.5 mm and XLR microphone connections on the artificial ears setup were wired off the same IEC711 coupler to where there is no difference in the measurement of either, and the two connectors were offered purely as options for different interfaces. Once again, only the right channel of the headphones was plugged into the standalone DAC/amplifier using the stock headphones cable, and three separate frequency response measurements were collected and averaged.

Figure 8 compares the frequency response of the headphone's right channel as measured with the control setup to that with the CNT/Cu cable as the microphone cable. In this case, there was no need to volume match given the headphones were powered from the same configuration across the two tests. There was an even lower discrepancy between the two frequency responses in this configuration, which is logical considering the variable of the headphones was common here. As before, the individual plots themselves were smoothened to an octave scale of 1/12th in Room EQ Wizard, and this did not affect the relative comparisons of the two. The results show that the CNT/Cu audio cable was equally capable of replacing commercial microphone cables.

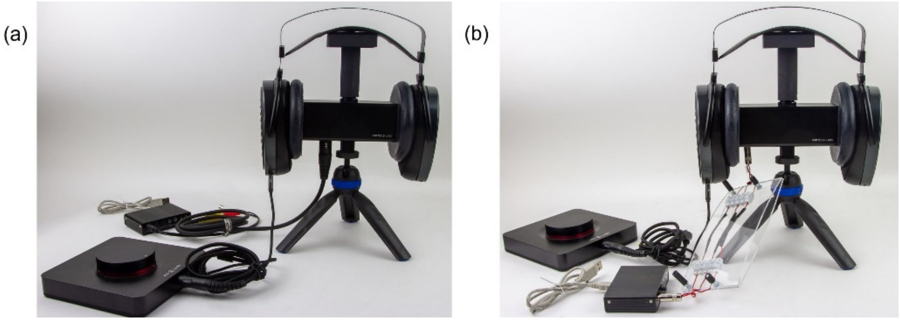

Figure 7. (**a**) Control setup for frequency response measurement of the HiFiMAN Arya headphones using commercial copper headphone and microphone cables and (**b**) the setup using the CNT/Cu audio cable as the microphone cable along with the same commercial headphone cable from before.

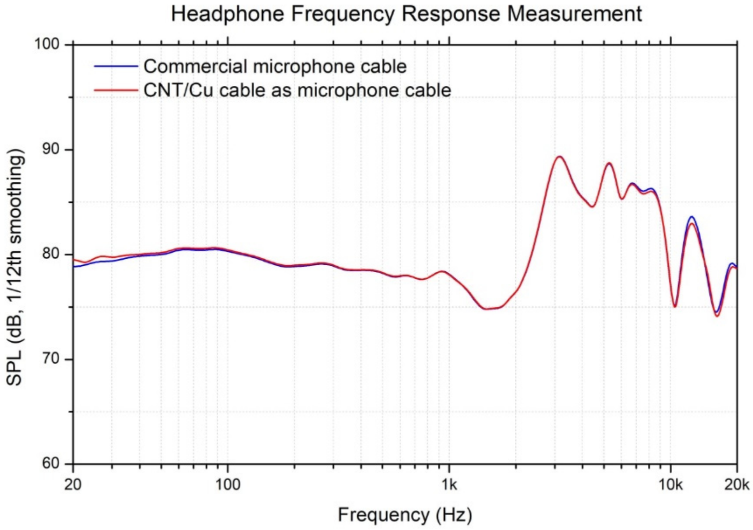

Figure 8. The frequency response of the HiFiMAN Arya headphones (right channel, averaged over three measurements) using a commercial microphone cable compared to the CNT/Cu cable as the replacement microphone cable.

There are other factors that contribute to how fitting a cable can be for audio transmission beyond just the frequency response measurements, and the cable resistance, capacitance, and impedance are a part of it. The raw CNTs had a measured capacitance of 3.83 nF for a chosen continuous section of CNT buckypaper, which after purification reduced favorably to 6.01 pF, thus indicating there is plenty of scope for improvement with CNT purification for CNT-based audio cables. There are also several subjective traits towards how a cable can influence the sound signature of headphones, but this cannot be quantified and is inherently not part of the scientific principle. Objectively, this proof-of-concept CNT/Cu audio cable has a higher electrical resistance than commercial cables owing to the intrinsic contact resistances previously mentioned, and a CNT/Cu cable made from purified CNTs, in addition to having a soldered connection with the copper wiring, will hypothetically achieve greater results. The small batch of purified CNTs made, whose capacitance was reported earlier, also demonstrated a much-reduced electrical resistance from an average of 2 Ω to 0.95 Ω, bringing it to the same order of magnitude as the copper control with the measured electrical resistance of 0.7 Ω as reported before.

The audio cable reported herein has proven to be durable over the nearly two years of continuous demonstration and use, showing that the less-than-ideal packing of CNTs and the contact with copper is not a detriment in the longevity of the concept itself. We will aim to also prepare other types of CNT/Cu cables in the future, including by using CNT fibers and impregnating Cu inside to have a continuous CNT-Cu-CNT electrical network, which should also make longer audio cables that can be used to power audio devices, such as headphones, microphones, and speakers just as well, if not better, as commercial copper-based cables. The source of the CNTs being waste plastics also makes for an eco-friendly approach, and there is plenty of scope for the upcycling of hydrocarbon wastes [16,17], such as spent surgical masks or supermarket plastic bags, etc., to make for commercial solutions that generate a positive product value, as opposed to having a net negative value in the waste handling process itself.

4. Conclusions

The scope of this work was initially limited to the use of CNTs, which were produced from carbon sources including polystyrene, to make for an audio cable that can be used for public outreach demonstrations and simple "show and tell" sessions to better showcase the potential of carbon nanotubes from upcycled plastics. The upcycling of waste plastics as a carbon source of the CNTs is also an excellent step towards solving the world's ever-increasing waste disposal problem. It was quickly realized that the CNT/Cu audio cable could be quantifiably compared to commercial copper cables, as both a headphone and microphone cable and a custom set of artificial ears were procured to aid in the same. This was paired with a set of headphones that used the same 3.5 mm stereo audio connectors for input, facilitating the use of the CNT/Cu audio cable in both use cases. Characterization of the CNTs confirmed again these were multi-walled in nature and conductive enough to perform the necessary actions. Once the volume matched to account for the higher contact resistances in the CNT cable, the objective performance of the CNT/Cu audio cable was found to be equivalent to commercial copper cables. There is scope for further improvement in terms of purification of the CNTs and the development of a more uniform CNT/Cu hybrid cable, which can also have the potential to be significantly thinner and stronger than traditional metal cables for audio applications.

5. Patents

Two patents have been filed from this work. A.O.W. filed: PROCESS FOR REUSE OF PLASTIC THROUGH THE CONVERSION TO CARBON NANOMATERIALS United States Patent Application 20190375639; and A.O.W. filed: CABLES AND METHODS THEREOF United States Patent Application 20210158995.

Author Contributions: Conceptualization, V.S.G., T.Y., F.B. and A.O.W.; methodology, V.S.G., T.Y. and F.B.; software, V.S.G.; validation, V.S.G. and F.B.; formal analysis, V.S.G. and F.B.; investigation, V.S.G.; resources, V.S.G. and A.O.W.; data curation, V.S.G.; writing—original draft preparation, V.S.G.; writing—review and editing, V.S.G., F.B. and A.O.W.; visualization, V.S.G.; supervision, A.O.W.; project administration, A.O.W.; funding acquisition, A.O.W. All authors have read and agreed to the published version of the manuscript.

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