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Abstract

Carbon nanotube (CNT) yarns are novel CNT-based materials that extend the advantages of CNT from the nanoscale to macroscale applications. In this study, we have modeled CNT yarns as potential data transmission lines. Test structures have been designed to measure electrical properties of CNT yarns, which are attached to these test structures using gold paste. DC testing and microwave S-parameter measurements have been conducted for characterization. The observed frequency independent resistive behavior of the CNT yarn is a very promising indicator that this material, with its added values of mechanical resilience and thermal conductivity, could be invaluable for a range of applications such as body area networks. A model is developed for the CNT yarn, which fits the measured data collected and agrees in general with similar data for non-yarn CNTs.

Keywords

characterization, carbon, nanotube, yarns, microwave, body, area, uwb, networks, medical, wireless

Disciplines

Engineering | Physical Sciences and Mathematics

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Microwave Characterization of Carbon Nanotube Yarns for UWB Medical Wireless Body Area Networks

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***Abstract*—Carbon Nanotube (CNT) yarns are novel CNT-based materials that extend the advantages of CNT from the nano-scale to macro-scale applications. In this work we have modeled CNT yarns as potential data transmission lines. The observed frequency independent resistive behavior of the CNT yarn is a very promising indicator that this material, with its added values of mechanical resilience and thermal conductivity, could be invaluable for a range of applications such as Body Area Networks (BAN). A model is developed for CNT yarn, which fits the measured data collected and agrees in general with similar data for non-yarn CNTs.**

Index Terms—*Carbon Nanotube, Carbon Nanotube Yarn, CNT Yarn model.*

I. Introduction

CARBON Nanotubes (CNTs) have emerged as potential candidates for replacement of conventional metals due to their significant mechanical, electrical and thermal properties and non-oxidizing abilities [1-4]. CNTs have been of interest in nanoelectronics and nanoantenna applications [5-7] since the density of CNT composites is about one fifth of that of copper and around half of that of aluminium. Also their thermal conductivity is about ten times that of copper. Electrical conductivity of CNT composites depends on the properties and loading of CNTs, the aspect ratio of the CNTs and the characteristics of the conductive network.

CNTs hold great promises in a number of related medical applications because of their remarkable physical properties. CNT has been used, for example, as the basic underlying material for an artificial muscle [8] due to their incredible strength-to-weight ratio. Electrically, as they are more conductive than copper in nano scales [9, 10], their potential use in in-body integrated-circuit-based ultra-wideband (UWB) wireless body area networks (WBAN) would go beyond the artificial muscle to RF/microwave dielectrics, conductors and sensors [11], suitable for EMI/EMC applications [12] to transistors [13].

Underlying any attempt to integrate CNT into such applications is establishing its properties in suitable fabrication technologies using compound semiconductor or CMOS. Recently, the investigation of the RF/microwave material properties of CNT bundles (on the order of tens of microns long) in single- and multi-walled configurations have been the subject of many studies with somewhat conflicting results [14]. While CNT bundles are the underlying building block for many applications, CNT yarns comprised of woven, individual nanotubes, can be made to be tens of millimeters in length and as such are suitable for MEMs, tunable dielectrics, and related electrical structures at UWB frequencies. Establishing the RF/microwave material properties of CNT yarns is an essential first step to their use in hybrid manufacturing technologies.

This paper reports the RF/microwave electrical characterization of CNT yarns up to 20 GHz with the goal of incorporating them in several roles in UWB WBAN. Section II provides an overview on CNT yarn fabrication and their fixturing. Test structures and measurement procedure are discussed in Section III. Results and circuit modeling are presented in Sections IV and V, respectively, while Section VI concludes the paper.

II. CNT Yarn Fabrication & Fixturing

A. Yarn Fabrication

The Multi Walled Carbon Nanotube (MWCNT) forest was synthesized by Catalytic Chemical Vapor Deposition (CCVD) using acetylene gas as the carbon source [15]. Carbon nanotubes, in the 300 μm tall forest, typically had diameters of about 10 nm. The yarns were drawn from the forest by pulling and twisting as described in [16, 17]. CNT composite yarns can be obtained using dry spinning process [18]. Processing them using volatile liquids (like ethanol and methanol) will reduce the manufacturing irregularities and make them smooth [19, 20].

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A Leica Stereoscan 440 Scanning Electron Microscope (SEM) was used for morphological studies of the fibers. SEM micrographs of the pristine CNT yarns (Fig. 1) show that the nanotubes are uniform, and predominantly oriented with a helix angle (α) ~ 25°. The CNT yarns in our experiments were drawn into 12 µm and 100 µm diameters. The twist is characterized by the helix angle (α), which depends directly upon the degree of twist and inversely on the yarn diameter. The number of twists is typically 20000 turns per meter. Earlier, Miao [21] has investigated electrical conductivity of CNT yarns, specifically relationships between number of CNT-to-CNT contact points, yarn surface twist angle and porosity, effects of yarn porosity on electrical conductivity and resistivity of pure CNT yarns.

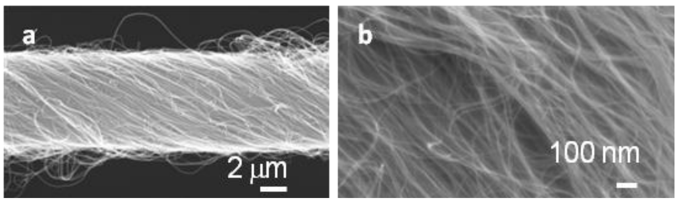

Fig. 1. SEM micrographs of pristine CNT yarn at (a) low and (b) higher magnification.

B. *Fixturing*

Prepared yarns of diameter 12 µm and 100 µm were attached using a two-step procedure. First, the ends were prepared so as to have a planar face by carefully cleaving them perpendicularly to the major axis of the yarn. Secondly, each yarn was electrically and mechanically connected to two launches of a test structure (described in Section III) using gold paste. Since CNTs, as the building blocks of CNT yarn, are quasi-one dimensional conductors, special care was taken to insure that the ends of each yarn had a continuous coating of gold from the end to the test structure launch.

A second test structure was prepared as a control for the attachment method. An enamel-coated wire, approximately 100 µm in diameter, was prepared in the same manner as the CNT yarns and fixed to this test structure.

III. Test Structures & Measurement Procedure

In order to get an indication of the distributed behavior of the CNT yarns, a test structure is needed which is a substantial fraction of a wavelength. To this end, test structures supporting yarn lengths of 3500 µm and 4500 µm were fabricated on 10 mil thick Rogers 4350® (εr = 3.66 and δ = 0.0037) substrates. A nominal 50 Ω line in this system is more than a tenth of a wavelength long for frequencies above 5 GHz for the 3500 µm long test structure.

In addition to the test structure to support yarn attachment, calibration structures were included on each test vehicle for short, open, and thru calibration in both microstrip and coplanar waveguide configurations. The entire test coupon is shown in Fig. 2a. Yarn samples were attached as shown in Fig. 2b. Electrical connection was made to the test structure through ground-signal-ground pads at the end. Both coplanar and microstrip structures are available but here we report on the microstrip results only.

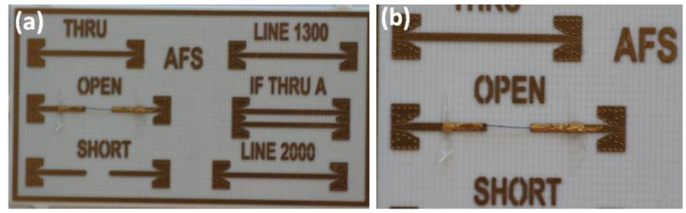

Fig. 2. (a) Photo of the test structure with calibration structures; (b) Close up of a sample attached to golden pads using gold paste.

Measurements were performed from 50 MHz to 20 GHz using an HP 8510C. Prior to measurements, a TRL calibration was performed using the calibration structures on the test coupon.

IV. Measurments Results

Testing was done in two phases. First, DC testing was done to characterize both the quality of the attachment and to get a measure of contact resistance. Second, the actual microwave measurements were performed. So as to eliminate any potential effects of gold paste diffusion into the CNT yarns, testing was done right after the preparation of the samples and both tests were performed consecutively.

Three samples of 12 µm and three samples of 100 µm yarns were tested. Three samples of the enamel-coated wire were also tested.

A. *DC Results and Analysis*

Test results are shown in Table I. The DC resistance of the thru line of the calibration structure was approximately 2 Ω which compared to the samples' resistances is negligible. The average measured resistance of the 12 µm and 100 µm yarns are 2.55 KΩ and 170 Ω, respectively. Taking the ratio of the length (l) to diameter (d) as proportional to an equivalent sheet carrying current along the yarn, the 12 µm sample is approximately 375 units long and the 100 µm sample is 35 units. The sheet resistance then for the 12 µm yarn is 6.8 Ω/square and the 100 µm sample is 4.9 Ω/square.

TABLE I
Yarns' Measured Data For DC

Diameter (µm)	Samples' Resistance Ω			Average Resistance Ω
	I	II	III	
100	186	167	158	170
12	2599	2570	2465	2545

It would be expected that equivalent CNT densities in the yarns would yield equivalent sheet resistivities (R_s). However, contact resistance (R_c) in CNTs is known to be high [22] and should scale approximately with the contact area. If the total resistance is taken as the sum of a contact resistance (R_c) that is inversely proportional to the contact area (or to the square of the yarn diameter so that thicker yarns have lower a contact resistance) and a sheet resistance that is directly proportional to the length of the yarn and inversely proportional to the sheet width (or yarn diameter so that thicker yarns give lower resistance and longer yarns give higher resistance), then an approximate contact resistance and sheet resistivity can be calculated using:

$$R \approx R_c + R_s \qquad (1)$$

$$R \approx \frac{4r_c}{\pi d^2} + \frac{lr_s}{d} \qquad (2)$$

The use of the 12 µm and 100 µm DC resistance values gives 855 Ωm2 and 12.3 Ωm2 for r_c, respectively. The r_s is a constant 4.5 Ω/square for both yarn lengths.

B. Microwave Results

Scattering parameters were measured from 50 MHz to 20 GHz for all samples. Measured S21 is shown on the Smith chart in Figs. 3-5 for the 12 µm, 100 µm, and enamel-coated wire, respectively.

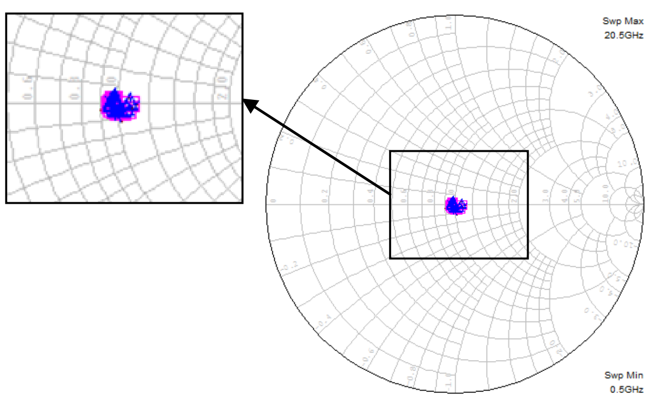

Fig. 3. 12 µm yarns' measured S21 for the three prepared samples on 4500 µm substrates.

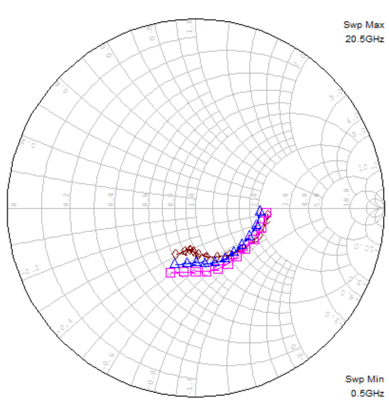

Fig. 4. 100 µm yarns' measured S21 for the three samples prepared on 3500 µm substrates.

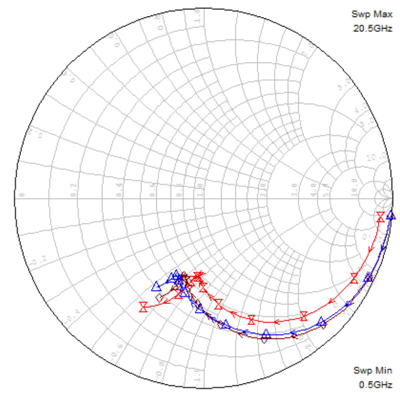

Fig. 5 100 µm enamel-coated wires' measured S21 for the three samples prepared on 3500 µm substrates.

V. Modeling

Distributed circuit modeling was performed to ascertain an understanding of the material characteristics from the test structure configuration. Previous models have been developed from first principles for single or bundled CNTs [23, 24], which are not directly applicable to CNT yarns as they are complex structures made out of CNTs. Therefore, a phenomenological model is used for CNT yarns here to identify their functional performance suitable for circuit design.

Several factors need to be addressed in the model to represent non-idealities in the test structure in the electrical model. First, the planar nature of the test structure launch does not provide any facility for repeatable positioning of the yarn or wire in the longitudinal dimension. As such, there is a potential error induced in the effective length of the line which can be corrected by introducing a series inductance or by lengthening the transmission line. Second, while the transmission structure is clearly a conductor over a ground-plane it is not truly microstrip since the conductor is circular and no physical means of adhesion between the conductor and the dielectric substrate is provided directly by the attachment technique beyond yarn/wire tension and gravity. This causes variability in the characteristic impedance. Third, the high contact resistance of the CNT must be accounted for with a fixed resistance. Finally, the gold paste on the narrow launch potentially adds a parasitic series inductance and a shunt capacitance or makes at least one of the ports appear to be complex relative to the calibration.

As a method of extracting reasonable material and circuit parameters from these measurements, a circuit-based model using lumped and distributed elements representing the effects mentioned above was developed using AWR Microwave Office [25]. The model topology for the enamel-coated wire is shown in Fig. 6 and its agreement with the measured data is shown in Fig. 7, showing excellent agreement up to approximately 15 GHz. This model of the wire (Table II) represents a characteristic impedance of approximately 130 Ω which correlates well to the expected value, not taking into account the enamel, as shown in Fig. 7 when compared to an EM-based model using the finite elements method.

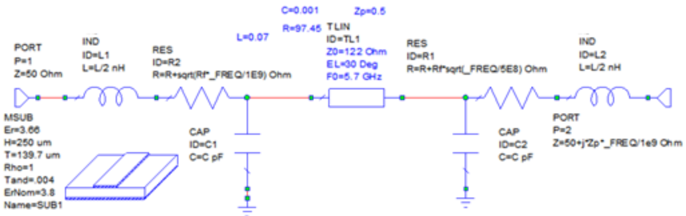

Fig. 6. Yarn and wire model of ideal transmission line with resistors for yarn loss and capacitor/inductor for non-ideal attachment.

Using the same basic model shown in Fig. 6, the 100 μm yarn was modeled. The results for this are shown in Fig. 8 comparing the measured data to the model from 0.05 GHz to 20.5 GHz. A least squares fit of the complete set of S-parameters for both reflection and transmission corresponding to this model as compared to the measured data was calculated and the worst case error between the measured and the modeled is better than 0.25%.

The value of the each inductor in the model (in Fig. 6) is 0.025 nH. This inductor models the extra line length from the calibration reference plane to the CNT yarn (modeled as the transmission line). The value of each resistor is 97.45 Ω plus a small frequency dependent portion that is proportional to $\sqrt{f}$, to model the skin depth of the conductive paste connecting the CNT yarn to the reference plane. The value of each shunt capacitor that takes into account the extra parasitic capacitance from the paste to ground and fringing capacitance of the discontinuity at the start/termination of the CNT yarn has a value of 0.5 fF. We also added a small frequency-dependent series reactive part (Z_p) to the 50 Ω termination at port 2 to model any asymmetry in the paste and CNT yard placement. However, the Z_p is only about 0.5 and contributes only 2% at 10 GHz to the magnitude of the load impedance (50 Ω); it only improves the fit to the measured data marginally. This leaves the ideal transmission line to have a characteristic impedance of 122 Ω and an electrically length of 30 degrees at 5.7 GHz, which is in fairly good agreement with a conducting wire which has the same dimensions as the CNT yarn.

TABLE II
YARN AND COPPER WIRE COMPARISON AT 5GHZ

Diameter & Type	Resistance (R) (Ω)	Transmission Properties		
		Z_o (Ω)	Phase (Deg)	f (GHz)
100 μm copper wire	0.3	128	38	5
100 μm yarn	196	133	29	5

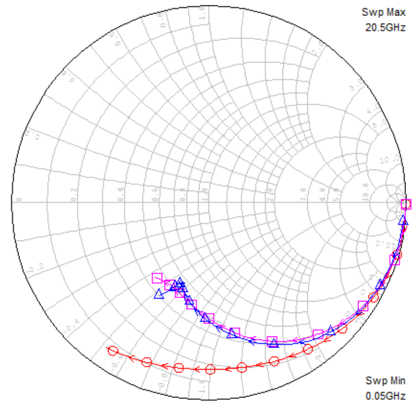

Fig. 7. Enamel-coated wire's S21 measured (blue diamond) vs. modeled (violet square) vs. ideal FEM analysis (red circle).

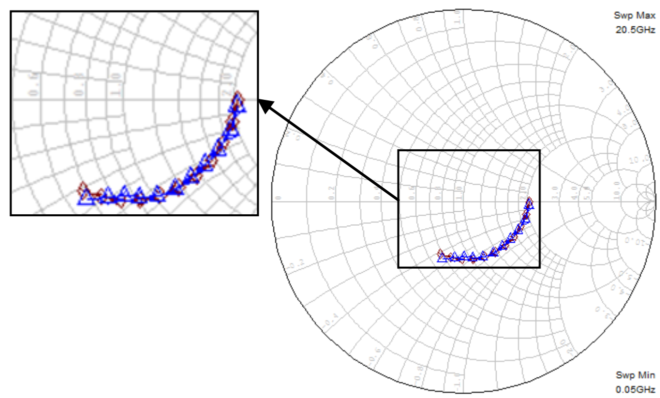

Fig. 8. 100 μm yarn's S21 measured vs. modeled.

The model extracted for the CNT yarn, after taking into account the non-idealities mentioned above, shows transmission line properties nearly identical to the wire (Table II) at 5 GHz. The difference in phase is partially due to the systematic error in this sensitive measurement and in the attachment procedure. The yarn model differs significantly from the wire model with a very high fixed resistance of 98 Ω for each of the resistors in the model. This accounts for the entire measured DC resistance and it is fixed, with no significant frequency-dependent contribution over the measured frequencies. The lack of a strong frequency dependent resistance in the yarn is consistent with that found elsewhere [14].

VI. CONCLUSIONS

CNT yarns were measured at RF/microwave frequencies in a microstrip configuration to ascertain their material properties for UWB WBAN system components as EM surfaces, dielectrics, and conductors. In this first such test for CNT yarns, the data suggests that the CNT yarn performs very much like the underlying multi-walled CNT bundles. Contact resistance is relatively high, but good conduction is found within the yarn itself. After accounting for the contact and an effective sheet resistance, the yarn presents a characteristic impedance that is well approximated through measurement and modeling by a copper wire of similar diameter and attachment method. This model for the CNT yarn gives very good agreement to both the transmitted and reflected S-parameters. The observed frequency independent resistive behavior of the CNT yarn is a very promising indicator that when the conductivity is improved as a result of ongoing research, this material, with its added values of mechanical resilience and thermal conductivity, could be invaluable for a range of applications such as BAN.

These results suggest that the CNT yarn can be used in microwave applications in a manner similar to resistive materials, such as NiCr or doped polysilicon. In this configuration, the CNT yarn could act as a probe or conductive structure that is acceptable to biological tissue. New CNT preparation techniques which include a dopant have been shown to further reduce the resistivity which may open up additional applications [26].

Work continues in this area and is focusing on more accurate measurements and varying yarn construction factors. To remove variability in the attachment method, the test structure launch is being redesigned to cradle the yarn in the transverse and longitudinal dimensions. This will have the additional benefit of better fixing the yarn lengths. Different length yarns will be tested as well to get better understanding of phase characteristics. Finally, denser and looser yarns will be tested along with doped yarns which have improved DC conductivity.

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