Experimental Study of Electrophoretic Deposited Carbon Nanotubes on Microstrip Transmission Line Resonators and Filters

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Abstract. *The electrical properties of single-walled carbon nanotube electrophoreses deposition on different types of gold-plated microstrip devices are investigated. Simple transmission lines, transmission line resonators and filters were subjected to deposition of functionalized tubes in an aqueous solution. It is found that the process lowers the resonant frequency of the resonators and filters compared to the untreated devices, at the cost of increased insertion loss and reduced resonator Q-factor.*

Keywords

Carbon nanotubes, frequency response, microstrip filters, resonator filters, surface treatment.

1. Introduction

Single-walled carbon nanotubes (SWCNTs) are monoatomic graphite layers rolled into tubes, having a diameter of a few nanometers [1]. They have found application in microwave and mm-wave engineering in, among others, MEMS devices and sensors [2], as antennas [3] and field-effect transistors [4].

The electrical properties of SWCNTs, as a conducting or semi-conducting medium in isolation, have been characterized through numerous means. SWCNTs have been measured as free-standing center conductors on coaxial probes [5] and as microstrip lines in themselves [3], [6], [7], in parallel wire transmission line configurations [8], cavity perturbation [9] and field excitation in a split-post dielectric resonator [10].

As for the effect of deposited CNTs as surface coating on conducting devices, this has been applied to aluminum wires [11] and was found to increase the net conductivity of the compound device. Contrary to this, on microstrip devices, examples of tests involving microstrip antennas have been published [12], indicating that CNT deposition both lowers the resonant frequency of the patch antenna and increases its gain bandwidth. Although a CNT resonator coupled to a microstrip line has been demonstrated [13], no results have, as yet, been published investigating the effects of SWCNT deposition on other microstrip devices. This paper presents measured results to illustrate the effects SWCNT deposition on gold-plated microstrip transmission lines, transmission line resonators and filters.

2. Methodology

Two techniques were used to gold-plate the copper-clad etched microstrip devices initially, namely Electroless Nickel Immersion Gold (ENIG) and Auto-catalytic Silver Immersion Gold (ASIG) [15], both applied to microstrip boards etched from Rogers RT/duroid 6002 substrate of 10 mil thickness with 0.5 oz. copper cladding. Both of these processes are commonly used in industry as anti-corrosive coatings for copper-clad PCBs. ASIG, however, eliminates the lossy nickel-phosphorous layer from the process, providing less insertion loss in microwave and mm-wave microstrip devices.

After initial characterization of the test devices to determine the properties of different gold platings techniques, the boards were treated by electrophoretic deposition (EPD) of CNTs, similar to the process in [11]. A 1 % functionalized SWCNT-COOH aqueous dispersion from Times Nano was used, with 10 ml of the dispersion diluted in 190 ml of distilled water to form the electrolytic suspension. Based on supplier data, it is estimated that 1/3 of the CNTs are metallic. The microstrip tracks on the test boards were separated by 3 mm from gold-plated counter-electrodes (Fig. 1). To allow for a DC path to all of the coupled hairpin resonators on the filters [15], a drop of removable conductive epoxy was used to bridge the coupling gap between resonators during deposition.

The microstrip tracks were connected to the positive terminal, and the counter-electrodes to the negative terminal of a 5 V_{DC} source, and the device immersed in the CNT solution for 30 seconds. After deposition the boards were rinsed with distilled water and cleaned with acetone to remove excess CNTs not electro-deposited to the gold, and baked at 100 ºC for 24 hours to remove any moisture left by the deposition process. The final CNT distribution is pictured in Fig. 2.

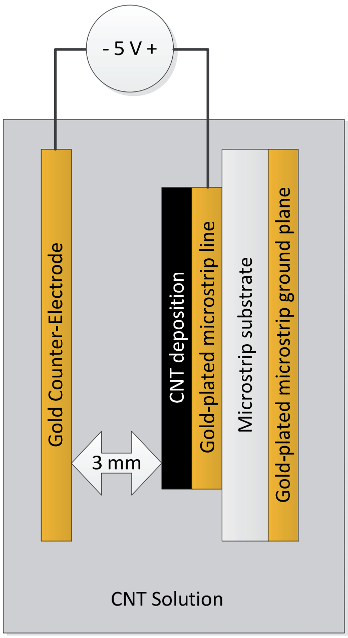

Fig. 1. EPD test setup.

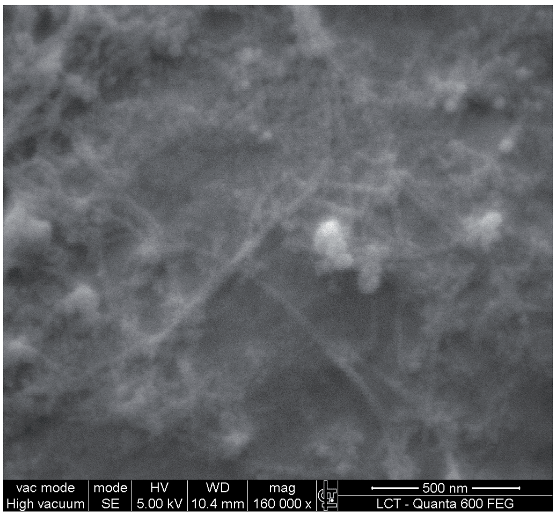

Fig. 2. CNT deposition pattern.

3. Experimental Results

3.1 Through Lines

The first sample set prepared was of 50 Ω through lines of 25 mm length (Fig. 3), with measurement results in Figs. 4 and 5. The transitions were matched to below -15 dB S_{11} in all cases, making port mismatch a negligible consideration in total loss.

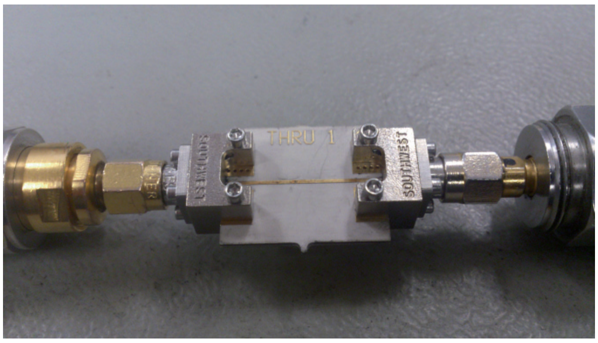

Fig. 3. CNT-deposited 50 Ω microstrip line on RT/duroid 6002, under test.

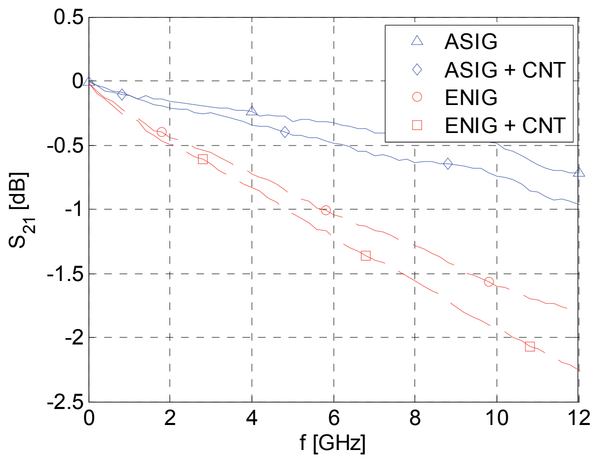

Fig. 4. Measured transmission response (S_{21}) of 50 Ω microstrip lines.

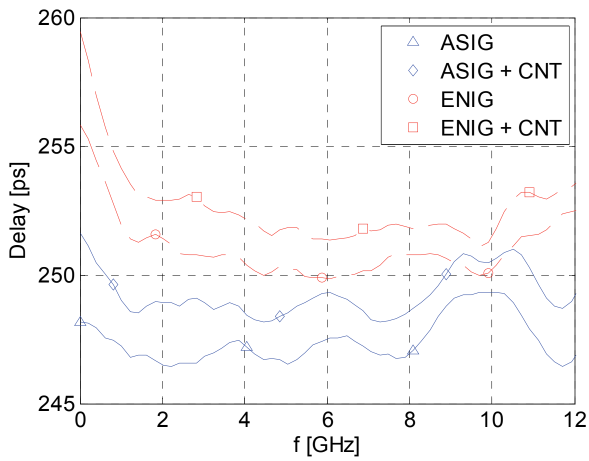

Fig. 5. Measured group delay of 50 Ω microstrip lines.

The through lines clearly indicate higher insertion loss from the ENIG lines than from the ASIG lines, as expected, with both lines' insertion loss increased with the application of CNTs. Previous work has estimated the conductivity of SWCNTs at 10 S/μm [11], far lower than the 41 S/μm of gold. Since the effective surface resistance of the microstrip line is increased, the increased insertion loss is expected. Another noticeable effect is the increase in time delay on both lines, indicating a decrease in group velocity v_p. Since

$$v_p = \frac{c}{\sqrt{\varepsilon_e}} \quad (1)$$

where ε_e is the effective dielectric constant of the medium, the measured increase in delay time indicates a decrease in v_p and, consequently, an increase in ε_e. Since the calculation of ε_e in microstrip assumes a perfect vacuum ($\varepsilon_r = 1$) above the substrate, the addition of any impurity with $\varepsilon_r > 1$ (such as a CNT coating) is expected to increase ε_e. This is in line with the measured results. This increase in dielectric constant varies from 2.7% at DC to 0.92% at around 10 GHz.

3.2 Hairpin Resonator

The second sample set consisted of single hairpin resonators, as shown in Fig. 6, with the measured results in Fig. 7 and Tab. 1.

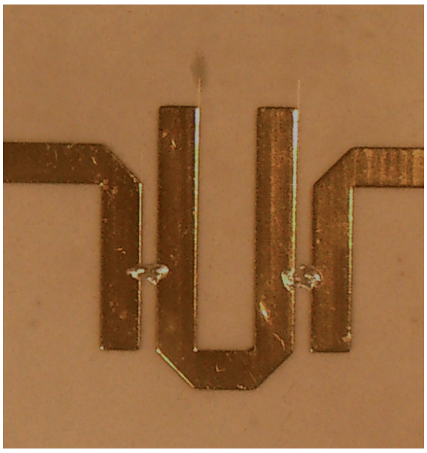

Fig. 6. Hairpin resonator on 10 mil RT/duroid 6002. Note the epoxy bridging the coupling gaps, to allow for a DC path between all microstrip lines.

As was the case with the microstrip lines, the resonator Q_0 deteriorates after CNT deposition for both the ASIG and ENIG cases. Another prominent effect by the CNT deposition is reduction of the resonant frequency (0.287 % for the ASIG case and 0.387 % in the ENIG case). This is less than the 1.5 % reduction demonstrated in [12], but in line with the 0.39 % reduction observed in [9]. This may be due to the similar use of SWCNTs in [9], whereas [12] used a composite of multi-walled CNT (MWCNT) and epoxy. These measurements are also in line with the 0.46% decrease predicted by the group delay measurement of the through-lines in Section 3.1, since

$$f_0 \propto = \frac{1}{\sqrt{\varepsilon_e}} \quad (2)$$

for a resonator of fixed length.

Since the resonant frequency of a distributed microwave resonator is inversely proportional to the dielectric constant of the transmission medium, this change in resonant frequency indicates a higher local dielectric constant (ε_r) in the area surrounding the microstrip line, as was inferred from cavity resonator measurements in [9].

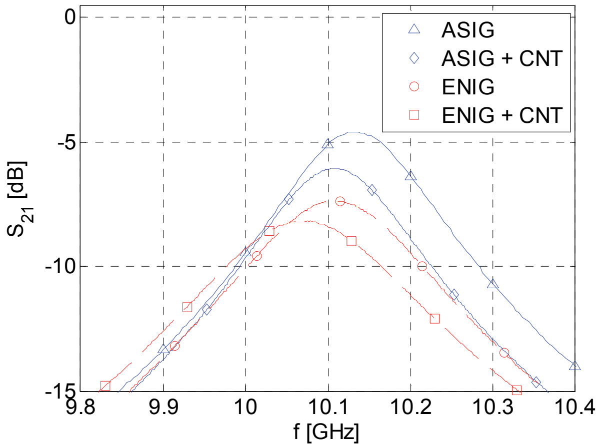

Fig. 7. Transmission responses of hairpin resonators.

Resonator	f_0 [GHz]	Q_0
ASIG	10.132	131.34
ASIG + CNT	10.103	105.93
ENIG	10.106	76.41
ENIG + CNT	10.067	64.28

Tab. 1. Resonator characteristics.

3.3 Coupled Resonator Filter

The final tests were performed on a set of 4th order coupled hairpin resonator filters (Fig. 8), the measured transmission responses of which are shown in Fig. 9. It is clear that the same shift in resonant frequency previously observed in the case of single resonators (as shown in Tab. 1) is translated to a shift in resonant frequency for the filter entire. This effect is, again, interpreted as a localized increase in (ε_r) around the conductor. The CNT coating increases the minimum insertion loss of the ASIG filter from 2.6 dB to 3.7 dB, whilst the coating has a less pronounced effect in the case of the ENIG filter (3.9 dB to 4.2 dB). Both of these changes are attributed to the decreased resonator Q-factor observed in Section 3.2.

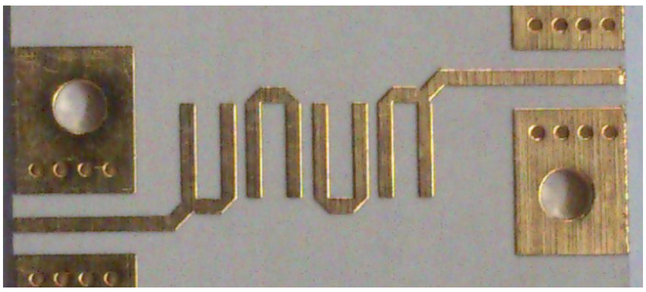

Fig. 8. Coupled hairpin resonator filter.

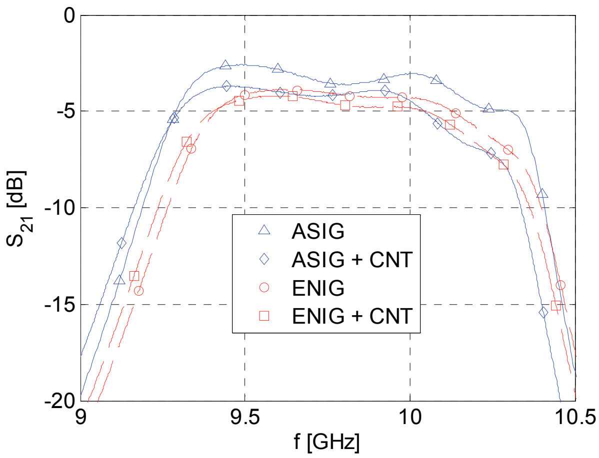

Fig. 9. Transmission responses of coupled hairpin resonator filters.

4. Conclusion

The effect of electrophoretic deposition of SWCNTs on gold-plated microstrip has been demonstrated. The changes in transmission line resonators' resonant frequencies were found to be in line to what was previously reported for microstrip patch antennas and SWCNT cavity perturbation. Increased transmission loss is also observed, again similar to previously reported results on microstrip patch antenna coatings.

Future studies will focus on removing the surfactant from the CNT coat or deposit CNT without surfactants in order to reduce the insertion loss by increasing the conductivity. Other studies will try to reduce the size of low frequency antennas by depositing CNT and trying to observe the same frequency shift as described. It may also be of interest to perform a pattern deposition of CNTs (as opposed to the full track surface) to obtain localized variation in dielectric properties, possibly applying these in synthesis.

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