Microwave Response of a Microstrip Circuit Embedding Carbon Nanotube Films

A. Maffucci[1,2], M.D. Migliore[1], S. Sibilia[1], A. Paddubskaya[3], D. Pinchera[1], and F. Schettino[1]

[1] DIEI, University of Cassino and Southern Lazio, Cassino, I-03043, Italy

[2] INFN, National Laboratory of Frascati, Frascati, I-00044, Italy

[3] INP, Belarusian State University, Minsk, BY-220030, Belarus

Abstract **This paper investigates the microwave range response of microstrip circuit where a film of carbon nanotubes is embedded into a microstrip-like circuit. Such a nanomaterial, as well as graphene, is currently embedded into planar structures like patch antennas, to exploit its novel features as, for instance, easy tunability. In view of these applications, in this paper it is analyzed the dependence of the scattering parameters from the geometrical and physical parameters of the circuit. The analysis is carried out either by means of experimental characterization via microstrip technique, and of numerical simulations with a full-wave electromagnetic simulation tool. In addition, by using these two results and by using structural characterization of the nanomaterial equivalent, an equivalent complex permittivity is retrieved, describing the embedded film.**

Index Terms **— Carbon nanotubes, complex permittivity, films, microstrip line, scattering parameters.**

I. Introduction

Carbon-based nanostructured materials, such as Carbon Nanotubes (CNTs) or graphene nanoplatelets (GNPs) are promising building blocks for nano-interconnects and nano-antennas, due to their outstanding physical properties: low electrical resistivity, high thermal conductivity, excellent mechanical behavior, [1]. Novel electromagnetic properties arise for the quantum phenomena related to the spatial confinement of the charge carriers motion to sizes comparable with the de Broglie wavelength [2]. Indeed, the resulting discrete spectrum of energy states provides an unusual electromagnetic response, including plasmon resonance effect and features like frequency-independent absorption and the presence of a gapless spectrum. All these features enable, for instance, the possibility of realizing nano-antennas capable to work efficiently in the THz range [3]-[4].

For the above reasons, in the last years many prototypes of antennas embedding carbon nanostructured materials have been proposed: thin-film antennas realized by means of multi-wall CNTs [5], as well as dipole antennas where a nano-sized graphene sheet has been placed in the nanogap, to realize an electrically tunable nano-circuit element [6]. Easy and broadband tunability of a patch antenna has been proved in [7] by embedding a patch of GNPs into the circuit.

However, despite the above-mentioned examples of real world applications, there are still challenges in the route towards the industrialization of these ideas, many of them related to integration problems. Indeed, when these materials are embedded in a conventional circuit, their performance may dramatically drop down [8]. For instance, the high-frequency behavior of such circuits is strongly affected by features like the contact resistance at the interfaces between nanomaterials and conventional metals.

In order to study these effects, in this paper a microstrip circuit embedding a film of CNTs is studied in the microwave range, following the same approach as in [9], where graphene nanoplatelets have been studied.

The details of the nanomaterial fabrication and its integration in the microstrip are in Section II. Section III describes the full-wave electromagnetic model used to perform sensitivity analysis. In Section IV an experimental characterization is carried out in the microwave range, by means of a microstrip technique. By matching the simulation and characterization results, the equivalent values of the real part of permittivity and the conductivity are retrieved.

II. Preparation of the Circuit

The microstrip circuit fabricated for this work is described in Fig.1, with the parameters given in Table 1: the signal and ground conductors were made by copper, and the signal line was cut into two parts by means of a gap. Three different gap lengths have been defined (see Table 1). An FR-4 dielectric has been used (PCL370HR), with relative permittivity falling between 4.17 and 3.92 in the range (1-10) GHz.

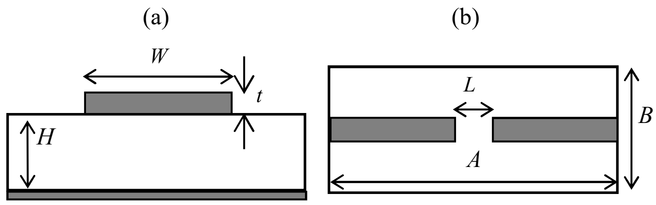


Fig. 1. Schematic of the designed microstrip with a gap in the signal line: (a) side view; (b) top view.

TABLE 1.
Geometrical Parameters for the Microstrip in Fig.1.

A (*mm*)	*B* (*mm*)	*W* (*mm*)	*H* (*mm*)	*L* (*mm*)
50	20	0.1, 0.5, 1.0	0.5	0.1

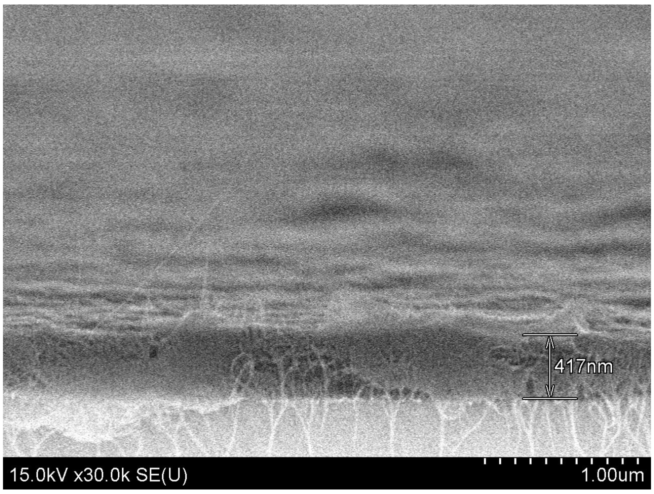


Fig. 2. SEM image of SWCNT2 film. The thickness of the film is measured as 0.42 μm.

Fig. 3. A picture of the realized microstrip embedding a film of carbon nanotubes (black patch).

TABLE 2.
CHARACTERISTICS OF THE FOUR SAMPLES OF THE CIRCUIT.

Sample	*Film Thickness*	*Gap length*
SWCNT1	1.12 μm	1 mm
SWCNT2.1	0.42 μm	0.1 mm
SWCNT2.2	0.42 μm	0.5 mm
SWCNT2.3	0.42 μm	1.0 mm

The gap was filled with a CNT thin film, fabricated starting from a commercial single-walled CNT powder (SIGMA-ALDRICH, median length = 1 μm). The powder was dispersed in Sodium Dodecyl Sulfate (SDS) solution (1%), that was further sonicated and centrifuged (15000 g). Finally, it was subjected to vacuum filtration, by using cellulose filters (0.22 μm pore size). Two types of films were realized, that only differ from their thickness values, that were found to be 1.12 and 0.41 μm, by means of a Scanning Electron Microscope (see Fig.2). In the following, we will refer to them as SWCNT1 and SWCNT2, respectively. A Raman spectroscopy analysis allowed to determine the average diameters of the CNTs to be around 1.22 – 1.24 nm.

The film was prepared with the following steps: a portion of the film was cut to dimensions suitable for the gap area; the film was immersed into acetone, in order to dissolve the filter paper and detach it from the polymer layer of the filter; the film was then immersed into propanol in order to clean it from the acetone; finally, it was immersed into water in order to further clean it.

To embed the film into the microstrip gap, a transfer technique was used, and after that the film stayed attached to the copper lines by Van de Waals forces. The final circuit is shown in Fig. 3: four samples were realized, differing from material thickness and gap length, see Table 2.

III. MODELLING AND SIMULATION RESULTS

The circuit described above has been modeled by means of a full-wave commercial FEM tool (CST Microwave Studio), with the simplified geometry described in Fig.4, where the gap is magnified in the inset and the red surfaces indicate the two waveports. A copper conductivity of $\sigma_{Cu} = 5.8 \cdot 10^7$ S/m has been assumed for the simulations, whereas the CNT film (including the contacts with the copper traces) has been described by a complex relative permittivity given by simple Drude model:

$$\varepsilon = \varepsilon^{'} + i\varepsilon^{''} = \varepsilon' - i\frac{\sigma}{\omega\varepsilon_0}, \qquad (1)$$

with a frequency-independent real permittivity ε' and conductivity σ, which are two parameters of the model.

The low cost assembly technique described above cannot provide a strict control on the contact shape, therefore extra material may be found outside the gap volume. Its presence influences the results in the microwave range, therefore it has to be taken into account by means of an additional geometric parameter to the model, i.e. the overlap length of the film. These three parameters sum to the design degrees of freedom listed in Table 1, that is the film thickness and the gap length. In the following, the numerical solutions are used to perform a parametric analysis of the scattering parameters. For instance, Fig.5 shows the results of the sensitivity analysis with respect to variations of the film thickness, assuming a film extra length of 1mm, a gap of 1mm, real permittivity $\varepsilon' = 10$ and conductivity $\sigma = 10$ kS/m. When increasing the thickness of the carbon layer, the transmission (S_{21}) increases while the reflection (S_{11}) decreases. This result is coherent with what expected, since with a thicker carbon sheet the amount of conductive material is increased. It is also coherent with the experimental evidence, as shown in the next Section.

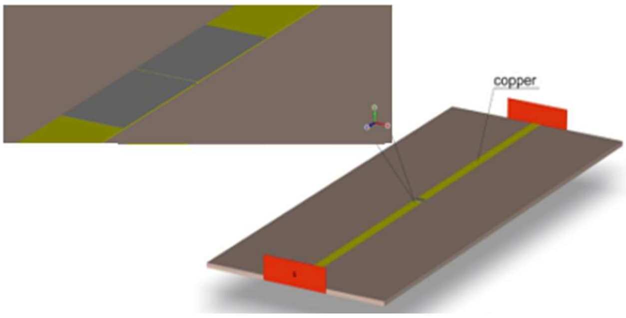


Fig. 4. The model of the microstrip adopted for the full-wave numerical simulations (red surfaces define the waveports). Inset: magnification of the gap area, with the film laying on copper traces.

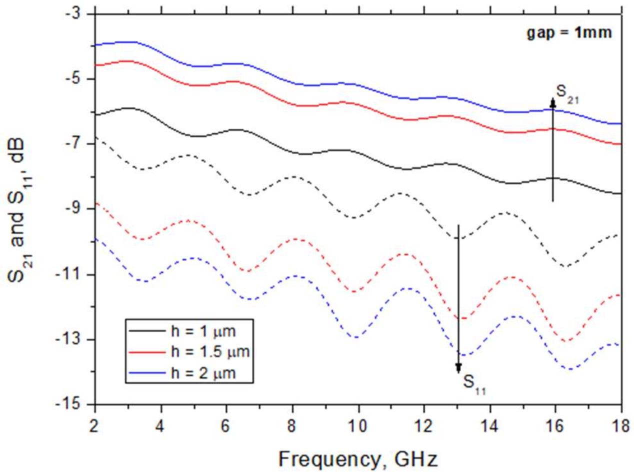


Fig. 5. Sensitivity of the S-parameters to the film thickness (assuming a film extra length of 1mm, a gap of 1mm, $\varepsilon' = 10$, and $\sigma = 10$ kS/m.)

By using this model, a similar analysis has been performed to study the influence of all the other model parameters on the scattering parameters.

IV. Experimental Characterization and Model Parameter Identification

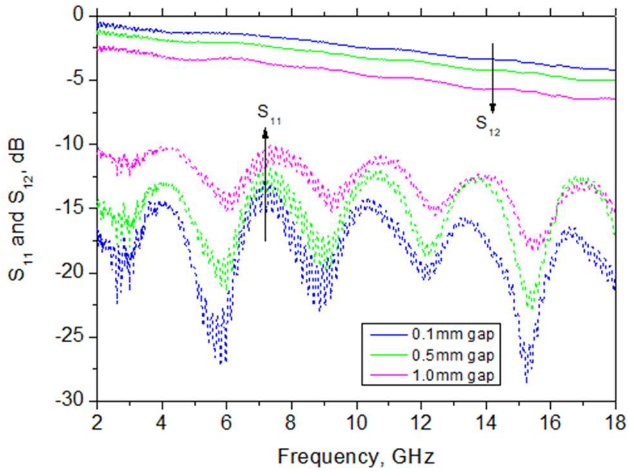
The circuits were characterized in the microwave range in terms of the scattering matrix by using a Vector Network Analyzer, VNA (Anritsu 37347C). A microstrip technique was used, with the set-up given in Fig.6, with the inset highlighting the test fixture (Anritsu Universal Test Fixture 3680-20). The latter consists of a fixed connector and a movable connector that can be positioned at required distance, up to 50.08 mm. Each connector is provided with spring loaded jaws, in which substrate can be placed. This system enables microstrip measurements.

The critical point in the measurement set-up is the transition between the microstrip under test and the coaxial cables connected to the two ports of the VNA. In practical cases, in spite of a careful design of the microstrip-cable transition, mismatch between the coaxial cables and the microstrip causes non negligible errors in both reflections and transmission measurements, whose reduction requires proper error correction techniques. To remove the errors coming from those mismatch, VNA systems require a proper calibration. Here we adopt the most common way to calibrate a system, that is the Short-Open-Load (SOL) method.

The results of the S-parameter characterization are shown in Fig.7. Different film thicknesses and circuit gap lengths are investigated. For a given thickness (SWCNT2 film), when increasing the gap length, the reflection increases and the transmission decreases (Fig.7a). For a given gap length (1.0 mm), when increasing the film thickness, the reflection decreases and the transmission increases (Fig.7b). This result is coherent with the sensitivity analysis performed in Fig.5.

Fig. 6. The set-up for the microwave characterization: the Vector Network Analyzer is connected to the text fixture (magnified in the inset).

(a)



(b)

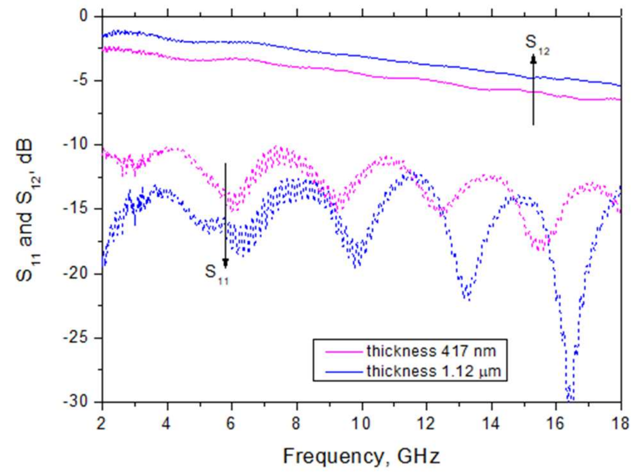


Fig. 7. Sensitivity of the measured transmission (S_{21}) and reflection (S_{11}) parameters to: (a) the gap length, and (b) the CNT film thickness.

The final step of the analysis was the identification of equivalent electrical parameters by comparing the simulation results to the experimental ones. To this end, the geometrical parameters were fixed by using their measured values. As already noticed, the film thicknesses were measured by SEM as 1.12 and 0.41 μm for the two film realization. The extra length of the film over the gap was measured by means of an optical microscope, and the results are given in Table 4.

By using these values, equivalent real permittivity and electrical conductivity values may be identified, by imposing the matching between the measured and simulated S-parameters. As an example, Fig.8 shows the results obtained for sample SWCNT2.3 in Table 2. For all the samples analyzed here, a matching as that in Fig.8 was found with the same values of equivalent electrical parameters, that resulted to be: $\varepsilon' = 20$ and $\sigma = 28$ kS/m. Being these values independent from the geometry, we can conclude that they are intrisinc values of the nanomaterial, including the effect of the CNT/copper contact). Note that the global electrical parameters (for instance the electrical resistance or capacitance) will of course depend on the geometrical dimensions of the sample.

TABLE 3.
EXTRA LENGTHS OF THE FILMS OVER THE COPPER TRACES.

SWCNT2	left (mm)	right (mm)
gap 0.1 mm	1.33	1.78
gap 0.5 mm	0.08	1.40

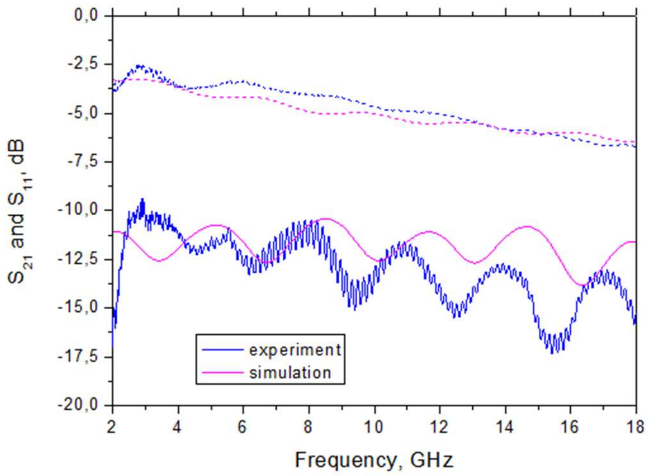


Fig. 8. Experimental and simulated values of the transmission (S_{21}) and reflection (S_{11}) for sample SWCNT2.3 (Table 2).

V. CONCLUSIONS

In this paper, we have fabricated a circuit embedding a carbon nanotube film, and characterized its scattering parameters in the microwave range. A full-wave model and an experimental characterization have been used to simulate and measure such parameters, in order to assess their dependence from the circuit design parameters, such as the film thickness or the material equivalent permittivity and conductivity. A microstrip embedding a 0.4 μm thickness SWCNT film is found to provide an equivalent conductivity of 28 kS/m and an equivalent relative real permittivity of 20.

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