SMART MULTILAYER FREQUENCY-SELECTIVE ABSORBER FOR MICROWAVE BASED ON HYBRID STRUCTURE OF POLYMER AND CARBON NANOTUBES

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Abstract - Telecommunication systems use advanced signal processing techniques based on multiple band operation/access, implying that frequency-selective EMI shielding solutions are preferred to classical broadband absorption. Mathematical considerations show that an arrangement of successive dielectric and conductive layers stands out as an attractive solution. A smart multilayer arrangement of polymer and carbon nanotubes produces an absorber where transmitted and blocked wavelengths can be controlled. The conductive layers are stacked in gradient of conductivity in order to limit the reflection of incident microwave and so increase absorption index. Thickness and permittivity of the dielectric polymer open up narrow transmission windows in the spectrum. It is therefore possible to isolate a room or building from a wide range of telecommunication systems except for narrow bands using a material with a total thickness lower than λ.

Keywords: Carbon nanotubes, multilayer, electromagnetic bandgap filter.

Introduction

The current telecommunication tools often require advanced technology beyond simple shielding or complete absorption [1]. The material should ideally filter out unwanted frequencies while being transparent to useful waves. The periodic structure of metamaterials is conducive to the creation of electromagnetic bandgap filters. We present here a thin microwave absorber based on carbon nanotubes (CNT) and a dielectric polymer. The polymer confers interesting mechanical properties to the device because of its strength, flexibility and easy thermoformability. The CNT network is obtained by depositing a waterborne CNT-based ink (AquaCyl^{TM}) on the substrate. These components are used to form submillimetric conductive and dielectric layers which are successively stacked. A smart periodic arrangement with increasing nanofiller concentration is obtained to absorb selected frequencies in the GHz range despite its overall millimetric thickness. This gives an advantage over recently described filter systems [2]. The system presented in this paper is producible on a large scale and relatively cheap. It is designed to cover wide surface such as an entire room or even a building.

Experimental

Electromagnetic absorption is defined as $A = \frac{P_{abs}}{P_{in}} = \frac{P_{in}-P_{ref}-P_{tr}}{P_{in}}$ where P_{tr} and P_{ref} are respectively transmitted and reflected power. It imposes the choice of a material with a low electromagnetic transmission but also a low reflection. In other words, this amounts to producing a conductive material (for low P_{tr}) with low permittivity (for low P_{ref}). Nonetheless no simple material gets those properties. An arrangement of successive dielectric and conductive layers stands out as an attractive solution to reach the aimed properties. Absorption increases further by reducing reflection if the stacking is organized in gradient of conductivity [3]. Making a gradient system requires producing a series of thin films having conductivity between ~1 and ~10^3 S/m. This range of conductivity is achievable thanks to carbon nanotubes composites or inks.

Most polymers have an intrinsic low permittivity. In this work, the dielectric layers are composed of pure polycarbonate (PC) chosen for its attractive mechanical properties. It is easily molded and thermoformed. Conductive layers are made from a dried carbon nanotubes (CNT) based ink deposited on PC films. For different reasons the nanotubes are probably the most suitable carbonated elements for this type of electromagnetic applications [4][5]. The wire-shape of CNT reduces the electrical percolation threshold. In addition, CNT have an extremely high intrinsic conductivity. The company NanoCyl provides the multi-walled nanotubes used in this paper. AquaCyl^{TM} is a CNT water-based ink from the same company. Its composition consists of 98% of pure water, 1% of multi-walled CNT and 1% of ionic surfactant. AquaCyl^{TM} is applicable on wide surfaces as a conventional ink. .

Actually, polycarbonate is hydrophobic; its wetting angle must be modified to allow a significant amount of CNT to be deposited as a homogeneous film on the polymer. A surface treatment is hence used to increase its wettability. A PC sheet is first activated by plasma. After several tests, it appears that a H_2O plasma is more efficient than O_3 or Ar plasma. Exposure for 5 minutes at a power of 150W alters the surface chemistry and roughness, so that the contact angle goes from 88° to 56°. The modified surface film is afterwards dipped in a solution of 3-aminopropyltrieth-oxysilane coupling agent during at least 1 hour at room temperature [6]. Thanks to the coupling agent, the prepared PC sheet can be dip coated in pure AquaCyl™ and enough CNT adhere to the surface to reach the upper limit of desired conductivity. A series of dip coatings is then performed with different dilutions of AquaCyl™. The amount of CNT attached to the polycarbonate surface is a function of ink dilution. As explained above, the conductivity of the films must cover a range of σ-values. In this manner, we produce coated films covering a range of conductivities for the gradient stacking. The resulting structure has the advantage of being especially thin since the conductive coat has a thickness of 2 to 6 µm. Figure 1 shows an example of a carbon nanotubes layer. The CNT density in the ink layer is also very high which implies a large σ.

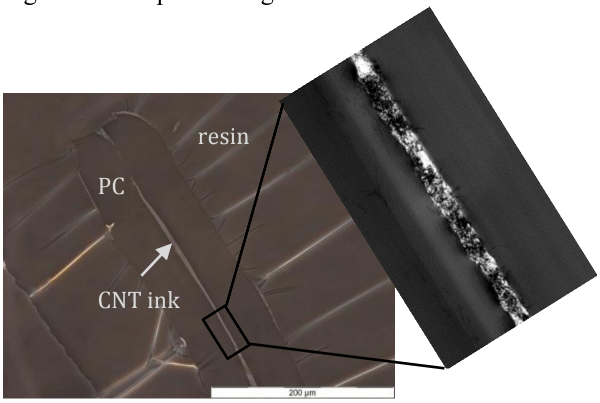

Figure 1 – Structure of CNT ink trapped between two polycarbonate sheets. The optical microscope image is zoomed 20x and the TEM one is zoomed 5000x.

Figure 2 confirms this observation since measurements of conductivity as function of concentration after dilution show that σ rises up to ~1500 S/m at GHz-frequency.

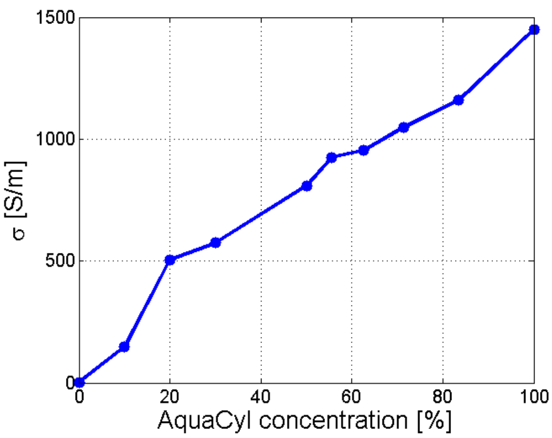

Figure 2 – Graph of conductivity at 33 GHz of carbon nanotubes layer dip coated on polycarbonate sheet according to dilution of AquaCyl™

Results and Discussion

The nanotubes deposits sandwiched between the polycarbonate sheets form the conductive films of the multilayer. To create the bandgap filter, conductive films are separated by insulating dielectric sheets made of a RF commercial substrate from Rogers Co. (RT/duroid®6010.2LM). The choice of this polymer is dictated by its high dielectric constant (ε = 10.2) in order to reduce the overall thickness of the bandgap filter.

Figure 3 illustrates the absorption index as a function of frequency and thickness of the dielectric. The simulation is based on a multilayer with 10 insulating dielectric sheets separated by 9 conductive layers showing linear progressive increase of conductivity from 1 to 10^3 S/m. For this example, we fix the thickness at 1.65 mm and we then observe two peaks of non-absorption.

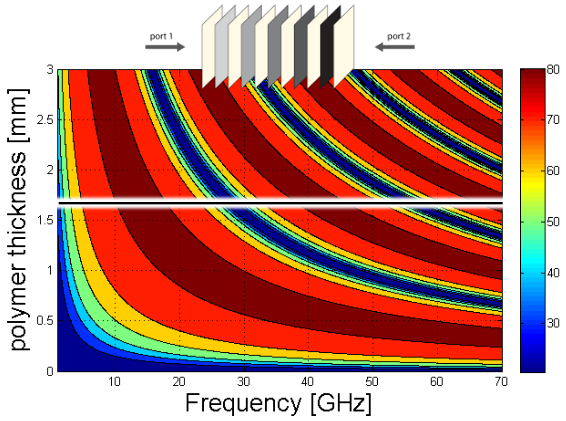

Figure 3 – simulation of absorption according to frequency and thickness of dielectric layer for whose permittivity is 10.2. The black line illustrates absorption corresponding to a dielectric thickness of 1.65 mm (as an example).

Electromagnetic characterization is performed with the help of a Vector Network Analyzer Model PNAX-70 from Agilent, on a multilayer having the same geometry and parameters than those considered for the analytical simulation above. Figure 4 shows measurement compared with theory.

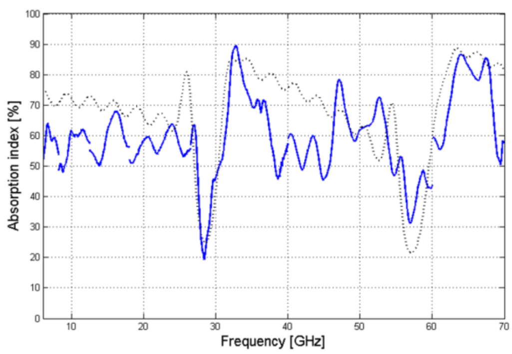

Figure 4 – Measured absorption of a AquaCyl™ based composite gradient multilayer, the thickness of the dielectric (ε = 10.2) is 1.65 mm compared with theory (dotted line).

The thickness of the dielectric plays an important role in defining the frequency bands where absorption occurs. It sets the distance between two conductive layers. But when the wave passes through the material, it is "trapped" between the conductive layers by multiple reflections. If this reflection region extends over n.λ/2 where n $\in \mathbb{Z}$, the incident and reflected waves are in phase. At frequencies matching this condition, the absorption is minimal. The phenomenon appears at 28 GHz and its harmonics corresponding to a half wavelength in the dielectric medium.
Theoretical analysis of metamaterial behavior proves that structural modification shifts the absorption peaks. The analytical simulation in Figure 5 shows a high absorption of Wi-Fi and almost transparency at lower frequencies like the ones used for mobile phones networks. This multilayer is produced from only two conducting layers separated by a dielectric layer of 9 mm and a permittivity of 10.2. The filter maintains a thickness of 27 mm while it works at frequencies at the entrance of GHz-range. The selected dielectric corresponds to Rogers substrate because the filter requires a high permittivity material to minimize the overall thickness. Ceramics such as granite or concrete would also reach such high values of permittivity. It is therefore possible to produce a filter from granite plates alternated with films of carbon nanotubes. They form quite reasonable candidates for the construction of isolated rooms. This theoretical study of multilayers is thus very encouraging because it demonstrates the versatility of our proposed system.

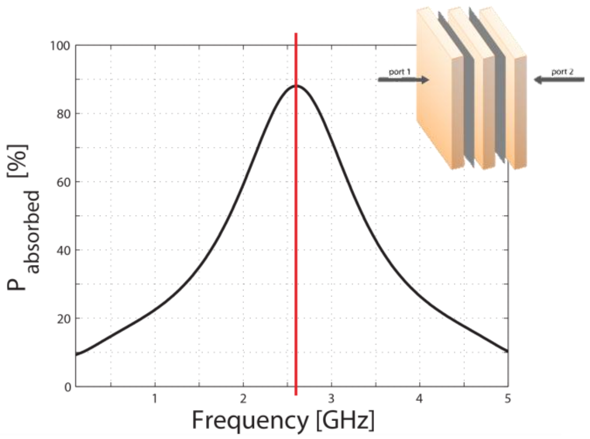

Figure 5 – simulation of filter based on 2 conductive layers separated by 3 dielectric substances 9 mm thick with ε=10.2

Two CNT coats are surrounded by the high-ε substrate that have a thickness of $\lambda/4 = 9$mm. This increases the "anti-resonance" effect in the 3 substrates and it reduces drastically incident reflection. The result is directly seen on the graph of absorption index dramatically increasing from 10 to 90% in the Wi-Fi frequency band.

Conclusions

The concept of lossy metamaterials opens up new avenues for microwave absorption. In this paper, we have developed an effective thin and flexible bandgap filter solution. This way, it should be possible to cover electronic, medical devices or others to isolate them from external and internal electromagnetic interferences. On a larger scale, companies could prevent data leakage from wireless LANs by isolating dedicated rooms or entire buildings. An analytical model has been developed to simulate the structures, using the simple but accurate chain matrix formalism. Its prediction of the metamaterial frequency response is in good agreement with measurements.

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