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Thin and flexible multilayer polymer composite structures for effective control of microwave electromagnetic absorption

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ABSTRACT

We describe a novel multilayer arrangement of polymer nanocomposites, which is able to very effectively absorb microwave radiation over a broad frequency range or selectively reflect desired wavelengths. The structure is built from alternating films of dielectric polymer and conducting layers. The latter are stacked in a precise gradient of conductivity. The conducting layers consist of either polycarbonate nanocomposite films with carbon nanotubes (CNT) or a very thin CNT coating deposited on insulating polymer from a CNT waterborne ink. In order to ensure good wetting of polycarbonate by the ink and high resulting conductivity of the dry coating, a plasma treatment of the polymer is essential.

The stacked multilayer structures are easy to make, modular, and open up new possibilities in the area of microwave management (broadband shielding by absorption or frequency-selective filtering, also called bandgap control). The analytical model developed to simulate the absorbers and filters is in good agreement with experimental characterisation and could be further extended to the design of systems operating in other frequency ranges.

1. Introduction

Wireless communication via electromagnetic (EM) transmission in the microwave range is a fast and simple solution for a lot of applications and has become ubiquitous in everyday life. In parallel, electronic devices are becoming ever more compact and integrated. These trends generate a growing issue with EM interference, which can occur between devices or, even worse, between subcomponents of the devices themselves. The consequences can range from simply annoying to outright dangerous [1]. Classical broadband EMI shielding is based on EM reflectors, usually metal foils or coatings, called Faraday cages [2]. These methods are less and less satisfactory in the present environment because the interfering EM signal is only deflected in another direction where it can still create havoc. This explains the growing popularity of EM absorbers, which truly eliminate the EM signal in directions or locations where it is unwanted.

As explained below, EM absorption is a delicate balance between high conductivity and low dielectric constant. Metal-based EM absorbing structures are impossible to obtain because EM waves do not penetrate the material but are reflected instead. Effective EM absorbing structures must comprise a large majority of low permittivity dielectric material and a small fraction of finely distributed conducting particles, which immediately suggests the use of polymer-based heterogeneous materials, in particular nanocomposites and hybrid structures [3]. The need for overall high conductivity also requires percolation of the conducting substructure in the matrix, hence conducting particles with high aspect ratio are preferred and an excellent control on dispersion of the conductive filler is essential. Multiwall carbon nanotubes (CNT) are a logical choice for the conductive filler [4,5] as their high aspect ratio and easy dispersibility in selected polymers allows reaching the percolation threshold at low loading level. In addition, CNT have an extremely high intrinsic conductivity. The low permittivity matrix allows EM waves to penetrate deeply in the absorbing structure but the conducting network dissipates the EM energy through complex resistive-capacitive coupling and multiple internal reflections [6]. Current polymer-based solutions and ideas for EM control use (nano) composites with carbon nanotubes, graphene [7] and/or metal particles [8]. These composites are inefficient in terms of EM absorption because their effective permittivity is still too high and they primarily reflect the signal. Foaming the polymer matrix is an efficient method to reduce reflectivity by decreasing the permittivity, but at the expense of thickness [9] and is thus not suitable for compact applications. A recently described multi-scale “hybrid” structure offers a better compromise between EM absorption and structure thickness [10].

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The current telecommunication devices require advancing technology further than uniform shielding at all frequencies. It is often necessary to selectively absorb undesired waves while transmitting the signal in other frequency bands [11]. It might be important to absorb all frequencies except for a narrow useful band. This level of control is called electromagnetic bandgap (EBG) filtering. It requires organised structures with defined periodicity, interacting selectively with certain EM frequencies, which fall under the broad definition of metamaterials [12].

This paper presents novel hierarchically organised multilayer polymer structures, very effective for EM absorption or EBG control in the typical microwave frequency range. The structures are obtained by stacking conductive and insulating layers. The conductive layers can either be obtained in the form of polycarbonate-carbon nanotubes (PC-CNT) nanocomposite films or as CNT-based ink coatings on neat PC films. PC has low relative dielectric constant in the GHz range ($\varepsilon = 2.8$). Compounded with CNT, it offers durable mechanical properties [13]. Multiwall CNT are also easy to disperse in this polymer [14]. The effectiveness of the multilayer structures stems from their gradient periodic arrangement. Indeed, a controlled gradient of conductivity across the stacked pile is the key to their shielding effectiveness. The structures are easy to make, very thin (thickness much lower than the centimetric wavelength) and conformable. Despite their small thickness, they can, depending on the specific arrangement, either absorb effectively over a broad frequency range [15], or allow certain frequencies over spectrum. In the latter case, we get a frequency selective surface, with high reflectance at a precise frequency but strongly absorbing everywhere else. Such structure can, for instance, function as a prefilter for an incoming signal, e.g. on a parabolic antenna. Usually, structures used for GHz-EBG are either complex/intricate [16,17], thick [18] or expensive [19]. The multilayers proposed in this work have the advantage of a very simple process. Moreover, they are "modular", i.e. they can easily be restacked to respond to a new frequency absorption target, without rebuilding them from scratch.

The paper is organised as follows. A quick reminder on EM absorption and bandgap control theory is first provided. Next, the experimental details on materials and methods are given. This is followed by a presentation of the main results. First, issues relating to the wetting of the PC films by a CNT water-based ink and the control of the conductive layers conductivity (ink-based and nanocomposites-based) are discussed. This is followed by a detailed presentation of the EM absorption and filtering results. Finally, conclusions are drawn.

2. EM absorption and bandgap control: main concepts

2.1. EM absorption

An incoming wave on a typical slab-shaped obstacle can be (partially) reflected, transmitted or absorbed. The absorption index is defined by $A = \frac{P_{abs}}{P_{in}} = \frac{P_{in} - P_{ref} - P_{tr}}{P_{in}}$ where P_{tr} and P_{ref} are respectively the transmitted and reflected power. For maximal absorption, a material with a low electromagnetic transmission but also a low reflection must be chosen. The extinction (also called attenuation) is controlled by the thickness and conductivity of the component as shown by the following equation: $E = -20 \cdot \log(e^{-t\sigma})$ [20]. Highly conductive components provide excellent extinction. On the other side, the reflected power also increases with conductivity, drastically reducing the amount of energy actually absorbed. Neglecting multiple reflections, the reflected power is $P_{ref} = |\Gamma|^2 \cdot P_{in}$ where Γ is the reflection coefficient at the interface with the incoming wave, expressed as $\Gamma = \frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}}$ [21]. Reflection is minimal if ε_r is equal to 1, namely for air. Those mathematical considerations show that an absorber must combine high conductivity and low permittivity. Unfortunately, no simple material combines those properties. A clever arrangement of high conductivity and low permittivity zones must be imagined. A stack of successive dielectric and conductive layers stands out as an attractive but little studied option to reach the aimed properties.

In addition to the intrinsic properties of the material, the arrangement of layers plays an important role for maximal absorption. A gradual increase in conductivity lets the wave propagate deeper into the material [22]. As the wave progresses in the multilayer, reflection increases but it takes place inside the multilayer. A conductivity gradient of the conductive layers hence leads to a higher overall absorption due to reduced reflected power. The direction of incidence becomes also critical. Referring to the inset of Fig. 1, the incident wave must penetrate the multilayer at the low conductivity end of the gradient, i.e. at port 1. Reflection would be prohibitive for a wave incident at input interface of port 2.

A simple method based on chain matrix conversion simulates the scattering parameters (S-parameters) and absorption index if the physical parameters of each layer are known. S-parameters are relevant quantities widely used in microwave measurements and analysis. They link, in matrix formalism, the incoming and reflected waves and are helpful to gain precise understanding of the electromagnetic behaviour of a multilayer. We use an analytical model, implemented in Matlab software, which is based on the theory and methodology detailed in Ref. [23]. As an example, analytical simulations in Fig. 1, compare two types of absorbers composed of 12 conductive layers, 5 μm thick and 13 dielectric layers, 300 μm thick. The conductive layers of the first system are arranged in a gradient of conductivity while, in the second system, they have the same fixed conductivity. The average conductivity of the two examples is identical and equal to 10^3 S/m. Fig. 1 shows a significant difference of absorption in favour of the gradient multilayer.

Making a gradient system requires producing a series of thin films with finely controlled conductivity. In this paper, we propose two versatile solutions to this problem, one based on CNT-PC nanocomposites and another using CNT water-based ink deposited on PC substrates.

2.2. Frequency-selective filtering

The absorber can be tuned to open narrow bands of weak-absorption at desired frequencies. Such a feature is possible by changing the geometric parameters of the multilayers described

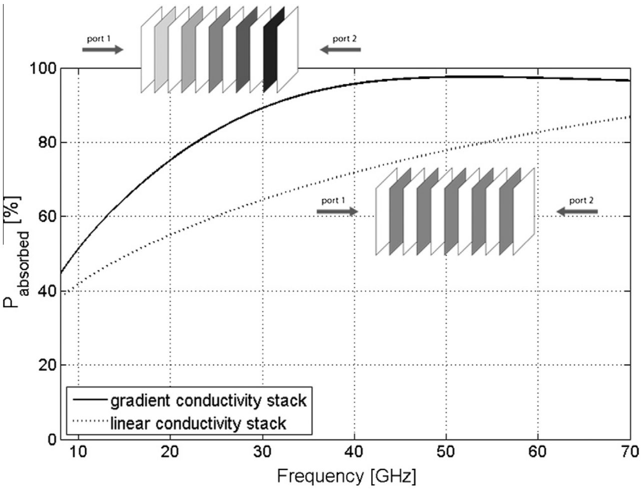

Fig. 1. Simulation of a gradient conductivity stacking (full line) and a constant conductivity system (dotted line). The systems have 12 conductive layers 5 μm thick and 13 dielectric layers 300 μm thick for an overall conductivity of 10^3 S/m. The inset shows a pile in gradient of conductivity of dielectric (white) and conductive (grey) layers.