MICROWAVE PROPERTIES OF HOLLOW CARBON SPHERES WITH DIFFERENT ELECTRICAL CONDUCTIVITIES

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Hollow carbon spheres (HCS) were prepared by hydrothermal treatment of sugar alcohols encapsulated in a UV-cured polymer followed by carbonization at different temperatures, ranging from 500 to 1500 °C. Spheres with a significant variation in electrical conductivity, in the range of 10^{-6} – 10^{4} S/m, were obtained in a controlled manner.

The electromagnetic properties of non-compact rectangular arrays of HCS were investigated in the microwave frequency range. The best absorption performance at 30 GHz was shown by the sample prepared at 700 °C, whose conductivity is optimized to achieve a high absorption ability at the given HCS shell thickness vs its skin depth.

Keywords: hollow carbon spheres; electromagnetic shielding; skin depth; metasurface.

Introduction

Metamaterials and metasurfaces are the most efficient approach to obtain the perfect absorption of the electromagnetic wave at subwavelength geometrical parameters of the structures. keeping the weight light and the thickness small as possible [1-3].

Unlike low-density carbonaceous porous irregular meshes such as aerogels [4, 5] and foams [6, 7], the hollow carbon spheres (HCS) manifested themselves as perfect resonant electromagnetic absorbers. With the dimensions of their geometrical features (pores, open windows between pores) close to electromagnetic radiation wavelength, HCS are potentially applicable as metaatoms or building blocks for metasurfaces or metamaterials of sophisticated geometry [8, 9].

The diameter of HCS is typically between ~100 nm to millimeters, while the wall thickness may vary from 2 nm and a few millimeters [10], while the surface porosity and conductivity may be also varied in a wide range. The high variability of HCS parameters makes them suitable for the development of different metastructures, which in turn could be used as functional components of numerous passive microwave devices (filters, polarizers, lens, collimators, attenuators, etc).

We propose here a simple geometry, namely the non-compact packing of HCSs, in order to establish the main trends that could be expected for metastructures composed of a carbon skeleton with substantially different conductivities determined solely by the HCS processing conditions.

Materials and methods

HCS were prepared hydrothermal treatment of UV-cured spherical capsules filled with sugar alcohols, immersed in a 7.4 wt. % aqueous sucrose solution autoclaved at 180 °C for 24 h [8]. Then, the spheres were recovered, washed, dried, and pyrolyzed in an inert atmosphere, and finally sieved to recover only those with an average diameter of ~800 μm. The average wall thickness was ~50 μm. The pyrolysis temperature was varied from 500 to 1500 °C, resulting in the following conductivity values, which correspond to the average of two measurements. As can be seen in Table 1, this simple difference in heat treatment provided a wide range of electrical properties, from dielectric to rather good conductors.

Table 1. Conductivity and skin-layer depth at 30 GHz of HCS prepared at different temperatures

Temp.°C	Conductivity, S/m	Skin-layer depth at 30 GHz, mm
500	3.9×10^{-6}	1471,39
600	0.0013	80,59
700	100	0,29
800	3065	0,05
900	11400	0,03
1500	11250	0,03

The investigation of HCS electromagnetic properties was performed in 26 - 37 GHz frequency region (Ka-band) using Elmika R2-408 scalar network analyzer. The rectangular array of 18 spheres was placed into the cross-section of 7.2×3.4 mm waveguide. Spheres were fixed by a double-sided scotch tape to avoid the electric contact between individual spheres. The array was oriented towards port 1 of the scalar analyzer in order to ensure the measurement of the spheres' reflection.

The scalar network analyzer records the relative amplitudes of the reflected and transmitted radiation, i.e., the scattering parameters of the system under study. The parameters S_{11} and S_{21} correspond to the reflection and transmission coefficients (R and T), respectively. The absorption coefficient can also be calculated as $A = 1 – R – T$.

Results and discussion

In Figure 1 the reflection, transmission, and absorption coefficients at 30 GHz frequency of HCS arrays with different electrical conductivity are shown.

It can be seen that the temperature dependencies of material conductivity and the reflection coefficient of HCS arrays are in agreement. The reflection coefficient increases monotonically with conductivity increase, while the transmission coefficient

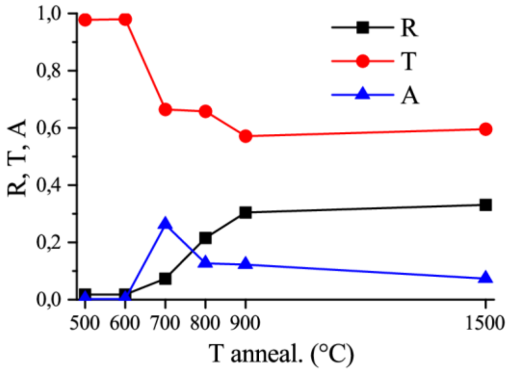

Fig. 1. Reflection (R), transmission (T) and absorption (A) coefficients at 30 GHz for rectangular arrays of HCS prepared at different temperatures

decreases. It is worth noting that the absorption coefficient, in this case, reaches a maximum for the sample prepared at 700 °C. This sample indeed combines two interesting parameters: its skin depth is higher than the HCS shell thickness, while the material remains sufficiently conductive to interact with the microwave radiation. Samples prepared at higher temperatures have a skin depth very close to the shell thickness, which means that their interaction with the EM-wave is similar to that of a solid sphere. HCS prepared at lower temperatures possess very low conductivity values, which makes their interaction with microwave radiation negligible compared to HCS prepared at higher temperatures.

Conclusion

Hollow carbon spheres of sufficiently different conductivity have been produced with constant diameter and shell thickness. The study of their electromagnetic properties in the microwave frequency region revealed the strong dependence of electromagnetic response on the processing temperature. The maximum absorption at 30 GHz was achieved with the sample prepared at 700 °C. The skin depth of that sample is higher than the shell thickness, i.e. the radiation partially penetrates the spheres. Simultaneously the conductivity of material remains sufficient to achieve the interaction between the microwave radiation and the spheres array.

Acknowledgements

This research was sponsored by the Horizon 2020 MSCA-RISE 734164 Graphene 3D project, NATO Science for Peace and Security Programme [grant G5697 CERTAIN "Globular carbon-based structures and metamaterials for enhanced electromagnetic protection"

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