# *Temperature-Dependent Complex Permittivity of Several Electromagnetic Susceptors at 2.45 GHz*

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## Introduction

Electromagnetic susceptors, understood as transductors of energy, from radiative to thermal, are of high interest when combined with materials that are non-efficient by themselves in a heating process using microwave technology. Susceptors can be either embedded into the material (as filaments, powders, etc.) or attached to them as a supplementary layer added on their interfaces.

The loss factor modelled as the imaginary part of the complex permittivity of a material can predict the result of the pyroelectric effects that underlies during its microwave heating process. Such mechanisms have a dependence on temperature, hence the heating process rate may evolve with time as the temperature varies. Furthermore, the heat transfer coefficient can also vary with the temperature. Both, the loss factor and the heat transfer coefficient are involved in the heat transfer equation, and their dependence with the temperature can largely justify the thermal runaway effects. Such effects are noticeable when the heat generation and transfer rates overcome the period of time required by any artifacts introduced inside a microwave exposure chamber for leveling the volumetric heating uniformity.

This study focuses on determining the complex permittivity of several susceptors at the 2.45-GHz frequency, in the temperature range 30-70 °C.

## Materials and methods

All the materials under test were solids in the form of powders. The samples were contained in test tubes for being measured with the dielectrometer ITACA's Dielectric Kit for Vials. The test tubes containing the samples were heated previously up to around 90°C in a water bath (Balneum Mariae), using a boiling recipient pre-heated in a domestic microwave oven. While the sample temperature was naturally cooling down towards the room temperature, as rules the Newton's law of cooling, the measurements of the dielectric constant and the loss factor were performed using the dielectrometer, and the temperature using an optical fiber temperature sensor (OpSens OTG-A) along with a signal conditioner (OpSens TempSens), following the methodology presented in the literature[1]. The experimental setup is shown in Fig. 1.

In order to get a fixed reference point for the temperature probe, the robust configuration depicted in Fig. 2 was designed. Such configuration is aimed to keep the fiber as straight as possible within the tube (adding 2 extra drilled caps), in order to avoid its crushing on the cap edges (inserting a Styrofoam piece into the outermost cap hollow), and to keep the fiber tip at a constant distance $d$ from the tube bottom (sticking a stop-tape around the fiber).

The distance $d$ = 23 mm was chosen to be as closest as possible to the measurable tube segment (which occupies part of the dielectrometer cavity) without getting into it for avoiding any possible disturbance in the complex permittivity measurements and get the most accurate temperature readings.

The tested materials are listed on Table 1. The density is a quotient of two variables, so its uncertainty has been estimated accordingly by computing the following equation:

$$\Delta\rho = \rho\left(\frac{\Delta m}{m} + \frac{\Delta v}{v}\right),$$

where $m$ and $v$ stand for the mass and volume, respectively, and $\Delta$ denotes the uncertainties.

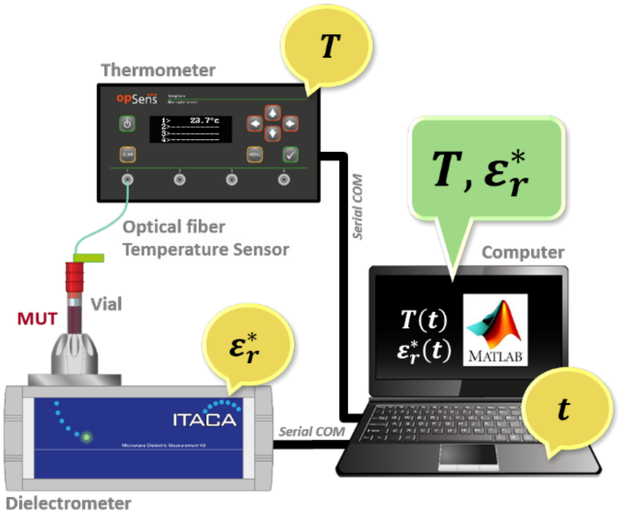

**Figure 1:** Experimental setup.

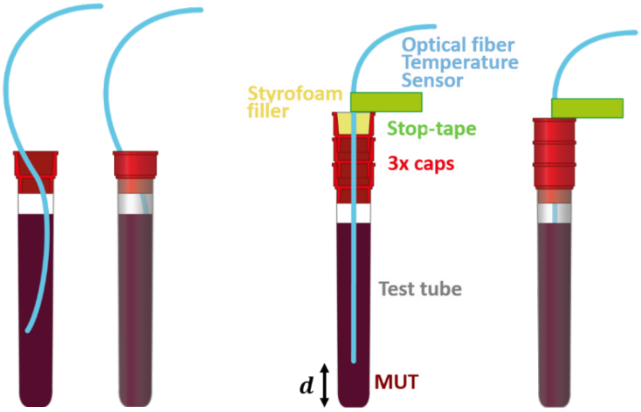

**Figure 2:** Detail of the temperature sensor configuration: weak (left) and robust (right) schemes.

For each material, the measurement protocol was repeated at least 3 times in order to get averaged values of their dielectric properties vs. temperature at 2.45 GHz.

**Figure 3:** Volumeter designed with a parallax error control (4.7 ± 0.1 cm$^3$ readable)

The raw data was processed under a Matlab platform. Each recorded measurement was interpolated to get a resolution of 0.1°C, and then trimmed to get all the set ready within the same temperature range (and values) for the averaging process, as shown in Fig. 4.

## Results

The averaged dielectric constant and loss factor curves versus temperature at the frequency of 2.45 GHz for each material listed in Table 1 are shown in Figs. 5-11. The values discretized at the temperatures of 30°C, 50°C and 70°C are listed conveniently in Table 2. Finally, the graphical comparison among all the materials is depicted in Figs. 12, 13.

**Table 1**. Tested materials

| Material | Chemical formula | CAS number | Mass (g)* | Volume (cm$^3$)* | Density (kg/m$^3$) |
|---|---|---|---|---|---|
| Activated Charcoal | C | 7440-44-0 | 1.2 | 4.0 | 300 ± 30** |
| Silicon Carbide | SiC | 409-21-2 | 8.7 | 4.6 | 1890 ± 60 |
| Silicon Dioxide | $SiO_2$ | 7631-86-9 | 4.0 | 4.6 | 870 ± 40 |
| Aluminum | Al | 7429-90-5 | 3.7 | 3.6 | 1360 ± 60 |
| Copper | Cu | 7440-50-8 | 26.9 | 4.8 | 5600 ± 100 |
| Copper Oxide | CuO | 1317-38-0 | 15.0 | 4.7 | 3190 ± 90 |
| Titanium Oxide | $TiO_2$ | 1217-70-0 | 4.0 | 3.9 | 1030 ± 50 |

* Uncertainty of ± 0.1. ** Density uncertainty is greater than 5%.

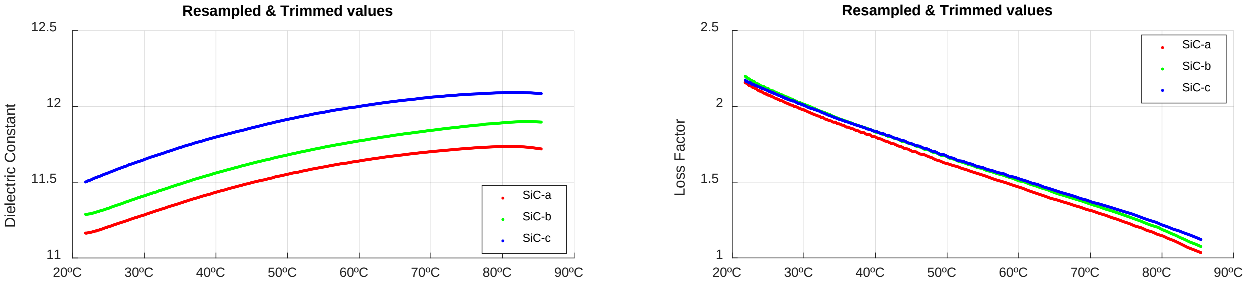

**Figure 4:** Raw data resampled for a resolution of 0.1°C, and trimmed.

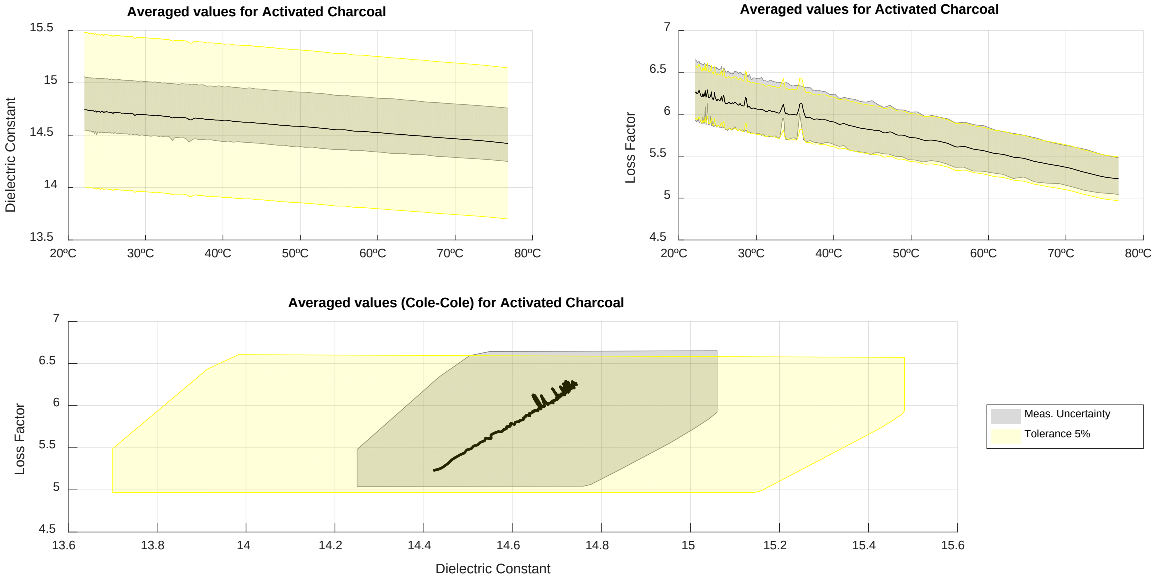

**Figure 5:** Averaged dielectric constant and loss factor for activated charcoal at 2.45 GHz

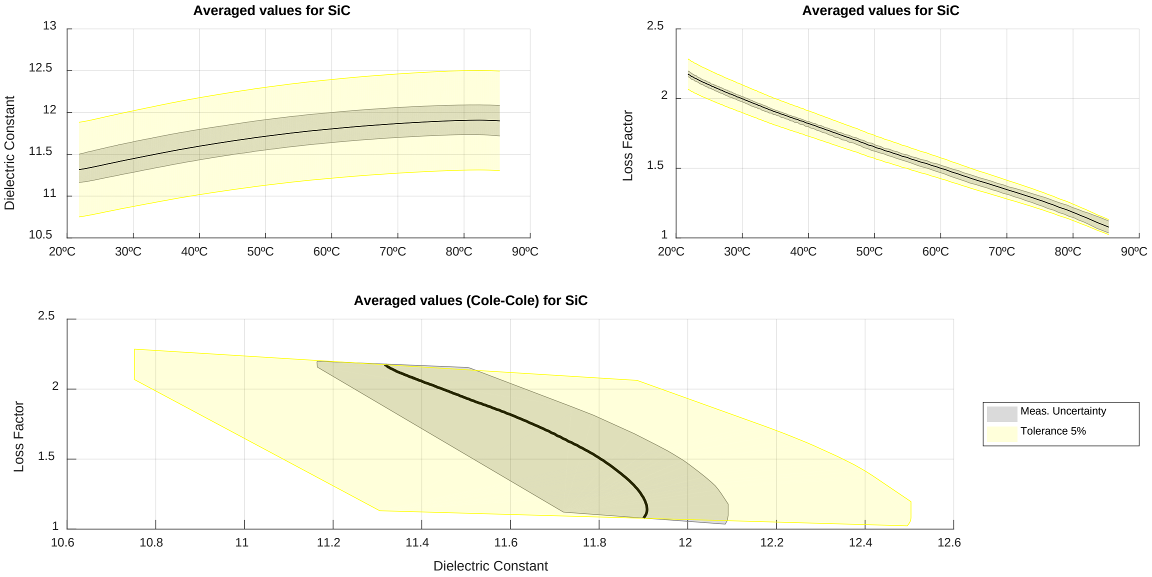

**Figure 6:** Averaged dielectric constant and loss factor for Silicon Carbide at 2.45 GHz.

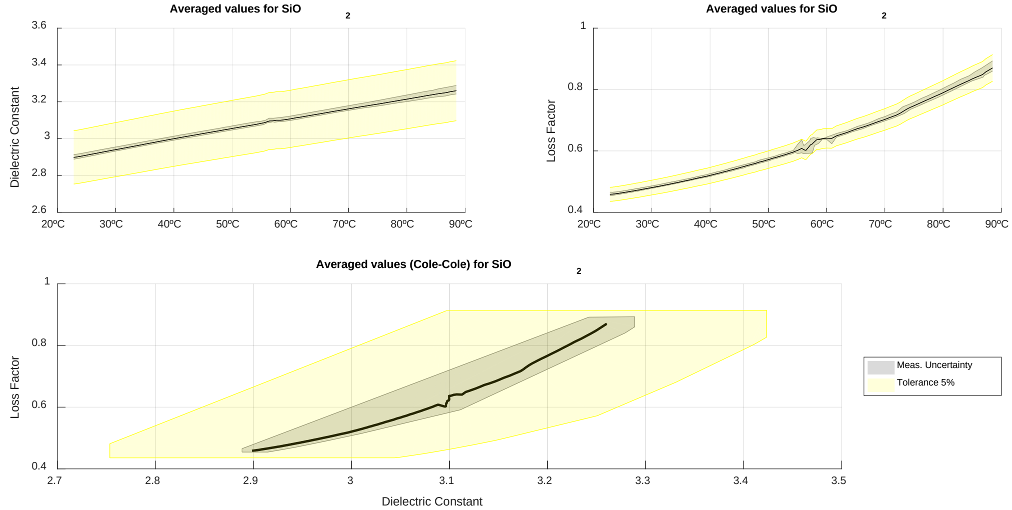

**Figure 7:** Averaged dielectric constant and loss factor for Silicon Dioxide at 2.45 GHz.

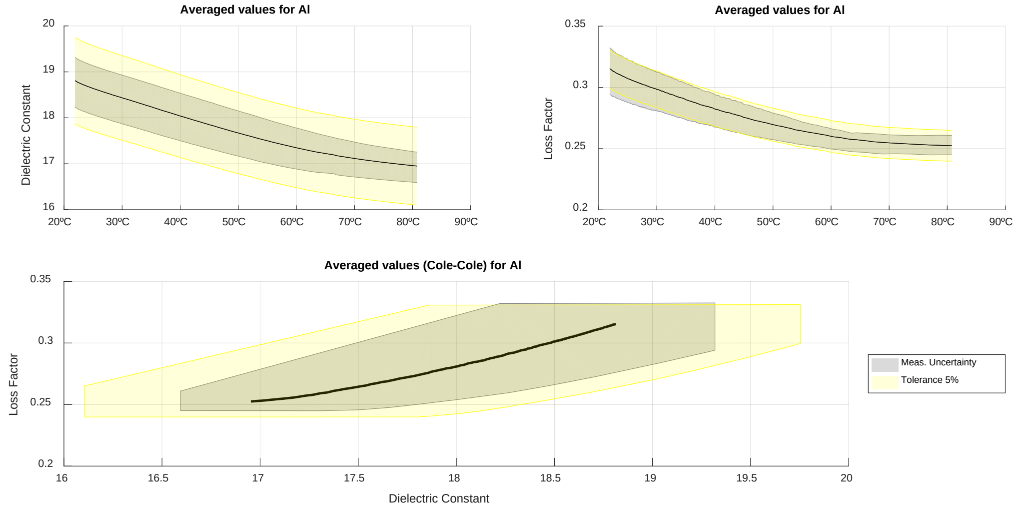

**Figure 8:** Averaged dielectric constant and loss factor for Aluminum at 2.45 GHz.

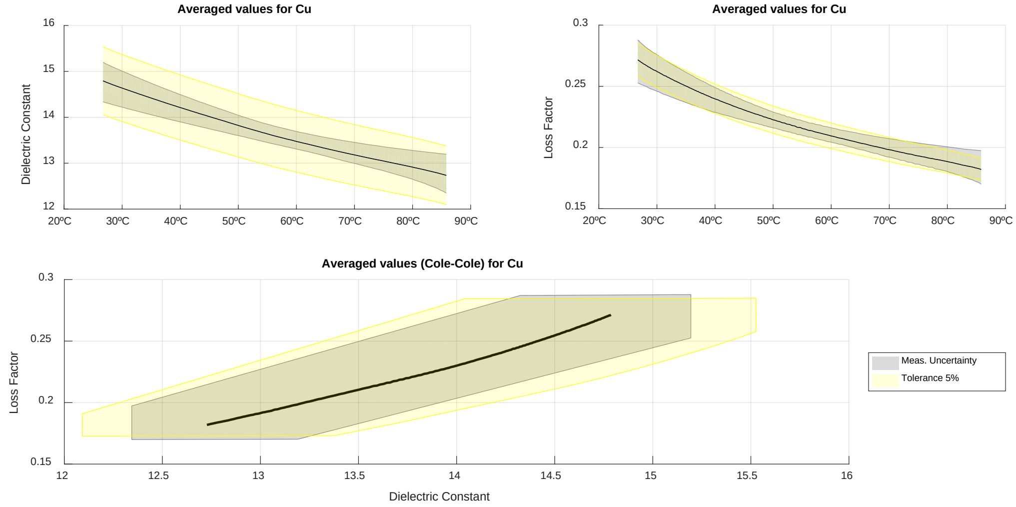

**Figure 9:** Averaged dielectric constant and loss factor for Copper at 2.45 GHz.

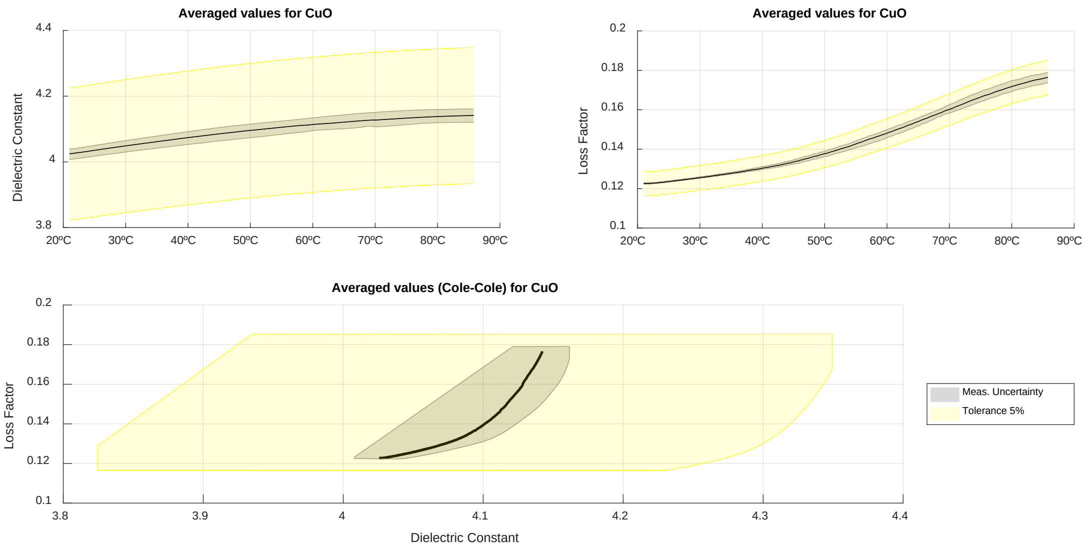

**Figure 10:** Averaged dielectric constant and loss factor for copper oxide at 2.45 GHz.

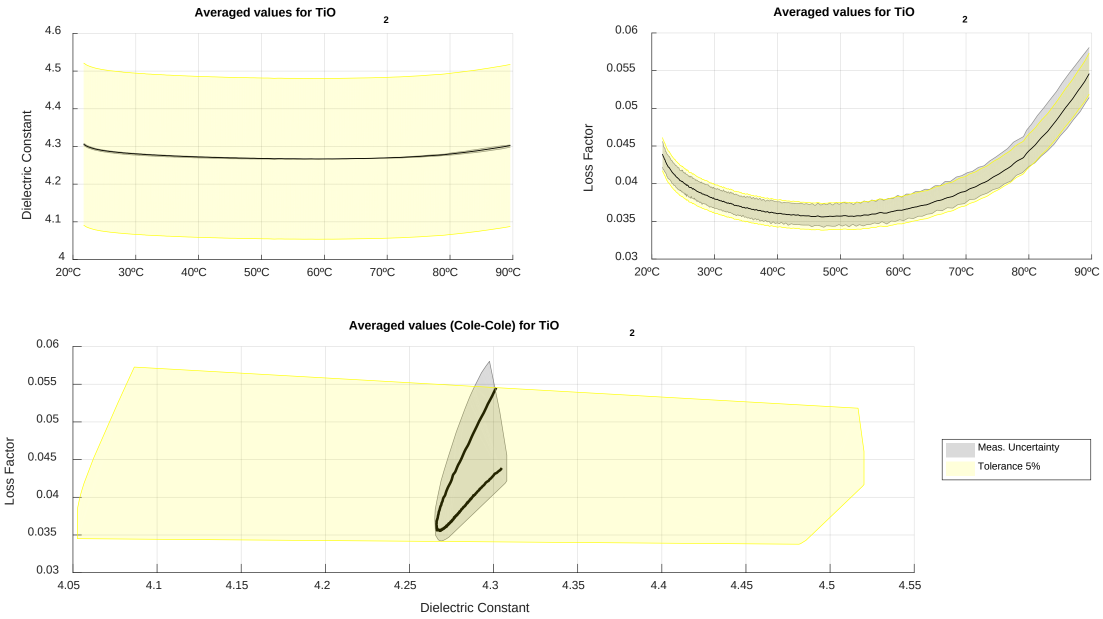

**Figure 11:** Averaged dielectric constant and loss factor for Titanium Oxide at 2.45 GHz.

**Table 2**. Complex relative permittivity values of the materials at 2.45 GHz vs. temperature.

| Material | Chemical formula | Complex relative permittivity $\varepsilon_r^*$ $(2.45\ \mathrm{GHz}, T)$ | | |
|---|---|---|---|---|
| | | T=30°C | T=50°C | T=70°C |
| Activated charcoal | C | $14.69 - j\,6.06$ | $14.5 - j\,5.72$ | $14.47 - j\,5.37$ |
| Silicon carbide | SiC | $11.45 - j\,2.00$ | $11.72 - j\,1.65$ | $11.87 - j\,1.35$ |
| Silicon dioxide | $SiO_2$ | $2.94 - j\,0.48$ | $3.06 - j\,0.57$ | $3.16 - j\,0.70$ |
| Aluminum | Al | $18.44 - j\,0.30$ | $17.67 - j\,0.27$ | $17.12 - j\,0.25$ |
| Copper | Cu | $14.63 - j0.26$ | $13.82 - j\,0.22$ | $13.17 - j\,0.20$ |
| Copper oxide | CuO | $4.05 - j\,0.13$ | $4.10 - j\,0.14$ | $4.13 - j\,0.16$ |
| Titanium oxide | $TiO_2$ | $4.28 - j\,0.04$ | $4.27 - j\,0.04$ | $4.27 - j\,0.04$ |

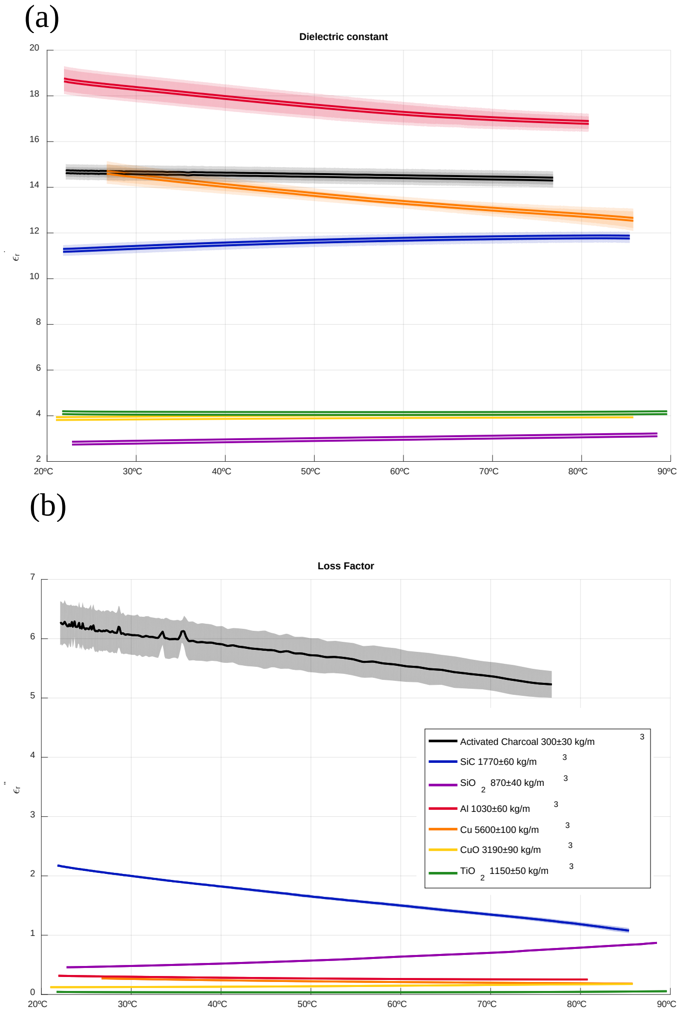

**Figure 12:** Curves for the dielectric constant (a) and the loss factor (b) vs. temperature of the listed materials at 2.45 GHz.

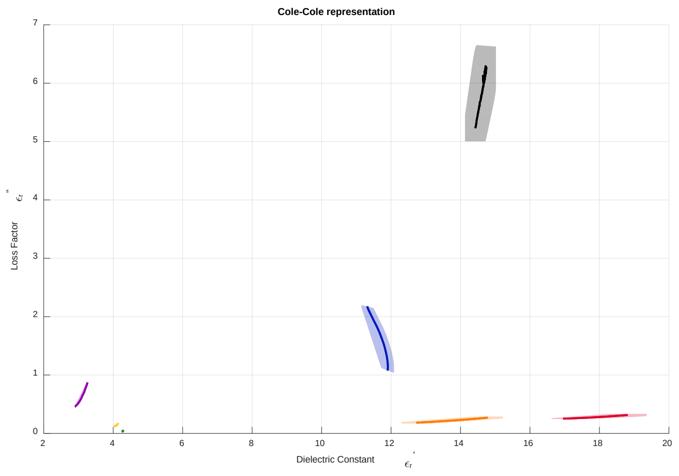

**Figure 13:** Curves for the dielectric properties (in a Cole-Cole representation) of the materials at 2.45 GHz.

## Conclusions

The silicon-carbide and active-charcoal loss-factor curves shown in Fig. 4 are decreasing as the temperature increases, with slopes of around $-0.016/°C$ and $-0.017/°C$ respectively. This means that they are good candidates for being electromagnetic susceptors, where the thermal runaway must be controlled. On the other hand, the loss factors of silicon dioxide and titanium oxide increase with temperature, hence they might be interesting susceptors to be considered where the application requires forcing a thermal runaway.

Regarding the dielectric constant, the susceptor might also be chosen for impedance mismatch considerations. For instance, copper or aluminum, instead of being good susceptors due to their low loss factor, they might be helpful where the introduction of partial shielding effect is required. Oxides of titanium and copper are neither good susceptors by themselves, also because of their low losses, but they show a relatively low dielectric constant which can be useful in combination with good susceptors to improve the impedance matching and achieve a better energy absorption.

It has to be noted that the activated charcoal used was an extremely refined powder composed of relatively tiny and light particles. It was not possible to measure it at higher densities since its dielectric parameters increased over the measureable limits of the dielectrometer. Moreover, while the sample was being heated, it was volumetrically expanded, probably due to the expansion of the air with temperature.

## For further reading

1. J. Fayos-Fernández, R. B. Mato, J. Monzó-Cabrera, M. J. Cocero-Alonso, "*Low-cost setup for the characterization of the dielectric properties of materials versus temperature*", AMPERE 15th Int'l Conf. Microwave and High-Frequency Heating, Krakow, 2015. DOI 10.13140/RG.2.2.11332.83843

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Prof. Monzo-Cabrera participates in the research group of Electromagnetism and Matter of the UPCT, activity that has been combined with innovation and technology transfer. He has specialized in microwave heating, the measurement of dielectric properties, and the instrumentation and measurement of microwave devices. Among other publications, he is co-author of more than 40 international Journal publications and 60 contributions to congresses. He has coauthored several book chapters as he is also a co-inventor of nine patents. He has been a researcher in 22 projects with private financing, and in 21 projects with public funding, two of them European. He is a member of the management Committee of AMPERE EUROPE and past General Secretary of this association.

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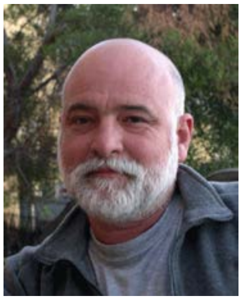

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