EPJ Web of Conferences **313**, 04007 (2024) https://doi.org/10.1051/epjconf/202431304007
EC22

Tuning optical properties to optimize microwave absorbers

Andreas Hentrich[1,*] and *Christian* Semmler[2]

[1]University of Stuttgart, IGVP, 70569 Stuttgart, Germany
[2]University of Stuttgart, IFKB, 70569 Stuttgart, Germany

Abstract. Microwave absorbing materials are critical for several components including bolometers and beam dumps. Profound knowledge of the material properties and the material-wave interactions is a necessity for both design and use of these components. With the strong focus of the ITER absorbing components on ceramic materials, a systematic study was performed to methodically investigate the optical properties of the aluminium oxide-titanium oxide material system.

1 Introduction

The investigation of optical properties in the sub-terahertz range is connected to a wide range of challenges, first of all that many electronic components do not work anymore and many optical components do not work yet for these frequencies. Thereby to extract material properties for this frequency range several indirect measurement procedures have been developed, like quasi-optical resonators [1] and the gap method [2].

In these, the material properties are obtained, by scanning a measurable value, usually the reflected or transmitted power percentage, over one or several parameters, usually the frequency or a geometrical property, and these scans are fitted to a model describing the geometry of the system.

2 Of methods and models

Thereby the investigation is two-fold in nature: An experimental part, which gives measured values as starting points for the fitting, and a theoretical part, with which these fits can be associated with material parameters, both of which will be shortly introduced in this chapter.

2.1 Measurement method

The measured value in this work is the reflectivity, the scanned parameters are the thickness of the coatings measured, the incidence angle of the incoming microwaves and the polarization. The respective values for the reflected power percentages were obtained in single-path measurements using a vector network analyzer and two horn antennas. The measured reflected powers of the samples were compared with the ones of an aluminum mirror at the position of the samples.

When the absorption of the sample is low, the accuracy of this setup is limited: As mentioned before, just the single-path absorption is obtained, so the difference between measurement and reference becomes negligible, leading to catastrophic cancelation and making single-pass measurements of reflectivities above 80% unreliable.

2.2 Modeling and fitting

The principle geometry of the system is very simple: The air/vacuum the microwave comes from and is reflected back into, a plane interface with the coating material, a slab of material and a plane interface to a metal wall. The only large complication is, that for the materials investigated the dielectric assumption of conductivity being negligible is not applicable, leading to a more complicated description of the transmission through the coating and slightly different descriptions of loss and refraction defining parameters [3].

Two options were implemented to model this system: A plane wave model, where all the different interfering waves inside the system are followed and calculated, allowing to get recursively better estimations of the reflectivity in the power equilibrium case, which usually is already reached after just a few internal reflections. The second model is a modification of the classical transfer matrix formalism adopted for reflections, giving instantly the steady-state case at the cost of useful intermediate results.

Both are consistent with each other and the measurements and the short computation time of the matrix model makes the fitting very straightforward: For a large range of optical properties the reflected power percentages are calculated for the parameter scans used in the measurements and in the end the optical properties with the smallest mean square average difference to the measurements are assumed to be the optical properties of the material.

---

[*] e-mail: andreas.hentrich@igvp.uni-stuttgart.de

3 Proportion dependency of optical properties

Six material proportions -the ones displayed in figure 1 and pure Al_2O_3- were investigated by the production of six to twelve samples each by atmospheric plasma spraying with varying thicknesses and measuring those at four different angles and both polarizations. These at least 50 points for every proportion were then fitted by a combination of refractive index and absorption coefficient. As to be expected, the optical properties change monotonously between the ones of pure Al_2O_3 (as in [2]) and TiO_2. Contrasting to prior expectation, the resulting data gives rise to a S-shaped transition of both material properties, which does not validate the first assumption of a linear change with the material composition. Both the formation of mixed phases like tialit [4] or a change in the microscopic geometry of the phase interfaces inside the coating [5] are possible explainations for this more complicated behaviour.

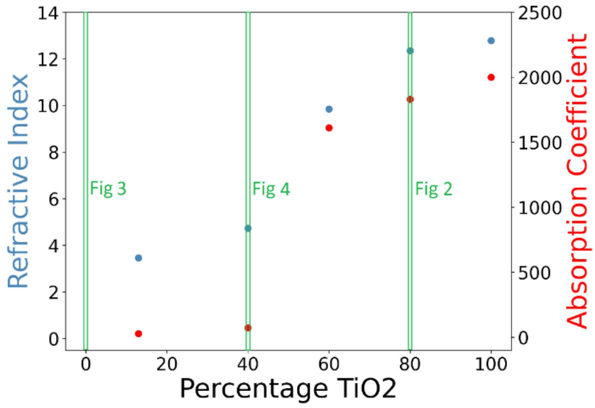

Figure 1. The relationship between the optical properties at 170GHz and the percentage of TiO_2 in the $Al_2O_3 - TiO_2$ coatings. The lines display the absorbing regimes described in the following chapter.

4 Absorbing regimes

To answer the fundamental optimization question of the paper, it is beneficial to have a closer look at the thickness dependency for the different compositions. Three regimes can be distinguished, which are described in the following.

4.1 High absorption coefficients

The obvious first choice for obtaining a material with beneficial absorbing behaviour would be to use a material with a high absorption coefficient. When having a look at the thickness dependence of any example for this regime, e.g. the 20/80 in Fig. 2, the absorption levels are actually quite low. This high total reflection is due the high initial reflection at the first air-coating interface, as suggested in the sketch. When the energy of the incoming wave penetrates into the sample, it is almost completely absorbed, but simply not a large fraction does so. This is due to the large refractive index, which comes with the high absorption coefficient. A very indicative sign for this dominance of the first air-coating interface is the very low thickness dependence after a certain point. When the coating is much thicker than the length required to completely absorb the wave, how much coating is still left is not relevant.

4.2 Low absorption coefficients

To solve the problem of the high initial reflection, it is reasonable to look on the opposite side of the spectrum for good absorbers. With the much lower refractive index, pure Al_2O_3 (Fig 3) for sure does not have this problem.

The problem with using these kind of materials as absorbers is a much more fundamental one: It simply does not absorb. So little in fact, that fitting does not give meaningful results. There is strong self-interference of the incoming microwaves, so when fullfilling the lambda quarter condition it is theoretically possible to create a resonator and increase the fields inside the layer drastically, which would also increase the theoretical possible absorption drastically. But fullfilling this condition is very challenging, the low absorption coefficient makes this theoretical absorption peak just appear in a very small thickness range.

4.3 Medium absorption coefficients

To widen up this range, one needs to have an at least slightly larger absorption coefficient, like for example the 60/40 in Fig fig:Med. Suddenly very good absorbers can be obtained even in practise for certain thicknesses, using this resonant absorbing effect.

This gives rise to a goldilocks zone situation for producing absorbers: If the TiO_2 content and thereby the absorption is too high, there is no self-interference and the initial reflection at the air-coating interface is really problematic. If the TiO_2 content and the absorption is too low, the resonant absorption peak is too sharp, making it impossible to actually produce these absorbers. But using a content of around 15-45% TiO_2 allows the production of very good absorbers, with increasing stray radiation absorption capabilities when being more in the center of this zone.

5 Conclusion and outlook

The optical properties at 170GHz of the $Al_2O_3 - TiO_2$ material system were investigated depending on the proportion of the constituents. The investigation consisted of two parts: Firstly an experimental one, in which the reflectivity of coatings on metal substrates with the required proportions was measured depending on coating thickness, incidence angle and polarization. Secondly the theoretical background, for which two models were developed to describe the wave-material interactions considering the geometry and the not purely dielectric nature of the materials. Due to the speed of the calculation, a brute force approach is sufficient to fit the model to the measurements,

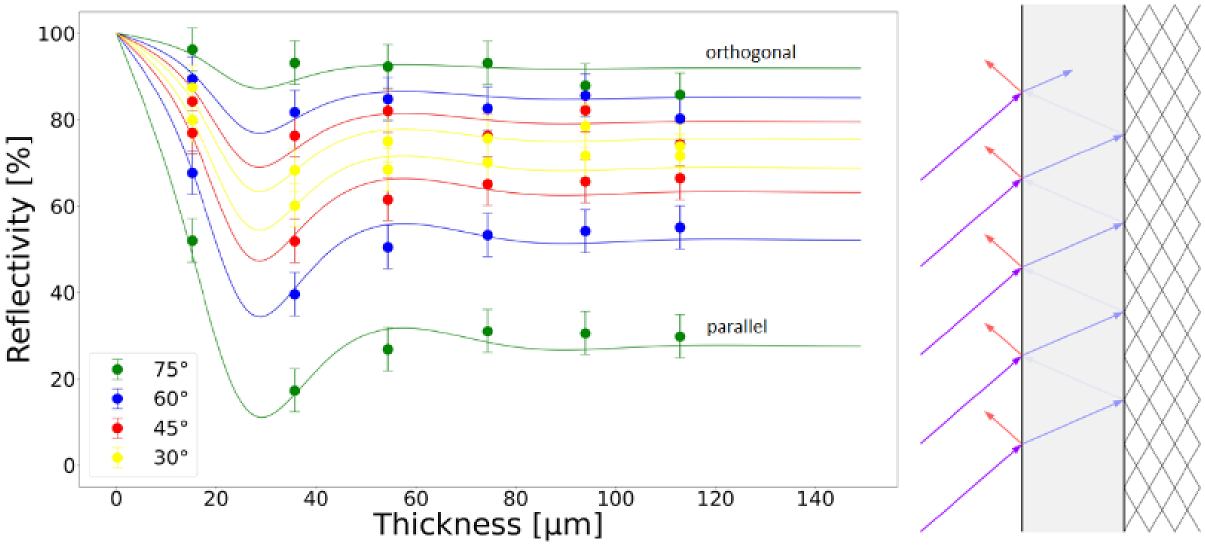

Figure 2. High absorption coefficient case. The graph displays the thickness dependency, with dots being measurements and lines the fitted model. The sketch displays the wave propagation.

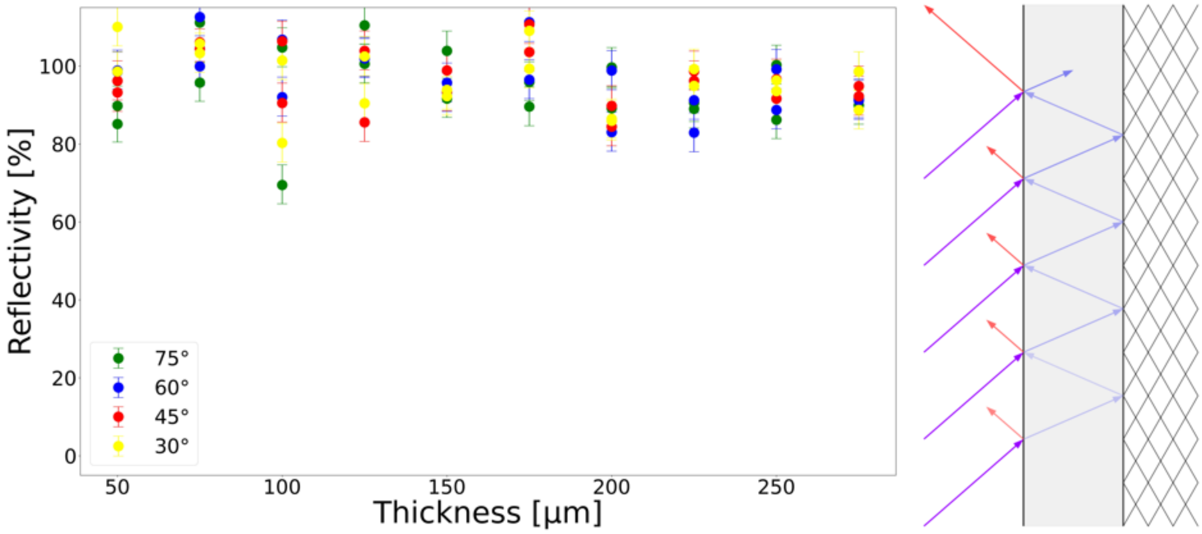

Figure 3. Low absorption coefficient case. The graph displays the thickness dependency, with dots being measurements. The sketch displays the wave propagation.

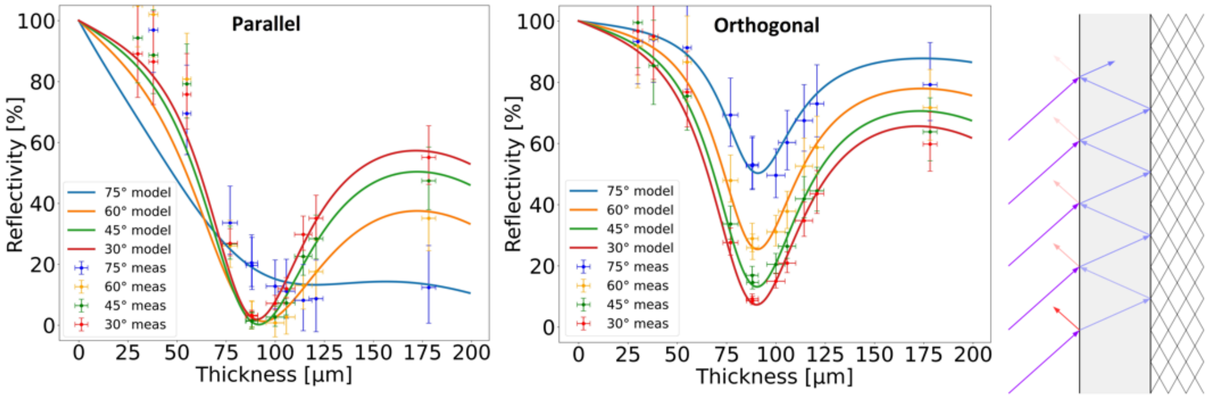

Figure 4. Medium absorption coefficient case. The graphs display the thickness dependency for both polarizations. The sketch displays the wave propagation.

which yields the optical parameters.

A non-linear S-shaped increase of both absorption coefficient and refractive index with TiO_2-content was determined, with a drastic increase of both property values at around 50%. Possible explanations for non-linearity are the formation of tialit or a change in the microscopic geometry. In the proportion spectrum three absorbing regimes could be identified, which all have different wave-material interactions. Of particular interest for the development of absorbing coatings is the regime with medium absorption coefficients, because the resonant nature of the prevalent wave-material interaction allows for a very strong suppression of reflections.

The completion of this study allows for further optimization of microwave absorbing coatings. One option is the fine-tuning of the TiO_2 proportion to optimize for improved stray-radiation performance. Another possibility is the development of multi-layer coatings by combing material proportions with known parameters with the same aim. Additionally the influence of two parameters are also still left to investigate: How is the resonant absorption affected by an increase of temperature and what effect does roughness of substrate or coating has on the performance, both of which will be discussed in further studies.

References

[1] W.Kasparek et al, Measurements of Ohmic Losses of Metallic Reflectors at 140 GHz Using a 3-Mirror Resonator Technique. Journal of IRMW **22** (2001). https://doi.org/10.1023/A:1015064616703

[2] H.E.Choi and E.Choi, High-Precision Complex Permittivity Measurement of High Loss Dielectric Materials Using a Geometrical Gap in Millimeter Wave Frequency. Journal of IRMW **45** (2024). https://doi.org/10.1007/s10762-023-00958-7

[3] A.Hentrich et al, Resonant Atmospheric Plasma-Sprayed Ceramic Layers Effectively absorb Microwaves at 170 GHz. Journal of IRMW **43** (2022). .https://doi.org/10.1007/s10762-022-00861-7

[4] A.Killinger et al, Plasma Spraying of a Microwave Absorber Coating for an RF Dummy Load. Coatings **11** (2021). https://doi.org/10.3390/coatings11070801

[5] G.P.De Loor, Dielectric properties of heterogeneous mixtures. PhD thesis - Universiteit Leiden, Instituut-Lorentz for theoretical physics (1956)