CHARACTERIZATION OF MICROWAVE ABSORBERS, INCLUDING MULTILAYER NANOABSORBERS

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Abstract

In this paper, we consider the characterization of microwave absorbers, including foam and rubber absorbing samples and coatings, composite absorbers with nanoparticle inclusions, meta-absorbers and gradient-carbon absorbers. Today, the development of new generation of effective absorbers is a big challenge because they are very promising materials for applications in the modern microwave 5G communication systems and antennas, where a reliable suppression of parasitically excited spurious fields must be achieved. The difficulties for characterization of such materials relate to the fact that they may have simultaneously as dielectric properties (usually big permittivity and dielectric losses), as well as expressed magnetic properties (non-zero permeability and big magnetic losses) and additionally – an increased conductivity. Therefore, the accurate determination of the full set of parameters can help the users to perform better design of microwave devices with incorporated absorbers and chemists and technology engineers to control the content, properties and applied technology of absorber materials. The paper presents and compares different measurement methods, models for extraction of the dielectric and magnetic parameters and conductivity and includes a lot of comparative results for a variety of absorbers. A new simple waveguide method has been presented for characterization of thin nano-composite absorbers with reliable separation of the equivalent dielectric and magnetic parameters.

Keywords*: composite materials, dielectric anisotropy, dielectric constant, magnetic constant, microwave absorbers, microwave measurements, nano-absorbers*

1. INTRODUCTION

The microwave absorbers are widely spread and important materials in the modern high-frequency electronics and communications. Their main role in the structures, where they have been incorporated, is to suppress the parasitic interferences, crosstalk interactions and reflections [1-5]. Usually most of the used absorbers are commercial products; the main absorbers' manufacturers try to present enough data for the users to facilitate their best choice for the needed absorber with the right characteristics: absorbing ability (dB/mm), reflectivity (dB), frequency range of application [6, 7]. However, in many cases this is not enough. Recently, the microwave engineers started to design the whole microwave devices together with incorporated absorbers; therefore, they need to know the actual electromagnetic parameters of these materials. Usually, the microwave absorbers have been offered as foams, rubber sheets, brushed coatings or thin films with absorbing inclusions, nanoabsorbers (with efficient nanoparticle inclusions) and recently absorbing metamaterials [2, 4, 8-13]. They consist of carbon, carbonyl iron, ferrites and other high-loss inclusions; therefore, they may have as pure dielectric properties (like the carbon-containing absorbers), as well as magnetic properties [14-18].

Characterizing such lossy materials with complex dielectric and (eventually) magnetic properties is not an easy task [19-23]. One of the most powerful methods suitable for absorbers' characterization is based on the free-space technique – a plane sample placed between two horn antennas [16, 24]. However, the method needs relatively big specimens and its accuracy for multilayer samples is not satisfactory. Another broadband technique relies on measuring the S parameters of waveguides with samples (coaxial [17], rectangular [18] (most used) or stripline). The waveguide method allows separate measurements of the samples' permittivity and permeability; however, it only yields the parallel (to the sample surface) components of these parameters (of course, different combinations can be proposed for realization of this method, as in the current paper). Among the wideband methods one should mention the method based on planar coplanar waveguides – the thin film is placed just below

the coplanar conductor [25]. Our review paper [26] presents another well-developed broadband method by covering of microstrip lines with absorber under test (AUT). The common disadvantages of the wideband methods are the needs of relatively big and well-sized samples and their moderate accuracy, which depends on the applied extraction approach and noisy measurements. From this point of view, the resonance measurements can ensure a considerably better accuracy of separate determination of the dielectric and magnetic parameters by different resonance modes with maximums of the electric (*E*) or magnetic (*H*) field within the sample. However, the resonance curves in the case of very lossy absorbers or big AUTs could be fully destroyed making the resonance measurements impossible. There exist several resonance solutions for such absorbers. One of them is to use high-quality (high-Q) resonators – dielectric, split-dielectric or whispering-mode resonators [14]. Another approach is the perturbation techniques with very small samples (examples have been given in [26]). The latter approach uses samples of small dimensions (disks, prisms, etc.) and thin films. In our last paper [27] for characterization of nanoabsorbers we combined two methods – a resonance one [28, 29 and a broadband one [30] and the results for obtaining of the full set of dielectric and magnetic parameters could be considered as successful.

In this paper, we continue these investigations. Now the accent is to show that one applied method is not enough for characterization of absorbers as materials with relatively high dielectric constants, big dielectric losses (and eventually big magnetic losses), different from unity magnetic constant and in many cases expressed conductivity. A reliable characterization of such AUT should rely on a combination of at least two and more methods as in the stage of development of these specific materials, as well as for already developed absorber products for commercial purpose; this approach must be used to obtain more valued and authentic information for each absorber. This assumption considers the complexity of the absorbing materials and the fact that the different method can give complementary information for the AUT. Therefore, in the next section "Materials and Methods", we selected several different types of absorbers (commercial product from the market and laboratory samples under development) with different absorbing abilities, construction and chemical content and several measurement methods for their reliable characterization and demonstrate how these methods can give the needed full information for each selected AUT and whether this information is different from the catalogue information, presented by the corresponding producers. In the section "Results and Discussion", we present results for such comparison for each selected AUT – commercial absorber or absorbers under development with unknown parameters (including thin-layer absorbers with nanoparticle inclusions) and combine pair of complimentary methods for their reliable characterization. The applied methods are different indeed (resonance and broadband) and only their combination gives the needed relatively full information for the material parameters of the considered known/unknown absorbers. Similar research looks like time-consuming one; however, it can be considered as a research for seeking of the most appropriate approach and combination of methods for characterization of each given absorber depending on its specificity. Finally, some conclusions have been formulated on the base of our experience for characterization of the microwave absorbers, for which no reference methods have been developed jet.

2. MATERIALS AND METHODS

2.1. Selected Absorbers for Characterization

As we already mentioned in the Introduction, there exist a lot of different types of microwave absorbers with different chemical content and mechanical and physical properties, offered as foams, rubber sheets, brushed coatings, thin films with absorbing inclusions, nanoabsorbers with nanoparticle inclusions and absorbing metamaterials [4]. For the aims of the research in this paper, we selected four AUTs: three commercial products as rubber sheets and foams and one type of thin layer nanoabsorbers, already investigated in [27] but here they are investigated with new methods. Among the commercial absorbers, we consider two products of Laird Technologies, Inc. The first one, Eccosorb MSF-124 [31] is a well-developed high-loss, non-rigid, magnetically loaded flexible stock and rubber sheet absorbers based on silicone. This product has absorbing abilities typically in the frequency range 1-18 GHz (see the catalogue data in Table 1); however, it can be used also at higher

frequencies. Our research for this product has been directed to verify the catalogue data (for the complex dielectric and magnetic constant and attenuation in dB/cm) in the pointed frequency range and to extend these data up to 40 GHz.

Table 1. Measured dielectric/magnetic parameters by Laird Eccosorb MSF-124 (catalogue data; the characterization method is not specified by the manufacturer)

f, GHz	10^{-7}	10^{-6}	10^{-5}	10^{-4}	0.001	0.01	0.1	1	3	8.6	10	18
$\varepsilon'/\tan\delta_\varepsilon$	260/0.4	205/0.39	145/0.36	95/0.31	70/0.26	52/0.20	40/0.14	32/0.08	25.8/0.05	23.8/0.05	23.6/0.03	23/0.04
$\mu'/\tan\delta_\mu$	7/0	6.9/0	6.8/0	6.7/0	6.6/0	6.3/0	6/0.2	5/0.45	3.8/069	2.5/1.1	1.5/1.4	1/2.5
dB/cm	0	0	0	0	0	0.03	0.48	6.5	20	63	67	149

Another commercial AUT in our research is the foam product Eccosorb® HR A15: a lightweight, flexible, flat-sheet, broadband absorber based on a reticulated (open-cell) polyurethane foam material impregnated with carbon black dispersions with controlled conductivity [32]. The specificity of this material is that it is a gradient loaded absorber, the back side of the absorber is marked, and this side should be bonded to the metal surface. The front surface should face the incident electromagnetic energy for proper performance. At these conditions the material ensure wideband small reflectivity even for samples with small thickness (15 mm in the considered case); typically return losses -20 dB and better from 15 GHz up to 90 GHz, which if fully applicable for many nowadays 5G applications of this product. Unfortunately, the producer of this carbon-based product (without magnetic properties) doesn't present any data for its complex dielectric permittivity; we already have preliminary investigations of this material [33].

The third commercial absorber, FM8® by Collector Magna Ltd., is not already in production. We have a lot of investigations of this rubber-sheet absorber in the X and Ku bands (8-18 GHz) [26] and use the obtained results here for verification of the new developed methods for AUT characterization.

Finally, we consider a non-commercial laboratory absorber, developed in the Institute of Electronics of the Bulgarian Academy of Science, based on thin layers (20-50 μm thick) with a combination of nanoparticle inclusions form Carbon and Fe_2O_3 [27].

2.2. Methods for Characterization of Commercial Absorbers

Fig. 1 illustrates pictures of the setups for several methods applicable for characterization of AUT, conditionally divided free-space (Fig. 1 *a,b*); waveguide (Fig. 1 *c*) and resonance methods (Fig. 1 *d*). We have realized all the considered methods in our Microwave Lab in the Faculty of Physics of Sofia University "St. Kliment Ohridski", Bulgaria [34].

There is no universal method, which can fit all requirements for the absorber characterization [35]. The measurement setup of the free-space method (in transmission or in reflection regimes), consists of two or one horn antennas and the flat AUT is placed between them or between the antenna and a reflecting screen – see the schematic view in Fig. 2 *a,b*. The measurements of the phase delay and the losses with and without AUT allow extracting the dielectric constant and dielectric loss tangent [36]. This method is very useful for measurements in the mm- and sub-mm-wave ranges but needs relatively big samples to avoid the diffraction effects near to the sample edge. The main problems are the reducing of the measurement errors due to multiple reflections and sample misalignment. By suitable extraction procedure, these errors could be reduced or measurements in a TDR gate could be used. Due to the TEM mode propagating in the structure, it can be used for extraction only of the parallel dielectric parameters of the sample in a transmission regime. The method is not well applicable for low-loss materials, but it is very popular for characterization of the known or new AUTs (see our review paper [27]; all the listed above methods are realized in our laboratory from C- up to Ka-bands).

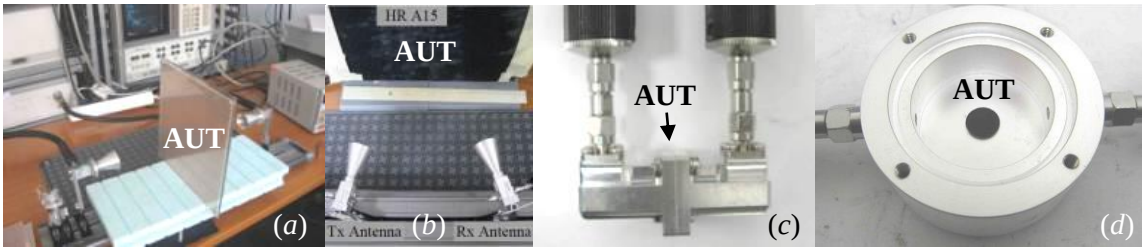


Fig. 1. Several methods used for characterization of absorber under test (AUT): (*a*) free-space method in transmission regime; (*b*) in reflection regime; (*c*) waveguide method; (*d*) resonance method

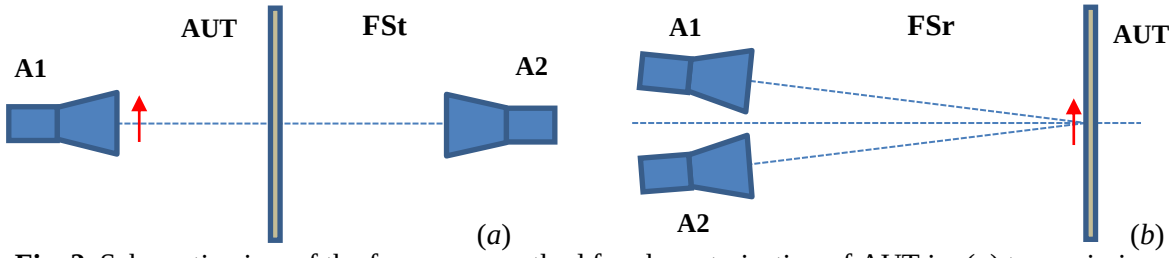


Fig. 2. Schematic view of the free-space method for characterization of AUT in: (*a*) transmission regime FSt and (*b*) reflection regime FSr (to determine the reflectivity). The red arrows show the E-field direction of the TEM wave

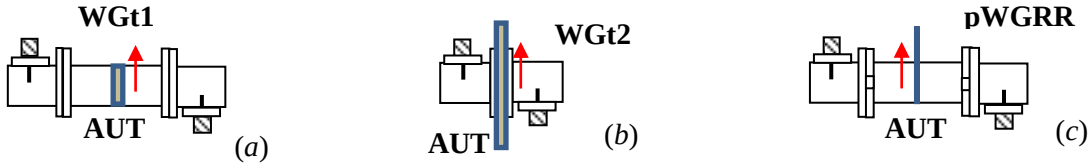


Fig. 3. Rectangular waveguide transmission method: (*a*) WGt1 (with AUT which fit the waveguide cross section) and (*b*) WGt2 (with AUT between the waveguide flanges); (*c*) Rectangular waveguide resonator pWGRR (perturbation technique with AUT as a small prism in the resonator centre). The red arrows show the E-field direction of the dominant mode TE(H)$_{10}$ in the rectangular waveguide

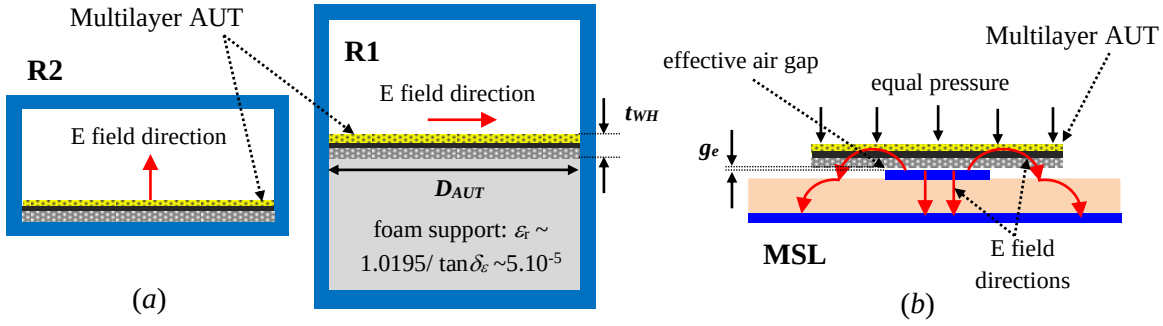


Fig. 4. Two authorship methods for study of thin and multilayer absorbers and nanoabsorbers: (*a*) two-resonator method [28, 29]; it uses measurements of the resonance frequencies and quality factors of the exited symmetrical TE$_{0mn}$ (in resonator R1; m = 1,2,3, n = 1,2) and TM$_{0m0}$ modes (in resonator R2; m = 1,2,3) to determine the dielectric (and eventually the magnetic parameters [27, 37-39]); (*b*) broad-band microstrip-line method [26, 27], based on covering a 50-ohm microstrip line (MSL) with the AUT and exciting a dominant quasi-TEM mode. The red arrows show the E-field direction of the exited modes in the structures

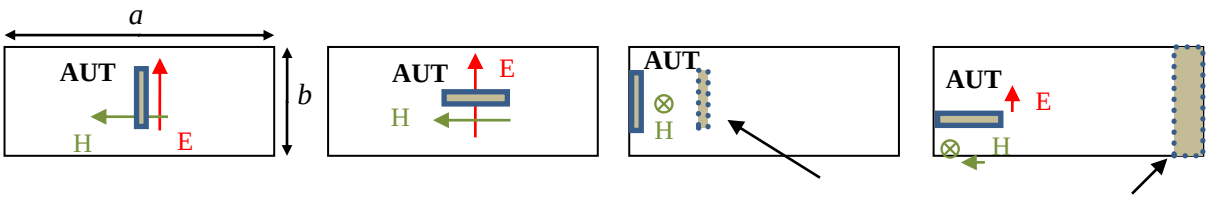


Fig. 5. Modified rectangular waveguide transmission method with small samples in four positions and orientations regarding E- and H-field of the dominant TE(H)$_{10}$ mode: Ev, Eh, Hv and Hh positions; for other positions EHv shifted and Hv perp. see the text below)

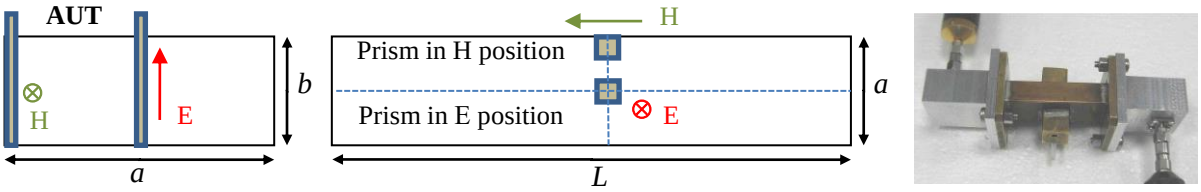


Fig. 6. Modified rectangular waveguide resonator perturbation method with small prisms in two positions in the centre (E and H positions) (not in scale); photo of the used resonator

The waveguide methods are also very popular in the dm-, cm-, mm-wavelength ranges and beyond, applying rectangular, circular or coaxial waveguides in transmission or reflection regimes. For rectangular waveguide in transmission regime, the thin sample can be placed between two waveguide flanges (as in Fig. 3*b*) or into the waveguide fitting its cross-section (as in Fig. 3*a*); the measurement of phase delay and insertion losses allows extraction of the sample dielectric parameters. Inserted in the waveguide aperture bulk samples can act as resonators in the corresponding frequency range; the extraction of the dielectric parameters is possible also by measurement of this resonance frequency and Q factor. For thin samples in reflection regime, both dielectric and magnetic parameters can be extracted if the sample is placed in two fixed positions at a quarter-wavelength distance. When the sample is placed in the natural vertical position according to the wider wall of the waveguide, the method gives the parallel dielectric parameters; if the sample lies horizontally on this wall, the method extracts the perpendicular parameters. Thus, the waveguide method is one of the few relatively broadband methods, which can determine the anisotropy of the sample. Due to this reason, it is very popular for characterization of absorbers [18-21], including in our laboratory [26] and this paper.

One of the very suitable for AUT absorber is the method, based on the perturbation technique for small samples (prisms, cylinders, disks) in rectangular resonator – see Fig. 3*c*. In such structure, a set of resonances of the dominant mode TE(H)$_{10p}$ (p = 1, 2, 3, 4, 5, 6,…) can be observed in the frequency range of the operation of the corresponding waveguide. A common property of the exited resonances is the observation of maximums of the vertical E fields for modes with odd values of the index p (but with expressed magnitude of the horizontal H field), and maximums of the H field (with practically zero E fields) for modes with even p values. From these dependencies we can extract the variations in horizontal external dc magnetic field as for the dielectric constant and dielectric loss tangent (from the resonance parameters of modes with index p = 1, 3, 5, 7,…), as well as for the magnetic constant and magnetic loss tangent (from the resonance parameters of modes with index p = 2, 4, 6, 8,…) of the considered AUT and these variations can be well separated (an example is given in the next section).

2.3. Authorship Methods for Characterization of Microwave Absorbers

The needs to determine the dielectric and magnetic parameters (relative dielectric ε_r and magnetic constant μ_r, and the corresponding dielectric tanδ_ε and magnetic tanδ_μ loss tangents require to apply methods that allow determination of these parameters for such lossy materials. However, similar materials, depending on the inclusions, usually show well-expressed anisotropy of the material

constants – different values of the dielectric and magnetic parameters in different directions regarding the sample volume. We have proposed in [28, 29] the two-resonator method using TE and TM modes exited in cylinder resonators with sample (AUT can be also measured by this method if they are thin [27] or with small sizes [41]) – see Fig. 4*a*. The considered modes have maximums of the electric field in mutually perpendicular directions and this allows development of a procedure for separate extraction of the dielectric and magnetic parameters of relatively thin absorbers in parallel and perpendicular directions to the sample surface. The of extraction procedure is described in detail in [27]: the parallel dielectric parameters, ε_{par}, $\tan\delta_{\varepsilon,par}$, can be extracted by the help of modes TE_{0mn} with m = 1, 2, 3 and n = 1, 3; perpendicular dielectric parameters, ε_{perp}, $\tan\delta_{\varepsilon,perp}$, – by modes TM_{0m0} with m = 1, 2, 3; parallel magnetic parameters, μ_{par}, $\tan\delta_{\mu_par}$ – by modes TM_{0mn} with m = 1, 2 and n = 2; and the perpendicular magnetic parameters, μ_{perp} $\tan\delta_{\mu_perp}$ – by modes TE_{0mn} with m = 1, 2, 3 and n = 2, 4.

The main disadvantage of the developed two-resonator method is that the information for the sample parameters is obtained for a set of fixed frequencies (the resonance frequencies of the excited symmetrical modes with different indexes). In our recent publications (e.g. [33]), we proposed a combination of the two-resonator method and a broadband method, where the AUT covers a 50-ohm microstrip line (MSL) printed on a standard commercial substrate. We already reported the use of a similar structure to characterize the absorbing properties of microwave absorbers [26], but in addition, we try to extract now the material parameters of AUT. The dominant mode in the MSL has the *E* fields placed high above the conductor layout (shown illustratively in Fig. 4b) thus penetrating the AUT. Due to the sample influence on the additional insertion losses S_{21} and insertion phase angle S_{21} in the entire transmission line, their frequency dependencies are representative measures of the AUT parameters, if a reliable extraction procedure is performed (details are presented in [30]). In fact, the *E* fields in the MSL have a mixed distribution (neither purely parallel, nor purely perpendicular); therefore, the covered MSL allows one to extract a mixed (equivalent) value between the parallel and perpendicular dielectric and magnetic constants, ε_{eq} and μ_{eq}. In our case, we simply introduce the parameters obtained by resonance measurements in the built 3-D model of the measurement structure and compare the simulated dependencies with the measured ones for all samples considered. However, there exists a measurement problem: usually, an unavoidable air gap with an effective thickness g_a appears between the sample bottom surface and the top MSL conductors (evaluated by the help of an isotropic PE sample; g_a ~2 ± 0.25 μm; figure 2 c) due to different reasons: small curvatures, roughness, surface irregularities, etc.

We continue to develop new methods for characterization of the microwave absorbers to determine their values in different directions. Fig. 5 illustrates schematically a modified rectangular waveguide transmission method, which uses small AUT samples in four positions and orientations regarding E- and H-field of the dominant $TE(H)_{10}$ mode: Ev, Eh, Hv and Hh positions (Fig. 7 illustrates the E and H-field distribution in the sample in some of these positions). The novelty is the sample in Hv position. Here the E field of the dominant mode is practically zero in the place of the used thin absorbers; therefore, the measurements of the insertion losses and phases in this waveguide structure with prism sample in Hv position allow determination of the pure parallel magnetic parameters (μ_{par}, $\tan\delta_{\mu_par}$) of AUT (in the frequency range of the corresponding waveguide). Then, after the measurement of the sample in Eh position with the already determined parallel magnetic parameters (or in Hh position with less accuracy), we can extract the perpendicular dielectric parameters (ε_{perp}, $\tan\delta_{\varepsilon,perp}$). The next step is the measure the sample in Ev position; here the combination of the parameters (ε_{par}, $\tan\delta_{\varepsilon,par}$) and ($\mu_{perp}$ $\tan\delta_{\mu_perp}$) influences the waveguide characteristics; therefore, we cannot immediately separate these parameters. For this purpose, two measurements in Ev and Hv shifted position can be performed to have two different set of parameters to extract parallel dielectric and perpendicular magnetic parameters of AUT. This is not an easy procedure; therefore, another approach can be used – measurement of the waveguide parameters in Hv perpendicular position (see Fig. 5; last picture). In this case, the perpendicular magnetic parameters can be determined (μ_{perp} $\tan\delta_{\mu_perp}$) (the E field influence in this case is relatively small) and then the measurement in Ev position can ensure the determination of the pair of the parallel dielectric parameters (ε_{par}, $\tan\delta_{\varepsilon,par}$). In all the considered cases, the determination of the material parameters is performed by numerical

simulations with electromagnetic simulator (ANSYS®HFSS in our case); the corresponding material parameters have to be tuned in the model until satisfactory (~1-2 %) coincidence between the simulated and measured parameters has been reached. Unfortunately, this method cannot ensure the accurate determination of the loss tangent of AUT in each case; if the additional losses are small or sample has small sizes, the dielectric and magnetic loss tangents cannot be determined accurately die to the lack of sensitivity.

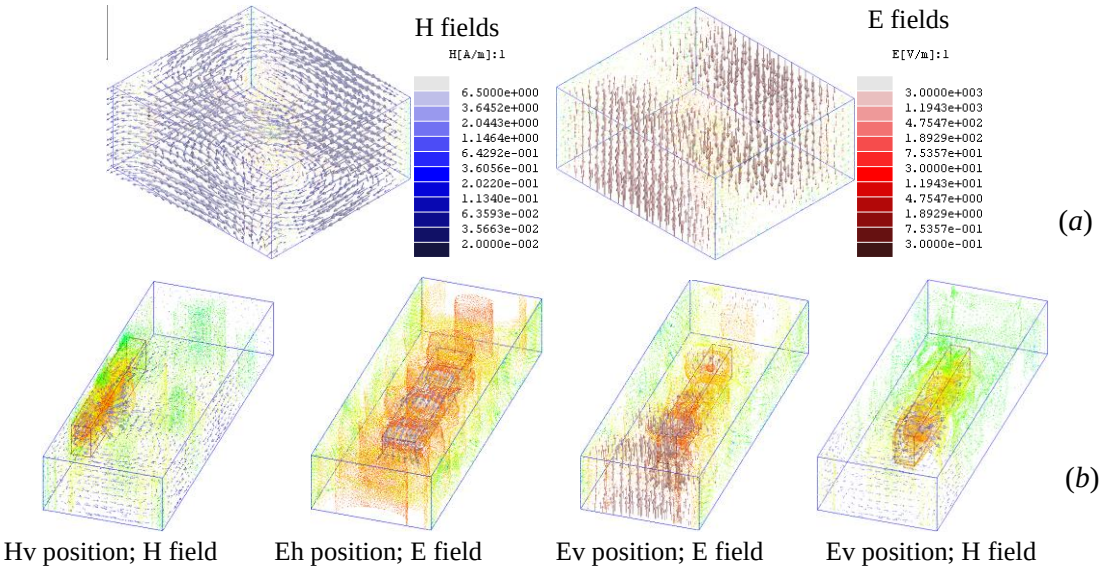


Fig. 7. Simulated E and H field of the dominant TE(H)$_{10}$ mode in rectangular waveguide: (*a*) empty waveguide in Ka band; (*b*) with small prism sample in Ev, Eh and Hv positions (see also Fig. 5)

The last proposed new method for AUT characterization is a modified perturbation technique on the base of rectangular resonator with small sample in two positions in the center (L/2) regarding the resonator length L – see Fig. 6. These positions are: E position, where the modes TE(H)$_{10p}$ with odd p = 1, 3, 5, 7… has maximum of the E fields; and H position, where the modes TE(H)$_{10p}$ with even p = 2, 4, 6, 8… has maximums of the H field. The method is very similar to the standard perturbation method, described in Fig. 3*c*, but now the sensitivity is better for determination of the magnetic parameters of the sample, if exist.

3. RESULTS AND DISCUSSION

In this section we present the results from characterization of the considered in the previous section absorber materials applying combination of two or more methods described in the same section.

3.1. Characterization of Commercial Absorbers to Verify and to Extend the Information for the Catalogue Data Given by the Manufacturer.

The selected for these purposes commercial absorber is Eccosorb MSF-124 [31] manufactured by Laird Technologies, Inc. Table 1 presents the main parameters of this product; the frequency range of application is typically from 1 to 20 GHz. Our needs are to extend this information up to 40 GHz and to evaluate the possibility to use this product in the extended frequency range (this situation is quite typical for many microwave engineers involved in development of active devices).

It is now discussed in [31] the test method for obtaining the catalogue data in Table 1. However, considering the technical notes of the company, their products should be characterized by the standard waveguide technique (rectangular or coaxial waveguides) [6] and free-space technique [7].

To verify the presented in Table 1 data we applied the rectangular resonator perturbation technique. Fig. 8*a* presents the used resonator in the X band (8-12 GHz). The resonator can be used in the extended frequency range 6.5-20 GHz, because the excited modes can be well identified and the fields on the resonances keep the structure of the dominant mode TE(H)$_{10}$ – Fig. 8*b*. Following the described above procedure for this method and using accurate numerical simulations to extract the magnetic parameters (by modes with even *p* index) and dielectric parameters (by modes with odd *p* index), we can fill the obtained results in Table 2. The mean parameters in separate frequency range (the material has expressed frequency dependence of these parameter) are presented in Table 3. Comparing the obtained results with the catalogue data in Table 1, we can conclude that the presented catalogue data are accurate. However, our aim is to extend these data up to 35-40 GHz, where we expect to use this absorber.

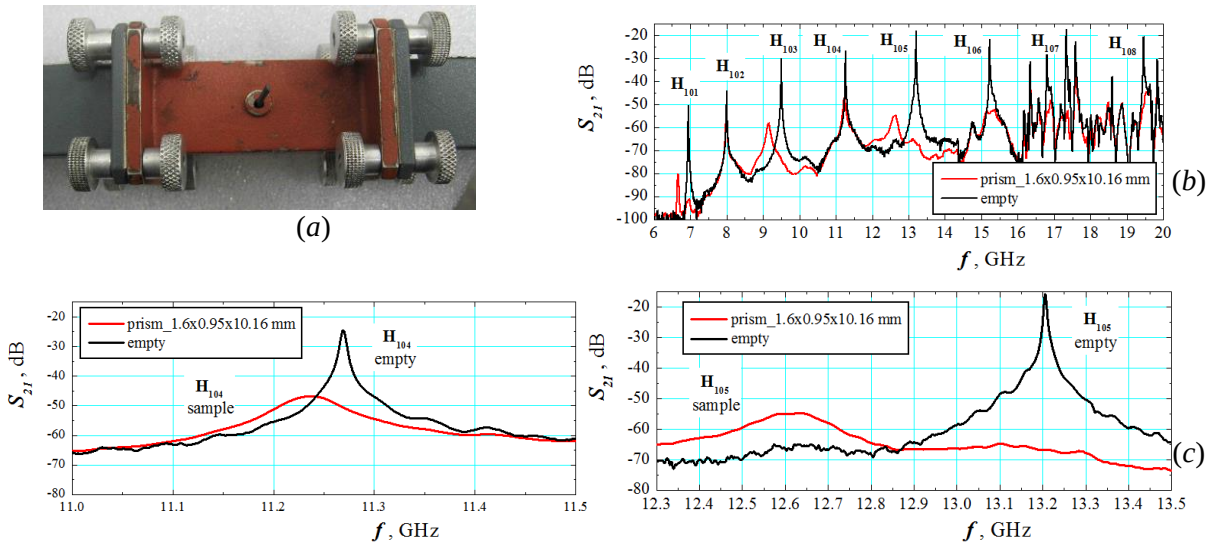


Fig. 8. Rectangular waveguide resonator (WR90; dimensions: 64.95 *x* 22.86 *x* 10.16 mm) with small prism (1.05 x 0.95 x 10.16 mm) (*a*) and the full spectrum of the exited TE(H)$_{10p}$ modes in the frequency range 6-20 GHz (*b*); Resonance curves of empty and AUT prism-loaded resonator for two modes TE(H)$_{104}$ and TE(H)$_{105}$

Table 2. Measured dielectric/magnetic parameters of the Eccosorb MSF-124 samples

ε	tanδ_ε	μ	tanδ_μ	frequency GHz, Q factor (mode) resonator with AUT	frequency, GHz, Q factor (mode) empty resonator
19.40	**0.019**			6.781/290.0 (H$_{101}$)	6.947/3601 (H$_{101}$)
		2.2	**0.89**	7.997/254.1 (H$_{102}$)	8.002/4993 (H$_{102}$)
19.62	**0.012**			9.272/1306 (H$_{103}$)	9.503/4777 (H$_{103}$)
		1.6	**1.5**	11.256/218 (H$_{104}$)	11.268/4992 (H$_{104}$)
19.60	**0.011**			12.817/202.1 (H$_{105}$)	13.204/5587 (H$_{105}$)
		1.5	**2.0**	15.210/193 (H$_{106}$)	15.226/5213 (H$_{106}$)
19.30	**0.015**			16.906/332 (H$_{107}$)	17.328/5215 (H$_{107}$)
		0.88	**~3**	19.433/309 (H$_{108}$)	19.456/4740 (H$_{108}$)

Table 3. Measured mean dielectric/magnetic parameters of Eccosorb MSF-124

f, GHz	6-8	8-12	12-16	16-20	Above 20 (from the free-space method)
ε; tanδ_ε	19.40/ 0.019	19.62/ 0.012	19.60/ 0.011	19.30/ 0.015	19÷19.3/ 0.015÷0.010
μ; tanδ_μ	2.2/0.89	1.6/1.5	1.5/2.0	0.88/~3.0	1÷0.8/2÷3

Now we can apply the free-space method. The measured attenuation and phase delay through bigger (200 *x* 200 mm) plate in the frequency range 8-40 GHz are presented in Fig. 9*a*. The catalogue dependencies for the frequency less 20 GHz have been confirmed; the new results show that the attenuation increases up to 25 GHz and then slightly decreases but remains high enough. The extracted parameters for the product $\varepsilon \times \mu$ (these values cannot be separated by the free-space method) fully confirm the presented catalogue data (Table 1) and our resonance measurements (Table 2). However, now we have extended information for these parameters up to 40 GHz (the magnetic constant is close to 1, while the dielectric constant keeps the values 19.0-19.3 in this range.

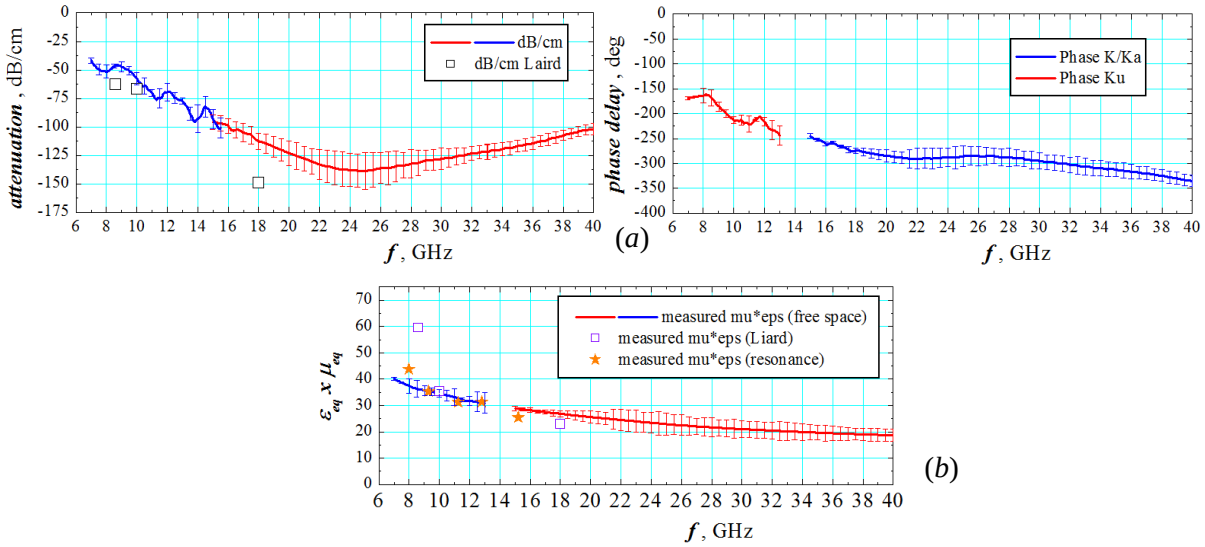


Fig. 9. (*a*) Measured attenuation and phase delay of sample Eccosorb MSF-124 by free-space method in Ka band (by two sets of waveguide horn antennas WR28, Ka band, and WR75, Ku band); (*b*) extracted $\varepsilon \times \mu$ values by the free-space method for frequency range 8-40 GHz

3.2. Characterization of Commercial Carbon-Gradient Absorbers.

The next example is very interesting – this is our experience for characterization of a complex AUT material – Carbon-gradient product Laird Eccosorb® HR A15 [32]. The manufacturer presents only data for the reflectivity of this material; any data for the dielectric parameters are not given (this material doesn't have any magnetic inclusions). In [33] we performed resonance measurements of this material by the two-resonator method.

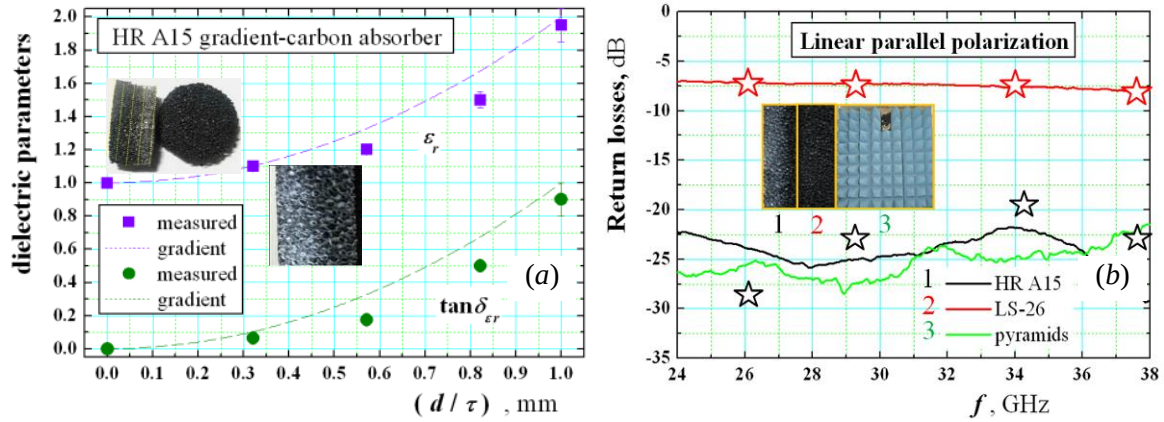


Fig. 10 (*a*) Dependencies of the dielectric constant and dielectric loss tangent of four disk slices from 15-mm thick Carbon-gradient absorber ECCOSORB® HR A15; (*b*) comparison between the measured and simulated (stars) reflectivity of ordinary and gradient-carbon flat foam samples and foam pyramids

The successful characterization of this material has been based on the possibility to slice the sample into several flat thinner samples and to measure their parameters in the frequency range of interest (from X up to Ka band). We performed relatively thin slices from the thick materials $\tau \sim 14$ mm and managed to confirm this distribution as for the dielectric constant $\varepsilon_r(d) = 1 + (d/\tau)^2$, as well as for the dielectric loss tangent $\tan\delta_{\varepsilon r}(d) = 0 + (d/\tau)^2$ (τ is the sample thickness; d is the distance from the top surface. Fig. 10*a* presents the results; the gradient distribution of the both dielectric parameters – dielectric constant and dielectric loss tangent has been fully confirmed. This behaviour explains the small reflectivity of this material, as the measured, as well as the simulated by us dependencies – see the comparison in Fig. 10*b*.

3.3. Characterization of ruber sheet AUT FM8 in the X and Ku band)

In our review paper [26] we summarized and compared the possible methods for characterization of the considered absorber FM8 (Collector Magma, Slovenia) by many methods. Thick absorber samples (τ >0.4 mm for this sample) cannot be well characterized by resonance methods due to the big losses. Fig. 11*a* presents measured dielectric ε_r and magnetic μ_r constants by the waveguide perturbation methods (shown in Fig. 12*a*), while Fig. 4.15*b* compares the product $\varepsilon_r \times \mu_r$, obtained by different measurement methods – two-resonator method, covered microstrip line and waveguide method in a transmission regime. The mean parameters of this commercial rubber absorber in Ku band are: ε_r ~18.0; μ_r ~1.5, $\tan\delta_\varepsilon$ ~0.2; $\tan\delta_\mu$ ~1.0.

However, there exist some differences, when sample from this absorber FM8 has been measured by the waveguide perturbation method using the setup in Fig. 12*a* and Fig, 12*b* (see also Fig. 6).

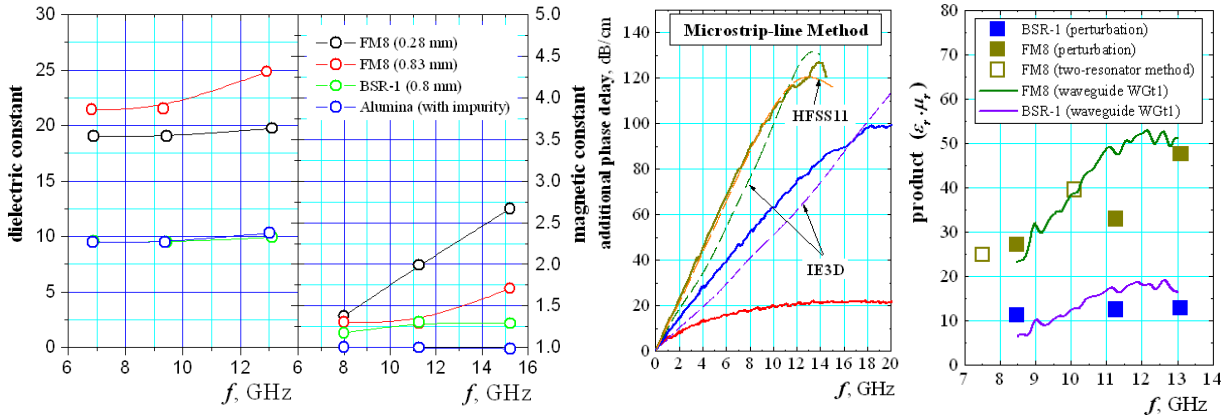


Fig. 11. Results for the material parameters of the absorber FM8 obtained by: (*a*) perturbation waveguide method (see Fig. 12*a*); (b) measured additional phase delay deg/cm for covered by FM8 MSL; (c) summarized data for the product ($\varepsilon_r \times \mu_r$) by different methods

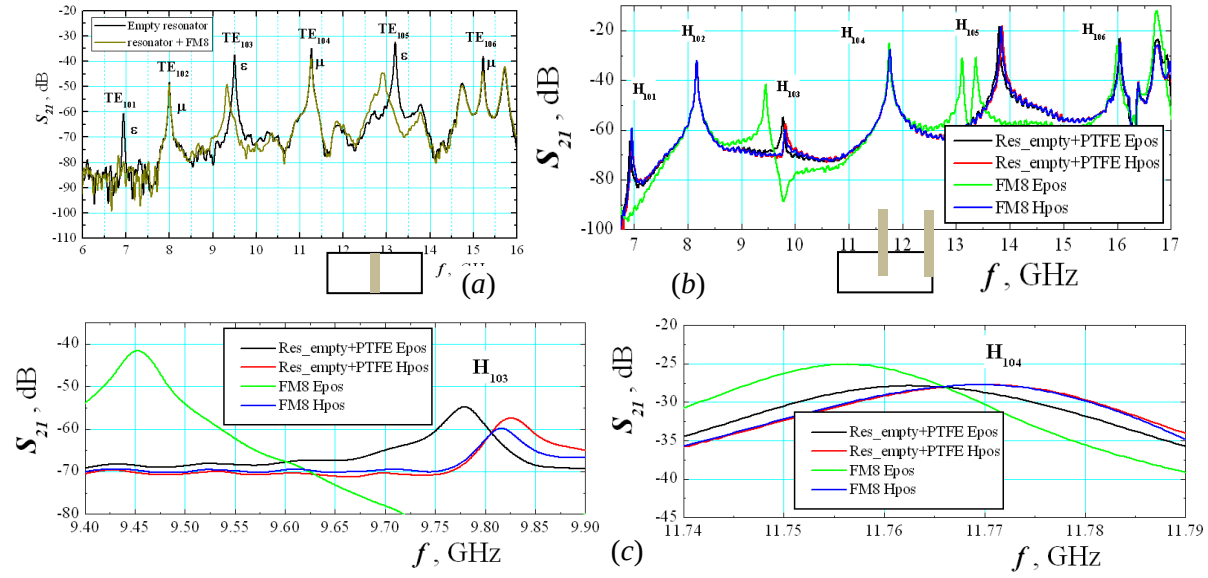


Fig. 12. Measured mode spectrum of rectangular waveguide resonator with prism sample from the absorber FM8, which length fit the waveguide height *b* (*a*) or measured in E or H position in the resonator (*b*) (see Fig. 6); (*c*) two resonance modes TE(H)$_{103}$ and TE(H)$_{104}$ measured in rectangular waveguide resonator in two positions of the AUT prism from absorber FM8

The full spectrum in both resonance structures looks quite similar, but there appear some differences, when the resonance curves have been observed in narrower frequency intervals. First, the modes with maximum of the H fields in the resonator centre have different resonance curves for prism in E or H positions (see resonance curves of TE$_{104}$ mode in Fig.12*c*). In H position, the H filed is small; the resonance curve is practically the same. In E position, the E field has minimum and the resonance curve depends only on the perpendicular magnetic parameters μ_{perp} and $\tan\delta_{\mu_perp}$ (in our case μ_{perp} ~1.4, $\tan\delta_{\mu_perp}$ ~0.85; close to values obtained by other methods). This allows now to determine the pure values of the parallel dielectric parameters – ε_{par} ~ 19.1; $\tan\delta_{\varepsilon,par}$) ~ 0.17. All these results practically coincide with the results obtained by other measurement method applied to this material.

3.4. Characterization of Multylayer Thin Nanoabsorbes

The last example relates to characterization of thin nanoabsorbers. We applied a combination of measurement method in our research of these materials in [27]. First, the measured and extracted dielectric and magnetic parameters of the considered nanoabsorbers, are presented in Table 4. These values are obtained by the two-resonator method. The measurements by the rectangular waveguide perturbation technique give very similar results (not presented here).

The new measurements are based on the modified waveguide method developed for measurement exactly of this type of thin AUTs in four positions in the waveguide; we apply bellow only positions Eh, Ev and Hv – see Fig. 5. The results for the phase delay in the waveguides WR90 (for the X band); WR42 (for the K band) and WR 28 (for the Ka band) are presented in Fig. 13 and Fig. 14. Only for the Carbon-content nanoabsorber nC(L) (deposited on a 100-μm thick plastic polyester support PE and covered by ~30-μm thick protective lacquer L for bigger mechanical stability), the measured dependencies in Eh, Ev and Hv position of the prisms are compared with the simulated by HFSS dependencies.

Table 4. Extracted values of the dielectric and magnetic parameters of 30-μm thick nano absorbers (AUT) mixed with protective lacquer L (nC – consists of nano-carbon particles of diameter ~3-4 nm; nF – nano-ferrite Fe_3O_4 particles of diameter ~20-30 nm; nFC – a mixture nF : nC = 1 : 1)

AUT + L	$\varepsilon_{par}/\tan\delta_{\varepsilon_par}$ (f, GHz)	$\varepsilon_{perp}/\tan\delta_{\varepsilon_perp}$ (f, GHz)	μ_{par} (f, GHz)	μ_{perp} (f, GHz)
nC	7.65/1.6 (12.8); 6.82/5.4 (22.1); 3.49/5.5 (32)	4.20/0.22 (7.6); 4.04/0.15 (17.5); 3.56/0.22 (27.4)	-	-
nF	3.75/0.58 (12.8); 3.73/4.1 (22.1); 4.17/1.70 (32)	2.05/1.93 (7.6); 2.54/0.55 (17.5); 2.24/0.26 (27.4)	1.06 (20.8)	0.93 (15.7); 0.51 (24.4); 0.45 (33.8)
nFnC	8.84/3.3 (12.8); 5.82/0.25 (22.1); 2.51/0.77 (32)	2.57/0.73 (7.6); 2.67/0.08 (17.5); 2.62/0.144 (27.4)	1.16 (20.8)	1.04 (15.7); 1.50 (24.4); 2.90 (33.8)

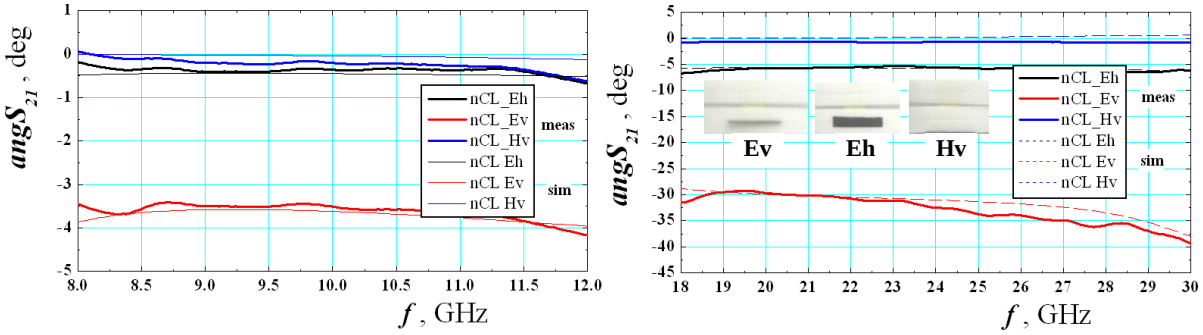


Fig. 13. Measured and simulated by HFSS additional phase delay of waveguides with prism samples of nanoabsorber nCL (see the denotations in Table 4) for the X band (*a*) and for the K band (*b*) with waveguides WR90 and WR42 respectively

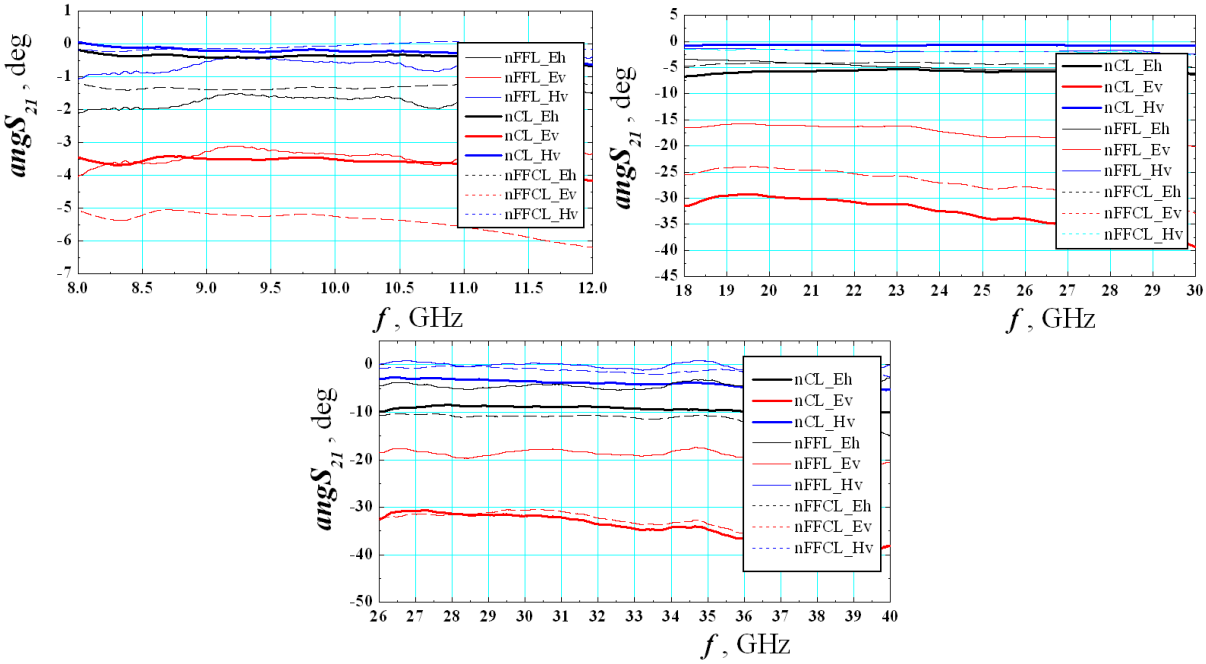


Fig. 14. Measured additional phase delay of waveguides with prism samples of nanoabsorbers nCL, nFFL and nFFCL (see the denotations in Table 4) for the X band (*a*), K band (*b*) and Ka band with waveguides WR90, WR42 and WR 28, respectively

The simulations are implemented with the values for the measured material constants given in Table 4 for the corresponding frequency range. The good coincidence is obvious; that explain the high accuracy of the obtained by the combination of these methods results. Fig. 14 presents the measured phase delays for other nanoabsorbers; a comparison with the simulated dependences is not presented for these samples; however, the obtained measured and simulated dependencies are very similar. The dependence in the different frequency range should not be compared, because the measurements have been performed with samples prisms with different dimensions in each frequency range.

5. CONCLUSIONS

In conclusion, the presented in this paper research for characterization of different types of microwave absorbers definitely confirm our assumption in the beginning – the reliable characterization of these complex lossy materials with combined dielectric and magnetic properties in most of the cases must be performed not with a single method, even very accurate, but with a combination of methods. These methods have to be complimentary and independent; the best choice is to combine an accurate resonance method – e.g. perturbation technique with rectangular resonator with small prisms or cylindrical resonators with disk samples, and a broad-band method, e.g. free-space method (if the samples have relatively big sizes), or transmission waveguide methods – with rectangular or coaxial waveguides with samples in different positions or transmission-line methods with covered by samples planar lines.

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