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DEVELOPMENT AND CHARACTERISATION OF AN ELECTROMAGNETIC ABSORBER

RAZVOJ IN KARAKTERIZACIJA ELEKTROMAGNETNEGA ABSORBERJA

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As a result of rapid advances in technology the use of wireless communications and radar systems is expanding very quickly, which leads to a significant increase in the levels of background electromagnetic (EM) radiation. Because of this it is necessary to protect both electronic devices and humans from the adverse effects of this EM radiation. The obvious solution is the application of a Faraday cage; however, such a cage only reflects the radiation and thereby further increases the level of background radiation. The alternative is to use absorbing materials; such materials absorb the EM radiation and convert it into heat. Although the principle of operation is relatively simple, the design and development of a practical absorber are complex problems and demand the optimization of a series of parameters. Here we present the operation of an electromagnetic absorber, its design and its key parameters. This is followed by an overview of recent R&D results from the cooperative work on ceramic composites and composites with nanoparticles undertaken by Iskra Feriti d.o.o. and the Advanced Materials Department of the Jožef Stefan Institute.

Keywords: electromagnetic absorber, composite, ferrite

Z razvojem tehnologije se skokovito povečuje uporaba brezžičnih komunikacij in radarskih sistemov in s tem tudi gostota elektromagnetnega (EM) smoga, zato je potrebno zaščititi elektronske naprave in ljudi pred neželenimi vplivi elektromagnetnega sevanja. Z uporabo Faradayeve kletke odbijemo vpadno EM-valovanje, vendar s tem povečamo število parazitskih signalov in motenj v okolici. Druga možnost je uporaba absorpcijskih materialov, ki absorbirajo vpadno EM-valovanje in ga spremenijo v toploto. Čeprav je princip delovanja relativno preprost, pa je zasnova in izdelava uporabnega absorberja kompleksen problem, ki zahteva optimizacijo vrste fizičnih in elektromagnetih parametrov. V prispevku je predstavljena zasnova, delovanje ter ključne veličine EM-absorberja. Temu sledi predstavitev nekaterih keramičnih kompozitov za absorberje ter potencial kompozitov z nanodelci, oboje rezultat razvojnega sodelovanja med Iskro Feriti, d. o. o., ter Odsekom za sodobne materiale, Institut "Jožef Stefan".

Ključne besede: elektromagnetni absorber, kompozit, ferit

1 INTRODUCTION

With the rapid advancements in wireless communications the density of radio-frequency (rf) waves and microwaves in our surroundings is becoming a serious problem. The use of electromagnetic absorbers – multipart materials that absorb incident electromagnetic radiation in a limited wave spectrum – can ease this problem and, therefore, absorbers of electromagnetic waves are becoming increasingly important for applications outside special fields like silent rooms, radar systems and military applications [1,2]. Given the wide range of applications with diverse requirements and the possibility to use a range of dielectric and soft-magnetic materials, it should not be surprising that there exist many different designs for these absorbers [1-3]. In this paper we present some of the basics relating to electromagnetic absorbers, the characterization of an absorber, and an evaluation of its properties. This will be followed by a presentation and discussion of the materials that we developed for absorbers and the absorber characteristics. We will finish with a short report on the application of composites with nanosized soft-magnetic particles as electromagnetic absorbers.

2 BACKGROUND

Aside from special variants like the quarter-wave-length resonant absorber [1], a typical absorber consists of an absorptive layer(s) that is backed with a metal sheet or foil, as shown in **Figure 1**. The principle of operation is that due to absorption in the active layer the reflected wave becomes significantly reduced. However, a significant part of the incident wave can be reflected at the air–absorption-sheet interface and the characteristics of the active material have to be adjusted in order to both eliminate this front reflection and achieve sufficient absorption. With a more complex geometry, e.g., a series of successive absorption layers or a pyramidal geometry [3,5], one can further reduce the level of reflection and increase the frequency range of the minimal reflection.

An absorptive layer can be made from either dielectric or soft-magnetic materials with an appropriate loss tangent. Usually, the absorber layers are made from

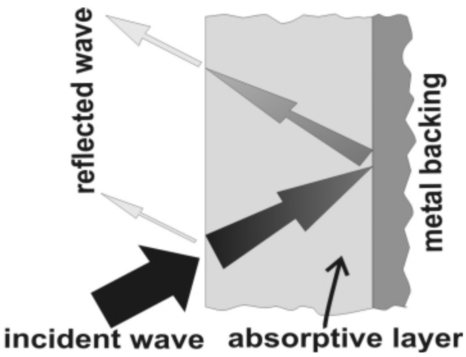

Figure 1: Scheme of a simple, one-layer absorber
Slika 1: Shema preprostega enoplastnega absorberja

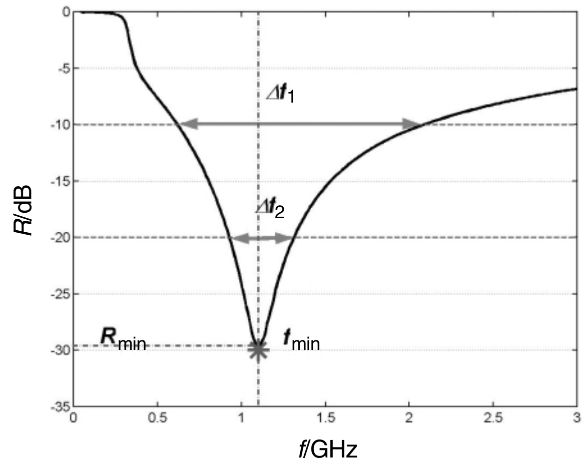

Figure 2: Typical reflection curve of a one-layer absorber as a function of frequency. Reflection levels –10 dB and –20 dB correspond to 10 % and 1 % reflection of energy respectively.
Slika 2: Značilna krivulja odboja enoplastnega absorberja v odvisnosti od frekvence. Nivo odboja –10 dB in –20 dB ustreza 10 % oziroma 1 % odboju energije.

composite materials, mixtures of dielectric (e.g., carbon black, aluminium flakes) and/or soft-magnetic (e.g., ferrites, carbonyl iron) particles in some kind of matrix [1,3,5,6,13]; however, excellent absorbers for use at lower frequencies can be made from ferrite ceramics [1,3,7]. Since every material has advantages and disadvantages, the selection of materials is difficult and depends on an actual application.

The characterization of absorbers can be made directly with standardized measurements of reflection in free space or indirectly through measurements of the constituent materials' electromagnetic properties. The latter method is frequently used in the designing phase, since in general the reflection from the absorber can be analytically calculated from the known characteristics and the geometry of the materials [8,9]. Furthermore, for simple geometries like a one-layer, flat absorber the deviation between the analytical calculations and experiments is so small that it is sufficient to characterize the material and calculate the reflection to obtain the absorber properties. In our work we adopted the latter approach since the absorber properties are only demonstrative and could be changed in real applications (e.g., with near-field sources).

For a simple one-layer absorber with metal backing the equation for reflection is [10]:

$$R/(\mathrm{dB}) = 20 \cdot \lg_{10}\left(\frac{iA\tan(kd)-1}{iA\tan(kd)+1}\right) \qquad (1)$$

$$A = \sqrt{\frac{\mu}{\varepsilon}},\ k = \frac{2\pi f}{c}\sqrt{\mu\varepsilon},\ i = \sqrt{-1}$$

where μ and ε are the complex permeability and the permittivity, respectively, f is the frequency of the incident EM wave, c is the speed of light in a vacuum, and d is the thickness of the absorbing layer. From this we can see that the key parameters that can be varied are the complex permeability and permittivity of the material and the thickness of the layer, whereas the frequency of the incident EM wave is an external factor. An example of the reflection curve as a function of frequency is shown in **Figure 2**.

Although equation (1) has a relatively simple form the relation between the material properties and the reflection is not simple and one cannot predict the behaviour on the basis of the material properties (e.g., high permeability, low permittivity, high loss tangent, etc.) alone. In the minimization problem we have to optimize the properties for two only loosely connected phenomena, i.e., the reflection from the front surface and the absorption inside the active layer.

In order to characterize the absorber properties three key parameters are used: the width of the absorption band Δf, the frequency range where the reflection is below some level, usually –10 dB (10 % reflection) or –20 dB (1 % reflection); the frequency of the minimum reflection $f_{\min}$; and the level of the reflection at $f_{\min}$, $R_{\min}$. An evaluation of the quality of the reflection curve is rather arbitrary and depends on the desired frequency range and the level of absorption, which usually differ for various applications.

3 EXPERIMENTAL PROCEDURE

Ferrite spinel powders or powders based on spinel/hexaferrite (S/M) and Z/W hexaferrite (Z/W) composites were prepared using conventional ceramic methods from Ba carbonate and/or oxides (Fe, Mn, Ni, Co, Bi) at temperatures between 1250 °C and 1300 °C. All the samples were characterized with X-ray diffraction (XRD) analysis using a D4 Endeavor (Bruker AXS) diffractometer and Cu K_{α} radiation. The microstructures were observed and the phase compositions were analyzed using a Jeol 5800 scanning electron microscope (SEM) connected to a LINK ISIS system for energy-dispersive spectroscopy (EDS) analysis.

The permeability of the materials was obtained by measuring the impedance with an HP 4291A Impedance

Analyzer (the measurements were made from 1 MHz to 1 GHz) and the S-parameters with an Anritsu 37369C Vector Network Analyzer (measurements were made from 100 MHz to >3 GHz). With the latter method we also determined the permittivity of the materials. The reflection of the simple, one-layer absorber with metal backing was calculated by using the measured $\mu(f)$ and ε in eq. (1).

4 RESULTS AND DISCUSSION

The reflection curve is a function of a complex interplay between the permittivity, the permeability and the thickness of the absorber. From a material point of view both the permeability and the permittivity can be varied, whereas by introducing design an additional degree of freedom is obtained (thickness). To get an ideal absorber a variation problem with (at least) five variables, e.g., real and imaginary parts of the permeability, the permittivity and the thickness, should be solved, which is an extremely challenging problem. Therefore, much of the designing is based on combinations of existing materials [4,8,9] and the time-honoured method of trial and error.

When a material is already prepared, the only variable parameter is the thickness. **Figure 3** presents three reflection curves from an absorber made from 1F material with three different thicknesses (d = 2, 4 and 6 mm). The material is a Ni ferrite with a relatively large initial permeability of about 100 and a resonance frequency at a few tens of MHz; however, the combination of all the parameters positions the reflection minimum at a significantly higher frequency (≈900 MHz).

Composites allow better matching of the optimal properties, especially if soft-magnetic particles are also used, since the permittivity and/or the permeability of the material can be varied substantially. Usually, carbonyl iron is used as the soft-magnetic component for composites [1,5,13]. However, due to their low conductivity ($\rho \approx 1\cdot10^5$ Ωm for the materials presented in this paper) ferrites can be used in (bulk) ceramic form, which offers a higher permeability compared to the reduced permeability of the iron in the composite. Furthermore, ferrites allow an easier variation of the frequency-dependent magnetic losses with composition[14], whereas

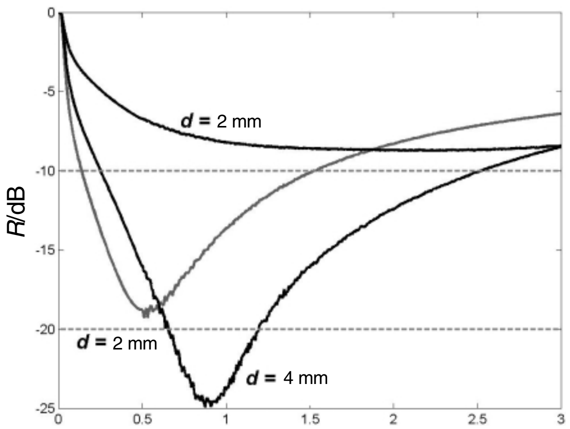

Figure 3: Reflection curves for different thickness d of absorption layer, made from 1F material. Permittivity of the material is approximately constant (ε = 11.5 – 0.05i) in the presented frequency range. Reflection-curve parameters for the curve with the lowest reflection are $\Delta f(-20\ \text{dB})$ = 550 MHz and $R_{min} \approx -25$ dB.

Slika 3: Krivulje odboja pri različnih debelinah absorpcijske plasti, izdelane iz materiala 1F. Dielektričnost materiala je približno konstantna (ε = 11.5 – 0.05i) v prikazanem frekvenčnem območju. Parametri krivulje odboja za krivuljo z najnižjim odbojem so $\Delta f(-20$ dB) = 550 MHz in $R_{min} \approx -25$ dB.

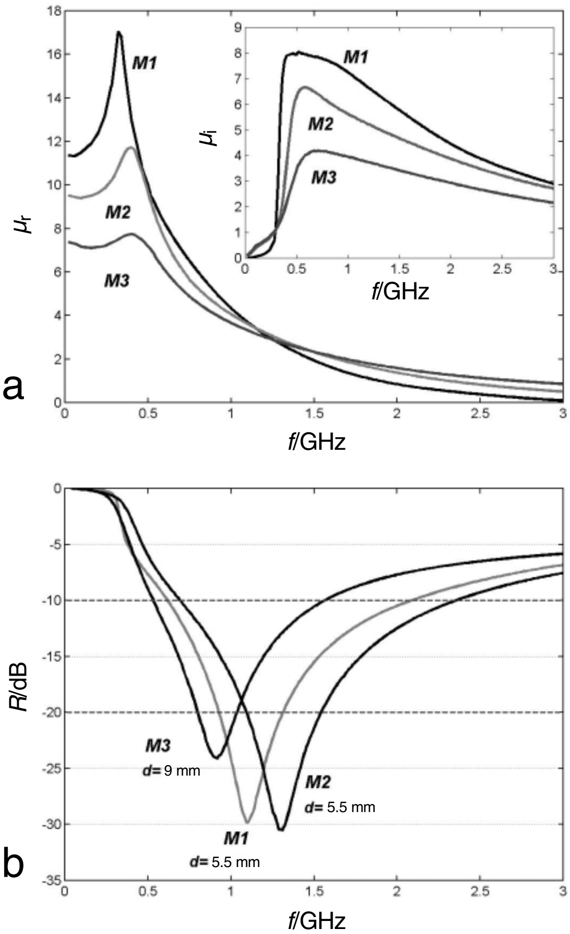

Figure 4: Real (μ_r) and imaginary (μ_i) permeability of three Ni ferrite-hexaferrite composite materials (a) and reflection curves for absorbers from these materials with optimum thickness (b). Permittivity of these materials is approximately constant (ε = 11 – 0.1i) in the presented frequency range. Properties of absorbers are: for M1 $\Delta f(-20$ dB) = 370 MHz, $R_{min} \approx -30$ dB; for M2 $\Delta f\,(-20$ dB) = 420 MHz, $R_{min} \approx -30$ dB; for M3 $\Delta f\,(-20$ dB)= 240 MHz, $R_{min} \approx -24$ dB.

Slika 4: Realni (μ_r) in imaginarni (μ_i) del permeabilnosti treh Ni ferit-heksaferit kompozitov (a) in krivulje odboja za optimalne absorberje iz teh materialov (b). Dielektričnost materialov je približno konstantna (ε = 11 – 0.1i) v prikazanem frekvenčnem območju. Lastnosti absorberjev so: za M1 $\Delta f(-20$ dB) = 370 MHz, $R_{min} \approx -30$ dB, za M2 Δf (–20 dB) = 420 MHz, $R_{min} \approx -30$ dB, in za M3 Δf (–20 dB)= 240 MHz, $R_{min} \approx -24$ dB.

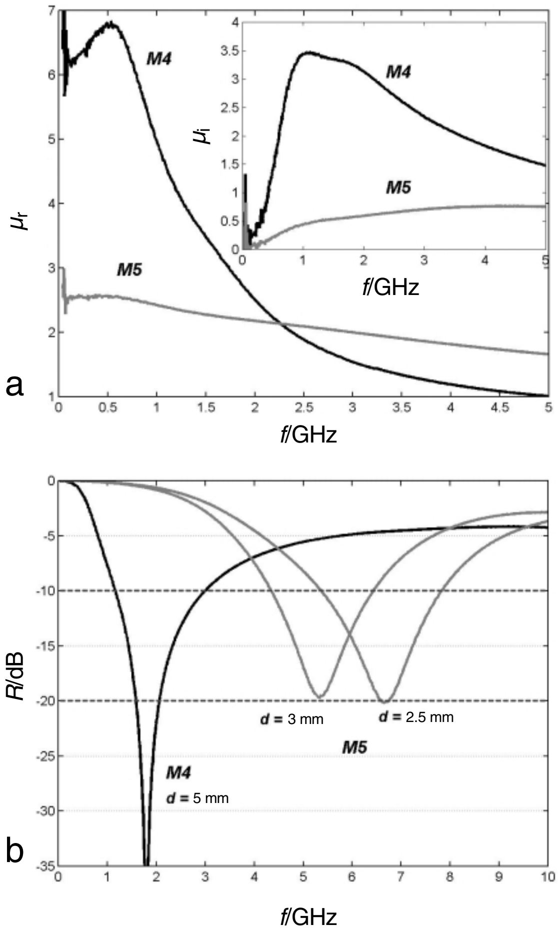

Figure 5: Real (μ_r) and imaginary (μ_i) permeability of two hexaferrite composite materials (a) and reflection curves for absorbers from these materials (b). For material M5 the reflection curves for two thicknesses are shown. As before, the permittivity of these materials is approximately constant (ε = 12 – 0.2i). Properties of absorbers are: for M4 Δf(–20 dB) = 400 MHz, R_{min} < –35 dB; for M5 R_{min} ≈ –20 dB.

Slika 5: Realni (μ_r) in imaginarni (μ_i) del permeabilnosti dveh heksaferitnih kompozitnih materialov (a) in krivulje odboja za optimalne absorberje iz teh dveh materialov (b). Za material M5 sta prikazani krivulji odboja pri dveh debelinah absorpcijske plasti. Dielektričnost materialov je približno konstantna (ε = 12 – 0.2i). Lastnosti absorberjev so: za M4 Δf(–20 dB) = 400 MHz, R_{min} < –35 dB in za M5 R_{min} ≈ –20 dB.

the permittivity is relatively constant. To add some flexibility to the ceramic material we developed a few ceramic composites: mixtures of different magnetic and non-magnetic phases sintered together. With variations in the composition, the microstructure and the sintering conditions we were able to vary the electromagnetic properties considerably in order to obtain good properties for the absorber.

The properties of the ceramic composites that we developed and the (calculated) characteristics of the absorbers made from such materials are presented in **Figures 4-5**. **Figure 4** presents mixtures of Ni ferrite and hexaferrite with varying ratios [11]. The variation of the permeability and resonance frequency with composition

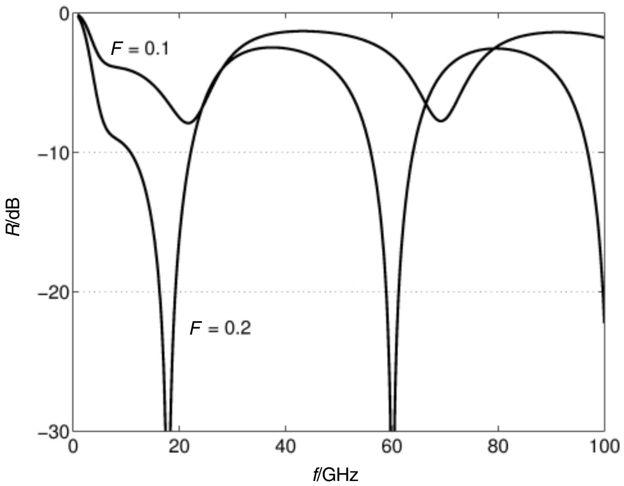

Figure 6: Calculated reflection curves for composite with nanosized iron particles in polymer matrix. Curves are shown for two volume fractions, F = 0.1 and F = 0.2, of nanoparticles in the composite. Diameter of particles is 10 nm, thickness of absorption layer is 1.4 mm, other parameters are in [12]. Widths of the absorption bands are over 2 GHz at –20 dB.

Slika 6: Izračunane krivulje odboja za nanokompozit z železovimi nanodelci v polimerni matrici. Krivulji sta prikazani za dva volumenska deleža nanodelcev v kompozitu, F = 0.1 in F = 0.2. Premer delcev je 10 nm, debelina absorpcijske plasti 1,4 mm, drugi parametri so podani v [12]. Širini absorpcijskih pasov sta preko 2 GHz pri nivoju odboja –20 dB.

translate into different reflection curves; however, the shift of the calculated reflection curves is only in a limited range of 0.5 GHz. A more significant change in the permeability is observed with two mixtures of different hexaferrites, presented in **Figure 5**, resulting in a much larger difference in the reflection curves. Also, since the wavelength of the electromagnetic wave reduces with increasing frequency, the required thickness of the absorbers generally diminishes with increasing frequencies, as seen in **Figure 5**. It is interesting to compare materials M3 and M4. Both have a fairly similar resonance frequency and permeability at frequencies below a few GHz, yet the reflection curves are distinctly different. This underlines the complex interplay of all the parameters in eq. (1) and reveals the problems with an intuitive estimation of the operating range.

Another interesting material for absorbers could be composites with soft-magnetic nanoparticles [12]. Nanosized ferromagnetic particles have properties that are different to those of bulk materials or large particles and can be somewhat varied with size selection and the method of preparation. This allows greater flexibility in the use of metallic nanoparticles. As our calculations show [12], the frequency range for significant magnetic losses can be extremely wide, resulting in the multiple absorption bands shown in **Figure 6**. Furthermore, the bands are wider and the same level of reflection can be obtained with a significantly thinner absorber.

5 SUMMARY

Due to the increasing importance of electromagnetic absorbers to material producers, wireless-communications providers and the general public, we have presented the basics of electromagnetic absorbers, their characterization and some areas of further development. We have also presented some materials that we developed for applications in the low-GHz region. These materials are ceramic composites and thus incorporate the advantages of ferrite ceramics with the parameters flexibility of composites. By comparing the reflection curves of two materials with relatively comparable electromagnetic properties, which differed significantly, we demonstrated the complex relationship between all the parameters of the absorber. We concluded with a composite containing soft-magnetic nanoparticles that can exhibit multi-band reflection characteristics with wide bands and is thus a potentially interesting material for absorbers.

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