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Electromagnetic radiation attenuation materials

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Abstract

The shielding electromagnetic (EM) waves is a very important field of the electronics, telecommunications and IT industries. The phenomenon of electromagnetic interference (EMI) can be a source of interference in electronic systems, which can both disrupt the operation of systems and provide a breach to intercept the flow of classified information. Hence, it is necessary to shield electronic and IT systems to prevent the coupling of circuits and prevent the monitoring of data emitted in the form of electromagnetic waves. An additional threat resulting from the EMI phenomenon is the possibility of inducing high voltages and currents in circuits that may temporarily or permanently damage electronic systems as a result of high-power electromagnetic pulses. Examples of sources of high-power impulses can be, for example, atmospheric discharges, gasoline engine ignition systems, electrostatic discharges, solar discharges, cosmic rays and military hardware, such as electromagnetic directed energy weapons.

The paper will present the results of research carried out as part of interdisciplinary projects related to security threats to ICT systems in the area of critical infrastructure.

Keywords: electromagnetic radiation, attenuation barriers, countering security threats, structures suppressing electromagnetic radiation

1 Introduction

Nowadays, electronic devices, IT and telecommunication systems are commonly used by the majority of society. These are no longer just mobile phones, desktop or portable computers but also devices used for communication between various civilian and military management of banking systems, electrical grids and many other areas of civilization activity. The issue of electromagnetic waves shielding is a very important area of the electronic,

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telecommunication and IT industries. The phenomenon of electromagnetic interference (EMI) can be a source of interference in electronic systems, which can not only disrupt the correct operation of systems but also create a channel for the outflow of sensitive information. Hence, it is necessary to shield electronic and IT systems to prevent the phenomenon of circuit coupling and prevent monitoring of data emitted in the form of electromagnetic waves.

An additional threat resulting from EMI is the possibility of inducing high voltages and currents in circuits that can temporarily or permanently damage electronic and telecommunication systems as a result of high-power electromagnetic pulses. Examples of sources of high-power pulses may include atmospheric discharges, ignition systems of gasoline engines, electrostatic discharges, solar discharges, cosmic radiation or sources of military significance, such as a nuclear electromagnetic wave as a component of a nuclear explosion (NEMP - Nuclear Electromagnetic Pulse) and electromagnetic weapons [1].

The threat from electromagnetic weapons is significant for many areas of modern technology and largely concerns electronic systems. The effects of a potential attack on strategic databases or networks, e.g., banking or government networks, could lead to the paralysis of entire systems. An additional threat is the use of such weapons to paralyze control systems in public transport, e.g., air transport, which could lead to transport disasters. Hence, there is a need to find effective solutions to protect various systems and circuits against the effects of high-power electromagnetic waves. One such solution is the use of a Faraday cage made of electrical conductors, which shields the protected elements relatively well if it is electromagnetically sealed, but the cage is not very mobile and is characterized by high mass, which makes its use difficult, for example, in aviation. Currently, many studies are being conducted on new lightweight materials with good EM wave attenuation properties using polymeric, metallic or carbon nanostructures [2-8].

Electromagnetic absorbers are chemical substances, special materials or multilayer composite material structures that can attenuate the reflection or transmission of electromagnetic radiation. For example, this can be achieved using materials such as dielectrics connected to metal plates arranged at specific intervals – distances depending on the wavelength of electromagnetic radiation. Individual absorption frequencies, thickness of the absorber layer, component arrangement and material configuration determine attenuation characteristics and applicability. Moreover, numerous works are performed on advanced material structures, such as metamaterials, which enable the improvement of attenuation efficiency and provide a variety of applications [9]. Some of the planned applications of the new absorbers include emitters, sensors, spatial light modulators, infrared camouflage, wireless communication, and thermophotovoltaic applications.

Practically, there are two types of absorbers among the electromagnetic radiation attenuation media: resonant absorbers and broadband absorbers. Resonant absorbers are dependent on the frequency of electromagnetic radiation due to the effect of resonance interaction of the material at a specific wavelength of radiation. Various types of resonant absorbers are Salisbury screen, Dallenbach layer, Jaumann absorber, cross-grating absorbers, and analogue absorbers (CA) [10]. Figure 1 shows a scheme of the Salisbury screen structure.

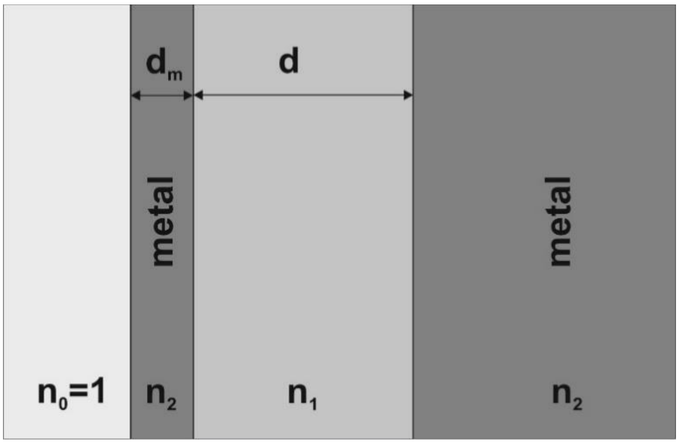


Figure 1. *Scheme of a simple Salisbury absorbing screen structure*
n_0 = 1 - refractive index of air,
n_1, d – refractive index and thickness of the absorber layer,
n_2, d_m- air refractive index and thickness of metallic layer

The Salisbury screen works on the basis of interference attenuation of reflected radiation. A thin metal layer is placed in front of the metal surface at a distance dm. The thickness of the layer dm must be comparable to the skin thickness to enable the transmission of EM waves through this layer. In this way, a cavity is created between the mirror and the thin layer of thickness dm, in which electromagnetic standing waves are created. The attenuation is the result of the presence of the imaginary part of the refractive index n1. It is also possible to introduce attenuation in the form of losses associated with the thick metallic layer that forms the mirror.

Dallenbach layers differ from Salisbury screens in that the gap between the resistive layer and the metallic substrate is filled with a layer of a lossy dielectric medium. In Dallenbach layers, the thickness of the separation between the resistive foil and the metallic substrate, and therefore the frequency to be absorbed, depends on the propagation constant of the lossy medium. In contrast to Salisbury screens, Dallenbach layers are very convenient for use in sandwich composite structures, due to the geometry control based on the lossy medium. On the other hand, both Salisbury screens and Dallenbach layers provide insufficient broadband efficiency.

A Jaumann absorber or Jaumann layer is a material structure that absorbs radar radiation. First introduced in 1943, the Jaumann layer consisted of two equally spaced reflective surfaces and a conductive ground plane. This structure is a generalized, multilayer Salisbury screen, as the principles of their implementation and calculation are similar. As a resonant absorber, it uses wave interference to quench the reflected wave. The Jaumann layer depends on the distance λ/4, (where λ is the wavelength of electromagnetic radiation), between the first reflective surface and the ground plane and between the two reflective surfaces (total λ/4 + λ/4). Since the E-M wave can resonate at two frequencies, the Jaumann layer produces two absorption maxima in a wavelength band (if a two-layer configuration is used). More complex Jaumann absorbers use a series of dielectric surfaces that separate the conductive layers. Circuit analog (CA) absorbers are constructed from a resistive sheet with a periodic pattern, composite material of glass fiber or epoxy as a spacer, and a composite of fabric with carbon nanostructures.

Broadband absorbers do not depend on the specific frequency and can therefore be effective over a wide spectrum of electromagnetic radiation.

2 ABSORBERS AND ELECTROMAGNETIC RADIATION SHIELDING MATERIALS

Recently, electromagnetic interference (EMI) shielding for radio frequency (RF) radiation has sparked much interest in the scientific community and the general public [11, 12]. It has become very important to provide EMI protection with specific properties, such as the lightness of shields, the effectiveness of monitoring the workspace and environment for radiation of computers and communication devices, as well as for the protection of sensitive circuits. Over the past decade, with the development of nanotechnology, radar absorber materials (RAMs) have gained much attention due to their ability to increase the effectiveness of protection and absorption of microwaves while at the same time reducing the mass and size of modern structures. In general, high-frequency electronic components often encounter problems such as frequency signal leakage when the electronic device is in the open state or is not sufficiently closed. It can be assumed that electromagnetic interference (EMI) and shielding is a process in which the interfering electromagnetic energy is transferred from one electronic device to another through radiation, as well as by connection by paths or wires. The statement that metals are the best material for reflecting electromagnetic waves is not borne out in real-world shielding systems as the reflected wave can interfere with the operation of an electronic component inside the housing or near it.

The most important electromagnetic parameters characterizing the material that attenuates the E-M radiation are the imaginary parts of the complex electric permittivity $\varepsilon^* = \varepsilon' + j \cdot \varepsilon''$, complex magnetic permeability $\mu^* = \mu' + j \cdot \mu''$ and complex conductivity $\sigma^* = \sigma' + j \cdot \sigma''$.

Since no material provides high values for all of these parameters over a wide frequency range, the condition for full impedance matching is $\mu'/\varepsilon' = 1$. In the microwave band, μ' is smaller than ε' for most materials, such as magnetic materials. Similarly, as in the case of the impedance matching, we can allow EM waves to enter the material, but then the next step is to attenuate them as much as possible. Some requirements concerning EM microwave parameters must be met to obtain the condition of maximizing attenuation. The higher the values of ε'' and μ'', the larger the attenuation constant will be, thereby increasing the overall attenuation. However, higher values of μ'' contribute to more intense heating of the dielectric, which is not desirable.

Electromagnetic shielding is a process aimed at reducing the penetration of EM waves into the desirable space. The shielding effectiveness (SE_T) is defined as a parameter that determines the quality of a material that attenuates EM energy at a given frequency passing through a medium. Generally, shielding effectiveness is measured in terms of the reduction in the intensity of electromagnetic radiation passing through the shield.

When an electromagnetic wave passes through a shielding material, it is subjected to reflection, transmission and absorption, as shown in Figure 2, which illustrates the basic physical effects that occur when electromagnetic radiation passes through an attenuating screen.

Figure 2 shows the skin depth – the parameter characterizing the absorption properties of materials that attenuate electromagnetic radiation. This is a depth at which the EM wave signal is attenuated to a value of 1/e, i.e. to c.a. 37% of the initial value. Skin depth is usually measured in meters and is related to the frequency (f) of the EM wave and the electrical conductivity (σ) of the medium through which the EM wave propagates.

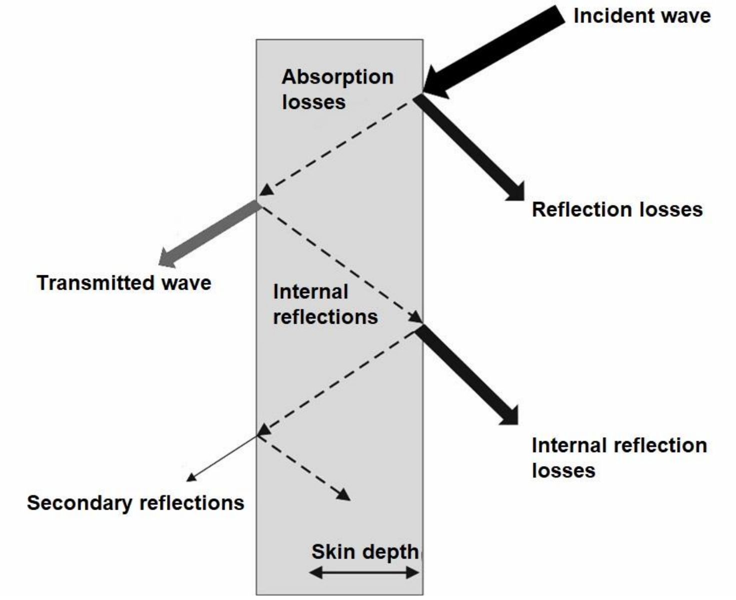


Figure 2. *Scheme of the basic physical effects that occur when electromagnetic radiation passes through an attenuation screen*

When an EM is incident on the front part of the material, a certain part of the incident power (P_I) is reflected (P_R), while another specific part of the incident power is absorbed and dissipated as energy losses and the remaining part is transmitted (P_T) through the shielding material. When the EM energy interacts with the electronic and molecular structures of the material, this reaction leads to the generation of heat inside the attenuating material due to the dissipation of energy, which in turn converts the incident EM wave into heat or other forms of energy.

Therefore, the electromagnetic shielding efficiency (SE_T) is the ratio of the transmitted energy to the incident energy, which also represents the sum of three different processes consisting of reflection (SE_R), absorption (SE_A) and multiple internal reflections (SE_M). These three processes contribute to the total attenuation of the shield:

$$SE_T = SE_R + SE_A + SE_M$$

From the plane wave theory, it is known that the amplitude of the electromagnetic wave decreases significantly inside the attenuating medium. As a consequence, there is a loss of absorption due to ohmic losses and heating of the material, as well as due to currents induced in the medium.

According to the definition, the shielding effectiveness (SE) is defined as the ratio of the power delivered from the radiation source (generator) to a specific location in space in the absence of an absorber, to the power delivered to that location with an absorber. Shielding effectiveness therefore determines the amount of reduction in the electromagnetic field intensity or power density behind the shield compared to the case when there is no shield. SE depends on many factors such as: frequency, distance from the shield, thickness of the shield and the type of material from which the electromagnetic shield is made.

The SE_T shielding efficiency is usually expressed in decibels L [dB] and can be mathematically expressed as a logarithmic function of the ratio of transmitted electric field intensity (E), magnetic field intensity (H) or plane wave power (P) to the incident radiation parameters:

$$L\ [dB] = 10 \cdot \log_{10} (P_T/P_I)$$

where: P_I - electromagnetic field power of the plane wave incident on the screen

P_T - electromagnetic field power of the wave passing through the screen (absorber)

SE can also be determined using field intensities, namely:

$$L\ [dB] = 20 \cdot \log 10\ (E_T/E_I)$$

$$L\ [dB] = 20 \cdot \log 10\ (H_T/H_I)$$

where:

E_I - electric field intensity of the plane wave incident on the screen

E_T - electric field intensity of the wave passing through the screen (absorber)

H_I - magnetic field intensity of the plane wave incident on the screen

H_T - magnetic field intensity of the wave passing through the screen (absorber).

When adopting one of the above mathematical definitions, it should be borne in mind that shielding effectiveness depends not only on the losses caused by the absorber but also on the matching of the absorber impedance to the impedance of free space. For this reason, two components can be distinguished in the expression for shielding effectiveness L [dB], namely the reflection losses LR [dB] and the absorption losses LA [dB], according to the relationship:

$$L = L_R + L_A$$

Shielding effectiveness L is also called as "total losses". Reflection losses LR determines what part of the energy of the incident electromagnetic wave will be reflected from the dielectric. On the other hand, absorption losses LA determine the absorption of the wave energy in the absorber itself. Determining the reflection losses and absorption losses allow us to also determine what is the contribution of reflection and absorption of energy in the absorber itself, in the total shielding (wave energy attenuation) provided by the screen.

It should be noted that a good absorber should be characterized by a high absorption and low reflection level of the field energy. Low levels of reflection attenuation is even required in many applications.

3 CHARACTERISTICS OF MATERIALS THAT ATTENUATE ELECTROMAGNETIC RADIATION

The search for materials that attenuate electromagnetic radiation in the range of microwave spectrum began as early as the 1930s. The impetus for conducting research in this area was the use of the first radar systems for detecting and targeting aerial objects. The absorbers at that time were a mixture of several materials with various loss mechanisms selected to optimize the width of the attenuation band.

The first patent for an absorber was granted in 1936 in the Netherlands. The carbon black was used as a loss material for its production. In order to reduce the thickness of the absorber, titanium dioxide (dielectric) was added, which is characterized by high dielectric permittivity (ε'= 110), meaning that it can store more energy of the electric field. Further attempts to produce an absorber were made in Germany during World War II. It was used as camouflage for submarines at the time. This material was called "WESCH". Its main component was iron carbonyl (in the form of powder) dispersed in rubber. As a whole, it took the form of sheets of 0.86 cm thickness with a resonance frequency of 3 GHz.

Work has also been undertaken on multilayer absorbers, which resulted in the creation of Jaumann-type absorbers. They were about 76 mm (3") thick with an exponentially decreasing resistance from the front of the material. The reflection coefficient of the absorber was -20 dB in the frequency range of 2-15 GHz.

At the same time, an absorber called HARP (Halpern Anti-Radiation Paint) was developed at the Massachusetts Institute of Technology (MIT). This was a paint that made it difficult to detect an object using radar. The version of the coating used in aircraft was 0.6 mm thick for X-band attenuation. The vessels were covered with the same paint, but its thickness was 1.8 mm for X-band. The losses in this case were caused by a dielectric, whose electrical permittivity was ε' = 150. The absorber consisted of a mixture of aluminum powder (in the form of very fine flakes) and carbon black that was distributed in a rubber matrix.

The period after World War II was characterized by further development of absorbers. The focus was on broadband absorbers in the form of polyhedrons, which allowed for gradual absorption of electromagnetic wave energy. The basic components of the absorber material were: graphite, iron oxide, powdered steel, powdered aluminum and copper, and steel wool. Various types of polymers and ceramics were used as the matrix.

The 1950s saw the production of commercial absorbers called "Spongex" that were manufactured by Sponge Products Company, a subsidiary of Goodrich. The absorber, at a thickness of about 51 mm (2"), achieved attenuation of 20 dB in the frequency range of 2.4 ÷ 10 GHz. The following years saw continued works on so-called analog circuits and attempts to reduce the thickness of absorbers by using ferrite layers. The term "analog circuit" comes from the use of circuit theory to represent the components and physical processes occurring in the absorber, and consequently to model the reflection coefficient. This technique was adopted from acoustic absorber research programs. Severin and Meyer created experimental absorbers based on resistance-loaded loops, slits in resistive foil, resistance-loaded dipoles, strips of resistive material with varying orientations, strips of magnetic material with different orientations, shaping the surface of magnetic material, and magnetic loading of resonant materials. This initiated a new area of research on frequency selective surfaces (FSS).

The 1960s and 1970s brought enormous progress in the field of designing absorbing materials. Pyramid-shaped absorbers (which had an attenuation of 60 dB), foams, honeycombs and paints containing carbon in the form of particles or fibers as well as nickel-chromium alloy particles were made from them. Over time, research progressed on the various aspects of absorbers. Thanks to Jaumann absorbers, the frequency range of absorber materials was extended. By mixing dielectrics with carbon materials, carbonyl iron and ferrites, absorbers were produced with increasingly better parameters in attenuating electromagnetic radiation in a wide range of frequencies. The development of organic chemistry or more precisely, the chemistry of conducting polymers – opened new possibilities in the design of absorbers, including Jaumann absorbers.

In the 1980s, the process of designing electromagnetic radiation attenuation structures was improved through numerical optimization techniques. Improvement of the attenuation bandwidth of Jaumann absorbers was achieved using layered structures and various resistive profiles to achieve maximum bandwidth. Carbon black or graphite, carbonyl iron and ferrites were mainly used in the construction of attenuation structures of electromagnetic radiation.

Nowadays, synthetic dielectrics are produced by adding inclusions such as rods, wires, disks and spheres. It was found that spiral inclusions improve absorption, which led to research on chiral materials. The theory of hybrid structures is used to calculate the dielectric and magnetic permittivity of new attenuation structures. Conducting polymers are emerging as potential radar absorbing materials.

From the 1990s to the present, many techniques for Jaumann structure optimization have emerged, including the genetic algorithm optimization of composite structures for attenuating electromagnetic radiation. Currently, research and implementation works are being conducted in the field of frequency-selective surface absorbers as well as composite materials with conductive fibers and fabrics covered with polymers, conductive polymers, carbon nanostructures (various structural forms of graphene, nanotubes, fullerenes, etc.). The resonance frequency of the electromagnetic radiation attenuation media is regulated by changing the resistive and capacitive characteristics in the absorber.

The absorber structure can consist of a single layer or several different attenuating materials connected together, taking a shape depending on the needs and requirements set for attenuation. Attenuating materials can also be classified according to the technology of the elements absorbing the energy of the electromagnetic field. Widely used methods of covering surfaces to attenuate the radio signal are primarily the methods of varnishing with special paints or varnishes and insulating with foil. In turn, lossy materials that constitute the basic building block of absorbers can be divided according to several criteria.

Taking into account the area in which the energy of the electromagnetic field is lost, volume absorbers are distinguished, in which the energy is lost in the entire volume of the material and is converted into heat. These include materials used to produce cones, pyramids, foams, honeycombs, etc. The second type of attenuating materials in this criterion are surface absorbers in which the energy of the electromagnetic wave is lost in the near-surface layer of the material. These absorbers are used to produce paints, varnishes, thin foils, etc.

The second criterion for categorization of materials that attenuate electromagnetic radiation is the type of losses that dominate in the material. One category includes absorbers in which electrical losses dominate (electric field energy losses occur as a result of dielectric losses associated with relaxation and conductivity phenomena), and the other includes absorbers in which magnetic losses dominate (magnetic field energy losses occur as a result of induction of eddy currents or resonance phenomena, such as ferromagnetic resonance). Lossy, volumetric materials are mainly used in microwave transmission line loads and as elements that attenuate reflected signals in anechoic chambers. Lossy surface materials are used to eliminate signals reflected from buildings or moving objects.

When designing an effective absorbing structure, the biggest emphasis should be placed on maximizing the absorption of EM wave energy and keeping the reflection from the absorber surface as small as possible. The attenuating nature of the material should be based on several loss mechanisms so that it can operate in a wide frequency range.

3.1 POLYMER COMPOSITES

Polymers are a very large group of materials with widely varying properties. One of the advantages of these materials is their favorable strength-to-weight ratio. This makes them suitable in some applications as replacements for, for example, metals, where weight reduction is desired without compromising on strength. The originally used solutions for elements absorbing electromagnetic waves were based on metallic materials, but the need to use them in mobile systems forces the search for new, lighter and more compact solutions. Hence, among others, polymeric materials have been sought as a carrier for other absorption particles or as an absorber itself as far as electrically conductive materials are concerned [13-15].

In the case of microwave radiation barrier composites, the phenomenon of polymer cross-linking after the formation of the product can be combined with a beneficial modification of the ferromagnet.

In other words, metallic glass powder particles are additionally fixed in the matrix through cross-links created as a result of radiation treatment. The process can be carried out using an electron beam (EB) or gamma radiation (γ) and, importantly, at any temperature (most often room temperature) [16].

3.2 METALLIC COMPOSITES

Metals are an important group of materials as far as electromagnetic wave absorption is concerned due to their good electrical and magnetic permeability. The requirements for reducing the mass of absorbers do not allow the construction of fully metal elements. This results in the creation of metal-polymer composites in which polymers form a support matrix for active metal particles.

An example of this type of material is a polymer-metal composite (PMC) based on polyvinylidene fluoride (PVDF) reinforced with dispersed iron nanocrystals [17].

The magnetic permeability of previously known metallic materials decreases dramatically above the frequency range of 100 kHz, hence the need to develop new materials capable of effectively absorbing EM waves in the microwave range [18-21].

3.3 NANOCOMPOSITES

In the search for effective components to create electromagnetic wave absorbers, various types of electrically conductive nanostructures were also used. An example of the use of conductive nanostructures is the work on a nanocomposite with high radar wave absorption (RAS - Radar Absorbing Structures). The strength properties of the composite are provided by fiberglass reinforced with epoxy resin containing electrically conductive carbon nanoparticles. Carbon black (CB), carbon nanotubes (CNT), graphene and fullerenes are used as carbon filler [22-24].

3.4 ELECTRONIC ABSORBERS

Electromagnetic waves used for radar detection in the UHF (Ultra High-Frequency) band are difficult to absorb. The solutions used so far have had a relatively large thickness and a narrow band of effectiveness. Therefore, an unconventional metamaterial absorber for the UHF band below 2 GHz was proposed. The proposed absorber consists of four layers:

1. 0.8 mm thick glass-epoxy composite layer coated with a copper layer
2. AFSS (Active Frequency Selective Surfaces) layer etched in copper applied to a 0.04 mm thick glass-epoxy composite (PCB method) filled with appropriately connected resistors and capacitors
3. 7 mm thick honeycomb separation layer made of a dielectric material with very low dielectric loss in the required frequency range
4. the layer forming the base made of metal sheet

Table 1 lists the characteristics of dielectric and magnetic parameters and attenuation properties of selected material structures used in electromagnetic radiation protection systems.

Absorber	Dielectric losses	Magnet losses	d [mm]	f_{MAX} [GHz]	RL [dB]	ε’	ε’’	μ’	μ’’
Fe - CF	CF	Fe	1,8	11,6	-36,98	14,4	2,5	1,18	0,23
MnONPs - SiCw-RGO	RGO, Si	MnONPs*	1,59	17,9	-54,04	11,2	3,1	1,30	0,10
SCFs - Fe_3O_4	SCFs	Fe_3O_4	1,9	11,9	-40,8	9,8	2,1	1,70	0,32
NSZnO/Zn - CF	CF	NSZnO/Zn	4,5	3,23	-39,42	10,9	27,8	0,94	1,15
CB - SiC	CB	SiC	2,0	9,0	-41	15,8	2,2	-	-
MWCNT- Ni	MWCNT	Ni	3,7	6,56	-46,85	11,0	3,1	1,04	0,56
$Sm_2Co_{14}B$ - PA	$Sm_2Co_{14}B$	PA	2,3	8÷12	-23,1	21,0	11,9	0.99	-0.22
Fe - Ti	TiO_2	Fe(CO)	1,62	7,8	-40	4,6	1,2	0,0	1,2
CoNi-SiO_2,TiO_2	SiO_2, TiO_2	CoNi	2,1	8,1	-58,2	-	-	-	-
ZnO - Fe_3O_4	ZnO	Fe_3O_4	5,0	1,66	-12,92	6,0	1,2	1,0	2,9
Sr-$La_{2x}Sr_xNiO_4$	Sr	NiO	1,9	10,4	-21,07	7,98	3,0	1,05	0,1
$Ba_{0,85}RE_{0,15}Co_2Fe_{16}O_{27}$	$Ba_{0,85}RE_{0,15}Co_2Fe_{16}O_{27}$	PANI	3,5	9,4	-15,1	5,2	0,95	1,37	0,33
BF-RGO-PANI	$Ba_{0,9}La_{0,1}Fe_{11,9}Ni_{0,1}O_{19}$	RGO, PANI	1,9	14,08	-49,1	14,9	10,5	0,94	0,0

Table 1. *Attenuation properties of selected microwave radiation absorbers [25]*

Description of abbreviations from Table 1:

CF – carbon nanoflakes, MnONPs – MnO nanoparticles, SCF – short carbon fibers, NSZnO – nanostructured zinc oxide composites, SiCw – SiC whiskers, RGO– reduced graphene oxide, MWCNT – multiwall carbon nanotubes, CNT – carbon nanotubes, CB (Carbon Black) – graphite, PA – polyaniline, PANI - Polyaniline Ternary Nanocomposites.

4 IMPACT OF ELECTROMAGNETIC PULSE ON CRITICAL INFRASTRUCTURE OBJECTS

An electromagnetic pulse causes damage to electrical and electronic circuits by inducing voltages (potential difference) and parasitic currents in them, which they are unable to transfer the released energy without damaging or even destroying the devices.

Figure 3 depicts optical microscope photos, showing the structure of a white light source (LED semiconductor element with a luminophore) with a diameter of 2 mm, before and after exposure to an electromagnetic pulse from a portable source with a Marx generator (frequency of 350 MHz, pulse energy of 200 mJ, pulse duration of 4 ns) from a distance of 2 m.

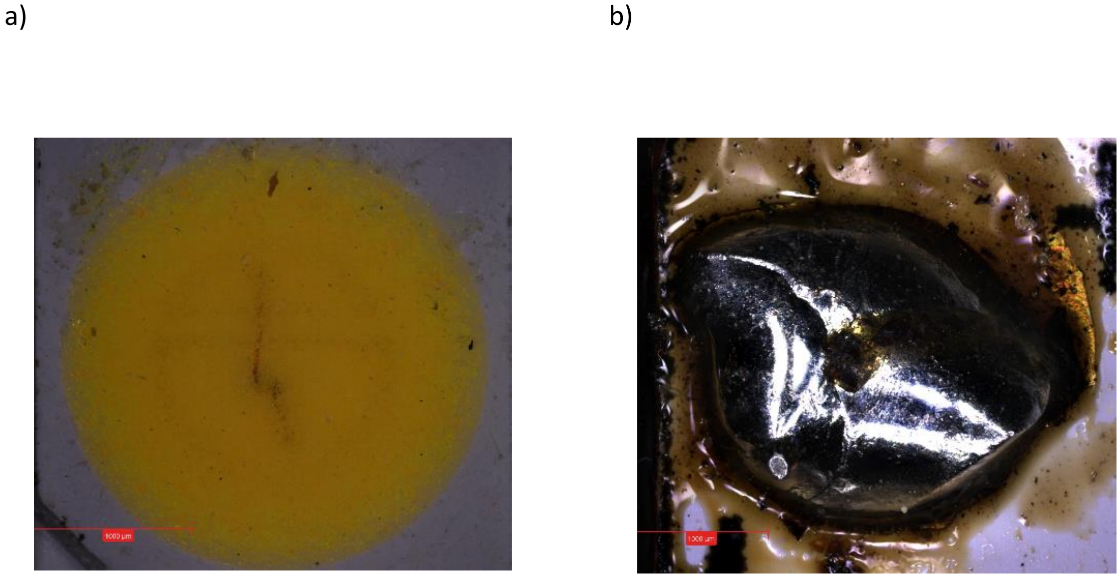


Figure 3. *Structure of a semiconductor white light source before (a) and after (b) exposure to a pulse of electromagnetic radiation with a frequency of 350 MHz and energy of 200 mJ. There was a complete destruction of the structure. (ZEISS Smartzoom 5 Microscope – Biomedical Engineering Center IOE WAT)*

A strong electromagnetic pulse affects virtually all elements of the infrastructure. Therefore, the safety of critical infrastructure depends on the effectiveness of shielding basic components, such as computer equipment and IT system accessories, through safe cabinets and thin, light and flexible materials, such as textiles, as well as heavy and large-sized materials, such as building construction elements and special rooms.

Due to the strong connections between individual elements, the destruction of any of them affects directly the functioning of the others. In order to recognize the seriousness of the electromagnetic pulse threat to military infrastructure, it is necessary to know how it affects individual devices.

An electromagnetic pulse is defined by the rise time (measured in V/sec), the electric field intensity (V/m) and the frequency in Hz. The combination of these parameters determines the effectiveness of electromagnetic pulses in destroying electronic systems. The rise time, i.e., the time it takes for a pulse to reach its maximum energy, is a basic parameter, the knowledge of which allows the protection of the system. If the pulse rise time is shorter than thousandths of a second, the standard protections installed in the devices will not respond in time.

The second parameter, the electric field intensity, determines the amount of available energy capable of being released in an electronic system. The last parameter, the frequency, significantly affects the efficiency of energy transfer. The combination of appropriate values of the three parameters described makes the electromagnetic pulse an effective weapon against electronic devices. The electromagnetic pulse induces high voltages and currents in electrical conductors. In the case of military equipment, such conductors can be radar antennas, radio stations, communication stations and various types of sensors located on board military vehicles: aircraft, vessels and vehicles.

An electromagnetic pulse can affect equipment in two basic ways, depending on the access path. The first way is for the pulse to pass through the antenna, and the second through various types of gaps, unprotected wires, etc. The efficiency of pulse penetration into the system depends on the pulse frequency and the conductivity of the material. When the operating frequency of the system overlaps with the frequency of the interference pulse, it leads to significant damage to the system, as a result of the interference effect. Circuits, in which the individual paths through which the signal flows are short, are more likely to be damaged under the action of a high-frequency pulse. The opposite is true for long transmission lines, e.g., power, internet cables, etc. In this case, the low frequency of the electromagnetic pulse poses a threat to the system. For this reason, electromagnetic pulses with a wide frequency band are used to shock as many devices as possible.

Regardless of how the pulse enters the system, the device will be damaged as a result of overload. An example is semiconductor computer processors, which are connected by very short paths. The processor contains billions of transistors connected to each other. As a result of interaction with a strong electromagnetic field, voltages of several tens of volts and currents of tenths of an ampere are induced in them. It is assumed that a pulse with an electric field intensity of 10 kV/m can cause large-scale damage. It can induce an electric charge a million times greater than that which usually flows in the system. Such a large charge can not only damage the system but even cause its meltdown.

As a result, unsecured computers, telecommunications systems, energy systems, flight control systems, radars, satellite systems are turned off or damaged. Considering the fact that modern armed forces are equipped with a large number of complex electronic devices, the impact of an electromagnetic pulse poses a huge threat to critical infrastructure facilities. Due to the not very selective nature of the electromagnetic pulse, it affects all elements of the infrastructure without exception.

The scope of the electromagnetic pulse can cover a very large area (e.g., during an atomic bomb explosion) or, on the contrary, a small area – as a result of the use of small generators. The fact is, however, that no matter which method is chosen, the effect will always be the same, i.e., neutralization of all or part of the infrastructure. Considering the potential use of electromagnetic weapons in the field, its greatest impact will be observed primarily on command systems, air defense systems, communication systems and devices, and energy systems.

When analyzing the impact of an electromagnetic pulse on infrastructure, one cannot forget about its negative impact on navigation systems, which consist of a network of satellites and their associated GPS transmitters. Most satellites are communication satellites, accounting for about 50% of the number of all satellites, while 10% of them are satellites belonging to the intelligence services of many countries. Satellites, due to the advanced electronics contained in them, are very sensitive to electromagnetic pulses caused by a high-altitude nuclear explosion. Some satellites are, to some extent, resistant to the effects of natural magnetic fields, but, unfortunately, a nuclear explosion is not one of these. Cosmic radiation, which includes streams of electrons, protons, heavy ions from solar radiation, does not damage the devices that are part of the satellite.

Two methods of interaction can be considered. The first is the so-called "front end" method, referring to the penetration of an electromagnetic wave through an antenna or transmission lines. The second is the so-called "back door" method, in which the electromagnetic wave penetrates through gaps, unshielded holes in housings. Depending on the power received by the antenna system, the electromagnetic pulse can cause, more or less, damage to the receiving systems. In order to systematize all the requirements for protection and resistance to, among others, the impact of the electromagnetic pulse, it was necessary to create defense standards in the field of electromagnetic compatibility [26-29] (corresponding to NATO Mil Standard standards), specifying what conditions and requirements electronic equipment should meet.

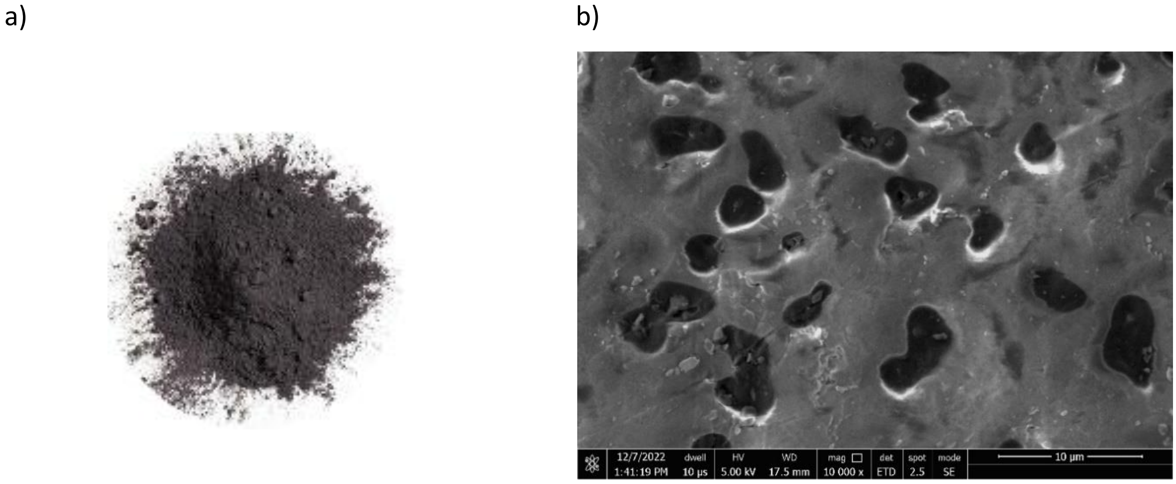
5 METHODS OF PROTECTION AGAINST THE HPM PULSE

There are two main directions of protection against the electromagnetic pulse: mechanical and electronic. In the case of mechanical protection, we deal with shielding devices, i.e., separating them from the external environment by using a Faraday cage, shielding and filtering cables or using materials that absorb electromagnetic radiation. Electronic protection methods include filters and sensors detecting electromagnetic radiation. Filtering is used to eliminate disturbances caused by electromagnetic radiation generated in network and signal cables. It is important that this process has as little impact as possible on the working signal and eliminates only disturbances. Most often, compact and discrete filters are used as network filters. Additionally, electromagnetic disturbances can be eliminated using chokes. In this case, the energy causing the disturbances is converted into thermal energy in the choke. However, the protection of devices to which cables are connected is not a simple issue, since protection is additionally determined by, for example, defects (leaks) of the device housing, the presence of connectors and connections, and the finite value of the cable screen attenuation.

Materials that absorb electromagnetic radiation have a wide range of applications in various areas of life. They are used to minimize the negative impact of electromagnetic waves in various devices such as research apparatus, computers used in civilian as well as military infrastructure. An electromagnetic wave energy absorber is designed both to absorb electromagnetic radiation in narrow and wide frequency bands, and to reduce (weaken) the radiation to such an extent that the smallest possible part of it is reflected. Absorbers are usually made of materials characterized by different energy absorption mechanisms. In addition to structurally homogeneous absorbers, composite absorbers are used, which consist of several materials characterized by different loss mechanisms. The efficiency of the absorber depends primarily on the type of material used, as well as its thickness. There are a number of parameters that determine the absorption of an electromagnetic wave by a material. These include the matching impedance, the resistivity of a given material, the frequency characteristics, the magnetic and dielectric losses. This is why different materials can behave differently in the same conditions.

The family of absorption materials is very large, but not all of them have the appropriate parameters to provide proper protection of devices against high-power electromagnetic pulses. The two main groups are dielectric materials and magnetic materials. The two most important parameters that characterize dielectric materials are dielectric losses and electrical permittivity, while magnetic materials are described by magnetic permeability and magnetic losses. Taking the value of magnetic permeability as a criterion of division, two types of materials can be distinguished: dielectric materials for which the magnetic permeability coefficient is equal to 1, and magnetic materials with a magnetic permeability coefficient > 1. For the absorption materials to work effectively, the following basic conditions must be met: matching of the impedance of the absorption element to the impedance of free space of 377 Ω, and the second condition is the appropriate thickness of the absorption element.

Figure 4 schematically presents selected examples of the solutions developed and optimized in the NCBiR project entitled "Methods of protection and defense against HPM pulses" (No. DOB-1-3/1/PS/2014) that studied various structures attenuating the electromagnetic radiation in a wide frequency range. As part of the project, research and implementation works were carried out, including the development of new dielectric and magnetic materials that attenuate high-power electromagnetic radiation, various material structures such as metallic and polymer composites, nanocomposites, multilayer structures, metamaterials as well as functional elements (shields, attenuation screens, large-size construction elements) that protect telecommunications and ITC devices and systems, elements of weapons and military equipment, as well as critical infrastructure facilities [30-31].



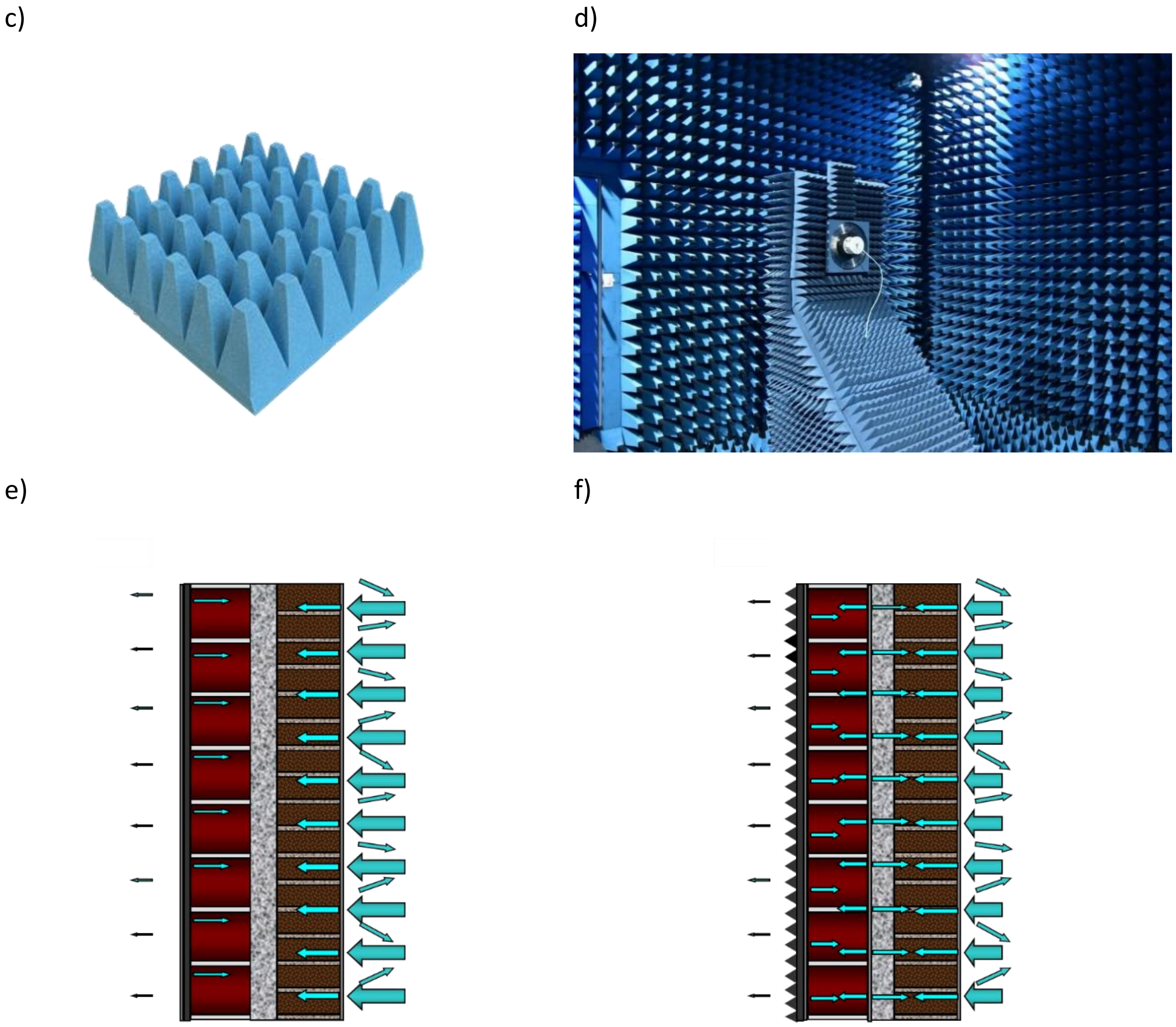


Figure 4. *Structures and diagrams of systems attenuating electromagnetic radiation in a wide frequency range:*
a) ferromagnetic powders,
b) SEM image of a composite absorber of ferrite in L284 epoxy polymer,
c) absorption-reflection and scattering pyramids,
d) application of pyramids in a microwave anechoic chamber,
e) diagram of a multilayer absorption-reflection structure,
f) diagram of a multilayer absorption-reflection structure with fittings made of broadband absorption materials

An important element of protection against the impact of electromagnetic pulses on electronic components and devices is the use of optical fibers. Optical fibers have found application in telecommunications, television, laser technology and many other areas of life. The glass fiber from which optical fibers are made has dielectric properties, so it is much more resistant to high-power electromagnetic pulses. Unlike metallic conductors, electric current is not induced in them under the influence of an electromagnetic field, which leads to increased insulation between circuits and electronic devices. By connecting individual devices with traditional cables, a network is created in which the electromagnetic pulse reaches each device one by one, thereby destroying it. By using optical fibers, we isolate individual devices from each other, which has a positive effect on the safety of systems, e.g., communications, command, telecommunications and energy systems.

6 SUMMARY

The development of elements, subassemblies, devices and systems protecting military equipment and armament as well as critical infrastructure facilities against the destructive effects of high-power electromagnetic radiation pulses was the subject of research and development work carried out by the research and development consortium in the project entitled "Methods and means of protection and defense against HPM pulses" implemented for the security and defense of the State as part of the NCBiR Strategic Program entitled "New weapon and defense systems in the field of directed energy" No. DOB-1-6/1/PS/2014 financed by the National Center for Research and Development.

The project, led by the Military University of Technology, was implemented in the years 2014-2020. Research and development works was carried out in five areas:

A. Development of methods and means of protection and defense of devices, military equipment and facilities against the destructive effects of high-power HPM pulses, in particular with regard to securing communication devices, radar devices and manned and unmanned objects and platforms.

B. Development of absorbers for various frequency ranges, in various forms and consistencies depending on the developed needs for protection and defense against HPM pulses.

C. Research on the biological effects of HPM exposure to high-energy low-frequency pulses.

D. Research on the biological effects of HPM at microwave frequencies.

E. Development of medical instruction regarding the medical effects of HPM pulses, Defense Standards for absorbers, and instructions for securing communication devices, radiolocation equipment and manned and unmanned objects and platforms.

The project’s products in the form of developed technologies for the implementation of individual electronic protections and absorber technologies were tested in laboratory and field conditions. The products of the project, in the form of instructions for the protection of electronic systems, telecommunication network protection instructions using software reconfiguration mechanisms as well as medical instructions and defense standards, were prepared based on guidelines obtained as a result of completed studies on the impact of high-power EM radiation pulses on the human body and absorber studies.

As a result of the project, the prototypes of the following devices and systems were developed:

- protection systems for mobile electronic modules designed to reduce the power level of waves reflected from the fuselage and aerofoils, enabling a reduction of the active cross-section for reflection and the probability of detection and destruction;

- a set of electronic security modules for a typical UAV platform designed to protect the avionics of an unmanned platform, usually containing an autopilot module with a GPS signal receiver, a UHF radio module designed to send telemetry data and a control equipment signal, a power supply module and a set of servomechanisms. The product consists of sets of filters intended for installation in data (digital) and power lines, on GPS and UHF radio paths as well as sets of housings and seals to protect electronic modules from high-power EM radiation;

- input and output circuits of power supply devices resistant to electromagnetic interferences and the impact of strong electromagnetic field pulses;

- a filter of the power supply connection board protecting against HPM pulses, designed to connect the 230 V AC alternating current supply voltage to military vehicles and containers at command posts for the safe supply of various internal devices;

- a power supply resistant to HPM pulses, designed for installation inside military vehicles, containers at command posts or in specialized buildings;

- a fiber optic connection resistant to HPM pulses, designed for installation on various types of objects (vehicles, containers, ships, buildings), through which it will be possible to safely connect the internal fiber optic network of the object with external fiber optic networks comprising transmission cables and internal metal elements;

- a portable high-power electromagnetic field meter designed to perform field measurements of the intensity of very strong pulsed electromagnetic fields (HPM) (operating frequency range from 10 MHz to 12 GHz, in the temperature range from 0°C to +45°C, electric field intensity from 60 V/m to 1.8 MV/m, EM field power density from 0.01 kW/m^2 to 8.9 GW/m^2)

- emergency power supply and control system for internal combustion engines, designed to provide the possibility of alternative (emergency) start-up and operation of the vehicle's internal combustion engine after damage to the electronics or electrical components of the fuel supply system (fuel injection equipment) and control of current operating parameters;

- microwave absorber for protecting electronic devices during transport and storage, which uses the technology of hybrid reflective-absorption screens, in particular new generation magnetics;

- construction absorbers: construction elements, including building openings, designed for the construction of monolithic and prefabricated concrete and reinforced concrete structures. The key function of the developed products is protection against HPM pulses without the need for additional coatings attached to the structure. The developed composite materials and structures allow for shielding of building infrastructure objects against HPM pulses, while providing mechanical (ballistic) protection at the same time;

- absorbers based on polymer composites in the form of a spatial, multi-layer structure constituting an element of the shield and screen, and acting as a broadband electromagnetic radiation absorber, which effectively protects the interior of a room or object;

- electromagnetic screens for applications in aviation technology, in the form of an under-wing aircraft container designed to protect its contents against the impact of the HPM pulse;

- reflective and absorption electromagnetic screens for selected electronic devices of marine technical objects.

The various materials and structures that attenuate electromagnetic radiation developed as part of the project can be used to create shields and screens against the destructive effects of electromagnetic, non-kinetic energy weapons directed at specific devices, equipment and military weapons as well as critical infrastructure objects and systems.

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