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Shielding Effectiveness of Unmanned Aerial Vehicles Electronics with Graphene Based Absorber

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Abstract: In the work the enhanced security of unmanned aerial vehicles (UAVs) electronics in RF environment was investigated. UAVs are commonly used in many areas and the cellular networks as the parallel helping networks for systems: LTE, 5G or especially for future 6G are very perspective and needed. For effective communications in channels: "air-to-ground" as well as "drone-to-drone" the important task is undisturbed work of transportation platforms, ie. UAV. However, high level of outside electromagnetic radiation can affect the correct electronics work. The problem is due to non-conformity of RF environment regulations. The electromagnetic compatibility (EMC) standards guarantee correct electronics work when the radiation level is not higher than established EMC levels. In case of commercially available devices, like UAVs, this level is 3 V/m. On the other hand, permissive exposure level, treated as RF environment emitted by cellular base stations, can reach the level of 61 V/m. Such level of electromagnetic wave pollution, can damage unprotected electronics with fatal consequences. This can cause the unchecked drone flight or unchecked fall down. As a result, due to unchecked flight, the UAV can cause the sudden communication interruption with operator or other drones. To reduce the level of damaging RF field we propose to cover the UAV housing with microwave absorber. In this case absorber must ensure good electromagnetic protection as well as lightweight and resistant on weather conditions. The shielding property of reduced graphene oxide (RGO) as an absorber was investigated. For proposed material the shielding effectiveness (SE) was investigated in the frequency range from 100 MHz to 10 GHz. It has been proved that such material can be a good candidate as an absorber for UAV having low reflection coefficient and high absorption ability. In this work the shielding effectiveness of RGO was analyzed for two layers of 3 and 5 mm at typical frequencies as RF environment, ie. 3.6 GHz (5G system) and 5.8 GHz (LTE). Investigated absorber guarantees the value of SE of 25 dB and 30 dB for 3 mm layer at 3.6 GHz and 5.8 GHz respectively and of 29 dB and 39.5 dB for 5 mm layer at these frequencies respectively.

Keywords: unmanned aerial vehicle (UAV); microwave absorber; reduced graphene oxide.

1. Introduction

The unmanned aerial vehicle (UAV) is the flight apparatus which does not require any crew on board to the flight. It is remote-controlled or realizes the flight autonomously. The entire system consists of the unmanned aerial vehicle with the task equipment, the ground station of the control served by the operator, the communication system between the station of the control and with the flight equipment and the auxiliary equipment. The demand on unmanned aircrafts, called generally as drones, is very large. UAVs find use in such fields as: the transport, the monitoring, medicine (the transport of medical materials), border and custom services, the fire brigade, the police, the forest-guard, the agriculture, the geodesy, the photograph and finally for fan and play. In the nearest future drones can be used to realize mobile communications as the helping platform or even parallel in LTE, 5G or especially in future 6G systems. Such application could be required to improve communications in the Internet of Things or other platforms for smart streets, etc. For such applications drone can be used as one element or as node in a grid. In this case the communications should be realized in communication channels: "air-to-ground" as well as "drone-to-drone".

Typical drone consists of non-metal frame which supports the entire construction. The propellers are attached to rollers going out from engines, supplied with batteries with voltage

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regulators. The number of propellers depends on drone mass and form of the flight. An essential element of every drone is the module IMU (Internal Measurement Unit), containing such components as the accelerometer, the gyroscope and the barometer, moreover better equipped devices have also a compass and the GPS module.

The UAV needs electronic circuits, which enable the realization of the flight and communicate with operator or other drones, susceptible on electromagnetic disturbances. This is why, UAV electronics must be protected against harmful electromagnetic (EM) radiation. The important problem with drones used as communicate node is the battery which limits the operating time. However, this disadvantage can be operationally solved in few ways. The more serious problem is when drone electronics is crashed or damaged in too high electromagnetic field. The possible electromagnetic field strength higher than EMC immunity threshold can have destructive results on drone electronics, being able to cause the unchecked drone flight or unchecked fall down. As a result, high level of EM field strength incidents to drone, due to unchecked flight, can cause sudden communication interruption with operator or other drones.

According to electromagnetic compatibility (EMC) regulations the electronic devices must be resistant on radiation [1]. Thresholds EMC immunities are defined in [1] for determined groups of devices. For typical, commercially available electronic devices - the class 2 - the threshold of the EMC immunity is 3 V/m. The higher protection, which must be guaranteed by producers - the class 3 – for medical and industrial devices for which the threshold of the EMC immunity is 10 V/m. Drones should be treated as class 2 with the threshold of 3 V/m. The thing is, that the level of electromagnetic immunity is much lower comparing the permissive electromagnetic pollution. According to the world and European Standards and guidelines the EM field emitted by mobile base stations to environment can reach the level of 61 V/m [2–4]. This EM level has been adopted by majority of European countries. Such value is much higher than obligatory EMC protection, so producers do not guarantee the correct work of electronic devices with such high radiation level.

The easiest protection form against harmful radiation is to cover the drone surface with the microwave absorber. Such material should have high level of shielding effectiveness (SE) in the wide frequency range. In addition, the absorber should also be light weight (not to ballast the drone) and resistance on variable weather conditions. There exist two types of materials fulfilling the requirement of microwave shielding, eg. ferrites and carbon-like materials. However, ferrites (eg. ferrite tiles) are too heavy for drone. The density of ferrite material is about 5 g/cm^3. On the other hand, absorbers based on carbon (eg. graphite [5–7]) having high conductivity can be a good candidate. In the work the reduced graphene oxide (RGO) has been proposed as microwave absorber suitable to be used for drones. The constitutive properties of RGO, i.e. permittivity and permeability were measured and shielding properties of RGO material layers were discussed in function of frequency. The shielding effectiveness of layers of RGO were investigated in the free-space condition treating drone housing material as transparent. Investigation, typically presented in the literature, analysis absorbers backed by metal layers so such model cannot be used in our case. Analysed shielding effectiveness allows to determine the reflectivity as well as absorption properties of material slabs in the free-space condition.

2. Absorber Characteristics - Reduced Graphene oxide

Graphene is an allotropous form of the carbon. Allotropous forms are also graphite, fullerenes, nanotubes. Graphene is built from the monolayer of atoms of the carbon, connected into six-element rings [8]. Popular form of this material is the graphene oxide where the oxygenic groups are joined to the coal-layers, however, such modification causes that material has low conductivity and thereby cannot absorb the EM energy. To improve the conductivity the oxygenic groups should be removed. The modified form is called as reduced graphene oxide (RGO) and has good conductivity, comparable to pure graphene [7].

To determine material constitutive properties the complex values of permittivity and permeability should be measured. The problem is that the final form of RGO is a powder and is difficult to prepare any sample to be measured. To solved this inconvenience, in the literature,

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powder of RGO is mixed with other materials, like wax, resin, styrofoam and so on [8–11]. It is easy to guess that the electromagnetic properties of such mixtures significantly depend on the proportional participation of filler used. In the work the RGO was investigated as the pure material without any additives. The solid state of sample was obtained by pressing the powder in the special housing using 2 kN force. The density of pressed sample was about 1.55 g/cm^3, so, such density is much lower comparing to ferrites.

3. Coaxial Line Method of Permittivity and Permeability Measurement

The electromagnetic properties of material can be described in term of relative complex permittivity and permeability:

$$\varepsilon = \varepsilon' - j\,\varepsilon'' \tag{1}$$

$$\mu = \mu' - j\,\mu'' \tag{2}$$

where:

ε', μ' are the electric and magnetic constants and ε'', μ'' are the electric and magnetic loss factors.

The permittivity and permeability measurements of solid materials are commonly performed using coaxial fixtures. At microwaves, the coaxial line technique is especially recommended for broadband frequency measurements. The method of measuring of ε and μ, based on determining the scattering parameters (S_{ik}) of the measured sample is the most popular. In this case, the measured material, having toroidal form, completely fills the cross section of the coaxial line. Such configuration guarantees that the only TEM mode propagates in the line.

Measurements of complex relative permittivity and permeability were carried out using a vector network analyzer. This system consisted of a 7 mm coaxial line is equipped with measurement cables and LPC7 connectors. The center conductor of the coaxial line is 3.04 mm in diameter to receive the 50 Ω characteristic impedance of the holder. At first, the empty coaxial line was employed to calibrate the system. After calibration the meas-urements were updated by the calibration coefficients. Data of calibration process and measurement of the sample were acquired using the MultiCal program [12,13]. The system measures the magnitudes and phases of S-parameters of a sample. Taking into ac-count that measured material is homogeneous the only S_{11} and S_{21} is enough to characterize the electric and magnetic properties. Values of these parameters have complex values depending on frequency and thickness of the sample and can be determined as [14,15]:.

$$S_{11} = \rho\frac{1 - T^2}{1 - \rho^2 T^2} \tag{3}$$

$$S_{21} = \frac{(1-\rho^2)\,T}{1-\rho^2 T^2} \tag{4}$$

where:

$T = e^{-\gamma\, d}$ – transmission coefficient,

$\rho = \frac{\sqrt{\mu_c}-\sqrt{\varepsilon_c}}{\sqrt{\mu_c}+\sqrt{\varepsilon_c}}$ – reflection coefficient at the boundary "air-material",

d - thickness of the measured sample,

Values of unknown complex ε and μ can be obtained solving the set of equations (3) and (4). It is possible to calculate the permittivity and permeability using the well-known method proposed by Nicolson, Ross and Weir (NRW method) [14,15]. In this method, values of complex permittivity and permeability can be determined according to the following formulas:

$$\mu = -j\frac{1+\rho}{1-\rho}\frac{\lambda}{2\pi d}\ln\left(\frac{1}{T}\right) \tag{5}$$

$$\varepsilon = -\frac{1}{\mu}\left[\frac{\lambda}{2\pi d}\ln\left(\frac{1}{T}\right)\right]^2 \tag{6}$$

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where parameters T and ρ can be also determied using S_{11} and S_{21}:

$$T = \frac{S_{11} + S_{21} - \rho}{1 - \rho(S_{11} + S_{21})} \tag{7}$$

$$\rho = X \pm \sqrt{X^2 - 1} \tag{8}$$

$$X = \frac{1 - V1\ V2}{V1 - V2} \tag{9}$$

$$V1 = S_{21} + S_{11} \qquad V2 = S_{21} - S_{11} \tag{10}$$

The above relationships allow to determine the complex values of permittivity and permeability of the RGO samples. The measurements were carried out in the frequency range from 100 MHz to 10 GHz. The obtained values of relative complex permittivity (ε', ε'') and permeability (μ', μ'') have been presented in Figure 1.

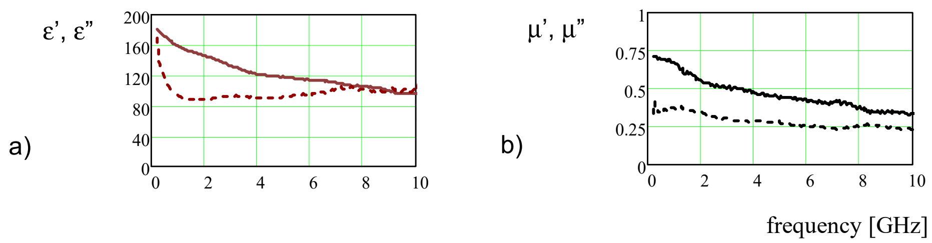

Figure 1. a) Permittivity (solid – real part, dotted – imaginary part), **b)** permeability (solid – real part, dotted – imaginary part).

Complex values of permittivity and permeability of solid state RGO have been presented in microwave frequency range. This frequency range includes frequencies emitted by GSM, UMTS, LTE as well as 5G mobile system. The electric constant of RGO has value above 100. The imaginary part of permittivity, being responsible to material loss, has high value and is quite stable in frequency above 1 GHz. On the other hand, the magnetic constant assumes values lower than 1, showing the diamagnetic nature of RGO. This phenomenon causes that the magnetic field strength is lower inside the material due to opposite magnetization. Despite low value, it is necessary to take into account magnetic permeability when analyzing the absorbed electromagnetic energy in the material. Sometimes the permeability of carbon-based materials is neglected but such simplification leads to incorrect final estimation. In fact, this diamagnetic phenomenon increases the absorption property of RGO, comparing to the simplified approach when permeability is taken as $\mu = 1$.

3. Shielding Effectiveness

The easiest way to protect drone electronics against harmful radiation is to cover the surface with broadband absorber. The parameter describing the electromagnetic protection ability is shielding effectiveness. According to the definition, the shielding effectiveness can be defined as the logarithmic ratio of the magnitude of the incident electric field to the magnitude of the transmitted electric field and can be expressed as [16–18]:

$$SE\ (dB) = 20log\left(\frac{E_i}{E_t}\right) \tag{11}$$

where:

E_i – incident electric field strength,

E_t – electric field strength beeing transmitted through the material.

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There are several factors that determine the effectiveness of shielding, like:
- frequency of the incident EM field,
- electromagnetic parameters (complex permittivity and permeability),
- absorber thickness.

With the measured values of permittivity and permeability it is possible to calculate the shielding effectiveness basing on scattering parameters of the material slab.

$$SE = -10\log(|S_{21}|^2) \tag{12}$$

where:

S_{21} is transmitting coefficient of a slab of material with thickness *d* taken for consideration.

Relationship (12) is well known four-terminal reciprocal network equation. This relationship can be also expressed as:

$$SE = -10\log\left(\frac{|S_{21}|^2}{1-|S_{11}|^2}\right) - 10\log(1-|S_{11}|^2) \tag{13}$$

The above modified equation allows to determine the part of electromagnetic energy being reflected and part of absorbed energy. The reflection coefficient LR and absorption coefficient LA are expressed with the following relationships:

$$LA = -10\log\left(\frac{|S_{21}|^2}{1-|S_{11}|^2}\right) \tag{14}$$

$$LR = -10\log(1-|S_{11}|^2) \tag{15}$$

The total shielding effectiveness is a sum of these components:

$$SE=LR+LA \tag{16}$$

Relationship (16) expresses electromagnetic losses of all rays propagating inside the material. It determines also external and internal reflections caused by absorber. The physical interpretation can be schematically illustrated analyzing incident ray and the infinite rays propagating inside material, as illustrated in Figure 2.

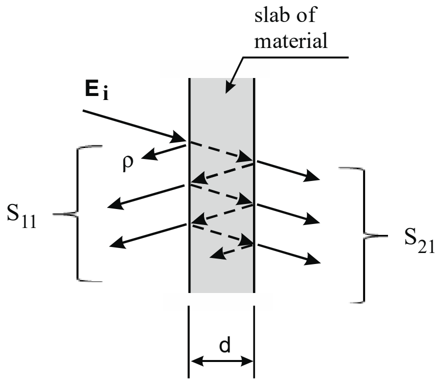

Figure 2. Multiple EM ray reflections inside the material.

Figure 2 shows EM rays propagating inside the slab of absorber in the free-space condition. Coefficient S_{21} is proportional to the energy transmitted through the material thus it illustrates the shielding properties of the absorber. The EM protection by such material is realized by reflecting rays and absorbing of energy of all rays propagating through the absorber. In many applications the important task is to minimize the reflected part of incident radiation so to minimize the LR. Such requirement is especially important for medical apparatuses and other devices when reflected radiation could influence other apparatuses being next door to.

When the permittivity and permeability are known it is possible to calculate the coefficients of S_{11} and S_{21} of the slab material with any thickness using relationships (3) and (4) then using (14) – (16)

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the LR, LA and SE can be calculated. Values of these parameters for two thicknesses: d = 3 mm and 5 mm have been presented in Figure 3.

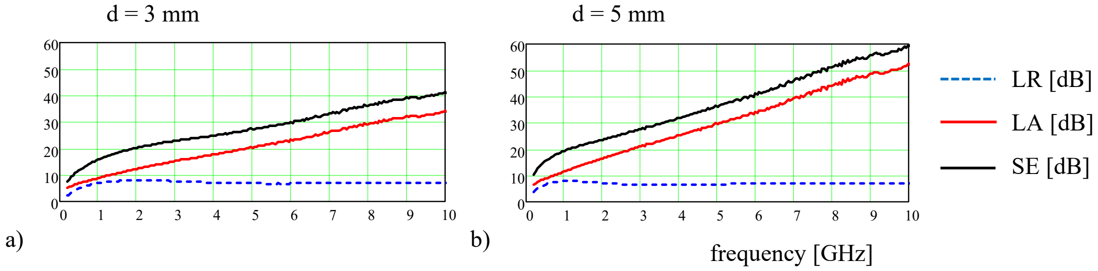

Figure 3. Values of of LR, LA and SE of 3 mm and 5 mm slabs of RGO.

Figure 3 shows reflection coefficient LR, absorption coefficient LA and shielding effectiveness SE in function of frequency, in the range from 100 MHz to 10 GHz. The shielding efficiency was analyzed for two example thicknesses of slabs, i.e.: 3 mm and 5 mm. Slabs were analyzed in free-space condition, with the TEM mode incidents perpendicular to the slabs. In low frequency range all shielding coefficients have low values and this is typical property of carbon-based materials. Reflecting coefficient is almost stable in function of frequency with value of near 7 dB. In fact, value of LR is mainly determined by reflection coefficient at the boundary "air-material" (ϱ) because the rays inside the absorber are strongly attenuated, so in this case, the LR does not depend on thickness of slab. In addition, values of LR are significantly lower comparing to absorption coefficient. Such low value of LR guarantees low reflection property of this material and from this point of view the device covered with such absorber will not disturb the work of other apparatuses being next door to. The important part of shielding efficiency of this material is an energy absorption. The function of absorption coefficient lineally rises with frequency. The components of shielding effectiveness, for slab of 5 mm, are as follow:

- at 3.6 GHz (system 5G): LR = 6.5 dB, LA = 23.5 dB and SE = 30 dB.
- at 5.8 GHz (system LTE): LR = 6.8 dB, LA = 32.7 dB and SE = 39.5 dB.

The UAV electronics covered with RGO absorber can be effectively protected against harmful radiation. In Table 1 the electric field strength reduced by absorber layers have been presented. In this Table the following parameters were identified. E_{EMC} – maximal level of electric field strength, according to EMC, that guarantees correct electronic device work. E_{in} –permissible value of electric field strength incidents to a drone. The value of 61 V/m has been considered as possible RF environment. E_{SE} – value of E_{in} reduced by absorber.

Table 1. Values of electric field strength reduced by absorber.

frequency [GHz]	E_{EMC} [V/m]	E_{in} [V/m]	SE [dB]	E_{SE} [V/m]
3 mm thickness				
3.6	3	61	25	3.4
5.8	3	61	29	0.6
5 mm thickness				
3.6	3	61	30	1.9
5.8	3	61	39.5	0.6

With the use of RGO as an absorber the level of RF environment can be effectively reduced to the safe level. The safe level, at frequencies emitted by mobile base stations, can be obtained using

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even thin layer of 3 mm. In this case the level of radiating penetrating through the housing of device is 3.4 V/m at 3.6 GHz and 0.6 V/m at 5.8 GHz. With thicker layer it can be much better.

4. Conclusions

The aim of this work was to proposed effective microwave absorber protecting of UAV electronics against harmful RF environment. UAVs can be used as transportation platforms allowing to build the mobile-aerial or stationary-aerial cellular networks. However, to fulfil the EMC requirement the level of incident of EM radiation for commercially available apparatuses cannot be higher than 3 V/m while the permissible RF environment can reach the values of 61 V/m. Proposed absorber made of reduced graphene oxide can be a good candidate as an absorber taking into account electrical as well as mechanical properties (light weight and resistant on weather conditions). The investigation of this material was performed in frequency range from 100 MHz to 10 GHz in coaxial line which guarantees the TEM field incidents to a slab of material. The analyzed shielding effectiveness was calculated for example material layers of 3 and 5 mm in free-space condition focusing the investigation for application as absorber for unmanned aerial vehicles. The material of drone housing is rather low permittivity with not electric loss, so it is transparent to incident EM field. The investigation of RGO has shown good absorption properties with low level of reflection coefficient and good absorption coefficient in total shielding effectiveness. The layer of 3 mm can reduced the maximum permissive RF environment to the safe level for drone electronics. Proposed absorber can protect UAV electronics what will prevent against system crashing or even damaging in the RF environment.

Samples of pure RGO for permittivity and permeability laboratory measurements had toroidal shape obtained by pressing the powder in the special housing. Currently, the work is carried on to build the forms allowing to mount such absorber to the UAVs.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, RK. RP. and DL; methodology, RK, DL.; software, RP.; validation, DL.; formal analysis, RK., RP.; writing—original draft preparation, RK,; writing—review and editing, RP., DL; All authors have read and agreed to the published version of the manuscript.

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