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ANALYSIS OF THE EFFECTS OF METAMATERIALS ON THE RADIO-FREQUENCY ELECTROMAGNETIC FIELDS IN THE HUMAN HEAD AND HAND

ANALIZA UČINKOV METAMATERIALOV NA RADIOFREKVENČNO ELEKTROMAGNETNO POLJE V ČLOVEŠKI GLAVI IN ROKI

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The development of split-ring resonators (SRRs) consisting of two concentric square rings of a conductive material exhibiting a resounding electric response at a microwave frequency is described in this paper. Each square ring has a gap and is oppositely placed in the gap of the other ring. A size reduction is always possible in this kind of structure, but one should be careful about the set frequency. The described square type of metamaterial design is completely novel in the context of the head and hand with respect to the specific absorption-reduction rate (SAR). This design was used because more arrays can be placed within a given area. Mobile phones are relatively small, requiring small metamaterial designs. The finite-difference time-domain method with the lossy-Drude model is adopted in this analysis by using CST Microwave Studio®. The technique of a SAR reduction is discussed, and the effects of the relating position, distance, and size of the square metamaterials on the SAR reduction were investigated. Using the square-type metamaterials, we have achieved a 53.03 % reduction of the initial SAR value for the case of 1 g SAR and a 68.08 % reduction for the case of 10 g SAR.

Keywords: antenna, head model, SRRs, SAR

V članku je prikazan razvoj resonatorja iz deljivih obročev (SRR), ki so sestavljeni iz dveh koncentričnih obročev kvadratnega prereza iz prevodnega materiala, ki kaže pomemben električni odziv pri mikrovalovni frekvenci. Oba kvadratna obroča imata režo in vsak obroč je nasprotno nameščen v reži drugega obroča. Zmanjšanje velikosti teh struktur je vedno mogoče, vendar pa je treba biti pozoren na načrtovano frekvenco. Trdimo, da je kvadratna oblika metamateriala popolnoma nov dizajn v okviru glave in roke za zmanjšanje stopnje absorpcije (SAR). Eden od pomembnih razlogov, zakaj je bila ta oblika uporabljena, je možnost več postavitev v danem področju. Mobilni telefoni so razmeroma majhni in zahtevajo majhne naprave iz metamaterialov. Domena končnih časovnih razlik z uporabo modela lossy-Drude je bila uporabljena v tej študiji uporabljajoč CST Microwave Studia®. Prikazana je tehnika zmanjšanja SAR ter preiskovanih učinkov priloženih pozicij, razdalje in velikosti kvadratnega metamateriala na zmanjšanje SAR. S kvadratno obliko metamateriala je bilo doseženo 53,03-odstotno zmanjšanje začetne vrednosti SAR pri 1 g SAR in 68,08-odstotno zmanjšanje pri 10 g SAR.

Ključne besede: antena, model glave, SRR, SAR

1 INTRODUCTION

Recently, there has been an increasing public concern about the health risk caused by electromagnetic (EM) waves emitted from cellular phones. These phones send their signals using very small surges of high-frequency EM waves, or microwaves, favored over most over-the-air telecommunication systems. The fundamental safety limits for the radio-frequency (RF) revelation are defined in terms of the immersed power per unit mass, which is expressed by the specific absorption rate (SAR) in watts per kilogram (W/kg). These protection guidelines are set in terms of the utmost mass-normalized rates of the electromagnetic energy deposition (SARs) for 1 g or 10 g of tissue. The two most generally used SAR limits today are IEEE, 1.6 W/kg for 1 g of tissue, and ICNIRP [1–8], 2 W/kg for 10 g of tissue, disregarding the extremities such as ankles, hands, and feet, where higher SARs, up to 4 W/kg for any 10 g of tissue, are allowed in both of these standards. Therefore, SAR becomes an important performance parameter for the marketing of mobile phones and underlines the interest in low-SAR mobile phones by both consumers and mobile-phone manufactures.

SAR is the parameter employed to properly quantify the response of the biological structure in terms of incident and induced field of the energy absorbed and maintained inside the human body. It is the time derivative (rate) of the incremental energy (dW) absorbed by or dissipated in an incremental mass (dm) contained in a volume element (dV) of a given density (ρ), as seen in (1):[4]

$$SAR=\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right)=\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\rho\mathrm{d}m}\right) \tag{1}$$

The SAR is expressed in units of watts per kilogram (W/kg) or, equivalently, in milliwatts per gram (mW/g). It can also be related to the induced electrical field using (2):

$$SAR = \sigma E^2/\rho \qquad (2)$$

where E is the electric field's root mean square (V/m), σ is the biological tissue's electrical conductivity (S/m) and ρ is the biological tissue's density (kg/m^3).

The demand on the portable mobile devices is increasing progressively with the development of novel wireless communication techniques. In this respect, compact size, light weight, low profile and low cost are now quite important challenges to be accomplished by the designers of any wireless mobile component. One of the most important components of any wireless system is its radiating element. In addition to the physical requirements, the emerging requirements of wireless systems are a high directivity, a large gain, and an efficient and broadband operability of the antennas. Many broadband techniques have been investigated to overcome the trade-off between the antenna size and the minimum achievable quality factor, which is dictated by Chu formulations[9]. These techniques are mainly increasing the thickness of the substrate, using differently shaped slots or radiating patches[10–14], stacking different radiating elements or loading the antenna laterally or vertically[12–17], utilizing magneto-dielectric substrates[18] and engineering the ground plane as in the case of EBG metamaterials[9].

Metamaterials are artificially structured materials providing electromagnetic properties not encountered in nature. A left-handed material was first implemented in a two-dimensional periodic array of split-ring resonators and long wire strips by Smith[19]. The logical approach was to excite the split-ring resonators and wire strips in order to force the structure to behave like magnetic and electric dipoles, respectively[12].

In references[20,21] it was found that the SAR value is affected by various parameters, such as the attachment position of conductive materials, the sizes and configurations of the antenna ground plane. In the reference[22] studies, a reflector used for a SAR reduction was inserted between the radiator and the head. Other studies applied ferrite sheets[2], shielding materials[23,24], resistive sheets[9], and artificial magnetic conductors[13] to reduce the EM field around the antenna.

Recently, metamaterials, including electromagnetic band-gap (EBG) structures, have been proposed for handset antennas with low SAR characteristics.

Metamaterials combining a negative permittivity and permeability, i.e., negative index materials (NIMs), can be obtained by using tiny electrical circuits called split-ring resonators and continuous wires as the metamaterial constituent units.

The specific absorption rate (SAR) in the head can be reduced by placing the metamaterials between the antenna and the head. In the case of studying the SAR reduction of an antenna operating at the GSM 900 band, the metamaterial parameter (i.e., the permittivity is $\varepsilon < 0$, hence, the refractive index is $n < 0$) and the effective medium would be set negative. Hence, the effectiveness of different positions, sizes, and metamaterials with various parameters are also analysed for SAR reduction.

2 MATERIALS AND METHODS

CST MWS is a device used as a major simulation instrument based on the finite-integral time-domain technique (FITD). An unvarying meshing scheme was chosen to make the major computation devoted to inhomogeneous mark boundaries and aimed at the fastest and faultless results. Two-cut schemes are needed for a complete model to show the region with the closely com-

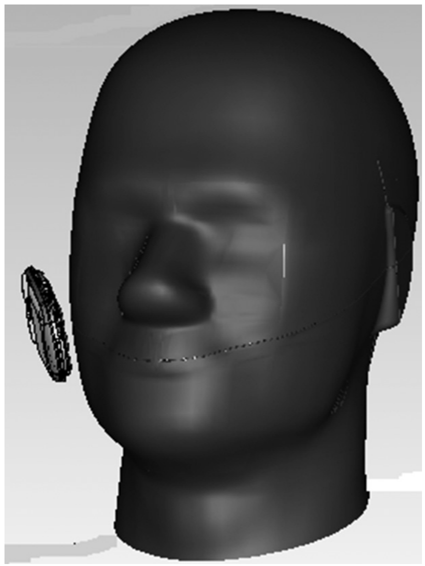

Figure 1: Head model with a handset antenna
Slika 1: Model glave z ročno anteno

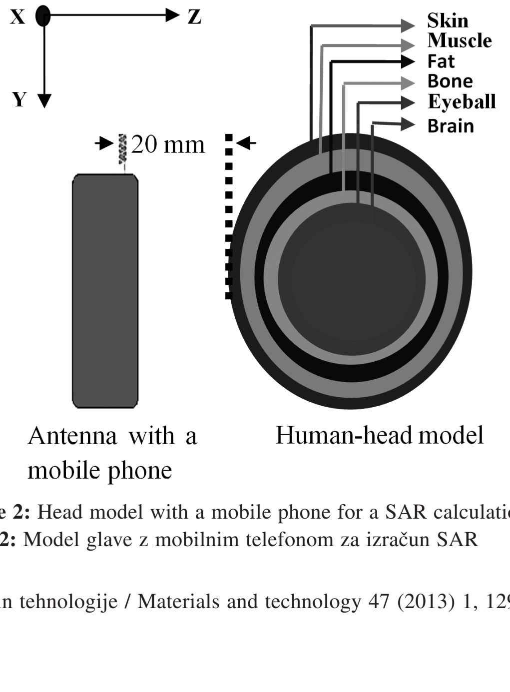

Figure 2: Head model with a mobile phone for a SAR calculation
Slika 2: Model glave z mobilnim telefonom za izračun SAR

pacted meshing onward to inhomogeneous boundaries. Here the lowest and highest mesh sizes were 0.3 mm and 1.0 mm, respectively. As a result, a total of 2 122 164 mesh cells were generated and the simulation time was 1208 s, including the mesh generation for each effort on an Intel Core ™ 2 Duo E 8400 3.0 GHz CPU with a 4 GB RAM system, for a complete model. It is noted here that at first the materials are placed between the antenna and the human head, and then all of these are replaced by a metamaterial.

For this research, the SAM head model was considered. It consists of about 2 097 152 cubical cells at a 1 mm resolution. **Figure 1** represents a portable telephone model with a handset antenna considered in the SAR calculation.

The head models used in this study were obtained from an MRI-based head model through the whole-brain Atlas website. Six types of tissues, i.e., bone, brain, muscle, eye ball, fat, and skin were involved in this model[9,19]. A space domain enclosing the human head and the phone model is also shown in **Figure 2**. **Tables 1** and **2** show their dielectric properties for 900 & 1800 MHz. Numerical simulations of the SAR value were performed by the FDTD method. The parameters for the FDTD computation were as follows. The simulation domain was 128 × 128 × 128 cells. The cell sizes were set as $\Delta x = \Delta y = \Delta z = 1$ mm. The computational domain was terminated with 8 cells of a perfectly matched layer (PML). A PIFA antenna was modeled with a thin-wire approximation.

Table 1: Dielectric tissue properties at 900 MHz
Tabela 1: Dielektrične lastnosti tkiva pri 900 MHz

Material	Density ρ/(kg m^{-3})	Conductivity σ/(S m^{-1})	Relative permittivity, ε_r
Fat, bone	1130	0.12	4.83
Muscle, skin	1020	1.5	50.5
Brain	1050	1.11	41.7
Eye ball	1000	2.03	68.6

Table 2: Dielectric tissue properties at 1800 MHz
Tabela 2: Dielektrične lastnosti tkiva pri 1800 MHz

Material	Density ρ/(kg m^{-3})	Conductivity σ/(S m^{-1})	Relative permittivity, ε_r
Fat, bone	1130	0.11	4.48
Muscle, skin	1020	1.35	47.80
Brain	1050	1.09	39.50
Eye ball	1000	1.99	65.3

3 SRRS STRUCTURE AND DESIGN

With this work we established that, using the FDTD analysis, square metamaterials (SMMs) can reduce the peak SAR for 1 g and SAR for 10 g in the head. In this section, the SMMs are evaluated in a cellular phone with the 900 MHz and 1800 MHz bands. Periodically arranged square split-ring resonators (SSRRs) can work as SMMs. The SSRR structure involves two conductive-material, concentric square rings. Both square rings have a gap, and each ring is placed in the gap of the other ring. The schematic of the SSRR structure used in this study is shown in **Figure 3**.

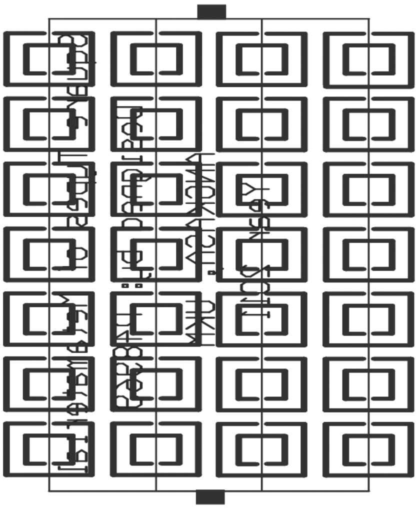

Figure 3: Square Metamaterial arrays used in this calculation
Slika 3: Kvadratna razporeditev metamateriala, uporabljena pri izračunu

To construct the SMMs for a SAR reduction, SSRRs were used as the resonator model, as shown in **Figure 3**. The resonators operated in the 900 MHz bands. The SSRRs contain two square rings, each with a gap on the opposite side[5]. The SSRRs were introduced by Pendry et al.[11] (1999), and subsequently used by Smith et al. (2000) to synthesize the first left-handed artificial medium[19].

Figure 4 shows the fabricated SMM arrays used in this measurement. The metamaterials in this work were designed with periodic SSRR arrangements to reduce the

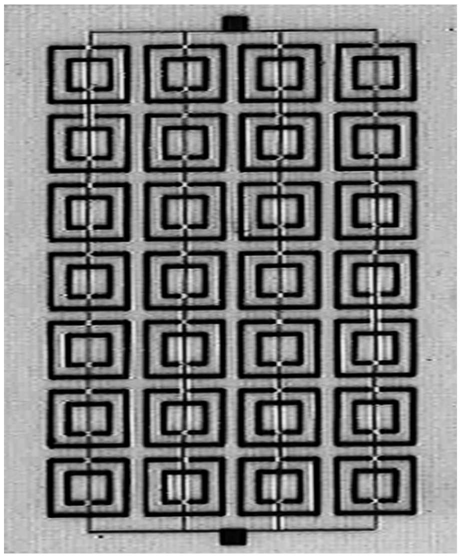

Figure 4: Fabricated square metamaterial arrays used in this research
Slika 4: Izdelana kvadratna razporeditev metamateriala, uporabljena v tej raziskavi

SAR value. By properly designing the SSRR structure parameters, a negative effective medium parameter can be achieved for the 900 Hz and 1800 Hz bands.

4 NUMERICAL RESULTS AND DISCUSSION

The designed SSRRs were placed between the antenna and the human head, thus reducing the SAR value. To study the SAR reduction of the antenna, operating at the GSM 900 band, different positions, sizes, and metamaterials for the SAR-reduction effectiveness are also analyzed by using the FDTD method in conjunction with a detailed human-head model. The antenna was put equidistant to the head axis. The distances from 5 mm to 20 mm were checked and ultimately the distance of 20 mm was selected. Moreover, the maximum SAR reduction was achieved when the proposed structure was placed to the near side of the cellular phone. In the present paper, the power output of the mobile was considered to be 600 mW at the operational frequency of 900 MHz. In the case when the main network station is far from the mobile phone, the actual power is 1 W to 2 W. The highest values were 2.002 W/kg for SAR 1 g and 1.293 W/kg for SAR 10 g, calculated when the cellular phone model was at a distance of 20 mm from the human-head model and without any metamaterial attachment. Obviously, this SAR reduction is more desirable than the metamaterial free attachment. The results quoted in[12,7] are 2.28 W/kg and 2.17 W/kg for SAR 1 g. This is due to the use of different antennae placed in different locations relative to the head model. These SAR values agree with the compared result reported in[5], i.e., 2.43 W/kg for SAR 1 g. This was achieved using different radiating powers and different antenna.

To study the effect of a SAR reduction with the use of SMMs, the radiated power from the PIFA antenna with $\mu = 1$ and $\varepsilon = -3$ was fixed at 600 mW. Calculating SAR at 900 MHz, we obtained the value of 1.673 W/kg for SAR 10 g without a metamaterial; however, in the case of a metamaterial, the reduced SAR value for 10 g was 0.737 W/kg. Thus, a reduction of 55.95 % was achieved, whereas the sketch furnish design in[5] acquired a 32.03 % reduction. The reasons for this difference are different densities, antennae, sizes of the metamaterial and types of conductivity. The result implies that only suppressing the maximum current on the front side of the conducting box contributes significantly to the reduction of the spatial-peak SAR, as the decreased quantity of the power absorbed in the head is considerably larger than that dissipated in the metamaterials. It is clear from the simulation results that metamaterials can reduce the peak SAR successfully where the antenna reduction is merely pretended. So, both the inner capacitance and inductance of the metamaterials are reinforced. At this stage, the mediums will exhibit stop band walks with a single negative medium parameter.

5 EXPERIMENTAL EVALUATIONS

The SAR measurement was performed using the COMOSAR measurement system. The system uses a robot to position the SAR probe inside the head phantom. The head phantom is filled with a liquid that has dielectric properties selected on the basis of the IEEE standard 1528, which are $\varepsilon_r = 41.5$ and $\sigma = 0.97$ S/m for 900 MHz and $\varepsilon_r = 40$ and $\sigma = 1.4$ S/m for 1800 MHz. The measured and simulated SAR values without the inclusion of TMMs are shown in **Table 3**.

Table 3: SAR simulation and measurement results without the inclusion of TMMs (distance between the head and the phone model, d = 20 mm)

Tabela 3: Simulacije SAR in rezultati meritev brez upoštevanja TMMs (razdalja med glavo in modelom telefona, *d* = 20 mm)

	Value of SAR	
	SAR 1 g	SAR 10 g
Simulated	2.002	1.673
Measured	1.936	1.609

Table 3 shows that the simulated SAR value is greater than 3.29 % for SAR 1 g and 3.82 % for SAR 10 g due to the fact that the distance between the head and phone model was not correctly set at the measurement stage. In addition, the distance between the source and the internal surface of the phantom affects the SAR. For a 5-mm distance, a positioning uncertainty of ±0.5 mm would produce a SAR uncertainty of ±20 %. An accurate device positioning is therefore essential for accurate SAR measurements.

The simulated and measured SARs are obtained using the tilted position of the SMMs with the antenna revealing the simulated and measured SAR values of 1.1673 W/kg and 1.0623 W/kg for SAR 1 g, respectively. The simulated and measured SARs differed by 6.27% for SAR 1 g. Regarding the difference in the absolute values of the peak SAR, the phone-model casing for the simulation was different from the casing used for the measurement. In addition, Scotch tape was used to attach the SMMs and antenna at the measurement stages. The simulated and measured results also differ because the parameters for the measurement system change with water evaporation and temperature. Furthermore, the measurement system contains several parameters (source, network emulator, probe, electronic evaluation procedures) that affect the SAR calculation but are not included in the simulation.

6 CONCLUSION

The process of the EM absorption between an antenna and the human head, while using new SMMs, has been thoroughly and intensively experimented and presented in this paper. After examining the substance of the developed SMMs for the phone model, the SAR values were found to be about 0.639 W/kg for SAR 10 g and 1.0623 W/kg for SAR 1 g. These results will be the core points when providing information in the field of designing communication equipment, safe from interruptions.

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