# Evaluation of EM Absorption in Human Head with Metamaterial Attachment

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***Abstract*** **─** The reduction of electromagnetic (EM) absorption with metamaterial is performed by the finite-difference time-domain method with lossy-Drude model by CST Microwave Studio in this paper. The metamaterials can be achieved by arranging split ring resonators (SRRS) periodically. The SAR value has been observed by varying the distances between head model to phone model, different distance, different thickness, and different size of metamaterial design. Metamaterial has achieved 53.94% reduction of the initial SAR value for SAR 10 gm.

***Index Terms*** **─** Antenna, human head model, lossy-Drude model, metamaterial, symmetry, SAR, SRRS.

## I. INTRODUCTION

Radio frequency (RF) safety guidelines have been issued to stop undue electromagnetic-field exposure. The guidelines are given in terms of the specific absorption rate (SAR). The revelation of the human head to the near field of a mobile phone has been evaluated by measuring the SAR in a human-head phantom, or by calculating it using a human-head numerical result.

The interaction of handset antennas with the human body is a great consideration in cellular communications. The user's body, especially the head and hand, influence the antenna voltage standing wave ratio (VSWR), gain, and radiation patterns. Furthermore, thermal effects, when tissues are exposed to unlimited electromagnetic energy, can be a serious health hazard. Therefore, standard organizations have set exposure limits in terms of SAR [1, 2]

Specifically, the problems to be solved in SAR reduction need to be a correct representation of the cellular phone; anatomical representation of the head; alignment of the phone and the head and suitable design of metamaterial [3-10].

In [7], for the SAR in human head, an effective approach is the use of a planar antenna integrated onto the back side (away from the head) of a phone model, but it brings additional design difficulties especially in achieving the required frequency bandwidth and radiation efficiency. Another approach is the use of a directional or reflectional antenna [10-15].

SAR is a measure of the rate at which radio frequency (RF) energy is absorbed by the body when exposed to radio-frequency electro-magnetic field. SAR is used to measure exposure to field between 100 KHz and 10 GHz [16-20]. It is commonly used to measure power absorbed from mobile phones and during MRI scans. The value will be defined heavily on the geometry of the part of the body that is exposed to the RF energy and on the exact location and geometry of the RF source. Metamaterials have inspired great interests due to their unique physical properties and novel application [10, 12].

Recently, there are many interests on metamaterial with split ring resonators (SRRS) structure were proposed to reduce the SAR value [4-12]. The SRRS was introduced by Pendry et al.

in 1999 [3] and subsequently used by Smith et al. for synthesis of the first left-handed artificial medium [7-9], [12-16]. A lot of effort worldwide has been spent studying single negative metamaterials, double negative metamaterials, their properties [12], applications in antennas [13], and other microwave devices. The negative permittivity can be obtained by arranging the metallic thin wires periodically [9]. On the other hand, an array of SRRS can exhibit negative effective permeability.

Some numerical results have implied that the peak 1 gm averaged SAR value (SAR 1 gm) may exceed the safety limits when a portable telephone is placed extremely close on reducing the SAR distribution in human head. At first, metamaterials are placed between an antenna and a human head. In order to study SAR reduction of antenna operated at the GSM 900 band, the effective medium parameter of metamaterials is set to negative at 900 MHz. Different positions, sizes, and negative medium parameters of metamaterials for SAR reduction effectiveness are also analyzed.

## II. SIMULATION MODEL AND TECHNIQUES

The simulation model which includes the handset with the helix type of antenna and the SAM phantom head provided by CST Microwave Studio (CST MWS) is shown in Figure 1. Complete handset model composed of the circuit board, LCD display, keypad, battery, and housing was used for simulation. The relative permittivity and conductivity of individual components were set to comply with industrial standards. In addition, definitions in [18-22] were adopted for material parameters involved in the SAM phantom head. In order to accurately characterize the performance over a broad frequency range, dispersive models for all the dielectrics were adopted during the simulation [18]. The electrical properties of materials used for simulation are listed in Table 1. Helix type antenna constructed in a helical sense operating at 900MHz for GSM application was used in the simulation model. In order to obtain high-quality geometry approximation for such helical structure, a predictable meshing scheme used in FDTD method usually requires a large number of hexahedrons which in turn makes it extremely challenging to get converged results within a reasonable simulation time.

Fig. 1. Complete model used for simulation including handset and SAM phantom head.

Table 1: Electrical properties of materials used for simulation

| Phone Materials | $\varepsilon_r$ | $\sigma(S/m)$ |
|---|---|---|
| Circuit Board | 4.4 | 0.05 |
| Housing Plastic | 2.5 | 0.005 |
| LCD Display | 3.0 | 0.02 |
| Rubber | 2.5 | 0.005 |
| SAM Phantom Head | | |
| Shell | 3.7 | 0.0016 |
| Liquid @ 900MHz | 40 | 1.42 |

CST MWS, which adopted the finite integral time-domain technique (FITD) proposed by Weiland in 1976 [19], was used as the main simulation instrument In permutation of the perfect boundary approximation (PBA) and thin sheet technique (TST), significant development in geometry approximation with computation speed is achieved with squashy highly accurate results. The non-uniform meshing scheme was adopted so that major computation endeavor was dedicated to regions along the inhomogeneous boundaries for fast and perfect analysis. The minimum and maximum mesh sizes were 0.3mm and 1.0 mm, respectively. A total of 2,097,152 mesh cells were generated for the complete model, and the simulation time was 1163 seconds (including mesh generation) for each run on an Intel Core $^{TM}$ 2 Duo E8400 3.0 GHz CPU with 4 GB RAM system.

Figure 2 shows a portable telephone model at 900 MHz for the present study. It was considered to be a quarter wavelength PIFA antenna mounted on a rectangular conducting box. The conducting box was 10 cm tall, 4 cm wide, and 3 cm thick. The PIFA antenna was located at the top surface of the conducting box. A space domain enclosing the human head and the phone model is also shown in Fig. 2. The time-stepping was performed for about eight sinusoidal cycles in order to reach a steady state. To absorb the outgoing scattered waves, the second order Mur absorbing boundaries acting on electric fields were used.

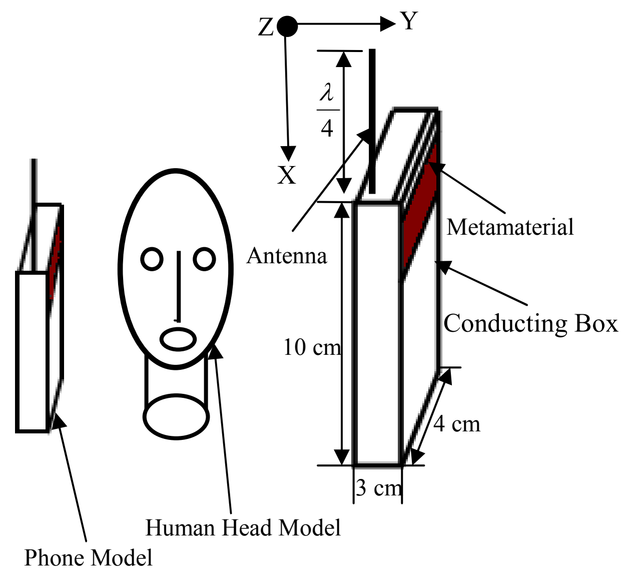


Fig. 2. The head and antenna model for SAR calculation.

The analysis workflow started from the design of the antenna with complete handset model in free space. The antenna was designed such that the $S_{11}$ response was less than -10 dB over the frequency band of interest. SAM phantom head was then included for SAR calculation using the standard definition as

$$SAR = \frac{\sigma}{2\rho} E^2,$$

where $E$ is the induced electric field (V/m); $\rho$ is the density of the tissue (kg/m$^3$) and $\sigma$ is the conductivity of the tissue (S/m). The resultant SAR values averaged over 1 gm and 10 gm of tissue in the head were denoted as $SAR$ 1 gm and $SAR$10 gm, respectively. These values were used as a benchmark to appraise the effectiveness in peak SAR reduction.

## III. REDUCTION OF SAR USING METAMATERIAL

The SAR in the head can be reduced by placing the metamaterial between the antenna and the human head. The metamaterial is on a scale less than the operating wavelength. The structures are resonant due to internal capacitance and inductance. The stop band can be designed at operation bands of cellular phone radiation. The metamaterial are designed on a printed circuit board so it may be easily integrated to the cellular phone. By arranging sub-wavelength resonators periodically, we get the metamaterial.

### A. SRRS configuration

We establish that metamaterials can be used to reduce the peak SAR 1gm and SAR 10gm in the head from the FDTD analysis. In this section, the metamaterials operated at 900 and 1800 MHz bands of the cellular phone were considered.

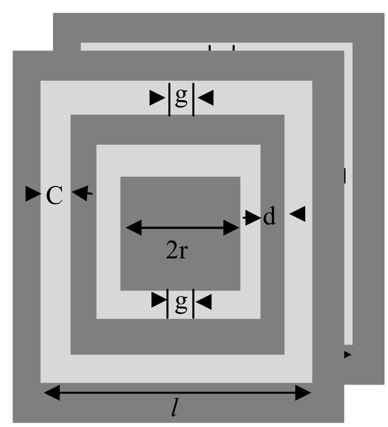


Fig. 3. The structure of SRRS.

The SRRS structure consists of two concentric annular of conductive material. There is a gap on each ring, and each ring is situated opposite to the gap on the other ring. The schematics of the SRRS structure that we used in this study are shown in Figure 3. The significant frequency of SRRS can be varied toward higher or lower frequency band by appropriately choosing these structure parameters.

### B. SRRS design and simulation

The metamaterials with a negative permeability medium can be obtained by arranging SRRS periodically. The resonant frequency $\omega$ is very sensitive to small changes in the structure parameters of SRRS. The frequency response can be scaled to higher or lower frequency depending on properly choosing these geometry parameters by utilizing the following equation (1) in [9]:

$$\omega^2 = \frac{3 l c_0^2}{\pi \ln \frac{2c}{d} r^3}. \qquad (1)$$

Numerical simulations could predict the transmission properties depending on various structure parameters of this system. Simulations of this complex structure are performed with the FDTD method. To construct the SRRS for SAR reduction, the SRRS that lie in the *x-z* plane are considered. The EM wave propagates along the y direction. The electric polarization is kept along the z-axis, and magnetic field polarization is kept along x axis. Periodic boundary conditions are used to reduce the computational domain and absorbing boundary condition is used at the propagation regions. The total-field/scatter-field formulation was used to excite the plane wave. The region inside of the computational domain and outside of the SRRS was assumed to be vacuums.

From this study, it is found that both of the two incident polarizations can produce a stop band. As shown in [23-27], the stop band corresponds to a region where either the permittivity or permeability is negative. When the magnetic field is polarized along the split ring axes, it will produce a magnetic field that may either oppose or enhance the incident field. A large capacitance in the region between the rings will be generated and the electric field will be powerfully concentrated. There is strong field coupling between the SRRS and the permeability of the medium will be negative at the stop band. Because the magnetic field is parallel to the plane of SRRS, we imagine the magnetic effects are small, and that permeability is small, positive, and slowly varying. In this condition, these structures can be viewed as arranging the metallic wires periodically.

The stop bands of SRRS are designed to be 900 MHz and 1800 MHz. The periodicity along x, y, z axes are $L_x$ = 63mm, $L_y$ = 1.5mm and $L_z$ = 63mm, respectively. On the other hand, to obtain a stop band at 1800 MHz, the parameters of SRRS are chosen as $c$ =1.8mm, $d$ = 0.6mm, $g$ =0.6mm, and $r$ =12.9mm.The periodicity along x, y, z axes are $L_x$ =50mm, $L_y$ =1.5mm, and $L_z$ = 50mm, respectively Both the thickness and dielectric constant of the circuit boards for 900 MHz and 1800 MHz are 0.508mm (Rogers 4003) and 3.38, respectively. After properly choosing geometry parameters, the SRRS medium can display a stop band around 900 MHz and 1800 MHz, respectively. From FDTD simulation, it is observed that the ring size is an important factor for operating frequency. The stop band can be shifted towards the lower frequency band by increasing the ring size.

We have tried to use a high impedance surface configuration [21] to reduce the peak SAR. However, we found that when these structures operate at 900 MHz, the sizes of these structures are too large for cellular phone application. A negative permittivity medium can also be constructed by arranging the metallic thin wires periodically [26-29]. However, we found that when the thin wires operate at 900 MHz, the size is also too large for practical application. Because the SRRS structures are significant due to internal capacitance and inductance, they are on a scale less than the wavelength of radiation. In this study, it is established that the SRRS can be designed at 900 MHz while the size is similar to that of a cellular phone.

## IV. IMPACT OF SAR BY METAMATERIAL ATTACHMENT

The SAR reduction effectiveness and antenna performance with different positions, sizes, and materials properties of metamaterials will be analyzed. The head models used in this study was obtained from the 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 [9-10].

Numerical simulation of SAR value was performed by the FDTD method. The parameters for FDTD computation were as follows. In our lossy-Drude simulation model, the domain were 128 × 128 × 128 cells in FDTD method. The cell sizes were set as $\Delta x = \Delta y = \Delta z$ = 1.0 mm. The computational domain was terminated with 8 cells PML. A helix antenna was modeled for this paper by thin-wire approximation. Simulations of materials and metamaterials are performed by FDTD method with lossy-Drude model [12]. The method is utilized to understand the wave propagation characteristics of metamaterials.

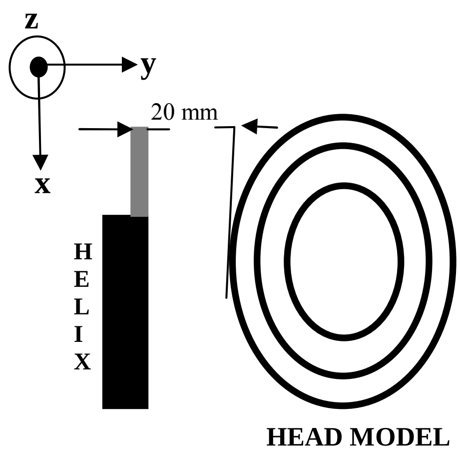


Fig. 4. The head and antenna models for SAR calculation.

Figure 4 shows the simulation model which includes the handset with a monopole type of helix antenna and the SAM phantom head that was provided by CST Microwave Studio® (CST MWS).

The dispersive models for all the dielectrics were adopted during the simulation in order to accurately characterize the metamaterials. The antenna was arranged in parallel to the head axis; the distance is varied from 5 mm to 20 mm; and finally, 20 mm was chosen for comparison with metamaterial. Besides that, the output power of the mobile phone models need to be set before SAR is simulated. In this paper, the output power of the cellular phone is 500 mW at the operating frequency of 0.9 GHz. In the real case, output power of the mobile phone will not exceed 250 mW for normal use, while the maximum output power can reach till 1W or 2W when the base station is far away from the mobile station (cellular phone). The SAR simulation is compared with the results in [11], for validation, as shown in Table 2. The calculated peak SAR 1 gm value is 2.002 W/Kg, and SAR10gm value is 1.293W/Kg when the phone model is placed 20mm away from the human head model without metamaterial. This SAR value we achieved is better compared with the result reported in [11], which is 2.43W/Kg for SAR 1 gm. The metamaterial is utilized in between the phone and head models, and it is found that the simulated value of SAR 1 gm is 1.16079 W/Kg, but in [11] they have reported 1.89 W/Kg. It is found that the use of metamaterials in this paper can reduce the peak SAR 1 gm by about 42.12% compared with the result of the SAR without attaching metamaterial where as the design reported in [11] has been achieved 22.63%. This is realized due to the consideration of different antenna, and different size of metamaterial and different positions, and it is because the electromagnetic source is being moved away from the head. Figures 5-9 show the SAR value in the distance between phone and head models without metamaterial, with metamaterial, distance between antenna and metamaterial 3-6 mm, thickness of metamaterial

Table 2: Comparisons of peak SAR without metamaterial

| Tissue | SAR value (W/kg) |
|---|---|
| SAR value for [11] | 2.43 |
| SAR value in this work for 1 gm | 2.002 |

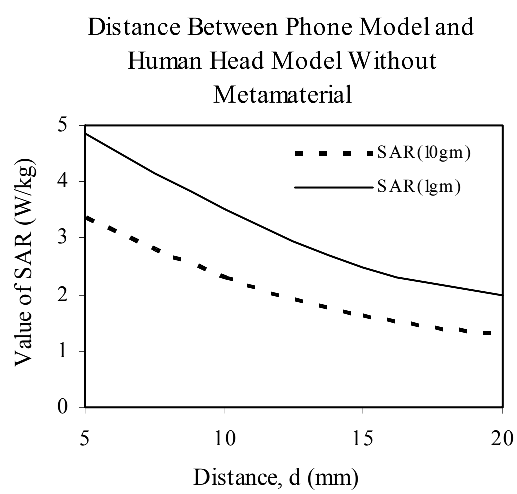


Fig. 5. SAR value compared the distance between phone model and human head model without metamaterial.

between 6-3 mm and size of metamaterial between 48 × 48 to 56 × 56 mm, respectively.

The reduction efficiency of the SAR depends on its thickness and ring size of metamaterials. In order to definitely confirm this, 1 gm and 10 gm average SARs versus distance, thickness, and sizes are plotted in the Figs. 5-9. In Figure 5, it is shown that if the distance between phone and human head models is varied then SAR value decreases. This is because dielectric constant, conductivity, density, and magnetic tangent losses are also varied. In Figure 6, it can be observed that the SAR value reduces with the attachment of metamaterial.

As shown in Figure 7, the distance between the antenna and metamaterials was changed from 3 mm to 6 mm. Figure 8 shows that the metamaterial thickness was reduced from 6 mm to 3 mm. It is found that both the peak SAR 1 gm and power absorbed by the head increase with the increase of distance or the decrease of thickness. The results imply that only suppressing the maximum current on the front side of the conducting box contributes significantly to the reduction of spatial peak SAR. This is because the

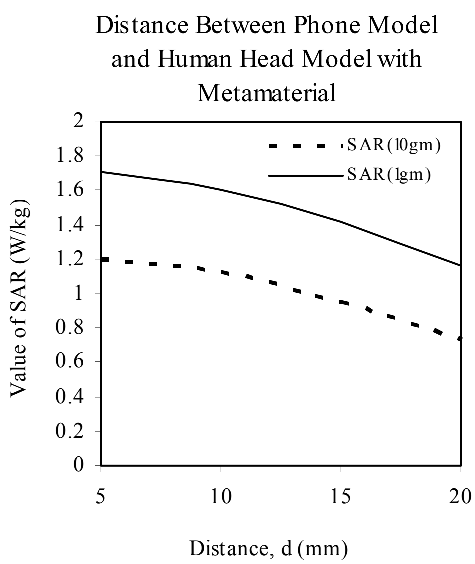


Fig. 6. SAR value compared the distance between phone model and human head model with metamaterial.

decreased quantity of the power absorbed in the head is considerably larger than that dissipated in the metamaterial and it is because the electromagnetic source is being moved away from the head. Figure 9 shows that, the size of the metamaterial was increased from 48 mm × 48 mm to 56 mm × 56 mm. It can be noted that the peak SAR 1 gm is reduced significantly.

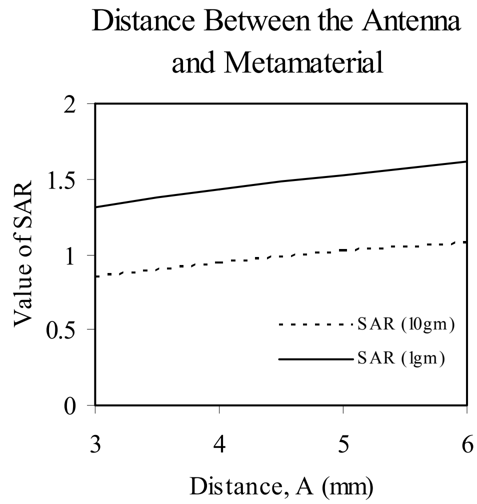


Fig. 7. SAR value compared the distance between the antenna and metamaterial.

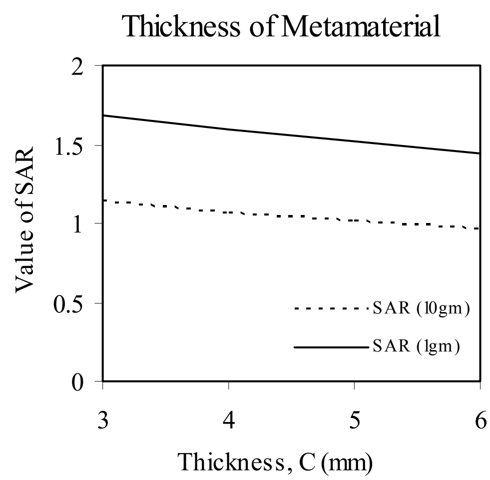


Fig. 8. SAR value compared the thickness of metamaterial.

The metamaterials can be obtained by arranging SRRS periodically [9-11]. The metamaterials were placed between the antenna and the human head. The distance between the antenna feeding point and the edge of metamaterials was 3 mm. The size of metamaterials in *x*-*z*-plane was 48 mm × 48 mm and the thickness was 6mm.

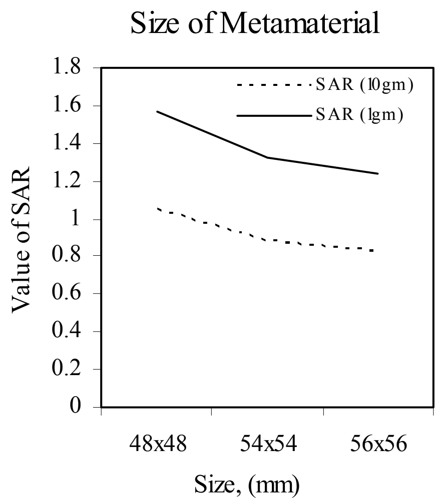


Fig. 9. SAR value compared the size of the metamaterial.

Different negative medium parameters for SAR reduction effectiveness were analyzed. We placed negative permittivity mediums between the antenna and the human head. First, the plasma frequencies of the mediums were set to be $\omega_{pe} = 9.309\times10^{9}$ rad/s, which give mediums with $\mu$ = 1 and $\varepsilon$ = -3 at 900 MHz. The mediums with larger negative permittivity μ= 1, and $\varepsilon$= -5; μ= 1, and $\varepsilon$= -7 were also analyzed. We set $\Gamma_e$ = $1.2\times10^{8}$ rad/s, suggesting the mediums have losses. The peak SAR 1 gm becomes 1.0697 W/kg with $\mu$ = 1 and $\varepsilon$ = -3 mediums. Compared to the condition without metamaterials, the radiated power is reduced by 13.9% while the SAR is reduced by 53.43%. With the use of and mediums, the SAR reduction effectiveness is decreased. However, the radiated power from the antenna is less affected.

Comparisons of the SAR reduction effectiveness with different positions and sizes of metamaterials were analyzed. Simulation results are shown in Table 3. In case 1, the distance between the antenna and metamaterial was changed from 3 mm to 6 mm. In case 2, the metamaterial thickness was reduced from 6 mm to 3 mm. It is found that both the peak SAR 1 gm and power absorbed by the head increases with the increase of distance or the decrease of thickness. In case 3, the size of the metamaterial was increased from 48 mm × 48 mm to 56 mm × 56

Table 3: Effects of sizes and positions of metamaterials on antenna performances and SAR values

| | $Z_R$ (Ω) | $P_R$ (mW) | $P_{abs}$ (mW) | SAR 1 gm (W/Kg) |
|---|---|---|---|---|
| Without material | 63.39+j94.53 | 600 | 268.83 | 2.002 |
| μ=1, $\varepsilon$=-3 | 51.43+j99.68 | 514.6 | 211.95 | 1.0697 |
| Case 1 | 58.37+j95.35 | 539.4 | 253.53 | 1.6105 |
| Case 2 | 62.19+j96.86 | 557.2 | 258.74 | 1.6893 |
| Case 3 | 69.15+j107.38 | 573.33 | 216.83 | 1.2346 |

mm. It can be noted that the peak SAR 1 gm is reduced significantly while the terrible conditions on the radiated power due to metamaterial is insignificant. To further examine whether the metamaterial affected the antenna performance or not, the radiation pattern of the PIFA antenna with the $\mu$ = 1 and $\varepsilon$ = -3 metamaterial was analyzed.

Table 4: Comparisons of SAR reduction techniques with different materials

| | $Z_R$ (Ω) | $P_R$ (mW) | SAR 1 gm (W/Kg) |
|---|---|---|---|
| μ= 1, $\varepsilon$ = -3 | 51.43+j99.68 | 514.6 | 1.0697 |
| PEC reflector | 66.83+j32.23 | 509.3 | 4.6803 |
| Ferrite sheet | 169.33+j153.69 | 519.3 | 1.043 |

The use of metamaterials was also compared with other SAR reduction techniques. A PEC reflector and a ferrite material are commonly used in SAR reduction. The PEC reflector and ferrite sheet were analyzed. The relative permittivity and permeability of the ferrite sheet were $\varepsilon$=7.0-j0.58

and $\mu$=2.83-j3.25, respectively. Numerical results are shown in Table 4.

A PEC placed between the human head and the antenna is studied. It can be found that the peak SAR 1 gm is increased with the use of a PEC reflector. This is because the EM wave can be induced in the neighbor of a PEC reflector due to scattering. When the size of the PEC sheet is small compared to the human head, the head will absorb more EM energy. Similar results of peak SAR increase with PEC placement were also reported in [14]. The use of a ferrite sheet can reduce the peak SAR 1 gm effectively. However, the degradation on radiated power from the antenna is also significant. In addition, compared to the use of a ferrite sheet, the metamaterials can be designed on the circuit board so they may be easily integrated to the cellular phone.

To study the effect of SAR reduction with the use of metamaterials, the radiated power from the PIFA antenna with $\mu$=1 and $\varepsilon$= -3 mediums was fixed at 600 mW. Numerical results are shown in Table 5. It is found that the calculated SAR value at 900 MHz, without the metamaterial, is 2.002 W/kg for SAR 1 gm and with the metamaterial, the reduction of the SAR 1 gm value is 1.16079 W/kg and SAR 10 gm value is 0.737 W/kg. The reduction is 42.12% for SAR 1 gm and 53.94% for SAR 10 gm.

Table 5: Effects of comparisons with metamaterials on SAR reduction ($P_R$ = 0.5 w for 900 MHz)

| | 900MHz | |
|---|---|---|
| | Without material | $\mu$=1, $\epsilon$=-3 |
| SAR 1 gm value for [11] | 2.43 | 1.89 |
| SAR 1 gm value in this work | 2.002 | 1.16079 |

To study the effect of SAR reduction with the use of metamaterials, it can be observed that the metamaterials can reduce peak SAR effectively and the antenna performances can be less affected. The metamaterials resonate due to internal capacitance and inductance.

## V. CONCLUSION

The EM interaction between the antenna and the human head with metamaterials has been discussed in this paper. Utilizing metamaterial SAR value is achieved about 1.16079 W/Kg for SAR 1gm and 0.737 W/kg for SAR 10 gm. Based on the 3-D FDTD method with the lossy-Drude model, it is found that the peak SAR 1 gm of the head can be reduced by placing the metamaterials between the antenna and the human head. Metamaterials were designed from periodical arrangement of SRRS. Numerical results can provide useful information in designing communication equipment for safety compliance.

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