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SAR reduction in the modelled human head for the mobile phone using different material shields

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Abstract
Every mobile phone emits radio frequency electromagnetic energy. The amount of this energy absorbed by the human head is measured by the specific absorption rate (SAR). There are standard limits, according to which phones sold should be below certain SAR level. To maintain these limits, shields can be used for the mobile phones. In this paper using ANSYS HFSS, modelling of the human head is done. The modern mobile phone design is used for simulation. SAR distribution is measured for different layers of the head due to exposure to radiation from the mobile phone operating at GSM-1800 frequency band. The performance of the mobile phone antenna due to different shields is observed. Proper shielding material properties are found.

Keywords: Specific absorption rate (SAR), Mobile phone shield, Human head modelling, Mobile phone antenna

Background

In this modern world, everyone uses mobile phones. Each mobile phone radiates a low level of radio frequency electromagnetic energy. This radiation has various effects on human health. Due to their heating effects, they can cause biological damage to cells. The majority of the people have reported that if they use mobile phones for more than 20 min, their ear lobes get warm; this is due to heating of blood by microwave energy of mobile phones. The problem starts with pain in the ear that gradually develops into tinnitus or a ringing sensation which finally leads to hearing loss and ear tumor. Furthermore, overuse of mobile phones leads to drying of the skin and fluid in the eyes, sleep disorder, lack of concentration, memory loss, and even cancer [1]. Many papers have been published on the biological effect of mobile phone radiation on the human body [2–7]. To avoid effects of mobile phone radiation on human health, various governments have defined maximum SAR levels for RF energy emitted by mobile phones [8, 9]. In India, United States, Australia, Canada and New Zealand, the SAR limit is 1.6 W/kg averaged over 1 g of tissues. In Europe, Korea, Japan and some other countries, the spatial average SAR limit is 2 W/kg averaged over 10 g of tissues. SAR is a measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency (RF) electromagnetic field. It is defined as

$$\text{SAR} = \frac{\sigma}{2\rho}E^2 \quad (1)$$

where σ is the Conductivity of body tissue (S/m), ρ is the density of body tissue (kg/m^3), E is the RMS value of the electric field strength in the tissue (V/m). SAR tests are performed for only 6 min of mobile phone usage, but practically, studies have shown that people use mobile phones for more than hours.

Over the years, a lot of attention have been paid to the analysis of SAR in the human head due to the complexity and large scale involved in this kind of problems. Recently, research efforts have been devoted to the reduction of peak SAR in the human head for handset applications. Mobile phone antenna performance gets affected due to the human head has been investigated in many published papers [10–14]. The impact of mobile phones on the human head can be measured using SAR [13–18]. The radiation from the mobile phones can be reduced using a shield that results in the decrease of SAR. However, this shield affects the performance of the mobile phone antenna. Proper shield material is to be selected such that it reduces the radiation while maintaining a good quality of signal transfer and reception from the mobile phone.

Global system for mobile communications (GSM) is a standard developed by the European Telecommunications Standards Institute (ETSI) to describe protocols for second-generation (2G) digital cellular networks used by mobile phones. In Africa, Europe, Middle East and Asia, most of the providers use 900 and 1800 MHz bands. The GSM-900 system uses the frequency band (890–915) MHz for uplink and the band (935–960) MHz for downlink. While, the GSM-1800 system uses the frequency band (1710–1785) MHz for uplink and the band (1805–1880) MHz for downlink. In GSM systems, up to eight users share the same frequency channel, and each phone transmits only one-eighth of the time as the time division multiple access (TDMA) is used, so the average power is one-eighth of the peak power. GSM-900 phones have a peak power of 2 W, and as the maximum average power is one-eighth of the peak power. Hence, the GSM-900 mobile phones radiate an average power of 250 mW. GSM-1800 phones have a peak power of 1 W; hence the GSM-1800 mobile phones radiate an average power of 125 mW [19]. In this paper, the mobile phone is designed to operate in GSM-1800 frequency band.

Some research was done in this area, where the old models of mobile phones with dipole and helix antennas were used [20–22]. The mobile phone models discussed in those papers are not used in this modern time. In a paper [21], aluminium was used as the shield, but using conductive materials as the shield will degrade the mobile phone antenna performance.

In this paper, modern type of mobile phone with the shield is tested. With the help of HFSS, 3D head model is designed. SAR in the human head is measured. In a modern mobile phone, Planar Inverted-F Antenna (PIFA) is used. The advantage of PIFA is that they are compact in size and have small back lobes, which make them ideal for mobile phone antennas. A mobile phone equipped with PIFA is analyzed.

Simulation Model

Head Model

The Head model used in this paper consists of four layers (skin, fat, skull, and brain) having dimensions 15 cm wide, 25 cm high, and the thickness of each layer is shown in the Fig. 1 [19]. Layers of the head are considered as flat layers because when mobile phones are used practically, it is placed with the face in such a way that it looks flat with the head. Only vertical half of the head is considered in the model to save simulation time. The human head biological tissues can be considered as lossy dielectric materials whose conductivity and relative permittivity depend on frequency. The properties of different layers of the head that are used are shown in Table 1 [1].

Phone Model

For excitation, the mobile phone will be the radiation source. The model consists of a mobile phone having a dimension of 7.5 cm wide, 14.5 cm high and 1 cm thick. The mobile phone case is made up of plastic having a thickness of 0.05 cm. In all modern mobile phones, Planar Inverted-F Antenna (PIFA) is used. Using the HFSS antenna designer kit, PIFA is designed having an operating frequency of 1.8 GHz. The PIFA of the mobile phone is oriented in such a way that the main beam is toward the opposite direction of the head and away from the brain so that the radiation effect on the brain can be reduced as much as possible by placement of the antenna in the mobile phone. As

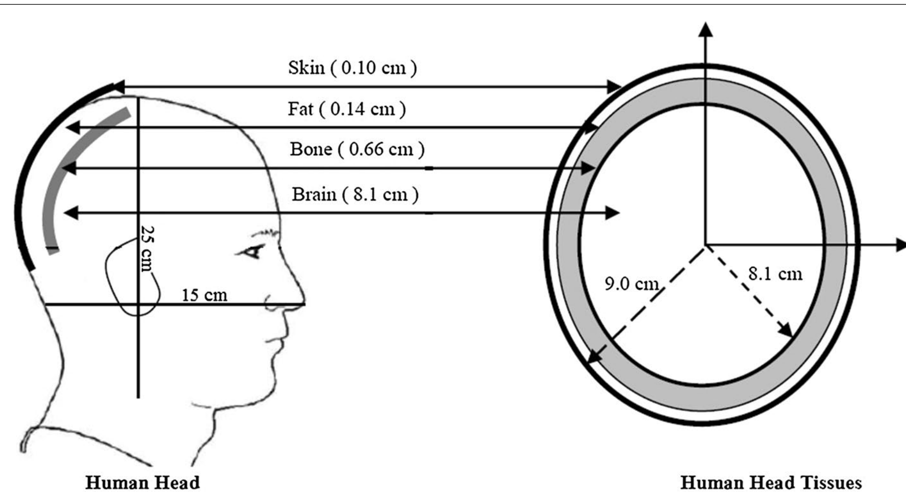

Fig. 1 Thicknesses of the layers of the head

Table 1 Properties of the layers of the head at 1.8 GHz frequency

Head layers	Conductivity (S/m)	Relative permittivity	Mass density (kg/m^3)
Skin	1.1847	38.872	1010
Fat	0.078,388	5.3494	920
Skull	0.27,522	11.781	1810
Brain	0.91,494	37.011	1040

the mobile phone is designed to operate as GSM-1800 mobile phones Fig. 2; hence the mobile phone is set to radiate a power of 0.125 W.

Shield

Two shapes of shields are used one without any slit and the other one with a slit as shown in Figs. 3 and 4, respectively. The slit is made in the shield to improve the mobile phone antenna performance.

Material properties

Material properties are required for each of the constituents of the model to represent them as real world materials. For electromagnetic problems in HFSS, materials can be defined using its conductivity, relative permittivity and mass density. The properties of the materials that are used in the model are shown in Table 2.

From the Eq. 1, it is observed that if a material has high conductivity and low mass density, then it will absorb a large amount of radiation. From this concept, five unknown materials are defined as shown in Table 3. These materials are tested as the shield to reduce SAR.

Geometry

The separation between the mobile phone and the head is considered as 0.5 cm. The shield has been placed in front of the mobile phone, between the head and mobile

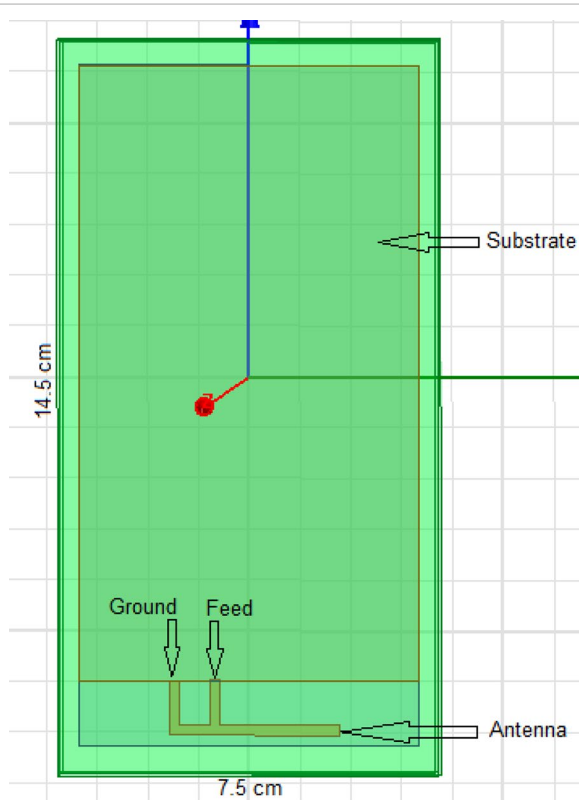

Fig. 2 Mobile phone with PIFA

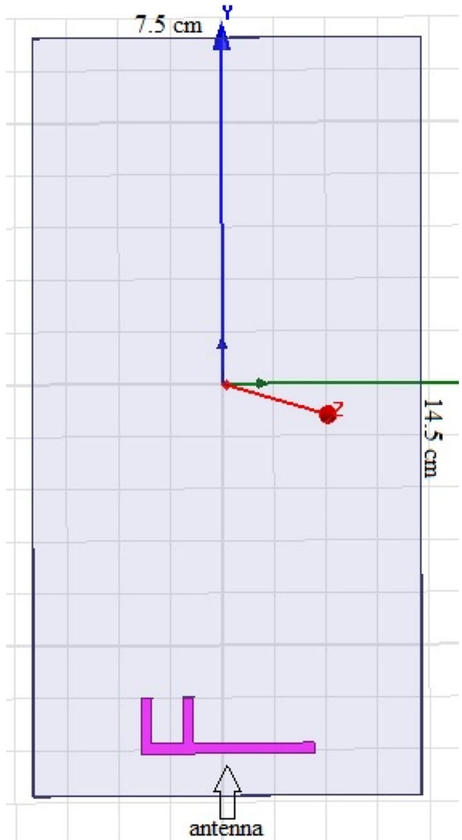

Fig. 3 Shield without slit

phone. The geometry of the whole model is shown in Fig. 5 and the final model in HFSS is shown in Fig. 6.

Results and discussion

Shields made up of conductors

Aluminium and copper shields are tested with and without slit. The thickness of the shields is taken as 0.1 cm.

From Fig. 7, it is observed that the return loss of the antenna increases at 1.8 GHz frequency to a value that cannot be used for the mobile phone antenna. From Fig. 8, it is observed that the radiation pattern gets changed due to shields made up of conductors, which is not desired. These conductor shields, depending on their density, will cause attenuation to the desired radiation pattern of the mobile phone antenna. It does not matter if the shield comes in contact with the mobile phone antenna or not; the signal strength will be reduced as it is unable to pass through the shielding material. Hence, a shield made up of a conductor cannot be used for the mobile phone radiation shielding purpose because they degrade the mobile phone antenna performance.

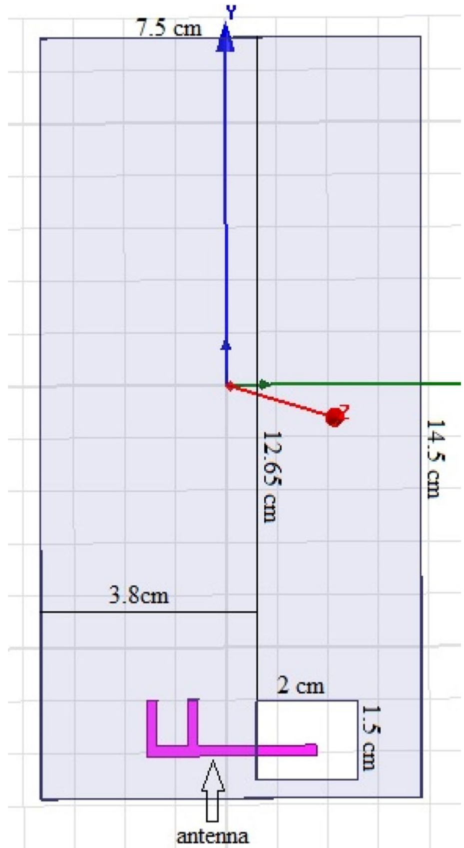

Fig. 4 Shield with slit

Table 2 Properties of materials used

Materials	Conductivity (S/m)	Relative permittivity	Mass density (kg/m^3)
Aluminium	38,000,000	1	2689
Copper	58,000,000	1	8933
Teflon	0	2.1	2250
Glass	0	5.5	2500
Plastic	0	2.25	930
Air	0	1.0006	1.1614
Germanium	2.17	16.2	5350

Table 3 Properties of unknown materials at 1.8 GHz frequency

Unknown materials	Conductivity (S/m)	Relative permittivity	Mass density (kg/m^3)
Material 1	1	1	1000
Material 2	10	1	1000
Material 3	100	1	1000
Material 4	1	1	10,000
Material 5	1	1	20,000

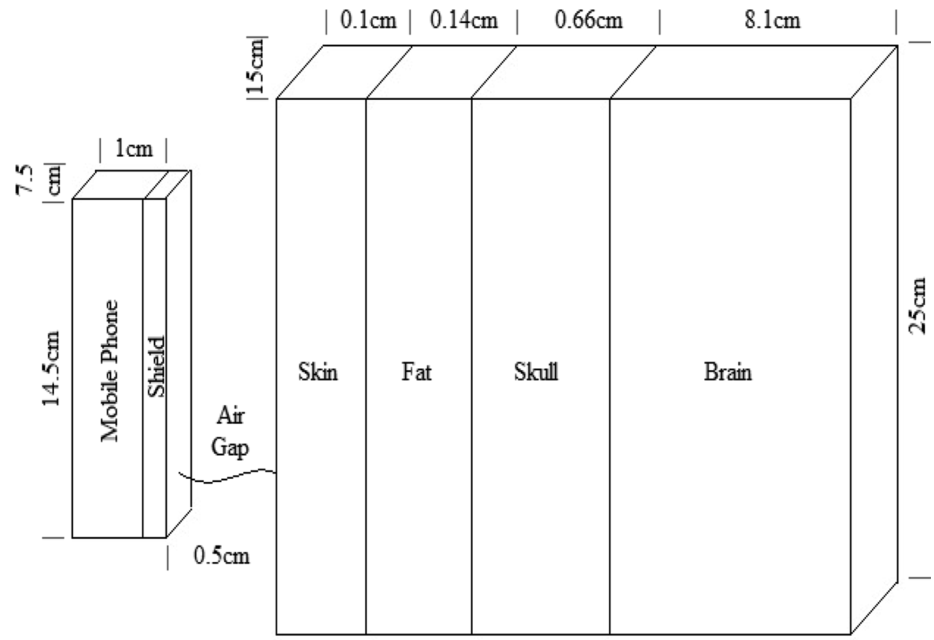

Fig. 5 Geometry of the model

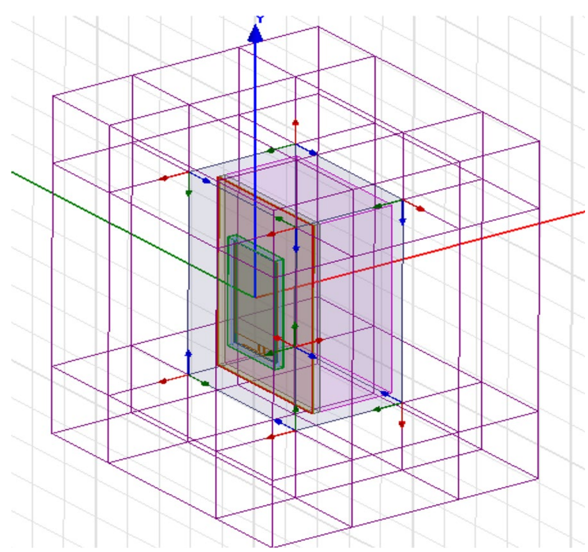

Fig. 6 Final model in HFSS

Shields made up of insulators

Teflon and glass shields are tested with and without slit. The thickness of the shields is taken as 0.1 cm.

From Fig. 9, it is observed that antenna return loss has a negligible effect due to shields made up of insulators, which is good. From Fig. 10, it is observed that there is no change in the radiation pattern of the mobile phone antenna due to shields made up of insulators, which is as desired. However, it is also observed that shields made up of insulators

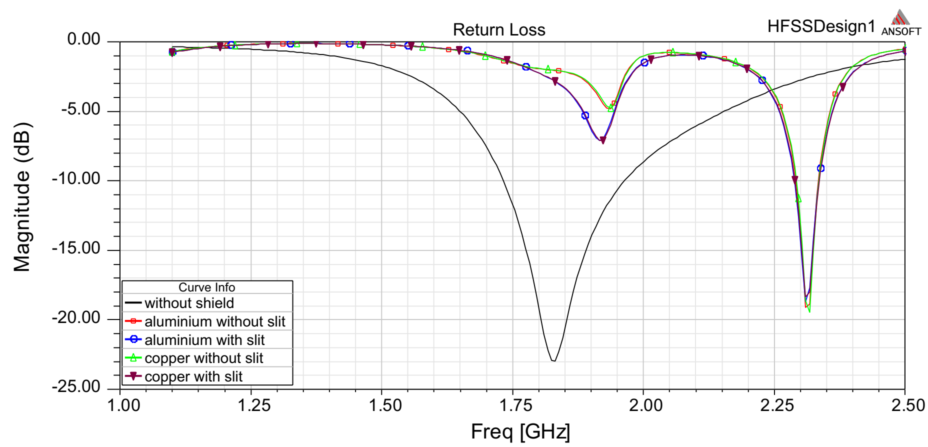

Fig. 7 Return loss of mobile phone antenna with shields made up of conductors

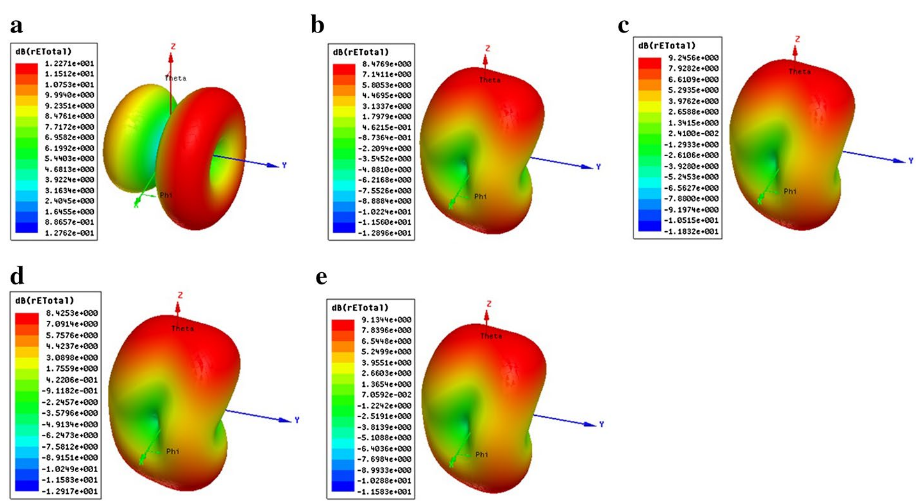

Fig. 8 3D radiation pattern of the mobile phone antenna with the shield of 0.1 cm thickness made up of materials: **a** without shield, **b** aluminium without slit, **c** aluminium with slit, **d** copper without slit, and **e** copper with slit

do not absorb any radiation as shown in Fig. 11. Hence, a shield made up of an insulator cannot be used for the mobile phone radiation shielding purpose. As insulators do not affect the mobile phone antenna performance, it will be a good material for using them as the mobile phone case.

Shields made up of unknown materials

Five unknown materials defined in "Simulation model" section are tested with and without slit. The thicknesses of the shields are taken as 0.1 and 0.2 cm.

From the Figs. 12, 13, 14 and 15, it is observed that shield having slit gives a better return loss value for the antenna compared to shield without slit.

The 3D radiation pattern of the mobile phone antenna with the shield made up of materials 1, 2, 3, 4, and 5 of 0.1 cm thickness is shown in Fig. 16.

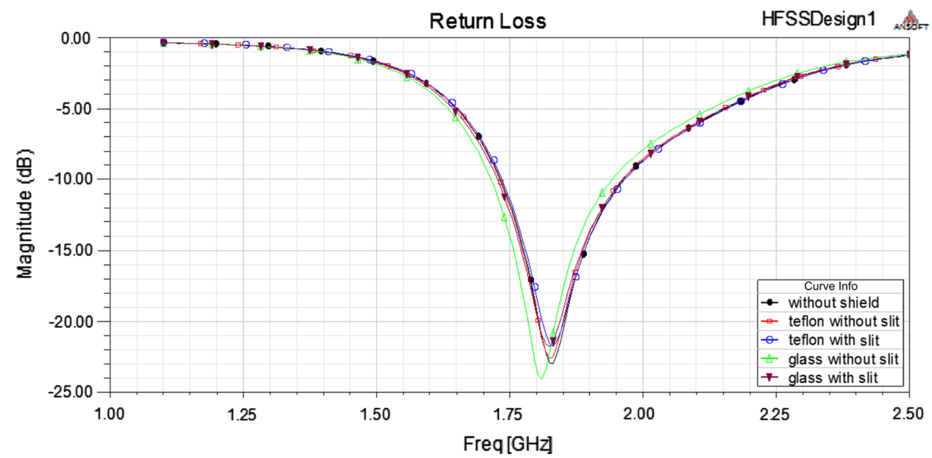

Fig. 9 Return loss of mobile phone antenna with shields made up of insulators

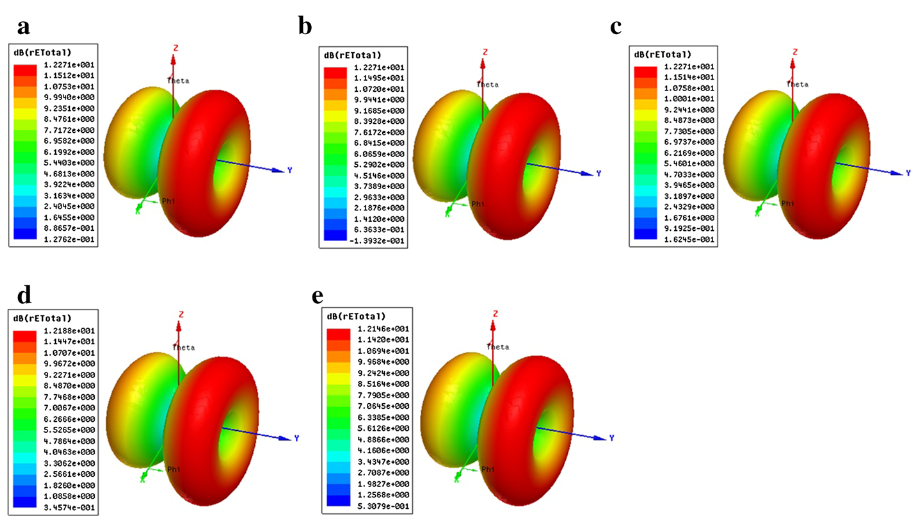

Fig. 10 3D radiation pattern of the mobile phone antenna with the shield of 0.1 cm thickness made up of materials: **a** without shield, **b** teflon without slit, **c** teflon with slit, **d** glass without slit, and **e** glass with slit

From Fig. 16, it is observed that for the shield made up of materials 1, 4, and 5 there is no change in the radiation pattern. For the shield made up of material 2 large loss in radiated power is observed. For the shield made up of material 3 change in radiation pattern is noticed. Same results are noticed with 0.2 cm thick shields made up of materials 1, 2, 3, 4, and 5, only the radiated power gets reduced in this case when compared with 0.1 cm thick shields.

SAR calculation

Local SAR in the skin and the brain is calculated without shield and with the shields (0.1 cm and 0.2 cm thick) having slit and made up of materials 1, 2, 3, 4, and 5 (Figs. 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27).

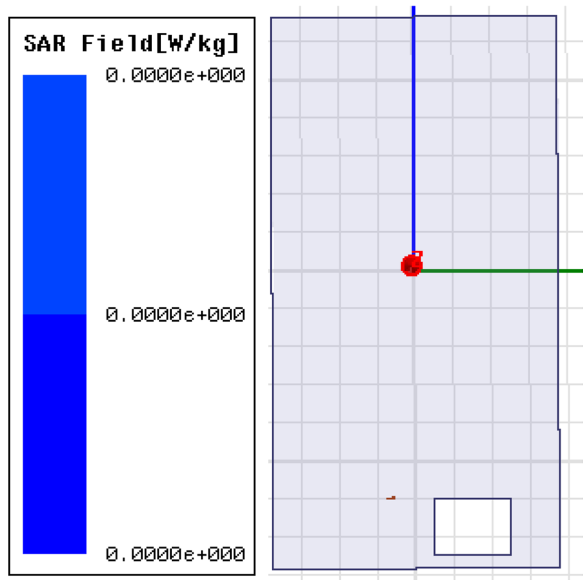

Fig. 11 SAR measured for the insulator shield

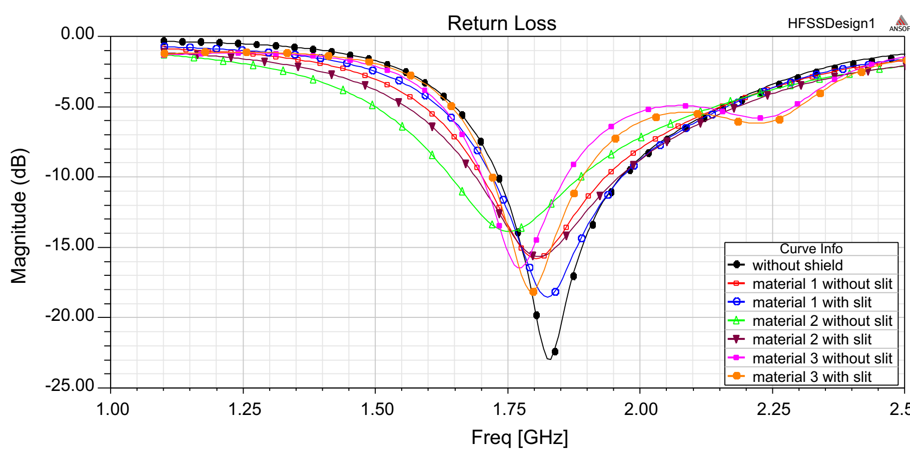

Fig. 12 Return loss of mobile phone antenna with shields made up of materials 1, 2, 3 and thickness of the shield is 0.1 cm

To compare the measured SAR for different materials, the maximum local SAR for skin and brain are represented in Tables 4 and 5.

From Tables 4 and 5, it is observed that a good amount of SAR reduction is achieved using shields made up of materials 1, 2, 3, 4, and 5. Shields made up of materials 1, 4 and 5 will be better mobile phone radiation shield as they have a negligible effect on mobile phone antenna performance. It is noticed that shield made up of material 1 absorbs more radiation compared to materials 4 and 5 due to less mass density; but due to the high mass density of materials 4 and 5, less SAR is observed in skin and brain because of less radiated power through them.

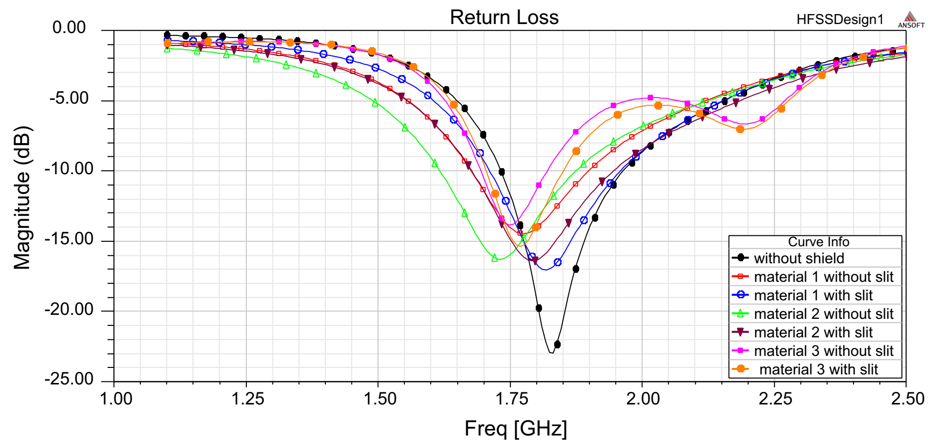

Fig. 13 Return loss of mobile phone antenna with shields made up of materials 1, 2, 3 and thickness of the shield is 0.2 cm

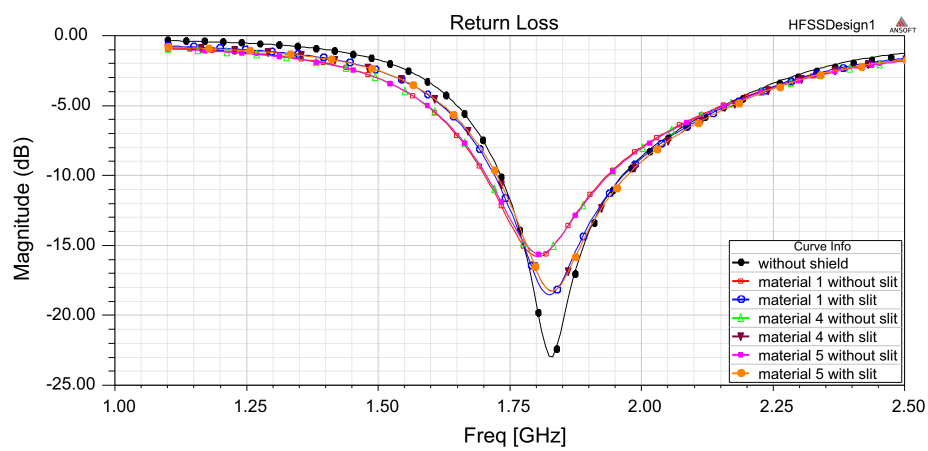

Fig. 14 Return loss of mobile phone antenna with shields made up of materials 1, 4, 5 and thickness of the shield is 0.1 cm

Shields made up of leather and germanium

After all the above analysis, it is observed that shields made up of conductors and insulators cannot be used for mobile phone shielding. Shields made up of materials 1, 4 and 5 can be used for mobile phone shielding. Few more tests are performed to find the exact properties of the materials that will give the best result in terms of reducing the radiation and maintaining good antenna performance of the mobile phone. There are three important properties of a shield material i.e. conductivity (σ), relative permittivity and mass density (ρ). From Eq. 1, it can be noticed that relative permittivity does not have any effect on SAR.

Coming to mass density (ρ), on earth the metal with highest mass density is osmium, having a mass density of 22,570 kg/m^3. Materials 1, 4 and 5 in Table 3, have a mass density of 1000, 10,000 and 20,000 kg/m^3, respectively. From Table 5, it can be observed that by increasing the ρ from 1000 to 10,000 to 20,000 kg/m^3, very small change in SAR

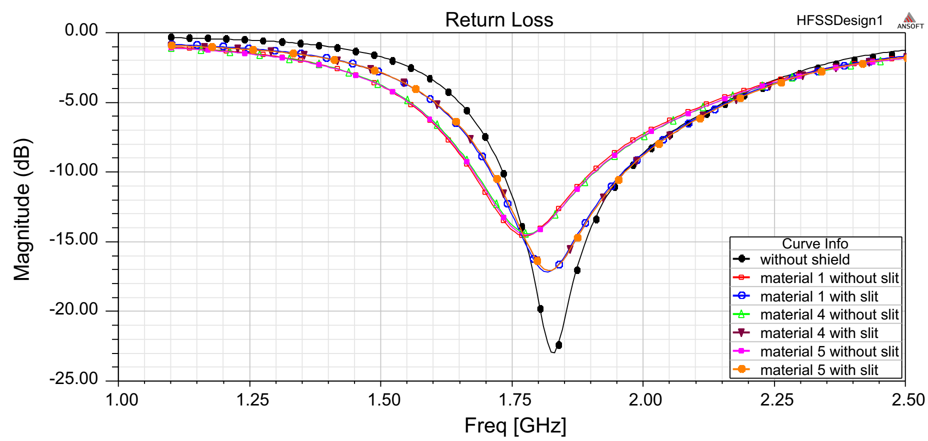

Fig. 15 Return loss of mobile phone antenna with shields made up of materials 1, 4, 5 and thickness of the shield is 0.2 cm

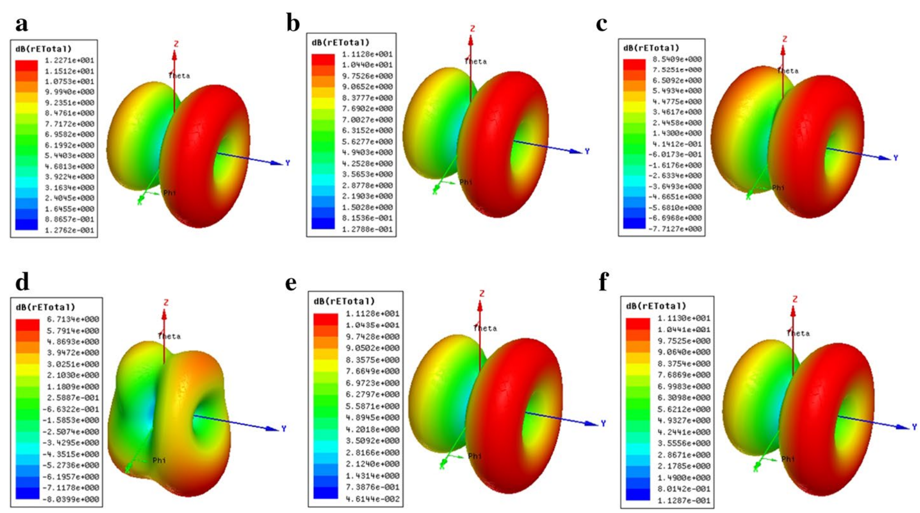

Fig. 16 3D radiation pattern of the mobile phone antenna with the shield of 0.1 cm thickness having slit and made up of materials: **a** without shield, **b** material 1, **c** material 2, **d** material 3, **e** material 4, and **f** material 5

is observed in skin and brain. Hence, if there are two materials with same conductivity, same relative permittivity, but different mass density then that material will be a better shield which has the lowest mass density.

Coming to conductivity (σ), which is the main parameter in deciding whether a material can be used as a shield for the mobile phone or not and which material will be a better shield. Comparing materials 1 and 2 having $\sigma = 1$ and $\sigma = 10$ S/m, respectively, it is noticed that material 1 gives good radiation absorption with good antenna performance whereas material 2 gives better radiation absorption but a poor antenna performance. So few more tests are performed by taking conductivity 0.1 S/m and incrementing it by 1 up to 9 S/m, keeping relative permittivity = 1, mass density = 1000 kg/m^3 and thickness of the shield as 0.1 cm. After these tests, it is found that materials having conductivity

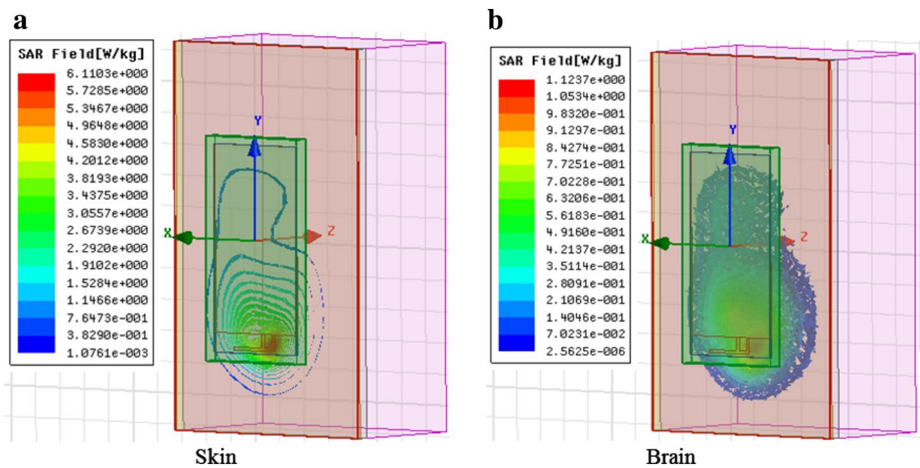

Fig. 17 SAR measured without shield

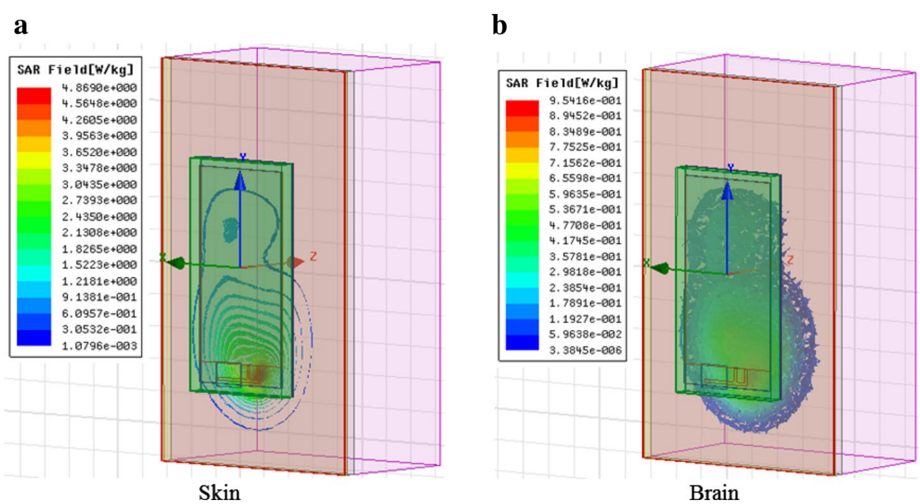

Fig. 18 SAR measured with 0.1 cm shield made up of material 1 having slit

between 0.1 and 3 S/m are suitable for mobile phone shield, as they have a negligible effect on mobile phone antenna performance. Compared to the mobile phone antenna without a shield, with a shield having $\sigma = 0.1$ S/m 0.24 % loss in radiated power is observed; with a shield having $\sigma = 1$ S/m 1.11 % loss in radiated power is observed; with a shield having $\sigma = 2$ S/m 1.74 % loss in radiated power is observed, with a shield having $\sigma = 3$ S/m 2.15 % loss in radiated power is observed. If conductivity is taken less than or equal to 0 S/m, it behaves like an insulator and do not absorb any radiation. If conductivity is increased above 3 S/m, increase in loss of radiated power and degradation of antenna performance is observed. If shield having a conductivity of 0.1 S/m is used, better antenna performance and less radiation absorption is achieved compared to shield having a conductivity of 3 S/m. So a trade-off is to be made between these two properties as per the requirement in the mobile phone.

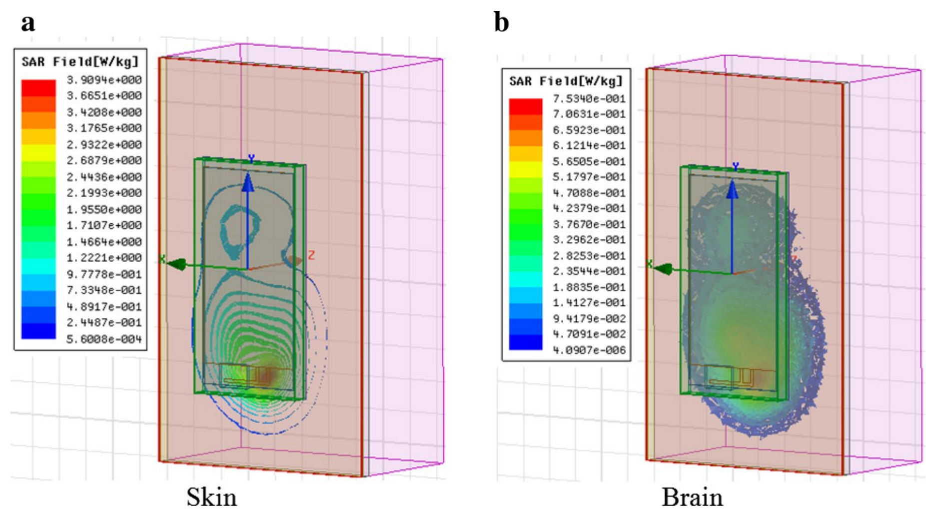

Fig. 19 SAR measured with 0.2 cm shield made up of material 1 having slit

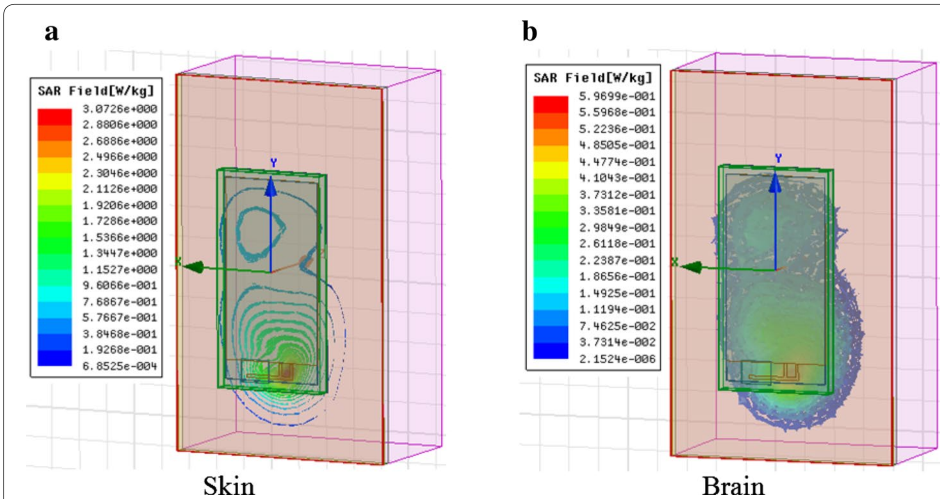

Fig. 20 SAR measured with 0.1 cm shield made up of material 2 having slit

Now, the properties of the materials are known; that will be a good shield for the mobile phone with good radiation absorption and negligible effect on the mobile phone antenna performance. Based on these properties, materials are searched that exist in the real world having conductivity between 0.1 and 3 S/m. Two materials those have these properties are skin (leather) having σ = 1.1847 S/m and germanium having σ = 2.17 S/m. The simulations are performed with the shields having slit and made up of skin (leather) and germanium having thicknesses of 0.1 and 0.2 cm. Results are shown below.

From Figs. 28 and 29, it is observed that shield made up of skin or germanium has a minor effect on the performance of the mobile phone antenna, which is acceptable.

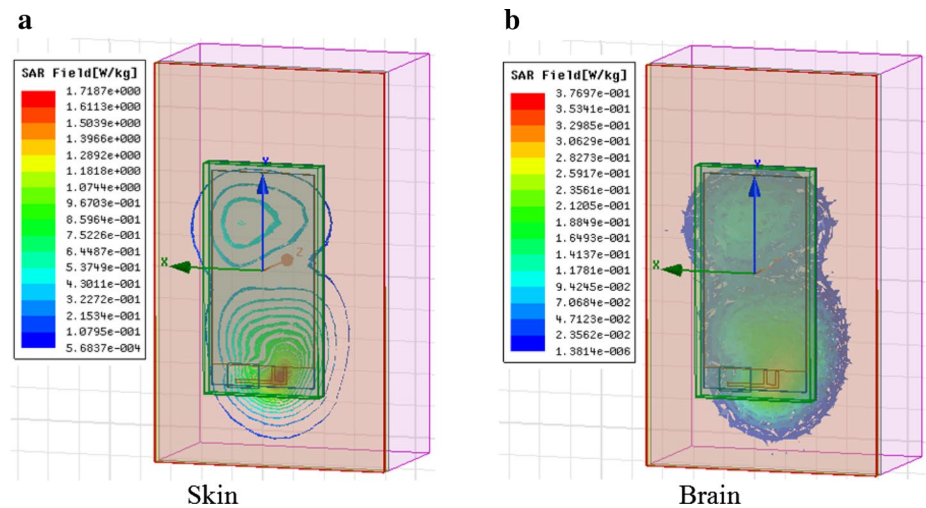

Fig. 21 SAR measured with 0.2 cm shield made up of material 2 having slit

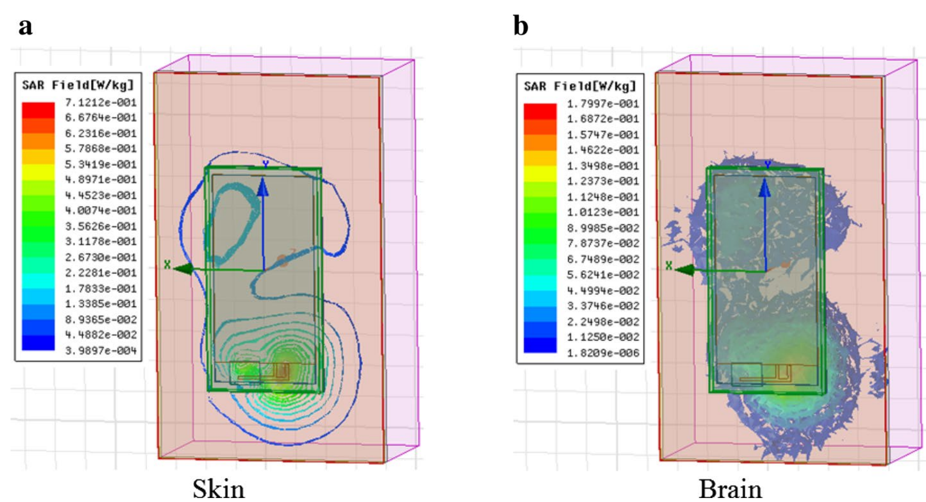

Fig. 22 SAR measured with 0.1 cm shield made up of material 3 having slit

SAR Calculation

Local SAR in the skin and the brain is calculated with the shields (0.1 and 0.2 cm thick) having slit and made up of material's skin (leather) and germanium (Figs. 30, 31, 32, 33).

To compare the measured SAR for skin (leather) and germanium, the maximum local SAR for skin and brain are represented in Table 6.

From Tables 4 and 6, it is observed that a good amount of SAR reduction is achieved using shields made up of skin (leather) and germanium.

Conclusion

In this paper, it has been observed that shield made up of conductors degrades the performance of the mobile phone antenna due to its high conductivity, and shield made up of insulators do not absorb any radiation due to zero conductivity. It is found that

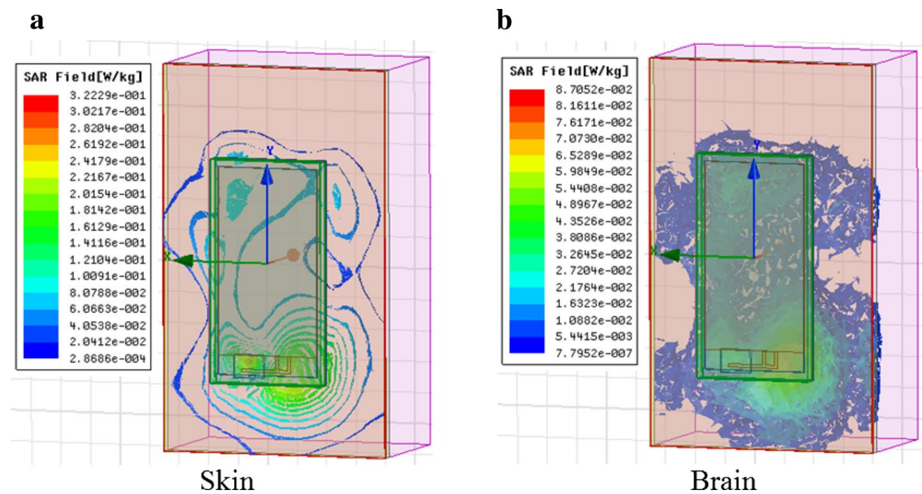

Fig. 23 SAR measured with 0.2 cm shield made up of material 3 having slit

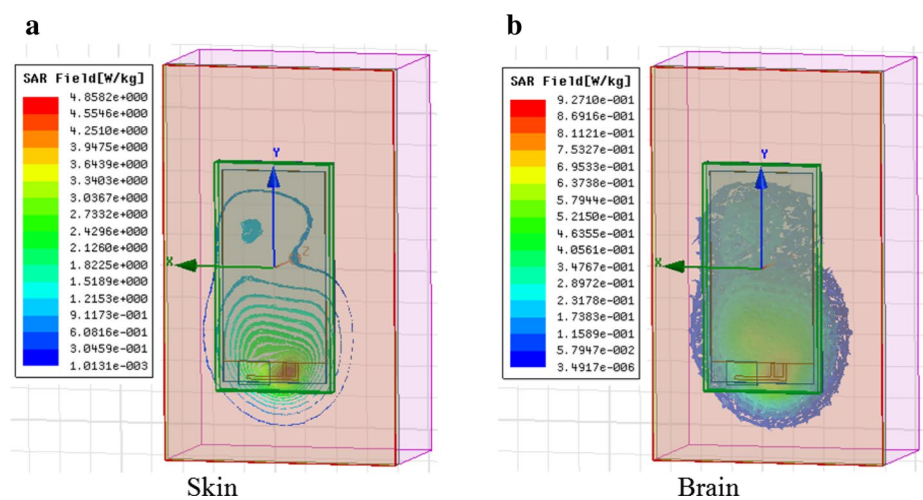

Fig. 24 SAR measured with 0.1 cm shield made up of material 4 having slit

materials having conductivity between 0.1 and 3 S/m can be used as good shields for the mobile phones. Based on these properties, materials are searched that exist in the real world having similar properties. Two materials that come under this category are skin (leather) and germanium. After performing tests with leather and germanium as the mobile phone shield, these results are obtained:

- Shield with slit having a thickness of 0.1 cm and made up of skin (leather) provides 20.49 % SAR reduction in the skin and 13.64 % SAR reduction in the brain with a change in return loss from −22.9 to −19.4 dB. Shield with slit having a thickness of 0.2 cm and made up of skin (leather) provides 36.07 % SAR reduction in the skin and 31.82 % SAR reduction in the brain with a change in return loss from −22.9 to −15.7 dB.

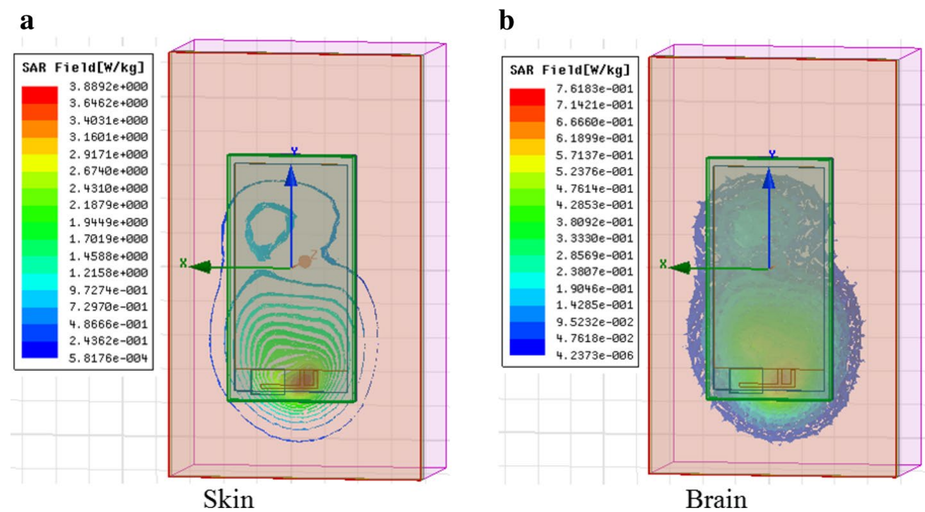

Fig. 25 SAR measured with 0.2 cm shield made up of material 4 having slit

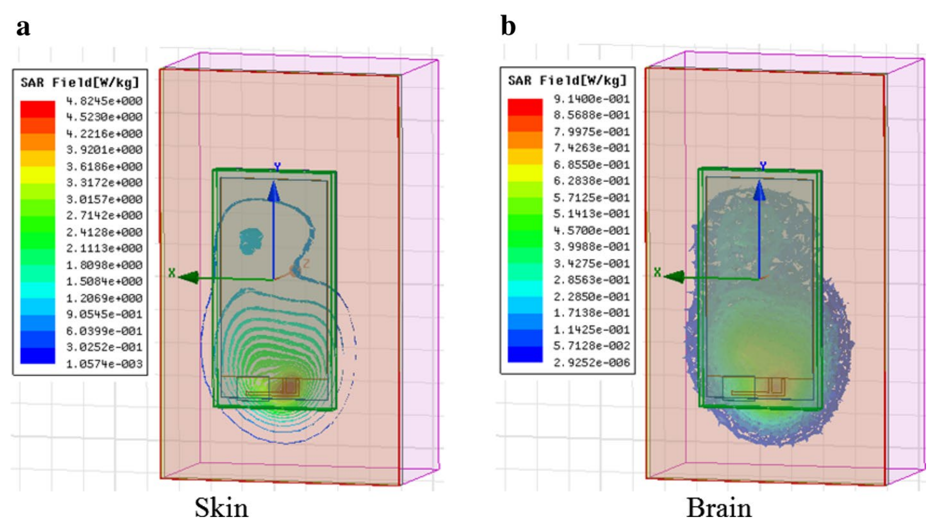

Fig. 26 SAR measured with 0.1 cm shield made up of material 5 having slit

- Shield with slit having a thickness of 0.1 cm and made up of germanium provides 21.14 % SAR reduction in the skin and 15.45 % SAR reduction in the brain with a change in return loss from −22.9 to −17.2 dB. Shield with slit having a thickness of 0.2 cm and made up of germanium provides 36.55 % SAR reduction in the skin and 33.63 % SAR reduction in the brain with a change in return loss from −22.9 to −16.4 dB.

It has been observed that the shield can be placed inside or outside of the mobile phone; same performance of the mobile phone antenna and SAR reduction is achieved. A solution for the practical application can be using the shield as the mobile phone flip cover case as shown in Fig. 34 with a shield made up of leather or germanium.

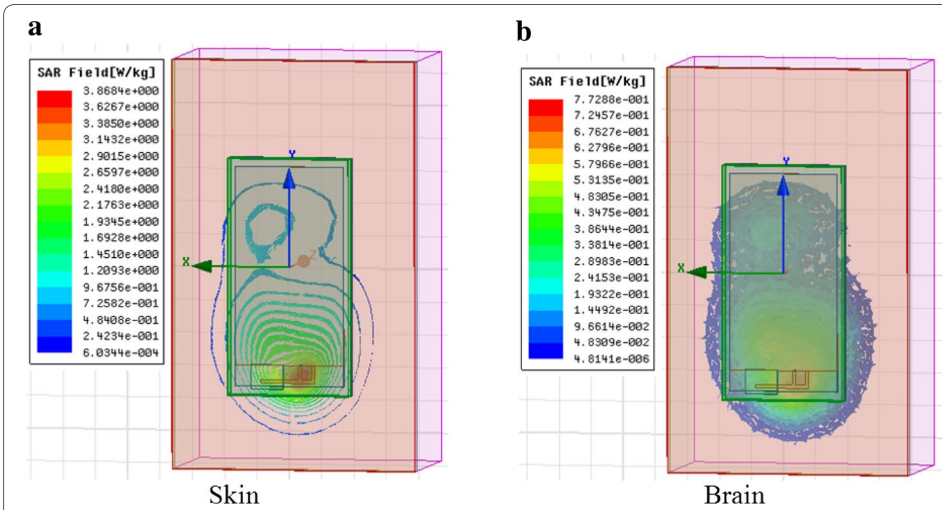

Fig. 27 SAR measured with 0.2 cm shield made up of material 5 having slit

Table 4 Maximum local SAR for skin and brain without shield

Local SAR in W/kg	
Without shield	
Skin	**Brain**
6.1	1.1

Table 5 Maximum local SAR for skin and brain with shields having slit by varying shield material and shield thickness

Shield material	Local SAR in W/kg			
	0.1 cm thick shield		0.2 cm thick shield	
	Skin	Brain	Skin	Brain
Material 1	4.86	0.95	3.9	0.75
Material 2	3.07	0.59	1.71	0.37
Material 3	0.71	0.17	0.32	0.08
Material 4	4.85	0.92	3.88	0.76
Material 5	4.82	0.91	3.86	0.77

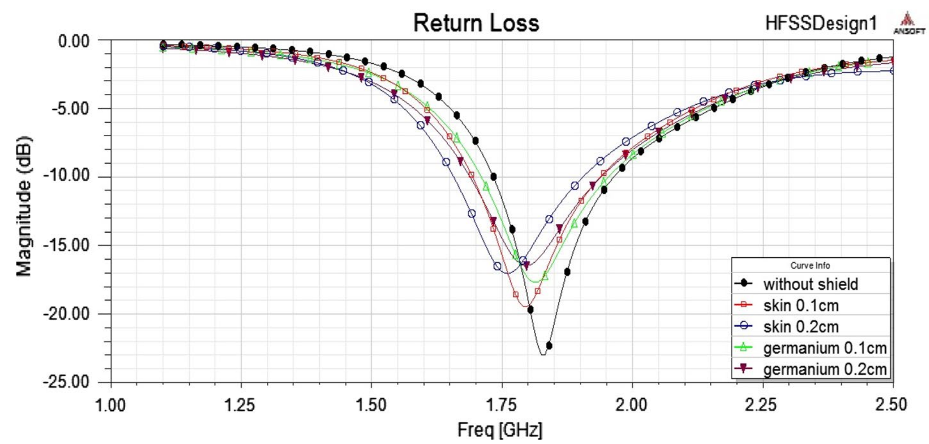

Fig. 28 Return loss of mobile phone antenna with shields made up of skin (leather) and germanium having thicknesses of 0.1 cm and 0.2 cm

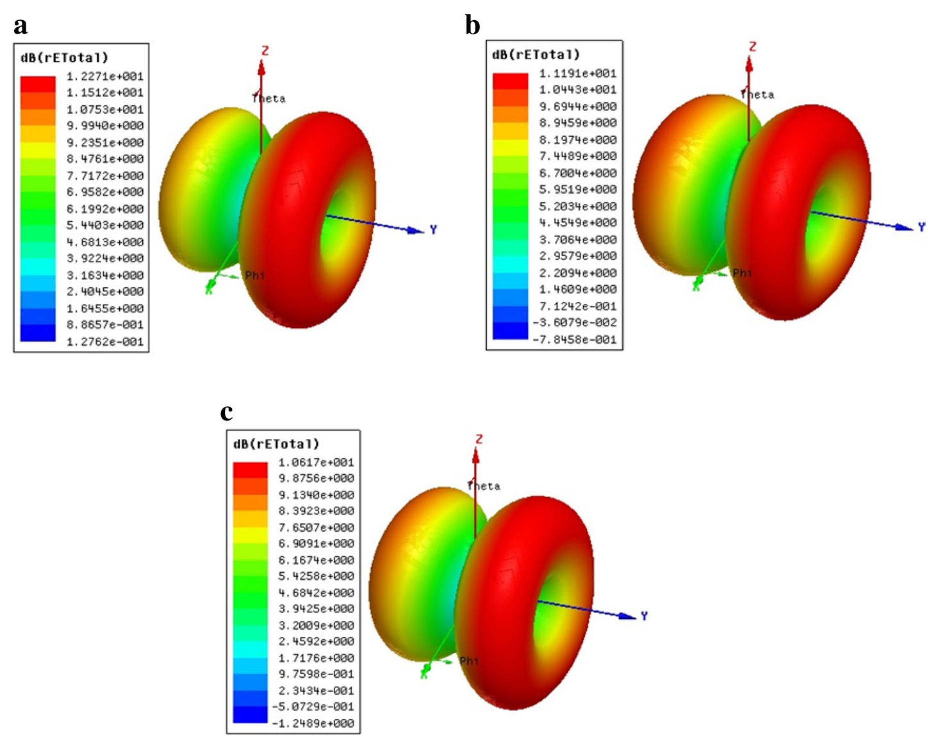

Fig. 29 3D radiation pattern of the mobile phone antenna with the shield of 0.1 cm thickness having slit and made up of materials: **a** without shield, **b** skin, **c** germanium

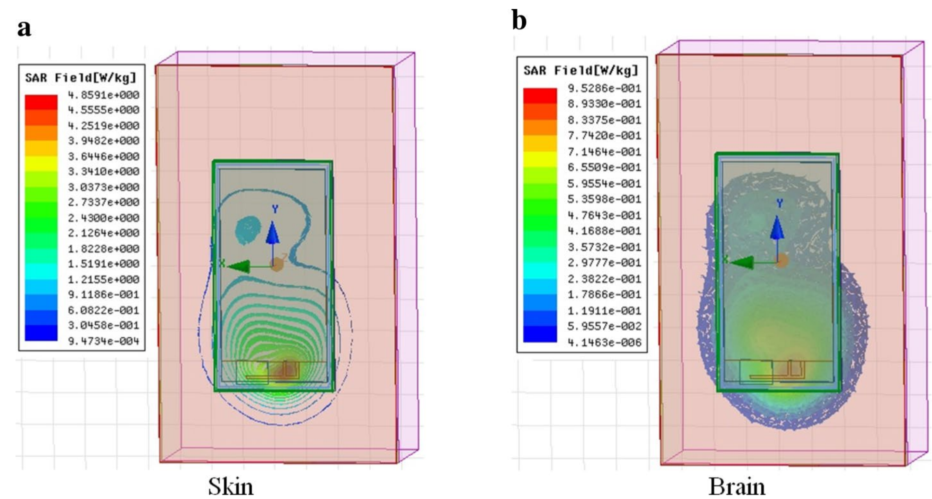

Fig. 30 SAR measured with 0.1 cm shield made up of skin (leather) having slit

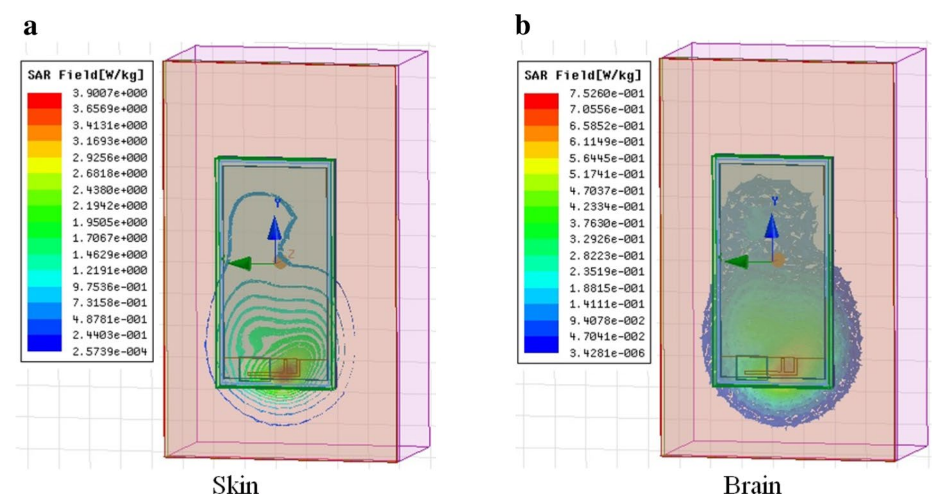

Fig. 31 SAR measured with 0.2 cm shield made up of skin (leather) having slit

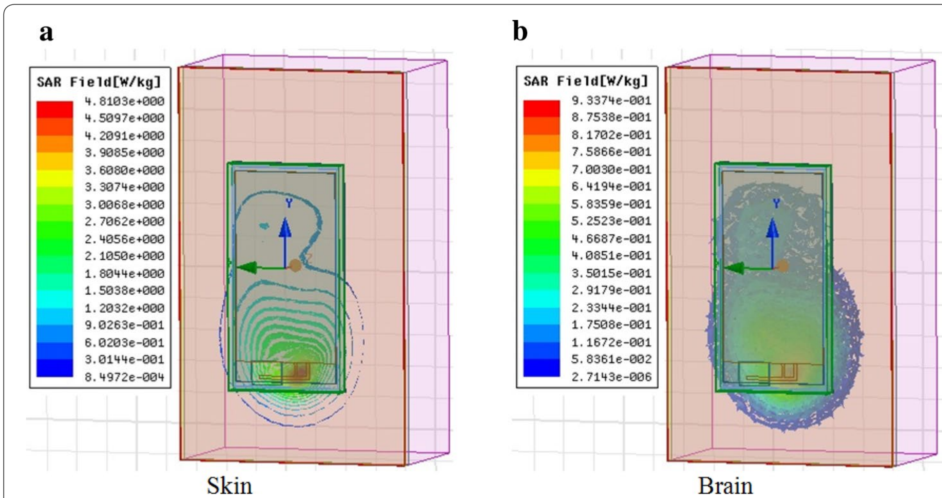

Fig. 32 SAR measured with 0.1 cm shield made up of germanium having slit

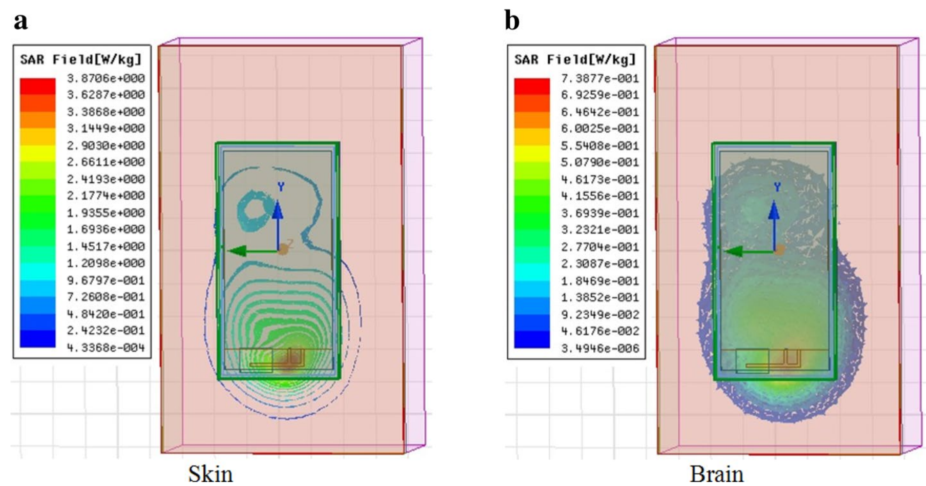

Fig. 33 SAR measured with 0.2 cm shield made up of germanium having slit

Table 6 Maximum local SAR for skin and brain due to shields having slit, made up of skin (leather) and germanium having thicknesses of 0.1 and 0.2 cm

Shield material	Local SAR in W/kg			
	0.1 cm thick shield		0.2 cm thick shield	
	Skin	Brain	Skin	Brain
Skin	4.85	0.95	3.9	0.75
Germanium	4.81	0.93	3.87	0.73

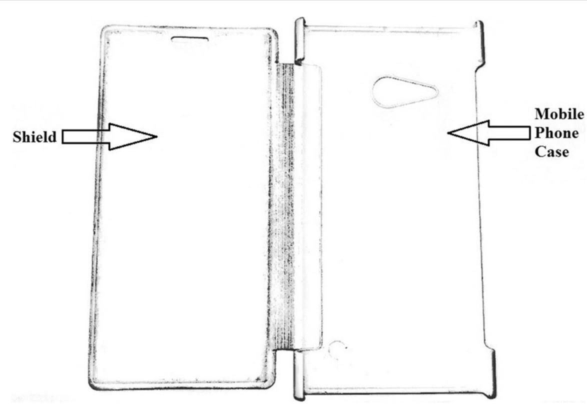

Fig. 34 Mobile phone flip cover case

Authors' contributions

Author PKD drafted this manuscript, performed simulation using the data sets and analysed the results. Authors Dr. PVYJ and Dr. VSSNSB suggested the methods used in this study and provided technical support throughout the project. All authors read and approved the final manuscript.

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