Eurasian Journal of Theoretical and Applied Sciences (EJTAS)

Volume 2, Issue 1, 2026, Page No: 05-13

Website: https://eurasian-journals.com/index.php/etjas/index

E-ISSN : 3062-3391

Design and analysis of a metamaterial shielding chip for mobile phones to reduce EM radiation in Human Head

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تصميم وتحليل لشريحة حماية من المواد الفائقة للهواتف المحمولة لتقليل الإشعاع الكهرومغناطيسي في رأس الإنسان

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Received: November 02, 2025	Accepted: December 26, 2025	Published: January 08, 2026

Abstract:

This study focuses on the development and evaluation of a shielding chip made from metamaterials, designed to decrease the absorption of electromagnetic (EM) radiation by the human head from mobile phones. As public concern rises regarding long-term exposure to radiofrequency (RF) emissions, effective personal protection technologies are increasingly important. The proposed shield uses a custom-engineered metamaterial pattern to absorb and deflect EM waves, which lowers the Specific Absorption Rate (SAR) in cranial tissues. Simulations using the Finite Element Method (FEM) were performed across various 5G frequencies. These simulations utilized a detailed, multi-layered anatomical model of the head, including skin, fat, bone, dura, cerebrospinal fluid (CSF), and brain tissues. The analysis assessed critical metrics under realistic conditions, including SAR distribution, electric field attenuation, penetration depth, reflection coefficient (S11), and induced temperature changes. The findings show that the metamaterial chip substantially reduces SAR levels, especially in tissues with high water content. Both the 1-gram and 10-gram averaged SAR results stayed under the 1.6 W/kg regulatory limit set by the Federal Communications Commission (FCC). The shield exhibited strong wave-absorbing properties, with a notable performance at 2.4 GHz characterized by low reflection and no substantial thermal increase in head tissues. The research concludes that the metamaterial-based shielding chip presents a practical and effective approach for mitigating EM radiation exposure from mobile phone usage.

Keywords: SAR, electromagnetic radiation, shielding, Metamaterial, human head.

الملخص

تركز هذه الدراسة على تطوير وتقييم شريحة واقية مصنوعة من مواد فائقة، مصممة لتقليل امتصاص الإشعاع الكهرومغناطيسي المنبعث من الهواتف المحمولة بواسطة رأس الإنسان. مع تزايد المخاوف العامة بشأن التعرض طويل الأمد لانبعاثات الترددات الراديوية، تزداد أهمية تقنيات الحماية الشخصية الفعالة. تستخدم الشريحة الواقية المقترحة نمطًا مصممًا خصيصًا من المواد الفائقة لامتصاص الموجات الكهرومغناطيسية وعكسها، مما يقلل من معدل الامتصاص النوعي (SAR) في أنسجة الجمجمة. أُجريت محاكاة باستخدام طريقة العناصر المحدودة (FEM) عبر ترددات الجيل الخامس المختلفة. استخدمت هذه المحاكاة نموذجًا تشريحيًا مفصلًا متعدد الطبقات للرأس، يشمل الجلد والدهون والعظام والأم الجافية والسائل النخاعي الشوكي وأنسجة الدماغ. قيّم التحليل مؤشرات حيوية في ظل ظروف واقعية، بما في ذلك توزيع معدل الامتصاص النوعي، وتوهين المجال الكهربائي، وعمق الاختراق، ومعامل الانعكاس (S11)، والتغيرات الحرارية الناتجة. تُظهر النتائج أن شريحة المادة الفائقة تُقلل بشكلٍ ملحوظ من مستويات معدل الامتصاص النوعي (SAR)، لا سيما في الأنسجة ذات المحتوى المائي العالي. وقد بقيت نتائج معدل الامتصاص النوعي (SAR) المتوسطة

لكلٍ من 1 غرام و10 غرامات أقل من الحد المعياري البالغ 1.6 واط/كغ الذي حددته لجنة الاتصالات الفيدرالية (FCC). وأظهرت الدرع خصائص امتصاص قوية للموجات، مع أداءٍ ملحوظ عند تردد 2.4 جيجا هيرتز، تميز بانخفاض الانعكاس وعدم وجود ارتفاع حراري كبير في أنسجة الرأس. ويخلص البحث إلى أن شريحة الحماية القائمة على المادة الفائقة تُقدم نهجًا عمليًا وفعالًا للحد من التعرض للإشعاع الكهرومغناطيسي الناتج عن استخدام الهاتف المحمول.

الكلمات المفتاحية: معدل الامتصاص النوعي (SAR)، الإشعاع الكهرومغناطيسي، الحماية، المادة الفائقة، رأس الإنسان.

I. Introduction

The electromagnetic radiation produced by electronic equipment can harm biological cells [1]. For instance, the mobile phone, now essential to daily life, exposes users more frequently to such radiation with increased usage [2]. Upon encountering a radiofrequency electromagnetic field, the human body takes in energy from radio waves [3]. This absorbed energy, measured in watts per kilogram (W/Kg), is quantified as the Specific Absorption Rate (SAR)—the rate at which RF energy is absorbed by the body [1]. While phones can be shielded to meet SAR non limits and reduce RF exposure to the head, the performance of various shielding materials for lowering SAR is not fully clear [4]. It should be emphasized that SAR values are highly influenced by the nature of the exposed tissue, the radiation's frequency, and the proximity to the source [5]. Research by Islam et al. in 2009 demonstrated that attaching a ferrite sheet to the head could lower SAR by 57.75%, with optimal placement and distance being key factors [4]. SAR is typically determined through two approaches: computational simulations or measurements using anatomical phantoms designed for thermal or electromagnetic analysis. Many investigations have used diverse methods to analyze the impact of mobile phone antenna waves on human tissue [5]. Our research applies the Finite Element Method (FEM). SAR emerged as a concept to measure the energy (averaged over 1g or 10g of tissue) absorbed from -ionizing electromagnetic radiation in the 100 kHz to 300 GHz range [6]. It is a vital metric for evaluating the safety of wearable electronics [7]. Absorption in near-field exposure varies with the phone's operating frequency and distance from the user. Contemporary smartphones, used for texting and video, expose the head and eyes to radiation from multiple angles and in different held positions. Additionally, low-cost phones made with inferior components may pose a greater health risk from long-term exposure [8], [9].

Research indicates that nanomaterials are the most efficient means for decreasing SAR in brain tissue [10]. Proposed shielding materials include carbon-based nanomaterials like single-walled and multi-walled carbon nanotubes (SWCNT, MWCNT), Graphene, and composites such as magneto-dielectric nanocomposites (MDNC) and reduced Graphene oxide (rGO-5, rGO-10), used alongside antenna elements. Efforts to mitigate radiation effects on the head have involved studying how SAR changes with phone frequencies and modeling antenna exposure for both adults and children [1]. In this work, we implement a Metamaterial sheet to protect head tissues from the radiofrequency emissions of mobile phones.

II. Electromagnetic wave absorption performance of diverse materials

Metals are the predominant choice for electromagnetic shielding because of their excellent electrical conductivity. Their use, however, is limited by significant drawbacks, including high weight, corrosion potential, and visible metallic reflectivity. These limitations have driven the search for alternative solutions. Conductive polymers (CPs) are now being utilized as next-generation EMI shielding materials, offering advantages like tunable mechanical properties (such as flexibility), low density, and cost-effective mass production [16].

Addressing electromagnetic interference necessitates the development of new, high-performance materials for absorbing and shielding EM waves. While traditional options like metals and ferrites are common, their high mass and limited chemical stability present significant shortcomings, creating a need for better alternatives [17]. Carbon-based materials, such as carbon nanotubes (CNTs), Graphene, and biomass-derived porous carbons (BDPCMs), are leading dielectric loss materials that have garnered significant interest for EM wave absorption. Their appeal lies in superior electrical conductivity, high specific surface area, and low weight. A key challenge, however, is their poor impedance matching; their high conductivity causes much of the incident EM wave to be reflected at the surface instead of penetrating the material to be absorbed [18].

This landscape presents a major opportunity to create multifunctional EM absorbing and shielding (EMAS) materials. Ideally, such materials would also provide high thermal insulation, enabling operation in high-temperature environments. An effective EM wave absorber functions by capturing radiation and converting its energy into heat, thereby blocking it. A critical measure of this effectiveness is the reflection loss (RL), measured in decibels (dB). To be deemed effective, a material must achieve an RL value below -10 dB, indicating it absorbs over 90% of the incident EM waves [17].

Table 1. Parameters of layers (tissues) of the human head**.**

Tissue	Density (kg/m^3)	Frequency (0.9 GHZ)		Frequency (1.8 GHZ)		Frequency (2.4 GHZ)		Frequency (3.35 GHZ)		Frequency (4.45 GHZ)	
		ε_r	$\sigma(\frac{S}{m})$	ε_r	$\sigma(\frac{S}{m})$	ε_r	$\sigma(\frac{S}{m})$	ε_r	$\sigma(\frac{S}{m})$	ε_r	$\sigma(\frac{S}{m})$
Skin	1100	41.4	0.87	38.9	0.87	38.1	1.44	37.1	1.93	36.18	2.68
Fat	920	5.46	0.05	5.34	0.05	5.29	0.102	5.18	0.14	5.076	0.21
Bone	1850	12.4	0.14	11.8	0.14	11. 4	0.38	10.8	0.5	10.28	0.84
Dura	1050	44.4	0.96	42.9	0.96	42.1	1.64	40.9	2.25	39.47	3.15
CSF	1060	68.7	2.41	67.2	2.41	66.3	3.41	64.8	4.39	62.85	5.87
Brain	1030	45.8	0.77	43.5	0.77	42.6	1.48	41.3	2.11	39.91	3.03

III. Model

we use model contains from head, mobile phone and shielding chip as shown in Fig. 1.the head model was designed with different characteristics and dimensions six tissue. shielding Material was created from Metamaterial to absorbing or reflecting electromagnetic fields (EMF) to prevent them from penetrating the human head. To modeling the head, phone and chip geometry by use FEM as an effective method in electromagnetic radiation, the inclusion of both phone and shielding chip establishes the complete source-shield-target system.

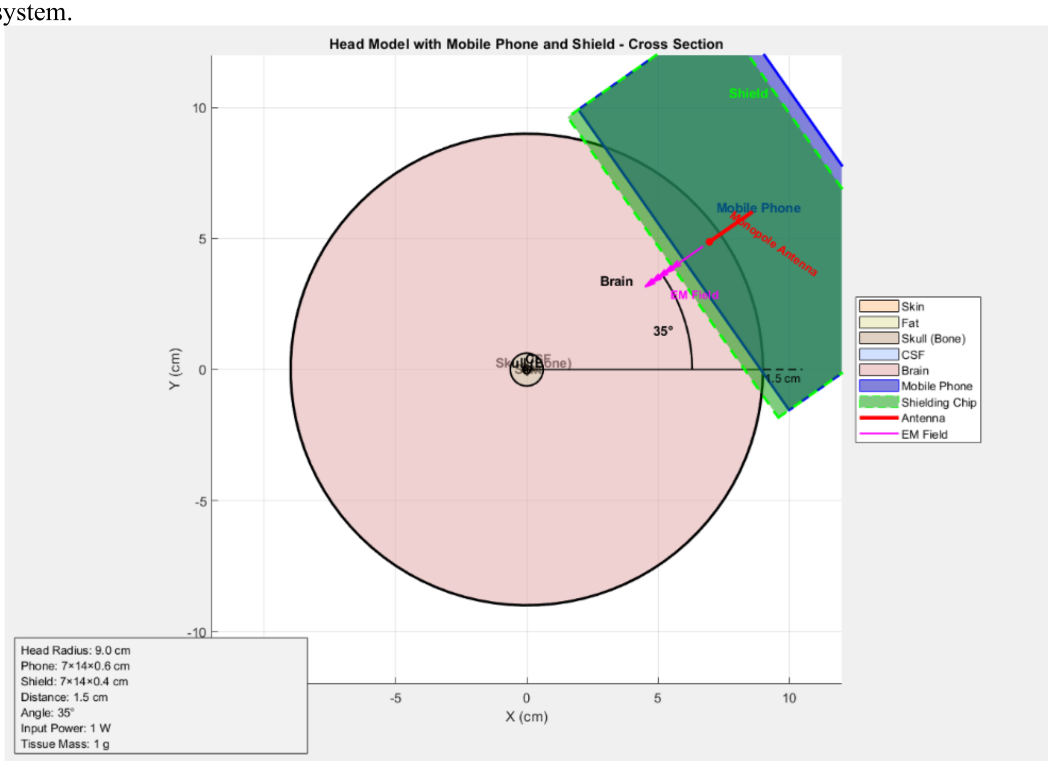


Figure 1 The head and Mobile phone model.

The proximity (0.5-1.0 cm) accurately represents realistic mobile phone usage scenarios. This geometry enables FEM analysis of wave reflection, transmission, and absorption at tissue interfaces. Assign electromagnetic properties (permittivity and conductivity) to different tissues within the head as shown in table.1. These properties influence how RF radiation interacts with and penetrates the tissues.

IV. SAR simulation Results

Here is the paraphrased text, with the original reference to Table (1) and all technical terminology preserved for accuracy. The outcomes from employing a superconductor chip for protection were derived from a MATLAB simulation. This simulation incorporated the real-world dimensions of a mobile phone and the biophysical properties of human head tissues, as detailed in Table (1).

The Finite Element Method (FEM) served as the primary computational technique for modeling electromagnetic radiation. The established schematic models the core electromagnetic boundary value problem relevant to near-field exposure. It utilizes a multi-layered head model comprising six different tissue types—skin, fat, bone, dura, cerebrospinal fluid (CSF), and brain—which encapsulates the key anatomical structures influencing electromagnetic wave behavior. Integrating both the phone and the shielding chip creates a complete representation of the source-shield-target system. The model's separation distance of 0.5 to 1.0 cm realistically mimics actual mobile phone usage conditions. This geometrical configuration is essential for FEM to analyze the reflection, transmission, and absorption of waves at tissue boundaries. Such analysis is vital for precise Specific Absorption Rate (SAR) calculation, as dielectric property differences between tissues can lead to the formation of standing waves and concentrated areas of heating.

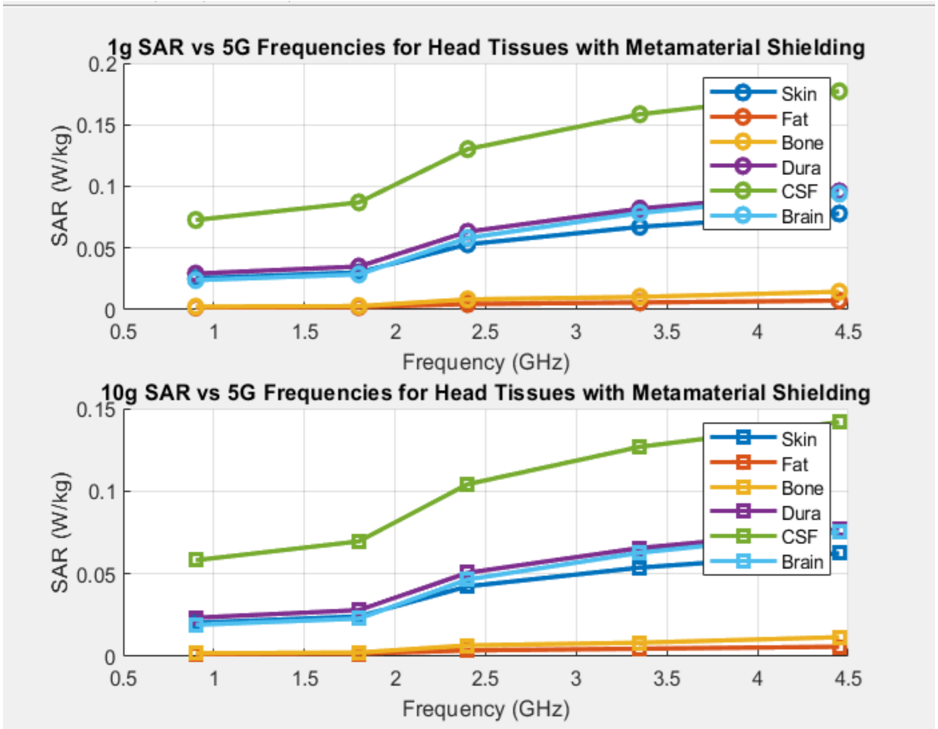


Figure 2 SAR vs frequencies for Head Tissues.

In Fig.2, the results show that the specific absorption rate SAR for 1g increases with frequency and is highest in spinal cord tissue due to its biological properties, followed by the skull and brain, then the skin, due to the similarity in their physical properties. In contrast, bones and skin record lower absorption due to their low permittivity and conductivity. For 10g, we also find that the decrease in the absorption rate occurs at the same rate as for 1g, but it is noted that it is much lower, where the highest value for 1g was 0.1772 W/kg in CSF tissue at 4.45 GHz and the highest value for 10g was 0.1418 W/kg in CSF tissue at same frequency. Most importantly, both readings are below the specified standard value by FCC (1.6 W/kg).

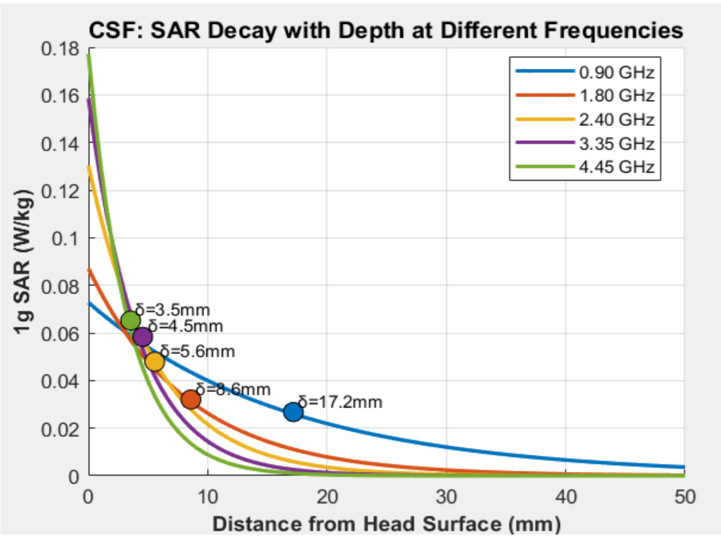


Figure 3 SAR decay with depth of CSF at different Frequencies.

The penetration depth (skin depth) of CSF tissue at 1g shown in fig.3, The penetration depth, which is lowest at the highest frequency of 4.45 GHz (3.5 mm), gradually increases as the frequency decreases, reaching its lowest value at 0.9 GHz (17.2 mm).

Fig.4 shown Tissues with higher water content (e.g., muscle, brain) tend to absorb more RF energy higher SAR at the same distance while Tissues with lower water content (e.g., fat, bone) have lower SAR at the same distance. We note that even at very small distances (e.g., phone against the ear), SAR values are highest — close to regulatory limits (e.g., 1.6 or 2.0 W/kg averaged over 1g or 10g tissue).

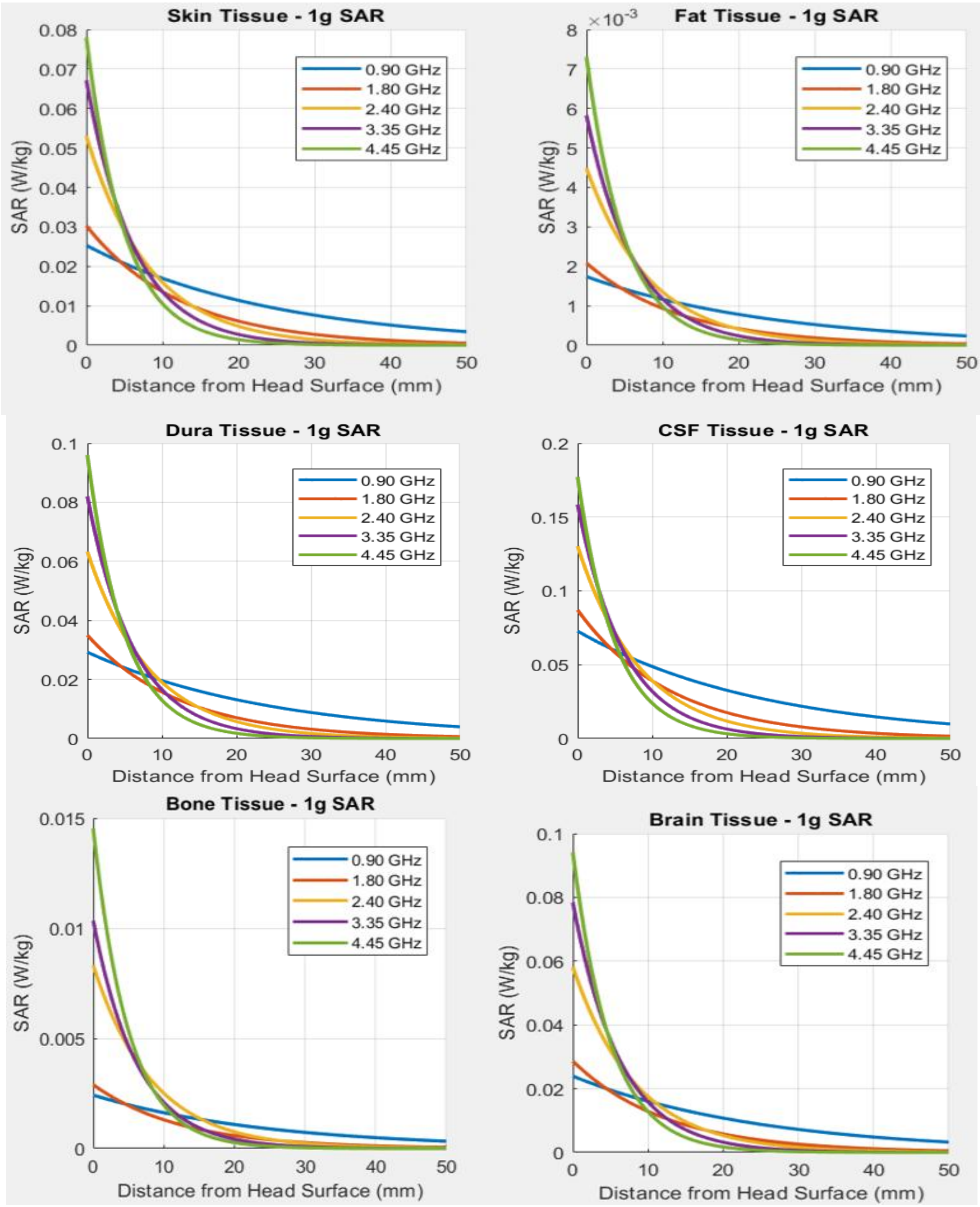


Figure 4 SAR vs distance for Head Tissues.

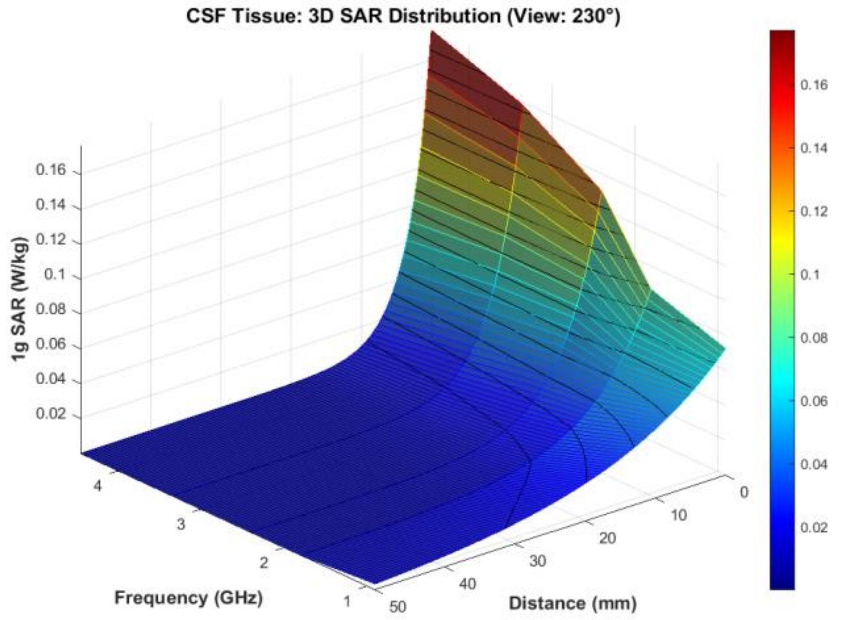


Figure 5 3D SAR vs distance and frequency for 1g

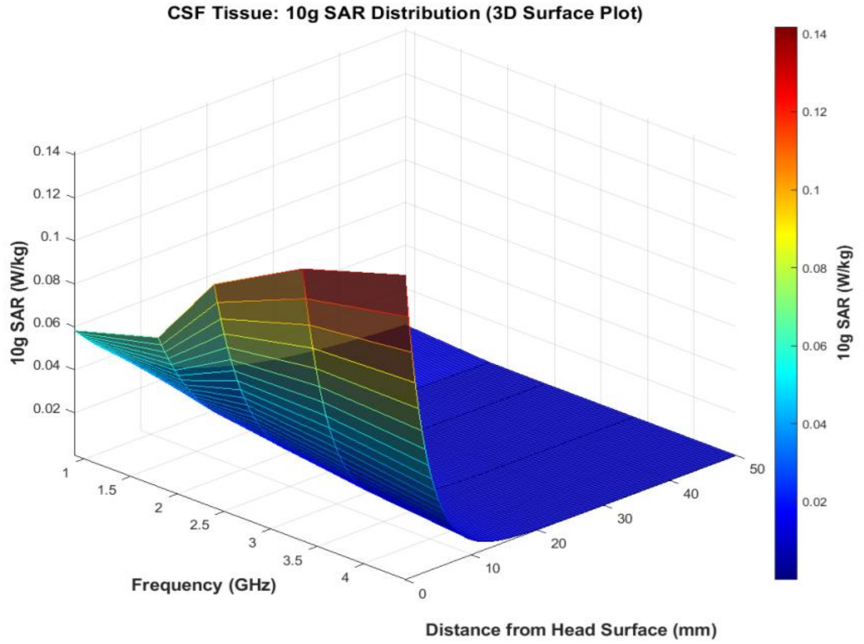


Figure 6 3D SAR vs distance and frequency for 10g

Fig.5,6 surfaces visualization reveals the complex interplay between frequency-dependent penetration depth and distance-dependent field decay. The concave curvature in the distance dimension shows accelerating attenuation (α increases with frequency). The color gradients illustrate that maximum energy deposition occurs at the surface for higher frequencies (skin heating dominant) while lower frequencies maintain significant penetration to deeper tissues.1g-averaged SAR surface would show higher peak values than 10g because the 10g average "smears" the highest local SAR over a larger tissue volume, reducing the numerical peak.1g average: Can show rapid variation with distance. You might see SAR drop quickly over just a few millimeters, then spike again near a standing wave maximum. However, 1g average might show narrower resonance peaks in frequency, while 10g average would show broader, flatter resonant bands.

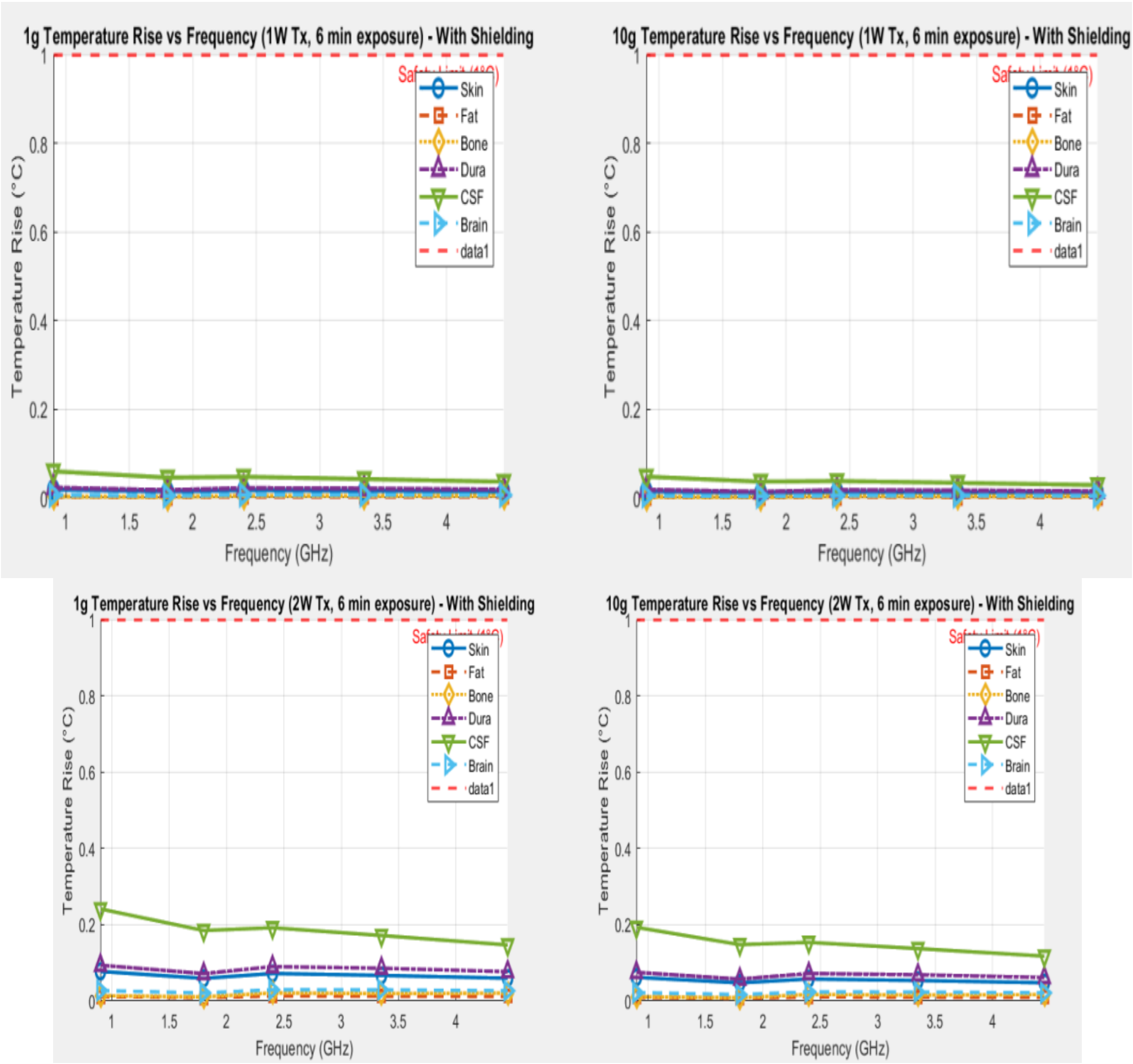


Figure 7 Temperature vs frequency for Head Tissues.

In Fig.7, the normal temperature of the human head $37C^{\circ}$ was fixed, and then the tissue temperature was measured with two different input powers during exposure to a beam for a period of 6 minutes for the 1g and 10g samples. The results show that the rate of increase is relatively higher in the 1g (spinal cord) than in the 10g for an input power of 1 w. As for the case of 2 W input power in the two figures below, we notice an increase in 1g in the spinal cord (above $0.2C^{\circ}$degrees Celsius) compared to 10g. In all cases, the highest temperature with shielding will be $37.2C^{\circ}$, which is a very normal temperature and does not cause any harm.

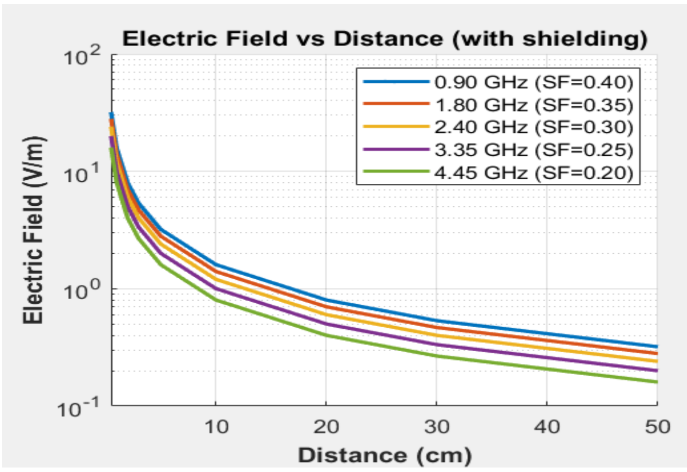


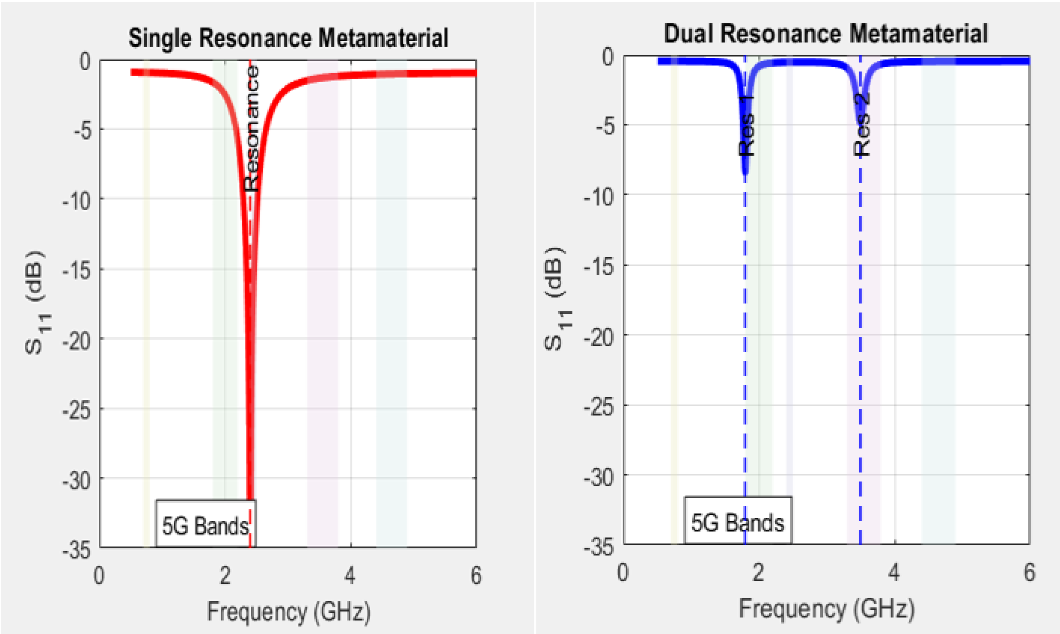
Figure 8 Electric field vs distance for Head Tissues**.**

Fig 8 shows the fundamental field penetration before conversion to SAR. The steeper decay in high-conductivity tissues (CSF, brain) demonstrates higher attenuation coefficients (α).

$$\alpha = \omega\sqrt{\mu\varepsilon/2}\ [\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\,]^{1/2}]$$

Where;
ω: Angle frequency (rad/s).
μ: Permeability (H/m) of the medium.
ε: Permittivity (F/m) of the medium.
σ: Conductivity (S/m) of the medium.

The non-uniform decay rates between tissues create complex interfacial field patterns due to impedance mismatches at boundaries. The near-field behavior (d < λ/2π ≈ 2 cm at 2.4 GHz) dominates, characterized by strong reactive components and non-propagating stored energy rather than radiative transfer. we note the values of the electric field (or power) decrease as frequency increases. A smaller SF means less field penetration (better shielding at higher frequencies in this case, if SF is a reduction factor).



(a) **(b)**

Figure 9 Reflection coefficient (S11) vs Frequencies.

Fig.9 shown S11 parameter which quantifies shield effectiveness and the absorption occurs by measuring reflected power. In (a) the -35 dB dip at 2.4 GHz indicates excellent impedance matching (99.9% power not reflected), suggesting the metamaterial is resonantly tuned for this frequency, but the high reflection (> -0.92 dB) at band edges could cause antenna detuning and reduced communication efficiency. The absorption range shown in (b) between 1.8 GHz to 3.5 GHz.

V. Conclusion

The simulation results confirm that the designed metamaterial chip successfully lowers the Specific Absorption Rate (SAR) within head tissues, with the most notable reduction occurring in tissues with high water content like the cerebrospinal fluid (CSF), brain, and skin. For all frequencies tested, the calculated SAR averages for both 1-gram and 10-gram tissue samples were substantially lower than the 1.6 W/kg safety threshold set by the FCC. The performance of the shielding chip was further validated by its reflection coefficient (S11), which showed a pronounced dip at 2.4 GHz. This indicates strong absorption and very little reflection of energy within the device's operating frequency band. Simulations of thermal effects affirmed that the chip prevents dangerous heating, with the highest temperature increase remaining below 0.2°C under standard use. Additionally, evaluations of electric field strength and penetration depth demonstrated the chip's capacity to weaken near-field radiation, effectively decreasing the amount of energy that reaches and is absorbed by deeper tissue layers.

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