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EMF Exposure Analysis for a Compact Multi-Band 5G Antenna

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Abstract—The fifth generation (5G) wireless communication systems are projected to work at millimeter wave (mm-wave) frequency bands that would bring new challenges with the implementation of antennas and safety level of electromagnetic field exposures. In this paper, a new design of 5G mm-wave antenna for multi-frequency bands has been introduced. The antenna is small enough and has a form factor that can be easily fit into the current available mobile handset devices. The proposed antenna covers all the nominated frequency bands by the FCC for 5G communications and has good radiation performances at 28 GHz, 37 GHz, 39 GHz, and 64–71 GHz. The electromagnetic field exposure to the human head model has been studied by means of numerical simulation for all above frequency bands. The feature of our proposed antenna is that all the frequency bands for the 5th generation mobile handset will be available in a single and simple antenna structure; hence, analysis of EMF exposure in a wide range of frequency can be done on a single antenna design.

1. INTRODUCTION

The fifth generation (5G) of wireless connectivity is coming to meet the requirements of future wireless communications with many promises not yet provided with any previous generations. It is expected to unlock many new futures, such as very high speed, very high data rate and low latency, with so many applications and services [1].

The next generation wireless communication comes with new concepts that will have an effect on antenna design and electromagnetic wave radiation. To bring 5G from concept to reality, there are a number of technical challenges that need to be addressed, such as maximum output power and related electromagnetic filed exposure.

An important and strategic issue is to explore the possibility to move to higher frequency band spectrum and to above those frequency bands used these days for mobile and wireless communication systems (sub-6 GHz band). In July 2016, the Federal Communication Commission (FCC), USA, adopted a new rule for wireless broadband operations in frequencies above 24 GHz. These new rules open up 10.85 GHz of high-frequency spectrum, 3.85 GHz of licensed spectrum and 7 GHz of unlicensed spectrum. The rule generates a new upper microwave flexible use service in the 28 GHz (27.5–28.35 GHz), 37 GHz (37–38.6 GHz), and 39 GHz (38.6–40 GHz) bands, and a new unlicensed band at 64–71 GHz [2]. With this new frequency spectrum, mobile communications shift from microwave frequency band to the millimeter wave (mm-wave) frequency band. The use of mm-wave frequencies will affect current mobile antenna configurations, along with a number of other antenna-associated challenges [3]. However, experimental results at 28 GHz frequency band have shown that the mm-wave band is suitable for the 5G wireless systems [4].

The maximum available output power of handheld and mobile devices has direct impact on link coverage, quality, and system capacity. On the other hand, maximum available output power has direct

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impact on the radio frequency (RF) electromagnetic field (EMF) exposure, absorbed by human body tissues. Hence, for safety reason of human body to the RF radiation, the EMF radiation has to be restricted to certain level.

The limits imposed by international organizations, i.e., International Commission on Non-Ionizing Radiation Protection (ICNIRP) [5], FCC [6], and IEEE [7] for the current generation of mobile and wireless devices are based on Specific Absorption Rate (SAR) with respect to the frequency band of use. SAR shows the amount of the radio frequency energy absorbed in biological tissues and is expressed in W/kg, and the result is the amount of heat generated in the surrounding tissues. However, at frequencies higher than 3–10 GHz restrictions on RF EMF exposure are defined in terms of the incident power density.

There is a relatively extensive body of published literature concerning the biological effects of RF radiation for current cellular systems at sub-6 GHz band. Some of them are [8–15]; however, at higher frequency bands such as frequency bands for 5G, electromagnetic field exposure is still unknown and worthwhile for further investigation. Therefore, one of the aims of this study is to investigate by numerical simulations that electromagnetic field exposure of 5G system in biological tissues, which is in the range limit provided by the international standardization organizations.

This paper describes an antenna design and characterization of electromagnetic exposure to the head model on the allocated frequency bands for 5G by FCC, i.e., 27.5–28.35 GHz, 37–38.6 GHz, 38.6–40 GHz, and 64–71 GHz. The purpose of this article is to study the 5G frequency bands antenna and electromagnetic field exposure associated with it in a single printed antenna.

The structure of this paper is as follows. In Sections 2, 3, and 4, antenna, antenna design, and its performance are discussed, respectively. Section 5 explains the head model and EMF study setup. In Section 6, results and analysis are presented. Finally, conclusion is given in Section 7.

2. ANTENNA

There is no doubt that antenna is one of the key components in a wireless system. Realization of an mm-wave centered wireless network needs enormous works, as the nature of millimeter wave frequency band is different from microwave frequency band. Compared to the current generation of mobile communications (sub-6 GHz frequency band), signal attenuation properties and path loss are higher at mm-wave frequency, and as a result, frequency allocation for 5G makes it very sensitive to the environment. By literature survey, in comparison to antennas for mobile handsets device (2G, 3G, and 4G), antenna technologies for mm-wave 5G mobile handsets remain imperceptible, and little is known about it [16–22]. Considering the importance and impact of antenna in the mobile networks, mm-wave antennas for 5G handsets can be regarded as one of the key enabling technologies to complete the roadmap and moving to 5G mobile networks.

3. ANTENNA DESIGN

Figure 1 shows the configuration and design structure (top view and side view) of the proposed four-band antenna, which consists of radiating element, substrate, ground plane and a port feed. The substrate used in this work is FR4-Epoxy with 0.5 mm thickness, which has the electrical properties of $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$, with 0.018 copper cladding on both sides. The antenna is fed by a 50 Ohm lumped port and has a compact size of $15.5 \times 14.5 \times 0.536\,\mathrm{mm}^3$, therefore can be used as an internal antenna for a mobile handset device.

Multiple resonance mode will be required for the proposed antenna, in order to have 5G four-band operations. The planar monopole antenna has a capability to provide a wide impedance bandwidth with respect to the shape and surface area. Moreover, printed monopole antennas have a simple design and easy integration with the RF circuit. Therefore, a monopole antenna is used for this study.

4. ANTENNA PERFORMANCE

Numerical analysis and optimization of the antenna have been performed using ANSYS HFSS (High Frequency Structure Simulator) software [23]. Fig. 2 shows the simulated antenna S_{11} function of

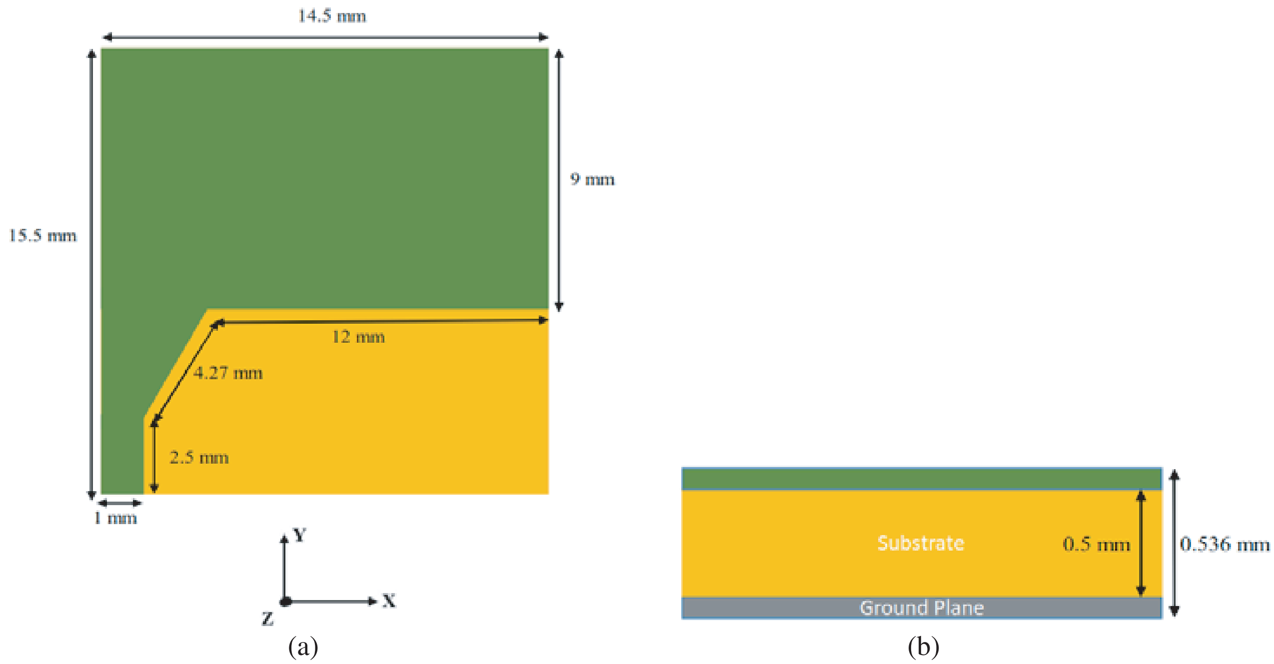


Figure 1. The antenna design configuration, (a) top view, (b) side view.

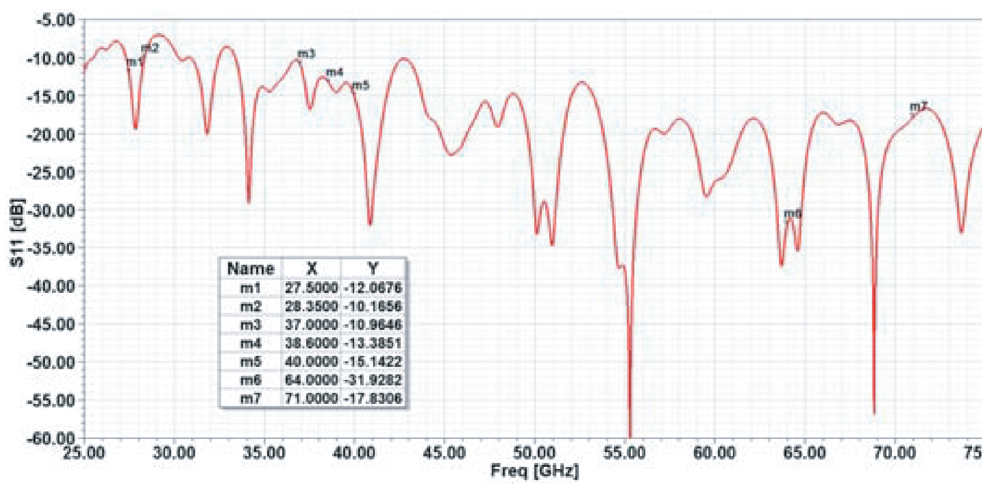


Figure 2. The antenna return loss in free space.

frequency. The 10 dB impedance bandwidth of the proposed antenna is 0.85 GHz from 27.5 GHz to 28.35 GHz, 1.6 GHz from 37 GHz to 38.6 GHz, 1.4 GHz from 38.6 GHz to 40 GHz, and 7 GHz from 64 GHz to 71 GHz, with total bandwidth of 10.85 GHz for the 5G applications.

From the S-parameters, Fig. 2, we can find that the voltage standing wave ratio (VSWR) is less than 2 : 1. It means that the antenna input impedance is well matched to the reference impedance. The simulated far-field radiation patterns of the antenna at 28 GHz, 38 GHz, 40 GHz, and 67 GHz are plotted and compared in Fig. 3. The antenna radiation patterns are presented in two different planes for $\varphi = 0°$ and $\varphi = 90°$.

The values of antenna parameters for the selected frequencies are shown in Table 1. It provides comparisons of antenna parameter at each frequency, while input power remains same for all the selected frequencies. Table 1 shows that among four selected frequencies, maximum gain of 2.46 dBi is available at 38 GHz with directivity of 9 dBi.

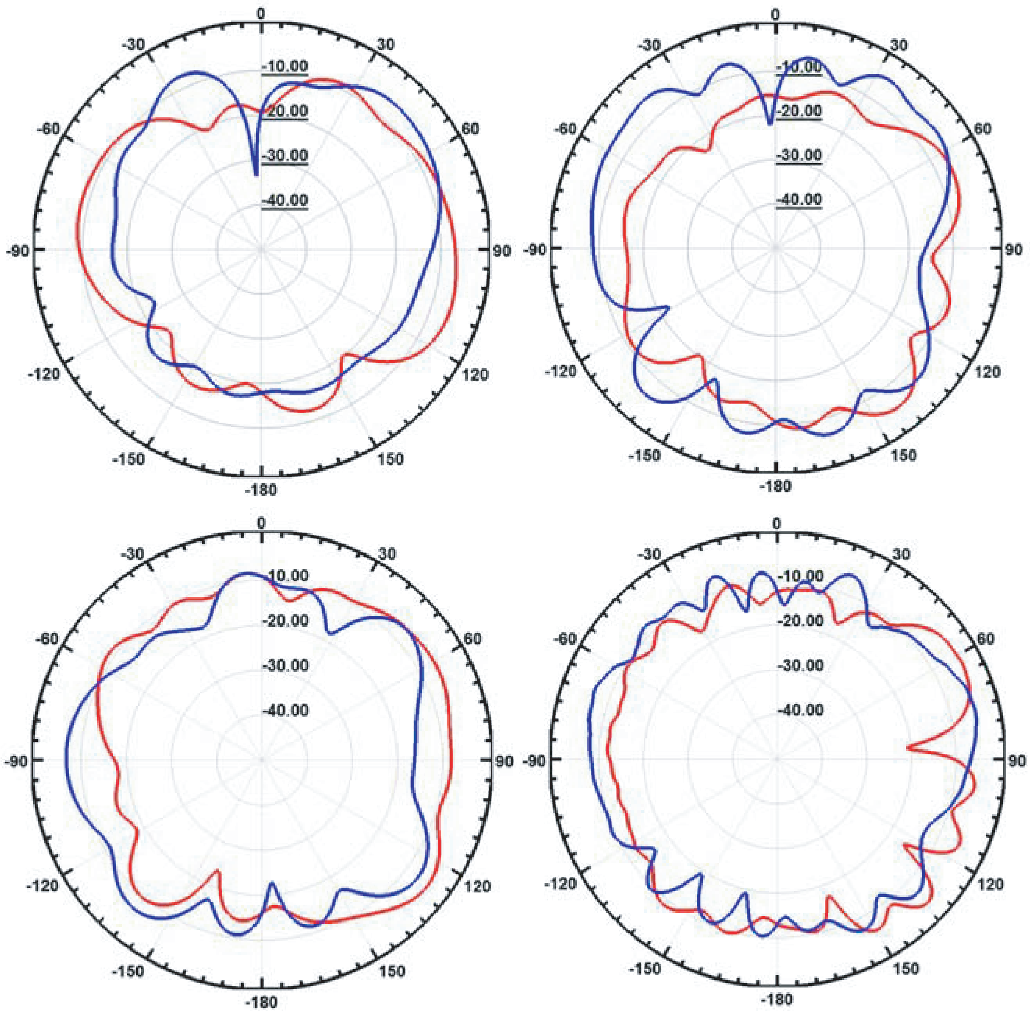


Figure 3. Radiation patterns at $\varphi = 0°$ and $\varphi = 90°$ at 28 GHz, 38 GHz, 40 GHz, and 67 GHz.

Table 1. Antenna parameters at 28 GHz, 38 GHz, 40 GHz, and 67 GHz.

	28 GHz	38 GHz	40 GHz	67 GHz
Input Voltage (V)	1	1	1	1
Radiated Power (mW)	1.42	2.07	2.36	2.59
Gain (dBi)	−2.33	2.46	1.69	2.17
Radiation Intensity (mW/sr)	0.45	1.32	1.14	1.32
Directivity (dBi)	6.04	9.02	7.82	7.78

5. ANTENNA AND HEAD MODELLING

Devices emitting RF EMF need to comply with relevant regulatory requirements and limits on human exposure to EMF [5–7]. The worldwide adopted RF exposure limit guidelines by governments are from [5] and [6]. In EU and most countries worldwide the ICNIRP limits have been adopted. In the US, the limits are provided by the FCC. These guidelines are represented by the specific absorption rate (SAR) for the frequencies used by 2nd, 3rd, and 4th generation mobile communications, and can be used to minimize local tissue heating and related thermal hazards for sub-6 GHz band mobile devices [5–7].

There are dosimetric quantities to assess EMF exposure: SAR and plane-wave equivalent power density. The exposure limits change from SAR to power density, at frequencies above 3 GHz (IEEE), 6 GHz (FCC), and 10 GHz (ICNIRP), as shown in the Table 2.

Table 2. General public (uncontrolled) basic restriction on power density. (Av: Averaging Area).

	ICNIRP	FCC	IEEE	
f (GHz)	10–300	6–100	3–30	30–100
S (W/m^2)	10 (Av: 20 cm^2) 200 (Av: 1 cm^2)	10 (Av: 1 cm^2)	10 (Av: 100 λ^2)	10 (Av: 100 cm^2)

The effects of the EMF exposure and limits above 6 GHz and up to 70 GHz, based on the maximum possible radiated power from a device are discussed in [24]. This paper provides relevant input and adds value to the 5G mobile networks, which is based on power density quantity.

To investigate the effect of mm-wave 5G antenna handheld devices, a human head model is used as shown in Fig. 4. The investigation of the human head tissues has been carried out using material parameters from [25]. To evaluate the effect of human head tissue on antenna characteristic and effect of RF EMF distribution in the human head at 5G frequency bands, the designed antenna is placed close to the ear at a distance of 10 mm. At mm-wave frequency bands, the absorption of electromagnetic fields is concentrated at the surface or near-surface of skin tissue layers, i.e., epidermis, the outermost layer, dermis, the middle layer, and subcutaneous tissue, the deepest and innermost layer of the three layers of skin.

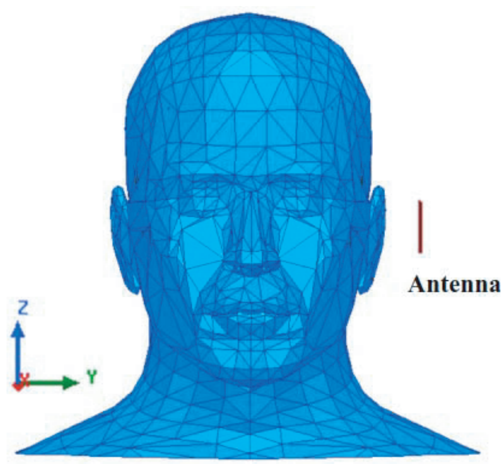


Figure 4. Head model setup.

To verify antenna performance close proximity to head tissue, antenna S-parameters are studied, as shown in Fig. 5. It confirms that 10 dB impedance bandwidth of antenna at close proximity to the head tissue was met for all the 5G frequency bands.

The maximum radiated power ($P_{\max}$) to be accommodated with the EMF exposure limits in Table 2 has been determined in the frequency range of 5G from 25 GHz to 75 GHz. All simulations on head tissues were conducted by the antenna presented in Section 2 for input voltage of 1 V to the port of antenna. Numerical simulations were conducted using ANSYS-HFSS, based on Finite Element Method (FEM), with frequency dependent head tissue model.

6. RESULTS AND ANALYSIS

The S-parameter and radiation patterns of the antenna are studied by numerical simulation. The results are presented in Fig. 2 and Fig. 3. The return loss (Fig. 2) is less than -10 dB within the operational

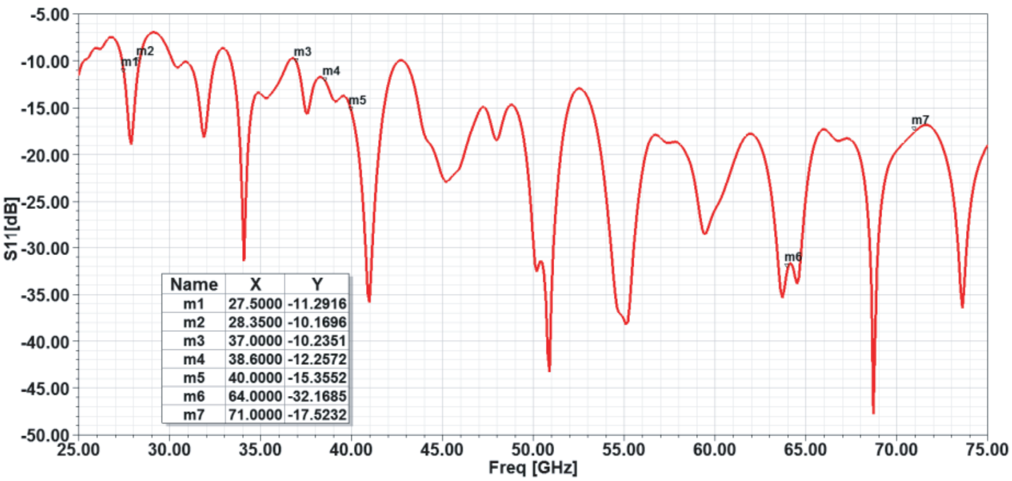


Figure 5. Antenna return loss at distance of 10 mm from head.

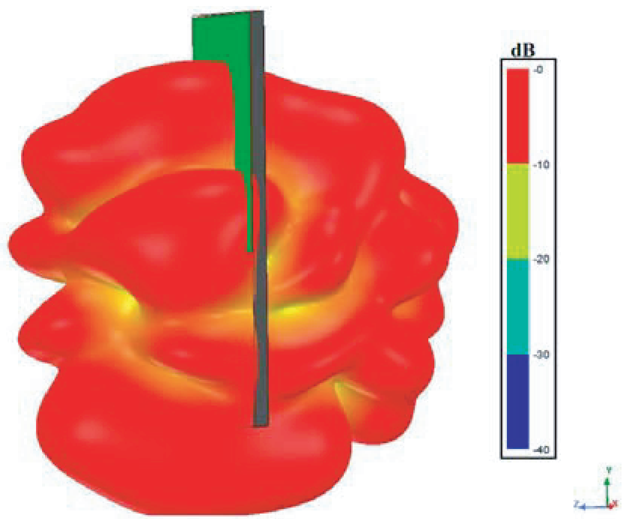


Figure 6. 3-D total radiation far-field pattern at 38 GHz.

frequency range 27.5 GHz to 71 GHz. It should be noted that the radiation patterns (Fig. 3) are similar for all the frequencies, knowing that the antenna covers very wide bandwidth. The return loss of antenna close to the head tissue with distance of 10 mm is presented in Fig. 5. It is confirmed that there is no frequency shift on the antenna characteristics due to the effect of head tissue electrical properties. Fig. 6 shows the antenna's 3-D total radiation pattern at 38 GHz.

The maximum radiated power ($P_{\max}$) with respect to the input voltage of 1 V is plotted in Fig. 7. At frequency bands of 5G, the antenna size is smaller than current generation handset devices. Moreover, higher frequency indicates more superficial exposure, which will result in less energy absorption in averaging area of 1 cm^2 or 20 cm^2 as required by Table 1. The maximum radiated power on tissue dependent on the distance from antenna and for this study antenna is placed in the close proximity of 10 mm from the head tissue.

The power density to be compliant with EMF exposure limits in Table 2 with gap of 1 cm from head model, which could be a realistic distance from handheld device to the head tissue, is presented in Table 3. The calculated maximum power density is based on the peak value of electric field intensity, Fig. 8, on the surface of tissue.

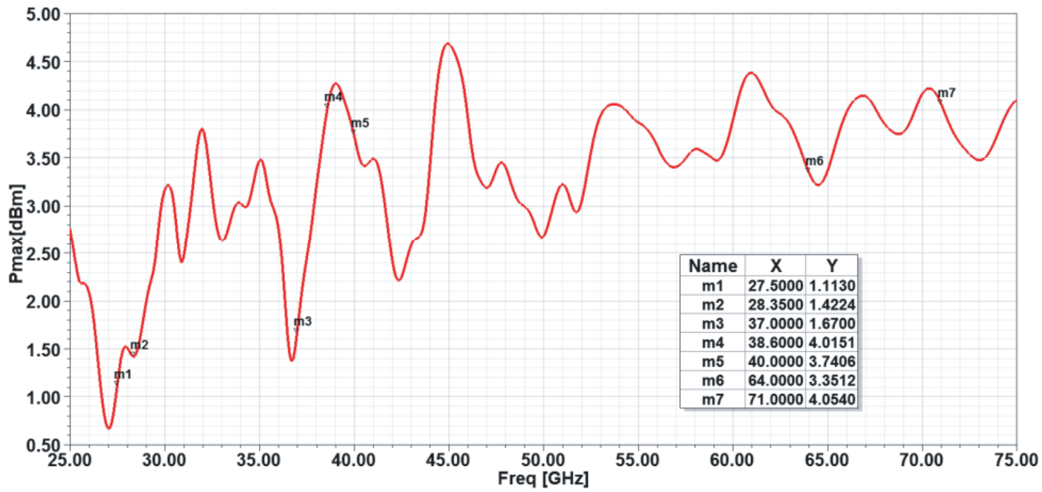
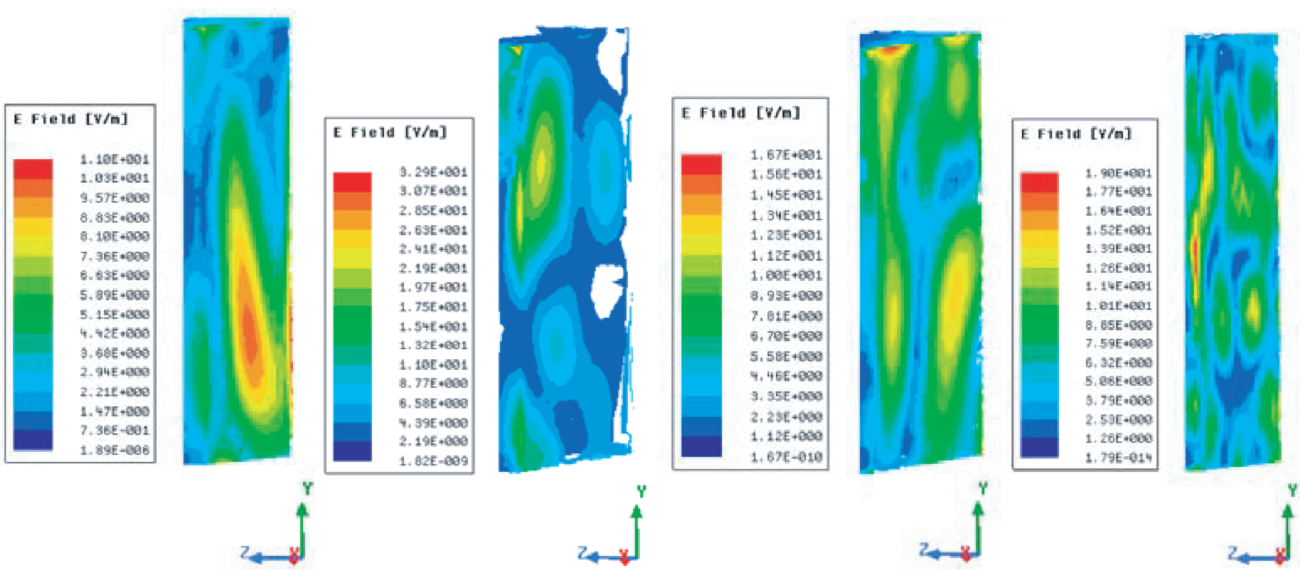


Figure 7. Maximum output power of the antenna.



(a) (b) (c) (d)

Figure 8. Electric field intensity on the surface of tissue at (a) 28 GHz, (b) 38 GHz, (c) 40 GHz, and (d) 67 GHz.

Table 3. Maximum Power density on the surface of head tissue.

	28 GHz	38 GHz	40 GHz	67 GHz
Power Density (W/m^2)	1.239	3.761	1.853	1.125

7. CONCLUSIONS

For devices such as handheld devices that intended to be used in the close proximity of human body, antenna characteristics and electromagnetic exposure are one of the main concerns.

An antenna design to cover the 5G frequency bands for a handheld device with realistic form factor to fit in the handset device is presented in this paper. It is shown that this design can cover four frequency bands of 5G, i.e., 27.5–28.35 GHz, 37–38.6 GHz, 38.6–40 GHz, and 64–71 GHz with a −10 dB reflection coefficient. The antenna scattering parameters were studied for the antenna design in free space and with head model, showing no significant detuning.

Finally, the RF EMF was studied with respect to the maximum electric field intensity at distance of 1 cm from head model. For a short distance, with antenna transmitting directly toward the head tissue, it is found that the maximum power density is much below the level of allowed limit, hence, that could allow for more output power. The obtained results in this work might provide valuable input to the design of the 5th generation mobile communication.

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