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REGULAR ARTICLE

Multi-Circled Planar MIMO Antenna on Flexible Substrate for 5G Applications

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In this article a planar microstrip multi-circle shaped antenna on flexible substrate (Kapton) has been designed and validated. The antenna is low profile with only 125 μm in hight. The antenna covers all 5G mid-bands from 3.17-6.42 GHz while exhibiting almost VSWR = 1 at 3.6 GHz. For biomedical application, the antenna has been realized on the human bio tissue fantom model. The estimated specific absorption rate (SAR) is within the standards with the highest value of 1.31 W/Kg at 6 GHz. Furthermore, to check the mobile application compatibility, 4 (4 × 4) and 6 (6 × 6)-element MIMO arrays are designed and validated. Both MIMO results show port to port (P2P) isolation of below – 18.7 dB. The efficiency is always above 90 % throughout the entire bandwidth (BW). Other MIMO parameters i.e., ECC and DG are always below 0.002 and almost 10, respectively. The far-field radiation results show that the array can radiate in all directions. In addition, the 6 × 6 is exposed with the hand and the head voxel phantom model to estimate the SAR. In each cases, the SAR values are well within the standard range.

Keywords: Planar microstrip, Low profile, 5G mid-band, MIMO, SAR.

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1. INTRODUCTION

The fifth generation (5G) wireless technology is revolutionizing the realm of communication on earth. With the prominent features such as high data rate, high throughput and a very low latency (1 ms), this evolution is transforming the transportation, mobile communication, healthcare and other applications into another paradigm[1], [2]. There are different frequency allocations for the 5G communication: sub-1 GHz (700 MHz), sub-6 GHz (3-6 GHz) and mmWave (24-90 GHz)[3-4]. Among these frequency bands, the sub-6 GHz bands are called the mid-band 5G. Implementation of the multiple input-multiple output (MIMO) antenna array is one of the key devices that is catering way forward for the 5G and beyond. However, it is still challenging for the antenna designers to produce a highly efficient, and low-profile array keeping the MIMO performance intact.

One of the earliest work on realizing the MIMO antennas on flexible substrate has been proposed in [5]. The authors realized that antenna on the Kapton substrate which works in the ultra-wide band (UWB). It's a low-profile 2-element MIMO antenna that has a small dimension of 22 × 22 × 0.125 mm^3. The authors utilized the *L*-patch and slots to improve the BW and the isolation. Despite the wideband capability, the MIMO suffers from a low minimum efficiency of 31.6 % only. Even though the isolation (– 15 dB) and the ECC (0.3) value is within the FCC standard (– 15 dB and 0.5 respectively)[6-7], they are at the higher side. Furthermore, while it is necessary to have a higher number of elements to achieve higher data speed the MIMO has only 2 elements which falls short in this proposed design [7]. Another, trident shaped dual band 2-elment MIMO antenna array is proposed for mid band 5G communications [8]. The proposed design uses the defected ground structure (DGS) and parasitic strip in between antennas to improve the resonance and isolation of the MIMO. The array exhibits a good isolation of – 25 dB in lower band of 3.5 GHz with a good efficiency in both band reaching up to 86 %. The ECC is remarkably low < 0.002 and DG is ≈ 10 in both bands. However, the dimension is large with 62 × 25.6 × 1.524 mm^3 for 2-element array. The isolation of the second band (4.53-4.92 GHz) is low with only – 16 dB. One more point, the antenna fabricated on RO3003 substrate which is although a bendable substrate but cannot perform well for higher angle of bending conditions.

One more proposal has been made in [9] with a 2 × 2 array on flexible polyimide substrate. The array is designed for vehicle to everything (V2X) application in 5G mid band frequencies. The single element antenna (SEA) of the proposed design utilizes the *L*-shape feed line with modified ground structure (MGS) to improve the isolation between the ports. The antenna exhibits a circular polarization within a wide-band range between 2.96-6.02 GHz with a low ECC of < 0.02. Aso, the efficiency is high < 94 %. However, the maximum mutual coupling between ports is a as high as – 16.2 dB which could be improved.

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A four port (4 × 4) MIMO antenna array is proposed in [10] which is suitable for the smartphone applications in 5G midbands. In this proposal the authors used simple planar loop shaped radiators to tune the SEA to work within 3-4.28 GHz. The array achieved a high efficiency around 90 % and also has a good radiation coverage. Yet, the important parameter Port to port isolation is suffer dropping down to – 10 dB which is lower than the FCC standard. Furthermore, the array is not realized on the flexible substrate. Another four element array is presented by Mahmoud et al. [11] for 5G band smartphones. The in band ECC results are remarkable < 0.01. The DG is always above 9.95 and the minimum antenna efficiency is around 84 %. However, the array achieved a moderate – 10 dB BW of only around 880 MHz which is low and does not cover all the mid band 5G frequencies. Also, the antenna is fabricated on RO3003 substrate which does not perform well in higher bending condition and the MIMO is not suitable for smartphone/biomedical applications as the authors have not made any SAR analysis.

Similarly in [12], a wearable MIMO is presented which is designed to locate the early stage tumor in the breast. However, the authors have not focused on assessing the MIMO performance. The parameter such as isolation, ECC, DG and others have not been presented. In [13] the authors have proposed another 4 × 4 MIMO in 5G frequencies for wearable applications. The antenna achieved a good isolation of over – 20 dB, throughout the three BWs. Also, the MIMO parameters such as ECC, DG, TARC are well within the standard. However, the efficiency is moderate around 80 %. Again, the antenna is on the RO3003 substrate which does not perform well in large bending scenarios.

Recently, one more flexible 4 × 4 MIMO array is presented in [14]. The array is realized on the polyimide substrate. The achieved BW is remarkable of 122.5 % of the center frequency. The antenna efficiency is > 93 % along with the ECC and DG of 0.002 and 9.99, respectively. However, the isolation is little bit on the lower side with mere – 17 dB value. It is also seen that despite the large BW, the array does cover the 3.5 GHz 5G band which means the design cannot be used for smartphone applications for all mid-band 5G. In table.1, a short summary is enclosed for better realization of the proposed work with the recently published works.

Table 1 – Comparison between recent works

ref	BW GHz	Ele.	Iso. dB	Effi. %	App.	Flex.
[5]	9.1	2	15	31.6	5G	yes
[8]	0.62/0.39	2	16	86	5G	yes
[9]	3.12	2	16.2	94	5G	yes
[10]	1.28	4	10	90	mobile	no
[11]	0.88	4	20	84	5G	yes
[12]	~10	4	na	91.3	bio	no
[13]	1.02/0.69/ 3.48	4	20	80	5G	yes
[14]	~12	4	17	93	UWB	yes
This work	**3.26**	**6**	**18.7**	**95**	**mobile**	**yes**

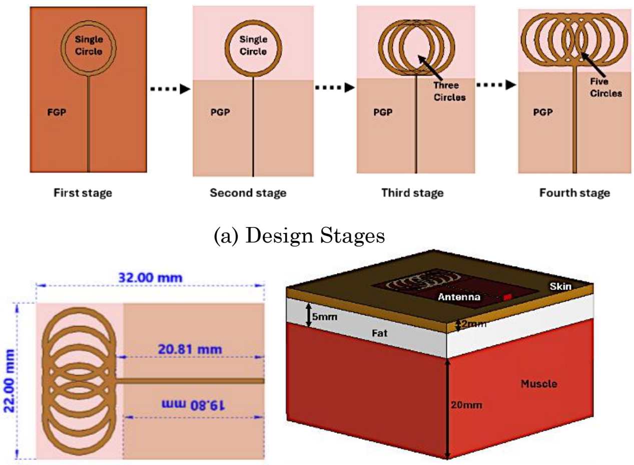
(Ele. = Elements, Iso. = isolation, Effi. = efficiency, App. = application and Flex. = flexible.)

To deal with the aforementioned issues, this work proposes a small in size and low profile planar multi-circled 6 × 6 MIMO antenna array on flexible (Kapton) substrate which have covered all the mid-band 5G frequency bands with – 10 dB BW from 3.17-6.43 GHz (3.26 GHz). The antenna efficiency is always above 95 %, minimum isolation of ~ 19 dB. The ECC is below 0.002 and the DG is almost 10. The SAR results also show that the SEA and the MIMO array are suitable for bio-medical and smartphone in 5G frequencies.

2. ANTENNA AND ARRAY DESIGN

Fig. 1 shows the design stages of the proposed SEA. It is seen that the stage one consists of one circular patch attached to a 50 Ω microstrip feed transmission line (TL) of to it with a full ground plane (FGP). The circle has a radius of 5.2 mm, and the TL length is 20.8 mm. At the second stage, the FGP is truncated to form a partial ground plane (PGP) leaving no ground plane at the bottom of the radiating circular patch. This technique is well known to make the patch antennas wide band. At the third stage, two more circles are added with the original single circle (three circle patch) to see the improvement in terms of the BW and gain. Finally, at the final stage, two more same circular shapes are added on the three-circle patch to make it a multi-circular patch antenna. All the circular patches are same in radius and the width of the line is 0.8 mm. Fig. 1b discloses the final optimized structure of the antenna with an overall dimension of 32 × 22 × 0.125 mm^3. The radius of the circular patch has been estimated and later optimized using equation (1)-(2) with an initial center frequency (*fc*) 4.5 GHz [15]. Later, the antenna is attached with a three-layer (skin, fat and muscle) bio-tissue phantom model in CST MWS. Fig. 1c illustrates the structure and the dimensions. Table 2 discloses the material properties of this model at initial center frequency where ε_r = dielectric constant, σ = conductivity, ρ = material density, k = thermal conductivity, C = heat capacity [16].

Fig. 2a and Fig. 2b comprises the layouts of the 4 × 4 and the 6 × 6 MIMO arrays respectively for the mobile/smartphones in 5G frequencies.



(a) Design Stages

(b) Final layout (c) bio-tissue phantom

Fig. 1 – The (a) stages of the proposed single antenna and the (b) final optimized structure of the antenna

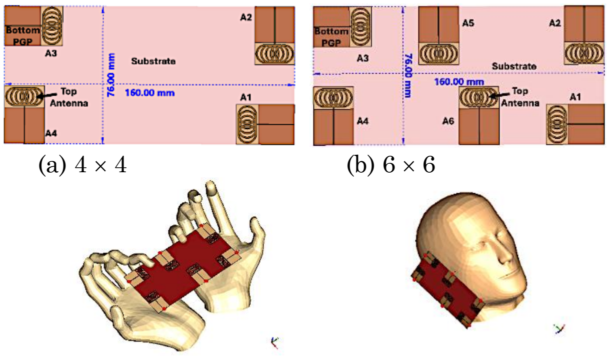
$$r = \frac{F}{\left\{1 + \frac{2h}{\pi \varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \quad (1)$$

$$F = \frac{8.791 \times 10^9}{f_c\sqrt{\varepsilon_r}} \quad (2)$$

Table 2 – Material properties of skin, fat and muscle

	ε_r	σ	ρ	k	C
		S/m	Kg/m^3	W/mK	J/gK
Skin	34.9	0.856	1100	0.3	3.5
Fat	9.8	0.051	900	0.2	2.5
Mus-cle	48.2	0.943	1080	0.5	3.5

For both cases, the array is modelled on a the Kapton substrate with a dimension for 160 × 76 mm^2 that resembles the 6.67-inch display smartphones. Also, for the arrangement of the elements of both MIMOs, 900 polarization diversity technique is adopted. All antennas are denoted as A1-A4 for 4-element and A1-A6 for 6-element MIMO. In case of the 6 × 6 array, the A5 and A6 are kept at the opposite side of the board. The distance between A1-A6 and A2-A5 is the same as 80 mm. Later, the 6 × 6 array has been validated with the hand and the head phantom separately to check the SAR performance. The setup with hand and head is illustrated in Fig. 2c and Fig. 2d, respectively. All the results are presented, analyzed and discussed in detail in the next section.



(a) 4 × 4 (b) 6 × 6

(c) MIMO with hand (d) MIMO with head

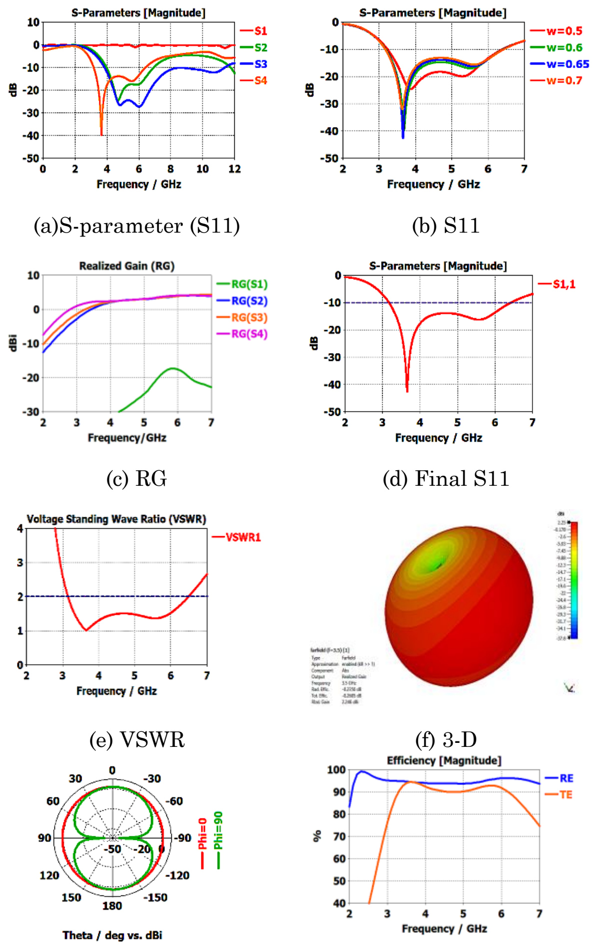
Fig. 2 – The MIMO layouts and the setups for the SAR calculation

3. RESULTS AND DISCUSSIONS

3.1 Single Antenna Results

Fig. 3a comprises the s-parameter (S_{11}) results for stages of the proposed SEA. The simulation is performed from DC-12 GHz in the beginning. At the first stage (S1) it is seen that there are no visible – 10 dB portions on the spectrum and almost all signal is reflected back to the source. At the second stage (S2), a clearly visible drop in the amplitude on the frequency vs S_{11} plot. It is realized that due to the modification of FGP to PGP, the antenna is exhibiting a wider – 10 dB BW from 4 GHz to 6.5 GHz. However, as the target BW should include all the mid-band 5G frequencies it still does not cover the 3.5 GHz band. At the third stage (S3), the BW is made wider as it starts from 4 GHz and reaches beyond 11 GHz. However, the 3.5 GH band is still not in the working BW and also, beyond 6.5 GHz is not in the scope of this design. The fourth stage solves this issue by adding two more circular patches and rearranging them. The S11 results show that the – 10 dB BW starts from 3.17 GHz and reaches 6.43 GHz. However, a small parametric study also did the final step on the microstrip feed width (w) of the SEA. Fig. 3b comprises the results. It can be seen that the best resonance can be obtained at w = 6.5 mm. Continuing with effect of design stages Fig. 3c reveals the realized gain enhancement of this proposed design. It is observed that the at first stage the gain in bad mostly staying below – 20 dB in the BW. However, as the stage progresses, the gain improves and at the last stage it is seen the gain becomes +(ve) at 3 GHz. Also, it stays positive throughout the BW and reaches 4.1 dBi at 6 GHz. So, it can be said that the gain is significantly improved by this proposed method. From Fig. 3d and 3e it is also confirmed the antenna in working around 3.26 GHz which is 68 % of the center frequency of 4.8 GHz and can be considered as an ultra-wide band antenna. Fig. 3f and Fig. 3g represent the 3-D and the 2-D far-field radiation patterns of the SEA.

It is seen that the intensity of the radiation is the highest on the z-x plane which can be considered as an omni-directional pattern and Fig. 3g confirms this as it is seen that the E-plane ($\varphi = 0$) is full circular,



(a)S-parameter (S11) (b) S11

(c) RG (d) Final S11

(e) VSWR (f) 3-D

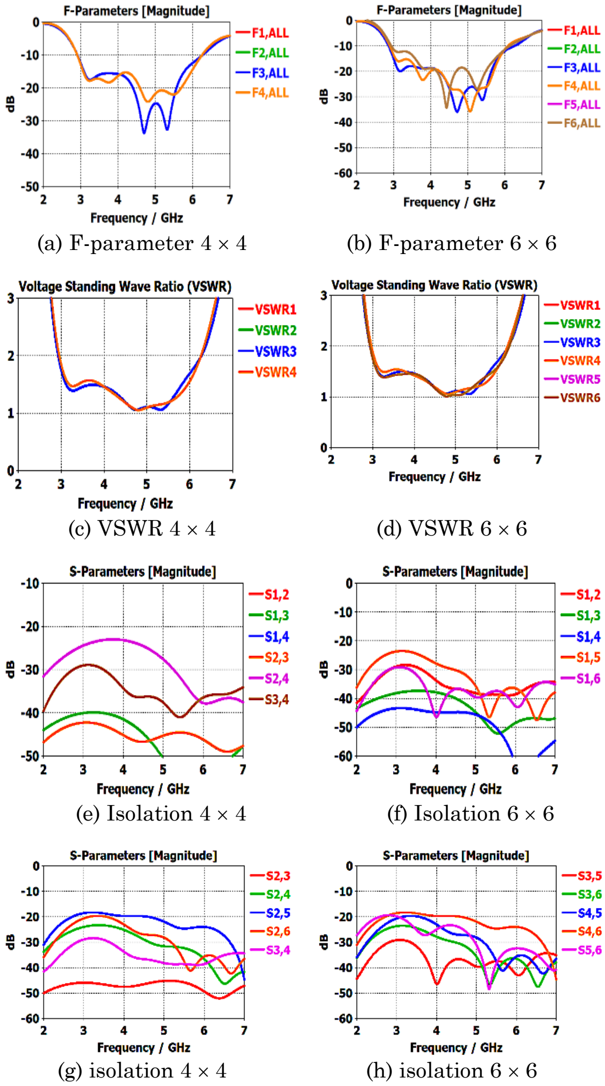
(g) 2-D (h) Efficiencies

Fig. 3 – The antenna design performance parameters of the SEA

and the *H*-plane ($\varphi = 90$) is a half-cut apple shape with two nulls exactly opposite to each other at 90° and – 90° from boresight. Lastly, from Fig. 3h it is seen that the radiation efficiency (RE) is always above 95 % and also the total antenna efficiency (TE) is mostly above 90 % throughout the BW. All of these antenna parameters' results show that the proposed antenna has good performance within the targeted operating BW. The following section reveals the results of the 4 × 4 and 6 × 6 arrays.

3.2 MIMO Design Results

Fig. 4 comprises the combined reflection parameters (F-parameter), VSWRs and the isolation characteristic of the 4 × 4 and 6 × 6 MIMO arrays. The F-parameter represents the S_{11} of the ports while in presence of other antennas. From Fig. 4a and Fig. 4b for 4 × 4 and 6 × 6 MIMO respectively, it can be seen that for both cases the targeted 3-6 GHz band is preserved as the value staying below – 10 dB throughout that range. Similarly, from Fig. 4c and Fig. 4d, it is seen that the VSWR values for 4 × 4 and 6 × 6 MIMO, respectively, of different ports are also staying below 2 throughout the BW.



(a) F-parameter 4 × 4 (b) F-parameter 6 × 6

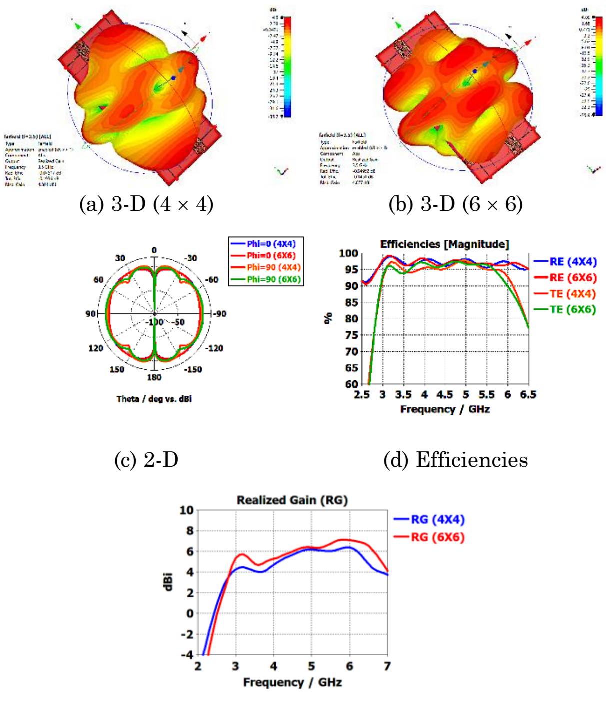
(c) VSWR 4 × 4 (d) VSWR 6 × 6

(e) Isolation 4 × 4 (f) Isolation 6 × 6

(g) isolation 4 × 4 (h) isolation 6 × 6

Fig. 4 – The F-parameter, VSWR and the Isolation characteristic of the 4 × 4 and 6 × 6 MIMO arrays

This confirms that both of the proposed MIMO arrays are working well within 3-6 GHz band. Fig. 4e-4h represent the port to port (P2P) isolation for both MIMO designs. In the case of 4 × 4 (Fig. 4e) it is seen that the lowest is – 23 dB between port 2 & 4. Fig. 4f illustrates the same scenario for 6 × 6 where it reveals the P2P isolation of port 1 with other five ports. It is observed that the lowest isolation is – 23.5 dB at 3.15 GHz between port 1 & 5. From Fig. 4g and Fig. 4h, it is seen that the isolation become a fraction low also between port 2 & 5 and port 4 & 6 with a value of – 18.3 dB at 3.2 GHz for both of the cases. As the minimum isolation standard set by FCC for P2P isolation is < – 15 dB it can be concluded that the all the P2P isolation is well within the standard. Next, Fig. 5 reveals some more performance parameters for both MIMO designs. Fig 5a and Fig. 5b the 3-D combined far-field radiation pattern for 4 × 4 and 6 × 6 MIMO respectively.



(a) 3-D (4 × 4) (b) 3-D (6 × 6)

(c) 2-D (d) Efficiencies

(e) Realized Gain (RG)

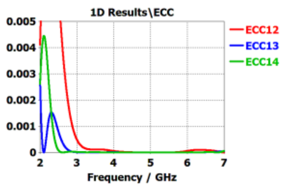
Fig. 5 – Far-field Radiation, efficiencies and the RG comparison between 4 × 4 and 6 × 6 MIMO

Despites some nulls in the radiation, it can be observed that the radiation has an all-directional characteristic. This scenario can be confirmed by looking in Fig. 5c where the 2-D *E*- ($\varphi = 0$) and the *H*-plane ($\varphi = 90$) radiation pattern is illustrated. It is clearly visible that the arrays can radiate/receive the electromagnetic signals from all direction which is necessary for the mobile phone application in any frequency. Fig. 5(d) comprises the RE and TE for both proposed MIMOs. It is seen that in terms of the RE both designs act almost similar by staying around 95 %-98 % inside the BW. However, while observing the TE responses, it is seen that the 6 × 6 MIMO outperforms the 6 × 6 MIMO in some points on the spectrum. While the highest value for 6 × 6 MIMO reaches around 97 %, the 4 × 4 MIMO stays below 95 % in certain frequency ranges. A similar situation can be observed about the combine RG results shown in Fig. 5e. It is realized that the RG of 6 × 6 MIMO is around 1 dB more throughout the entire BW. It means the increase in the element number can improve the efficiency and the gain of the array. Fig. 6 reveals the other two important parameters named ECC (ρ_e) and associated DG of the proposed MIMO. The standard permits the ECC to be as low as possible and the DG should be as close as to 10 [17]. These parameters are calculated by using (3) and (4) where $a = 1$ & $b = 2, 3, 4, 5, 6$.

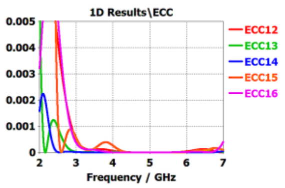
$$\frac{|S_{aa}S_{ab}^{*} + S_{ba}S_{bb}^{*}|}{(1 - |S_{aa}|^2 - |S_{ba}|^2)(1 - |S_{bb}|^2 - |S_{ab}|^2)} \quad (1)$$

$$DG = \sqrt{1 - |\rho_e|^2} \quad (2)$$

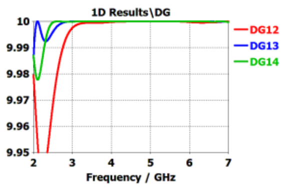
Fig. 6a and Fig. 6b illustrate the ECC for 4 × 4 and 6 × 6 MIMO respectively. From both results it can be seen that the values are always below 0.001 from 3-6 GHz and also, they stay below that beyond 6 GHz which is remarkable for MIMO arrays. Similarly, Fig. 6c & Fig. 6d reveal the associated DG results. As expected, it is seen that the values are above 9.99 and mostly 10 throughout the entire BW and this confirms the quality performance of the proposed design. Next section reveals a detailed SAR analysis to affirm the compatibility of this design for bio-medical and mobile phones.



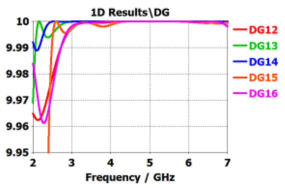
(a) 4 × 4



(b) 6 × 6



(c) 4 × 4



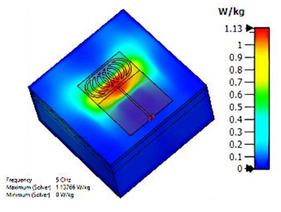
(d) 6 × 6

Fig. 6 – ECC and DG responses for 4 × 4 and 6 × 6 MIMO

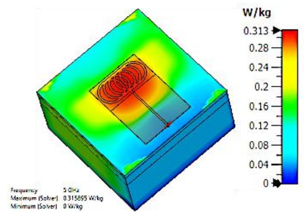
3.3 SAR Results

Fig. 7 reveals the SAR calculations of the SEA (Fig. 7a & Fig. 7b) and the MIMO (Fig. 7c-7f). The reference power and the averaging method is chosen as 50 mW (+ 17 dBm) and IEEE C95.3 for the calculation. It is seen from Fig. 7a and Fig. 7b that the SAR is 1.13 W/Kg and 0.313 W/Kg for 1 g and 10 g tissue respectively. As we know the FCC standard for 1 g and 10 g tissue are 1.6 W/Kg and 2.0 W/Kg respectively [2], the values are well within the range and suitable for bio-medical applications. Moving onto the MIMO, the 6 × 6 array is chosen for its superior results in terms of the efficiencies and the realized gain. Fig. 7c and Fig. 7d comprise the port 1 and port 2 SAR results respectively for hand phantom model. The results for port 1 and port 2 are presented as the other ports nominally resemble the results. At port 1 it can be seen that the SAR value is 0.461 W/Kg. Similarly, at port 2 it is seen that the SAR is lower with a value of 0.293 W/Kg. So, it can be concluded that for hand, the SAR results are remarkably low which is suitable for smartphones.

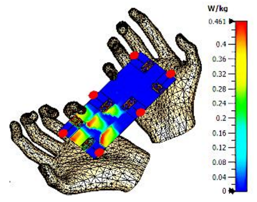
Fig. 7e and Fig. 7f continue to show the port 1 and port 2 SAR values for the head phantom. It is observed that the MIMO exhibits lower SAR values with the proximity to a head model. The port 1 and 2 SAR values are 0.106 W/Kg and 0.172 W/Kg respectively. These very low SAR values confirm that the proposed design is suitable for the smartphone applications. However, all these results are taken at 5 GHz which is close to the center frequency. Finally, the detailed SAR values at different frequencies are presented in Table 3. Where, it can be seen that the SEA SAR values are between 0.84-1.31 W/Kg and for the MIMO it's between 0.16-0.97 W/Kg in different frequencies which are all within the SAR standard.



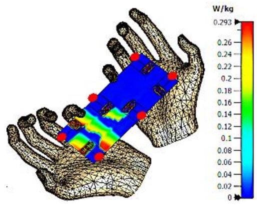
(a) Bio-tissue (1 g)



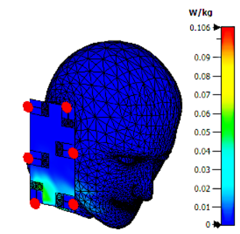
(b) Bio-tissue (10 g)



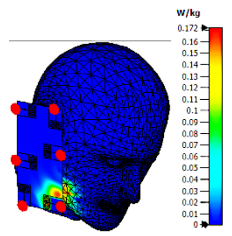
(c) Hand port 1



(d) Hand port 2



(e) Head port 1



(f) Head port 2

Fig. 7 – The SAR responses on different phantoms with SEA and MIMO

Table 3 – SAR values for different phantom with SEA and MIMO

Freq (GHz)	SAR(SEA) (W/Kg)		SAR (6 × 6 MIMO) (W/Kg)			
	Bio-tissue Model		Hand Model		Head Model	
	10g	1g	10g	1g	10g	1g
3	0.273	0.839	NA	0.22	0.32	0.67
4	0.313	1.13	NA	0.16	0.34	0.92
5	0.295	1.1	NA	0.29	0.17	0.97
6	0.35	1.31	NA	0.26	0.66	0.187

4. CONCLUSION

Here, a SEA and MIMO array is designed and realized on flexible substrate (Kapton) with only 125 µm in hight. The antenna covers all 5G mid-bands from 3.17-6.42 For biomedical application, the antenna has been assessed on the human bio tissue fantom model. The SAR is within the standards with the highest value of 1.31W/Kg at 6 GHz. Furthermore, to check the mobile application compatibility, 4 × 4 and 6 × 6 MIMO arrays are validated. Both MIMO results show port to port (P2P) isolation of below – 18.7 dB. The efficiency is always above 95 % throughout the entire BW. Other MIMO parameters i.e., ECC and DG are always below 0.002 and almost 10, respectively. The 6 × 6 is exposed with the hand and the head voxel phantom model to estimate the SAR. In each cases the SAR values are well within the standard range.

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Плоска MIMO-антена з кількома овалами на гнучкій підкладці для 5G застосунків

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Розроблено та перевірено планарну мікросмужкову антену на гнучкій підкладці (Kapton). Антена має низький профіль і має висоту лише 125 мкм. Антена охоплює всі середні діапазони 5G від 3,17 до 6,42 ГГц, демонструючи майже VSWR = 1 на 3,6 ГГц. Для біомедичного застосування антена була реалізована на моделі фантома біотканини людини. Розрахунковий питомий коефіцієнт поглинання (SAR) знаходиться в межах стандартів із найвищим значенням 1,31 Вт/кг на частоті 6 ГГц. Крім того, для перевірки сумісності мобільних додатків розроблено та перевірено 4 (4 × 4) та 6 (6 × 6)-елементні масиви MIMO. Обидва результати MIMO показують ізоляцію між портами (P2P) нижче 18,7 дБ. Ефективність завжди вище 90 % по всій смузі пропускання (BW). Інші параметри MIMO, наприклад ECC і DG, завжди нижче 0,002 і майже 10 відповідно. Результати випромінювання в дальньому полі показують, що масив може випромінювати в усіх напрямках. Крім того, 6 × 6 експонується за допомогою воксельної фантомної моделі руки та голови для оцінки SAR. У кожному випадку значення SAR знаходяться в межах стандартного діапазону.

Ключові слова: Планарна мікросмужка, Низький профіль, Середній діапазон 5G, MIMO, SAR.