Slotted planar patch antenna array design for 5G applications

MOHAMMAD TARIQUL ISLAM[a], WALED YOUSEF NOOR ABOARESH[a], DINH NGUYEN QUOC[b], RABAH W. ALDHAHERI[c,*], KHALID HAMED ALHARBI[c], ABDULAH JEZA ALJOHANI[c], MD SAMSUZAMAN[d,*]

[a]*Dept. of Electrical, Electronics and System Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Malaysia*

[b]*Le Quy Don Technical University, Ha Noi-City, Vietnam*

[c]*Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia*

[d]*Dept. of Computer and Communication Engineering, Faculty of Computer Science and Engineering, Patuakhali Science and Technology University, Bangladesh*

The millimetre-wave communication technique has drawn great attention in the research community and the industry as a key technology in a fifth generation (5G) mobile communications systems. However, as the 5G mobile communication is going to use higher frequency bands beyond the traditional ones, then there will an essential need for a higher gain antenna for 5G to overcome the path loss due to the atmospheric absorption of electromagnetic waves at higher frequencies. Hence, this article focuses on designing antennas that work on the frequency band of 11 GHz, which is one of the 5G frequency band candidates. The design aims to achieve a higher gain and to observe the visibility of the design in terms of cost, size, and performance. The proposed patch antenna resonates at 11 GHz and designed on low cost 1.6 mm FR4 substrate which has a compact structure of 20×40 mm^2, 40×40 mm^2, and 80×40 mm^2 for a single element, 1×2 array antenna, and 1×4 array antenna, respectively. Also, the antennas have a realized gain of 2.95, 4.6, 6.17 dBi for a single element, 1×2 array antenna, and 1×4 array antenna, respectively. In this work, CST Microwave Studio 2018 is used for simulation and analysis for various parameters such as return loss plot, gain plot, radiation, and pattern. Finally, the simulated model is fabricated, and the measured result is correlated with simulation results for verification.

(Received January 6, 2020; accepted December 7, 2020)

Keywords: 5G, Microstrip patch antenna, Antenna array

1. Introduction

Currently, there is a substantial focus on antenna design for 5G mobile devices, which is promising higher data rates that can reach up to 1000 times higher compared to 4G technology. The 5G technology will greatly extend its capacity by opening up higher frequency bands and less congested frequency spectrum. Consequently, higher bandwidth will be achieved, which was the main limitation of previous technologies. However, this opens up a series of challenges, such as a need for designing an antenna with higher gain to overcome the path loss due to the atmospheric absorption of electromagnetic waves at higher frequencies.

To enable the 5G, FCC divided the key spectrum into low-band (up to 1 GHz), mid-band (sub-6 GHz) and high-band (mmWave). The mmWave offer lightning fast data rates above 2 Gbps and huge capacity, while low-band offers good 5G coverage, and mid-band offer a blend of both. It is clear that to attain the target of ultra-fast data rates, the use of 5G mmWave spectrum is desirable. However, some crucial challenges must be fulfilled before the implementation of mmWave mobile communications. The Sub-1 GHz band is used for providing widespread coverage in the cities, suburban, and village areas and help to support the Internet of thing services[1-3]. On the other hand, the 1–6 GHz band provides both capacity and coverage advantages. The band above 6 GHz (mmWave) fulfills the requirements of an ultra-high broadband speed of 5G [1, 4-10] compare to low-band (up to 1 GHz), mid-band (sub-6 GHz) .The 5G spectrum bands have not been finalized yet but there are some regulatory agencies already declared some potential frequency bands for the 5G network such as OFCOM; the communication regulator in the UK. A mobile antenna must be small, light in weight and fit into amounted allotted space in the design's devices, one antenna type that meets these conditions and can fulfill the wireless communication system requirement is the microstrip patch antenna, also this type of antenna has a lot of merits such as low profile, planar structure, multiband properties, low cost, moderate to high gain, and easy to fabricate. The microstrip patch antenna is the most used elements especially with the development of various multiband technique and the enhancement technique that allows us to improve the gain and bandwidth.

Several works have been reported in frequency bands above 6 GHz for the 5G application[2, 11-14]. For example, Sam et.al. presented a patch antenna operating at 11 GHz. with Rogers RT5880 as a substrate of size 22 ×19 mm^2 and 0.6 mm thickness used to achieve a gain of 6.35 dB [11]. The reflection coefficient level of -36.54 dB for the 300 MHz bandwidth is obtained. Another work conducted was also proposed as a single band microstrip patch antenna consist of a new H slot and E slot-loaded on the radiating patch with the 50 ohms microstrip line feeding [12]. This single band antenna is simulated on a Rogers RT5880 dielectric substrate and has relative permittivity 2.2. This design result shows the center frequency at a 59.93GHz with a bandwidth of 4.028 GHz ranging from 57.981GHz up to 62.009GHz. The proposed microstrip patch antennas have a gain of up to 5.42 dB for the millimeter-wave wireless application. It is observed that those antenna substrate structures designed based on a Roger material, which is a bit costly compared to the other material used such as FR4. Another work by [13] presented a patch slotted antenna with FR4 substrate of size 20×20 mm^2 size with 1.66 mm thickness to provide a gain of 4.46 dB at 10.15 GHz. The proposed design simulated with FR4 material, which is considered cheaper compared to Roger. Also, [15] presented a design of a 28 GHz phased array antenna for future 5G mobile-phone applications. The proposed antenna implemented using FR-4 substrates while maintaining good performance in terms of gain and efficiency. This is achieved by employing a new air-filled slot-loop structure as the radiator. The simulated and experimental results show that the antenna has the S_{11} response of less than -10 dB in the frequency range of 27 to 29 GHz. It is been noticed from the above mentioned designed that they adopted using FR4 as substrate material, which a low-cost material that can significantly reduce the cost, particularly in a mass production case. Another work proposed by [14], where they come up with a small antenna with coplanar feeding. The Rogers RT5880 is used as a substrates material of 0.254mm thickness, and the size of the patch where 5 × 5 mm^2. The overall design used to achieve a maximum gain with a value of 6.6 and 5.6 dB at 28 and 38 GHz, respectively. Furthermore, the design of an 8-element microstrip patch antenna (MPA) array was proposed for dual-band 5G communications [16]. The proposed antenna array is compact, with a size of 16× 16 mm^2 at 28 and 39.95 GHz, respectively. The dual-band response is achieved by etching an inverted U-shaped slot from the main radiator. It is observed from the results that the proposed array is able to provide resonance for desired frequency bands. Furthermore, the proposed offer an acceptable gain for both frequency bands. Another approach of including an array antenna to further improve the gain is also considered. For example, the array antenna of 1×2 structure is conducted as well. For LTE-R and 5G lower band, in [17], an ellipse-shaped patch antenna is reported. With an overall size of 180 × 60 mm^2, the designed antenna is able operate over dual bands of 0.66 - 0.79 GHz and 3.28 - 3.78 GHz. In [18], a monopole antenna is introduced for 4G/5G applications. The studied single-element antenna attained a -6-dB operating bands of 1.24 - 2.64 GHz and 3.34 - 5.0 GHz. But it possesses a large dimension of 150 × 80 mm^2 and cannot cover the N79 band. In [19], an UWB antenna is presented for lower 5G communication. With an overall size of 80 × 50 mm^2, the studied design was able to operate over 2.32 - 5.24 GHz band. In this design a simple rectangular patch is used to achieve an operating band centered at 2.425 GHz. But it possesses a large volumetric size of 114 × 77 × 1.6 mm^3. A dipole antenna for 4G/lower 5G base station applications is presented in [20]. Khraisat et. al. designed a 1×2 array antenna that operates at 2.4 GHz with a substrate of 2.2 and thickness h=1.6 mm is used. The antenna achieved an overall gain of 9.6 dBi with 100 × 100 mm^2 size. In addition to the 1×2 design, a 2×2 circularly polarized array antenna was designed [21] This array antenna is that due to the simple and symmetric structure, the proposed antenna is suitable to expand array size, i.e. 4 × 4, 8 × 8 and so on. The antenna operated at a center frequency of 10 GHz. In addition, the antenna is designed using Teflon glass fiber substrate with a thickness of 0.8 mm and dielectric constant of 2.15. The dielectric loss tangent of the substrate is 0.000194. Copper with a thickness of 0.018 mm is used as radiating plane and ground plane conductor. Also a high performance of coaxial feed ultrawide band (UWB) array antenna was designed with parasitic element [22]. The 1×4 array antenna consists of four identical copper circular patches that are appropriately connected using a quarter-wavelength transformer transmission line. Taconic associated with 2.2 dielectric constant and thickness of 1.6 mm is used as the antenna substrate. The proposed antenna recorded reflection coefficient less than -10dB started from 2.5 to 12.6 GHz which fulfilling the requirement of UWB. Dimensions of 80 × 45 mm^2 and maximum gain of 12.12 dB made it as small and high gain UWB antenna. The proposed antenna performance finds it very suitable to be applied in human brain microwave imaging.

In this article, 1×1, 1×2, and 1×4 planar patch antenna array are designed, simulated, and fabricated for 5G applications. The proposed antenna is designed with low-cost FR4 substrate material for the frequency band of 11 GHz to achieve higher gain and to observe the visibility of the design in terms of cost, size, and performance. Presented simulation results are obtained with the Finite Integration technique based full-wave 3D electromagnetic simulator CST Microwave studio.

2. The methodology of the antenna design structure

The design of the antenna is based on Computer Simulation Technology (CST) that operates on microwave studio within the CST Studio Suite[23]. The basic construction of the patch antenna begins with the design synthesis. After the design is completed, the microwave studio within the CST Studio Suite 2018 is used to perform a simulation of the 3D full-wave electromagnetic structure [23]. The simulation tests several designs that require modifications and tunings, which are carried out in the software to obtain a suitable design for optimal antenna performance. The selected design is then fabricated using a photolithographic process. Lastly, the fabricated antennas are tested, and antenna parameters are measured to be analyzed. In short, the construction of the patch antenna requires precise dimension calculation, careful simulation tunings, and accurate measurements. The fabrication process is a crucial stage as it requires precise work to ensure that the fabricated antenna structure is the exact replica of the designed and simulated antenna.

The final proposed patch antenna (single element, 1×2 array antenna, and 1×4 array antenna) using a microstrip line with feeding is given in Fig. 1. The patch antenna has an E-shape patch of 6.88 mm × 14.5 mm. Various parameters such as dielectric constant (ε_r = 4.3), resonant frequency (f_r =11 GHz), and thickness of the substrate (h= 1.6 mm) are considered while designing the proposed antenna. With near zero water absorption, FR-4 is most commonly used as an electrical insulator possessing considerable mechanical strength compare to other material. The material is known to retain its high mechanical values and electrical insulating qualities in both dry and humid conditions. FR4 epoxy glass substrates are the material of choice for most PCB applications. The material is very low cost and has excellent mechanical properties, making it ideal for a wide range of electronic component applications. In this structure, the SMA port is used to excite the antenna. The overall dimensions are 20 mm × 40 mm × 1.6 mm. The detailed dimensions of the proposed single element patch antenna are given in Fig. 1(a). To calculate the width required for each specific amount of impedance, the CST impedance calculator is used, which results in the following values listed in Table 1.

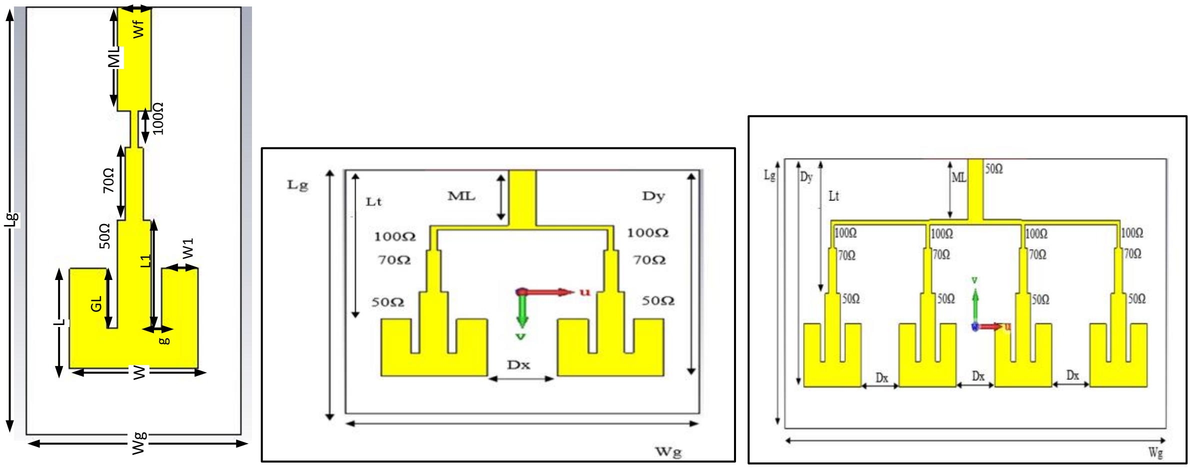
A quarter-wave transformer is used for splitting the power, which is commonly used in impedance matching in order to minimize the energy, which is reflected when a transmission line is connected to a load. The quarter-wave transformer uses a transmission line with different characteristic impedance and with a length of one-quarter of the guided-wavelength to match a line to a load [24]. The quarter-wave transformer in this example connects a 50 Ω line from the source load to a 100 Ω and to 70 Ω impedance then eventually to 50 Ω impedance that excites the antenna patch. This is realized using a microstrip technology on an FR-4 substrate and modeled in CST STUDIO SUITE. After impedance matching, every single patch of antenna needs to be adjusted with respect to the horizontal and vertical axis to get the maximum constructive signal to get maximum possible gain. The best possible horizontal displacement between each of the patches was realized to be 8 mm while the vertical displacement from the SMA connector is found to be 33.95 mm. Also, the single element patch antenna needed to be adjusted in terms of length and width to take into account the shifting of the resonant frequency to the lower side by reducing the size of width to 12 mm and increasing the length to 9.36 mm. Fig. 1(b) and Fig. 1(c), summarize all the parameters and geometric layout of the designed 1×2 and 1×4 array antennas, respectively. Fig. 2 illustrates the surface magnitude current distribution of the proposed designed antennas at (single element, 1×2 array antenna, and 1×4 array antenna) 11 GHz frequencies. The current single element current mostly resonates in the middle of the E shaped part and 1×2 and 1×4 currents mostly resonances the upper side of the E shaped patch.

Table 1. Dimensions for impedance

Impedance Ω	**Value (mm)**
50	3.137
70	1.67
100	0.72

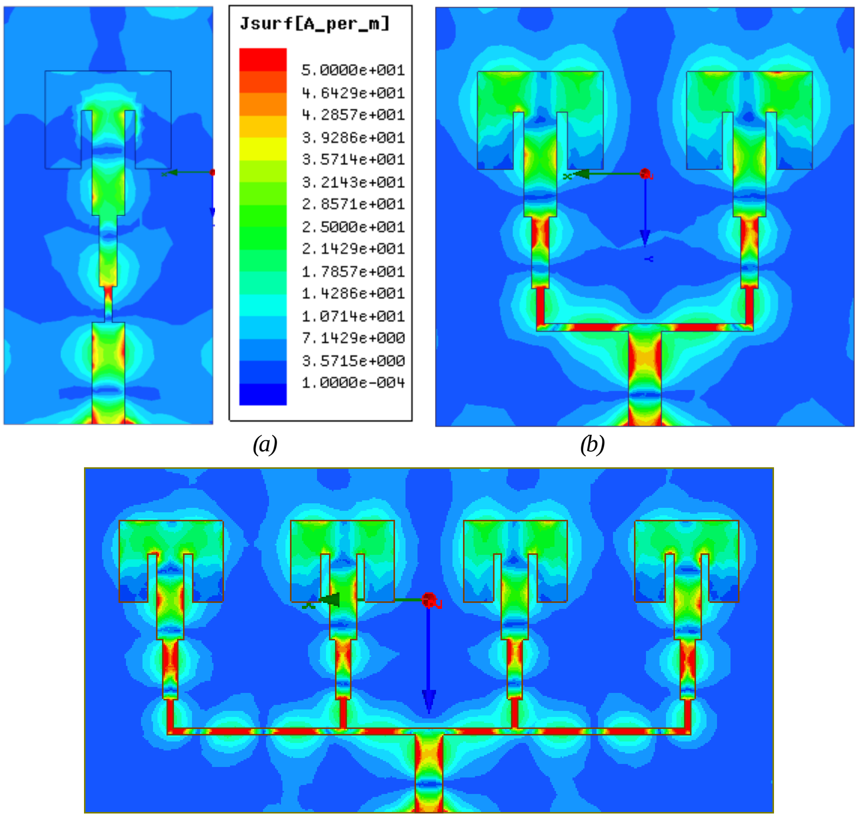
Table 2. Dimensions for impedance

Parameter	**1×1 Value (mm)**	**1×2 Value (mm)**	**1×4 Value (mm)**
Ground Plane Length *Lg*	40	40	40
Ground Plane Width *Wg*	20	40	80
Patch Length *L*	9.36	9.36	9.36
Patch Width *W*	12	12	12
Feed Line Length *ML*	9.04	9.04	9.04
Feed Line Width *Wf*	3.137	3.13	3.13
Substrate Height *h*	1.6	1.6	1.6
Slot Gap *g*	1	1	1
Horizontal Distance Dx		8	8
Vertical Distance Dy		33.95	33.95
Transformer Length		22.35	22.35



(a) (b) (c)

Fig. 1. Geometric layout of the proposed (a) 1×1 (b) 1×2 and (c) 1×4 antenna array antenna (color online)



(a) (b)

(c)

Fig. 2. Surface magnitude current distribution of a) 1×1 Antenna b) 1×2 array antenna and c) 1×4 array antenna at 11 GHz (color online)

3. Results and discussions

The single element antenna prototyped and other simulated (CST and HFSS) and measured reflection coefficient and gain results of the proposed 1×1 antennas are depicted in Fig. 3. Based on the return loss plot (S_{11} dB) for Fig. 3(b), which shows a significant drop reach up to -15.33 dB at 11 GHz. This means that the resonant frequency lies at 11 GHz. The bandwidth of the antenna design can be found at – 10 dB, which lies between 10.66 – 11.14 GHz (HFSS), 10.78-11.13 GHz (CST) in simulated and measured in (10.60-11.48 GHz) which is almost 900 MHz bandwidth. From Fig. 3 (c), it can be stated that the 1×1 antenna array is achieved a gain in simulation 2.88 dBi (HFSS), 2.25dBi (CST), and 2.95dBi in measured. The far-field solver can be run on the CST Microwave Studio to view the graphs of directivity, and maximum gain can be achieved for the designed antennas, which is shown in Fig. 3(e). The single patch antenna shows a realized gain of 2.95 dBi, as shown in Fig. 3(b). The 2D E and H plane radiation pattern of the proposed single antenna is described in Fig. 3(d). It can be sated that the main beam direction towards the + Z axis. The cross polarization is low compare to co polarization in E plane. The 1×1 antenna directivity gain was about 5.28 dBi at 11 GHz, which is shown in Fig. 3(e). The antenna radiation pattern is called nearly directional.

After obtaining results from the design of a single element on the directivity gain, which is relatively small, the design of antenna proceeded with the array design of two and four elements uniform array antenna with a feeding network of a quarter wavelength. The research scope of this study is to investigate the results of three different array configuration types and compare the result of each antenna configuration. For power impedance matching, a quarter-wave transformer impedance matching is used for this project to couple the power to each element for radiation. Antenna prototyped and other simulated (CST and HFSS) and measured reflection coefficient and gain results of the proposed 1×2 antennas are depicted in Fig. 5. Based on the return loss plot (S_{11} dB) for 1×2, which is shown in Fig. 4 and shows a significant drop in the reflection coefficient, then rise back again to the starting point at 11 GHz. This means that the resonant frequency lies at 11 GHz.

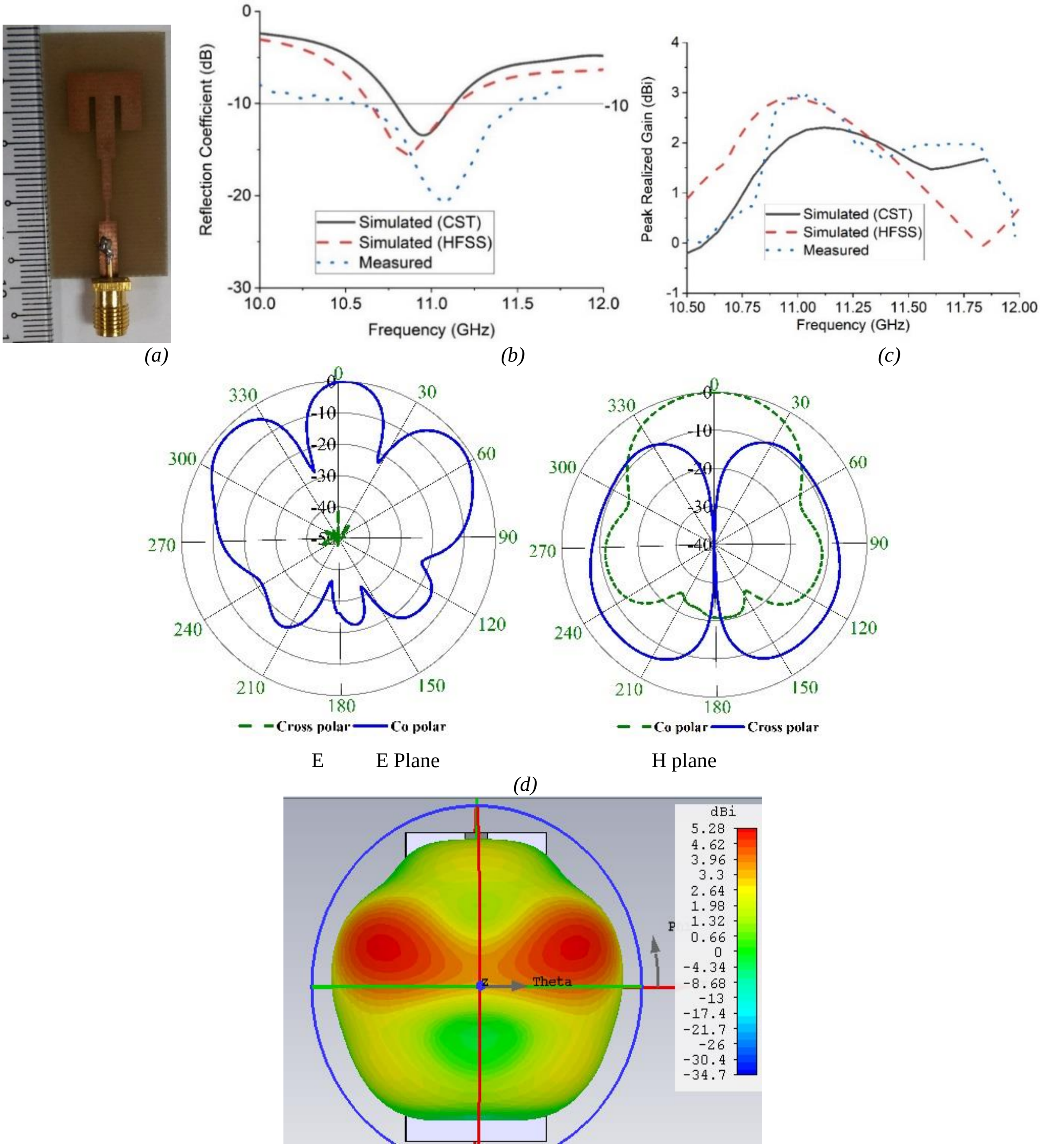


Fig. 3. Single antenna (1×1 antenna) a) Fabricated Prototype b) simulated and measured reflection coefficient (S11) c) simulated and measured peak realized gain d) 2D radiation pattern of E plane and H plane e) 3D directivity far field gain at 11 GHz (color online)

The bandwidth of the 1×2 array design can be found at – 10 dB, which lies between 10.82 – 11.22 GHz (HFSS), 10.90-11.28 GHz (CST) in simulated and measured in (10.34-11.70 GHz) which is more than 1 GHz bandwidth.

From Fig. 4(c), it can be stated that the 1×2 antenna array is achieved realized gain in simulation 5.01 dBi (HFSS), 4.90 dBi (CST), and 4.61dBi in measured. The 2D E and H plane radiation pattern of the proposed single antenna is described in Fig. 4(d). It can be sated that the main beam direction towards the + Z axis. The cross polarization is low compare to co polarization in E plane. The far-field solver can be run on the CST Microwave Studio to view the graphs of directivity, and maximum gain can be achieved for the designed antennas. The 1×2 antenna array antenna shows a maximum directivity gain of 8.78 dBi at 11 GHz, as shown in Fig. 4(e).

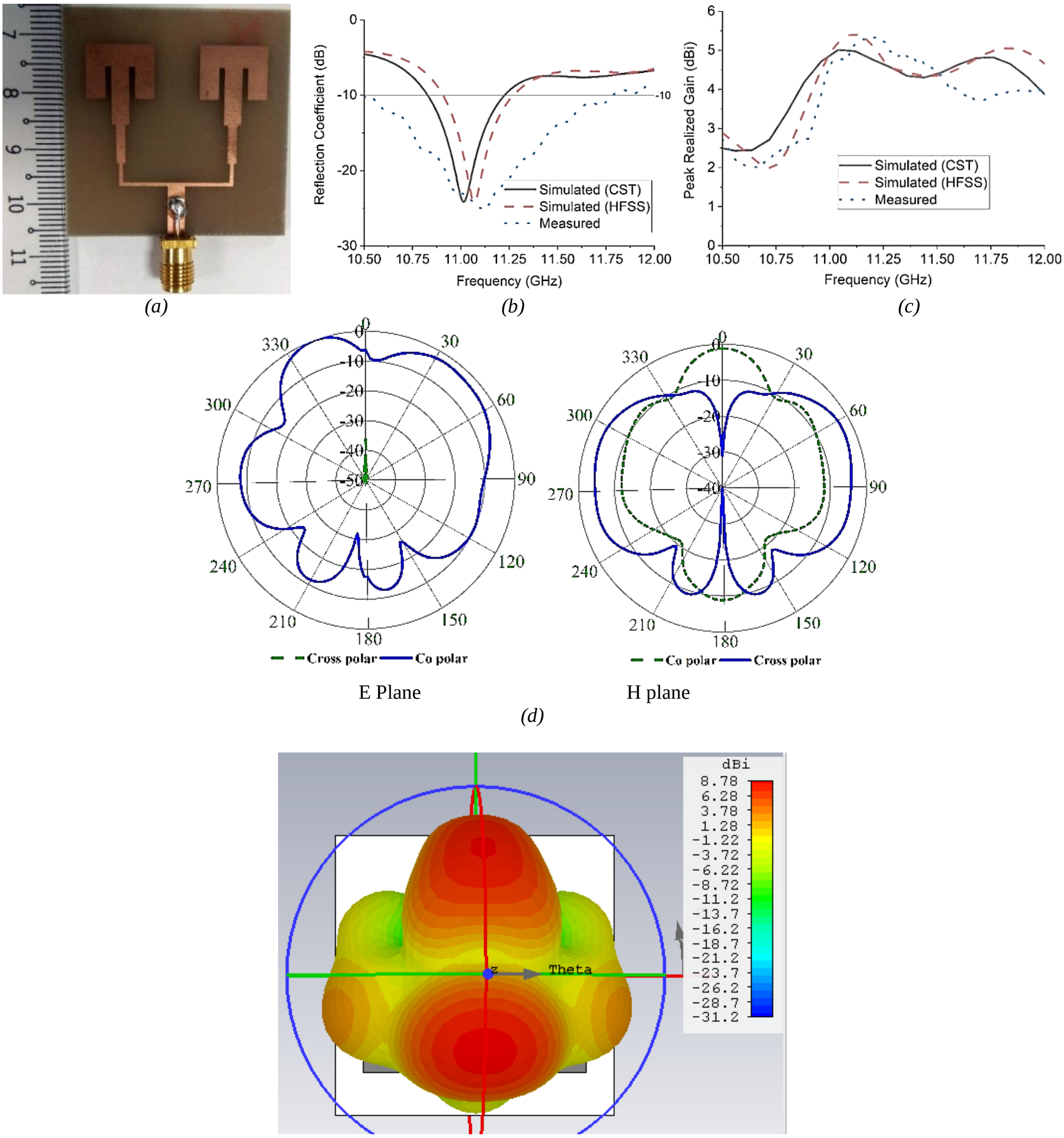


Fig. 4. 1×2 antenna array a) fabricated prototype b) simulated and measured reflection coefficient (S_{11}) c) simulated and measured peak realized gain d) 2D radiation pattern of E plane and H plane e) 3D directivity far-field gain at 11 GHz (color online)

Antenna prototyped and other simulated (CST and HFSS) and measured reflection coefficient and gain results of the proposed 1×4 antennas are depicted in Fig. 6. Based on the return loss plot (S_{11} dB) for 1×2, which is shown in Fig. 5(b) and shows a significant drop in the reflection coefficient, then rise back again to the starting point at 11 GHz. This means that the resonant frequency lies at 11 GHz. The bandwidth of the 1×4 array design can be found at – 10 dB, which lies between 10.84 – 11.78 GHz (HFSS), 10.26-11.94 GHz (CST) in simulated and measured in (10.80-11.82 GHz) which is more than 1 GHz bandwidth. From Fig. 5(c), it can be stated that the 1×4 antenna array is achieved realized gain in simulation 6.98 dBi (HFSS), 7.66 dBi (CST), and 6.17 dBi in measured. The 2D E and H plane radiation pattern of the proposed single antenna is described in Fig. 5(d). It can be sated that the main beam direction towards the + Z axis. The cross polarization is low compare to co polarization in E plane. The far-field solver can be run on the CST Microwave Studio to view the graphs of directivity and maximum gain can be achieved for the designed antennas. The 1×4 antenna array antenna shows a maximum directivity gain of 12 dBi at 11 GHz, as shown in Fig. 5(e). There are always discrepancies between the fabricated and simulated results due to various factors such as differences in substrate material as sometimes the commercially available material slightly different in terms of thickness and permittivity. Also, measurement environment and the surrounding may have its reflection, particularly when measurement taken in a place surrounded by metallic objects, which are highly influential to results, in that case, it is preferred to perform the measurement in the designated chamber. Moreover, manufacturing error tolerances could be considered as a factor to describe the reason behind such kind of differences. However, slight differences are acceptable in case the shifted frequency is not out of the rang of the application requirement. Table 3 shows the comparison of all the related work mentioned with the important parameters achieved of the designed antenna. The proposed antenna has achieved a comparatively better result in terms of different antenna parameters.

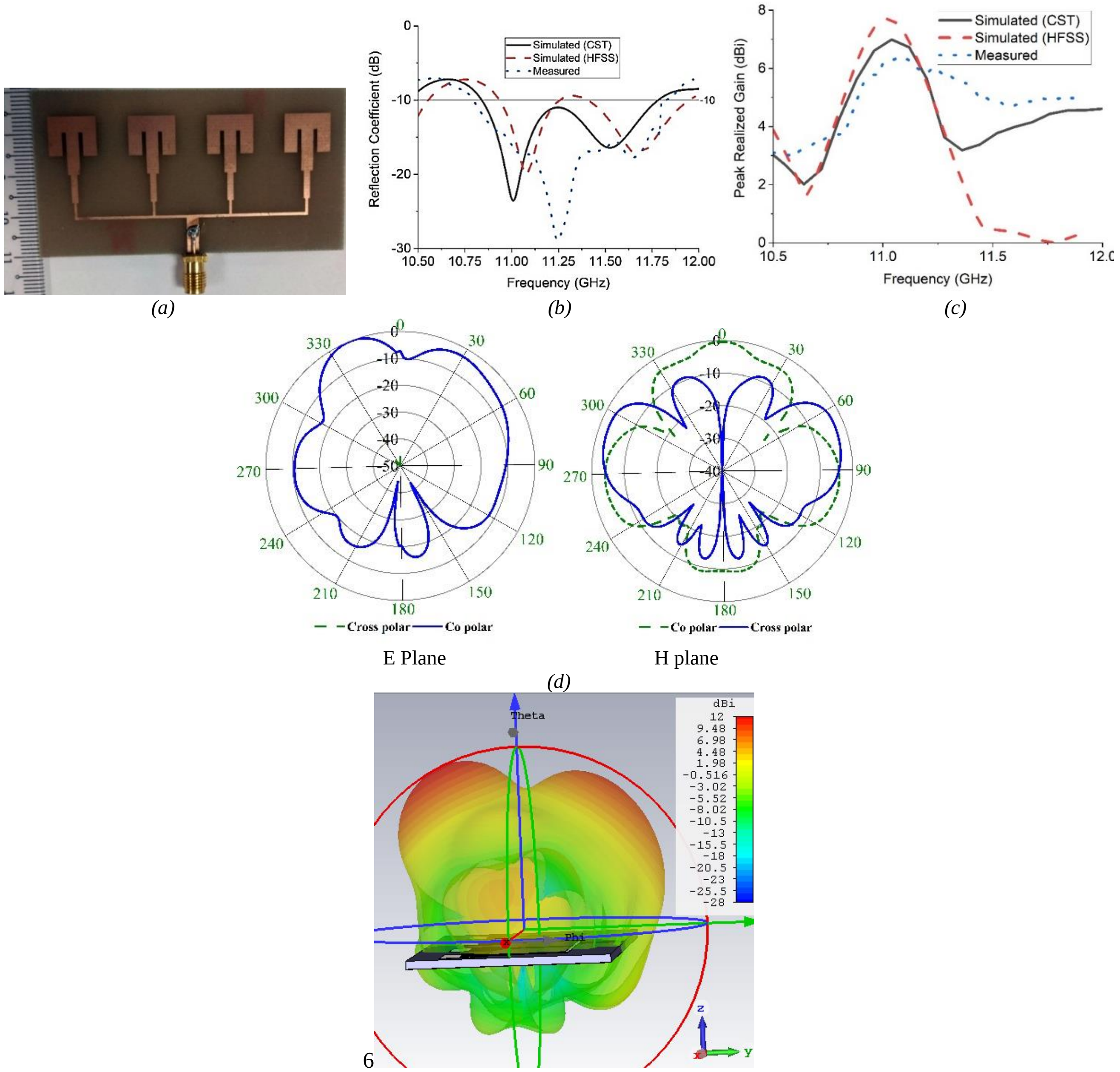


Fig. 5. 1×4 antenna array a) fabricated prototype b) simulated and measured reflection coefficient (1) c) simulated and measured peak realized gain d) 2D radiation pattern of E plane and H plane e) 3D directivity far-field gain at 11 GHz (color online)

Table 3. Comparison table of the proposed antenna with existing antenna research

Reference	Type	Size (mm^2)	Center Frequency (GHz)	Operating Band(GHz)	Gain (dBi)	Substrate Material	Thickness (mm)
[25]	Single element	22 × 19	11.2	11-11.3	6.35	Rogers RT5880	0.6
[26]	Single element	5 × 5	60	57.98 - 62	5.42	Rogers RT5880	0.254
[13]	Single element	20 × 20	10.15	9.95-10.35	4.46	FR4	1.66
[15]	Array	55 × 7	28	27-29	13	FR4	0.8
[14]	Single element	5 × 5	28 , 38	27.5-28.7, 37.8-38.2	6.6, 5.6	Rogers RT5880	0.254
[16]	8- elements	16 × 16	28 , 39.95	NA	15.6, 10	FR-4	0.8
[27]	2×2 Array	50 × 50	10	9.75-10.25	9.36	Teflon Glass fiber	0.8
[17]	1x1 array	180 × 60	0.7 3.5	0.66 - 0.79 3.28 - 3.78	2.4 ~ 6.1	FR4	1.6
[18]	1x1 array	150 × 80	5	1.24 - 2.64 (-6dB) 3.34 - 5.0(-6dB)	4.25 ~ 6.0	Fr4	1.6
[19]	1x1 array	80 × 50	3	2.32 - 5.24	4.25 ~ 6.0	Fr4	0.508
Proposed Design	Single Element 1×2 Array 2×2 Array	20×40 40×40 80×40	11	10.60-11.48 10.34-11.70 10.80-11.82	2.95 4.61 6.17	FR4	1.6

4. Conclusion

The aim of this work is to design and fabricate a patch antenna for 5G applications that work on one of its frequency band candidates. In this project, we have investigated the visibility of the design in terms of performance, cost and size. The results show that tradeoff should be considered in selecting the proper antenna for the required application. The results were obtained from testing single element patch and array antennas of 1×2 and 1×4. Bandwidth, directivity, efficiency, and gain were identified, compared, and discussed. Furthermore, the fabricated antennas were tested and result correlated with simulated results for validation. The proposed patch antenna resonates at 11 GHz and built on low cost 1.6 mm FR4 substrate which has a compact structure of 20×40 mm^2, 40×40 mm^2 and 80×40 mm^2 for a single element, 1×2 array antenna and 1×4 array antenna, respectively. Also, the antennas have a realized gain of 2.95, 4.6, 6.17 dBi for a single element, 1×2 array antenna and 1×4 array antenna, respectively. The antenna can be a good candidate for 5G application due to high directivity gain.

Acknowledgments

This work is funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah under grant No (RG-2-135-41). The authors, therefore, acknowledge with thanks DSR technical and financial support

References

[1] M. M. Rahman, M. S. Islam, H. Y. Wong, T. Alam, M. T. Islam,Sensors **19**, 2634 (2019).

[2] M. Samsuzzaman, N. Misran, M. T. Islam, and M. T. Islam, J. Optoelectron. Adv. M. **14**, 163 (2020).

[3] N. Ojaroudi Parchin, H. Jahanbakhsh Basherlou, M. Alibakhshikenari, Y. Ojaroudi Parchin, Y. I. Al-Yasir, R. A. Abd-Alhameed et al., Electronics **8**, 521 (2019).

[4] M. K. Ishfaq, T. A. Rahman, Y. Yamada, K. Sakakibara, in 2017 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), 2017, p. 160.

[5] S. I. Orakwue, R. Ngah, T. A. Rahman, in 2016 IEEE Wireless Communications and Networking Conference, 2016, p. 1.

[6] X. Wu, Y. Zhang, C.-X. Wang, G. Goussetis, M. M. Alwakeel, in 2015 9th European Conference on Antennas and Propagation (EuCAP), 2015, p. 1.

[7] K. H. Alharbi, M. Moniruzzaman, R. W. Aldhaheri, A. J. Aljohani, S. Singh, M. Samsuzzaman, et al.,Int. J. Appl. Electromagnet. Mech. Preprint 1(2020).

[8] T. C. Limited. (2019). 5G and EME. Available: https://www.telstra.com.au/consumer-advice/eme/5g-and-eme?fbclid=IwAR1Tyy3zELtxZi7bvzAar9Avc-wHmFQc7G1yePzeiobhkJH-KvaXvMy6nJ8

[9] A. Rahman, Y. Ng M, A. U. Ahmed, T. Alam, M. J. Singh, M. T. Islam, IEICE Electronics Express **13**, 20160377 (2016).

[10] Y. Rahayu, M. I. Hidayat, in 2018 2nd International Conference on Telematics and Future Generation Networks (TAFGEN), 2018, p. 93.
[11] R. Azim, A. K. M. M. H. Meaze, A. Affandi, M. M. Alam, R. Aktar, M. S. Mia, et al.,Int. J. Microw. Wirel. Technol. Preprint, 1(2020).
[12] M. Persson, A. Fhager, H. D. Trefná, Y. Yu, T. McKelvey, G. Pegenius et al., IEEE Transactions on Biomedical Engineering **61**, 2806 (2014).
[13] S. Verma, L. Mahajan, R. Kumar, H. S. Saini, N. Kumar, in 2016 5th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions)(ICRITO), 2016, p. 460.
[14] M. M. M. Ali, A.-R. Sebak, in 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), 2016, p. 399.
[15] N. Ojaroudiparchin, M. Shen, G. F. Pedersen, in 2015 International symposium on Antennas and propagation (ISAP), 2015, p. 1.
[16] U. Rafique, H. Khalil, in 2017 Progress in Electromagnetics Research Symposium-Fall (PIERS-FALL), 2017, p. 55.
[17] A. K. Arya, S. J. Kim, S. Kim, Progress In Electromagnetics Research **88**, 113 (2020).
[18] M. Khalifa, L. Khashan, H. Badawy, F. Ibrahim, in Journal of Physics: Conference Series, 2020, p. 012049.
[19] X. Tang, Y. Jiao, H. Li, W. Zong, Z. Yao, F. Shan et al., in 2019 International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), 2019, p. 1.
[20] G. Gopal, A. Thangakalai, Appl. Comput. Electrom. **35**, 16 (2020).
[21] M. A. Rahman, Q. D. Hossain, M. A. Hossain, E. Nishiyama, I. Toyoda, Int. J. Microw. Wirel. Technol. **8**, 921 (2016).
[22] M. Jamlos, M. Jamlos, S. Khatun, A. Ismail, in 2014 IEEE 2nd International Symposium on Telecommunication Technologies (ISTT), 2014, p. 72.
[23] D. Systèmes. (2018). CST STUDIO SUITE 2018. Available: https://www.3ds.com/products-services/simulia/products/cst-studio-suite/?utm_source=cst.com&utm_medium=301&utm_campaign=cst
[24] C. A. Balanis, Antenna theory: analysis and design: John Wiley & Sons, 2016.
[25] C. M. Sam, M. Mokayef, EPH-International Journal of Science And Engineering **2**, 19 (2016).
[26] J. Saini, S. Agarwal, in 2017 international conference on Computer, Communications and Electronics (Comptelix), 2017, p. 227.
[27] M. A. Rahman, Q. D. Hossain, M. A. Hossain, E. Nishiyama, I. Toyoda, Int. J. Microw. Wirel. Technol. **8**, 921 (2016).

* Corresponding authors: samsuzzaman@ukm.edu.my; raldhaheri@kau.edu.sa