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Compact Four-Element Phased Antenna Array for 5G Applications

MUHAMMAD KAMRAN ISHFAQ[1], THAREK ABD RAHMAN[2], MOHAMED HIMDI[3], HASSAN TARIQ CHATTHA[4], (Senior Member, IEEE), YASIR SALEEM[5], BILAL A. KHAWAJA[4,6], (Senior Member, IEEE), AND FARHAN MASUD[7]

[1]Department of Electrical Engineering, Government College University Faisalabad, Faisalabad 38000, Pakistan
[2]Wireless Communication Centre, Universiti Teknologi Malaysia (UTM), Johor Bahru 81310, Malaysia
[3]Institut d'Electronique et Télécommunications de Rennes, University of Rennes 1, 35000 Rennes, France
[4]Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, AlMadinah 41411, Saudi Arabia
[5]Department of Computer Science and Engineering, University of Engineering and Technology (UET), Lahore, Lahore 54890, Pakistan
[6]Department of Electronic and Power Engineering (EPE), PN-Engineering College (PNEC), National University of Sciences and Technology (NUST), Karachi 75104, Pakistan
[7]Department of Statistics and Computer Science, University of Veterinary and Animal Sciences, Lahore 54000, Pakistan

Corresponding authors: Muhammad Kamran Ishfaq (kamranzarrar@gmail.com) and Hassan Tariq Chattha (chattha43@hotmail.com)

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ABSTRACT This paper presents a four-element compact phased Planar Inverted-E Antenna (PIEA) array for 6 GHz beamforming applications. For compact phased arrays, the mutual coupling is a severe performance degrading factor. Therefore, three mutual coupling reduction techniques are employed, which include (i) PIEA as an array element which is a modified version of Planar Inverted-F Antenna (PIFA) by inserting another shorting plate, (ii) slots in the ground plane and (iii) two slits in each etched ground slot. With these techniques, the mutual coupling is reduced below −19 dB in the operational bandwidth from 5.7 to 6.4 GHz. The compact design with an inter-corner spacing of $0.013\lambda_o$ and an inter-element spacing of $0.3\lambda_o$ is achieved. The peak gain obtained by this compact phased array is 8.36 dBi. This array can scan up to a maximum scanning angle of $\pm 70^o$. A good general agreement is found between the measured and simulated results.

INDEX TERMS Antennas, phased array, PIFA, beamforming, mutual coupling.

I. INTRODUCTION

5G represents a revolution in telecommunication, which will bring a paradigm shift in the way we communicate for the years to come [1]. It will provide a data rate up to 10 Gbps, fibre-like user experience, 1 ms over-the-air latency, user capacity up to several billion, and many more [2], [3]. For achieving this greater capacity, a large bandwidth is needed. Hence, 5G is looking beyond the presently used 3 GHz spectrum band. The spectrum of 3–30 GHz is referred to as microwave while 30-300 GHz is referred to as the millimetre-wave (mm-wave) bands. In recent years, studies for the next-generation wireless communication systems have begun to shift from UHF frequencies (i.e. 300 MHz-3 GHz) to the new spectrum in the microwave range, including mm-wave spectrums. Currently, the spectrum below 6 GHz is not enough to meet future needs, which means that new spectrum allocations in the mm-wave frequency bands above 6 GHz are required to alleviate the current spectrum shortage. This is the primary driver in the development of fifth generation (5G) wireless communication systems. Hence, the microwave range above 6 GHz and mm-wave bands are the primary keys for resolving 5G challenges. Due to the increase in the number of subscribers and the need for high data-rate in wireless communication systems, the demands for an increase in channel capacity, mitigation of multi-path fading, and co-channel interference are paramount for mobile and satellite communication systems. As the number of users increases, the co-channel interference also increases that leads to poor Quality of Service (QoS). This has triggered a lot of research effort in the area of phased arrays to tackle this problem and improve the quality of communication even in unfavourable conditions. On the other hand, electronic gadgets are becoming more and more compact.

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Therefore, designing compact antennas and arrays with enhanced performance poses a challenge for the antenna design researchers [4]–[6]. Small cell base stations will require a compact beamforming antenna array. Thereby, the researchers have proposed different approaches for designing compact beamforming arrays such as a beam-switching array using Yagi-like parasitic elements and employing complex mutual compensation algorithms [7], [8]. The task of designing a compact beamforming array is also a challenge due to the mutual coupling being a severe performance degrading factor. The effects of mutual coupling intensify as the inter-element spacing is reduced.

Planar Inverted-F Antenna (PIFA) has been a very popular candidate in portable wireless systems due to its appealing characteristics, such as low-profile, ease of fabrication and robustness etc. [9], [10]. Also, it does not require any matching network when connected to the 50 Ω coaxial input [11]. It is also a suitable candidate for building compact arrays because it is comparatively less affected by another neighbouring PIFA [4], [12]–[15]. In the literature, few PIFA antennas and arrays are reported for 5G applications [15]–[20]. An 8-element phased array using open-slot PIFA antenna at mm-wave is designed for beamforming applications with an inter-element spacing of half a wavelength, reporting only simulated results [15]. In [16], a 4-element MIMO PIFA array is presented at 28 GHz. Three MIMO array models/arrangements are presented using space diversity where each element is located in a different arrangement with an inter-element spacing of half a wavelength [16]. A two-element MIMO antenna in which the elements are in anti-parallel arrangement facing each other is reported in [17] having an inter-element spacing of more than half a wavelength. Further, in [18], a three-element MIMO PIFA design is proposed with each element in a different direction/arrangement, but no fabrication is reported. However, this MIMO antenna also has half a wavelength inter-element spacing. Another six-element MIMO PIFA was reported and designed at 28 GHz in [19]. In this design, the PIFA elements were arranged in different directions using space diversity with an inter-element spacing of half a wavelength [19].

In this paper, a design of compact phased array using Planar Inverted-E Antenna (PIEA) elements is presented having a resonant frequency of 6 GHz, by employing three mutual coupling reduction techniques, which are: dual-shorting pins, thus making it a PIEA instead of a PIFA, ground slots in-between adjacent array elements and two slits in each of these slots with an inter-element spacing of $0.3\lambda_o$(where $\lambda_o = \lambda$ at 6 GHz $= 50$ mm).

The rest of the paper is organized as follows: Section 2 discusses the proposed array configuration. Section 3 presents the antenna array design approach using a parametric study. Section 4 compares the simulated and measured results, whereas Section 5 discusses the beam steering capabilities of the designed antenna array, and finally, Section 6 draws conclusions.

II. ARRAY CONFIGURATION

Fig. 1 shows the configuration of a single dual-shorting PIFA element, thus becoming a PIEA. It consists of a ground plane with dimensions $L_g \times W_g$. The PIEA top plate has dimensions of $W \times L$, while the antenna height is h. The two shorting plates of width W_s are located on each corner of the top edge of the antenna. Table 1 shows the optimised values of the design parameters of a single PIEA element.

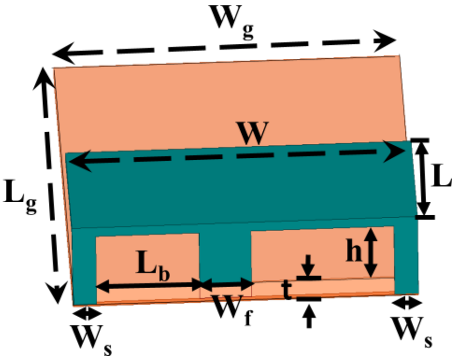


FIGURE 1. Single Planar Inverted-E Antenna (PIEA).

TABLE 1. Parameters of a PIEA.

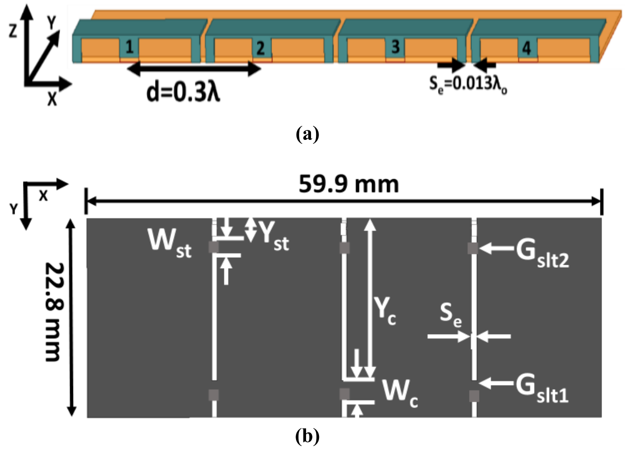
Parameters	Value (mm)
W=W_g	14.5
L_g	22.8
W_S	1
W_f	2.17
L	7.51
h	1.825
L_b	4.34
t	0.5

Fig. 2 shows the 3D view and back view of the compact antenna array having four PIEA elements. The inter-element and the inter-corner spacings are d and S_e respectively. The ground slots are introduced in-between the adjacent array elements with a width equal to the inter-corner spacing of adjacent elements i.e. S_e. Further, two slits named G_{slt1} and G_{slt2} are added in each of these slots at distances Y_c and Y_{st}, respectively from the upper edge of the array. The widths of slots G_{slt1} and G_{slt2} are W_{st} and W_c respectively. The dielectric material used is Roger RT/Duriod 5880 having a thickness $t = 0.5$ mm and a relative permittivity $\varepsilon_r = 2.2$. Table 2 shows the optimised values of the design parameters of the compact PIEA array.

III. ARRAY DESIGN APPROACH USING PARAMETRIC STUDY

The compact array is developed by employing the design approach given as under:

1. Dual-shorting pin PIFA antenna, i.e. PIEA being more suitable regarding reducing mutual coupling explained in detail in the next section.



(a)

(b)

FIGURE 2. **Compact phased PIEA Array (a) 3D view, (b) Bottom view.**

TABLE 2. **Parameters of compact PIEA array.**

Parameters	Value (mm)
Y_{st}	0.715
W_{st}	0.3
Y_c	18.55
W_c	1.856
d	15.15
S_e	0.65
λ_o (6GHz)	50

2. Introducing a ground slot between the adjacent array elements.
3. Introducing a slit in the ground slots at a distance Y_c from the upper edge of the array.
4. Introducing another slit in the ground slots at a distance Y_{st} from the upper edge of the array.

A. SINGLE ELEMENT ANTENNA DESIGN AND PARAMETRIC STUDY

The single-element PIEA is designed by applying parametric study approach to study the effects of antenna parameters on its performance. After observing the effects of all parameters, the design is optimised by using the Particle Swarm Optimisation (PSO) algorithm approach. The CST Microwave Studio (v. 2016) simulation software is used for this purpose.

The width W of the top plate of PIEA is changed from 12 mm to 15 mm, while other parameters are held constant at $W_f = 2$ mm, $h = 1.9$ mm, $L = 7.5$ mm, $Wg = 14$ mm and $Lg = 22.5$ mm. Figure 3 shows that the resonant frequency is inversely proportional to the width of the top plate as its value is decreased with an increase in the width. The width of nearly 14 mm is found to be suitable for the design. Further, the length L of the top plate of PIEA is varied while other parameters are held constant. Similar to the width of the top plate, it is found by the parametric study that the increase in the length of the top plate decreases the resonant frequency as being inversely proportional to each other.

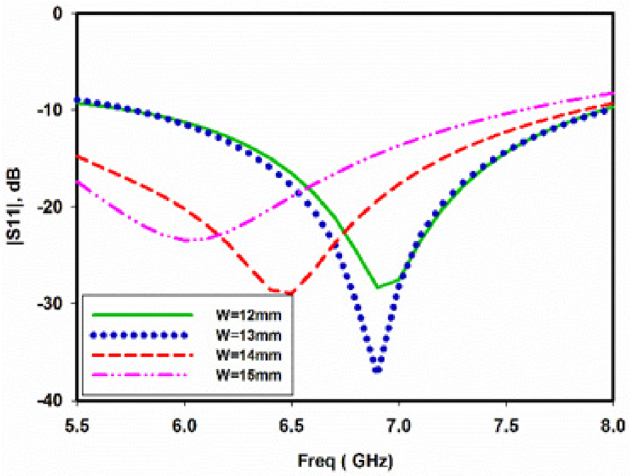


FIGURE 3. **Parametric study for width W of the top plate of PIEA.**

Next, the distance of the feeding plate from the shorting plate i.e. L_b is changed from 2.5 mm to 5.5 mm while other parameters are held constant. Fig. 4 shows that the L_b is an important parameter for obtaining the matching, and its value in the range of 3.5 to 4.5 mm can achieve the required resonant frequency.

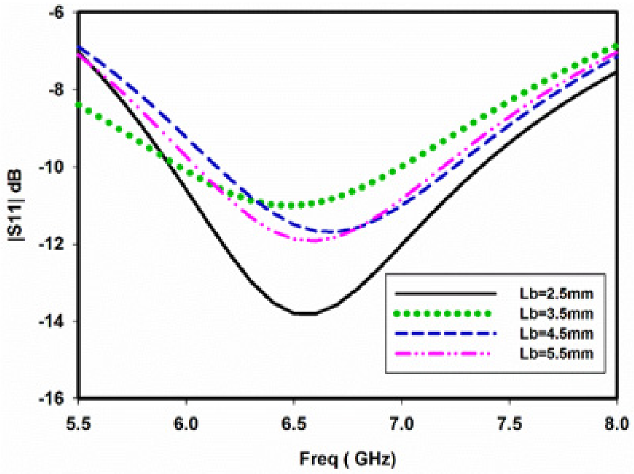


FIGURE 4. **Parametric study for distance L_b of feeding plate from shorting plate.**

Further, the feeding plate width of the PIEA i.e W_f is varied from 2 mm to 6 mm, while other parameters are held constant. The results in Fig. 5 suggest that the feed plate width affects the matching as well as the overall antenna bandwidth. The increase in feed width increases the bandwidth. Finally, with the values obtained from the comprehensive parametric study, the optimisation is performed by using the PSO algorithm. The optimised design values of single PIEA element are given in Table 1 as shown in the previous section.

B. ARRAY DESIGN AND PARAMETRIC STUDY

Like the single element PIEA, a parametric study is carried out to get an understanding of the behavior of different parameters and for obtaining the right size and positions of

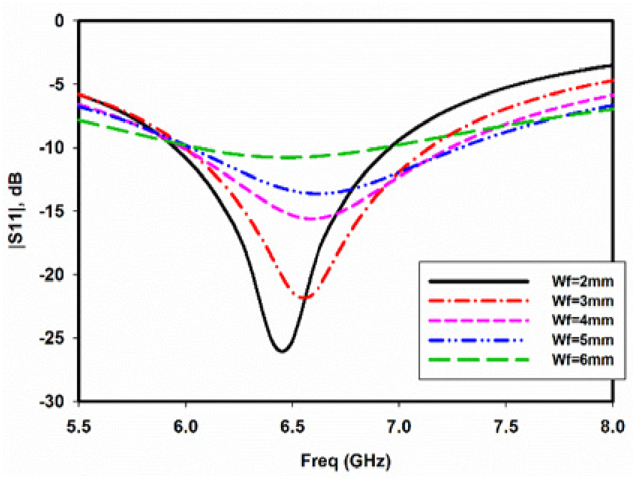


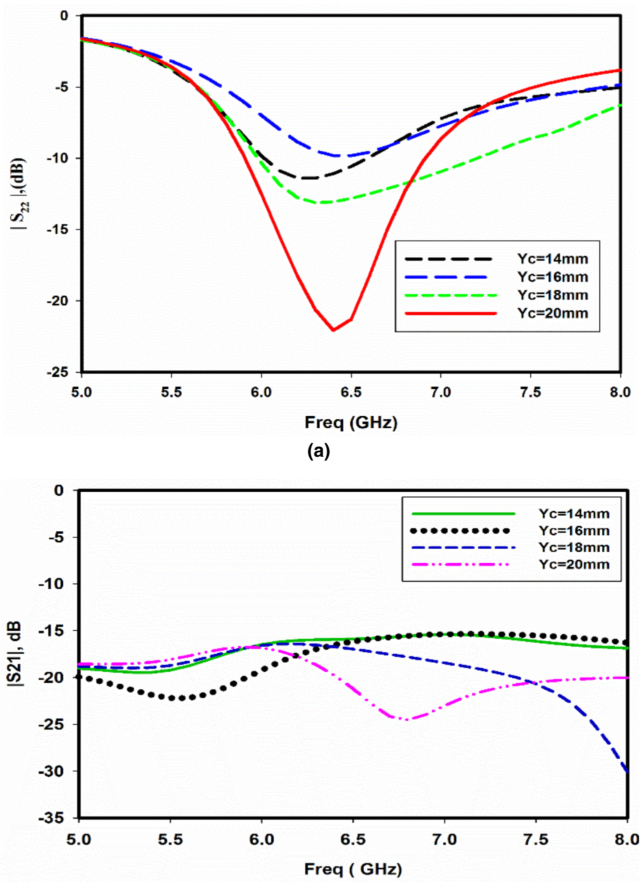
FIGURE 5. Parametric study for the width of the feeding plate W_f.

these different parameters for reducing the mutual coupling between array elements. In the parametric study, the same approach of changing one parameter at a time while others being held constant at the values provided in Table 2. When the position of G_{slit1} from the upper edge of the ground plane, i.e. Y_c is varied from 14 mm to 20 mm, it is observed that it significantly affects the values of S_{22} and S_{12} but not affecting much to that of $S_{11,}$ where S_{11} and S_{22} are reflection coefficients of PIEA elements 1 and 2 respectively and S_{12} being the mutual coupling between these two elements. Therefore, the results related to S_{22} and $S_{21} = S_{12}$ are shown in Fig. 6. It is evident from the results shown that the value of Y_c between 18 to 20 mm would show better performance in terms of S_{22} and the reduced mutual coupling effect i.e. enhanced isolation between the two elements.

Similarly, Fig. 7 shows the effects of changing the position of G_{slit2} from the upper edge of the array i.e. Y_{st} on mutual coupling S_{21}. It is evident from the figure that the insertion of slit G_{slit2} and small variation in its position significantly affects the mutual coupling S_{21}. And its appropriate position is required to achieve the maximum isolation between the two elements. An addition of slits at the position Y_c and Y_{st} jointly create a long slot in the ground plane, which blocks the coupling currents.

Finally, the inter-element spacing i.e. d is varied to obtain a compact design. In Fig. 8, the inter-element spacing d is varied from 15 mm to 25 mm with a step of 2 mm while all other parameters are unchanged. It is clear from the Figure that increasing the distance between elements increases the isolation but since we need a compact design, we need to have a minimum distance with the acceptable value of isolation. As the figure depicts that at an inter-element spacing of 0.3λ i.e. d = 15 mm, still provides good results with regards to isolation i.e. below -15 dB. Therefore, the separation $d = 15$ mm is suitable for the compact array design.

After iterative simulations, parametric studies and introducing mutual coupling reduction techniques described above, the inter-element spacing i.e d is achieved to be just $0.3\lambda = 15$ mm whereas the inter-corner distance i.e. S_e is just 0.65 mm $= 0.013\lambda_o$ while maintaining good isolation between antenna elements.



(a)

(b)

FIGURE 6. Parametric study of Position of G_{slt1} i.e. Y_c in the ground plane (a) S_{22} (dB) (b) S_{21}(dB).

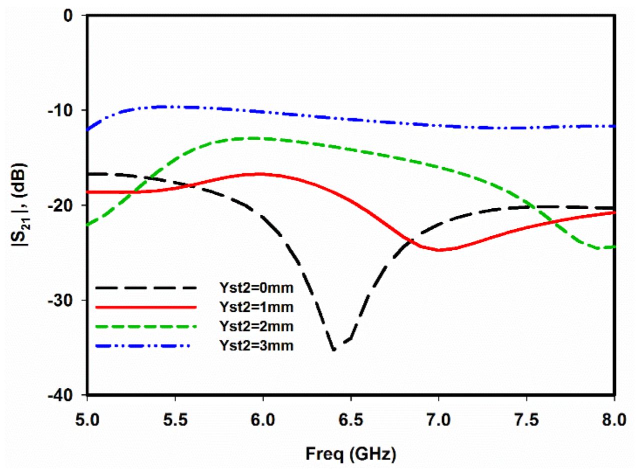


FIGURE 7. Effects of position variation of G_{slt2} i.e. Y_{st} on S_{21} (dB).

IV. RESULTS AND DISCUSSION

The simulated reflection coefficient S_{11} in dB for single element PIEA is presented in Fig. 9. The results show that it

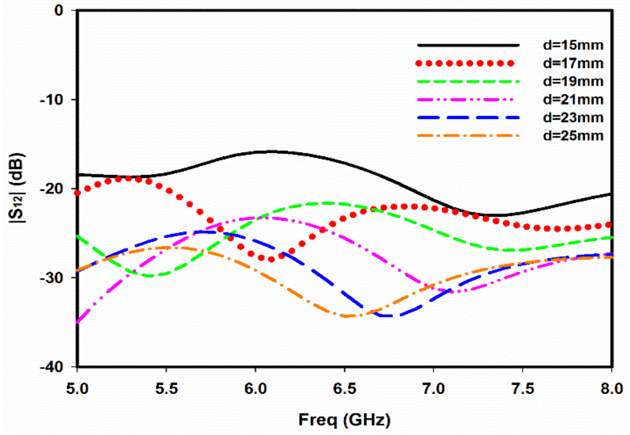


FIGURE 8. Parametric study for observing the effects of inter-element spacing d on S_{21} (dB).

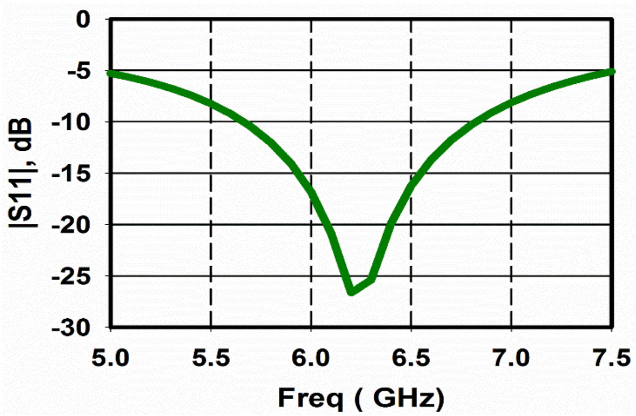
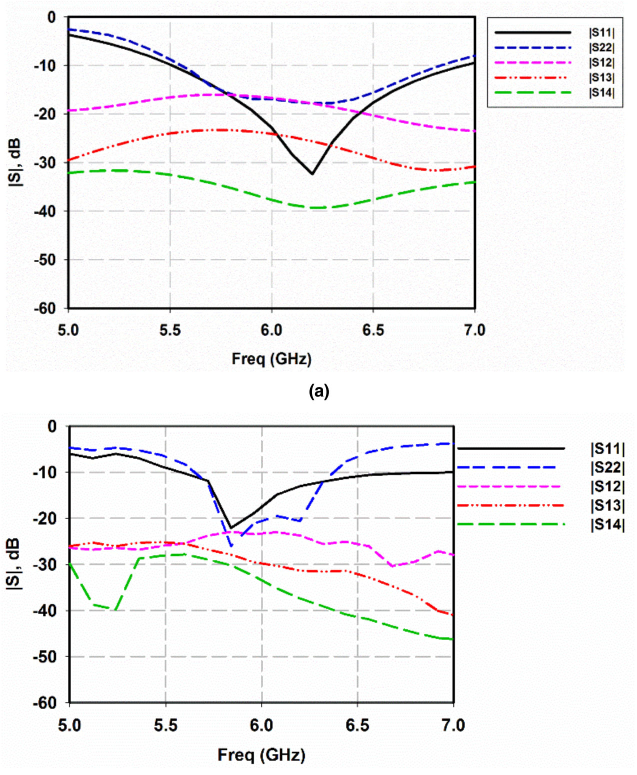


FIGURE 9. Simulated S_{11} [dB] of single element PIEA.

is a wideband design with a frequency ranging from 5.7 GHz to around 6.8 GHz for $S_{11} < -10$ dB. It is found to have an adequate simulated gain of 4 dBi at 6 GHz. This PIEA antenna is compact and low-profile as the height of this antenna is just 1.8 mm. Secondly, it shows an inherent mutual coupling reduction capability when used as an array element which is shown in the compact phased array design.

Fig. 10 shows the fabricated prototype of 4-element compact phased PIEA array. Figure 11 shows the simulated and measured s-parameters of the proposed compact PIEA array, which confirms that the array is well matched and present a low mutual coupling between the ports, from 5.7 GHz to 6.4 GHz. The design achieves excellent performance with the use of the proposed methods, having isolation better than −19 dB in the operational bandwidth. The current distributions in Fig. 12 shows that shorting pins on both sides of the PIEA forms a built-in folded slot antenna in between,

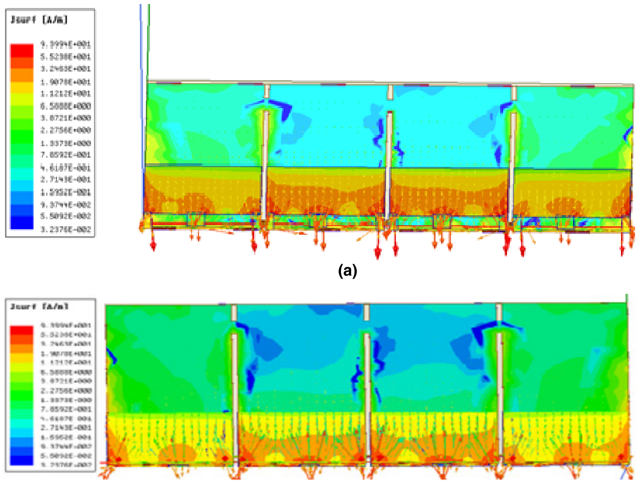
FIGURE 10. Fabricated prototype of 4-Element compact phased PIEA array.



(a)

(b)

FIGURE 11. S-parameters of the compact phased PIEA Array (a) simulated, (b) measured.



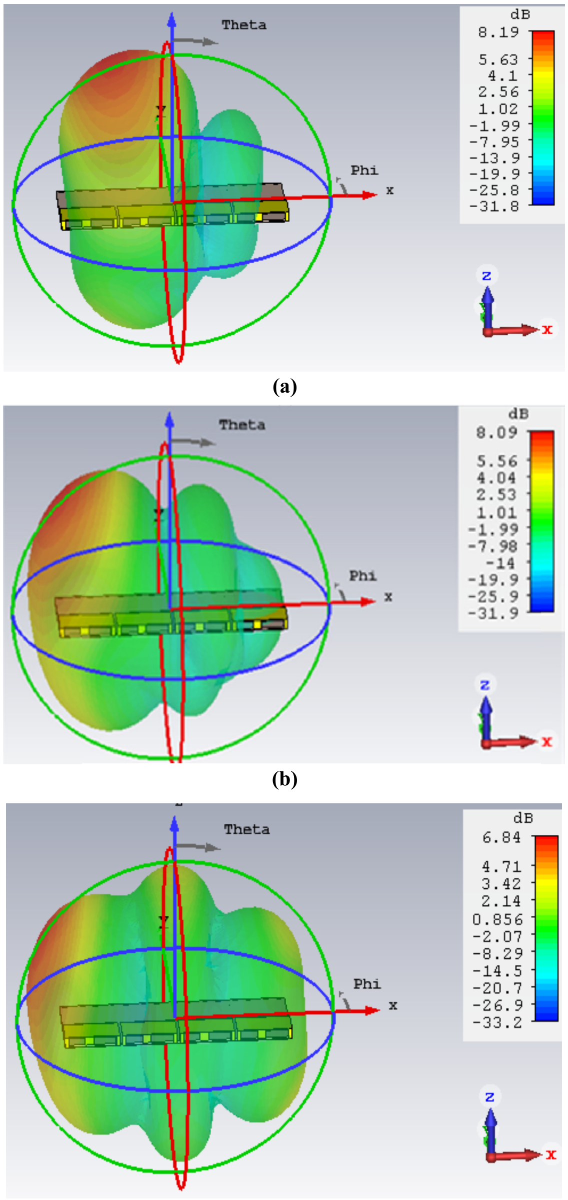
(a)

(b)

FIGURE 12. Current distribution on the array at 6 GHz (a) Top, (b) Bottom.

TABLE 3. Comparison with previous work.

Design	Frequency Band	Antenna Structure	Bandwidth (%)	Spacing, d	Coverage	Remarks
[8]	2.4 GHz	DRA	4.1%	0.32 λ	±20°	Compact, Limited scanning
[7]	15 GHz	DRA,	6.6%	0.4λ	±32°	Compact, Limited scanning
[15]	28 GHz	PIFA	20%	0.5λ	±60°	Larger size, No fabrication
This Work	6 GHz	PIFA	20%	0.3λ	±70°	Compact, More scanning range



(a)

(b)

(c)

FIGURE 13. Simulated 3D pattern having thebeam-steering capability at 20°, 40°, and 70°.

which cause the coupling energy to radiate in the air and hence reduce the mutual coupling. Also, the slots between array elements, along with the two slits in each slot, block the coupling currents in the ground plane. The position of Y_{st} decides the size of the folded slot antenna which affects the mutual coupling. Despite that, the mutual coupling is below −19 dB, which represents the effectiveness of applied techniques.

V. BEAM STEERING CAPABILITY

Figure 13 shows the simulated 3D radiations patterns having the beam-steering capability at 20°, 40°, and 70°.

The beam at 40° is providing a 3-dB scanning range of 70°, while the beam at 70° is providing a scanning range up to 90°. Figure 14 shows the measured 2D beam-steering capability at three angles by applying the adequate phase shifts between elements to have 20°, 40°, 70° beams with the peak gain of 8.13 dBi, 6.8 dBi and 3.1 dBi respectively. The loss in gain is higher at far-angle due to higher cross-polarization as well as higher sidelobe levels at that angle. The results of active-S parameters in Fig. 15 show that the array is well-matched throughout the scanning range.

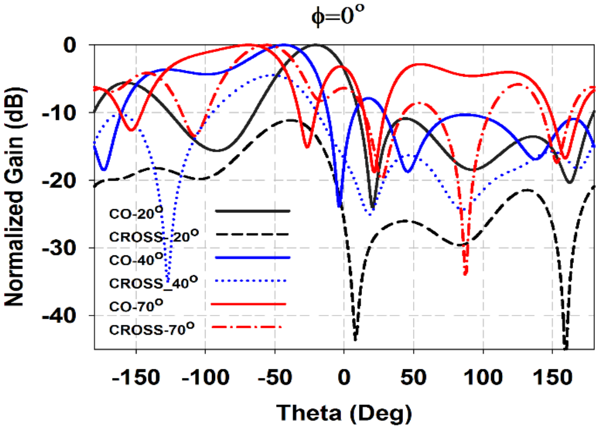


FIGURE 14. Measured 2D beam-steering capability at 20°, 40°, and 70°.

Since only a few compact PIFA phased arrays exist in the literature, therefore, the comparison of the proposed work is made with DRA-type compact phased array and a PIFA array for mobile applications. Table 3 shows the comparison between previous works on the compact arrays and the proposed design presented in this paper. The design presented in [8] is compact as having an inter-element spacing of 0.32λ, but it has limited scanning range and lower bandwidth. The design shown in [7], is bigger as inter-element spacing is 0.4λ

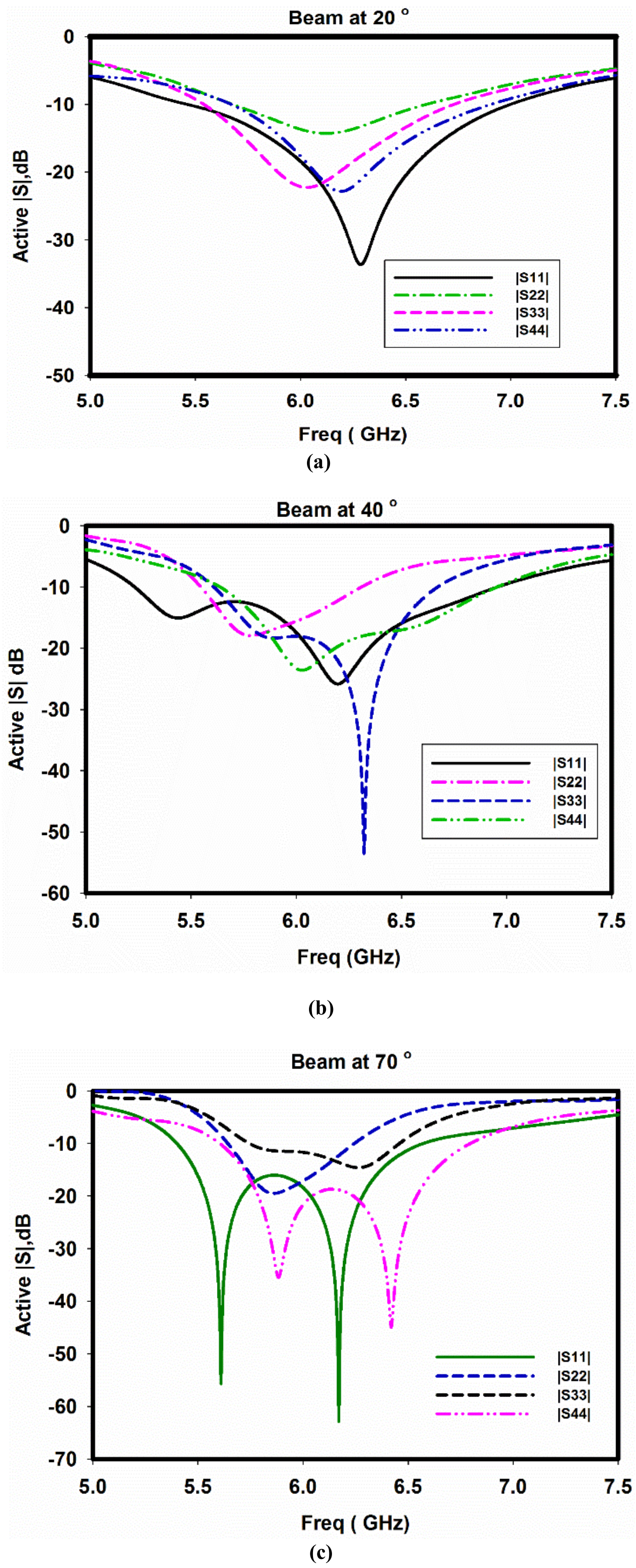


FIGURE 15. Active S-parameters for scanning angles, (a) 20°, (b) 40°, (c) 70°.

and also it has limited scanning range. Further, the design in [15] is bigger as inter-element spacing equals 0.5λ, and has a scanning range of up to 60^0 while no fabrication is done.

In comparison to these works, the proposed design is more compact with an inter-element spacing of just 0.3λ and has a scanning range of up to 70^o.

VI. CONCLUSION

In this paper, a compact phased PIEA array has been proposed, designed, fabricated and characterised for the upcoming 5G applications. Since the mutual coupling is a severe performance degrading factor in compact phased arrays, hence three mutual coupling reduction techniques are employed. With these mutual coupling reduction techniques, compact phased PIEA array with an inter-element spacing of $0.3\lambda_o$ is achieved which can work from 5.7 GHz to 6.4 GHz, with a maximum beam scanning angle of $\pm 70^o$. However, the cross-polarization and sidelobe level are higher at far beams which will be addressed in the future work.

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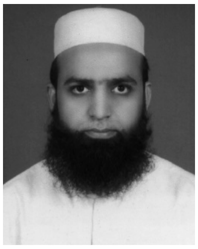

MUHAMMAD KAMRAN ISHFAQ received the bachelor's and master's degrees in electrical engineering from the University of Engineering and Technology Lahore, in 2005 and 2011, respectively, and the Ph.D. degree in phased arrays and multibeam antennas for 5G from the Wireless Communication Centre, Universiti Teknologi Malaysia, in 2018. He is currently an Assistant Professor with the Department of Electrical Engineering, Government College University Faisalabad, Pakistan. He has authored and coauthored journal and conference papers in the field of antennas, electrical and computer science. His current research interests include antennas, phased arrays, microwave systems, and computer networks.

THAREK ABD RAHMAN received the B.Sc. degree in electrical and electronic engineering from the University of Strathclyde, U.K., in 1979, the M.Sc. degree in communication engineering from UMIST, Manchester, U.K., and the Ph.D. degree in mobile radio communication engineering from the University of Bristol, U.K., in 1988. He is currently a Professor with the Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), where he is also the Director of the Wireless Communication Centre (WCC). He has been conducting various short courses related to mobile and satellite communication to the Telecommunication Industry and Government body, since 1990. He has a teaching experience in the area of mobile radio, wireless communication systems, and satellite communication. He has published more than 120 articles related to wireless communication in national/international journal and conference. His current research interests include radio propagation, antenna and RF design, and indoors and outdoors wireless communication.

MOHAMED HIMDI received the Ph.D. degree in signal processing and telecommunications from the University of Rennes 1, Rennes, France, in 1990. Since 2003, he has been a Professor with the University of Rennes 1. He is currently the Head of the Center National de la Recherche Scienti_que, High Frequency and Antenna Department, Institut d'Electronique et Télécommunications de Rennes, Unité Mixte de Recherche. He has authored or coauthored over 73 journal articles, over 170 papers in conference proceedings, and two book chapters. He holds 24 patents in the area of antennas. His research activities concern passive and active millimeter-wave antennas. His current research interests include theoretical and applied computational electromagnetics, development of new architectures of printed antenna arrays, and new 3-D antenna technologies. He was a recipient of the 1992 International Symposium on Antennas and Propagation Conference Young Researcher Scientist Fellowship, Japan, and the 1995 Award from the International Union of Radio Scientists, Russia. He was a Laureat of the Second National Competition for the Creation of Enterprises in Innovative Technologies, Ministry of Industry and Education, France, in 2000.

HASSAN TARIQ CHATTHA (M'12–SM'17) received the B.Sc. and M.Sc. degrees from the University of Engineering and Technology, Lahore, Pakistan, and the Ph.D. degree from the University of Liverpool, U.K., in 2010, all in electrical engineering. From 2005 to 2007, he was a Laboratory Engineer with the Faisalabad Campus, University of Engineering and Technology, Lahore. From 2010 to 2011, he was a Postdoctoral Researcher with the University of Liverpool, U.K. From 2011 to 2015, he was an Assistant Professor with the University of Engineering and Technology, Faisalabad Campus, Lahore, Pakistan. He is currently an Associate Professor with the Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Saudi Arabia. He has published around 70 technical articles in the leading international ISI-indexed journals and peer-reviewed reputed international conferences. He is the principal author of the majority of these articles. His research article was shortlisted as one of the best student articles at the International Workshop on Antenna and Technology (IWAT), Lisbon, Portugal, in 2010. He did the pioneering work in the design of single element dual-port antennas for diversity and MIMO applications and his articles on MIMO antennas have been published as featured articles in the *IET Electronics Letters* and the IEEE ANTENNA AND WIRELESS PROPAGATION LETTERS (AWPL). He is an active reviewer for many reputed IEEE and IET journals and letters. His current research interests include MIMO and diversity antennas, antennas for portable applications, reconfigurable antenna systems for 4G and 5G, multiband 5G antennas, UWB and wideband antennas, massive MIMO antenna systems, antenna systems for the IoT, and smart antennas.

YASIR SALEEM completed the secondary education (O-level and A-level) from England. He received the bachelor's, master's, and Ph.D. degree from the Electrical Engineering Department of the University of Engineering and Technology (UET), Lahore, Pakistan, in 2002, 2004, and 2011, respectively, and the MBA degree from ICBS, Lahore, in 2015, for better understanding of management and industry-academia relationship. During the Ph.D., he did research work for one semester with the Renewable Energy and Power Electronics Laboratory, Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia. He is currently an Associate Professor with the UET, Lahore, Pakistan. He has authored and coauthored journal and conference papers in field of electrical and computer science and engineering. His current research interests include computer networks, information/network security, DSP, power electronics, computer vision, image processing, simulation and control systems.

BILAL A. KHAWAJA (M'08–SM'18) received the B.S. degree in computer engineering from the Sir Syed University of Engineering and Technology, Karachi, Pakistan, in 2002, the M.Sc. degree in communication engineering and signal processing from the University of Plymouth, Plymouth, U.K., in 2005, and the Ph.D. degree in electrical engineering from the University of Bristol, Bristol, U.K., in 2010. From 2003 to 2004, he was a Software Engineer with Simcon International (Pvt.) Ltd, Pakistan. From 2010 to 2016, he was an Assistant Professor with the Electronics and Power Engineering Department, PN-Engineering College, National University of Science and Technology (NUST), Karachi, Pakistan. In 2015, he was a Visiting Postdoctoral Researcher with the Lightwave Systems Research Laboratory, Queens University, Kingston, Canada, involved in the Natural Sciences and Engineering Research Council (NSERC)-Canada CREATE Next Generation Optical Network (NGON) project on the characterization and measurements of 25GHz RF signal generation optical comb sources. He is currently an Associate Professor with the Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madina, Madina, Saudi Arabia. He has authored and coauthored several journals and IEEE proceeding publications. His current research interests include next-generation of millimetre-wave (mm-wave) radio-over-fiber and optical communication systems, mm-wave and THz signal generation mode-locked lasers and RF transceiver design and antennas design/characterization for the Wi-Fi/IoT/UAVs/FANETs/5G systems/UWB wireless body area networks, wireless sensor networks, and millimeter-wave frequency bands. He is an active reviewer for many reputed IEEE journals and letters.

FARHAN MASUD received the Ph.D. degree from the Universiti Teknologi Malaysia, in 2019. He is currently an Assistant Professor with the Department of Statistics and Computer Science, University of Veterinary and Animal Sciences, Lahore. He has authored and coauthored journal and conference papers in the field of computer science and electrical engineering. His current research interests include wireless sensor networks and antennas.

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