Received September 12, 2019, accepted September 30, 2019, date of current version October 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2945810

An FSS Based Multiband MIMO System Incorporating 3D Antennas for WLAN/WiMAX/5G Cellular and 5G Wi-Fi Applications

RASHID SALEEM[1], MUHAMMAD BILAL[2], HASSAN TARIQ CHATTHA[3], (Senior Member, IEEE), SABIH UR REHMAN[4], ANUM MUSHTAQ[1], AND MUHAMMAD FARHAN SHAFIQUE[5] (Senior Member, IEEE)

[1]Department of Telecommunication Engineering, University of Engineering and Technology, Taxila 47050, Pakistan
[2]Department of Telecommunication Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta 87300, Pakistan
[3]Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Medina 42351, Saudi Arabia
[4]School of Computing and Mathematics, Charles Sturt University, Wagga Wagga, NSW 2678, Australia
[5]Centre for Advanced Studies in Telecommunication (CAST), COMSATS University Islamabad (CUI), Islamabad 45550, Pakistan

Corresponding author: Muhammad Bilal (muhammad.bilal4@buitms.edu.pk)

ABSTRACT A compact 3-dimensional dual-element, multiband antenna for Multi-Input-Multi-Output (MIMO) applications is proposed in this paper. Folding technique along with various impedance matching structures are employed for miniaturization and multiband operation while maintaining the desired S-parameter performance. A grid of Frequency Selective Surface (FSS) patch based decoupling structure is introduced to achieve measured isolation of more than 30 dB between antenna ports. In addition to this decoupling structure, a meandered line based defected ground plane configuration helps to retain the multiband response while maintaining the optimum isolation performance. This 3D-MIMO antenna is fabricated and measured for its performance in different bands of WLAN, WiMAX, 5G cellular and 5G Wi-Fi along with different MIMO performance parameters. The reported design is a suitable option for multiband MIMO applications for future wireless technologies.

INDEX TERMS Antenna arrays, frequency selective surfaces, multifrequency antennas, MIMO, 5G mobile communication, WiMAX.

I. INTRODUCTION

Exponential growth in adoption of portable devices has raised the miniaturization standards and demand for value added features. High data rate services complement this evolution and a number of wireless standards have been proposed to cater for these demands in short range and long-range applications. Realization of compact RF front-end systems supporting multiple frequencies and various communication standards are necessary for next generation mobile devices [1]. A single antenna supporting multiple frequency bands for different standards e.g. Wireless Local Area Network (WLAN), Bluetooth, Global System for Mobiles (GSM), 5th generation (5G) mobile services and Worldwide Interoperability for Microwave Access (WiMAX) is an optimum solution to integration and space constraints since it is impractical to employ separate antennas for all these applications [2]–[4].

In addition to multiband operation, high data rates with low power requirements are best achievable through MIMO technology. Additionally, MIMO configuration is suitable to overcome the multipath fading effect [5], [6]. Although MIMO antenna system has a potential application in wireless communications to transmit data efficiently; however, when several antenna elements are placed in a close proximity, the data transmitted through different channels develop correlation, owing to undesired coupling between antennas, which in turn degrades the diversity performance of the MIMO system [7]. In particular, the mutual coupling causes blind scanning angles in phased arrays systems and also reduces diversity gain of MIMO arrays [13]. To overcome this limitation, antenna elements are separated by a distance equal to one half wavelength or more. However, this solution increases the overall size of the system and compromises the

The associate editor coordinating the review of this manuscript and approving it for publication was Akram Alomainy.

compactness [8]. Therefore, an efficient decoupling structure is required to reduce mutual coupling between antenna elements without increasing the separation [9], [10].

FSSs are generally employed in antennas to serve the purpose of miniaturization, gain enhancement, multiband operation and various others [11]. A distinct feature of reconfigurabilty and tunability can be introduced as well in miniature antennas when FSSs are employed along with switches or varactors. FSSs are also extremely beneficial in order to suppress mutual coupling among array elements [12]. The mutual coupling between antenna array ports is caused by undesired surface wave phenomenon and FSS is capable of suppressing these surface waves by acting as resonators at the desired decoupling frequency.

A large number of multi-band MIMO antenna systems are reported in recent literature. In [14], a dual-band microstrip patch antenna (MSA) is reported for MIMO applications. This system employs Substrate Integrated Waveguide (SIW) and miniaturized Spoof Surface Plasmon Polariton (SSPP) to achieve 20 dB isolation while keeping large footprint of 60 mm × 120 mm. A dual-band decoupling split EBG structure is reported in [15] in order to isolate a couple of meander-line antennas. This 44 mm × 58 mm configuration achieves isolation of 26 and 44 dB at 3.48 and 4.88 GHz respectively. Another study presents a 2 × 1 multi-band MIMO array comprising 3D antenna elements [16]. This configuration achieves isolation of 23 dB while having large dimensions of 300 mm × 200 mm. Likewise a two-port dual-band pattern diversity patch antenna is reported in [17]. The folding microstrip line and coplanar waveguide (CPW) structure are printed on the two sides of single feeding network with overall system size of 120 mm × 47 mm including ground plane. This configuration offers an isolation of 20 dB at the cost of larger dimensions while maintaining impedance matching. An Inverted-F Antenna (IFA) for 5G mobile MIMO application is reported in [18]. This proposed system offers isolation of 20 – 40 dB with large dimension of 100 mm × 50 mm. In [19], a 60 mm × 100 mm dual element multiband MIMO antenna system is reported for indoor wireless applications. This proposed structure maintains less than 30 dB isolation over a limited frequency spectrum. A couple of semi-printed fractal antennas having 121.8 mm × 61.45 mm dimensions are presented in [20]. This reported system achieves less than 20 dB isolation in 2.4 – 2.489 GHz band. In [21] a 120 mm × 80 mm dual-antenna system with a folded fork-shaped ground branch for electromagnetic decoupling is proposed. This multiband MIMO achieves isolation of maximum 15 dB in the operating band. A decoupled dual-antenna system with crossed neutralization lines is studied in [22]. This reported system offers less than 15 dB isolation with relatively high footprint of 120 mm × 80 mm. In [23], a reconfigurable MIMO antenna is reported with dimensions of 65 mm × 120 mm. An overall isolation of 20 dB is attained by this system. From the literature reported here it can be inferred that compactness and isolation are challenging to achieve together while achieving multiband operation and the desired diversity performance.

In this paper, a compact 3D dual Folded Monopole Antenna (FMA) system exhibiting multiple resonances is proposed. A combination of resonant structures including T-shaped and rectangular slots, meander-line structure and folded armatures are employed to achieve resonances at the desired frequencies. The operating frequency bands of the proposed FMA are 2.4 GHz – 2.48 GHz [24], 2.91 GHz – 3.49 GHz and 3.27 GHz – 3.97 GHz [25], [26], 3.4 GHz – 3.8 GHz [27] and 5.15 GHz – 5.85 GHz [28] for WLAN, WiMAX, 5G cellular and 5G Wi-Fi services respectively. Moreover, a planar array of square patch FSS is introduced to suppress the overall undesired mutual coupling between antenna pairs.

The rest of this paper is arranged as follows: Section II presents FMA antenna element configuration. Design of the decoupling structure is presented in Section III. In section IV, simulated and measured results are discussed. MIMO performance parameters are reported in section V, Section VI presents detailed comparison of proposed system with existing literature and finally section VII concludes the paper.

II. DESIGN CONFIGURATION

The proposed dual element FMA-MIMO is realized on a low cost 1 mm thick FR-4 laminate having compact dimensions of 70 mm × 50 mm. The employed laminate has relative permittivity $\varepsilon_r = 4.4$, and a dielectric loss tangent $tan\delta = 0.02$. The proposed FMA pairs are fabricated with a copper sheet having a thickness of 0.2 mm.

This geometry has evolved from a conventional 3D IFA system to achieve a wideband response initially. MIMO configuration is achieved by separately designing a pair of FMAs on two feeding strips for multiband response. FMAs are then connected to feeding strips through 1-mm thick shorting pins on the upper metallic layer. A staircase profile is added near the feeding edge to achieve the impedance match over lower frequencies. The separation between FMAs and substrate surface is kept at 1 mm to maintain the impedance performance [29]. However, improved resonance performance is observed when another set of FMAs are mirrored on the same feeding lines (Fig. 1 step. 3). Square aperture is machined at the base of each FMA pair which helps to improve overall impedance response. A T-shaped slot and two sets of stubs, S_1 and S_2 (three on each sides), tunes and strengthens the resonances of antenna at each band while maintaining impedance bandwidth. Moreover, rectangular strips are introduced on either side of the FMA pairs to offer a resonance at 3.2 GHz (WiMAX band) and it also aids to reduce the effect of induced currents on the ground plane [30].

Polystyrene blocks having dimensions 11 × 10 × 11 mm^3 are placed inside the square aperture in order to further support these FMA pairs. All evolution steps and their respective reflection coefficient response are shown in Fig 1. The overall geometrical configuration of the finalized 3D antenna system

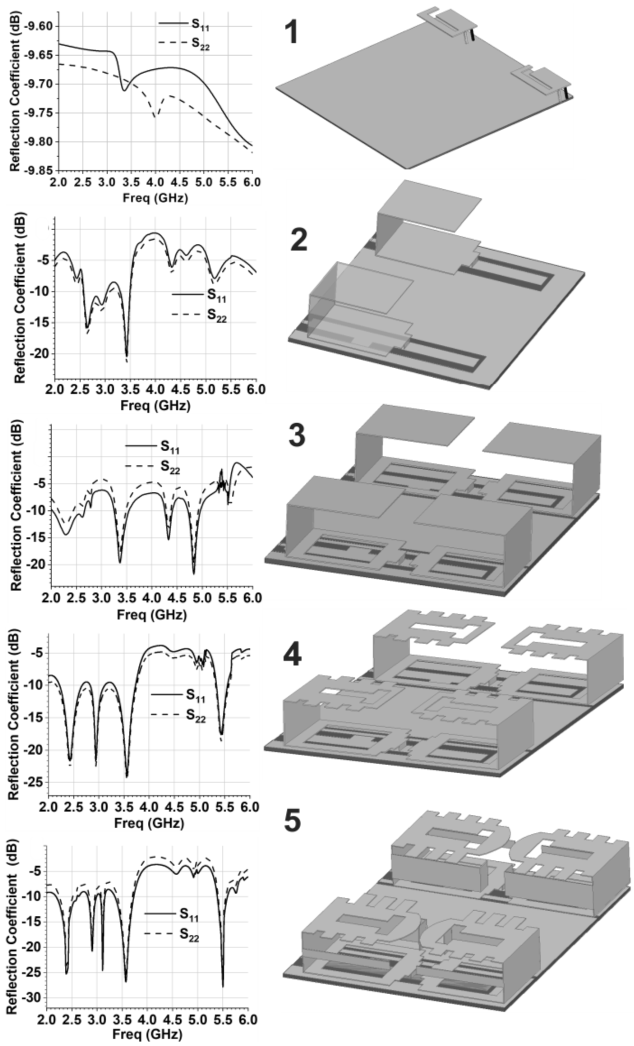


FIGURE 1. FMA-MIMO design evolution with flat metallic ground and without decoupling.

is illustrated in Fig. 2 and 3 and the optimized dimensions are listed in Table 1.

III. DECOUPLING CONFIGURATION

Owing to good reflectivity and overall mutual coupling suppression characteristics, a grid of metallic square patch FSSs are introduced to decouple FMA pairs on upper layer as shown in Fig. 3a. Initially, four longer slits T_1 to T_4 are introduced among FMA pairs followed by an optimized FSS array of 4 × 17 cells that is enclosed in these four slits to achieve the desired isolation. Moreover, a defected ground plane configuration is devised by employing meandered structure in the ground plane as shown in Fig. 3b. This meandered structure act as an interdigital capacitor to trap the surfaces currents and improves multi-band performance after inserting lossy FSS based decoupling mechanism. The number of turns in the meandered structure is optimally selected to achieve stronger resonances in the desired bands.

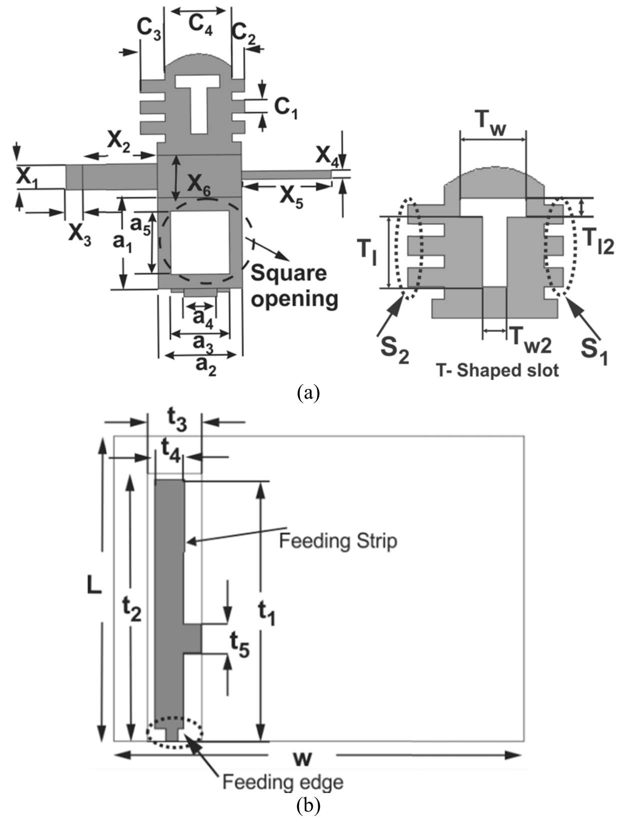


FIGURE 2. FMA-MIMO design configurations, (a) unfolded view of FMA with T-shaped configuration and (b) feeding strip.

TABLE 1. Dimensions of FMA-MIMO.

Variables	Optimized dimension (mm)	Variables	Optimized dimension (mm)
L	50	T_l	11
W	70	T_{w2}	4
a_1	11	T_{l2}	3
a_1	21.5	t_1	45.5
a_2	20	t_2	45.8
a_3	14	t_3	10
a_4	10	t_4	7
a_5	15	t_5	5
$C1$	3	e_1	10
$C2$	3	e_2	1
$C3$	5	e_3	2
$C4$	16	e_4	17
X_1	5.5	e_5	25
X_2	22	e_6	34
X_3	4	e_7	48
X_4	3	f	45.5
X_5	21.5	m_1	6
X_6	9.5	m_2	2
T_w	10.5	m_3	15

A. FSS ANALYSIS

The employed square patch FSS unit cell has compact dimension of $e_3 \times e_8$. The unit cell analysis and optimization is

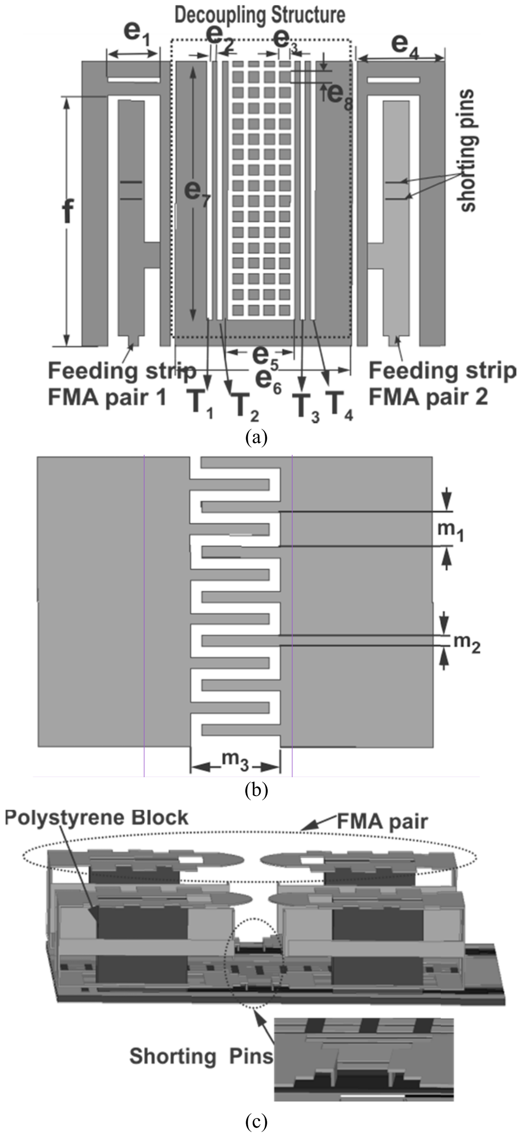


FIGURE 3. Decoupling configurations (a) square patch FSS based decupling structure on upper layer (b) menderline configuration at ground plane and (e) finalized 3D view.

performed by using a full-wave finite-element method based electromagnetic solver (Ansys HFSS®). In addition to the Floquet analysis of the FSS grid, the Finite Element Boundary Integral (FE-BI) analysis is also carried out to validate the actual performance of the finite elements of FSS grid as illustrated in Fig. 4a. This FSS achieves at least 17 dB reflectivity over the desired band as shown in Fig. 4b.

IV. SIMULATIONS AND MEASUREMENTS

The prototype of the proposed FMA-MIMO is fabricated (Fig. 5) to test and verify the simulations. The simulated and measured results of FMA-MIMO are presented in the following subsections.

A. REFLECTION COEFFICIENT PERFORMANCE

This system is simulated and measured with and without decoupling structure to demonstrate the effect of decoupling

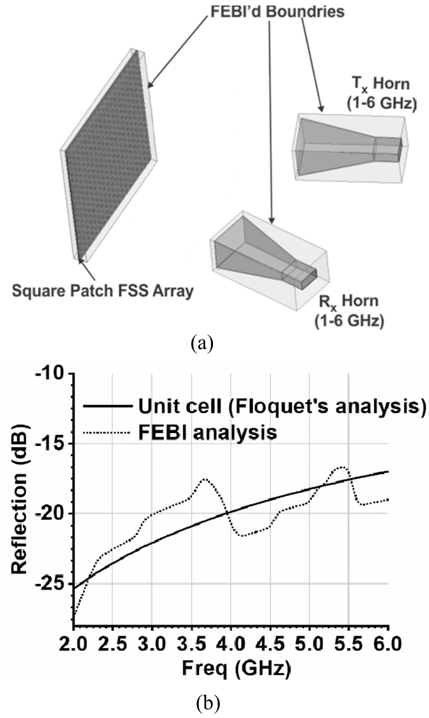


FIGURE 4. Square patch FSS analysis (a) FEBI analysis setup and (b) reflection response.

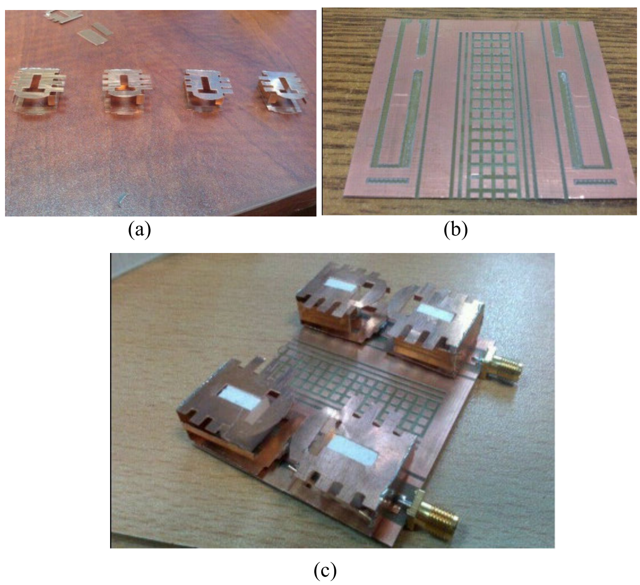


FIGURE 5. Fabricated dual-element FMA MIMO. (a) Folded radiators/ armatures. (b) Ground plane with decoupling and feed line structures and (c) Dual-channel FMA-MIMO system.

structure. The resonant frequencies of the proposed FMA are 2.4 GHz (WLAN), 2.95 GHz and 3.2 GHz (WiMAX), 3.6 GHz (5G cellular) and 5.5 GHz (5G Wi-Fi) as shown in Fig. 6. It can be observed form the results that the reflection coefficient performance is slightly degraded with the introduction of the decoupling structure. This is however compensated with the help of mender line structure and reverted

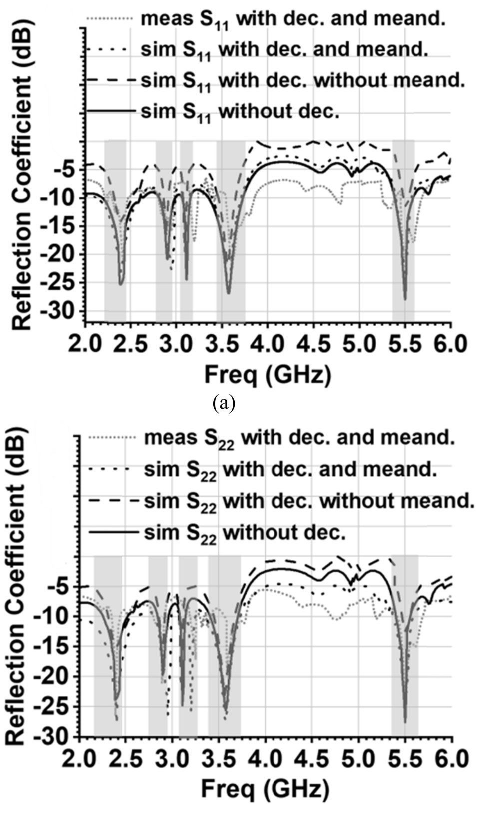


FIGURE 6. Reflection coefficient performance (a) FMA pair 1 and (b) FMA pair 2 reflection response.

back to optimum limits. Overall, simulated and measured reflection coefficient are in agreement within the allowable limits.

B. DECOUPLING PERFORMANCE

The simulated and measured mutual coupling results of dual-element FMA-MIMO system are shown in Fig. 7. The proposed FSS based decoupling structure suppresses the undesired mutual coupling and improves isolation between FMA pairs considerably to 30 dB in the desired bands.

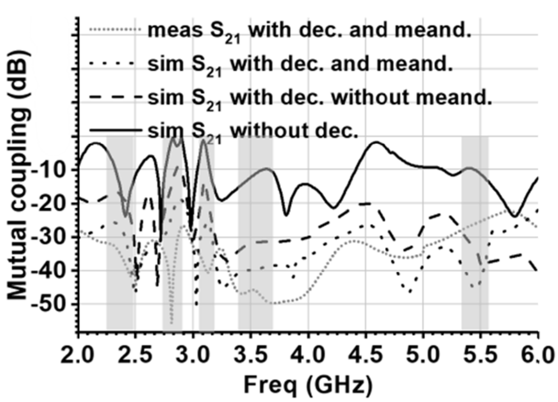


FIGURE 7. Decoupling performance of the proposed FMA-MIMO.

C. SURFACE CURRENT DISTRIBUTION

The surface current distribution with decoupling mechanism at 2.4 GHz and 5.5 GHz is presented in Fig. 8. By introducing the decoupling structure, currents induced on the non-excited element are suppressed effectively as observed from the surface current distribution. However, a slight coupling is inevitable between the FMA elements.

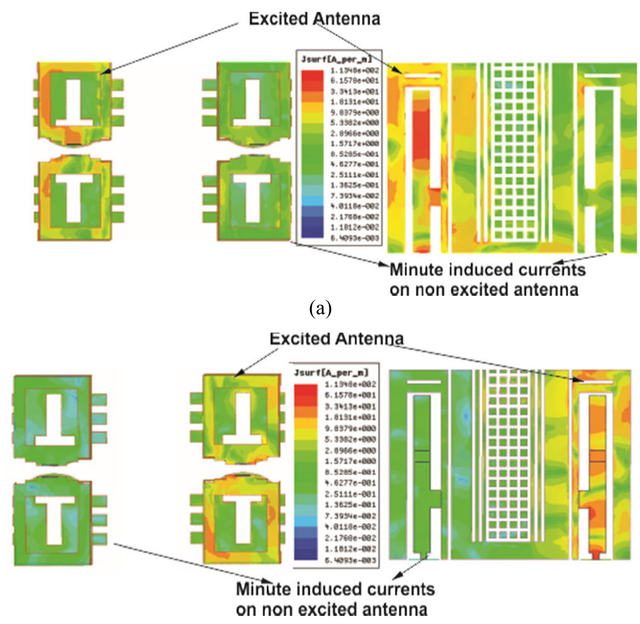


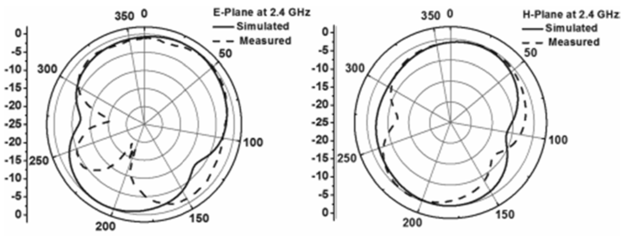
FIGURE 8. Surface current density with decoupling structure (a) 2.4 GHz and (b) 5.5 GHz.

D. RADIATION CHARACTERSTICS

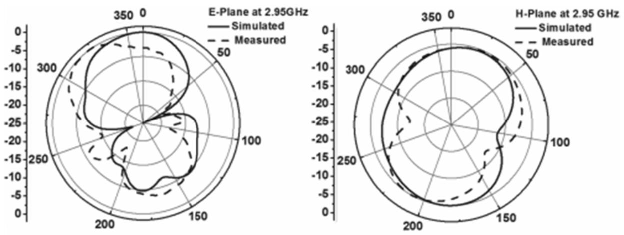
The simulated and measured E-field and H-field patterns of the proposed FMA-MIMO system design are shown in Fig. 9. The patterns are obtained at frequencies 2.4 GHz, 2.95 GHz, 3.6 GHz and 5.5 GHz. The simulated and measured results reveal that proposed FMA-MIMO antenna system provides quasi omnidirectional patterns in both the planes. The patterns exhibit slight distortion in the measurements process owing to the non-planar configuration and fabrication imperfections. Moreover, for higher frequencies, in this case 5.5 GHz, patterns tend to distort because of smaller wavelengths and less tolerance to the geometry imperfection.

V. MIMO PERFORMANCE

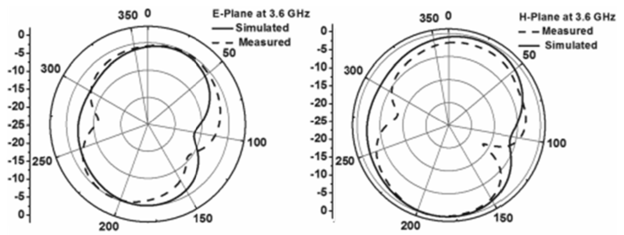
The MIMO performance of the proposed system is evaluated through certain parameters including Envelope Correlation Coefficient (ECC), Channel Capacity Loss (CCL), Diversity Gain (DG) and Total Active Reflection Coefficient (TARC). For an acceptable MIMO performance ECC and CCL should be less than 0.5 whereas TARC should be below 0 dB [30]. ECC, DG and TARC are calculated using the relations given in [31]. ECC can be evaluated through scattering parameters



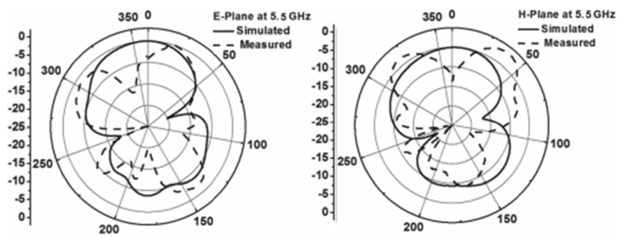
(a)



(b)



(c)



(d)

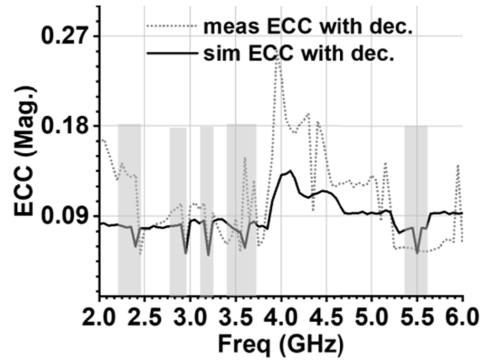
FIGURE 9. **Radiation patterns at (a) 2.4 GHz, (b) 2.95 GHz, (c) 3.6 GHz and (d) 5.5 GHz.**

that offer an accurate estimation of the envelope correlation in an isotropic and rich scattering environment. Moreover, diversity gain is related to the calculated ECC value of the MIMO antenna system as given in (1) [32]

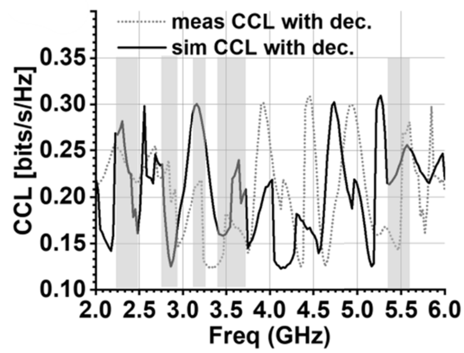
$$DG = 10\sqrt{1 - |ECC|^2} \tag{1}$$

Fig. 10. presents MIMO performance parameters for the proposed FMA-MIMO. It can be observed that all parameters are within the acceptable range i.e, ECC is less than 0.18, CCL is less than 0.3 bits/s/Hz, TARC achieves the overall value of less than -15 dB with some variations at resonant band. Furthermore, the radiation efficiency and peak gain of the proposed MIMO antenna is shown in Fig 11a and Fig 11b respectively.

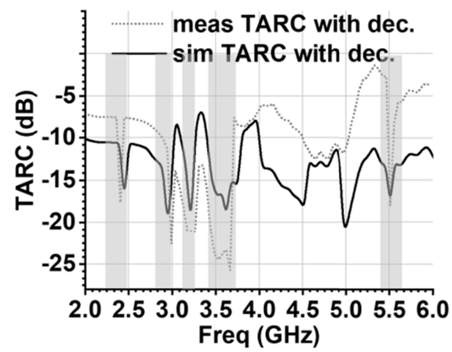
The simulated radiation efficiency varies between 65% and 75% without decoupling structure. The decoupling structure slightly reduces the radiation efficiency at resonant frequencies to vary between 55% and 65%. However, considerable improvement (over 45%) in MIMO performance parameters and better isolation is achieved. The radiation



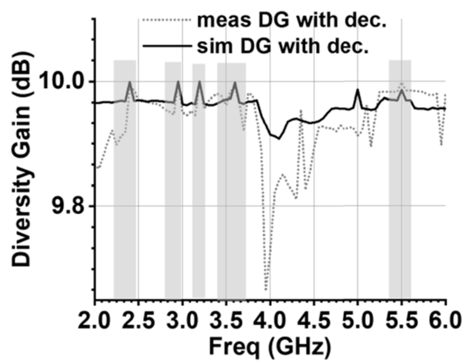
(a)



(b)



(c)



(d)

FIGURE 10. **MIMO performance (a) ECC, (b) CCL, (c) TARC and (d) DG.**

TABLE 2. Comparison with existing literature.

References	Ports	Dimensions (mm^3)	Isolation (dB)	ECC	TARC	CCL	Gain (dBi)	Band coverage
[14]	2	60 × 120 × 0.8/1	30	-	-	-	-	Two
[15]	2	44 × 58 × 1.2	35	0.007	-	-	-	Two
[16]	2	300 × 200 × 1	25	0.001	-	-	<5	Three
[17]	2	120 × 47 × 1	20	<0.04	-	-	2.6-4.5	Two
[18]	2	100 × 50 × 1.6	20-40	0.0007	-	-	2.7	One
[19]	2	60 × 100 × 0.8	<30	-	-	-	3-4	Four
[20]	2	121.8 × 61.45 × 0.812	<20	<0.1	-	-	-	Two
[21]	2	120 × 80 × 0.8	>15	<0.5	-	-	-	Four
[22]	2	120 × 80× 0.8	<15	<0.5	-	-	-1.79 – 3.75	Four
[23]	2	65 × 120 × 0.8	<20	<0.028	-	-	0.5-5.2	Four
This work	**2**	**50 × 70 × 1.6**	**<30**	**<0.25**	**<-8**	**<0.3**	**3-4**	**Five**

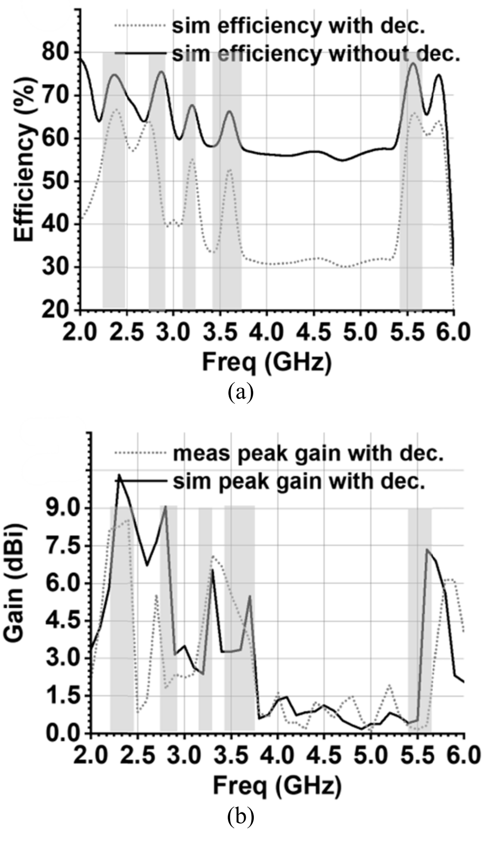


FIGURE 11. FMA-MIMO performance (a) radiation efficiency (b) peak gain.

efficiency is low primarily because of the lossy nature of FR-4, and it can be increased by using low-loss substrates. The antenna has reasonable gain values in the desired frequency bands in particular 9 dBi (WLAN), 7.5 dBi & 6.5 dBi (WiMAX), 4 dBi (5G cellular), and 7 dBi (5G Wi-Fi).

VI. COMPARISON WITH OTHER DESIGNS

The proposed MIMO system is designed for various wireless applications altogether. The existing literature reports several MIMO antennas. However, the proposed design is highly competitive to the reported designs in terms of isolation, size/profile and overall bands coverage. This 3D MIMO antenna system not only has a compact size but also exhibits efficient performance. A comprehensive comparison with the recent literature is shown in Table 2. The proposed work is compared with two-port 2D and 3D reported designs. Moreover, proposed design has desirable values of ECC, CCL and TARC and the optimum values of gain in comparison, whereas most of the reported designs in table are not evaluated in terms of CCL and TARC

VII. CONCLUSION

A dual-element, multiband FMA-MIMO antenna system is proposed in this work. This design finds its applications where multiband and MIMO functionalities are required simultaneously. FMA pairing on sophisticated feeding strips, optimum shorting pins, slotting technique and menderline configuration are the few highlighting features of the proposed design. These features help to achieve multiband communication for WLAN, WiMAX, 5G cellular and 5G Wi-Fi services while maintaining optimum impedance match. The mutual coupling between FMA pairs is effectively suppressed by employing an array of square patch FSS structures. To verify the simulated results, a prototype FMA-MIMO system is fabricated and tested. An overall measured isolation of 30 dB is achieved between FMA pairs. Alongside, the mutual coupling suppression and other performance characteristics like radiation pattern, ECC, CCL, TARC, DG and radiation efficiency signify that the proposed antenna system is a promising candidate for multiservice software defined radio (SDR) devices and various other wireless communication systems like airport communications, automotive communications, subway communication systems and railway communication systems.

REFERENCES

[1] L. Liu, S. W. Cheung, and T. I. Yuk, "Compact MIMO Antenna for portable devices in UWB applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 8, pp. 4257–4264, Aug. 2013.

[2] Y. Yao, X. Wang, X. Chen, J. Yu, and S. Liu, ''Novel diversity/MIMO PIFA antenna with broadband circular polarization for multimode satellite navigation,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 65–68, 2012.
[3] K. Zhao, S. Zhang, Z. Ying, T. Bolin, and S. He, ''SAR study of different MIMO antenna designs for LTE application in smart mobile handsets,'' *IEEE Trans. Antennas Propag.*, vol. 61, no. 6, pp. 3270–3279, Jun. 2013.
[4] B. Mun, C. Jung, M.-J. Park, and B. Lee, ''A compact frequency-reconfigurable multiband LTE MIMO antenna for laptop applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1389–1392, 2014.
[5] J.-F. Li, Q.-X. Chu, and T.-G. Huang, ''A compact wideband MIMO antenna with two novel bent slits,'' *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 482–489, Feb. 2012.
[6] J. Ø. Nielsen, B. Yanakiev, I. B. Bonev, M. Christensen, and G. F. Pedersen, ''User influence on MIMO channel capacity for handsets in data mode operation,'' *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 633–643, Feb. 2012.
[7] M. Ayatollahi, Q. Rao, and D. Wang, ''A compact, high isolation and wide bandwidth antenna array for long term evolution wireless devices,'' *IEEE Trans. Antennas Propag.*, vol. 60, no. 10, pp. 4960–4963, Oct. 2012.
[8] A. Toktas and A. Akdagli, ''Wideband MIMO antenna with enhanced isolation for LTE, WiMAX and WLAN mobile handsets,'' *Electron. Lett.*, vol. 50, no. 10, pp. 723–724, May 2014.
[9] A. P. Feresidis and Q. Li, ''Miniaturised slits for decoupling PIFA array elements on handheld devices,'' *Electron. Lett.*, vol. 48, no. 6, pp. 310–312, Mar. 2012.
[10] J. Xiong, M. Zhao, H. Li, Z. Ying, and B. Wang, ''Collocated electric and magnetic dipoles with extremely low correlation as a reference antenna for polarization diversity MIMO applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 423–426, 2012.
[11] B. F. Gross, *Frontiers in Antennas: Next Generation Design & Engineering*. New York, NY, USA: McGraw-Hill, 2011.
[12] Y. Rahmat-Samii and E. Michielssen, *Electromagnetic Optimization by Genetic Algorithms*. Hoboken, NJ, USA: Wiley, 1999.
[13] R. Saleem, M. Bilal, K. B. Bajwa, and M. F. Shafique, ''Eight-element UWB-MIMO array with three distinct isolation mechanisms,'' *Electron. Lett.*, vol. 51, no. 4, pp. 311–313, Feb. 2015.
[14] B. C. Pan and K. J. Cui, ''Broadband decoupling network for dual-band microstrip patch antennas,'' *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5595–5598, Oct. 2017.
[15] X. Tan, W. Wang, Y. Wu, Y. Liu, and A. A. Kishk, ''Enhancing isolation in dual-band meander-line multiple antenna by employing split EBG structure,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2769–2774, Apr. 2019.
[16] Z. H. Jiang, L. Zhang, Y. Zhang, C. Yu, L. Cai, S. Zheng, and W. Hong, ''A compact triple-band antenna with a notched ultra-wideband and its MIMO array,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 7021–7031, Dec. 2018.
[17] X. Liu, Y. Wu, Z. Zhuang, W. Wang, and Y. Liu, ''A dual-band patch antenna for pattern diversity application,'' *IEEE Access*, vol. 6, pp. 51986–51993, 2018.
[18] X. Zhao, S. P. Yeo, and L. C. Ong, ''Decoupling of inverted-F antennas with high-order modes of ground plane for 5G mobile MIMO platform,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4485–4495, Jun. 2018.
[19] Y. Yang, Q. Chu, and C. Mao, ''Multiband MIMO antenna for GSM, DCS, and LTE indoor applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1573–1576, 2016.
[20] A. Peristerianos, A. Theopoulos, A. G. Koutinos, T. Kaifas, and K. Siakavara, ''Dual-band fractal semi-printed element antenna arrays for MIMO applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 730–733, 2016.
[21] S. Wang and Z. Du, ''A multiband dual-antenna system with a folded fork-shaped ground branch and folded asymmetric U-shaped slots for smartphone applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1626–1629, 2015.
[22] S. Wang and Z. Du, ''Decoupled dual-antenna system using crossed neutralization lines for LTE/WWAN smartphone applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 523–526, 2015.
[23] R. Hussain and M. S. Sharawi, ''Integrated reconfigurable multiple-input–multiple-output antenna system with an ultra-wideband sensing antenna for cognitive radio platforms,'' *IET Microw., Antennas Propag.*, vol. 9, no. 9, pp. 940–947, Jun. 2015.
[24] L. Dong, Z.-Y. Zhang, W. Li, and G. Fu, ''A compact CPW-fed monopole antenna with triple bands for WLAN/WiMAX applications,'' *Prog. Electromagn. Res. Lett.*, vol. 39, pp. 103–113, Apr. 2013.
[25] M. M. Hasan, M. R. I. Faruque, and M. T. Islam, ''Dual band metamaterial antenna for LTE/Bluetooth/WiMAX system,'' *Sci. Rep.*, vol. 8, Jan. 2018, Art. no. 1240.
[26] Y. F. Cao, S. W. Cheung, and T. I. Yuk, ''A multiband slot antenna for GPS/WiMAX/WLAN systems,'' *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 952–958, Mar. 2015.
[27] A. Zhao and Z. Ren, ''Size reduction of self-isolated MIMO antenna system for 5G mobile phone applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 1, pp. 152–156, Jan. 2019.
[28] L. Ge, X. Yang, M. Li, and H. Wong, ''Polarization-reconfigurable magnetoelectric dipole antenna for 5G Wi-Fi,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1504–1507, 2017.
[29] H. T. Chattha, Y. Huang, S. J. Boyes, and X. Zhu, ''Polarization and pattern diversity-based dual-feed planar inverted-F antenna,'' *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1532–1539, Mar. 2012.
[30] M. S. Sharawi, ''Printed multi-band MIMO antenna systems and their performance metrics [wireless corner],'' *IEEE Antennas Propag. Mag.*, vol. 55, no. 5, pp. 218–232, Oct. 2013.
[31] R. Chandel, A. K. Gautam, and K. Rambabu, ''Tapered fed compact UWB MIMO-diversity antenna with dual band-notched characteristics,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 1677–1684, Apr. 2018.
[32] F. Amin, R. Saleem, T. Shabbir, S. Rehman, M. Bilal, and M. F. Shafique, ''A compact quad-element UWB-MIMO antenna system with parasitic decoupling mechanism,'' *Appl. Sci.* , vol. 9, no. 11, p. 2371, Jun. 2019.

RASHID SALEEM received the B.S. degree in electronic engineering from the Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan, in 1999, the M.S. degree from the Center for Advanced Studies in Engineering, UET Taxila, Pakistan, in 2006, and the Ph.D. degree from The University of Manchester, U.K., in 2011. He was with telecommunication industry for several years while continuing education. He worked on antennas, channel modeling, and interference aspects of Ultra Wideband systems, during his Ph.D. degree. He was also a member of a team designing and testing arrays for the Square Kilometer Array project. He is currently an Assistant Professor with the University of Engineering and Technology (UET), Taxila, Pakistan, where he is also supervising several master's degree students and heading the Microwave Antennas and Propagation (MAP) Research Group. His research interests include antennas, angle-of-arrival-based channel modeling, microwave periodic structures, and metamaterial.

MUHAMMAD BILAL received the B.S. degree in telecommunication engineering from the Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Quetta, Pakistan, in 2011, and the master's degree in telecommunication engineering and the Ph.D. degree in antennas and electromagnetics from the University of Engineering and Technology (UET) Taxila, Pakistan, in 2014 and in 2018, respectively. Since February 2018, he has been an Assistant Professor with the Department of Telecommunication Engineering, BUITEMS, where he is currently heading Higher Education Commission (HEC) funded research project while supervising the bachelor's and master's degree students. He has published articles in many reputable scientific journals and conferences. His current research interests include UWB-MIMO systems, high gain portable devices, frequency selective surfaces and reflectarrays. He was a recipient of a fully funded scholarship for his master's degree.

HASSAN TARIQ CHATTHA (M'12–SM'17) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, and the Ph.D. degree in electrical engineering from the University of Liverpool, U.K., in 2010. From 2005 to 2007, he was a Lab Engineer with the University of Engineering and Technology, Lahore, Faisalabad. From 2010 to 2011, he was a Postdoctoral Researcher with the University of Liverpool. From 2011 to 2015, he was an Assistant Professor with the University of Engineering and Technology. 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 60 articles in the leading international ISI-indexed journals and peer-reviewed and reputed international conferences. He is the principal author of most 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 multiport 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 Antennas and Wireless Propagation Letters (AWPL). His research interests include 4G and 5G systems, MIMO systems for portable applications, massive MIMO systems, reconfigurable and smart cognitive systems, the Internet of Things (IoT) and smart city applications, body area networks and wearable devices, wireless sensor networks, rectenna arrays for power collection and energy harvesting, and teaching methods and assessments for engineering students. He is also an Active Reviewer for the many reputed IEEE and IET journals and letters. He has been an Associate Editor of IEEE Access, since 2017, and has hosted two special issues as the Lead Guest Editor and the Guest Editor in *Wireless Communications and Mobile Computing* and the *International Journal of Antennas and Propagation*.

SABIH UR REHMAN received the bachelor's degree (Hons.) in electronics and telecommunication engineering from the University of South Australia, Adelaide, and the Ph.D. degree in vehicular ad-hoc networks from Charles Sturt University, Australia, where he is currently a Lecturer in computing with the School of Computing and Mathematics. His research interests include quality of service (QoS), cross-layer protocol architecture designing, wireless propagation and antenna modeling using mathematical/stochastic models and conducting performance analysis, and the Internet of Things (IoT) especially in the context of intelligent transport systems and precision agriculture. He was a recipient of a Competitive Scholarship for his Ph.D. degree.

ANUM MUSHTAQ received the B.Sc. degree in telecom engineering from the University of Engineering and Technology, Taxila, Punjab, in 2011, and the master's degree in telecom, in 2015. She joined as a Lab Engineer with UET Taxila, Pakistan, in 2011, where she is currently a Research Assistant. Her main research interests include partial reflecting surfaces, UWB systems, metamaterials, and high gain antennas.

MUHAMMAD FARHAN SHAFIQUE (S'08–M'11–SM'15) received the B.Eng. degree from Hamdard University, Karachi, Pakistan, in 2003, the M.S. degree from the University of Paris East Marne-La-Vallee, Paris, France, in 2005, and the Ph.D. degree in electronic and communications engineering from The University of Leeds, Leeds, U.K., in 2010. From 2007 to 2010, he was involved in establishing the LTCC fabrication facility with the Institute of Microwave and Photonics, The University of Leeds, U.K. He has extensive experience of laser micromachining and multilayer LTCC device modeling and fabrication. He is currently an Associate Professor with COMSATS University Islamabad (CUI), Pakistan. He is also a Founder Head the of MCAD Research Group, the Associate Director of the Center for Advanced Studies in telecommunications. He is also involved in dielectric characterization of materials using microwave techniques and fabrication of ceramic microfluidic devices. His research interests include multilayered-microwave device fabrication on LTCC and thick-film technology, RF antenna and antenna arrays, ultra wideband diversity antennas, and MEMS packaging.