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28/38 GHz Dual-Band Yagi-Uda Antenna with Corrugated Radiator and Enhanced Reflectors for 5G MIMO Antenna Systems

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Abstract—A novel design of an enhanced Yagi-Uda antenna is introduced for dual-band operation at 28/38 GHz. The antenna is constructed by a corrugated dipole strip and a capacitively end-coupled extension strip as the driving element, two reflectors, and one director. Periodic parasitic elements are added in front of the reflectors to enhance the antenna gain and improve the impedance matching. The driving dipole is fed through a coplanar strip line, and in order to facilitate the experimental measurements using a coaxial feed line, a microstrip to coplanar strip (CPS) line transition is employed. A four-port MIMO antenna system is constructed using the proposed Yagi-Uda antenna arranged at the edges of the mobile handset. Numerical and experimental investigations are achieved to assess the performance of both the single-element antenna and the four-port MIMO antenna system. It is shown that the simulation results agree with the experimental measurements, and both show good performance of the single antenna as well as the MIMO antenna system. The bandwidths achieved around 28 GHz and 38 GHz are about 3.42 GHz and 1.45 GHz, respectively, using the microstrip feed line. Each antenna has a maximum gain of about 9 dB. The four antenna configuration shows radiation pattern diversity required for MIMO system. The envelope correlation coefficient (ECC) and diversity gain (DG) are calculated, and the results show that the proposed MIMO antenna system is suitable for the forthcoming 5G mobile communications.

1. INTRODUCTION

It has been recently reported that mm-wave in 28 GHz and 38 GHz frequency bands can be used in wireless cellular communication systems [1]. The future fifth generation (5G) applications requires higher bandwidths for higher data rates provided by the millimeter wave bands [2]. However, as the operating frequency increases, the wavelength of the signal becomes shorter, and consequently the free-space path loss is higher, according to Friis transmission equation [3, 4]. Thus, High gain antennas may be needed to compensate the large free-space path losses and various forms of fading that can be observed in the communication channel [5, 6]. MIMO antenna system can offer advantages when considering multipath effects. The combination of both high gain and MIMO configurations can provide some novel antenna and circuit solutions for mobile communication applications at mm-wave frequencies. This can minimize the operating costs of any supporting power amplifiers and other control circuitry [7].

The frequency spectra around 28 GHz, 38 GHz, 60 GHz, and 73 GHz are estimated bands under consideration for 5G technology. These millimeter wave bands would bring new challenges in the implementation of MIMO antennas for handheld devices [8]. With the fast development of the industry of wireless communication, there is an increase in the demand of multiband and highly isolated MIMO antennas for terminal users of cellular networks. Various dual band MIMO antennas have been reported in literature. In [8], a 4×4 28/38 dual-band MIMO antenna system employing a round patch EBG cell is introduced with low mutual coupling at both bands even at a close distance of 0.7 mm. In [9], a

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dual-band MIMO antenna system is composed of two orthogonal elements operating in the frequency bands 1.62–3.2 GHZ and 4.4–5.9 GHz. In [10], a 28/38 dual-band slotted rectangular patch antenna with proximity coupled feed is built on a multilayer substrate of low temperature co-fiber ceramics. The antenna achieves wide bandwidth of more than 4 GHz at both operating frequencies. In [11], a dual-band 28/45 circular microstrip patch antenna with an elliptical slot is presented with bandwidths of 1.3 GHz and 1 GHz at 28 GHz and 45 GHz, respectively. A circular radiating patch placed non-concentrically inside a circular slot etched off the ground plane is presented in [12], operating in 28 and 38 GHz bands.

Yagi-Uda antennas are good candidates for millimeter wave and microwave applications due to their high gain, high efficiency, low-cost, and ease of fabrication. They are one of the most known endfire radiation pattern antennas that can achieve medium gain. In [13] a Yagi-Uda antenna operating at 24 GHz is implemented in a 11-beam system using a planar array and a 2-inch Teflon spherical lens. The use of Yagi-Uda antenna for millimeter-wave applications is also demonstrated in [14] where a corrugated ground plane is employed as a reflector to improve the gain for a linear antenna array operating at 60 GHz. A substrate-integrated waveguide Yagi-Uda antenna having the advantages of low profile and light weight is reported in [15]. In [16], a modified Rotman lens feeding an antipodal Yagi-Uda antenna array is designed and fabricated for 5G wireless communications at 28 GHz band. Other types of high gain antennas have been investigated in literature for mm-wave MIMO application. For example, the antenna proposed in [17] consists of a substrate integrated waveguide (SIW) slot and two SIW grooves operating in the Ka-band with a gain of 9.5–11 dBi and good isolation in the frequency range 26.8 to 28.4 GHz, but this antenna occupies large space (39.8 mm $\times$ 33.4 mm) on the board.

This paper presents a compact printed dual-band Yagi-Uda MIMO antenna system for 5G mobile communication. The modified Yagi-Uda design in this work can be very attractive for next generation wireless terminals due to its high gain, good wideband performance, and small form factor. Practically, the proposed MIMO antenna system can be integrated on the far top or bottom side corners of a mobile phone backplane, or positioned at the edges of the mobile chassis. The detailed literature review described above shows that the simple MIMO antenna design, as proposed in this paper, has not been investigated previously offering good integration, compact size, high gain, and simple fabrication for 5G mm-wave mobile handset applications.

2. THE PROPOSED DUAL-BAND YAGI-UDA ANTENNA

The present section describes the design of the proposed enhanced Yagi-Uda antenna. The methods of excitation are introduced. The first method suggests a CPS feeder whereas the second method suggests a microstrip line feeder.

2.1. Coplanar Strip-Line (CPS) Fed Yagi-Uda Antenna

In this section, a coplanar strip line (CPS) is employed to feed a modified Yagi-Uda antenna. The proposed Yagi-Uda is constructed as a corrugated driving dipole antenna, one director and two reflectors. The length of the dipole is set such that its resonance is around 38 GHz. Periodic parasitic hexagon shape elements are added in front of each reflector to enhance the gain and improve the front to back ratio. Each dipole arm has three equally spaced corrugations with dimensions set for good impedance matching. For dual-band operation, an extension strip is capacitively end-coupled to each of the dipole arms through an infinitesimal gap. The length of the strip and the gap are set so that the resulting extended corrugated dipole structure has additional resonance at 28 GHz. The geometry with indicated symbolic dimensional parameters of the proposed antenna fed by CPS line is shown in Figure 1.

The scattering caused by the reflectors is enhanced by placing periodic hexagonal patches in front of each reflector as shown in Figure 1. The corrugations made in the driven dipole with strip extensions are required to get the resulting structure resonant at 28 GHz.

2.2. Microstrip-Line (MS) Fed Yagi-Uda Antenna

In order to facilitate the practical measurements using coaxial feed line, a microstrip line to CPS line transition is employed. The transition is composed of three cascaded strip line regions with different

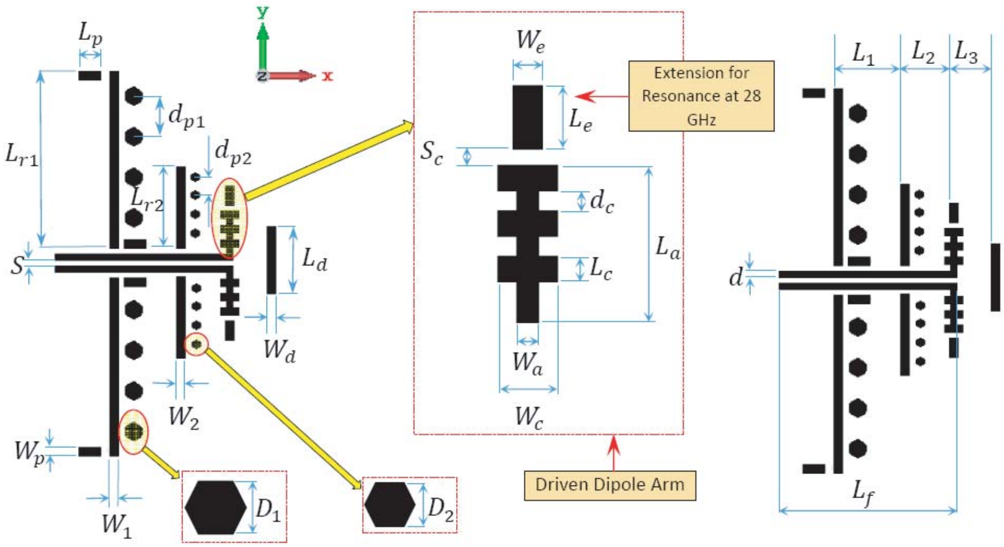


Figure 1. Schematic of the proposed design for the CPS fed Yagi-Uda antenna.

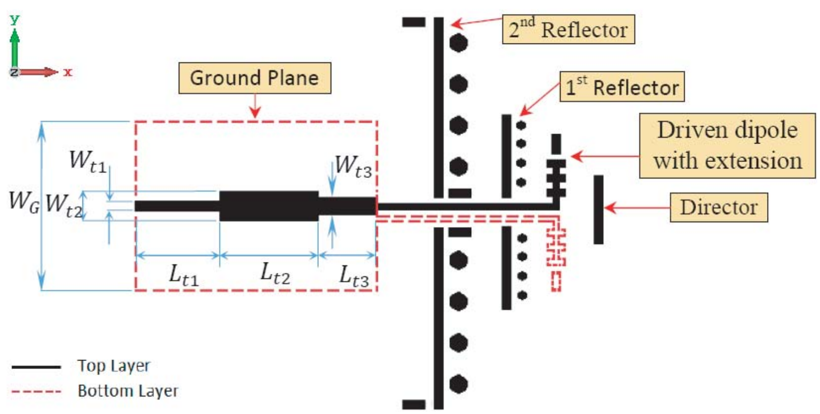


Figure 2. Schematic of the proposed design for the improved Yagi-Uda antenna excited through a feed line of three cascaded microstrip line regions.

lengths and widths designed for 50 Ω impedance matching. One of the dipole arms and its extension strip are printed on the bottom layer of the substrate and connected to the ground plane. Figure 2 shows the proposed design with the dimensional parameters of the microstrip-line. The dotted red line denotes the borders of the printed regions on the back side of the substrate.

3. MIMO ANTENNA SYSTEM FOR MOBILE 5G PHONES

A MIMO antenna system is constructed using four elements of the proposed dual-band Yagi-Uda antennas operating in 28/38 GHz bands for the forthcoming 5G mobile phones. The four antennas are suggested to be placed on the edges of a mobile phone as shown in Figure 3. The separations among the four antennas lead to the spatial diversity required for the target 5G applications allowing high performance at high bit rates. The performance of the MIMO antenna system including the return loss at each antenna port and the coupling coefficients between the different ports is investigated. The radiation patterns produced when each port is excited alone are shown to be suitable for the pattern diversity scheme.

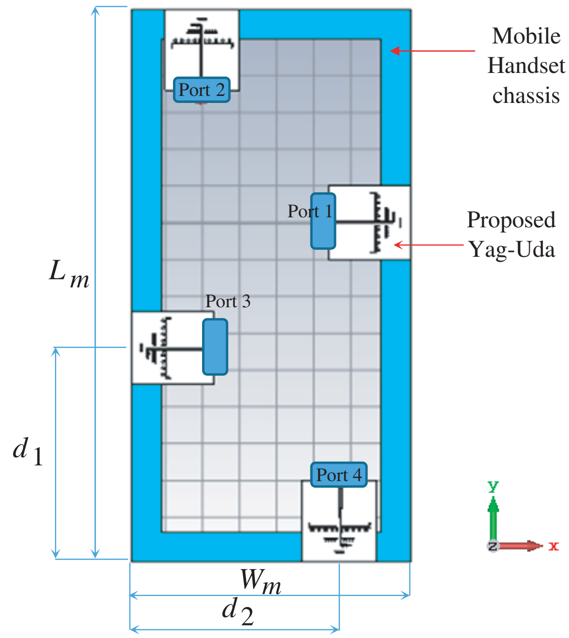


Figure 3. The 4-port MIMO antenna system proposed for 5G mobile phones.

4. RESULTS AND DISCUSSIONS

In this section, both the numerical results obtained by electromagnetic simulations and the experimental results obtained by microwave measurements for the fabricated prototypes of the single antenna and the MIMO antenna system are presented, discussed, and compared. The presented results are concerned with investigating the return loss and radiation patterns of the single CPS- and MS-fed Yagi-Uda antenna. Also, the results are concerned with the coupling coefficients, radiation patterns, and diversity gain (and the corresponding envelope correlation coefficient) of the four-port MIMO antenna configuration.

4.1. Performance Assessment of the Proposed Dual-Band Antenna

4.1.1. Return Loss and Bandwidth

The proposed Yagi-Uda antenna is designed on Rogers RO3003C$^{\text{TM}}$ with dielectric constant $\varepsilon_r = 3$, dielectric loss tangent $\tan\delta = 0.0021$, and height $h = 0.25$ mm. The metal strips and ground are made of copper with conductivity $\sigma = 5.6 \times 10^7$ S/m and thickness $t = 0.032$ mm. The design parameters are listed in Table 1. The antenna is placed in the xy-plane with the feed line aligned with the x-axis. The dependencies of the reflection coefficient, $|S_{11}|$, on the frequency over a wide band for the proposed CPS- and MS-fed dual-band Yagi-Uda antenna are presented in Figure 4. It is clear that for the CPS-fed Yagi-Uda antenna, the impedance is perfectly matched at the two frequencies 28 and 38 GHz with reflection coefficients −32 and −27 dB, respectively. At 28 GHz, the bandwidth is about 1.1 GHz (27.45–28.55 GHz), whereas at 38 GHz, the bandwidth is about 1.35 GHz and can operate with matched impedance over the frequency range (37.32–38.67 GHz). The radiation efficiencies are 95.5% at 28 GHz and 96.2% at 38 GHz.

For the MS-fed Yagi-Uda, the impedance matching bandwidth at 28 GHz is about 3.42 GHz and is 1.45 GHz at 38 GHz. It is clear from the figure that the proposed antenna has a very good matching at the required operating frequencies 28 and 38 GHz. The radiation efficiencies are 98.3% at 28 GHz and 96.5% at 38 GHz.

Table 1. Dimensional parameters for the proposed CPS-fed Yagi-Uda antenna.

Name	Value	Name	Value	Name	Value	Name	Value
L_a	1.79	d_c	0.33	W_1	0.25	S	0.45
W_a	0.25	S_c	0.2	W_2	0.25	d_{p1}	1.75
L_c	0.25	L_{r1}	7.6	L_1	2.95	d_{p2}	0.8
W_c	0.65	L_{r2}	3.4	L_2	2	D_1	0.8
L_e	0.8	L_d	2.4	L_3	1.75	D_2	0.4
W_e	0.25	W_d	0.25	L_f	7.7	L_p	0.8
L_{t1}	3.62	L_{t3}	2.5	W_{t2}	0.62	W_G	6.67
L_{t2}	4.02	W_{t1}	0.5	W_{t3}	0.35		

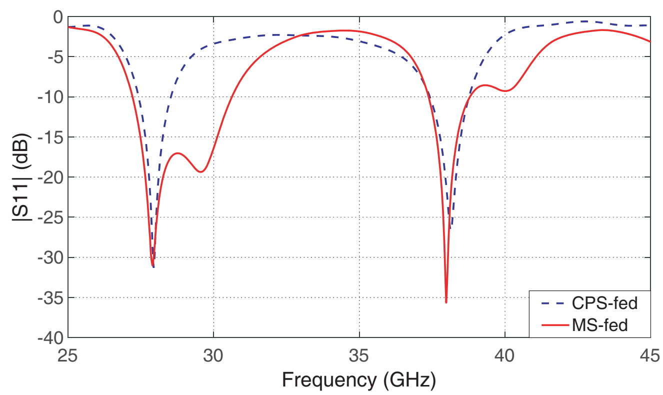


Figure 4. The frequency responses of the reflection coefficients $|S_{11}|$ of the proposed CPS-fed and MS-fed Yagi-Uda antennas with the dimensional parameters listed in Table 1.

4.1.2. Radiation Patterns

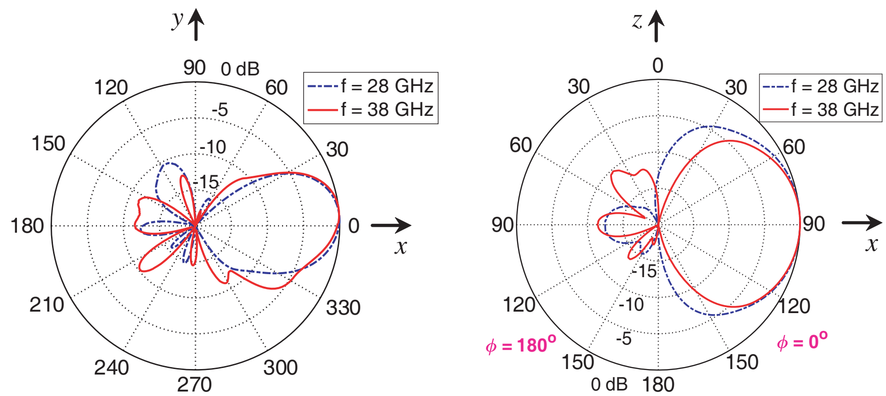
The normalized radiation patterns for the proposed MS-fed dual-band Yagi-Uda antenna at 28 GHz and 38 GHz in the planes $\phi = 0°$ (xz-plane) and $\theta = 90°$ (xy-plane) are presented in Figures 5(a) and 5(b), respectively. The maximum gain is 9.05 dBi at 28 GHz with SLL -10.5 dB, and 9.4 dBi at 38 GHz with SLL -10.1 dB. Such radiation patterns are proper for a MIMO antenna system composed of multiple units of such dual-band radiating elements for pattern diversity schemes.

4.2. Performance Assessment of the Proposed Four-Port MIMO Antenna System

This section is concerned with the presentation and discussion of the numerical results obtained through electromagnetic simulation using the commercially available CST^{TM} software package for the purpose of performance assessment of the proposed MIMO antenna system.

4.2.1. Impedance Matching and Coupling Coefficients

A four-port MIMO antenna configuration mounted on a mobile phone chassis with dimensions $L_m = 150$ mm and $W_m = 75$ mm, and separation distances between the antennas $d_1 = 58$ mm and $d_2 = 56$ mm is presented in Figure 3. Each antenna is printed on a 0.25 mm Rogers RO3003 substrate with the dimensional parameters listed in Table 1. Figure 6 shows the dependence of the self and mutual scattering parameters on the frequency over a very wide band. It is shown that the reflection coefficients at different antenna ports are almost identical and satisfy the impedance matching condition (low return



(a) $\theta = 90^{\circ}$ (xy-plane) (b) $\phi = 0^{\circ}$ (xz-plane)

Figure 5. Normalized radiation patterns of the proposed MS-fed dual-band antenna at 28 and 38 GHz in the xy-plane ($\phi = 0°$) and xz-plane ($\theta = 90°$).

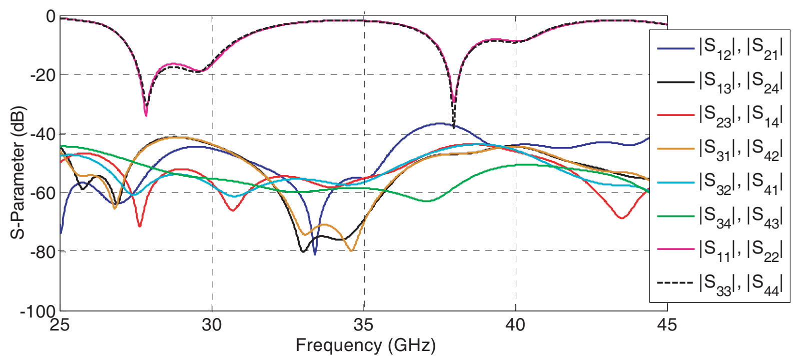


Figure 6. Simulated frequency response of the reflection and transmission coefficient of the four-port Yagi-Uda MIMO antenna system.

loss < -25 dB) over the lower and upper operational frequency bands which are centered at 28 and 38 GHz, respectively. On the other hand, the mutual scattering parameters show very weak coupling between the antennas ports, where all these coefficients are maintained below -35 dB over the entire frequency range.

4.2.2. Radiation Patterns of the MIMO Antenna System

The radiation patterns produced by the proposed MIMO antenna system when exciting each port alone are presented in Figures 7 and 8 at 28 and 38 GHz, where the radiation patterns are shown to satisfy the diversity required for the mobile phone MIMO systems. The maximum achieved gain at 28 GHz is about 9.29 dBi for both antenna 1 and antenna 3, and 8.95 dBi for antenna 2 and antenna 4, whereas the maximum gain at 38 GHz is about 9.72 dBi for both antenna 1 and antenna 3, and 9.5 dBi for antenna 2 and antenna 4. Besides the reasonable size of the MIMO antenna system and the fairly wide separations between the antennas that produce high diversity gain, the obtained pattern diversity provides excellent solution for the forthcoming 5G mobile communication systems.

4.2.3. Envelope Correlation Coefficient and Diversity Gain of the 4-Port MIMO Antenna System

The frequency responses of the envelope correlation coefficient (ECC) and the diversity gain (DG) of the proposed four-port MIMO antenna system are presented in Figure 9. It is shown that the ECC is almost 0, and consequently, the DG is almost 10 over the lower and upper frequency bands centered at 28 and 38 GHz, which is the best achievable performance for a MIMO antenna system.

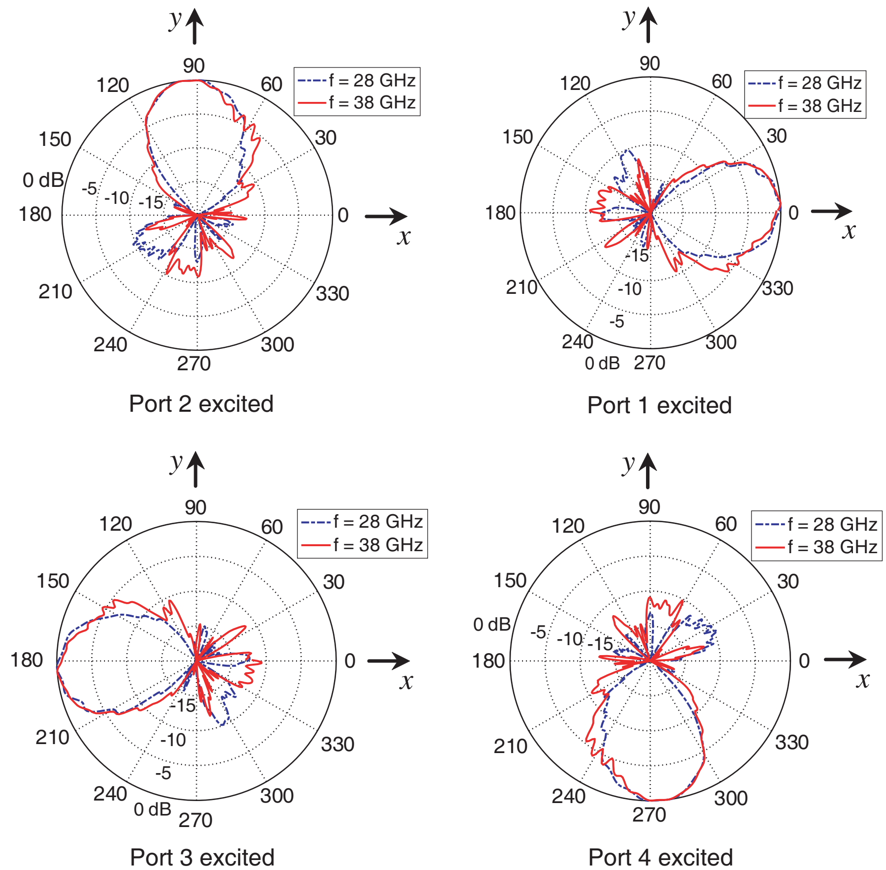


Figure 7. Radiation patterns in the antenna plane for the 4-port MIMO antenna using the proposed dual-band antenna at 28 and 38 GHz.

4.3. MIMO Antenna Fabrication and Experimental Assessment

This section is concerned with the presentation and discussions of the experimental measurements of the dual-band Yagi-Uda antenna and the proposed MIMO antenna system whose simulation results are presented and discussed in the previous sections. Prototypes are fabricated for the single antenna as well as the four-port MIMO antenna system. To confirm the accuracy of the assessed performance for both the single antenna and the MIMO system, the measurement results are compared to those obtained by electromagnetic simulation using the commercially available CST$^{\text{TM}}$ software package.

4.3.1. Fabrication and Measurements of the Single Antenna Prototype

4.3.1.1. Measurement of the Return Loss

A prototype of the proposed dual-band Yagi-Uda antenna is fabricated for experimental verification of the simulation results concerning the dependence of the reflection coefficient on the frequency and the radiation patterns. The substrate used for fabrication is Rogers RO3003$^{\text{TM}}$, with substrate height $h = 0.25$ mm, dielectric constant $\varepsilon_r = 3$, and dielectric loss tangent $\delta = 0.0013$. The same design dimensions given in Section 4.1.1 are used for the fabrication process. Top and bottom views of the fabricated prototype are presented in Figure 10. The 2.4 mm end launch connector from Southwest Microwave Inc. is used to measure the port performance of the prototype antenna shown in Figure 10 using the vector network analyzer (VNA) from Rohde and Schwartz model ZVA67. After performing the required settings and calibration procedure, the antenna prototype under test is connected to the VNA as shown in Figure 11(a), and the return loss $|S_{11}|$ is measured. The results of measurements are compared

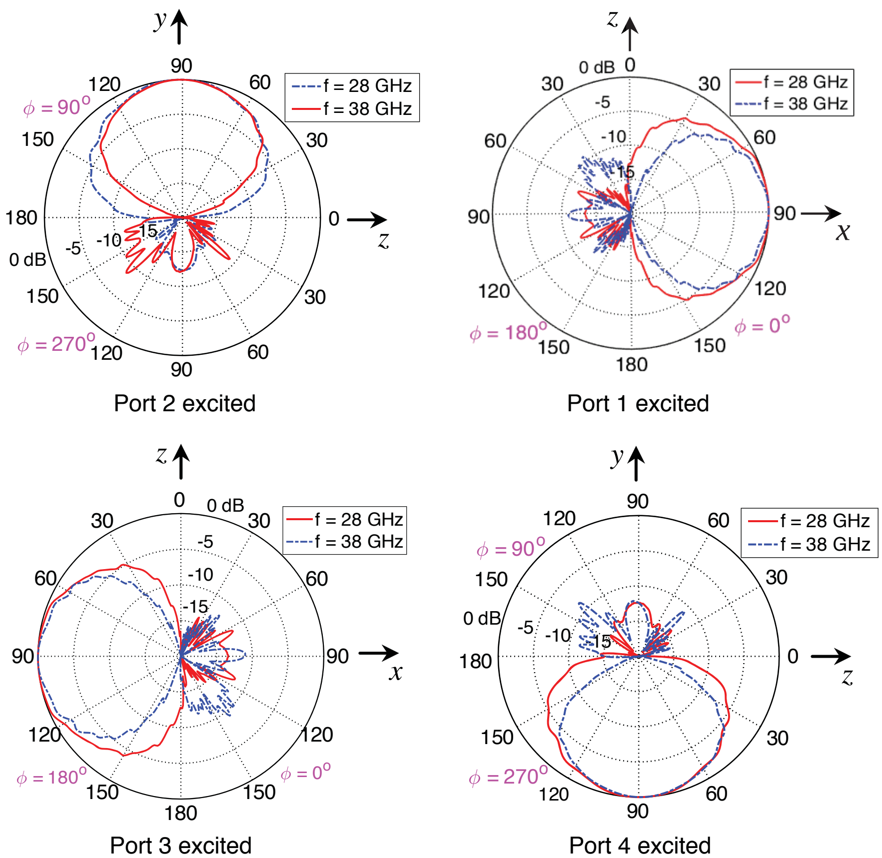
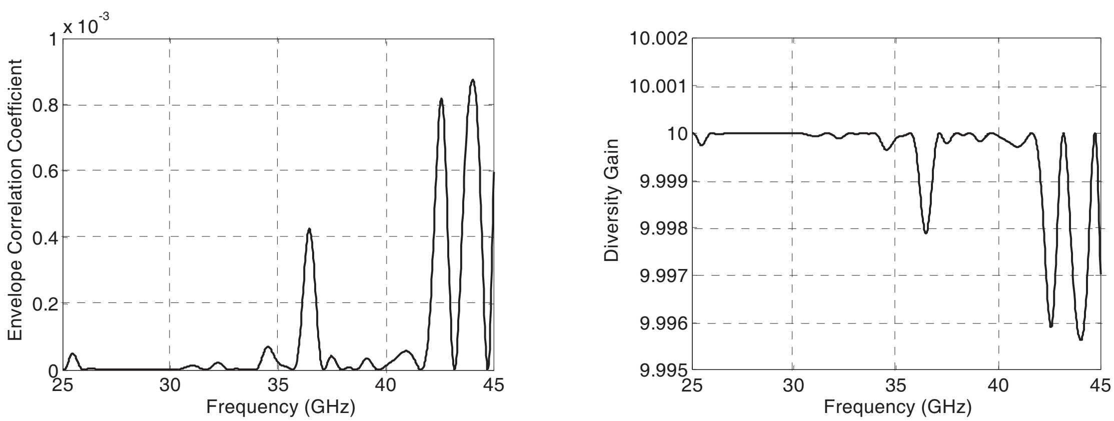


Figure 8. Radiation patterns in the plane normal to the antenna plane for the 4-port MIMO antenna using the proposed dual-band antenna at 28 and 38 GHz.



(a) ECC (b) DG

Figure 9. Frequency dependence of the ECC and DG of the 4-port MIMO antenna proposed in the present work.

to that obtained by simulation using the CST® software package and plotted in Figure 11(b) showing good agreement. The measurement results for $|S_{11}|$ show that the proposed antenna has an impedance matching bandwidth about 2.7 GHz (27.5–30.2 GHz) for reflection coefficient < -10 dB around 28 GHz band and 1.7 GHz (37.3–39 GHz) around 38 GHz band.

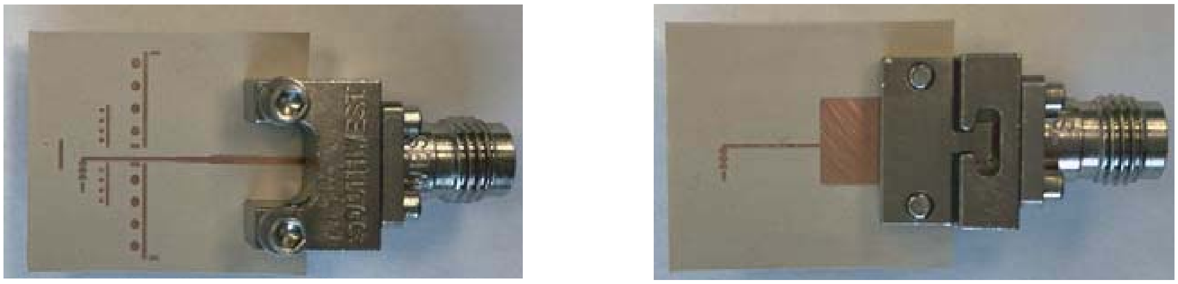
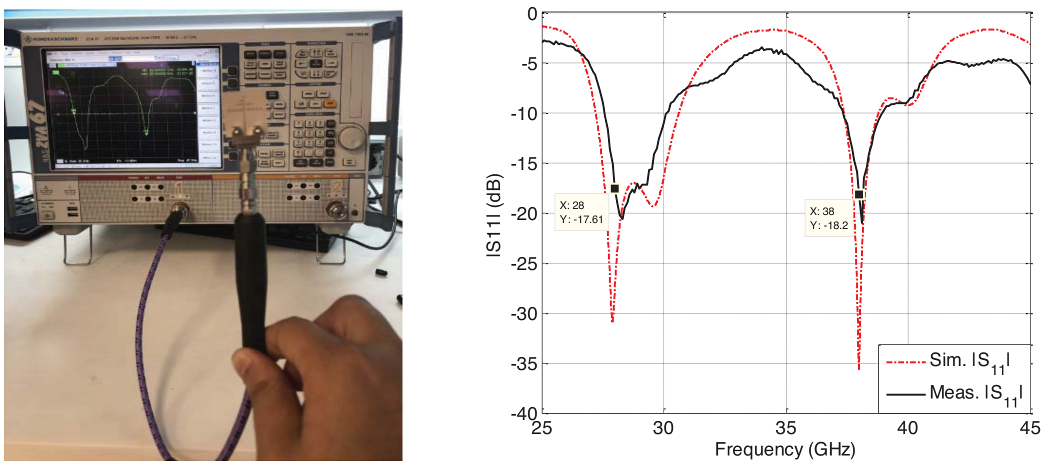


Figure 10. Photograph of the fabricated prototype of the dual-band 28/38 GHz Yagi-Uda proposed for MIMO antenna systems of 5G mobile handsets.



(a) (b)

Figure 11. (a) Experimental setup for measuring the return loss of the dual-band antenna. (b) Measured frequency response of the return loss of the dual-band antenna compared with the simulation results.

4.3.1.1. Measurements of the Radiation Patterns and Maximum Gain

For experimental measurement of the radiation pattern of the fabricated dual-band antenna, the standard gain linear-polarized horn antenna model LB-180400 is used as a reference antenna, and the experimental setup is made as shown in Figure 12. The measurements are performed in an anechoic chamber with the vector network analyzer Rhode and Schwartz model ZVA67. The distance between the reference antenna and the antenna under test is 40 cm. The radiation patterns are measured at 28 and 38 GHz in the two principal planes $x - z$ ($\phi = 0°$) and $x - y$ ($\theta = 90°$). The radiation patterns obtained through simulation and experimental measurements are presented in Figure 13 showing good agreement. The measured maximum gain is 8.3 dB at 28 GHz and 8.8 dB at 38 GHz.

4.3.2. Fabrication and Measurements of the MIMO Antenna System

In this section, the proposed dual-band antenna is employed to construct a four-port MIMO antenna system for a mobile phone handset. A mockup for the handset with the proposed MIMO antennas configuration is shown in Figure 14. The mockup is constructed of a solid rectangle shape of dimensions $75 \times 150\,\text{mm}^2$ with four openings of the same size as the single antenna at the specified locations shown in Figure 3 with $d_1 = 58$ mm and $d_2 = 56$ mm. The four-port MIMO antenna system mounted on the antenna mockup is shown in Figure 14. The 2.4 mm end launch connectors from Southwest Microwave Inc. are used for measuring the return loss of each antenna and the mutual coupling between each

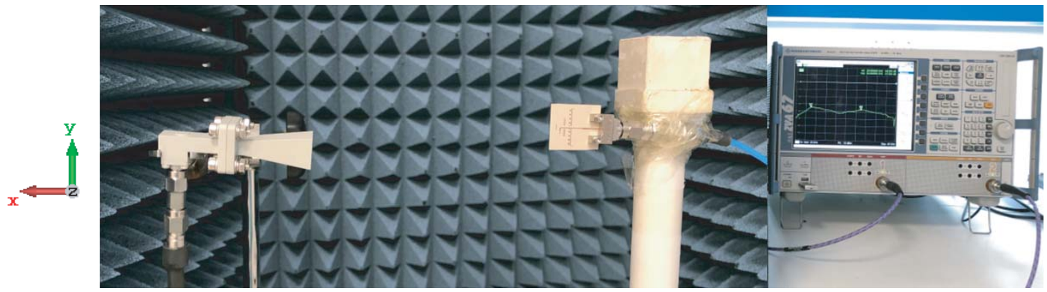
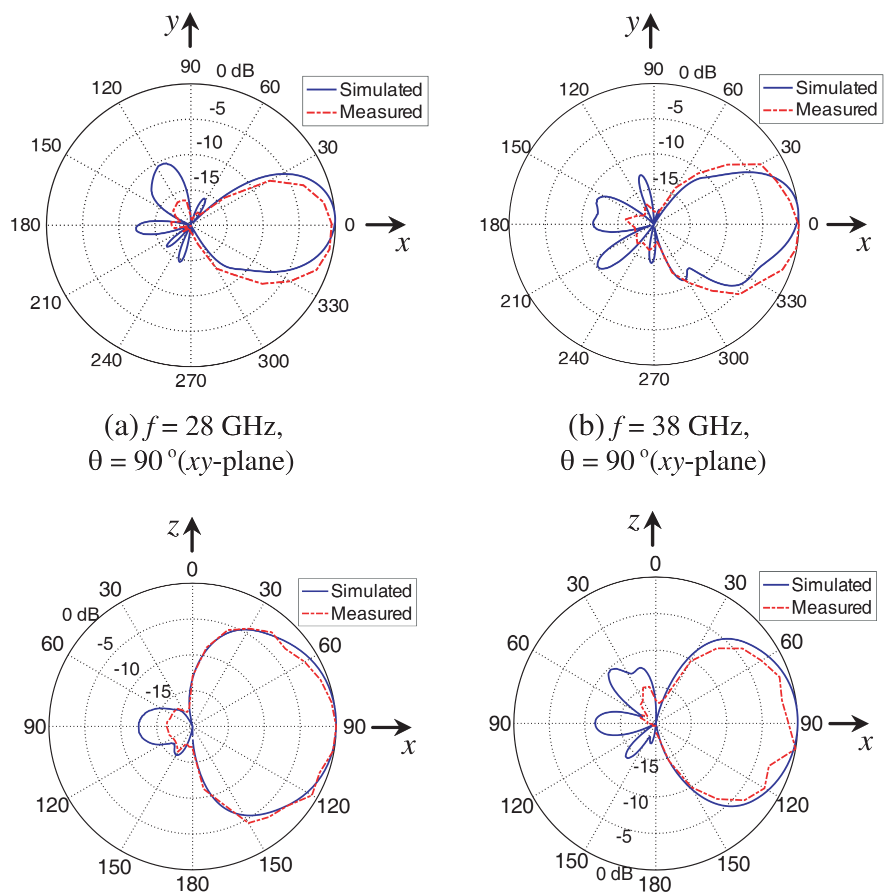


Figure 12. Experimental setup for measuring the radiation pattern and gain of the dual-band antenna.



(a) $f = 28$ GHz, $\theta = 90^{\circ}$ (xy-plane)

(b) $f = 38$ GHz, $\theta = 90^{\circ}$ (xy-plane)

(a) $f = 28$ GHz, $\phi = 0^{\circ}$ (xz-plane)

(b) $f = 38$ GHz, $\phi = 0^{\circ}$ (xz-plane)

Figure 13. Measured radiation patterns of the dual-band antenna compared with the simulation results.

antenna pair using the VNA Rhode & Schwartz model ZVA67. During the measurement process, 50 Ω loads are connected to the elements not under test to avoid their effects. Figure 15 illustrates the measured return loss for each antenna in the frequency band 25–45 GHz. It is evident that the MIMO antenna system exhibits good impedance matching at both the operating frequencies 28 and 38 GHz. The mutual coupling coefficients are measured and plotted as shown in Figure 16. It is clear that the MIMO antenna system has very low mutual coupling < -38 dB over the entire frequency range.

Figure 14. Fabricated prototype for the four-port MIMO antenna system constructed on a mockup with four Yagi-Uda antennas arranged on the edges.

4.4. Comparison with Similar Work

In this section, a comparison between the proposed design and the antennas proposed in literature for mm-wave applications is performed. First, the proposed Yagi-Uda is compared to similar Yagi-Uda antennas in literature. The comparison criteria are the size, number of bands, the bandwidth for each band, and antenna gain, which are presented in Table 2(a). The proposed design is also compared to the dual-band designs found in literature from the point of view of size, bandwidth, and isolation, which are presented in Table 2(b). To the best of our knowledge, the present work proposes a dual-band Yagi-Uda antenna for MIMO applications which is not found in literature. In addition to its dual-band operation, the proposed design still has compact size, high gain, bandwidth, very low mutual coupling, and very high radiation efficiency, and it also has nearly perfect ECC and DG.

Table 2. (a) Comparison with similar Yagi-Uda antennas for MIMO. (b) Comparison with similar 28/38 dual-band antennas for MIMO.

Reference	Size (mm)	Number of Bands	Bandwidth (GHz)				Gain (dBi)
			First Band		Second Band		
			Freq.	BW	Freq.	BW	
Presented Work	$21.6 \times 20 \times 0.25$	2	28	3.42	38	1.45	9
[16]	$14.8 \times 5.1 \times 0.2$	1	28	3.7	——	——	8
[13]	$11.2 \times 8.1 \times 0.25$	1	24	0.7	——	——	9.3
[18]	$40.7 \times 22.9 \times 0.38$	1	24	4.1	——	——	8

(a)

Reference	Size (mm)	Bandwidth (GHz)		Isolation (dB)
		28 GHz	38 GHz	
Present Work	$21.6 \times 20 \times 0.25$	3.42	1.45	−38
[19]	$16 \times 16 \times 0.8$	1.46	1.4	−16
[10]	$15 \times 20 \times 1.27$	5.9	4.94	——
[20]	$55 \times 110 \times 0.508$	1.4	0.9	−30

(b)

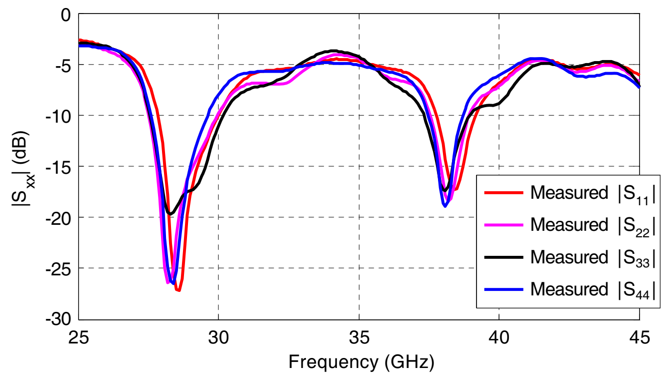


Figure 15. Measured frequency response of the return loss of the 4-port MIMO antenna system.

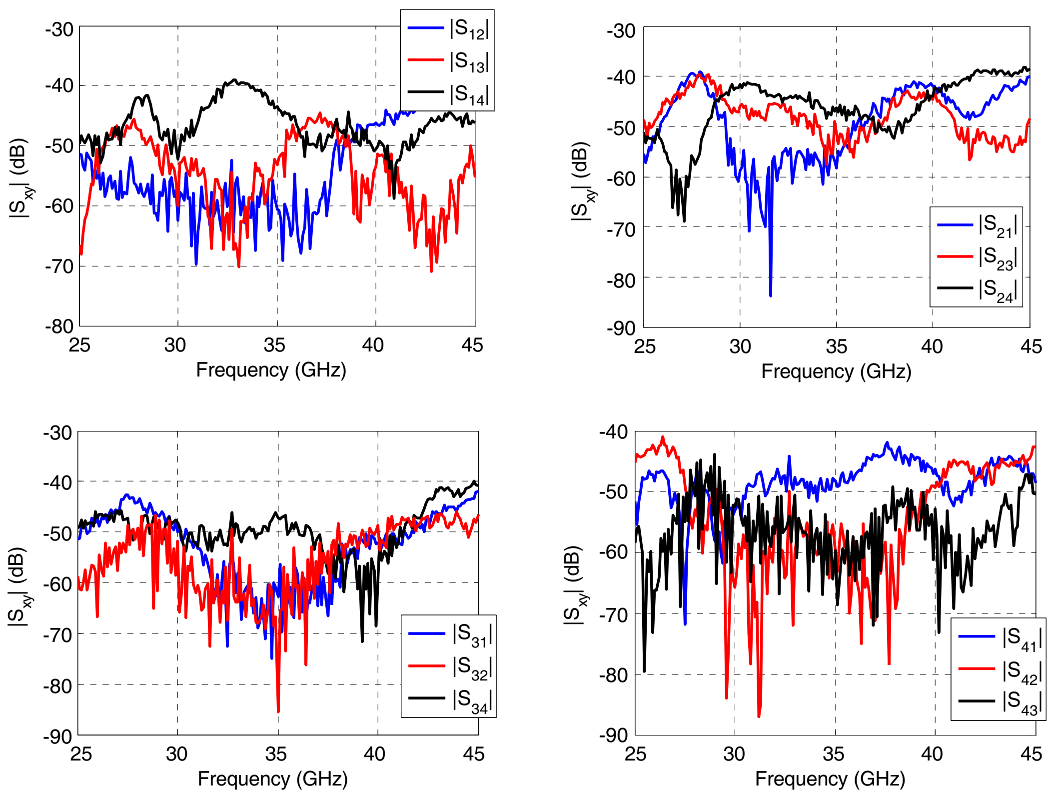


Figure 16. Measured frequency response of the mutual coupling coefficient of the 4-port MIMO antenna system.

5. CONCLUSIONS

An enhanced modified Yagi-Uda antenna design is introduced for the 28/38 GHz dual-band operation. The antenna is constructed from a driving corrugated dipole and a capacitively end-coupled extension strip with two reflectors and one director. Periodic parasitic elements are added in front of the reflectors to enhance the antenna gain and improve the impedance matching. Two feeding mechanisms are examined, coplanar strip and microstrip line feeding. A four-port MIMO antenna system for mobile handsets is constructed using the proposed Yagi-Uda antenna. Numerical and experimental investigations are carried out to assess the performance of both the single antenna and the four-port MIMO antenna system. It is shown that the simulation results agree with the experimental measurements, and both show good performance of the single antenna as well as the MIMO antenna system. The bandwidths achieved around 28 GHz and 38 GHz are about 1.1 GHz and 1.35 GHz, respectively, using the CPS feed line, and about 3.42 GHz and 1.45 GHz, respectively, using the microstrip feed line. Each antenna element has maximum gain about 9 dB. The four-antenna configuration shows radiation pattern diversity which is required for MIMO system operation. The calculated envelope correlation coefficient (ECC) and diversity gain (DG) show that the proposed MIMO antenna system can serve as a mobile phone antenna.

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