A Triband Circular-Polarized Four-Port MIMO Antenna With Compact Size and Low Mutual Coupling

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***Abstract*—This letter presents a compact triband circular polarized (CP), multiple-input–multiple-output (MIMO) antenna by using the ground plane excitation technique, where four simple E-shape meander lines are designed at the top of the low-cost substrate. The electrical dimensions of the proposed four-port MIMO antenna are 0.33λ × 0.33λ × 0.012λ, where (λ) is the free-space wavelength at the lower operating frequency. The prototype is intended to be single-layered and manufactured on the FR-4 substrate. The MIMO antenna covers the impedance operating bands of 2.14 GHz to 2.49 GHz, 3.4 GHz to 3.81 GHz, and 4.7 GHz to 6.6 GHz, with the isolation of ≥18.2 dB, ≥23 dB, and ≥27 dB, respectively. The CP properties and isolation are achieved by the installation of an optimized special connected ground plane. With the help of this technique, the axial ratios are obtained below 3 dB at the required operating frequencies. The simulated and measured *S*-parameters, axial ratios, radiation patterns, gain, and efficiency agree with each other and have better results. The diversity parameters are also calculated and have an acceptable value in both simulated and measured. The proposed MIMO antenna is a good candidate for wireless local area network and worldwide interoperability for microwave access.**

***Index Terms*—Axial ratio (AR), channel capacity loss (CCL), circular polarized (CP), diversity gain (DG), envelope correlation coefficient (ECC), ground excitation, multiple-input–multiple-output (MIMO) antenna, mean effective gain (MEG), wireless local area network (WLAN), Worldwide Interoperability for Microwave Access (WiMAX).**

I. Introduction

With the booming growth of wireless communication technologies, the demand for high-speed data transmission and seamless connectivity has increased in the era of widespread wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMAX) applications. However, the limited frequency range has become the acute factor in restrictive the progress of wireless communication [1]. To maximize the utilization of the limited frequency spectrum, multiple-input–multiple-output (MIMO) technology can significantly increase the channel capability without raising the spectrum capacity overhead and also accomplish higher spectral efficiency and better data rates in wireless communication systems [2], [3]. Moreover, circular-polarized (CP) antennas have increased importance due to their capability to enhance signal robustness, diminish multipath fading, and accommodate varying polarization states in wireless communication channels. In comparison with linear-polarized (LP) antennas, the CP MIMO antennas eliminate polarization mismatch and increase transmission range [4].

Recently, the implementation of MIMO systems with CP antennas has drawn a lot of attention for its potential to improve system performance and spectral efficiency in WLAN and WiMAX applications. CP MIMO system provides enhanced coverage, throughput, and reliability by concurrently utilizing spatial and polarization diversity. This makes them ideal for use in challenging contexts, where polarization fading effects and multipath propagation are present [3].

There are many challenges in the design of CP MIMO antenna for WLAN and WiMAX applications, such as the requirement of reducing the mutual coupling between antenna elements, compact size, wide bandwidth achievements of axial ratio (AR), and filtering unwanted frequency bands. The techniques used for isolation improvements are defected ground structure [5], electromagnetic bandgap (EBG) [6], metamaterial [7], nonorthogonal metasurfaces [8], and frequency selective surface [9], [10]. Each configuration that has been previously documented has greater dimensions. Furthermore, integrating multiple bands of frequencies requires careful optimization to assure integration with WLAN (2.4 GHz), WiMAX (3.5 GHz), and WiMAX (5.8 GHz) standards, and this process is also complicated. Different types of antennas were designed to cover WLAN and WiMAX frequency bands with LP MIMO [11] and CP MIMO [12] properties. Mostly the MIMO antennas have LP properties or CP properties but have single band [13], and those have multiple lower frequency bands with dual ports that are large in dimension [14].

In this letter, we describe the design, optimization, and performance assessment of triband CP MIMO antenna systems for sub-mmWave (6 GHz), WLAN, and WiMAX applications. The four CP antenna elements in the suggested antenna system are

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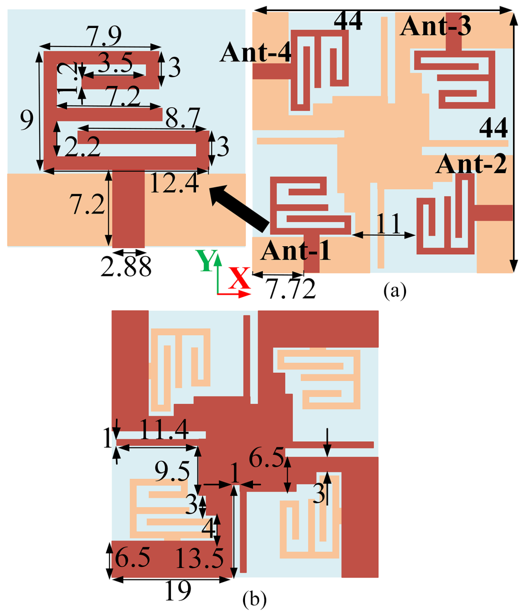

Fig. 1. Geometry of the proposed MIMO antenna: (a) front side view and (b) back side view (unit: mm).

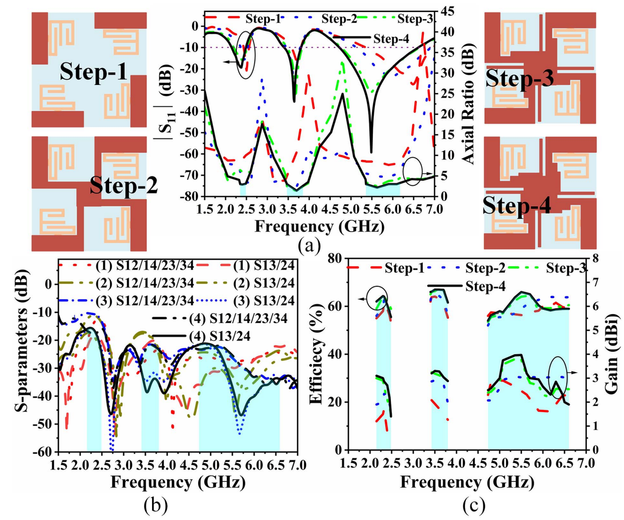

Fig. 2. (a) Simulated reflection coefficient (dB) and AR (dB) results, along with its four steps design layout of the CP MIMO antenna, (b) simulated four steps design isolation (dB) plots, and (c) the four steps simulated gain (dBi) and efficiency (%) comparison plots.

placed in an orthogonal manner with a shared ground plane to take advantage of polarization, same voltage flow, and acceptable diversity parameters, which improves system output and reliability. We can develop a compact MIMO antenna layout with triband CP functioning, single-layered, low cost, compact size, and high isolation between elements by utilizing ground excitation tools and optimization methodologies.

The main contributions of this letter are as follows. First, we design an innovative E-shape meander line for triband CP MIMO antennas that can function in various frequency ranges associated with WLAN and WiMAX protocols. Second, we fabricated and measured to carry out systematic performance assessments to show the effectiveness of the suggested antenna designs in practical situations. These assessments include CP radiation pattern analysis, *S*-parameters for isolation and matching at tribands, diversity parameters calculation, wide-band of ARs, size, gain, and efficiency. Finally, the comparison concludes that no work has combined properties of compact size, shared ground, triband CP properties, four elements, single-layered, low cost, and high isolation.

II. MIMO Antenna Design Process

The presented CP MIMO antenna is designed into four steps with ground optimization to achieve triband properties, compact size, and acceptable isolation. A transmission line theory is used to fix the resonant lengths of the antenna, and approximately 100 Ω E-shape meander line radiators with half wavelengths are preferred because of their small size and capacity for multiband operation. A 50 Ω microstrip line is connected with the radiator by using the power splitter concept for best matching. Finally, a novel shared ground structure is used for CP, isolation purposes, and also for the same voltage flow across the elements. The proposed MIMO antenna is depicted in Fig. 1 along with its dimensions.

A. CP MIMO Antenna Design and Simulated Results

The four-step triband CP MIMO antenna is discussed in Fig. 2. In Step 1, four elements of antenna are arranged orthogonally with the same spacing to achieve tribands with excellent matching and high isolation. An FR-4 substrate with thickness = 1.6 mm, permitivity = 4.3, and tangent loss = 0.025 is used due to its low cost, ease of fabrication, and compatibility with small antenna design. At this step, the antenna is operating at the tribands with center frequencies of 2.6 GHz, 3.7 GHz, and 6.5 GHz with AR values above 3 dB and a high value of mutual coupling at the lower operating frequency. In Step 2, the ground is connected for the same voltage flow but its mutual coupling increases and has enhancement in the gain, efficiency, AR, and return loss. At this step, the higher two bands are shifted to the lower range and operating at 3.5 GHz, and 6 GHz, and AR is below 3 dB at the middle operating frequency band. The ground plane is excited more by adding an "L-shaped" patch to optimize the values of isolation, gain, efficiency, and AR, and achieve the targeted operating frequency bands, in Step 3. The antenna is operating at 2.15 GHz to 2.486 GHz, 3.4 GHz to 3.8 GHz, and 4.73 GHz to 6.6 GHz, but their AR is operating only at the two higher frequency bands. The mutual coupling value is also $\leq$11 dB, at the lower frequency band. The simulated return loss (dB) and AR (dB) of all the steps are shown in Fig. 2(a), and isolation (dB) is presented in Fig. 2(b). In Step 4, "L-shaped" embedded with a rectangular patch to achieve third AR band at lower frequency, and decrease the mutual coupling. There is a small change as compared with Step-3, in the operating impedance bandwidth where the MIMO antenna is operating at three wide bandwidths of 2.14 GHz to 2.49 GHz, 3.4 GHz to 3.81 GHz, and 4.7 GHz to 6.6 GHz, and the corresponding AR bands below of 3 dB are 2.35 GHz to 2.485 GHz, 3.47 GHz to 3.85 GHz, and 5.36 GHz to 6.1 GHz. The isolation at 2.4 GHz, 3.5 GHz, and 5.8 GHz are below −17.5 dB, −21.6 dB, and −33 dB, respectively. The gain and efficiency of all the steps are presented in Fig. 2(c). The proposed MIMO antenna gains of all three bands are 3 dBi, 3.3 dBi, and 4 dBi, respectively, and their efficiency values are 63%, 67%, and 65%, respectively.

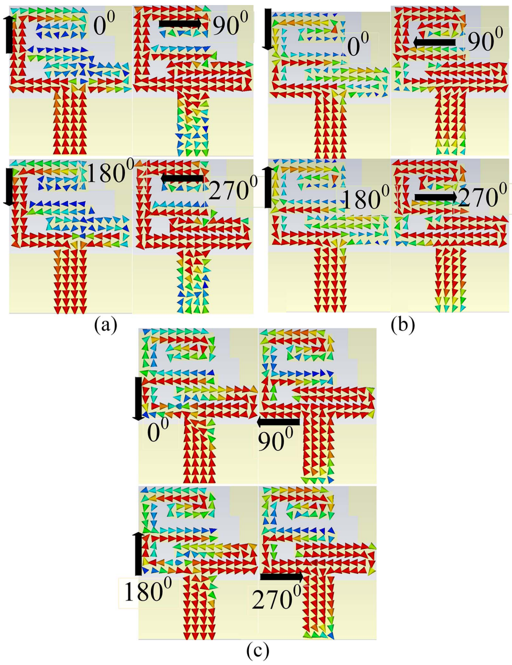

Fig. 3. Surface current distributions of port 1 and terminated other ports, with the orientation of different phase angles at the frequencies of (a) 2.4 GHz, (b) 3.5 GHz, and (c) 5.8 GHz.

B. Surface Current Distribution

The surface current distributions are important to show the performance of the CP MIMO antenna. In this case, port 1 is operated and the other three ports are terminated at the center frequency of 2.4 GHz, 3.5 GHz, and 5.8 GHz with an orientation of four orthogonal angles (0°, 90°, 180°, and 270°). The surface current distributions for the lower operating frequency band (2.4 GHz), middle-frequency band (3.5 GHz), and higher frequency band (5.8 GHz) are presented in Fig. 3(a)–(c), respectively. The current flow of all the bands with different phase orientation angles is in opposite directions with a difference of 180° but has the same magnitude, which presents the property of CP antennas. It is presented that the current distribution is clockwise at all operational frequencies, so the MIMO has left-hand circular polarization (LHCP) properties.

III. Fabrication and Measurement

The proposed MIMO antenna is fabricated on the FR-4 substrate and four SubMiniature version A (SMA) connectors are installed with the help of soldering. The prototype front and back views are presented in Fig. 4(a). The *S*-parameters, such as return loss (dB) and isolation between antenna elements, are tested by vector network analyzer (VNA) measurements. The comparison of the simulated and measured return loss (dB) and AR (dB) is shown in Fig. 4(b), which has a good agreement. The measured results cover three impedance operating bandwidths, but all the ports have different values due to fabrication and soldering tolerance, and the minimum values are 2.21 GHz to 2.47 GHz, 3.42 GHz to 3.78 GHz, and 4.75 GHz to 6.6 GHz. The corresponding AR (≤3 dB) values are 2.35 GHz to 2.47 GHz, 3.472 GHz to 3.79 GHz, and 5.5 GHz to 6.3 GHz. In Fig. 4(c), the measured isolation of the operating resonant bands at 2.4 GHz, 3.5 GHz, and 5.8 GHz is less than −18.2 dB, −23 dB, and −27 dB, respectively. Testing of the radiation patterns in an anechoic chamber checks the features of the simulated radiation, such as CP and omnidirectional analysis. The measured gain (dBi) values of the targeted bands are 3.8 dBi, 4.1 dBi, and 4.3 dBi, and their corresponding efficiencies (%) are 69%, 70%, and 72%, respectively, as mentioned in Fig. 4(d). Fig. 5(a) presents the testing setup of the proposed MIMO antenna in an anechoic chamber along with VNA (Rohde & Schwarz-ZVA 40) and a control system (Laptop). Fig. 5(b) explained the simulated and measured normalized LHCP, and right-hand circular polarization (RHCP) radiation patterns comparison at 2.4 GHz operating frequency, with the orientation of phi = 0° and 90°. Also, Fig. 5(c) and (d) presented the same results at 3.5 GHz and 5.8 GHz, respectively. There is a small variation between simulated and measured radiation patterns, which occur due to imperfect placement and cable connection. All the radiation plots show that the LHCP and RHCP overpass each other by

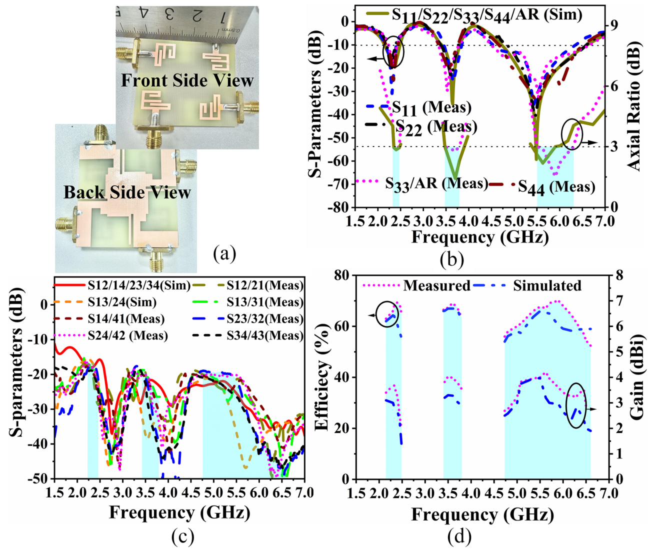

Fig. 4. (a) Front and back side views for fabricated four-port CP MIMO antenna prototype, (b) Return loss (dB) and AR (dB), (c) transmission coefficient (dB), and (d) gain (dB), and efficiency (%) for simulated and measured proposed CP MIMO antenna.

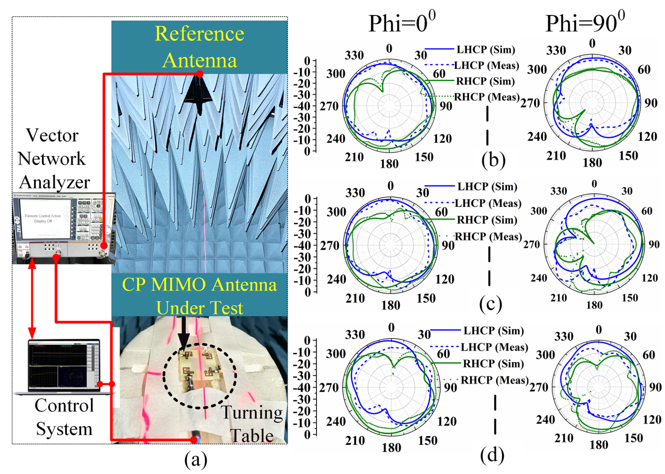

Fig. 5. (a) Testing setup of the proposed CP MIMO antenna in an anechoic chamber. Comparison of the simulated and measured LHCP and RHCP radiation patterns with the variation of phase angle phi = 0° and 90° at the frequency: (b) 2.4 GHz, (c) 3.5 GHz, and (d) 5.8 GHz.

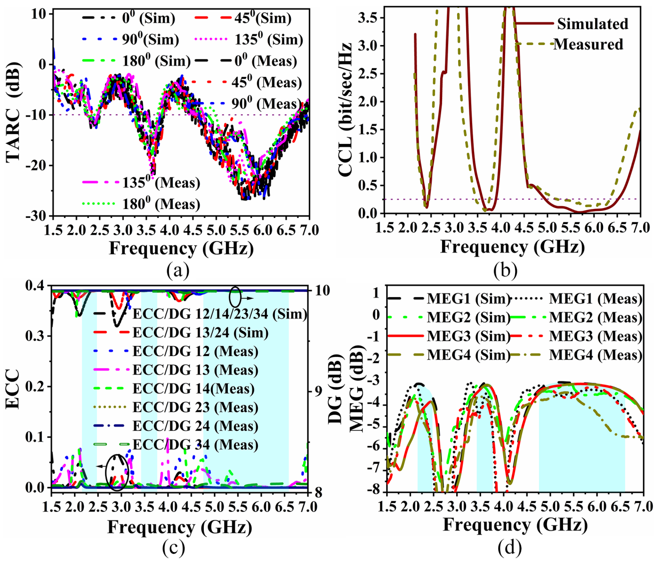

Fig. 6. Comparison of simulated and measured results of (a) TARC (dB), (b) CCL (bit/s/Hz), (c) ECC and DG (dB), and (d) MEG (dB).

the minimum difference of ≥18 dB, which cleared good CP properties of the MIMO antenna.

IV. Diversity Performance

In MIMO antenna systems, the diversity analysis plays an essential role in extending coverage, increasing throughput, improving signal quality, mitigating interference, maximizing performance, and ultimately creating more reliable and effective wireless communication networks. Its parameters consist of channel capacity loss (CCL), total active reflection coefficient (TARC), diversity gain (DG), envelope correlation coefficient (ECC), and mean effective gain (MEG). Moreover, all of these parameters are calculated by equations discussed in [15]. TARC plays an important role in calculating the actual bandwidth and is essential for testing mutually coupled signals at various phase excitations. Fig. 6(a) shows the simulated and measured TARC values with the phase excitation of 0°–180° with the intervals of 45°, which shows ≤−10 dB values at the operating bands. CCL is an essential factor since it has a direct impact on the system's capacity, interference control, and spatial diversity, where the designers can measure and control CCL to improve the effectiveness and reliability of MIMO systems in many wireless communication applications. The four ports' simulated and measured CCL values are presented in Fig. 6(b), and the measured values are smaller than 0.25 bps/Hz, 0.1 bps/Hz, and 0.18 bps/Hz of the three bands.

The ECC is used to measure the correlation between the signal patterns received by the various antennas of a MIMO system. The measured values of ECC are 0.002, 0.006, and 0.009, respectively, of the operating CP bands, as presented in Fig. 6(c). The DG parameter has a direct relation with ECC, when the ECC values are smaller than the DG values will be near 10 dB. This work presented measured DG values at the targeted bands are ≥ 9.99 dB at all three bands as depicted in Fig. 6(c). The parameter MEG refers to the average gain of the MIMO channel across all useful transmit and receive antenna arrangements, taking spatial multiplexing and diversity into account. The simulated and measured MEGs of each element are presented in Fig. 6(d).

TABLE I
Comparison of the Proposed MIMO Antenna With Previous Works

Ref. Number	[13]	[14]	[16]	[17]	This Work
Size (λ^3)	0.82 ×0.51 ×0.17	0.71 ×0.27 ×0.02	0.71 ×0.71 ×0.02	1.5 ×0.96 ×0.01	0.33 ×0.33 ×0.012
Impedance bandwidth (GHz)	1.3	0.4, 0.2 0.4, 0.3	0.52	0.31, 0.75	0.35, 0.41 1.9
Number of ports	2	2	4	4	4
Polarization	CP	CP	CP	CP	CP
AR (%)	13.2	10, 4, 5.6, 3.6	29	17.8, 5.6	5, 9, 13.6
Gain (dBi)	6.3	4, 4, 3, 5	5.3	4, 5	3.8, 4.1, 4.3
Isolation (dB)	≥ 20	≥ 22, 35, 30, 22	≥ 16	≥ 15	≥ 18.2, 23, 27
ECC/ DG (dB)	–	≤ 0.13/ ≥ 9.98	≤ 0.07/–	≤ 0.04/–	≤ 0.009/ ≥ 9.99
MEG (dB)/ CCL (bps/Hz)	–	≤ −3/ ≤ 0.15	–	–	≤ −3.2/ ≤ 0.25

V. Comparison

Table I presented the comparison of the proposed triband CP MIMO antenna with previous works. In previous works, the size and structure of the MIMO antennas are large; moreover, some MIMO antennas have generally been limited by the number of frequency bands. The proposed MIMO antenna maintains a compact size and structure elements with three operating frequency bands with wide bandwidth as compared to other works, which are ideal for integration into WLAN and WiMAX devices. Some references have fewer ports so that the capacity for spatial multiplexing and diversity is reduced. However, the proposed MIMO antenna has four ports, thus spatial multiplexing and diversity are obtained. It is important to attain better data rates and reliability in the MIMO systems. Currently, some designs have no CP properties. However, the proposed MIMO has triband CP properties, which are important to increase signal propagation, efficiency, and interference mitigation. The triband AR bandwidth of the present work is wider than that of the previous works, and the proposed MIMO antenna has good values of gain and isolation. There is a lack of diversity parameters analysis in the previous works, which is mandatory in MIMO antenna performance. The presented work has excellent diversity parameters results as compared to the previous works.

VI. Conclusion

This letter designed a four-port MIMO antenna with E-shape meander line radiators to achieve a triband with good matching by using a simple microstrip line and placing it orthogonally for good isolation and size reduction. The suggested triband CP MIMO antenna systems present a viable way to improve the spectral efficiency and performance of WLAN and WiMAX communication systems, providing the growing demand for fast wireless connectivity across a range of applications. It has a compact size, high isolation, triband wide bandwidth of AR (5%, 9%, and 13.6%), and higher values of diversity parameters (TARC, ECC, DG, CCL, and MEG) as compared to the ordinary values. Due to these features, this MIMO antenna is a suitable applicant for modern WLAN and WiMAX applications that claim CP properties, good isolation, reliable connectivity, compact size, and efficient triband lower frequency utilization.

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