Ultra-Compact Three-Port MIMO Antenna With High Isolation and Directional Radiation Patterns

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***Abstract*—In this letter, a disk-shaped ultra-compact three-port planar multiple-input–multiple-output (MIMO) antenna is proposed and fabricated. The antenna is designed for the 2.4-GHz WLAN band, the radius of which is only 16 mm (0.13λ). Three microstrip-fed T-shaped open-ended slots are used as radiating elements, whose edge-to-edge separation is only 0.006λ. They are rotationally symmetric and generate directional patterns that aim at 0°, 120°, and 240°, respectively. The peak gain of these patterns is 2.3 dBi, and the pattern correlation coefficient is below 0.03, which provides good pattern diversity for an MIMO system. Meanwhile, the 3-dB beamwidth of these patterns is 105°, which can realize nearly full azimuth coverage with its three beams. By introducing a newly designed neutralization network, the isolation between elements reaches 24 dB at the resonant frequency. Moreover, the proposed antenna is manufactured on the FR-4 substrate, which is cost-effective and easy to be implemented in a size-limited MIMO application.**

***Index Terms*—Antenna radiation patterns, multiple-input–multiple-output (MIMO), mutual coupling, slot antennas.**

I. Introduction

MULTIPLE-INPUT–MULTIPLE-OUTPUT (MIMO), as a technique that can offer significant performance improvement without using additional bandwidth or transmission power, has received growing interest ever since it was introduced in the 1990s [1]. By using multiple antennas in both the transmitter and receiver, the MIMO technique can detect multiple independent channels in free space, which can achieve a higher bit rate compared to the classic single-antenna design.

Attracted by this unique feature, newly developed wireless communication devices, such as the 802.11ac receiver, have adopted this technique [2]. The miniaturization trends in these devices impose more stringent requirements on the MIMO antenna design. A state-of-art design should not only possess good impedance matching and low mutual coupling, but should also have small size, low price, and full-range coverage along with similar radiation patterns. Undoubtedly, achieving such a design is very challenging because of the tradeoffs existing between these features. Many attempts have been taken in this area, such as those reported in [3]–[9].

To fit the MIMO antenna into a limited space, the element size should be as small as possible. Many miniaturization methods, such as folded or meander-line technique, have been adopted in [3] and [4], which can reduce the element size effectively. However, with the planar inverted-F antenna (PIFA) or monopole as the radiating element, the metal ground in these designs also participates in the radiation. It cannot be separated from the radiating elements, which are still too large for size-sensitive applications.

Apart from the element design, lowering the intensified mutual coupling between highly integrated elements is another challenge. Orthogonally placing the elements in an MIMO antenna is one solution [5]. This will be very effective if the elements have directional patterns. However, the elements are independent, which cannot push the size into the limit. In similar fashion, the mutual coupling can be controlled by combining the elements with orthogonal modes/polarizations [6]; nevertheless, the various element types provide different radiation patterns and gains, which cannot achieve consistent performance in all angle ranges. In addition, the modifying ground structure [7], electromagnetic band-gap (EBG) material [8], and neutralization line techniques [9], [10] can also reduce the mutual coupling effectively. However, these structures are wavelength-related, which makes them difficult to apply in an ultra-compact MIMO antenna design.

In this letter, an ultra-compact three-port planar MIMO antenna designed for the 2.4-GHz WLAN band is proposed and fabricated. The antenna has a round contour with a radius of 16 mm (0.13λ), which is the most compact planar multielement ($N > 2$) MIMO antenna design in the existing literature. By introducing three rotationally symmetric T-shaped open-ended slots as the radiating elements, the proposed antenna provides three directional patterns with an interval of 120°. The peak gain reaches 2.3 dBi, and the 3-dB beamwidth covers 105°, which can provide good pattern diversity and nearly full azimuth coverage in free space. Moreover, a newly designed neutralization network is applied to reduce the mutual coupling. This network reuses the feeding structure to reduce the size, and -24 dB coupling level is achieved with an edge-to-edge separation of 0.006λ between adjacent elements. Section II shows the geometry of the proposed antenna and describes the size reduction and decoupling techniques in detail. Section III shows the simulation and measurement results, which verify the antenna performance and feasibility in practice. Section IV discusses the MIMO performance and provides a comparison to other planar multielement MIMO antennas.

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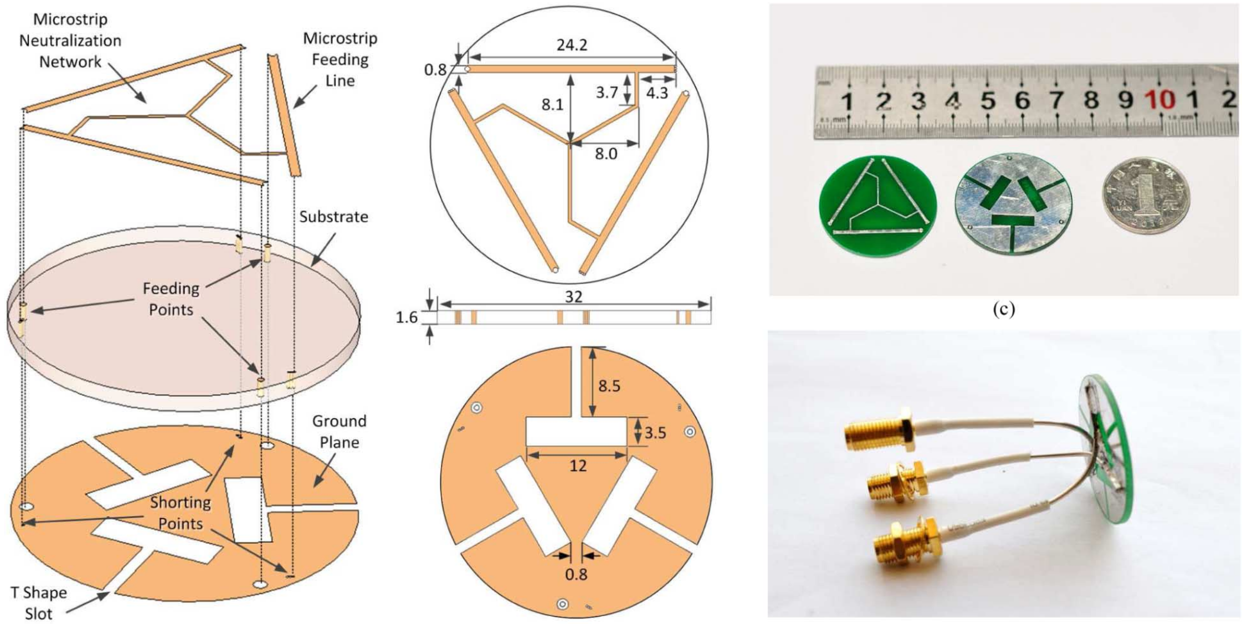

(a) (b) (c) (d)

Fig. 1. (a) Geometry, (b) dimensions in millimeters, and (c), (d) prototype of the proposed antenna.

II. Antenna Design

Fig. 1 shows the geometry of the antenna, which is fabricated on a double-sided FR-4 ($\varepsilon_{\rm r} = 4.4$, $\tan\delta = 0.02$) substrate. The antenna has a rounded contour with a radius of 16 mm (0.13λ).

In the bottom layer, three open-ended slots are etched on the metal ground, which are rotationally symmetric with an interval of 120°. The open end of the radiation slot acts as a magnetic wall, and the base mode (TM10) is excited with a resonant length of $\lambda/4$. To further minimize the size, a T-shaped slot is applied in this design, with which the edge-to-edge separation between elements is only 0.8 mm (0.006λ). Compared to the $\lambda/4$ straight slot, the T-shaped slot can be fitted into $\lambda/8$, and its bandwidth can cover the whole 2.4-GHz WLAN band.

In the top layer, three microstrip feeding lines are placed above the T-shaped slots; these lines feed the slots through electromagnetic coupling. Three feeding ports and three shorting points are placed at the two ends of the feeding lines; these provide 50-Ω interfaces and achieve the impedance matching at the desired frequency.

To deal with the mutual coupling, a newly designed three-port neutralization network is introduced. This network is composed of three rotationally symmetric neutralization lines, which connect the feeding lines near the shorting points together. Through this neutralization network, a portion of the signal propagates from one port to the adjacent ports, which has the same amplitude but inversed phase to the original coupling signal. As a result, the original coupling signal is canceled out, and the total coupling level is reduced. Fig. 2 shows the current distribution and the S-parameters comparisons with and without this network. As indicated in this figure, the current density around the adjacent ports is greatly reduced by introducing this network. The S_{21} improves from -8 to -24 dB at the central resonant frequency and stays below -15 dB throughout the band. Compared to the traditional neutralization line technique proposed in [9], this design reuses the electric length existing in the feeding line, which further minimizes its length to fit into the limited space.

III. Simulation and Measurement Result

To validate the performance of the proposed antenna, a prototype is fabricated and tested in this study. Fig. 1(c) and (d) shows the photographs of the antenna, in which three semi-rigid coaxial cables are connected to perform the measurements. In the following, the S-parameters, radiation pattern, gain, and efficiency are measured and compared to the results acquired in the full-wave simulation software HFSS.

A. *S-Parameters*

The S-parameters are measured with the Agilent VNA E5071B. The results are shown in Fig. 3. Good impedance matching and high isolation are achieved in both the simulation and the measurement. Since the radiating elements are rotationally symmetric, only the return loss in port one (S_{11}) and the mutual coupling between ports 1 and 2 (S_{12}) are provided.

In simulation, the return loss (S_{11}) is lower than -10 dB from 2400 to 2480 MHz, and the coupling level (S_{12}) is below -15 dB throughout this band. In measurement, the return loss and mutual coupling traces show similar trends to the simulation ones. Comparatively, the matching range shifts around 25 MHz toward the higher frequency, which may result from uncertainty in the substrate permittivity or size error in manufacturing. The isolation is better than 15 dB in the whole matching band and reaches 24 dB at the central resonant frequency, which verifies the effectiveness of the proposed neutralization network.

B. *Radiation Pattern*

Due to the existence of the metal ground, the wave propagation in the inward direction is blocked. As a result, three directional patterns are generated in the radial direction; these are toward 0°, 120°, and 240° as shown in Fig. 4.

Because these patterns are rotationally symmetric, the measured patterns of port 1 are provided in Fig. 6. These normalized patterns are measured in an ETS-Lindgren AMS-8500 anechoic chamber, where a 3-D pattern is provided to show the coordinate system. The measured patterns match the simulation re-

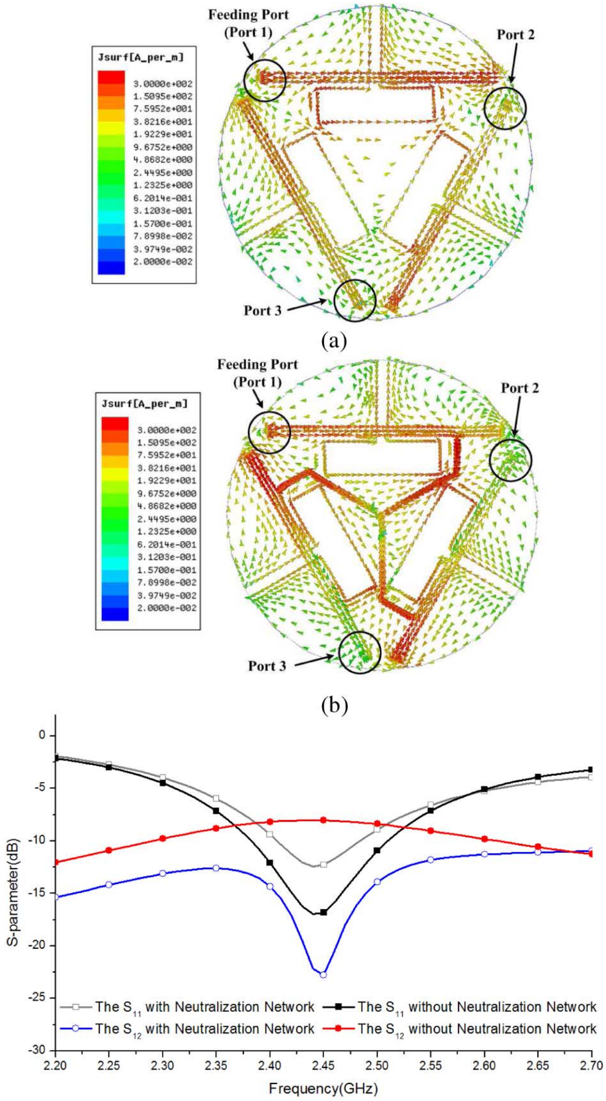

Fig. 2. Current distribution and the S-parameters comparison with/without the neutralization network.

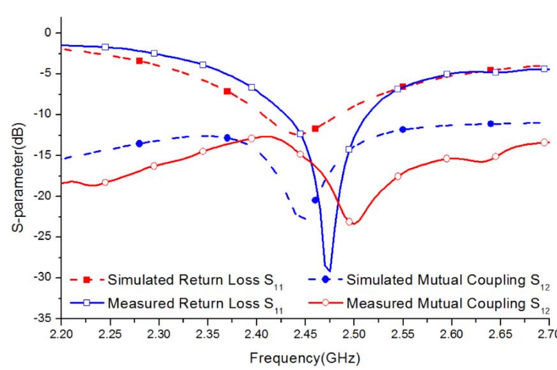

Fig. 3. Simulated and measured S-parameters of the proposed antenna.

sults well, and the front-to-back ratio reaches 3.3 dB. The 3-dB beamwidth in the xoy-plane covers 105°, which can not only provide good pattern diversity to boost the channel capacity but also catch the signal from every angle with its nearly full azimuth coverage.

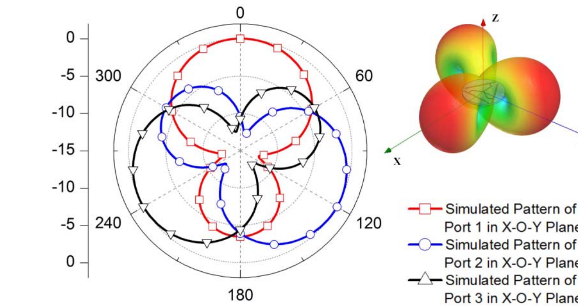

Fig. 4. Directional pattern and the beam coverage of the proposed antenna.

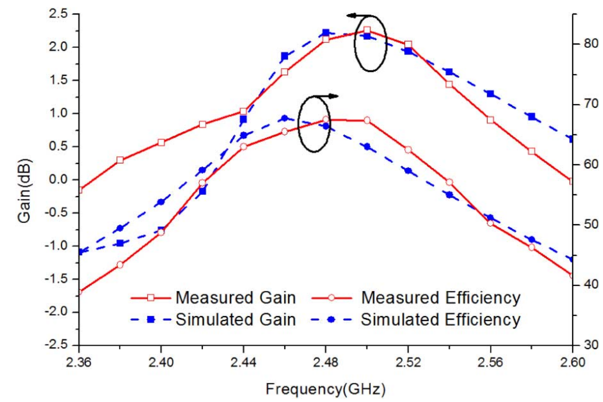

Fig. 5. Simulated and measured gain and efficiency of the proposed antenna.

C. Gain and Efficiency

The gain and efficiency are also measured in the AMS8500 anechoic chamber; the values are plotted in Fig. 5. Similar to its resonant character, the measured gain and efficiency shift a little toward the higher frequency, but share the same trends as in the simulation. The gain stays above 2 dBi throughout the band, and the peak rises to 2.3 dBi at the central resonant frequency. Meanwhile, the efficiency remains above 60% in the working band and reaches around 68% at the peak.

IV. MIMO Performance and Size Comparison

In MIMO antennas, the pattern correlation coefficient [11] between elements is the key parameter in evaluating performance. This can be calculated as

$$\rho_e \approx \left| \frac{\oiint A_{12}(\Omega)d\Omega}{\sqrt{\oiint A_{11}(\Omega)d\Omega}\sqrt{\oiint A_{22}(\Omega)d\Omega}} \right|^2$$

$$A_{ij} = \Gamma E_{\theta,i}(\Omega)E^*_{\theta,j}(\Omega)\cdot p_\theta(\Omega) + E_{\phi,i}(\Omega)E^*_{\phi,j}(\Omega)\cdot p_\phi(\Omega) \quad (1)$$

where E_θ and E_φ denote the two orthogonal components of the complex electrical field of the antenna patterns; $p_\theta(\Omega)$ and $p_\varphi(\Omega)$ are the multipath angular density function of the θ and φ polarization; and Γ is the average cross-polarization ratio that reflects the polarization environment applied in the calculation.

Consider that the proposed antenna is potentially applied in an indoor WLAN system. Γ is set to 0 dB, which simulates a rich multipath environment with evenly distributed vertical and horizontal polarization components. Benefitting from its directional radiation patterns, a low correlation between patterns is acquired in the measurement. The maximal value at the central

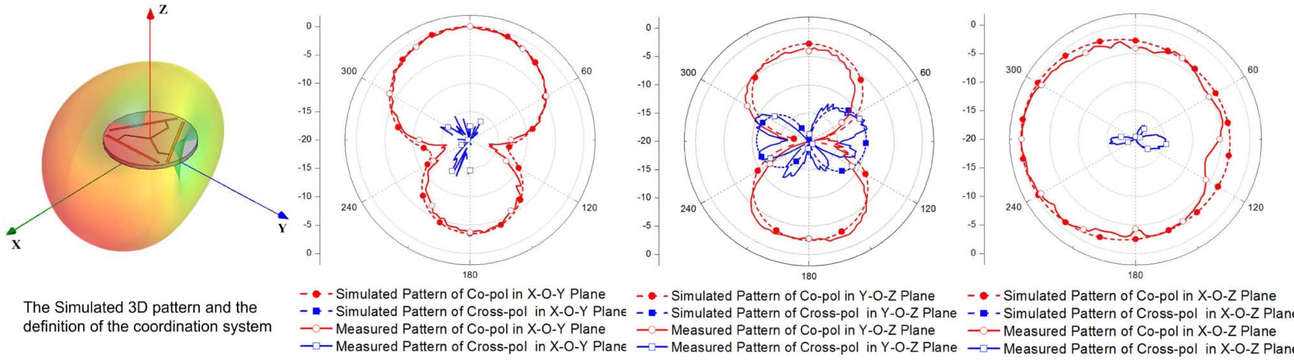

Fig. 6. Normalized simulated and measured pattern of the proposed antenna when feeding port 1.

TABLE I
COMPARISON BETWEEN THE PROPOSED ANTENNA AND OTHER PLANAR MULTIELEMENT ($N > 2$) MIMO ANTENNAS

Ref.	Number of Element	Area(in λ^2)	Area Per Element(in λ^2)	Bandwidth (-10dB Lower Band)	Maximal Mutual Coupling	Pattern Type	Peak Gain
[5]	4	0.59	0.15	5.10GHz-6.00GHz	-17.0dB	Directional	5.0dBi
[6]	4	0.31	0.078	2.40GHz-2.50GHz	-25.0dB	Irregular	3.5dBi
[12]	4	0.30	0.076	2.28GHz-2.66GHz	-14.0dB	Irregular	4.9dBi
[13]	4	0.11	0.028	2.41GHz-2.54GHz	-8.5dB	Irregular	2.4dBi
[14]	3	0.27	0.090	2.23GHz-2.62GHz	-8.6dB	Irregular	4.1dBi
This Paper	3	0.053	0.017	2.45GHz-2.55GHz	-15.0dB	Directional	2.3dBi

resonant frequency is 0.0289, which proves that this design can provide considerable pattern diversity for an MIMO system.

Table I shows a comparison between the proposed antenna and other planar multielement ($N > 2$) MIMO antennas in terms of size, bandwidth, mutual coupling, pattern type, and gain. It can be observed that the proposed antenna is the most compact planar multielement MIMO antenna characterized by low mutual coupling and directional radiation patterns.

V. CONCLUSION

In this letter, an ultra-compact three-port MIMO antenna designed for the 2.4-GHz WLAN band is proposed and fabricated. The antenna is fabricated on 1.6-mm-thick disk-shaped FR-4 substrate with a radius of 16 mm (0.13λ), which is the most compact planar multielement ($N > 2$) MIMO antenna in existing literature. To fit three radiating elements into such a compact area, T-shaped slots and a newly designed neutralization network are introduced to achieve size reduction. The slots provide three directional radiation patterns to increase the pattern diversity, whereas the neutralization network introduces a new coupling component to achieve coupling cancellation. As a result, the gain reaches 2.3 dBi at the peak, and the 3-dB beamwidth covers 105°. The pattern correlation coefficient between elements is only 0.028, and the mutual coupling remains below -15 dB in the whole working band. To verify its feasibility in practice, a prototype is built and measured. The measurement results show good agreement with the simulation ones. Benefiting from its planar structure, this antenna can be reproduced with the traditional printed circuit board (PCB) manufacturing process, thus making it a low-cost and promising design for use in size-limited MIMO applications.

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