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Conception and Fabrication of a New Steerable Microstrip Antenna for ISM Band Applications

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ABSTRACT: This paper presents the conception and fabrication of a new steerable microstrip antenna for ISM band applications. At first, the fundamental antenna element is designed, optimized, and miniaturized to operate at 2.45 GHz, exhibiting a narrow impedance bandwidth and a good gain. However, the standalone element lacks beam steering capability. To enable directional control of its radiation pattern, a novel 3 dB hybrid coupler is used to feed two identical optimized elements, forming a switched array antenna. The resulting configuration achieves a wide impedance bandwidth and improved gain with beam steering capability. The proposed steerable antenna is designed and fabricated on a Rogers RT/duroid 5880 substrate. The simulated results are validated with measured data, showing good agreement and confirming the design's performance.

1. INTRODUCTION

In recent decades, radio frequency identification (RFID) technology has replaced traditional object identification methods like paper and cards, enabling contactless identification through radio waves. It is widely used worldwide, especially in ultra-high frequency (UHF) and super high frequency (SHF) applications such as vehicle tracking, industry, smart cards, monitoring, and real time location systems [1–3]. Current RFID readers typically use a single microstrip patch antenna. However, these antennas suffer from several drawbacks, including the limited bandwidth, low gain, limited directivity, and a lack of agility in their radiation patterns, producing only a single fixed beam [4–11]. Researchers have improved certain performance aspects of these antennas by employing two-element microstrip arrays [11–15], four-element arrays [16–20], and eight-element microstrip arrays [21, 22], achieving higher gains and enhanced directivity. Nevertheless, these array antennas continue to radiate energy in a single direction, resulting in only a fixed beam. In specific applications like RFID tag tracking, conventional antennas are inadequate, making steerable antennas a promising solution [23]. These antennas can dynamically control their radiation pattern, allowing them to focus on specific tags and select from predefined beam directions.

To implement a steerable antenna, a phased array antenna requires the use of circuit beamformers as a feeder. Due to its parallel feeding capability and the phase shift provided between its two output ports, hybrid coupler is a solution for this purpose. The hybrid coupler used most in the literature [24, 25] is 3 dB coupler that divides the input power into equal quantities with the phase shift of $\pm 90°$. Hence, in this work, instead of using the traditional hybrid coupler, we propose a novel 3 dB directional coupler that introduces phase shifts of $-135°$ and $45°$ when either input port 1 or port 2 is fed. This coupler will then be used to feed two identical patch antennas, enabling the realization of a broadband steerable 1×2 array antenna.

In addition, recent studies have shown a growing emphasis on the development of compact, high-performance multiple-input multiple-output (MIMO) and array antenna systems tailored to the evolving demands of modern wireless communications. For instance, some works [26] have utilized characteristic mode analysis to design tri-band MIMO

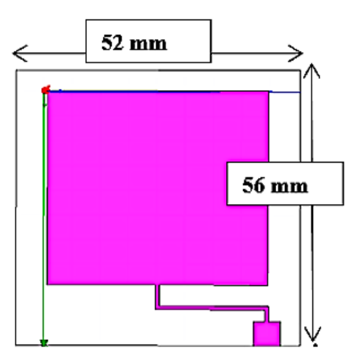

FIGURE 1. The design of the basic antenna element.

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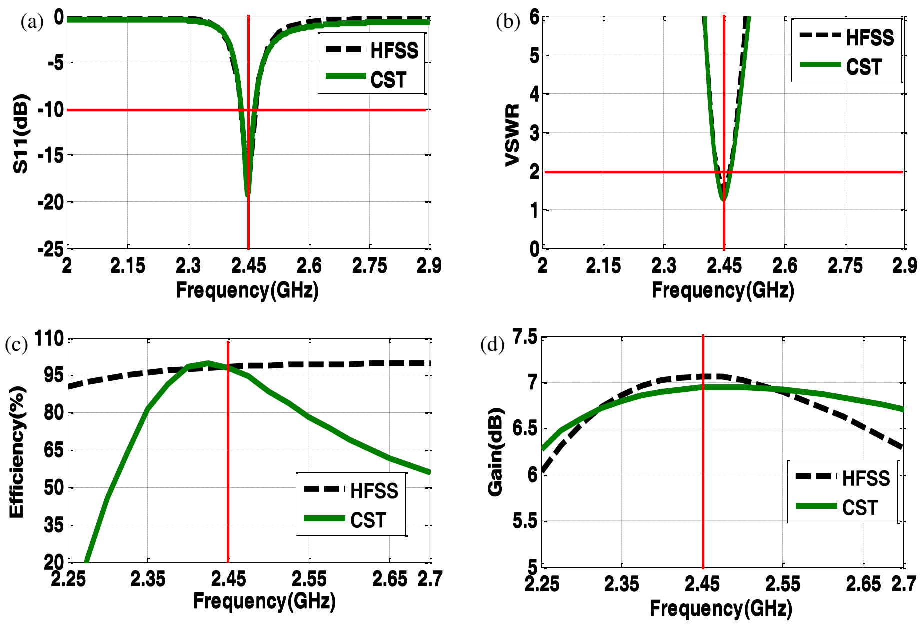

FIGURE 2. Comparison of HFSS and CST results for the basic element.

antennas offering enhanced isolation and miniaturization. Others [27, 28] have focused on compact MIMO configurations targeting millimeter-wave and multi-band applications such as 5G and Wi-Fi 6. Additional research [29] has explored compact MIMO solutions for mobile devices using metamaterials to optimize performance at 28/38 GHz. In the context of beam-steering and array architectures, further efforts [2, 25] have introduced wideband and broadband microstrip arrays utilizing coupler and magic-T power divider techniques for industrial, scientific, and medical (ISM) and terahertz (THz) bands. Compared to these designs, the proposed antenna not only achieves compactness and high directivity but also uniquely integrates beam-steering functionality at 2.45 GHz, along with a significantly wide impedance bandwidth of 0.845 GHz, as presented in Table 1. This combination of characteristics highlights the suitability of the proposed structure for reconfigurable and adaptive wireless systems.

Following this introduction, this paper will be organized as follows. Section 2 presents the basic element antenna design. Section 3 shows the proposed directional coupler. Section 4 presents design and fabrication of the proposed beam steerable array antenna. Section 5 will be the conclusion of this article.

2. THE BASIC ELEMENT ANTENNA

The proposed radiating element design is shown in Figure 1. It contains a rectangular microstrip antenna fed via 50 Ω microstrip line. The impedance matching between them is achieved via a curved microstrip quarter-wave impedance transformer. The quarter-wave transformer is curved to achieve a miniaturized size for the basic element. The analytical equations for calculating the parameters of the radiating element, 50 Ω feedline, and quarter-wave impedance transformer are provided in our published paper [23]. These equations are implemented through MATLAB programming [30].

Initially, the design was carried out using High Frequency Structure Simulator (HFSS) software, and the simulation results were later validated with another 3D simulator, Computer Simulation Technology (CST). Figure 2 compares the HFSS results with those obtained from CST. As shown, the two simulators produce nearly identical results. Figures 2(a) and 2(b) show the S_{11} variation versus frequency and voltage standing wave ratio (VSWR) versus frequency, respectively. In these figures, the antenna resonates at 2.45 GHz with a narrow bandwidth of 32 GHz. Figure 2(c) plots efficiency versus frequency. Figure 2(d) exhibits the antenna gain versus frequency. It is clear that at the operating frequency, the two simulators yield a similar gain of approximately 7 dB.

3. THE PROPOSED DIRECTIONAL COUPLER

A hybrid coupler is a microwave device that splits input power between two output ports, either equally or unequally. The most commonly used coupler is 3 dB coupler, which divides the input power equally between the two output ports, introducing a $\pm 90°$ phase shift between the output signals.

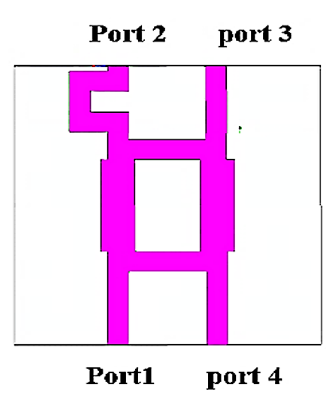

FIGURE 3. The proposed directional dB hybrid couplers ($-135°/45°$).

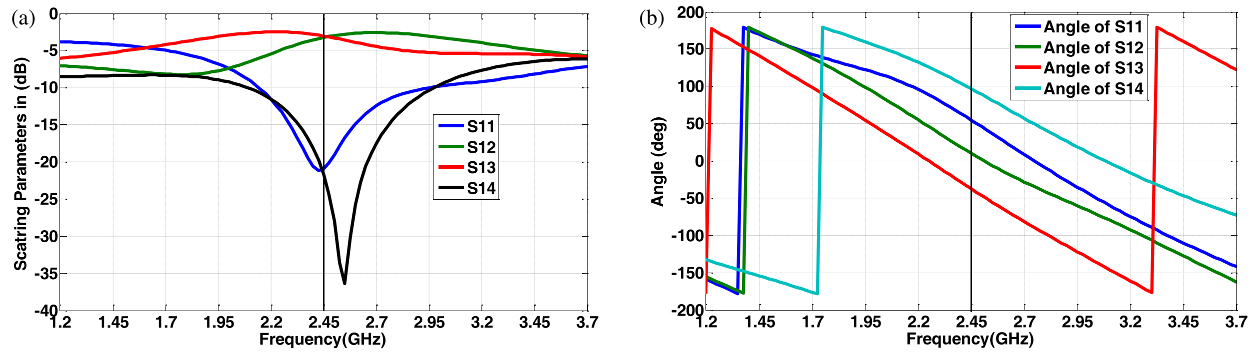

FIGURE 4. Simulation results of the proposed 3 dB $-135°/45°$ hybrid coupler; (a) Module of the scattering parameters versus frequency; (b) Angles of the transmission coefficients versus frequency.

TABLE 1. Performance comparison of the proposed antenna with previous works.

Works	Operating frequency (GHz)	Size (cm^2)	Peak directivity (dB)	Impedance bandwidth (GHz)	Beam-steering capability
[4]	2.45	8×9.5	4.68	0.086	No
[8]	2.45	22.5×22.5	7.7	0.063	No
[9]	2.45	23.27×7.81	8.35	0.111	No
[10]	2.4–2.5	9×6.5	5.2	0.114	No
[12]	2.45	9.6×27.5	7.97	0.094	No
This work	**2.45**	$\mathbf{11.3 \times 11.2}$	**8.88**	**0.845**	**Yes**

In this section, we will show a modified version of the classical coupler to create a novel design that equally divides the input power between two output ports, introducing a phase shift of $-135°$ or 45° when port 1 or port 2 is fed, respectively. The design of the proposed novel 3 dB directional coupler is shown in Figure 3.

Figure 4 presents the simulation results of the enhanced 3 dB hybrid couplers ($-135°/45°$) in terms of scattering parameters. Figure 4(a) shows module of the scattering parameters in dB versus frequency, while Figure 4(b) shows angles of the transmission coefficients in degree versus frequency when port 1 and port 4 are powered. According to this figure, it is clear that at the operating frequency, the transmission coefficients are equal to approximately -3.09 dB which means that the power supply is divided into two equal quantities. Moreover, the reflection coefficient (S_{11} or S_{44}) and isolation coefficient (S_{14} or S_{41}) are less than -20 dB which means that input power is almost transmitted to output ports 2 and 3. It can also be observed that when port 1 is excited, the phase shift between the output ports is $-133.5°$, whereas when port 4 is excited, the phase shift is $45.31°$.

4. DESIGN AND EXPERIMENTAL VALIDATION OF THE PROPOSED BEAM-STEERABLE ARRAY ANTENNA

In this section, the enhanced hybrid coupler is used to fed two identical elements, as shown in Figure 5, which presents both the design and fabricated prototype. Figures 5(a) and 5(c) show the top view, while Figures 5(b) and 5(d) illustrate the bottom view. The proposed steerable array antenna is developed and fabricated on a Rogers RT/duroid 5880 substrate ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$), with overall dimensions of $112 \times 113\,\mathrm{mm}^2$, as depicted in Figure 5. The simulation results are validated through experimental measurements, demonstrating good agreement, as shown in Figures 6 and 7.

The printed circuit board (PCB) fabrication of microstrip antenna array follows a photolithography process. First, the PCB antenna design is created using Eagle software and printed on a transparent sheet. The antenna is then fabricated on an RT Duroid substrate, with the required size cut and edges smoothed. The board is cleaned with steel wool, and a liquid photoresist is applied for 1 second, followed by 4 minutes of baking for uniform coating. After baking, the PCB is exposed to UV light using the negative film to emboss the design, then baked again for 2 minutes. The image is developed by placing the PCB in an liquid photo-imageable (LPI) developer for 1 minute, followed by post baking in the dryer for 2 minutes. The unwanted copper is etched away using an Easy Etcher unit, and the PCB is cleaned with water. Any excess substrate is cut, and SMA connectors are soldered to the antenna ports for feed line connections, enabling measurements with a Vector Network Analyzer (VNA) for parameters like return loss, bandwidth, and center frequency.

The simulation results obtained using HFSS versus measured results are presented in Figures 6 and 7, illustrating two sce-

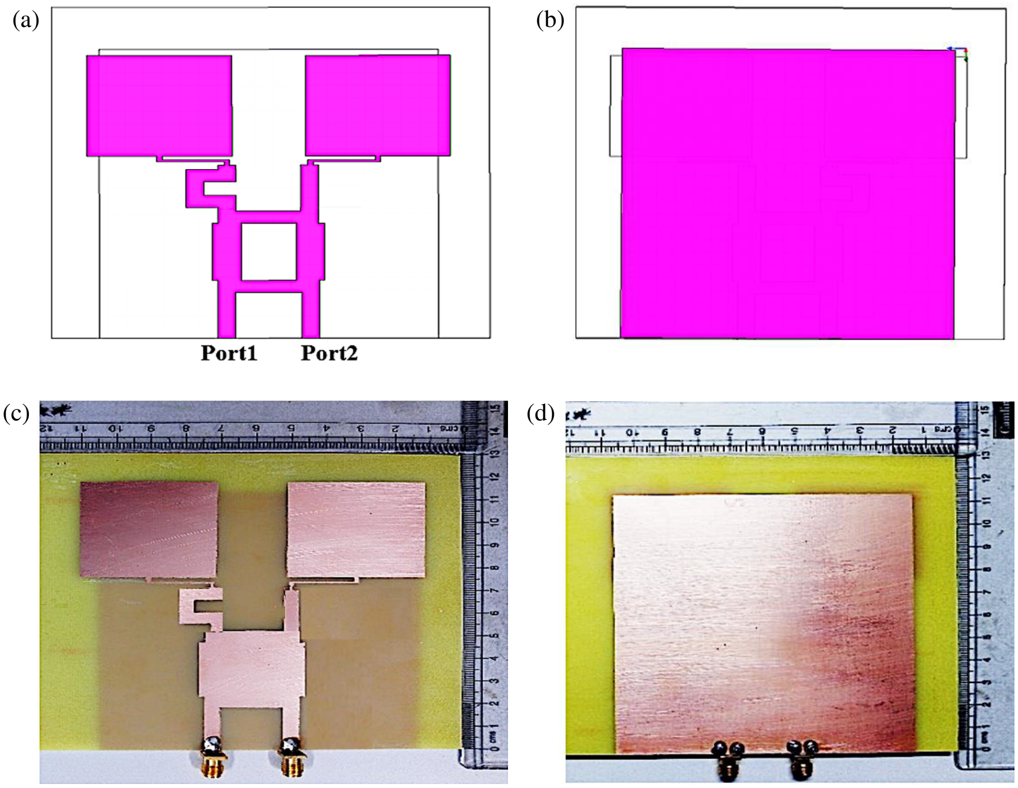

FIGURE 5. Design and fabricated prototype of the agile 1 × 2 array antenna utilizing a novel 3 dB hybrid coupler ($-135°$/45°), (a), (c) top view, (b), (d) bottom view.

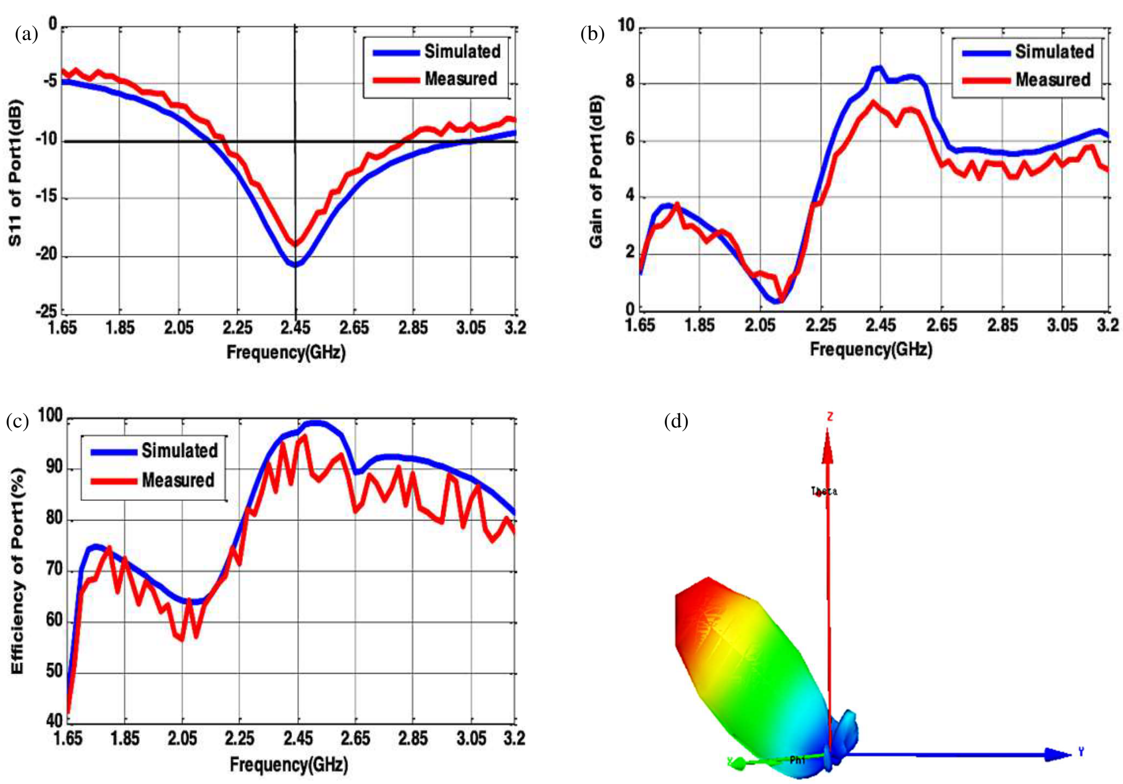

FIGURE 6. Simulated results versus measured ones when input port 1 is fed. (a) S_{11} against frequency; (b) Gain against frequency; (c) Radiation efficiency against frequency; (d) Maximum beam direction.

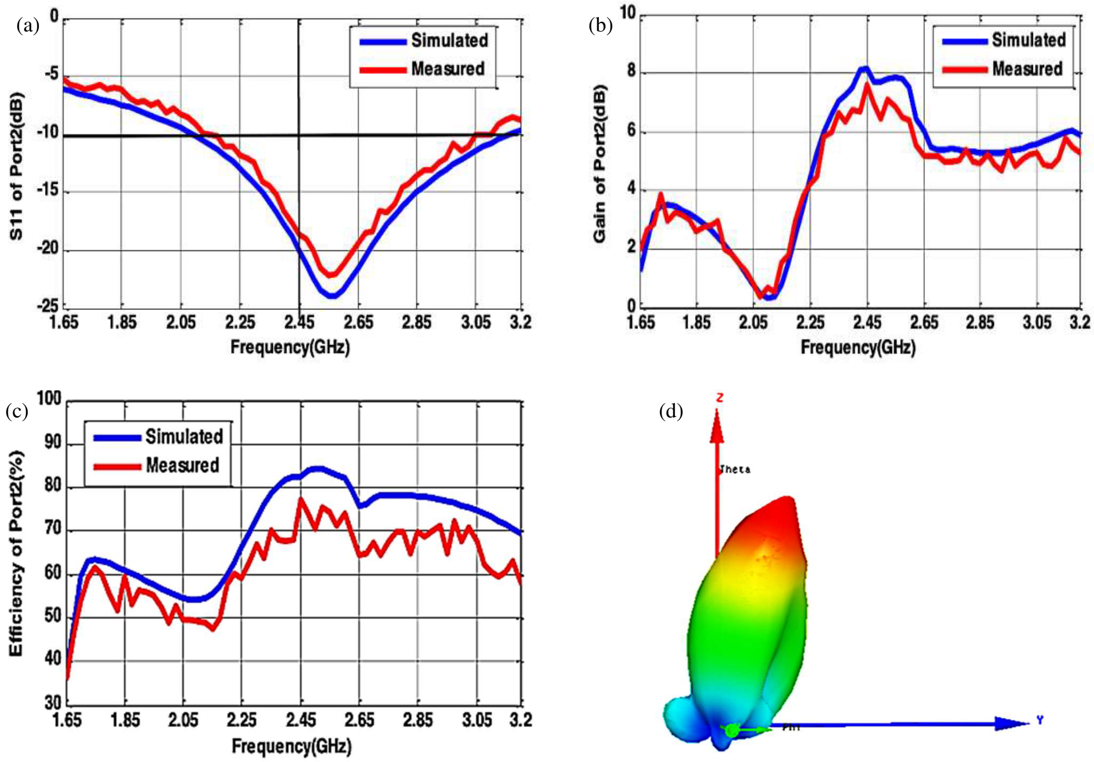

FIGURE 7. Simulated results versus measured ones when input port 2 is fed. (a) S_{11} against frequency; (b) Gain against frequency; (c) Radiation efficiency against frequency; (d) Maximum beam direction.

narios: when input port 1 is fed and when input port 2 is fed, respectively. The radiation pattern agility of the proposed antenna is achieved by switching the input power between input ports 1 and 2 of the proposed coupler.

Regarding the obtained results, the issue of narrow bandwidth, reflected in insertion loss (S_{11}) has been effectively addressed. The bandwidth has been significantly enhanced, reaching approximately 845 MHz, as shown in Figures 6(a) and 7(a). Figures 6(b) and 7(b) illustrate gain versus frequency, demonstrating that the peak gain is approximately 8.88 dB in both cases. This improvement resolves the previous limitation of low gain, increasing it to 8.88 dB, which is a favorable enhancement in both the scenarios. Figures 6(c) and 7(c) depict radiation efficiency versus frequency, where both scenarios indicate a peak efficiency about 98%, signifying nearly total power transfer to the output ports. Figures 6(d) and 7(d) show the maximum beam direction, i.e., when port 1 is fed, the beam is steered to the left by $-45°$, and when port 2 is fed, the beam is also directed to the left by $15°$.

Table 1 presents a comparative analysis between the proposed antenna and several recent works operating at similar frequencies. The proposed design achieves a significantly wider impedance bandwidth (0.845 GHz), which is nearly an order of magnitude larger than previous designs, while maintaining a compact size ($11.3 \times 11.2\,\text{cm}^2$) and high peak directivity (8.88 dB). Moreover, it is the only design among the listed works to demonstrate effective beam-steering capability, making it highly suitable for dynamic wireless applications.

5. CONCLUSION

In summary, a low-cost, low-profile broadband steerable dual-beam microstrip antenna array has been presented for ISM band applications. The design utilizes a novel directional coupler to dynamically adjust its radiation pattern by simply switching between input ports, enabling electronic beam steering without the need for mechanical movement. This approach significantly reduces complexity and improves reliability compared to conventional mechanically steered systems. Moreover, unlike traditional single-beam or narrowband phased arrays, the proposed antenna achieves dual-beam radiation with wide impedance bandwidth, high gain, and excellent directivity which demonstrates broader coverage and greater flexibility. These advantages make it a strong candidate for modern wireless communication systems requiring agile, efficient, and compact beamforming solutions.

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