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Broadband Circularly Polarized Microstrip Patch Antenna with Diamond-Shaped Artificial Ground Structure

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ABSTRACT: This paper presents a broadband circularly polarized patch antenna with an artificial ground structure (AGS), which has rotated rectangular unit cells with respect to the sides of the rectangular ground plane, as a polarizer. A two-element (2×1) array configuration of the antenna is also presented. The rectangular unit cells are rotated by 45° with respect to the sides of a square dielectric substrate, named a diamond-shaped AGS (DAGS). The overall dimensions of the AGS are smaller than those of the ground plane. The rotated unit cells and the smaller AGS patch dimensions effectively suppress surface wave resonance on the AGS. The proposed antenna achieves a wide 3-dB axial ratio bandwidth in the boresight direction. The proposed design has a flatter gain curve in the operating frequency band compared to that for conventional designs. It is found that the array configuration outperforms the single element structure.

KEY WORDS: Cylindrical dielectric antenna, ultra-wideband, defected ground structure

I. INTRODUCTION

The development of aerial drones has captured a lot of attention due to their widespread applications, such as aerial photography, event monitoring, and delivery of goods. Regardless of the application or the size of the drones, antennas are necessary for remote control and data transmission. Electric monopole antennas are widely used in drones because they have omnidirectional radiation patterns in the azimuth plane. Most drones operate at altitudes below 200 meters. When they are flying at different altitudes, as shown in Fig. 1, the elevation angle from the drone to the ground controller varies. However, a conventional monopole antenna produces a conical beam with a elevation angle, which limits the coverage area of the antenna. To improve the transmission between the aerial drone and the ground controller, a beam-steering antenna is a promising solution. In the recent decade, many reconfigurable antennas have been proposed with different beam-steering techniques. Reconfigurable parasitic elements [1]_[4] and frequency selective surfaces (FSS) [5]_[7] are widely used in beam-steering antennas. They are arranged as directors or reflectors to steer the main beam in different directions. Leaky-wave antennas are good candidates for beam-steering applications because their main beam can be frequency controlled. By loading switchable shorting vias [8], [9] or lumped elements [10], frequency beam-scanning leaky-wave antennas are obtained. Beam steering is also achieved by employing an asymmetrical arrangement of the PIN diodes on a symmetrical structure [11], [12]. However, most of the beam-steering reconfigurable antennas produce directional radiation, which does not provide stable coverage for all azimuth directions. Recently, several reconfigurable patch antennas [13]_[16] were reported to achieve switchable broadside and conical radiation for indoor wireless applications. Different radiation patterns are achieved by using the monopolar patch and normal patch modes of the square [14], [15], circular [16], or square-ring [13] patches. However, the elevation angles of the conical beams produced by these antennas are less than 50°. The small elevation angle limits the transmission distance for drone applications. Microstrip magnetic dipole antennas [17], [18] were first proposed to design low-profile vertically polarized Yagi arrays. They provide an omnidirectional radiation pattern similar to that of an electric dipole and can be implemented to design omnidirectional circular polarized antennas [19], [20]. In this paper, a novel microstrip magnetic dipole antenna with switchable conical beams is proposed. The conical beams with different elevation angles are produced by different resonant modes of the microstrip magnetic dipole antenna. The radiation patterns of these resonant modes are analyzed in Section II. The antenna configuration is depicted in Section III. The parameter study in Section IV is conducted to show the design process of the proposed antenna. The measurement and comparison are discussed in Section V.

II. RELATED WORK

FD (Full-duplex) antenna systems have garnered significant attention in the context of high data rate wireless communication system design, since they concurrently use same time/frequency slot for both transmission and reception, leading to enhanced spectral efficiency compared to their half-duplex (HD) counterparts [1] (See Fig. 1 for a schematic representation of HD and FD communication system). However, the FD communication system suffers from self-interference (SI) problem, that occurs due to the signal emanated by the device's own transmitter, which interferes with the received signal of interest [2]. In a broad sense, the SI cancellation approaches available in literature can be classified in two modes: *passive* and *active*, where the *active* strategy can be subdivided into analog and digital techniques [2]. *Passive* mode of SI cancellation (also known as "antenna cancellation") relies on mutual coupling reduction between the transmitter and receiver antenna in the bandwidth. The proposed antenna is a square ring structure and it is fed by EM FD system, while the *active* SI reduction strategies are implemented in the analog/digital base-band stages. However, analog SI cancellation cannot provide sufficient isolation to prevent the saturation of active components such as low noise amplifier (LNA) and analog-to-digital converter (ADC), prior to the digital SI cancellation [3]. Therefore, to augment the active (analog and digital) SI cancellation techniques and reduce the system cost, it is judicious to use passive antenna mutual coupling (MC) reduction techniques in FD antenna systems. Apart from the FD technology, MIMO (multiple-input multiple-output) antenna system is another enabling technology for the advanced 4G/5G wireless communication that provided high data rate and enhanced spectral efficiency. However, MIMO antenna systems also require low inter-port mutual coupling to cater optimum performance. It should be noted that, MIMO antenna systems can operate with port-to-port MC level of ≤ 15 dB. For example, a three-element diversity MIMO antenna with MC less than 15 dB is presented in [4]. MC less than 20 Db

between two microstrip MIMO antenna using an inverted fork shaped decoupling structure (IFSD) is presented in [5]. excitation thereby improving the cross-polar response and the dimension of the DGS determines stop band effect by incorporating transmission zero at the frequency of interest [27], [28]. The height between NFDS and the antenna ground plane determines the phase of the partially diffracted wave to cancel out the coupled wave. Also, height between defected ground and NFDS such ensures extremely low value of the inter-element mutual coupling. The dimensions of DGS and NFDS as well as the height between them is carefully decided using parametric analysis. The close proximity between the two planar conductors suggests that the electric \vec{E}_{eld} only consists of the x -component and thus the magnetic \vec{H}_{eld} has only yz - components in the region bounded by the planar conductors. Therefore, the modes supported by the cavity model are transverse magnetic with respect to the x -direction (TM $_x$). The electro-magnetic \vec{E}_{eld} inside the cavity can be expanded in terms of the TM $_x$ m n mode of the corresponding rectangular waveguide. For TM $_x$ m n modes of the conventional rectangular waveguide, the transverse magnetic fields are characterized by $H_x D 0$ and the solution of E_x can be found by solving the Helmholtz wave equation. To understand the effects of the parasitic elements, four configurations of MIMO antennas are investigated with performances. For the antenna without parasitic element (Antenna-H1), the impedance BW is quite small, i.e. about 4%, which is typical of a simple patch antenna (Fig. 3(a)). Besides, poor isolation is observed within this band, which is worse than 10 dB. Again, this is typical with a spacing s of only about $0.09 \lambda_0$ where λ_0 is the free-space wavelength at the center frequency. When the parasitic elements are introduced, the operating BW, isolation, and realized gain are significantly improved. In terms of refection coefficient, the parasitic elements produce additional resonance in the higher frequency range, which combines with the lower resonance generated by the driven patch to broaden the overall ≤ 10 -dB impedance BW of the antenna. For the isolation response, the antennas with parasitic elements show much better performance than those without parasitic elements. Furthermore, more parasitic elements result in better gain radiation.

III. PROPOSED SYSTEM

MICROSTRIP patch antenna was proposed in the 1950s [1]. It has been then widely studied and developed. In the past decades, extensive research has been carried out to widen its operating bandwidth in impedance [2], [3]. With the growth of the communication distance, the gain of the traditional patch antennas cannot meet the actual needs in some cases [4], [5]. Therefore, improving the gain of traditional patch antennas is crucial. The high-gain antenna could be used in mid-range or high-data-rate communications for compensation of propagation loss. Several methods have been proposed to improve the gain of microstrip antennas. For instance, the method in [6]–[9] consists in forming an antenna array. However, this may increase the design and manufacturing complexity. A substrate with a lower dielectric constant is used in [10], [11] to increase the gain. However, this requires a larger volume or higher profile. Parasitic radiation elements in stacked or planar structures are used in [12]–[14]. However, these antennas usually have a high profile or low aperture efficiency. The parallel inductive loading technology was also proposed [15], [16]. It consists in expanding the overall chip size at resonance. It is shown in [15] that the radiation gain increases with the expansion of

the radiation area by loading the short pin. Another technology is developed in the high mode operation of the patch antenna, due to the fact that the electrical size of the patch is much larger than that of the first mode [17]–[19]. However, the corresponding sidelobe level is high. The meta surface based patch antenna achieves a high gain or wideband by manipulating the electromagnetic waves [20], [21]. This method consists in combining the meta surfaces (MSs) with the patch. The microstrip leaky-wave antenna (MLWA) is a type of traveling-wave antenna [22] which is widely used in planar integrated communication systems due to its beam scanning characteristics and high directivity [23]. An offset periodic structure loaded in a traditional microstrip antenna was presented in [24]. A patch antenna based on the periodic leaky-wave structure was also proposed in [25]. It has the multi frequency characteristics of the traditional patch antenna. This paper proposes a gain-enhanced patch antenna with a periodic microstrip rampart line. That is a novel method designed to effectively improve the gain of the traditional microstrip patch antenna. The periodic microstrip rampart This antenna is composed of two FR4 substrates with a thickness t of 1 mm, a relative dielectric constant of 4.4, and distance h of 4.8 mm. The shape of the substrate is a combination of three rectangles. Each substrate has a metal patch on the back, and the two metal patches are connected by shorting sidewalls to form a cavity. There are six shorting posts (a1, a2, a3, b1, b2, and b3) with a diameter of 1 mm. These posts are divided into two groups (Group#A and Group#B) and are connected to two DC biasing lines with voltages of DC#1 and DC#2. The shorting posts divide the proposed antenna into three rectangular sub-cavities (ABCD, CDEF, and EFGH).

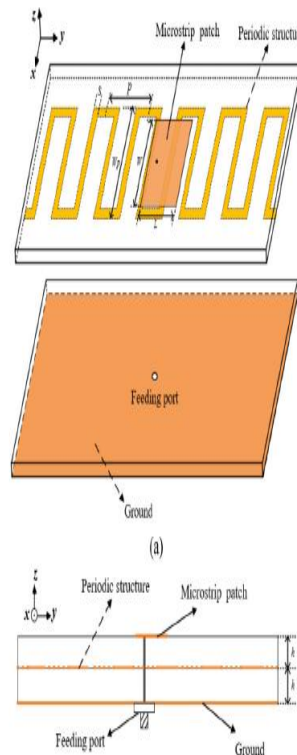


Fig.1 Proposed Design

the ground plane length effect on the rejection coefficient. It is clearly seen that it acts most strongly on frequencies below 10 GHz. In this case, the optimal value for x_1 is 6.5 mm. The width of the second truncation (y_1) is in the y -direction. It is noted that the effect is clearly visible in the frequency band 3-10 GHz. In this case, the impedance matching is better at y_1 D 8:75 mm, where the mismatch between 7 and 10 GHz decreases with respect to y_1 and is optimal for y_1 D 8:75 mm for frequencies beyond 10 GHz, which are less affected by the truncation of the ground plane

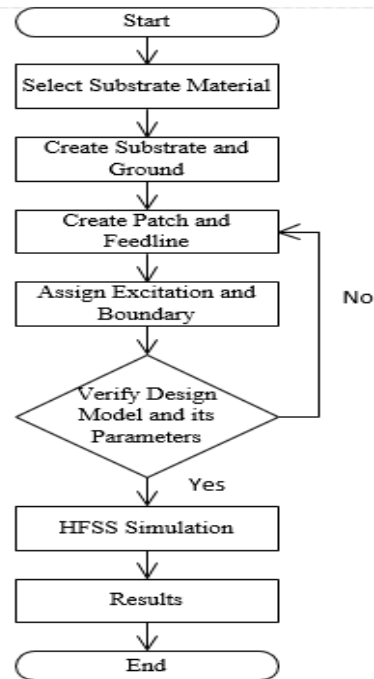


Fig.2 Flowchart

The antenna is fed by a single meandered feed line. Two of the unit cells around the center of the DAGS are partially drilled, and two other unit cells near the feed line are fully removed to prevent the meandering probe from coupling with the unit cells. The diameter of the vias is 1.27 mm. The feeding point of the radiating patch is 5 mm from the center of the truncated patch along the x axis for sufficient impedance matching and AR over a broad bandwidth. Furthermore, the unit cells are partially (some are mostly) cut around the edges of the DAGS to be along the rectangular contour. Here, the optimized size of the DAGS patch is smaller than those of the dielectric substrates and the ground plane.

IV. RESULTS AND DISSCUSIONS

S Parameter

The proposed gain-enhanced patch antenna with a periodic microstrip rampart line and the traditional patch antenna, which is close to the simulation. The resonance frequency (f) of the proposed antenna can be adjusted to 5.8 GHz, which is similar to that of the conventional rectangular patch antenna. The operating frequency bands of the two antennas are almost the same. It can be seen that the impedance bandwidth of the proposed antenna ($S_{11} < -10$ dB) is almost 4% (5.66 GHz-5.87 GHz), which is a little bit larger than that of the traditional antenna. Due to the periodic structure, the S -parameter (S_{11}) of the proposed antenna has a periodic variation along the wide frequency range. Fig. 9 shows the simulated and measured radiation patterns of the xoz and yoZ planes of the proposed gain-enhanced patch antenna and the traditional patch antenna, in the polar coordinate system. It can be seen that the radiation pattern of the proposed antenna is similar to that of the traditional patch antenna. The gain of the proposed antenna (cf. Fig. 1) in the normal direction is 2.55 dB higher than that of the traditional patch antenna. As shown in Fig. 10, the measured gain of the proposed patch antenna is 10.0 dBi while that of the conventional patch antenna is 7.45 dBi. Consequently, the proposed antenna achieves a gain enhancement of almost 2.55 dB (or 79.9%). In addition, the proposed antenna reaches a good cross-polarized level with a front-to-back ratio of almost -15 dB, which is comparable with that of the traditional patch antenna.

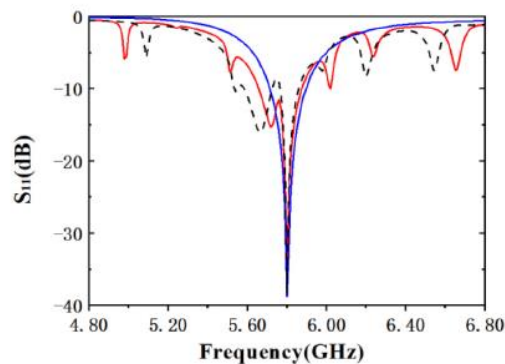


Figure.4 S parameter

Gain

The performance of the antenna with an SDAGS (31 mm × 30.4 mm) is compared with that of an antenna with an LDAGS (40 mm × 39.4 mm) with the unit cell dimensions shown in Figs. 1(a) and 1(b), respectively. The performance obtained with an SDAGS is also compared with that obtained with an AGS, where the sides of the unit cells are parallel to those of the substrates and ground plane, as shown in Fig. 1(b). The proposed antenna structure was fabricated and tested to verify the simulation results. Its characteristics and radiation pattern were measured. All metallic patterns were fabricated by the RT/Duroid 5880 dielectric substrate material using etching technique. Fig. 3 shows a photograph of the fabricated antenna. Fig. 4 shows a wider -10 -dB S_{11} bandwidth of 74.39% (from 4.12 to 9.00 GHz) for the SDAGS in the simulation; it is almost identical to that obtained with the LDAGS. The -10 -dB bandwidth for both DAGSs is considerably wider than that for the AGS. As shown in Fig. 4, the simulated and measured impedance bandwidths for the proposed antenna with an SDAGS ($|S_{11}| \leq -10$ dB) are 79.71% and 76.57% in the frequency ranges of 4.21–9.79 GHz and 4.15–9.30 GHz, respectively, with good agreement.

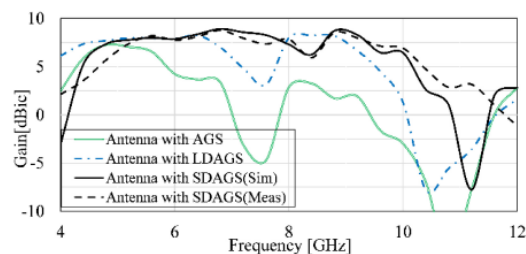


Fig.5 Gain

Radiation Pattern

In the AGS or DAGS, linear polarization (LP) or high-AR polarization can be potentially converted to circular polarization in the frequency where the difference of reflection phase shift between x - and y -components in Fig. 2 is close to 180° [14]. As the effect of the extra resonances has become weak, the x - and y -components can be balanced for CP generation. The weakened resonance is due to that the electromagnetic energy in the DAGS has been spread in several resonances with various path lengths of magnetic. The peaks of ~ 15 dB and ~ 10 dB are observed at resonance frequencies of 6.25 and 7.00 GHz in amplitude ratio response. These high amplitude ratios exceed the condition for CP of 0 dB. At 7.71 GHz, the amplitude ratio satisfies this condition; however, the only phase difference is far from the condition, as shown in Fig. 5(c). For the proposed structure with an SDAGS, such resonances at the deterioration frequencies are not observed. According to Fig. 5(a)–(c), the 3-dB AR bandwidth is expanded up to 40.7% (5.40–8.16 GHz). As described above, the AR is deteriorated in an AGS due to resonances at some frequencies;

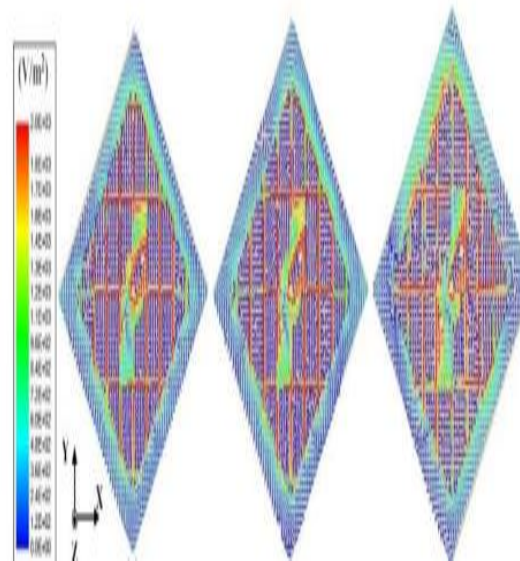


Fig.6 Radiation pattern

V. CONCLUSION

This paper proposed a gain-enhanced patch antenna with a periodic microstrip rampart line. The proposed antenna consists of a rectangular patch, a substrate embedded with periodic leaky wave structure and a complete ground plane. The periodic microstrip rampart line changes the dielectric constant of the dielectric plate and affects the electric field distribution on the rectangular patch, so as to improve the gain. Some formulas are derived to calculate the equivalent permittivity of the proposed model, so as to calculate the high gain frequency point position. The simulated and measured results show an excellent agreement, thus demonstrating that using the proposed approach, a rectangular patch antenna can be raised to 10.0 dBi with excessive 2.55 dB (or 79.9%). The proposed design is an extension of a multi-frequency antenna, which results in a single-frequency high-gain antenna. It requires multiple periodic units, and therefore the ground area should be increased. Finally, the proposed method can efficiently improve the gain of the microstrip antenna. In future work, we aim at increasing the gain of multiple frequency points.

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