Low-Profile Polarization-Adjustable Ring Slot Antenna for Millimeter-wave Applications

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Abstract—In this paper, a dual-port antenna with polarization adjustability is proposed for millimeter-wave applications. The loading effect of four ring slots stimulates a hybrid mode in the cylindrical cavity that generates eight magnetic monopoles with high gain in boresight. Through controlling the phase difference between the two ports, six types of polarization can be demonstrated. Simulation results in 28 GHz show a maximum gain of 13 dBi, 10% bandwidth, and a good cross-polarization level in all polarization states. Distinct features including low-profile, low-cost, single-layer, and simple feeding network make the antenna a suitable candidate for upcoming millimeter-wave and 5G applications.

Index Terms—antenna, dual-port, polarization, low-profile, 5G

I. INTRODUCTION

Polarization flexibility has always been an exciting feature for various applications. By the advent of 5G and other millimeter-wave technologies, this feature could be a promising solution to increase the channel capacity, alleviate the multipath fading effect, and reduce the size of the system. Moreover, antennas with dual polarization characteristics attracted significant attention in MIMO applications, especially for the base station. Therefore, developing an antenna with these properties at millimeter-wave can be very beneficial [1].

Numerous studies have been done in low frequencies to realize reconfigurable antennas with an integrated switching system [2]-[5]. However, in millimeter-wave frequencies, integrating an active circuit is challenging; hence limited studies focused on this capability. Micro-electromechanical system (MEMS) was employed in [6] and [7] to realize a reconfigurable polarization antenna at 77 GHz and 60 GHz, respectively.

Due to these challenges, a few studies have been done to develop adjustable polarization antennas for millimeter-wave applications [8]-[12]. In [8], a 3-layer aperture-coupled microstrip antenna is presented in order to realize six types of polarization. In [9], a microstrip antenna array is proposed at 60 GHz. The antenna has two input ports to be adjusted with a proper phase difference, and a feeding network comprises branch-line couplers and a power divider. In [10], a 4-port antenna with quadri-polarization is reported at 60 GHz. The antenna is realized on three substrate layers, two of which designated for feeding network and one for radiating elements. A microstrip antenna based on higher-order modes driven by one layer of a substrate integrated waveguide is demonstrated in [11]. A four-port frequency scanning antenna is also presented in [12] with quadri-polarization at 33 GHz. Furthermore, in [13], [14] a dual-band polarization-flexible CRLH antenna is investigated in the ISM band.

As it is mentioned, due to lack of PIN diode availability in millimeter-wave, the phase difference for adjusting the polarization needs to be obtained from an external active circuit ideally generated by Microwave Monolithic ICs. Hence, the antenna itself should add the least complexity to the system. In addition to low complexity, the antenna should be planar to be integrated with other planar circuitries. All of the studies except [12], [13] and [14] require complex feeding network in a multilayer structure which increases the size, complexity, and weight of the system.

In this paper, a compact single-layer dual port polarization-adjustable antenna is presented at 28 GHz. Four slots are etched on the cavity to generate a hybrid mode. By providing a phase difference between two ports, six types of polarization can be achieved.

II. ANTENNA STRUCTURE AND WORKING MECHANISM

The proposed antenna is illustrated in Fig. 1. A cylindrical cavity is realized on a substrate with post vias, and four ring slots are etched on the cavity as radiating elements. To excite the cavity, a coaxial probe has been used and by applying an offset to the feed point, higher-order modes can be stimulated. The antenna is designed on Rogers 5880 substrate with a thickness of 0.787 mm, $\varepsilon_r=2.2$, and loss tangent of $\tan\delta=0.0009$. Detail elaboration on the working mechanism of antenna can be found in [16]. The antenna exploit TM$_{11}$ and
TM$_{12}$ to form a hybrid mode that has electric field vector distribution demonstrated in Fig. 2. The electric field has four peaks in the cavity, with nulls in the center of slots. Electric field vectors distribution on slot aperture is shown in a closer view in Fig. 2(b). Electric fields on all slots are almost in phase in the same direction. Each slot generates two equivalent magnetic monopoles, and overall, we have an array of 8 magnetic monopoles. The alignment of magnetic monopoles yields a high gain.

The effect of adding shorting pins on the reflection coefficient can be observed in Fig. 3. By adding the pins, antenna bandwidth increases, and the isolation is improved for higher frequencies but deteriorated for the lower ones. Although the ports are connected directly to the same cavity, the isolation is good since each port is in the null of the electric field that is excited by its counterpart. The broadband characteristics of the antenna are due to the presence of two modes in close proximity and the resultant hybrid mode in a wide frequency span. A simulation has been carried out with CST Microwave Studio, and a set of final parameters are obtained and listed in TABLE I. A parametric study has been carried out on reflection coefficient, isolation, input impedance, and maximum gain. As shown in Fig. 4(a), the increase of $L_s$ would improve the matching over the bandwidth and reduce the isolation. As the value is increased, the peak gain is decreased for the first resonance, and the input resistance increases for the second resonance. Fig 4(b) displays the effect of feeding offset. As it shifts toward higher values, the matching is improved over the frequency bandwidth, and the isolation is reduced. Since the feed location moves from the peak of the electric field of one mode (TM$_{31}$) to another (TM$_{12}$), the increase of offset decreases the first resonance input resistance and increases the second resonance input resistance. The peak gain remains almost unaffected over the bandwidth since there is no change in the slot aperture. Fig. 4(c) illustrates the impact of $R_S$. As the value increases, matching is improved over the bandwidth, and the resonant of the second mode shifts toward lower frequencies, whereas the isolation increases. Moreover, the input resistance for the first and second modes is decreased and increased, respectively. Also, the peak gain is enhanced in the bandwidth of interest. Fig. 4(d) demonstrates the effect of $W_S$. As it shifts toward higher values, the matching for the frequencies between the two resonances is enhanced. Isolation for the first resonance is improved, and the second one is deteriorated. The input resistance is increased for the frequencies between the two modes. In fact, the increase of $W_S$ escalates the loading effect on the cavity, thus removes the degeneracy. Also, the peak gain is increased for the first resonance.

The dual-port scheme enables polarization adjustability with the help of the relative phase difference between the two ports. In the practical sense, the phase difference should be generated via millimeter-wave circuitry, integrated underneath the antenna. With custom design MMIC or millimeter-wave switches such as SPDT and SP4T. For measurement in the Lab, the phase difference can be achieved via commercially available power dividers and couplers. A set of phase and magnitude states are demonstrated in TABLE II for six types of polarization.

### TABLE I

| Para | Value (mm) | Para | Value (mm) | Para | Value (mm) |
|------|------------|------|------------|------|------------|
| $R_s$ | 1.69       | $R_c$ | 8.25       | $d_{pin}$ | 0.7        |
| $R_{out}$ | 11.75  | $W_S$ | 0.45       | $d_{pout}$ | 0.5        |
| offset | 5.35      | $L_s$ | 4.65       | $d$ | 0.5        |

### III. RESULTS AND DISCUSSION

First, the dual-polarization capability has been confirmed by simulating antenna in CST Microwave Studio and validated by Altair FEKO. S-parameters, maximum gain, and radiation
efficiency are illustrated in Fig. 5. Since the design is symmetrical, only S-parameters for one port are shown. The port-to-port isolation, which is a fundamental factor in a dual-polarized antenna, is below -20 dB. Antenna \(|S_{11}|\) is less than -10 dB from 26.5 GHz to 29.5 GHz, which covers the entire standard n257 5G band. For gain pattern radiation measurement in a real-world scenario, one port is connected to the source while the other one is terminated in a matched load. As it is shown in Fig. 5(b), the realized gain is over 11.7 dBi in the band of interest with a maximum of 13 dBi at 29 GHz. The simulated radiation efficiency is over 90% in the entire bandwidth. The simulated radiation pattern obtained from CST Microwave Studio and Altair FEKO for horizontal polarization in E-plane and H-plane at 28 GHz and it is depicted in Fig. 6. The cross-polarization level is 20 dB less than the co-polarization level in the boresight direction.

For the slant polarization, since the configuration is symmetrical, only \(\phi = 45^\circ\) is considered. The input ports of the antenna should be connected to a power divider that renders two outputs with equal magnitude and 180° phase difference to generate a slant polarization. Simulated gain from CST is displayed in Fig. 7. The peak gain is above 12 dBi over the bandwidth. The antenna radiation pattern for slant polarization is plotted in Fig. 8.

To evaluate the circular polarization performance, a hybrid coupler with equal magnitude output and a 90° phase difference is required to generate circular polarization.

### Table II

AMPLITUDE AND PHASE FOR SIX TYPES OF POLARIZATION

| Polarization mode | Linear along y-direction | Linear along x-direction | Linear along \(\varphi = 45^\circ\) | Linear along \(\varphi = 135^\circ\) | Right Hand Circular Polarization ( RHCP ) | Left Hand Circular Polarization ( LHCP ) |
|-------------------|--------------------------|--------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Amplitude and phase state | \(A_2 = 0, A_1 \neq 0\) | \(A_1 = 0, A_2 \neq 1\) | \(A_1 = A_2\) | \(A_2 = A_1\) | \(A_1 = A_2\) | \(A_1 = A_2\) |
| Total E-field on the aperture | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) | ![Image](image5) | ![Image](image6) |

Fig. 4. Simulated \(|S_{11}|, |S_{21}|\) (left), gain and input resistance (right) for different values of (a) \(L_S\), (b) offset, (c) \(R_S\) and (d) \(W_S\).

The simulated axial ratio (AR) and peak gain are depicted in Fig. 7. The 3-dB AR bandwidth covers the entire impedance bandwidth, and the maximum gain is over 12 dBi.

### Table II

| POLARIZATION TYPE | Amplitude and phase state |
|-------------------|--------------------------|
| Linear along y-direction | \(A_2 = 0, A_1 \neq 0\) |
| Linear along x-direction | \(A_1 = 0, A_2 \neq 1\) |
| Linear along \(\varphi = 45^\circ\) | \(A_1 = A_2\) |
| Linear along \(\varphi = 135^\circ\) | \(A_2 = A_1\) |
| Right Hand Circular Polarization (RHCP) | \(A_1 = A_2\) |
| Left Hand Circular Polarization (LHCP) | \(A_1 = A_2\) |
The antenna radiation pattern for RHCP is shown in Fig. 9. The cross-polarization is less than -20 dB in the boresight. Due to the symmetrical layout, other polarizations (vertical, $\varphi = 135^\circ$, and LHCP) indicate the same results.

![Fig. 9. RHCP polarization radiation pattern at 28 GHz](image)

![Fig. 8. Slant polarization radiation pattern at 28 GHz](image)

![Fig. 7. Peak gain for slant and RHCP polarization and the axial ratio at 28 GHz](image)

![Fig. 6. Dual-polarized antenna radiation pattern at 28 GHz](image)

IV. CONCLUSION

A dual-port polarization-adjustable antenna is proposed by introducing four ring slots on a cylindrical SIW cavity. Owing to the symmetrical configuration, any given polarization can be achieved via proper amplitude and phase difference between the two ports. In dual-polarized mode, the antenna offers –20 dB port-to-port isolation and 10% fractional bandwidth in 28 GHz. For flexible polarization performance, all six types of major polarizations can be obtained with a high gain and good cross-polarization level. The direct probe feed excitation eliminates the feeding network and adds the least complexity to the communication system. The antenna features low-profile, low cost with adequate bandwidth, and gain for millimeter-wave applications.

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