60-GHz wideband circularly polarized antenna array based on $TE_{340}$-mode SIC and sequential rotation feeding technique

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Abstract
The authors propose a 4 × 4 circularly polarized (CP) antenna array with wide impedance bandwidth and axial-ratio (AR) bandwidth and design the same for 60-GHz applications. The overall structure of the proposed antenna array consists of a cavity-back circular patch array and two layer feed-networks. The upper feed-network is with four $TE_{340}$ high-order mode substrate integrated cavities (SIC). Fed with SIC, circular patches with a pair of 42°-inclined slits can achieve circular polarization. In order to improve the AR bandwidth and gain performance, the substrate integrated waveguide (SIW) sequential rotation feeding technique is utilized in the lower feed-network. For proof of concept, the 4 × 4 array is fabricated and measured. Measured results show that −10-dB impedance bandwidth of the proposed antenna array is 27.2% from 52 to 68.4 GHz and 3-dB AR bandwidth is 18.9% from 55.7 to 67.3 GHz. Furthermore, the 3-dB gain bandwidth is 26.2% from 53 to 69 GHz with a peak gain reaching 19.3 dBiC at 62 GHz.

1 | INTRODUCTION

Due to the large amount of available spectrum resources and relatively small wavelengths, the millimeter-wave band, especially the 60-GHz band, has become one of the most promising candidates for future wireless communications. The 60-GHz communication systems are potentially attractive for point-to-point moving links, urban applications, and wireless data transmission, such as uncompressed HD video and ultra-fast files. However, it is a major challenge for 60-GHz antennas to reduce the loss of energy in the feed-network and increase the gain of the antenna due to the presence of atmospheric oxygen absorption peaks.

Antennas [1, 2, 3, 4, 5, 6] based on high-order mode substrate integrated cavities (SIC) have been raised by researchers because of the advantage of high efficiency in millimeter-wave band. Compared with the conventional substrate integrated waveguide (SIW) power divider, the high-order mode SIC not only has lower path loss, but also uses fewer vias, making the structure of the feed-network simple, compact and reducing the manufacturing cost. However, their impedance bandwidths are relatively narrow. In [1], a $TE_{440}$-mode groove gap cavity is achieved to feed 4 × 4 slots at 37.5 GHz. Even though the aperture efficiency can reach up to 63%, its impedance bandwidth is only 16%. In [2], $TE_{560}$-mode is used in 20 × 40 and 40 × 80 slot arrays with −10 dB impedance bandwidth of 6.3% and 6.8%, respectively. In [3], a 140-GHz 8 × 8 slot array based on $TE_{340}$-mode low temperature co-fired ceramic SIC is presented with a peak gain of 20.5 dBi. However, the impedance bandwidth is only 10.7%.

Compared to linearly polarized (LP) antennas, circularly polarized (CP) antennas are capable of reducing the sensitivity...
direction between the transmitting and receiving antennas and mitigating the multipath interference [7]. For this, various types of CP antennas have been extensively studied in the millimeter-wave band. In [8], L-shaped branches and truncated corners are introduced to a microstrip antenna array to obtain CP characteristics. Although the impedance bandwidth is greater than 24.4%, the 3-dB axial ratio (AR) bandwidth is only 16%, which obviously limits the performance of the antenna. In [9], a CP aperture-coupled magneto-electric (ME) dipole antenna is proposed. The antenna element has a wide impedance bandwidth of 28.8% and a wide 3-dB AR bandwidth of 25.9%. However, the impedance bandwidth and AR bandwidth of its 8 × 8 array is reduced to only 18.2% and 16.5% respectively, caused by the use of a full-corporate SIW feed network. Therefore, it is a major challenge to solve narrow AR bandwidth while maintaining good impedance characteristics in array. So, the sequential rotation technique was proposed in [10, 11, 12, 13, 14]. In [10], a two-level sequential feeding network based on the ridge gap waveguide technology is designed which can expand the AR bandwidth and improve the polarization purity with the 2-dB AR bandwidth of 16.1%. Here, the simulated AR bandwidth can be increased from 4.86% of the subarray to 29.9% of the array by using the sequential rotation technology.

To achieve high gain and wide impedance and AR bandwidths, a combination of high-order mode SICs and sequential rotation technique is adopted in a CP patch array at 60 GHz. The slot-coupled circular patches with a pair of 42°-inclined slits are used as radiating element, which can obtain CP characteristic. Measured results show that −10-dB impedance bandwidth of the proposed antenna array is 27.2% from 52 to 68.4 GHz and 3-dB AR bandwidth is 18.9% from 55.7 to 67.3 GHz with a peak gain of 19.3 dBi at 62 GHz.

2 | SLITS LOADED CIRCULAR PATCH
2 × 2 SUBARRAY

The proposed 2 × 2 subarray is shown in Figure 1. It consists of three Rogers 5880 substrate layers with a dielectric constant of 2.2 and a loss tangent of 0.0009. Four circular patches with a pair of 42°-inclined slits are placed on M1 layer for circular polarization. One TE340-mode SIC is introduced in D2 layer and four coupling slots on M2 layer to excite the patches. A coupling slot is located on M3 layer on the wide wall of the SIW to feed the SIC. The diameter and spacing of the vias in the SIW are 0.3 and 0.6 mm, respectively. The complete parameters of the proposed antenna subarray are listed in Table 1.

The authors use a commercial three-dimensional electromagnetic simulation software namely Ansys HFSS 18.0 to analyze the performance of the proposed antenna and the maximum delta |S| is set to 0.02. Figure 2(a) depicts that the simulated impedance bandwidth of the 2 × 2 subarray is 23.18% (53.08–67 GHz) for |S| ≤ −10 dB covering the required frequency band for 60-GHz. As shown in Figure 2(b), the 3-dB AR bandwidth is 4.86% (58.82–61.75 GHz) with a peak gain of 14.9 dBi.

FIGURE 1 Geometry of the proposed 2 × 2 subarray. (a) Exploded view, (b) Top view of each layer of the 2 × 2 subarray

| Parameters | L1 | L2 | L3 | L4 | L5 | L6 | W1 | W2 |
|------------|----|----|----|----|----|----|----|----|
| Values     | 1.86 | 1.89 | 3.86 | 3.49 | 8.06 | 3.86 | 0.23 | 0.26 |

| Parameters | W6 | W8 | R_p | L_p | D_p | d | p |
|------------|----|----|-----|-----|-----|---|---|
| Values     | 8.06 | 3.49 | 0.57 | 0.48 | 0.24 | 0.3 | 0.6 |

Compared with the feed-network composed of conventional TE10/TE20-mode SIW power dividers, the high-order mode SIC makes the antenna utilize reduced number of vias and reduced area of the feed-network [3]. The cross section of the high-order SIC in this design is 8.06 mm × 8.06 mm, which allows the TE340 mode to be excited in the cavity. The electric field distributions at 53, 57, 63, and 67 GHz are shown in Figure 3. It can be seen that the TE340 mode can always be excited in the bandwidth, even if the mode is somewhat deteriorated at 53 GHz, but within an acceptable range.

As can be seen in Figure 4(a), E_total is the total electric field at the coupled feed port, while E1 and E2 are two mutually orthogonal and equal amplitude components of E_total. Figure 4(b) and (c) shows the vector current distributions under E1 and E2 excitation, respectively, and the electromagnetic waves formed by each of the two in the space are linearly polarized waves. Due to the introduction of a pair of slits in the patch, the paths (indicated by black line and blue line) which current flows in b and c are different. By reasonably adjusting the size of the slit, a 90°-phase difference can be obtained between the two orthogonal electric fields, and circular polarization is finally achieved. To explain the mechanism of the
circular polarization, the current distributions on a circular patch at the phase of 0°, 90°, 180°, and 270° are illustrated in Figure 5. The black arrow in the Figure 6 represents the
direction of the current on the patch. It can be observed that the magnitude of the current is substantially uniform at each phase, and the black arrow rotates antickwise with the phase, and thus a right-hand circular polarization is achieved.

To provide a better understanding of the proposed array antenna, a parametric study of several geometrical parameters is conducted. Figure 6(a) and (b) shows $|S_{11}|$ of the antenna is affected by the location of the coupling slots on M2, denoted by L3 and L4 in Figure 1. By reducing L3 to 3.66 mm, the matching performance is greatly improved at high frequencies, but worse at low frequencies. The in-band performance of $|S_{11}|$ is improved when L4 is increased. However, the impedance bandwidth becomes narrow if the value of L4 is too small. Figure 6(e) shows the influence on $|S_{11}|$ by varying the size of the high-order mode SIC. It is observed that by increasing L5, the resonant points are shifted to a lower frequency. Therefore, an appropriate L5 must be chosen to achieve the desired frequency bands.

3 | 4 × 4 ANTENNA ARRAY

To obtain higher gain and improve the AR bandwidth, a 4 × 4 CP antenna array using a sequential rotating feed-network is designed as shown in Figure 7. The detailed dimensions are given in Table 2. The sequential rotation feed-network is located at the D3 layer and is used to excite four 2 × 2 subarrays as shown in Figure 1. The sequential rotating network is fed by a standard WR-15 waveguide port. So as to make the output ports (2–5) of the sequential rotating network have a phase delay of 90° in sequence, the difference between path 1 and path 2 is $\lambda_g/4$ ($\lambda_g$ is the waveguide wavelength at the center frequency), and moreover feed-network is symmetrical about the center point. The simulated results of the sequential rotation feed-network are plotted in Figure 8. The simulated bandwidth of the network is from 55 to 68 GHz for $|S_{11}| \leq -15$ dB, the output power of port 2–5 is basically identical, and the maximum difference is less than 0.6 dB from 54 to 70 GHz, whereas the output phase of the 2–5 port is delayed by 90° in sequence.

4 | RESULTS AND DISCUSSION

The photographs of the fabricated 4 × 4 antenna array are shown in Figure 9. The total size of the prototype is 21 ×
23 × 2.4 mm³, and the size of the effective radiating aperture is only 18.23 mm × 16.88 mm. Screws located around the antenna are used to press the entire antenna together. A vector network analyzer is used to measure the S-parameter of the antenna. The simulated and measured |S₁₁| are given in Figure 10(a). There exists some difference between the measured and the simulated results, which is acceptable due to experimental imperfections. The simulated impedance bandwidth is 29.2% from 50 to 67.07 GHz for |S₁₁| ≤ −10 dB, and the measured bandwidth is 27.2% from 52 to 68.4 GHz.

It can be observed from the Figure 10(b), that the measured peak gain of the proposed antenna array is 19.3 dBiC and the gain is greater than 16.6 dBiC within the band of 53–69 GHz. The dielectric loss give rise to the reduction of the measured gain due to the loss tangent of Rogers 5880 increases from 0.0009 at 10 GHz to 0.002 at 60 GHz [15]. The simulated peak gain with tan δ = 0.0009 is 20 dBiC which is 0.3 dB higher than the result with tan δ = 0.002. The simulated 3-dB AR bandwidth is 50–67.56 GHz (29.9%), while the measured one is 55.7–67.3 GHz (18.9%). The measured AR bandwidth is lower than the simulated one, which is attributed to the fabrication tolerance and measurement errors.

The simulated and measured radiation patterns of the antenna array at 58, 62, 64, and 66 GHz are plotted in Figure 11. It can be seen that the measured results of the right-hand circularly polarization are in good agreement with the simulated results, and the maximum side-lobe levels of the antenna is below −10 dB across the entire operating band. In the boresight direction, the cross-polar fields are 15 dB weaker than the copolar counterpart. In addition, it is shown that the beamwidths at both planes are identical. Some discrepancies of left-hand circularly polarization can be observed from the results. The cause of this phenomenon may be that in the millimeter wave band, the measured environment has a greater influence on the far-field radiation pattern.

Since the proposed antenna array is assembled through screws, air gaps may be introduced between each layer. So, the influences of the air gaps on the reflection coefficient, gain and AR are analyzed. Figure 12(a) shows the effects on |S₁₁| with air gaps of 0, 10, 20, and 30 μm, respectively. It is worth mentioning that as the air gap increases, matching performance gets worse and the bandwidth shifts to higher frequencies. The effect of the air gaps on the gain is illustrated in Figure 12(b). It can be seen that the introduction of the air gaps does not change the maximum gain over the entire frequency band, but the 3-dB gain bandwidth decreases and the gain performance at low frequencies deteriorates. As shown in Figure 12(c), as the air gap increases, the AR performance in the low frequency band continuously deteriorates. This is also the reason why the measured AR bandwidth is narrower than the simulated one. Meanwhile, it can be concluded that the thickness of the introduced air gap is between 20 and 30 μm.

The comparison of the proposed antenna array and different types of published CP antenna arrays is given in Table 3. It is observed that the proposed antenna shows larger impedance bandwidth and AR bandwidth. Unlike designs [11, 12], the SIW feeding network is utilized for eliminating
large propagation loss, therefore a higher gain can be achieved in proposed antenna array. Compared with [13] and [14], they all use PCB processing technology and three Rogers 5880 substrate layers. Although the height is the same, the size of the proposed antenna array is more compact and has a greater advantage in bandwidth.

**FIGURE 11** Simulated and measured radiation patterns for the proposed antenna array. (a) 58 GHz, (b) 62 GHz, (c) 64 GHz, (d) 66 GHz.
5 | CONCLUSION

The author proposed a broadband CP antenna array operating at 60 GHz and $TE_{340}$ mode SIC is adopted in the $2 \times 2$ subarray with reduced number of vias resulting in a compact and high-efficient power divider. For the $4 \times 4$ array, sequential rotation technique has been utilized to improve the impedance matching bandwidth and AR bandwidth. A reasonable agreement between the measurement results and the simulation results has been observed. Measurement results show that the $|S_{11}| \leq -10$ dB bandwidth of the proposed antenna array is 52–68.4 GHz (27.2%), and the 3-dB AR bandwidth is 55.7–67.3 GHz (18.9%). The overlapping bandwidth of the $|S_{11}|$ and the AR can cover

**FIGURE 12** Simulated results of the proposed antenna array with different thicknesses of air gaps. (a) $|S_{11}|$, (b) Gains, (c) ARs

**TABLE 3** Comparison between proposed and reported 60-GHz CP antenna arrays

| Antenna type | Feeding mechanism | No. of elements | Size (λ₀) | Imp. BW (%) | AR BW (%) | Peak Gain (dBi) | Fabrication tech. | Sidelobe level (dB) | Aperature Eff. (%) | Proposed work or model |
|--------------|-------------------|-----------------|-----------|-------------|------------|-----------------|-----------------|---------------------|----------------------|------------------------|
| Patch [11]   | Seq. (CPW)        | $4 \times 4$    | $4 \times 4 \times 0.076$ | 15.6       | 16         | >-10            | PCB             | < -10.4             | 60.37                | Patch [12]             |
| Patch [12]   | Seq. (stripine)   | $4 \times 4$    | $6 \times 6 \times 0.18$ | 14.37      | 17.1       | < -10.4         | LTCC            | < -10.4             | 52.4                 | Patch [13]             |
| Spiral [13]  | Seq. (SIW)        | $4 \times 4$    | $5 \times 5 \times 0.48$ | 18.8       | 20         | < -10           | LTCC            | < -10.4             | 52.4                 | Spiral [14]            |
| Spiral [14]  | Seq. (SIW)        | $4 \times 4$    | $6 \times 6 \times 0.48$ | 21.1       | 19.5       | < -10.4         | PCB             | < -10.4             | 65.45                | Spiral [15]            |
| Patch [15]   | Seq. (SIW)        | $8 \times 8$    | $6.5 \times 6.5 \times 0.7$ | 35.8       | 24         | < -10.4         | PCB             | < -10.4             | 67.45                | Aperture [16]           |
| Proposed work or model | Seq. (SIW)        | $4 \times 4$    | $4.2 \times 4.6 \times 0.48$ | 18.9       | 19.3       | < -10.4         | PCB             | < -10.4             | 55                    |                        |

Abbreviations: Dif., Differential feed; Seq., Sequential rotation feed; $\lambda_0$, The wavelength at 60 GHz in free space.
57–64 GHz. 3-dB gain bandwidth is 26.2% from 53 to 69 GHz with a peak gain reaching 19.3 dBiC at 62 GHz. These good characteristics demonstrate that the proposed antenna array can be a good candidate for the future 60-GHz communication system.

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