Air-Filled Substrate Integrated Waveguide Fed Magneto-Electric Dipole Antenna Array for Millimeter-Wave Applications

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ABSTRACT A substrate integrated magneto-electric (ME) dipole antenna array with an improved radiation efficiency is presented in the 28-GHz band. A novel full-corporate air-filled substrate integrated waveguide (SIW) feed network with low losses is designed and realized by utilizing the low-cost printed circuit board (PCB) facilities. Different from most previous millimeter-wave planar arrays consisting of 2 × 2 sub-arrays, an SIW fed sub-array with a larger size of 2 × 4 is investigated to simplify the configuration of the major portion of the array feed network, which is of importance to the successful realization of the air-filled SIW feed network. An 8 × 8 array prototype with a four-layered geometry is fabricated and measured to verify the design. The array has an impedance bandwidth of 25.9%, a gain up to 26 dBi and stable radiation patterns over the operating band. Benefited from the absence of the significant dielectric loss in the feed network, a high antenna efficiency of 80% is also achieved. The proposed design provides an effective method to improve the achievable gain and efficiency characteristics of the substrate-integrated arrays with a large size that are attractive for millimeter-wave wireless applications.

INDEX TERMS Antenna array, air-filled substrate integrated waveguide (SIW), feed network, dielectric loss, aperture-coupled magneto-electric (ME) dipole antenna, millimeter-wave.

I. INTRODUCTION

High-gain planar antenna arrays are of significance to guarantee the required link-budget in millimeter-wave wireless communications [1]. By employing several fabrication methods, including the printed circuit board (PCB) [2]-[3] and the low-temperature co-fired ceramic (LTCC) [4]-[5] techniques, the overall array configuration can be designed in various dielectric laminates, which enables the radiating structure to integrate with the millimeter-wave circuits conveniently. Moreover, the relatively low fabrication costs of the substrate-integrated antenna arrays are also desirable for large-scale applications. As a result, investigations on these antennas received increasing attention in the last decade.

Achievable gain property of an antenna array with a fixed radiating aperture size is determined by its aperture efficiency and radiation efficiency, while the two parameters are affected by both the radiating elements and the feed network composing the array. In terms of the substrate-integrated radiating elements, a promising radiation efficiency can be obtained in the millimeter-wave bands by adopting the dielectric materials with low losses [6]. Moreover, the surface waves existing in the array environment, especially in the microstrip patch arrays with a thick supporting substrate to widen the operating bandwidth [7], can disturb the aperture-field distribution and introduce extra dielectric losses, which lead to the degradation of the aperture and radiation efficiencies of the array simultaneously. In order to overcome the issue, a series of methods have been reported in the literature, such as the cavity-backed antenna elements [8]-[9], the arrays loaded with soft-surfaces [10], and the arrays with partially removed supporting substrates [11]-[12]. Improved efficiency and gain characteristics have been achieved by these designs. The feed network plays a crucial role to the gain of the millimeter-wave substrate-integrated arrays as well. With the use of a well-designed feed network, the input power can be...
distributed to all radiating elements uniformly, and thus resulting in a high aperture efficiency of the array [13]. On the other hand, the radiation efficiency of the array with a large size is significantly influenced by the losses from the feed network. In comparison with the microstrip line [14] or the coplanar waveguide (CPW) [15] with an opened structure, the substrate-integrated waveguide (SIW) [16] or the printed ridge gap waveguide [17] with a quasi-closed configuration has better attenuation features in millimeter-wave bands. Nevertheless, with the increase of the array size, the dielectric loss from the feed network can still decrease the radiation efficiency remarkably. The arrays with a size of $8 \times 8$ usually had a radiation efficiency of less than 80%, even though the dielectric material with a low loss-tangent value was used [18]-[21]. According to the analysis in [7], the achievable maximum gain of the array is about 35 dBi, which makes the substrate-integrated antenna arrays difficult to utilize in millimeter-wave applications with requirement of quite high gain. The combination of the substrate-integrated arrays with a feed network composed of metallic waveguides can further promote the gain performance [22], but the geometry advantages of the substrate-integrated array would be sacrificed inevitably.

Recently, a new kind of the SIW structure named as the hollow, empty or air-filled SIW has been studied in [23]-[25]. By removing the substrate filled in the conventional SIW, the dielectric loss can be nearly prevented. A few works have been dedicated to design the millimeter-wave components and antennas based on the air-filled SIW technology [26]-[28], but unfortunately, the investigation on the high-gain antenna array fed by an air-filled SIW feed network has been seldom addressed up until now.

A high-gain wideband substrate-integrated planar antenna array with an improved radiation efficiency is presented in the 28-GHz band in this paper. With the aid of the proposed $2 \times 4$ SIW-fed sub-array configuration that is different from the $2 \times 2$ ones in most reported substrate-integrated arrays, the designed novel full-corporate air-filled SIW feed network can be realized successfully by using the low-cost epoxy/glass (FR-4) PCB laminates. It is experimentally confirmed that the radiation efficiency and gain results of the design are improved significantly and comparable with the arrays with metallic geometries [29]-[33]. Besides, a wide operating band and satisfactory radiation performance are obtained as well. Considering the good operating features and the geometry merits, the proposed antenna array is attractive to the millimeter-wave applications in the fifth-generation (5G) mobile communications.

The paper is organized as follows. Section II depicts the geometry of the proposed array and the design procedure is investigated in Section III. Measured results are discussed in Section IV and a brief conclusion is finally summarized in Section V.

![Geometry of the proposed antenna array. (a) Perspective view, (b) top view of Substrate 1, (c) top view of Substrate 2.](image)

**II. ANTENNA GEOMETRY**

Configuration of the proposed $8 \times 8$ substrate-integrated antenna array is implemented in four PCB laminates as illustrated in Fig. 1. The linearly polarized aperture-coupled...
magneto-electric (ME) dipole antenna initially reported in [34] with a wide bandwidth and good radiation performance is employed as the radiating elements of the array, which are integrated in the top Substrate 1. The radiating elements are divided into 2 × 4 sub-arrays that are fed by the SIW feed networks located in Substrate 2 as indicated in Fig. 1 (b) and (c). Furthermore, the major part of the array feed network constructed by the air-filled SIWs is realized in Substrate 3, which is different from the one composed of the SIWs in [18]. For antenna measurement, a transition between the air-filled SIW and a standard WR-28 waveguide is designed in Substrates 3 and 4. In this work, two Rogers 4350B PCB laminates with a permittivity of 3.66 and a thickness of 1.524 mm and two FR-4 PCB laminates with a thickness of 1.5 mm are utilized as Substrates 1 and 2 and Substrates 3 and 4, respectively. All the PCB substrates are low-cost and suitable for large-scale manufacture. Besides, three Rogers COOLSPAN conductive adhesive films with a thickness of 0.05 mm [35] are applied to bond the four substrates together. The required coupling apertures between adjacent substrates and the profile of the air-filled SIW channels are etched on the bonding films by applying laser cutting. The location holes close to the edges of the array are used for alignment. The detailed fabrication procedure are same with those stated in [18].

III. ANTENNA DESIGN

The antenna array operating in the 28-GHz band for 5G millimeter-wave applications is designed in this section with the assistance of a full-wave electromagnetic solver Ansys HFSS [36].

A. RADIATING ELEMENT

Fig. 2 presents the configuration of the linearly polarized aperture-coupled ME-dipole antenna used as the radiating elements in the array. The entire radiating structure is designed in Substrate 1. Four rectangular metallic patches etched on the top copper-clad surface of Substrate 1 form a pair of electric dipoles lying on the xoz-plane. The inner corners of the four patches are connected by a crossed metallic strip, such that the combination of the crossed strip and the patches construct two quarter-wavelength apertures that are equivalent to the magnetic dipole parallel to the yoz-plane. Moreover, four metallic pins are employed to link the four patches with the metallic ground plane of the antenna that has a size of $\lambda_0 \times \lambda_0$ at 26 GHz. Furthermore, an offset longitudinal Aperture 1 cut on the broad wall of the short-ended SIW section integrated in Substrate 2 is employed as...
the feed scheme of the ME-dipole, whose planar geometry is more suitable for the substrate integration at millimeter-wave frequencies in comparison with the normal probe feed. The power coupled from the SIW can be transmitted to the radiating structure effectively with the help of the vertical pins and then excite the required ME-dipole mode. An additional metallic pin arranged in the SIW is applied for impedance matching of the antenna. The design guideline summarized in [34] is used for tuning the dimensions of the antenna. More importantly, it is found that a wider operating bandwidth in comparison with the original design in [34] can be achieved by appropriately extending short-ended SIW with a length of $\text{offset}_2$ as given in Fig. 2 (c). Final values of the configuration parameters are listed in Table I.

In order to verify the operating mechanism of the antenna, the simulated electric current distributions on the antenna surfaces and the electric field distributions on the radiating aperture are given in Fig. 3. It is seen in Fig. 3 (a) that at $t = 0$, the electric currents concentrate at the outer edges of the planar patches and follow a sinusoidal distribution lying along the $x$-direction, which indicates that the electric dipole is excited. Meanwhile, as shown in Fig. 3 (c), the electric field over the two quarter-wavelength apertures parallel to the $y$-axis is strong. Therefore, the equivalent magnetic dipole is excited as well. On the other hand, Figure 3 (b) and (d) demonstrates that the currents along the electric dipole and the filed over the apertures are weak at $t = T/4$. The above discussion confirms that the electric and equivalent magnetic dipoles orthogonal to each other are excited simultaneously in this design, such that the required ME-dipole mode can be realized.

Simulated $|S_{11}|$ and gain of the ME-dipole antenna element are shown in Fig. 4. The impedance bandwidths of the antenna for $|S_{11}|$ of less than -10 dB and -15 dB are 40% (from 20.7 to 31 GHz) and 34% (from 20.9 to 29.6 GHz), which are about 10% wider than the counterparts of the
FIGURE 8. Simulated electric field distribution over the coupling apertures of the ME-dipole antennas in the sub-array.

TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$d_3$</th>
<th>$w_{a1}$</th>
<th>$w_{a2}$</th>
<th>$l_3$</th>
</tr>
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<tr>
<td>Value</td>
<td>2.02</td>
<td>1.73</td>
<td>1.5</td>
<td>1.51</td>
<td>1.05</td>
<td>2.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$l_0$</th>
<th>$offset_{1}$</th>
<th>$offset_{2}$</th>
<th>$offset_{3}$</th>
<th>$offset_{4}$</th>
<th>$w_1$</th>
<th>$l_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>3.9</td>
<td>0.57</td>
<td>4.05</td>
<td>4.95</td>
<td>1.58</td>
<td>1.5</td>
<td>0.45</td>
</tr>
</tbody>
</table>

original design in [34]. The gain of the ME-dipole element is up to 8.1 dBi with a variation of less than 1.4 dB throughout the entire operating band. Moreover, it is seen in Fig. 5 that the symmetrically unidirectional radiation patterns are almost identical in the E- and H-planes, which confirms the advantages of the ME-dipole antenna. Besides, a cross polarization level of smaller than -20 dB and a front-to-back-ratio (FTBR) of higher than 20 dB can also be obtained over the operating band as exhibited in Figures 5 and 6.

B. 2 × 4 SUBARRAY

Sub-arrays with a small size of $2 \times 2$ were selected by most reported millimeter-wave substrate-integrated antenna arrays with full-corporate feed networks as the in-phase excitation to all radiating elements can be realized conveniently. However, considering the required element spacing of less than one operating wavelength to guarantee the sidelobe level of the array, the width of the air-filled waveguide of larger than half wavelength, and the available space in Substrate 3, the use of sub-arrays with the size of $2 \times 2$ would increase the complexity of the topology of the air-filled SIW feed network and make it difficult to design in Substrate 3. Therefore, a novel sub-array with a larger size of $2 \times 4$ is investigated in this section. As shown in Fig. 7, two $2 \times 2$ SIW parallel feed networks located in Substrate 2 are combined together to construct the feed structure of the sub-array. Additional pins with offsets $d_1$ to $d_4$ are utilized to improve the impedance matching of the T-junctions. For the purpose of saving the occupied space, a number of the metallic pins are shared by the neighboring SIWs in the feed network. Moreover, an H-shaped Aperture 2 with a longer equivalent length is used for coupling the power from the air-filled SIW in Substrate 3 to the above SIW feed network. The position of the pins close to the two ends of the aperture is adjusted and an iris is introduced in the air-filled SIW to get a good impedance matching.

In this design, the power fed to the left and right halves of the SIW feed network is out of phase. Therefore, in order to meet the in-phase excitation to all antenna elements, a 180° phase delay should be added to one-half of the feed network. It is well known that the direction of currents on the left half of a waveguide broad wall is opposite to the counterpart on the right half. Inspired by the property, the offset longitudinal coupling apertures are etched on the opposite sides of the SIW for the antenna elements fed by the two parts of the SIW feed network as illustrated in Fig. 7 (b). It can be observed in Fig. 8 that the uniform in-phase aperture field distributions can be achieved successfully by the proposed feed configuration. The element spacing between the antenna elements is 8.9 mm in both the E- and H-planes, corresponding to 0.77 $\lambda_0$ at 26 GHz. Detailed values of the geometrical parameters of the $2 \times 4$ sub-array are listed in Table II.

The proposed $2 \times 4$ ME-dipole sub-array has a wide impedance bandwidth of 26.4% from 22.7 to 29.6 GHz for $|S_{11}|$ of less than -10 dB as provided in Fig. 9. The simulated gain of the sub-array varies from 14.2 to 16.3 dBi within the
operating band, which is about 0.55 dB of less than the simulated directivity. Hence, the estimated radiation efficiency of the sub-array is around 88%. Furthermore, the simulated unidirectional radiation pattern of the sub-array at 26 GHz is given in Fig. 10, which is symmetrical in the two orthogonal planes. The backward radiation is less than -25 dB, while the cross polarization is lower than -30 dB. The promising operating performance verifies the effectiveness of the proposed 2 × 4 sub-array.

C. AIR-FILLED SIW FEED NETWORK

The air-filled SIW feed network in the proposed high-gain antenna array is presented in Fig. 11, which consists of the T-junctions with two pairs of irises for impedance matching. It is seen that with the help of the 2 × 4 sub-arrays discussed in the above section, the topology of the feed network is simplified compared with the counterparts in the previous array designs composed of 2 × 2 sub-arrays. Actually, it is quite difficult to arrange another stage of the feed network in the area indicated by the red meshes because in that case the remaining part of the PCB substrate is thin and not robust enough during the fabrication procedure. To demonstrate the feasibility of the air-filled SIW feed network, a prototype illustrated in Fig. 12 is fabricated by applying the standard PCB facilities. It is noted that the copper-clad surface has been removed for better observing the profile of the feed network. Clearly, the overall geometry including the irises can be well realized. The final dimensions of the feed network are given in Table III.

As shown in Fig. 13, the simulated impedance bandwidth of the air-filled SIW feed network for |S11| of less than -15 dB is 27.3% from 22.5 to 29.6 GHz, while the simulated |S21| is almost larger than -9.1 dB, which indicates that the insertion loss of the feed network is less than 0.1 dB.

D. AIR-FILLED SIW TO STANDARD WAVEGUIDE TRANSITION

A transition between the air-filled SIW and a standard WR-28 waveguide is designed for antenna measurement,
which is connected with the input port of feed network as shown in Fig. 10. It is seen in Fig. 14 that a rectangular air-filled cavity is introduced between the short-ended air-filled SIW and the standard waveguide, which works as a bend structure to change the transmitting direction of the TE_{10} mode. By properly tuning the position and dimensions of the cavity, a good impedance matching can be expected. Moreover, a pair of irises is also assigned in the air-filled SIW to further widen the bandwidth of the transition. Detailed values of the geometrical dimensions are summarized in Table IV.

Fig. 15 presents the simulated S-parameters of the transition. The simulated |S_{11}| is less than -20 dB throughout a bandwidth of 42% from 21.8 to 33.4 GHz with an insertion loss of less than 0.03 dB.

IV. MEASUREMENT AND DISCUSSION

A prototype of the proposed 8 × 8 air-filled SIW fed aperture-coupled ME-dipole antenna array was fabricated and tested as illustrated in Fig. 16. A WR-28 to coaxial cable adapter was linked with the input port on the bottom side of the array during the measurement. An Agilent Network Analyzer E8363C was employed to perform the reflection coefficient of the array. The radiation characteristics were measured in a far-field anechoic chamber, while the gain of the array was obtained by comparing with standard gain horns.

TABLE V
MEASURED AND SIMULATED 3-dB BEAMWIDTHS OF THE ANTENNA ARRAY

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>E-plane Simulated</th>
<th>E-plane Measured</th>
<th>H-plane Simulated</th>
<th>H-plane Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>9°</td>
<td>9.1°</td>
<td>9°</td>
<td>8.6°</td>
</tr>
<tr>
<td>27</td>
<td>8.1°</td>
<td>7.9°</td>
<td>8°</td>
<td>8.2°</td>
</tr>
<tr>
<td>29</td>
<td>7.2°</td>
<td>7.2°</td>
<td>6.9°</td>
<td>7.6°</td>
</tr>
</tbody>
</table>

A. IMPEDANCE BANDWIDTH, GAIN AND EFFICIENCY

Fig. 17 depicts the measured and simulated |S_{11}| and gain of the array, which are in promising agreement. The measured and simulated impedance bandwidths of the array for |S_{11}| of less than -10 dB are 25.9% from 22.5 to 29.2 GHz and 25.7% from 22.7 to 29.4 GHz separately, which can cover the whole 28-GHz band from 24.25 to 28.35 GHz for the 5G millimeter-wave applications. It is noted that the measured result is slightly higher than -10 dB at 23.6 and 28.6 GHz, which is mainly caused by the fabrication tolerance. Furthermore, the maximum measured gain is 26 dBi, which is close to the simulated result. The variation of the gain is less than 2.6 dB across the operating band of the array. Additionally, the estimated radiation efficiency of the fabricated antenna array is 87% at 26 GHz by comparing the measured gain with the simulated directivity. As the size of the radiating aperture is 71.2 × 71.2 mm², the calculated aperture efficiency of the array is 92% at 26 GHz.

B. RADIATION PATTERN

As shown in Fig. 18, the measured radiation pattern of the antenna array at different frequencies is almost consistent with the simulated one. The radiation pattern is symmetrical.
FIGURE 18. Measured and simulated radiation patterns of the fabricated 8 × 8 air-filled SIW fed aperture-coupled ME-dipole antenna array. (a) f = 24 GHz. (b) f = 27 GHz. (c) f = 29 GHz.

TABLE VI

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type of feed network</th>
<th>Radiating element</th>
<th>No. of elements</th>
<th>Volume (λ₀³)</th>
<th>f₀ (GHz)</th>
<th>Imp. BW</th>
<th>Max. gain (dBi)</th>
<th>Total efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>[14]</td>
<td>Microstrip line</td>
<td>Loop-loaded dipole</td>
<td>50</td>
<td>7.1×7.1×0.05</td>
<td>61</td>
<td>16.7%</td>
<td>25.2</td>
<td>47%</td>
</tr>
<tr>
<td>[17]</td>
<td>Printed ridge gap waveguide</td>
<td>ME-dipole</td>
<td>4×4</td>
<td>3.5×3.4×0.3</td>
<td>30</td>
<td>16.5%</td>
<td>21.2</td>
<td>63%</td>
</tr>
<tr>
<td>[19]</td>
<td>SIW</td>
<td>Cavity backed dipole</td>
<td>8×8</td>
<td>6.6×6.6×0.6</td>
<td>64</td>
<td>22.9%</td>
<td>26.7</td>
<td>70%</td>
</tr>
<tr>
<td>[31]</td>
<td>Air-filled ridge gap waveguide</td>
<td>Slot</td>
<td>8×8</td>
<td>9.1×9.1×2.8</td>
<td>59</td>
<td>30%</td>
<td>27.5</td>
<td>82%</td>
</tr>
<tr>
<td>[33]</td>
<td>Air-filled waveguide</td>
<td>Horn</td>
<td>8×8</td>
<td>7.4×7.4×1.5</td>
<td>32</td>
<td>25.8%</td>
<td>27.5</td>
<td>84%</td>
</tr>
<tr>
<td>This work</td>
<td>Air-filled SIW</td>
<td>ME-dipole</td>
<td>8×8</td>
<td>6.2×6.2×0.5</td>
<td>26</td>
<td>25.9%</td>
<td>26</td>
<td>80%</td>
</tr>
</tbody>
</table>

in both the E- and H-planes and stable throughout the entire operating band. The simulated backlobe is less than -25 dB, while the measured results are not easy to obtain accurately due to the existence of the measurement setup behind the antenna under test. The measured cross polarization is lower than -25 dB. Besides, it is seen in Table V that the measured 3-dB beamwidth agrees well with the simulation. With the increase of operating frequencies, the beamwidths in the two dominant planes decrease gradually.

C. COMPARISON AND DISCUSSION

Geometry features and the operating performance of the proposed design are summarized in Table VI to compare with the counterparts of the previous wideband high-gain arrays operating in millimeter-wave bands, including the substrate-integrated ones with the microstrip line, printed ridge gap waveguide and SIW feed networks, and the metallic arrays fed by the air-filled ridge gap waveguides and rectangular waveguides. In terms of the array geometries, clearly a thinner thickness can be achieved by the designs in [14], [17], [19], and this work, which demonstrates the advantages of the arrays integrated in substrates. Furthermore, beneficial from the wideband properties of the ME-dipole antennas and the proposed feed network, the operating bandwidth of this work is comparable with the reported wideband millimeter-wave antenna arrays. More importantly, mainly due to the influence of the dielectric losses, the total efficiency, i.e. the product of the radiation and aperture efficiencies, is usually not higher than 70% for the reported substrate-integrated arrays with a size of 8 × 8 or smaller one [14], [17], [19]. By employing the air-filled SIW feed network without the undesirable dielectric losses, an overall efficiency of 80% is realized in this work, which is significantly improved in comparison with the previous results and is close to those of the metallic arrays fabricated by milling or 3D printing technologies [31], [33]. Therefore, the proposed design provides a new mean to increase the achievable gain characteristics of the millimeter-wave large-size substrate-integrated antenna arrays without sacrifice of the configuration superiority. It is noted that because of the smaller element spacing and the radiating aperture size in this
work, the maximum gain of the array is lower than the counterparts of the design in [19], [31], and [33].

V. CONCLUSION

A substrate-integrated aperture-coupled ME-dipole antenna array with a full-corporate air-filled SIW feed network has been investigated. An SIW fed sub-array with a size of $2 \times 4$ has been proposed to simplify the topology of the major portion of the feed network. By this mean, the space in a single-layered dielectric laminate is enough to locate the feed network composed of the air-filled SIWs. An $8 \times 8$ antenna array designed in four substrate layers has been fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities. A wide impedance bandwidth of 25.9%, a maximum gain of 26 dBi and stable fabricated by utilizing PCB facilities.

REFERENCES


