A Magnetoelectric Dipole Leaky-Wave Antenna for Millimeter-Wave Application

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***Abstract*— This paper presents a novel frequency beam scanning slotted leaky-wave magnetoelectric (ME) dipole antenna array for the fifth generation (5G) application. The proposed antenna, which has eighteen elements of slots and electric dipoles, is built on a two-layer printed circuit board. In the lower layer, it is a conventional slotted substrate integrated waveguide (SIW) leaky-wave antenna (LWA). In the upper layer, electric dipoles are attached to the design. As for each element unit, the magnetic dipole is realized by each lower-layer aperture, while the electric dipole is realized by each pair of patches in the upper layer. The design concept is that two modes are excited together in orthogonal directions to realize the ME dipole. By introducing electric dipoles to the conventional slotted LWA, the antenna exhibits less gain variation over a wide bandwidth. The SIW leaky-wave ME dipole antenna array is designed and fabricated to operate at the 28-GHz band. It operates with wide impedance bandwidth and a peak gain of 16.55 dBi with less than 3-dB gain variation throughout the frequency range from 27 to 32 GHz.**

***Index Terms*— Leaky-wave antenna (LWA), magnetoelectric (ME) dipole, substrate integrated waveguide (SIW).**

I. Introduction

THE Federal Communications Commission (FCC) announced the operating frequency spectrum on the development of 5G technology and mobile wireless networks in July, 2016. The next generation 5G services would provide speedier delivery with higher data rate than today's 4G wireless networks. The FCC adopted new rules for wireless broadband operations in frequencies above 24 GHz, making the United States the first country in the world to make this spectrum available for the next generation wireless services. One of the spectrums in the higher bands for the new Upper Microwave Flexible Use service is in 28 GHz (27.5–28.35 GHz). Prof. Rappaport from New York University has already demonstrated that 5G cellular will work by using 28- and 38-GHz frequencies [1].

With the development of the higher frequency services, planar LWAs are more popular and have received more attention in millimeter-wave applications due to their low profile and compact size structure, achievable high directivity by simply extending the physical length, simple, and low-cost feed networks for numbers of elements. In a 1-D leaky-wave antenna (LWA), the wave is guided in one direction along the guiding structure. The antenna is typically fed at one end and the wave propagates, leaking out from the slots, along the axis of the structure. The explanation of the operating principle of LWAs has been reported in [2] and [3].

Although LWAs have the above mentioned advantages, the conventional LWAs also suffer from limited scanning range, forward quadrant, and large gain variation within the pattern bandwidth. In order to enhance the beam steering range by radiating both forward, broadside and backward quadrants, periodic, or metamaterials incorporation into the unit cells of the antenna reported in [4]–[14]. In the substrate integrated waveguide (SIW)-based periodic LWAs proposed in [4] and [5], the leakage power is obtained by increasing the spacing of vias at one or both side walls. Metamaterial-based LWAs are able to increase the scanning range [10], [12], [13] to radiate both forward and backward directions, enhance the gain, and reduce the gain variation across the operating frequencies. These kinds of geometries consist of different shapes of nonradiated slots to operate both the forward- and backward-wave propagation in their right- and left-handed region. However, the antenna with a metamaterial structure may increase the complexity of the structure at millimeter frequencies.

In this paper, an electric dipole is introduced to add on each slot of LWA for smoothing the gain within the pattern bandwidth. By applying the concept of the magnetoelectric (ME) dipole in [15]–[29] for each element, a novel planar LWA is proposed in this paper for 28-GHz applications. The idea of complementary antenna has been widely investigated in standing wave antennas for accomplishing better electrical characteristics, such as wide bandwidth, high gain, high front-to-back ratio, and symmetrical radiation patterns in the principal planes. However, it seems that this concept has not yet applied to LWAs in the literature. Based on the slotted SIW LWA, a new 18-element slotted LWA with electric dipoles is proposed in this paper. The magnetic dipoles due to the slot elements and the electric dipoles from the pair of patches are two modes to be excited simultaneously to realize the ME dipole in this design. The proposed antenna is simply fabricated in a two-layered substrate and is fed by an SIW. The new design has the advantages of low profile, low cost, and stable gain within the scanning frequency range. A compact broadband rectangular waveguide to SIW transition [30] is

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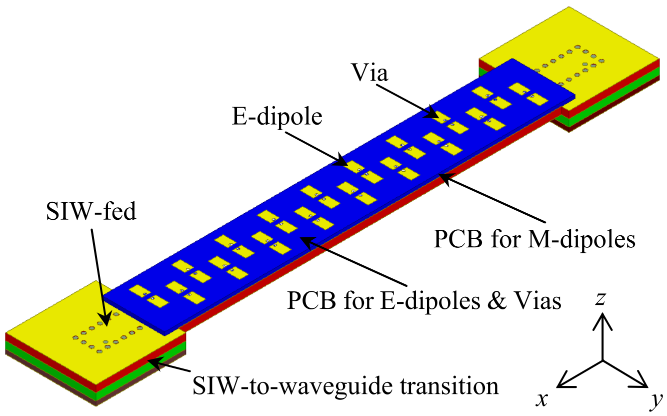


Fig. 1. Geometry of the leaky-wave ME SIW-fed antenna.

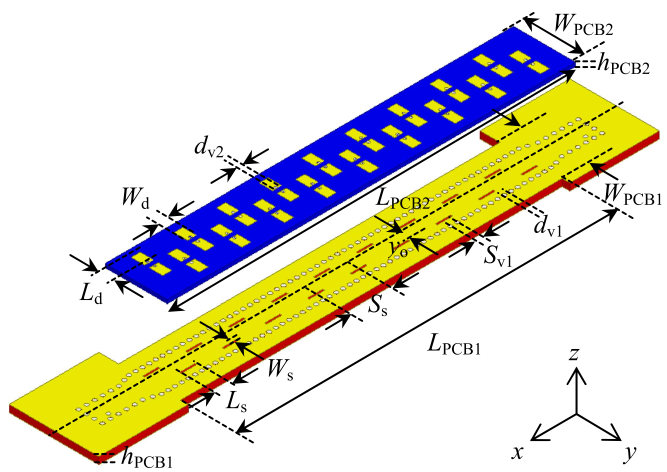


Fig. 2. Detailed structure of the leaky-wave ME dipole antenna.

employed in the simulation, which is an important component for antenna testing. Both simulated and measured results are presented to demonstrate the design idea.

II. Geometry

The geometry of the SIW-fed leaky-wave ME dipole antenna array is illustrated in Fig. 1. Basically, the antenna is composed of a two-layer substrate, and the detailed structure of which is displayed in Fig. 2. The first layer (bottom layer) is an SIW-fed longitudinal shunt slot antenna array. Totally 18 rectangular slots are etched on a double-sided Rogers RT/Duroid 5880 substrate with a thickness of 1.57 mm and a dielectric constant of $\varepsilon_r = 2.2$. The slots are placed in an alternating manner. Slots offset $y_o = 1.5$ mm with respect to the SIW center axis. Slot lengths $L_s = 3.4$ mm. For the SIW structure, metal via side walls are formed. The separation between adjacent vias and diameter of each via is 1.5 and 0.9 mm, respectively. The separation distance of the vias should be sufficient small to restrict the power leakage. By connecting the upper metal sheet to the ground plane with rows of plated vias on the two sides, a rectangular dielectric waveguide is created within a substrate to confine the signal traveling.

The second layer (top layer) of the antenna includes 18 pairs of planar electric dipoles. In this layer, Roger 5880 printed

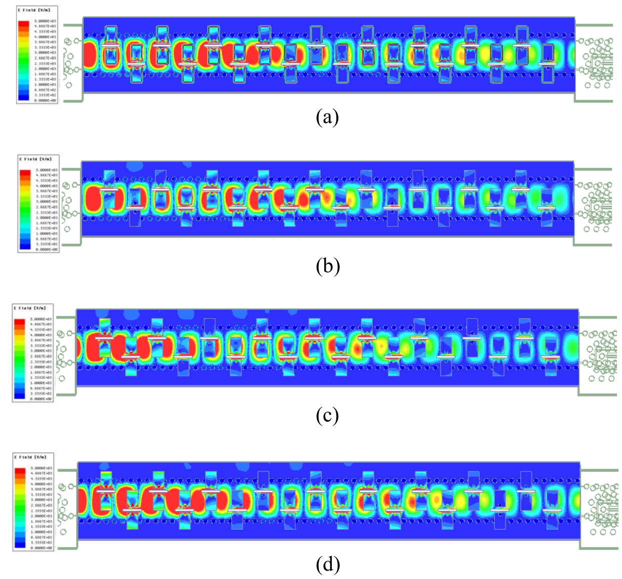


Fig. 3. Current distribution. (a) $t = 0$. (b) $t = T/4$. (c) $t = T/2$. (d) $t = 3T/2$.

circuit board (PCB) substrate with a thickness of 0.787 mm is used. Each planar electric dipole is formed by a pair of vertical pins and horizontal patches. For each dipole, two vertical pins, with radii 0.3 mm, made of via holes, are located 0.8 mm away from the center of slots. Two patches, with size 3×2 mm^2, separated by 1 mm are etched on the dielectric substrate and aligned on the top of the center line of the corresponding aperture.

With the presence of the electric dipoles, the longitudinal shunt slot antenna array becomes a leaky-wave ME dipole antenna. The detailed dimensions of the antenna are tabulated in Table I.

III. Operating Principle

The antenna array is excited from one port and the other port is terminated by a match load to absorb the remaining signal power, preventing it from reflection. The electromagnetic field of a TE_{10} mode incident wave excites magnetic currents on the slots. A leaky wave comes from the SIW guiding structure with periodic discontinuity that allows energy leakage or radiates electromagnetic fields into free space.

The lower layer of the antenna is a longitudinal shunt slotted SIW LWA array, where the surface of the SIW is cut with periodic slots in the structure, which causes a phase delay between the succeeding slots. The magnitude and phase of the voltage excited in the slot depend on the slot offset and the length of the slot [29]. In the design, the spacing between the two neighboring slots is slightly larger than $\lambda_g/2$ in order to avoid total reflection accumulating at each slot.

The current distribution on the proposed antenna from $t = 0$ to $t = 3T/2$, where T is a period of time, is illustrated in Fig. 3. It is observed that the current is restricted inside the via walls and moving along the $-x$ direction. It demonstrates that it is a traveling wave antenna array. Majority of energy leaks out through the slots in the first half of the antenna and only a few is left in the other end, which indicated that the residual energy is minimized when it reaches the other port.

TABLE I
DIMENSIONS OF THE LEAKY-WAVE ME DIPOLE ANTENNA

Parameters	L_{PCB1}	W_{PCB1}	h_{PCB1}	L_s	W_s	S_s	y_o	d_{v1}	S_{v1}	L_{PCB2}	W_{PCB2}	h_{PCB2}	L_d	W_d	d_{v2}
Values (mm)	85.1	13.9	1.57	3.4	0.4	9.5	1.5	0.9	1.5	91.1	13.9	0.787	3	2	0.6

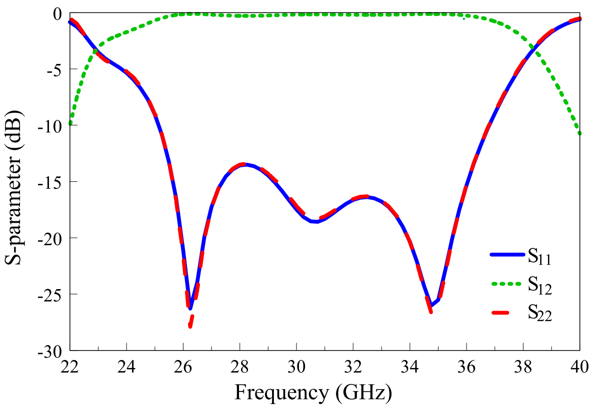


Fig. 4. Simulated S-parameter of the transition.

In this design, the upper layer of the antenna has many pairs of planar electric dipoles which are located on the top of the slots, while the magnetic dipoles are realized by the apertures in the lower layer. It is well known that a ME dipole would be realized if both electric and magnetic dipoles are excited together in orthogonal directions. The combination of the electric dipoles in the y-direction and the magnetic dipoles in the x-direction would radiate together in this design. According to the explanation in [15], the features of the radiation pattern can be improved. The proposed antenna array possesses wideband and less peak gain variation across the operating band.

IV. PARAMETRIC STUDY

In the previous section, the operating principle has been explained. In this section, a series of parametric studies is discussed to show the effect of the presence of the electric dipoles. The results were simulated with Ansys High-Frequency Structure Simulator (HFSS) version 17.

A V-band rectangular waveguide to SIW transition [30] at 28 GHz is designed for the input–output (I/O) ports of the proposed antenna. Roger 5880 PCB laminates with $\varepsilon_r = 2.2$ are also used in the design. Fig. 4 shows the simulated reflection coefficient at both I/O ports and insertion loss of the transition. A simulated bandwidth of 38.2% from 25 to 36.8 GHz for reflection coefficient less than–10 dB is achieved and the insertion loss over the operating band is better than 0.3 dB, which implies that the transition is sufficient wideband to be implemented into the proposed antenna.

Figs. 5–7 show the simulated peak gains and reflection coefficient between 27 and 32 GHz of the proposed antenna with and without electric dipoles. The influences of the dimension of the electric dipoles are investigated. They include the dipole length "L_d," the dipole width "W_d" and the height "h_{PCB2}." When studying the effect of a parameter, the other parameters of the antenna are remained unchanged. In the figures, it means no electric dipole in the structure when L_d, W_d, and h_{PCB2} are equal to 0 mm.

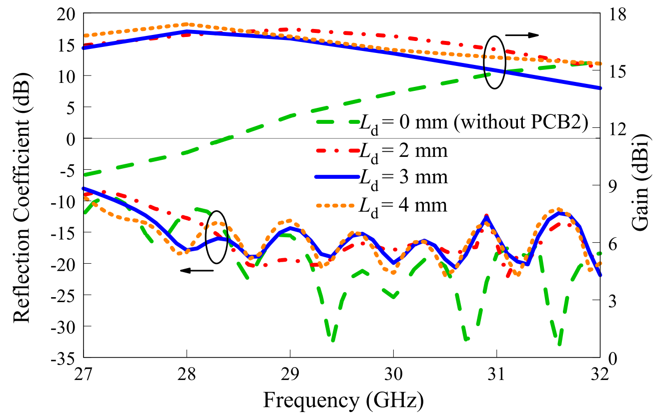


Fig. 5. Simulated reflection coefficient and gain for different L_d.

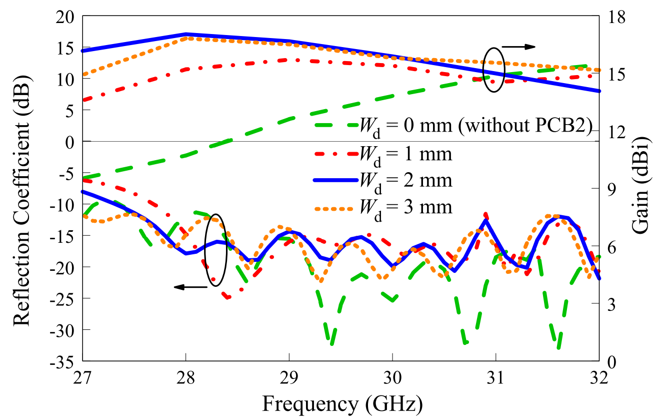


Fig. 6. Simulated reflection coefficient and gain for different W_d.

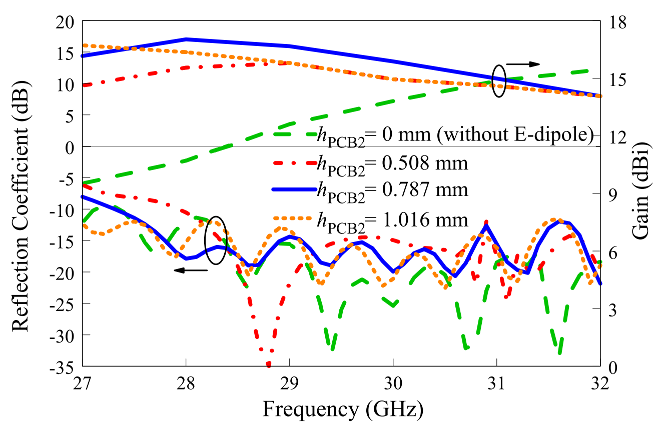
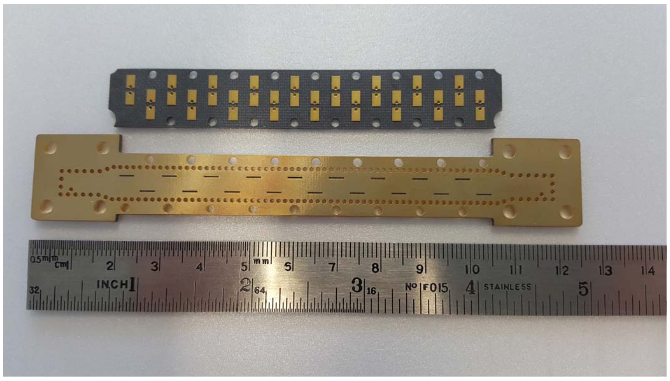
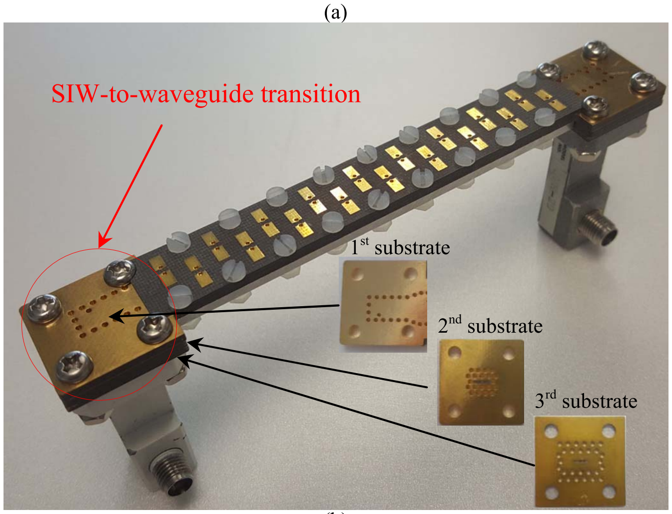


Fig. 7. Simulated reflection coefficient and gain for different h_{PCB2}.



(a)



(b)

Fig. 8. Prototype of the fabricated 18-element antenna array. (a) Top view of the upper- and lower-layer PCBs of the antenna. (b) Whole test model with waveguide to coaxial adaptors.

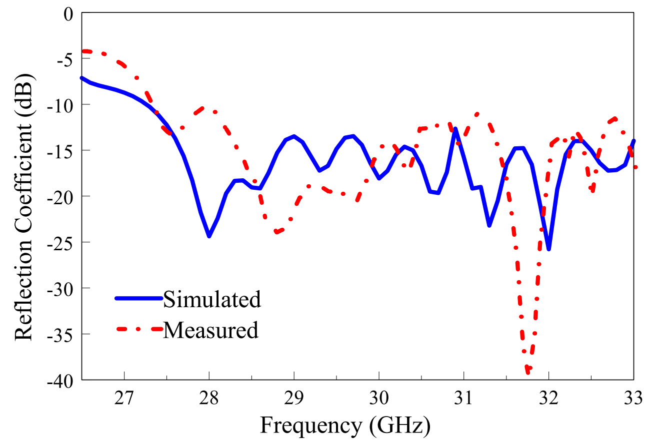


Fig. 9. Measured and simulation reflection coefficient of the 18-element antenna array.

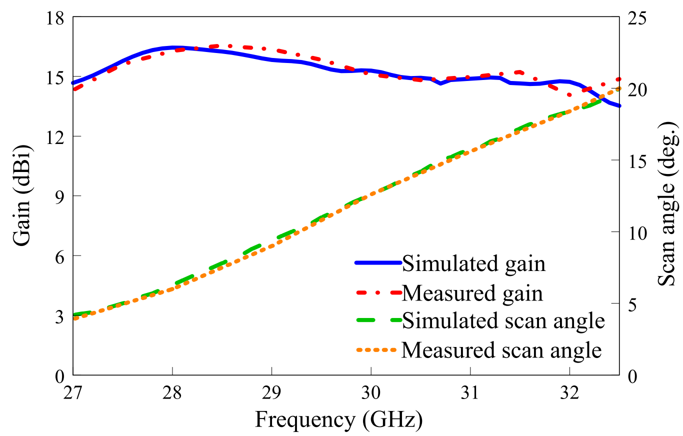


Fig. 10. Measured and simulated gain and scan angle of the 18-element antenna array.

The effects of L_d on the reflection coefficient and the gain are depicted in Fig. 5. When L_d is varied from 0 to 4 mm, the impedance matching is not affected dramatically. Yet, the peak gains at lower frequencies are enhanced so that the value of the peak gain difference across the frequency is reduced. At 28 GHz, the simulated gain can be greatly increased by 6.32 dB from 10.71 to 17.03 dBi, when $L_d = 3$ mm. It is $0.22\lambda_g$ long.

In Fig. 6, when W_d is adjusted from 0 to 3 mm, the frequency range of the impedance matching is more or less the same. Yet, the gain is increased at the lower frequencies from 27 to 30 GHz with increasing W_d. When $W_d = 2$ mm ($0.15\lambda_g$), the antenna reaches its highest gain of 17 dBi at 28 GHz.

The effect of the height h_{PCB2} of the electric dipole is displayed in Fig. 7. The thickness of 0.508, 0.787, and 1.016 mm of the dielectric substrate is available when conducting the research. It is seen that the gain can be gradually improved with the increase of h_{PCB2} and is optimized when $h_{\text{PCB2}} = 0.787$ mm. Similarly, the change of the impedance bandwidth is not significant.

Based on the above studies, it can be concluded that higher gain can be attained at the lower frequencies and smoother peak gain across the operating bandwidth is obtained when a series of electric dipoles are added. From 27 to 32 GHz, the simulated peak gain variation of the antenna with and without electric dipole is less than 3 and 5.9 dB, respectively. Obviously, the gain variation of the antenna is improved without deteriorating the operating bandwidth. The peak gain at main beam can be easily enhanced by adjusting the patch size of the electric dipoles, while the frequency range of the impedance matching is mainly determined by the lower part (slotted LWA) of the antenna.

V. Measured and Simulated Results

In this section, the insulated and metallic screws used in the antenna prototype are taken into consideration in the simulation. No significant change of the results is observed in the simulation with screws. For verification, a prototype has been fabricated and is shown in Fig. 8. The reflection coefficient is measured using Agilent PNA E8361A. The gain and radiation pattern are measured with a near-field antenna measurement system by Nearfield Systems Inc., (NSI).

A. Fabrication of the Proposed Antenna

The fabrication of the proposed antenna array is carried out by the standard low-cost PCB process. In Fig. 8(a), the upper- and lower-layer substrates for constructing the main body of the antenna are shown. The SIW structure is formed by via hole plating technology while the electric dipole patches and slots are created by stripping the excess copper using a PCB milling machine. The entire

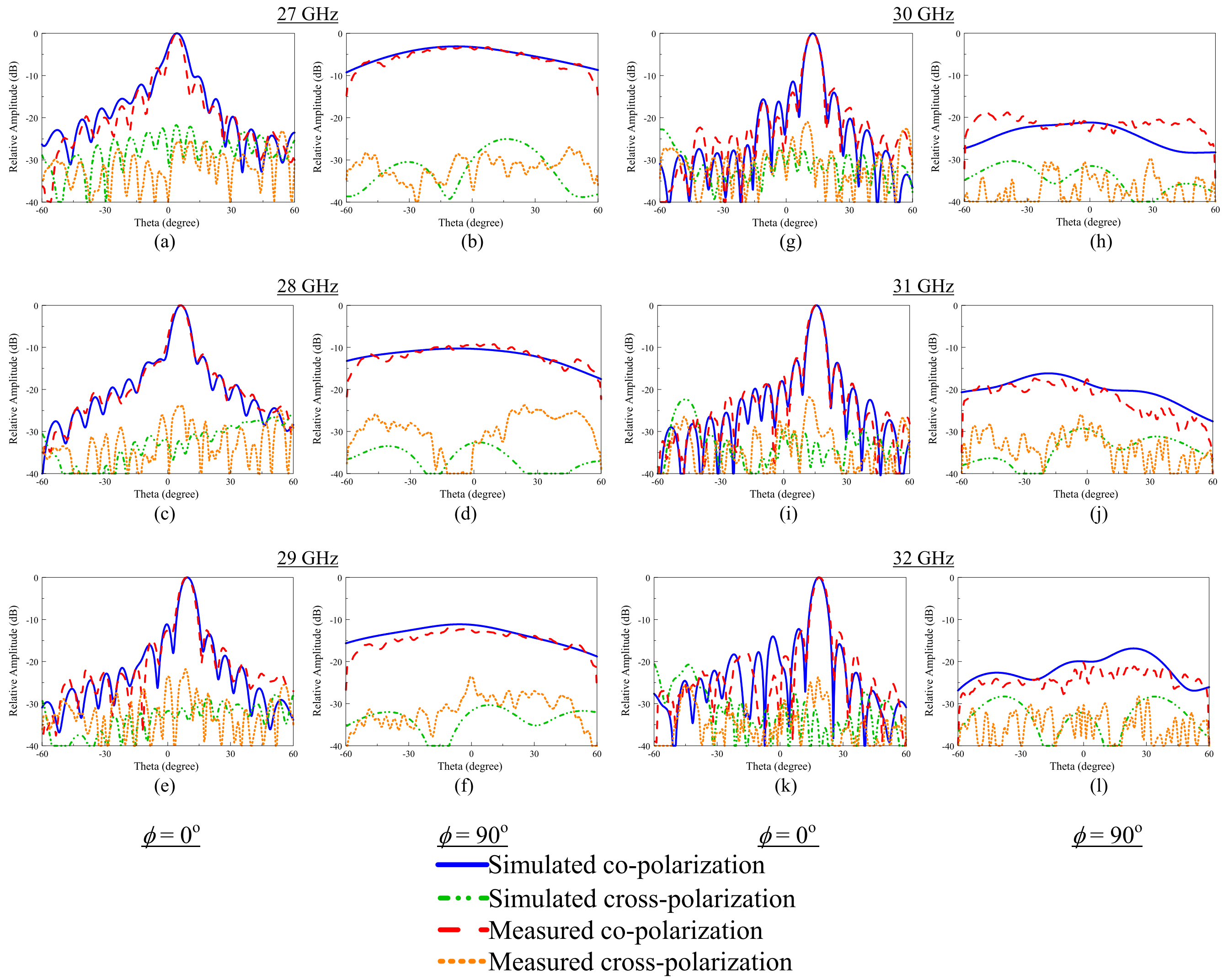


Fig. 11. Measured and simulated radiation pattern of the 18-element antenna array.

structure is exhibited in Fig. 8(b). Two standard waveguide horn (SWH)-29 waveguide-to-SubMiniature version A (SMA) adaptors are connected to the two I/O ports for testing. A 2-mm-thick aluminum plate is placed underneath the lower layer PCB for supporting the PCB structure not to be bent. The two-layer PCB and the aluminum plate are combined by eighteen insulated screws. At both ends of the antenna, the SIW-to-waveguide transitions are linked. Each transition is also made of Rogers 5880 substrates and divided into a three-layer dielectric substrate. The first substrate is the extension of the lower layer PCB of the antenna at both sides and the second substrate is a coupling slot in a 1.57-mm thick dielectric. The third substrate (waveguide) is formed by stacking two pieces of 0.508-mm thick dielectric. Finally, the transition is formed by tightening all the layer substrates together with four metallic screws. The detailed operating principle of the transition can be referred to [28].

B. Reflection Coefficient, Gain, and Radiation Pattern

As mentioned above, two rectangular SWH-29 waveguide-to-SMA adaptors are mounted on the transitions for measurements as shown in Fig. 8. One end of the antenna is connected to a match load and the other end is linked to the excitation source. Fig. 9 shows the measured and simulated reflection coefficient of the proposed antenna array. It can be seen that the measured and simulated operating frequencies are in good agreement. Starting from 27.3 GHz, the measured and simulated reflection coefficients are less than −10 dB. At 28 GHz, the measured and simulated values are −10.4 and −24.4 dB, respectively. Across the operating band, wide impedance bandwidth is observed.

The measured and simulated peak gains are illustrated in Fig. 10, where the average gains of 15 dBi across the operating band are attained. A measured gain up to 16.6 dBi is obtained at 28.5 GHz, which is close to the simulated one. Compared to the gain of the antenna without electric dipoles, the variation of the gain throughout the band is greatly improved from 5.9 dB to less than 3 dB. It proves that the attractive effect of the presence of the electric dipole on the performance of the slotted LWA. Fig. 10 also indicates the measured and simulated scan angles of the peak gains across the frequency band. Both of the scan angles are swept between 4° and 20°, almost in linear relationship across the band. The measured and simulated radiation patterns at 27, 28, 29, 30, 31, and 32 GHz are depicted in Fig. 11, where the measured beam tilted co-polarized fields are demonstrated

TABLE II

3-dB BEAMWIDTH, ϕ_{3dB}, FIRST SIDELOBE LEVEL, SL_{1st}, CROSS-POLARIZED LEVEL AT SCAN ANGLE AT $\phi = 0°$ PLANE OF THE 18-ELEMENT ANTENNA ARRAY

Frequency (GHz)	Measured ϕ_{3dB} (°)	Simulated ϕ_{3dB} (°)	Measured SL_{1st} (dB)	Simulated SL_{1st} (dB)	Measured X_{pol} (dB)	Simulated X_{pol} (dB)
27	5.7	7.9	-8.2	-9.4	-25.8	-21.8
28	7	7	-11.6	-12.2	-24.1	-32.6
29	6.3	6.4	-12.5	-11.1	-22	-33.6
30	6.1	6.1	-13	-11.4	-26.6	-31.3
31	6	6	-12.5	-13	-27.3	-32.3
32	5.8	5.9	-12.7	-12.2	-24.5	-37.2

at $\phi = 0°$ plane. At the main beams, symmetrical unidirectional radiation patterns are observed. At $\phi = 90°$ plane, the measured broadside co-polarized fields are decreased with the operating frequency. In Table II, the measured and simulated 3-dB beamwidth (ϕ_{3dB}), first sidelobe level (SL_{1st}), and the cross-polarized level at the scan angle (X_{pol}) at $\phi = 0°$ plane are summarized. From 28 to 32 GHz, it is noted that the ϕ_{3dB} decreases monotonically from 7.9° to 5.9°. From 28 to 32 GHz, the measured SL_{1st} and X_{pol} are less than -11.1 and -22 dB, respectively. The measured results agree well with the simulation. The efficiency of the proposed ME dipole LWA is above 83% from 27 to 31 GHz, and is up to 97% at 28 GHz. Only 62% efficiency is found at 28 GHz from the antenna structure when the electric dipoles are removed.

It is worthwhile to compare the performance of the proposed antenna arrays with some conventional designs available in the literature [10]–[14]. It is suggested to increase the gain of a periodic slotted LWA with more elements as demonstrated in [11], but the gain variation of the LWA cannot be improved by using more rows of array elements. Besides, the projection area will be enlarged with the increase of the number of elements. High gain ripple of 3 dB in the 1-GHz band is found, even though the gain has increased. In [10], it presents a composite right/left-handed SIW and a half mode SIW LWA. The corresponding gain variation is around 3 dB across the 3-GHz frequency band. Another multilayered composite right/left-handed LWA is presented in [12]. The gain variation is around 3 dB in the 4-GHz band. In [13], it is reported that the gain ripple of the conventional slotted waveguide slot array is 6 dB in the 3-GHz band from 24 to 27 GHz, and the gain variation can be improved to less than 2 dB throughout the band by integrating with metamaterials. The periodic collinear-slotted LWA [14] using different dimensions of the ridges shows 2-dB gain variation in the 4-GHz band. Regarding the ME dipole LWA, it is clearly seen from Figs. 5 to 7 that the gain enhancement, especially at 28 GHz, is significant in the presence of the electric dipoles. Also, the gain variation has remarkable improvement across the 5-GHz band from 27 to 32 GHz. If the 4-GHz frequency band is considered, the gain ripple is about 1.5 dB; whereas the gain variation is about 3 dB if the 5-GHz band is considered. The result is comparable to the conventional designs.

VI. CONCLUSION

In this paper, a novel 18-element SIW LWA has been proposed. It successfully demonstrates the application of ME dipole concept on slotted LWA for the gain enhancement at 5G frequency band. The whole antenna is only built with low-cost PCB technology. With the help of electric dipoles, the antenna gain of slotted LWA can be greatly improved at 28 GHz, without significantly affect other radiation characteristics. In addition, the gain variation between 27 and 32.5 GHz can be reduced effectively. The scan coverage for the frequency steering of the antenna is from 4° to 20°.

For the antenna design at millimeter-wave, the size of the antenna is extremely compact and small. LWA benefits from its simple feed network, which avoids complicated feeding technique on the structure, and thus decreases the difficulty in the manufacturing process. Based on the research carried out in this paper, it remains a lot of future work to be done by applying electric dipole on different types of slotted LWAs.

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