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Corporate-Fed Planar 60 GHz Slot Array Made of Three Unconnected Metal Layers Using AMC pin surface for the Gap Waveguide

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***Abstract*—This paper presents the design of a high efficiency corporate-fed 8×8-slot array antenna in the 60 GHz band. The antenna is built using three unconnected metal layers based on Artificial Magnetic Conductor (AMC) in gap waveguide technology. A 2×2 cavity-backed slot subarray is designed in a groove gap waveguide cavity. The cavity is fed through a coupling slot from a ridge gap waveguide corporate-feed network in the lower layer. The subarray is numerically optimized in an infinite array environment. The corporate-feed network is realized by a texture of pins and a guiding ridge. There is very good agreement between simulated and measured results. The fabricated antenna shows a relative bandwidth of 14% with input reflection coefficient better than -10 dB and an overall aperture efficiency larger than 65% (i.e. – 2 dB) with about 25 dBi realized gain between 56.2 and 65.0 GHz.**

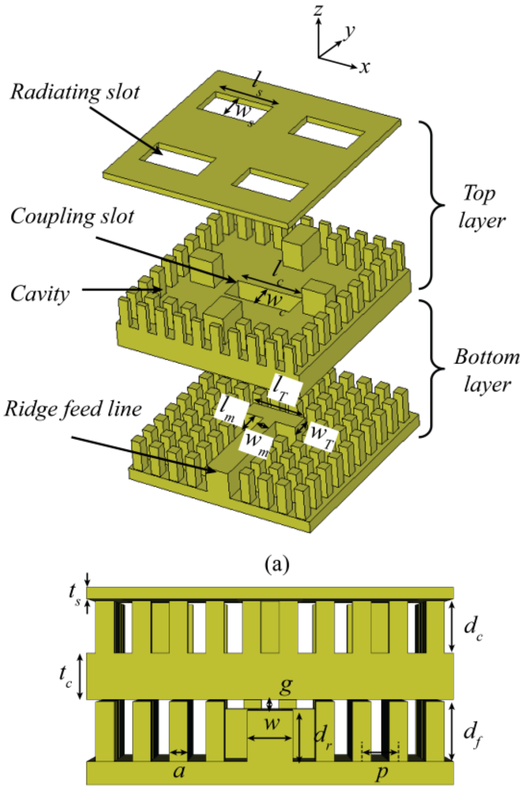
***Index Terms*— Artificial Magnetic Conductor (AMC), gap waveguide, high efficiency, millimeter wave, slot array antenna.**

I. INTRODUCTION

High gain, high efficiency and low profile antenna is one of the main challenges of millimeter wave wireless systems. Millimeter wave applications such as 77 GHz high resolution automotive radar and unlicensed 60 GHz high data rate radio links have got more attention over the last few years. Directive antennas for radio links are normally realized by using reflector antennas [1]. However, thin planar antennas are more desirable for millimeter wave applications because of their lower volume and weight. Microstrip and Substrate Integrated Waveguide (SIW) arrays have low profile. However, they suffer from dielectric losses, which are a disadvantage for high gain millimeter wave applications [2], [3]. The losses can be partly reduced by using low loss dielectrics, but these materials are expensive, and also quite soft. Therefore, it becomes difficult to machine and make via holes through those types of planar structures. Hybrid corporate-fed array antennas are proposed in [4] and [5] to reduce the dielectric loss of the distribution network, by using a microstrip ridge gap waveguide feed network and Substrate Integrated Cavity (SIC) radiating layer.

An alternative is to use the double-layer slot array presented in [6]. This is based on normal rectangular waveguide technology realized by diffusion bonding of many thin perforated metal plates. It shows high efficiency and wideband performance, but the diffusion bonding is expensive in mass production. Therefore, we will instead realize a similar slot array antenna by using three separate metal layers that are integrated without requiring any metal contact between them. This is possible by using new materials in the form of an Artificial Magnetic Conductor (AMC).

The gap waveguide technology [7], [8] shows good characteristics such as low loss, flexible planar manufacturing, and cost effectiveness in particular at millimeter wave



(a)

(b)

Fig. 1. 2×2 cavity-backed slot subarray realized in gap waveguide technology.

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TABLE I
DIMENSIONS OF 2×2 CAVITY-BACKED SLOT SUBARRAY
(REFERS TO FIG. 1)

Parameter	Value (mm)	
	4	Slot spacing in the *x* and *y* direction
w	1	Width of the ridge
d_r	1.1	Height of the ridge
g	0.25	Air gap
t_c	1	Thickness of the cavity layer
t_s	0.3	Thickness of the slot layer
d_c	1.15	Height of the cavity pins
d_f	1.3	Height of the feeding pins
p	0.8	Pins period
a	0.4	Width of pins
w_m	0.5	
w_T	0.86	
l_m	0.88	
l_T	2	
w_c	0.89	Width of the coupling slot
l_c	2.8	Length of coupling the slot
w_s	1.54	Width of the slot
l_s	2.7	Length of the slot

frequencies. In gap waveguides, AMCs (e.g., in the form of metal pins) are used in combination with a smooth metal plate, with an air gap between them. When the gap is smaller than quarter wavelength [9], there is a cut-off of all mode propagation within the gap. This can be used to control waves by introducing grooves or ridges between the pins. Thereby, there is no need for electrical contact between the textured surface and the metal plate. Therefore, gap waveguides can be mass-produced by molding, die pressing or die-sink EDM (Electrical Discharge Machining). This offers new opportunities for making cost-effective antennas and in particular corporate feed networks [10]-[12]. Moreover, the AMC of the gap waveguide technology can be used to package active circuits [13], [14] and low-cost bandpass filters [15],[16], which thereby could be integrated with the feed network. The metamaterial/metasurface background in gap waveguide technology is described in more detail in [17]. The book chapter in [18] gives a handbook description of all works on gap waveguides till now with 107 references including related works.

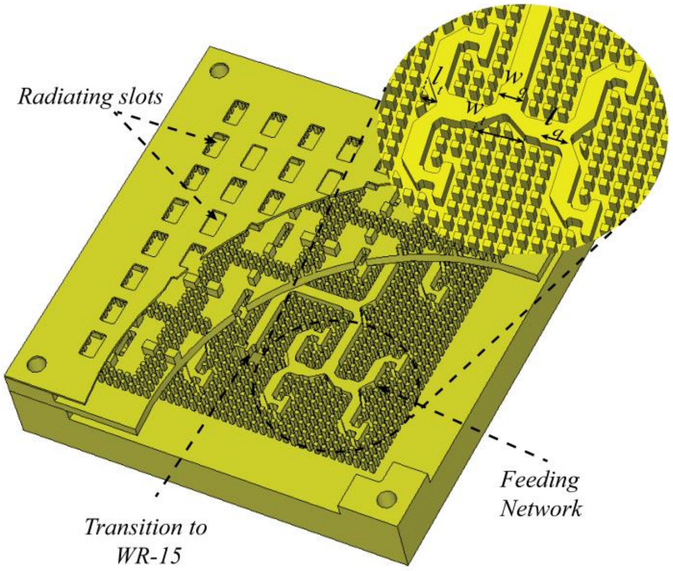


Fig. 2. Configuration of the proposed corporate-fed 8×8 slot array antenna; w_q = 1.35 mm, l_q = 1.35 mm, w_t = 2.66 mm, l_t = 0.85 mm.

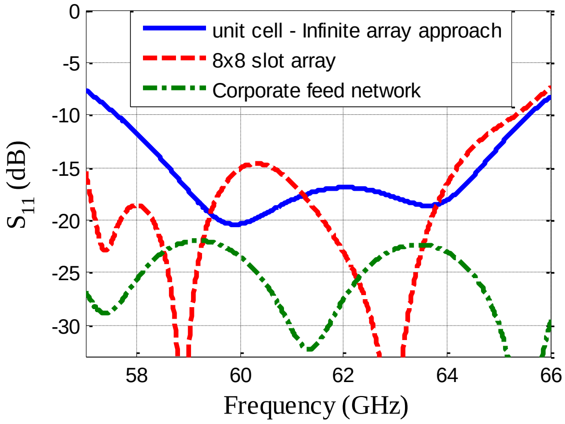


Fig. 3. Simulated reflected coefficient of subarray, 4×4 ridge gap waveguide feed network and complete antenna.

In this paper, we propose a high efficiency and low profile planar antenna working at 60 GHz. This is a corporate-fed 4×4 subarray realized by three unconnected metal layers. The subarray is optimized in an infinite array environment. Thereafter, the feed network for 4×4 subarray is designed, and the whole antenna is manufactured and measured. This paper presents for the first time such 8×8-slot planar array based on a fully corporate distribution network in ridge gap waveguide technology.

II. ANTENNA CONFIGURATION AND DESIGN

The subarray consists of two layers as illustrated in Fig. 1. There is an air-filled cavity formed by pins, and this feeds four radiating slots in the top layer. The slots have a spacing of nearly one wavelength. The lower layer contains pins and ridges forming a ridge gap waveguide distribution network hat excites the cavity via a coupling slot. There is a small air gap between each layer so there is no requirement for

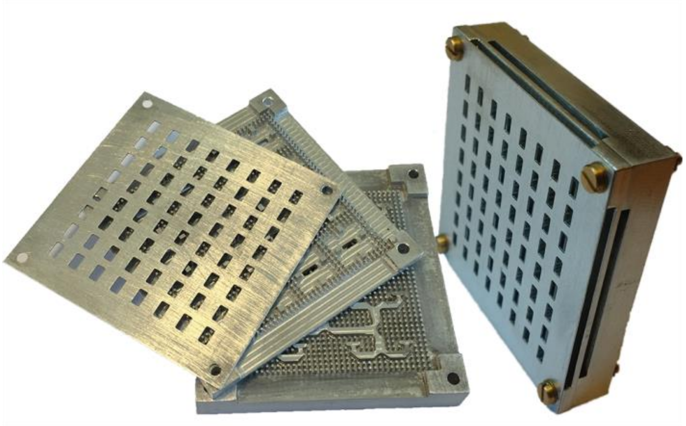


Fig. 4. Fabricated antenna made of three separate metal layers.

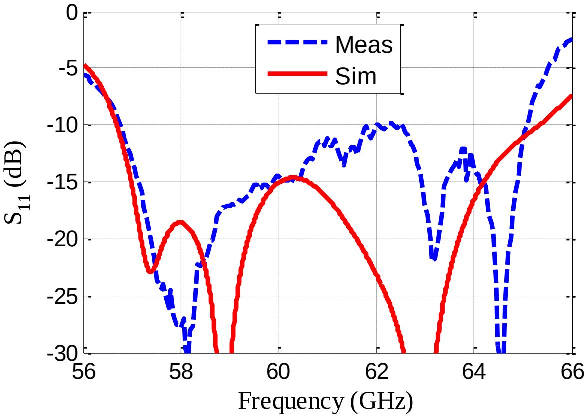
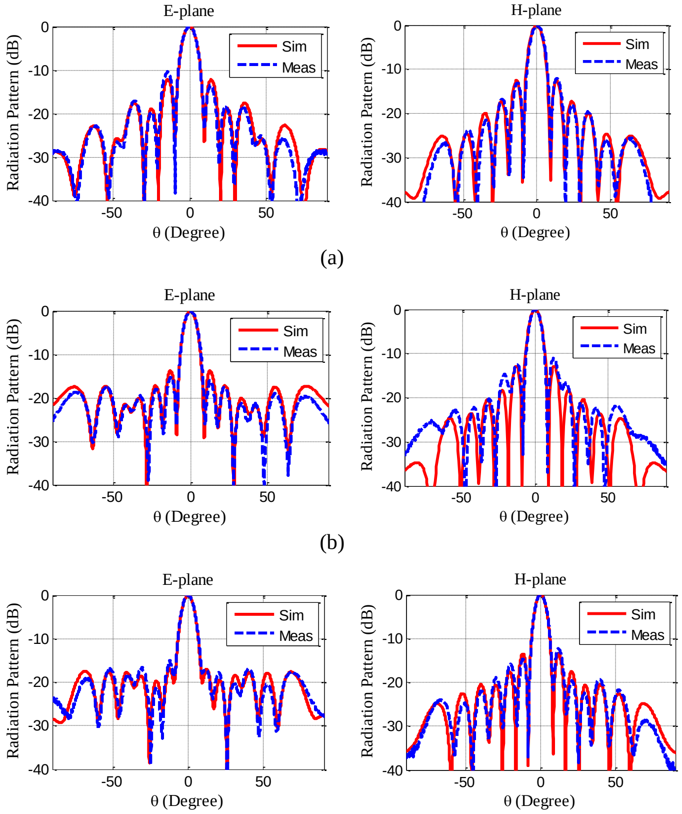


Fig. 5.Simulated and measured reflected coefficient of the 8×8-element array.

electrical contact between them. The pins in the top and bottom layers present a stopband for parallel-plate modes [9]. The designed subarray has 8×8 mm^2 dimensions in E- and H-plane. The subarray is optimized in the infinite array environment by using CST Microwave Studio by cut-and-try method, based on using the geometry in [6] as a starting point. The mutual coupling between subarrays are automatically included by using the infinite array approach. The slot spacing is close to one wavelength in order to give as large gain as possible, but we had to be careful to avoid grating lobes. The subarray was also carefully optimized to avoid grating lobes around 30° due to the two wavelength subarray spacing.



(a)

(b)

(c)

Fig. 6. Measured and Simulated radiation pattern in E- and H-plane at (a) 57 GHz, (b) 62 GHz, and (c) 65GHz.

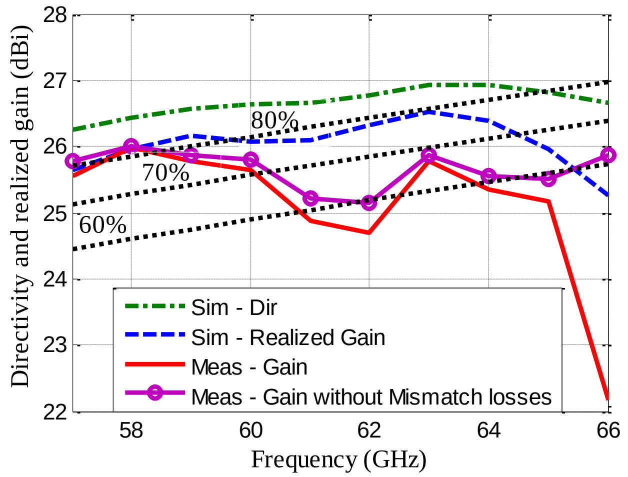


Fig. 7. Measured gain compared with simulated gain and directivity. The dashed lines show directivities for an aperture of the same size when the aperture efficiencies are 80%, 70%, and 60%.

The antenna configuration is shown in Fig. 2. The distribution network feeds all 2×2-slot subarrays with the same amplitude and phase. This has been designed gradually by using knowledge from previous papers on ridge gap waveguides [10]. It was a big challenge to realize the distribution network in the limited space available, in such a way that there is no observed effect of mutual coupling between close ridges. This was ensured by keeping at least two pin row between neighboring ridges, except for a few places, such as near some of the T-shaped ridges feeding the coupling slots to the upper cavities. The distribution network is fed from a simple transition to WR-15 rectangular waveguide in the bottom plate.

Fig. 3 shows the simulated input reflection coefficient S_{11} for the subarray in the infinite array, the whole feed network with terminated ports (without radiating elements), and of the complete full 8×8 slot array as seen on the input WR-15 port. The latter was determined by full wave simulation. We see that the feed network works very well with an S_{11} below -22 dB over a very large bandwidth. The final simulated S_{11} is below -15 dB between 57 and 64 GHz.

III. MEASURED RESULTS

The fabricated antenna is illustrated in Fig. 4. It manufactured by a Computer Numerical Control (CNC) milling machine. The measured and simulated reflection coefficient of the whole 8×8-element slot array are shown in Fig. 5. There is some discrepancy between simulated and measured results, explained by manufacture tolerances. Still, the measured reflection coefficient is below -13 dB from 56.8 to 65 GHz except for an increase of 3 dB from 60.5 to 62.8 GHz. The computed and measured far-field patterns are shown in Fig. 6. We see an extraordinary good agreement between them. This means that the feed network is working well and has wide bandwidth, and that the element spacing is small enough to avoid grating lobe problems.

The simulated and measured directivities and gains are shown in Fig. 7. The results illustrate that the simulated aperture efficiency (i.e. the directivity relative to the maximum available directivity of an array) over the whole band is above 80% (-1.0 dB), over most of it is actually close to 90% (-0.5 dB). The simulations show larger aperture efficiencies for larger arrays, so this reduction is due to the finiteness of the array, i.e. edge effects. The simulated and measured realized gains are very close at the lower end of the band, but has a difference of about 1 dB at the higher end. Thus, there is a potential for improvements. It should here be noted that the antenna is made of aluminum, and that this has almost a factor two larger surface resistance than Silver, so the losses could probably be reduced by a factor two by silver-plating. Above 65 GHz the gain drops fast due to the mismatch. The discrepancies between measured and simulated results can also be allocated to measurement uncertainties because the measurements were done in an outdoor range. The manufacturing tolerances can also explain the gain reductions.

IV. CONCLUSION

We have presented an 8×8 slot array realized by three metal layers that do not need any electrical contact between them. This has been possible by using an AMC to control the wave propagation between the plates, i.e. gap waveguide technology. The subarray shows better radiation pattern and higher aperture efficiency than the presented unit cell in [12]. The unique mechanical design opens up for new fabrication methods such as die-sink EDM or die forming that can provide low-cost millimeter wave antennas for 5G applications.

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