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Ka band Microstrip Fed Slot Array Antenna with PMC Packaging

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Abstract: A wideband slot array antenna fed by PMC (Perfect Magnetic Conductor) packaged microstrip lines at 28 GHz frequency range is presented. The slot array is designed with conventional microstrip technology and a PMC layer is used as a packaging solution to stop surface waves, cavity modes or any unwanted field leakage, coupling or radiation from the feeding lines. The PMC is implemented with a periodic metal pin structure. The array is fed by a corporate feed system and a good agreement with experimental results is obtained.

Keywords: PMC (Perfect Magnetic Conductor) packaging, slot array antenna, corporate feed network

1 Introduction

With the new 5G cellular networks, low cost, medium to high directivity antennas are demanded. One of the bands in use is the low millimeter wave frequency band (Ka band), more specifically 28 GHz. In this band, printed technology exhibits a significant amount of losses and for this reason low-loss full metal waveguide based slot arrays with high efficiency are one of the favorite options for high gain application scenarios.

However, simple waveguide slot arrays are typically narrow band and wideband slot arrays (of more than 10% bandwidth) are complex as they use multiple layer geometry [1–4]. More recently, single layer slot arrays based on gap waveguide technology [5], [6] have been proposed [7], [8]. Still these solutions are not as low cost as the PCB based antennas.

A combination of microstrip technology with gap waveguide technology was presented recently [9]. Here, printed technology was only used for the radiating element whilst the low-loss feed network was implemented in gap waveguide technology. Also, examples based on SIW are a good trade-off between cost and efficiency [10], [11].

Microstrip arrays are compact, easy to manufacture, cost-effective and easy to integrate with active electronics [12], [13]. Apart from the mentioned dielectric losses, the microstrip feed networks suffer from spurious radiations and leakage in the form of surface waves which are always major concerns and are difficult to handle [14]. There is also concern regarding the cross-talk and isolation problems among several closely spaced active electronic components. Some of these problems can be alleviated by using a packaging technique based on gap waveguide technology. This was first proposed in [15] and later demonstrated also with the inclusion of active components [16]. In most of the cases, the pin structure [17] is used for the packaging, but other unit cells have been also proposed [18–22].

The use of the combination of a conventional microstrip line with this packaging based on the gap waveguide concept was first proposed in [23]. In this work we show how this can be used to design a low cost wideband 8 by 8 planar slot array which can be extended further to build a high performance beam steering active array.

The novelty of the work is the aperture coupled slot array antenna which does not have back radiation. In all the traditional aperture coupled antennas back short cavities are often used to suppress the back radiation. That solution is not really suitable for beam scanning array integrated with active circuits which will be really the key part in 5G systems. This is because any metal back short over a large array will act as an over-moded cavity and will create lots of packaging problems such as unwanted cavity modes, spurious coupling among critical active components, unwanted oscillation of amplifiers etc. The unwanted coupling among the feed lines also may have detrimental effect in the radiation pattern of the array. Thus traditional PCB antennas typically use several PCB stacks to isolate the active circuitry, feed layer and the radiating elements. This complicates the RF signal routing path and increases the RF loss as multi-layer transitions are needed in this case and at the same time complicates the fabrication at mmWave frequency range and increases the cost of the PCB antenna.

In our proposed design, the aperture coupled concept can be easily implemented without the problems mentioned above. The periodic pin structure which works as the PMC surface suppresses the unwanted back radiation and the unwanted coupling among the feed lines. As a consequence, a single PCB can be used for the feed as well as radiating layer. Moreover, the active components can be placed in the same layer.

The paper is divided as follows. Section 2 contains the design of the feed network, starting from an ideal PMC and considering later on a real periodic structure. The design of a 2x2 subarray is presented in Section 3 whilst the final antenna design, including the experimental results can be found in Section 4. The main conclusions of the work are summarized in Section 5.

2 Feed network design

The array is fed by a corporate feed network designed in microstrip technology. The goal is to design a 8×8 element slot array and the design strategy is to first design a feed network dividing the input power in 1 to 16 and separately optimize the 2x2 subarray element as shown in Fig. 6. After several initial studies, the inter-element space was selected to be 7 mm, i.e. $0.65\lambda_0$ at the center frequency (28 GHz). As a dielectric material, RO5880$^{\text{TM}}$ substrate with 0.5 mm thickness was selected.

The packaging with the gap waveguide concept is ideally equivalent to locate a PMC layer at a distance g from the printed lines (seen in Fig. 6). The PMC condition together with the ground plane of the circuit avoid the propagation of any mode outside the microstrip lines. Initially, a PMC boundary condition is used in simulations for design and afterwards it is replaced by a periodic structure (in this case a bed of nails) that provides the same boundary condition in the frequency range of interest.

The 1 to 16 feed network when designed using the PMC boundary condition has a performance as shown in Fig. 1.

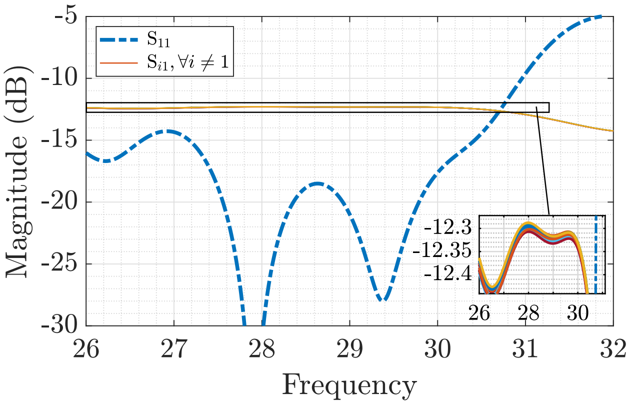


Fig. 1: Simulated S parameters for the 1 to 16 power divider using PMC.

A bed of nails was then designed to behave as PMC in the frequency range of interest. The dispersion diagram of the unit cell considering also the substrate to be used is included in Fig. 2. The selected pins have a 2.5 mm height, 1 mm widht, 2 mm periodicity and a 0.5 gap to the substrate described before. The stop band goes from 25.6 GHz to 37.7 GHz covering the band of interest.

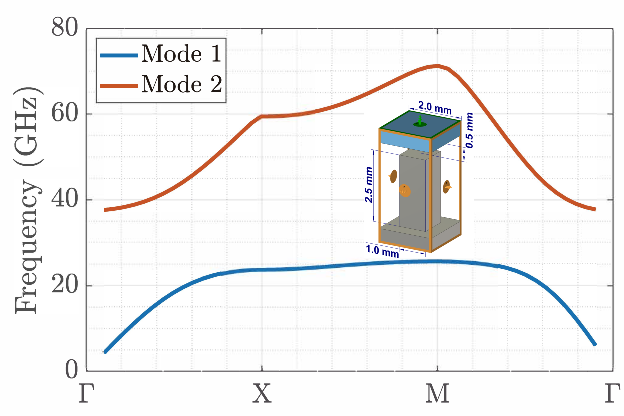


Fig. 2: Dispersion diagram of the unit cell of the pin's structure combined with the substrate of the microstrip circuit on top.

The next step is to simulate and optimize the feed network using the bed of nails as packaging structure instead of the ideal PMC condition. The feed network was slightly optimized again and the results can be seen in Fig. 3. A good matching and low losses are observed from 26 GHz to 30 GHz.

As an example of the influence of the pins dimensions into the results, Fig. 4 shows the same design when the pins have a longer length (3 mm instead of 2.5 mm) still the stop band covers the band of interest (now from 21.8 to 33.4 GHz).

Finally, in Fig. 5 the behaviour of the feed network without any packaging and when packaged with a smooth metal layer located at $0.25\lambda_0$ are presented. The open case exhibits much higher losses than the packaged case as observed in the transmission coefficients and the use of a metal layer produces parallel plate modes and consequently unwanted coupling and losses. The advantages of using the PMC packaging are evidenced here.

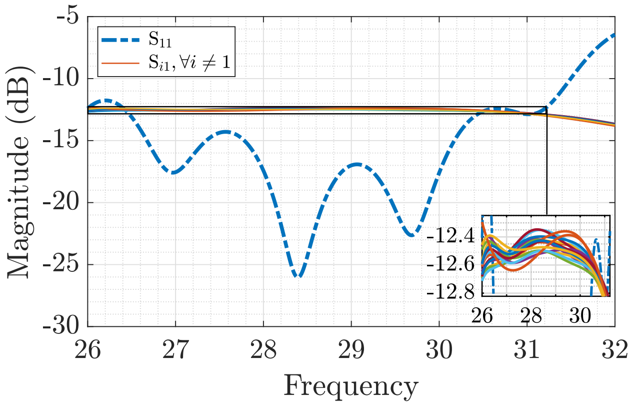


Fig. 3: Simulated S parameters for the 1 to 16 power divider using pins.

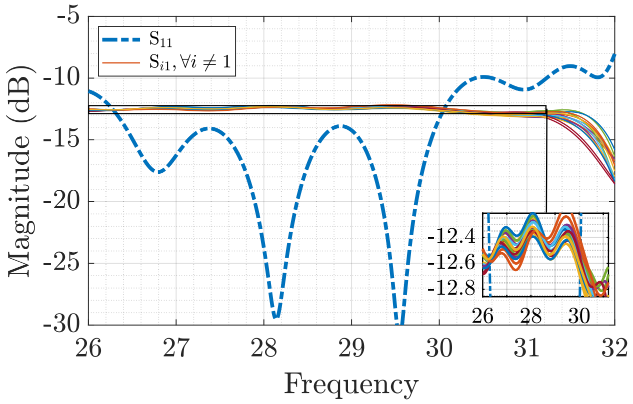


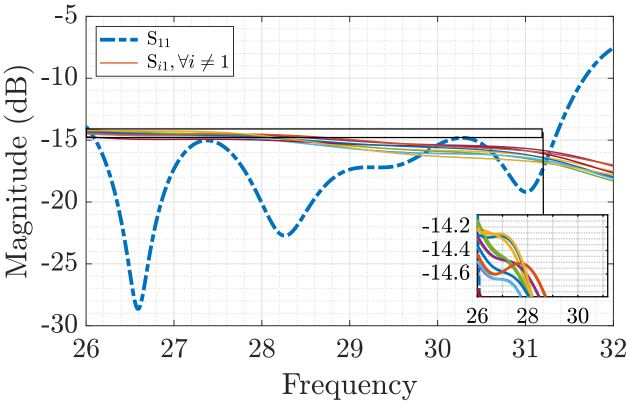
Fig. 4: Simulated S parameters for the 1 to 16 power divider using the pins with h= 3 mm.

3 Subarray design

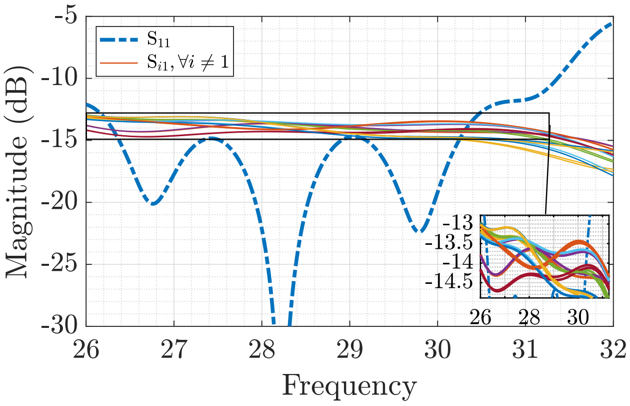
The four element subarray is now designed. It consists of a conventional PCB antenna with the microstrip feed line in one side and the etched slots in the ground plane. The packaging structure emulating the PMC is placed on the bottom of the microstrip feed line at a distance of g= 0.5 mm from the PCB as described in Fig. 6. The element spacing in both E and H planes are considered to be 7 mm. The slots have a length of 4.161 mm and a width of 1.675 mm. The power division in the feeding network has been achieved by conventional microstrip T-junction based 3 dB power dividers. The T-junctions in the feed network have been designed with gradual tapering and in this design quarter wavelength based transformers have been avoided due to the required compactness of the sub-array.

As mentioned in the introduction, the design strategy includes the design of 2x2 subarrays. The simulated subarray matching both with ideal PMC and with the structure of pins described in the previous section are both presented in Fig. 7. A good matching is obtained from 27.4 GHz to 30.2 GHz in the case of the pins and a bit wider in the case of ideal PMC.

The subarray radiation patterns at four different frequencies from 27.5 to 30 GHz are presented in Fig. 8 in the two main planes. Here the results are computed assuming 4 × 4 subarrays, periodic boundary conditions and pins as PMC. The directivity is close to 25 dB (but only half space is considered due to the periodic boundary condition) and the SLL are below -12 dB in all planes and frequencies.



(a) Unpackaged



(b) With a PEC ground plane

Fig. 5: Simulated S parameters for the 1 to 16 power divider

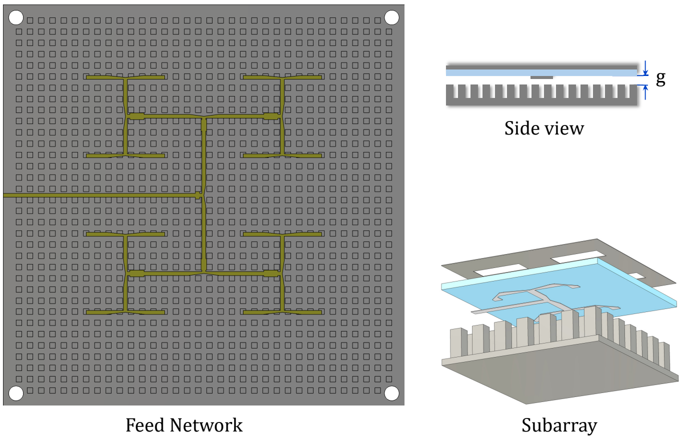


Fig. 6: Description of the feed network and the subarray structure.

Finally, in Fig. 9 a comparison of the field distribution among the Open, PEC, PMC and our designed packaging solution with pins is presented. The field is represented in the plane of the feed network. Only in the case of our design the ports are combined into a single port. In the other three cases the excitation of the antenna is made by subarrays (four ports).

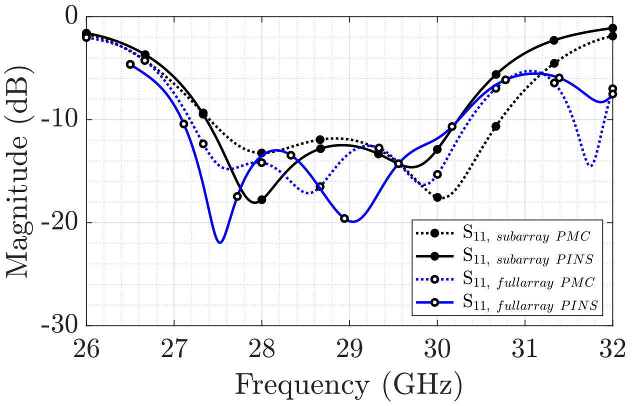
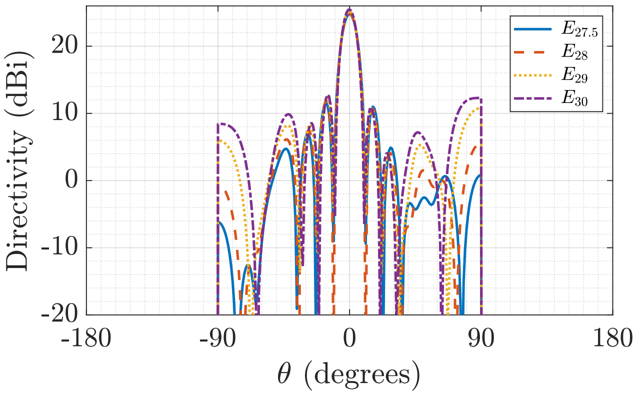
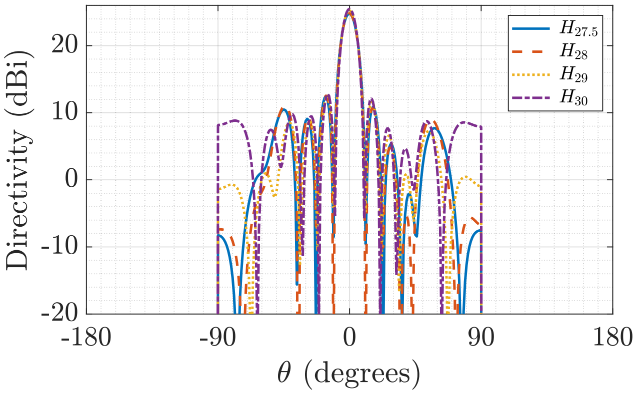


Fig. 7: S_{11} parameter for the subarray both with PMC and with pins VS S_{11} parameter for the full array both with PMC and with pins.



(a) E plane



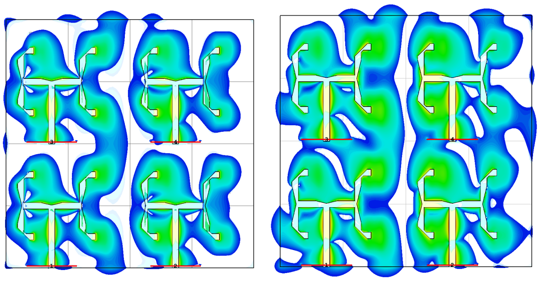
(b) H plane

Fig. 8: Radiation patterns of the subarrays at different frequencies.

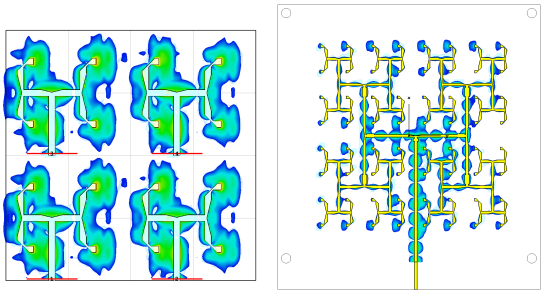
4 Antenna performance

The 8x8 array has been designed and optimized. Fig. 10 shows the antenna matching with pins and with an ideal PMC. A bandwidth of more than 3 GHz is observed.

The corresponding radiation patterns in the same frequency range as for the subarray are presented in Fig. 11 for the case with pins. Here the directivity changes between 22.8 and 24.5 dBi (22.3 and 23.6 dBi for the realized gain) whilst the SLL have increased in the H plane compared to the subarray case. All the results are detailed in Table 1.



(a) Open (b) PEC at 2.75mm



(c) PMC (d) Our design

Fig. 9: a) Four subarray of 2x2 slots with 4 simultaneous excitations with open boundary, no lid. b) Four subarray of 2x2 slots with 4 simultaneous excitations and PEC layer at 2.75mm from slots plane (simulating metal packaging). c) Four subarray of 2x2 slots with 4 simultaneous excitations with lid of nails (0.25 mm of air gap). d) Our final design. All at feed plane and normalized to dBmax (0 to -40dB).

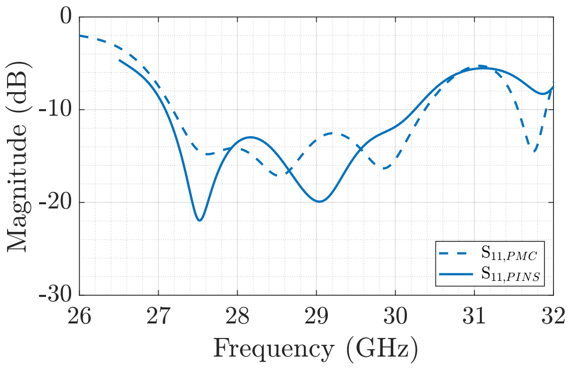
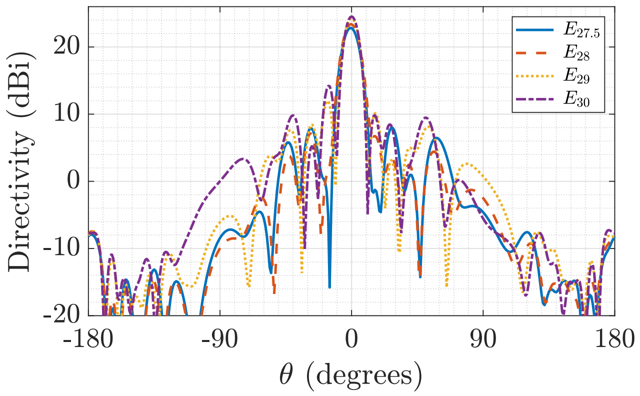


Fig. 10: S_{11} parameter for the full array both with PMC and with pins.

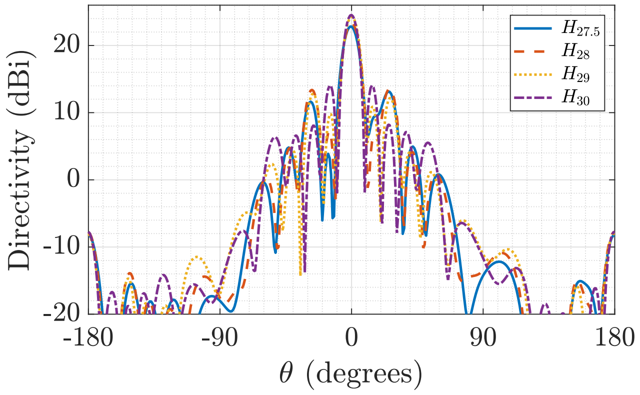
4.1 Experimental Results

A prototype has been manufactured and measured. To integrate the prototype with an end-launch connector a transition was first designed. The microstrip prototype and the bed of nails used can be seen in the Fig. 12. The measured S_{11} is presented in Fig. 13 where two different measurements are shown, the directly measured S_{11} and the same measurement after removing the effect of the connector by means of a TRL calibration kit. We can see how this second measurement agrees reasonably well with the simulated results (only a slight shift to higher frequencies is observed) and as before, an impedance bandwidth of more than 3 GHz is achieved.

Finally, the radiation patterns of the antenna have been measured at the different frequencies. The results can be seen in Fig. 14 represented as normalized radiation patterns. We can see how the beamwidth and the SLL levels are almost constant from 27.5 to at least 30 GHz.



(a) E plane



(b) H plane

Fig. 11: Simulated Radiation patterns of the full array for different frequencies.

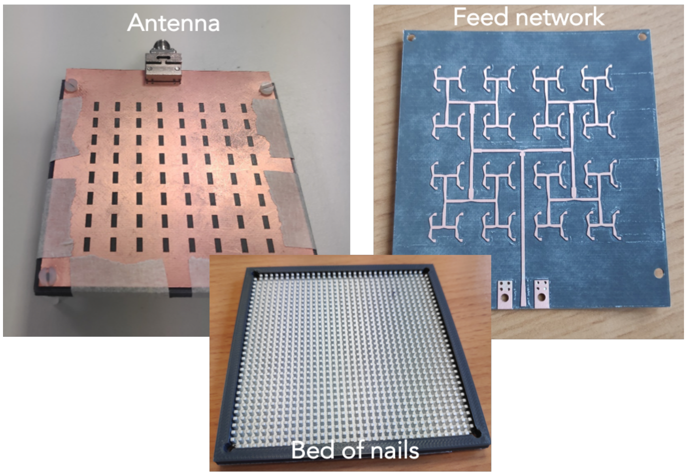


Fig. 12: Manufactured prototype.

A good agreement is observed with respect to simulations and the detailed values are included in Table 1.

5 Conclusion

This work has shown how the use of a PMC packaging made with a bed of nails can be used to design a slot array in conventional microstrip technology in the Ka band. The use of the PMC suppresses any unwanted radiation from the discontinuities of the feed

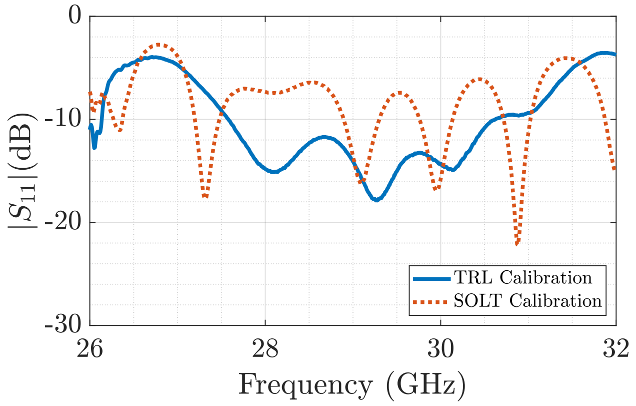
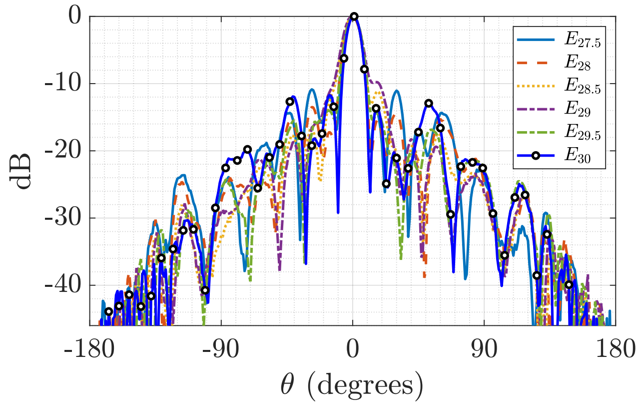
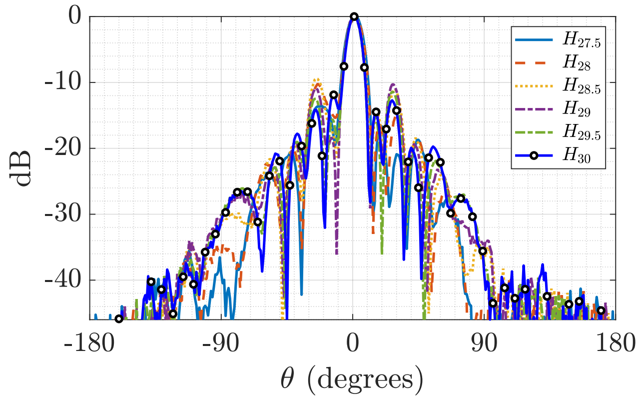


Fig. 13: Experimental results before and after using a TRL calibration kit.



(a) E plane



(b) H plane

Fig. 14: Measured radiation patterns of the full array for different frequencies.

Table 1 Antenna parameters

Frequency [GHz]	**27.5**	**28**	**29**	**30**
Sim. Directivity [dB]	22.8	23.4	24.3	24.5
Sim. Gain [dB]	22.3	22.7	23.6	23.5
Meas. Gain [dB]	19.6	21.5	22.2	23.5
Sim. SLL (E)	-14.9	-16.2	-12.3	-10.3
Sim. SLL (H)	-9.7	-9.8	-11.5	-10.5
Meas. SLL (E)	-10.9	-13.5	-9.8	-11.7
Meas. SLL (H)	-13.6	-10.2	-10.3	-11.9

Table 2 Comparison with other PCB-based planar arrays

	f_0 **(GHz)**	**#Els**	**#Lay**	**Size** (λ_0)	**BW** (%)	**Gain (dBi)**	**SLL (dB)**	**Rad.eff** (%)	**Type**
[10]	20	256	2	12x12.6	15	29.1	-17	76	SIW
[24]	60	50	1	7x7	12.5	25.2	-9	63.7	Mstrip
[25]	12.5	64	2	6.3x6.3	13	24	-12	NA	SIW/Mstrip
[26]	60	144	1	NA	4.16	22	-15	68	SIW/Mstrip
[13]	30	64	12	6x7.6	13.3	22.5	-12	57.8	Mstrip
Our	**30**	**64**	**2**	**7.2x7.7**	**11.1**	**23.5**	**-11.7**	**79.4**	PMC+Mstrip

network or unwanted leakage via the substrate mode which are severe in conventional microstrip technology in this frequency band. At the same time, the antenna back radiation is also avoided and active components can be easily integrated in the same PCB as packaging is provided. The proposed design is wideband and the same concept can be used to extend the design for bigger arrays to be used in this millimeter wave band for the new 5G wireless systems.

A comparison with other works in printed technology in similar frequency bands is shown in Table 2. The radiation efficiency is estimated with the measured realized gain and the simulated directivity.

Acknowledgment

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