Reflectarray Resonant Element based on a Dielectric Resonator Antenna for 5G Applications

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Abstract **─** The performance of a proposed cross hybrid dielectric resonator antenna (DRA) element for dual polarization configuration operating at 26 GHz for 5G applications is presented in this paper. The new cross hybrid DRA unit cell is introduced which combines a cross shape DRA with a bottom loading cross microstrip patch. This technique of a bottom loading cross microstrip patch is chosen as the tuning mechanism (varying the length of the microstrip to tune the phase) instead of changing the DRA dimensions because of their ease of implementation and fabrication. By doing so, high reflection phase range with low reflection loss performance can be obtained, which is essential for a high bandwidth and high gain reflectarray for 5G applications. The design and simulation have been done using commercial software of CST MWS. The reflection loss, reflection phase and slope variation were analyzed and compared. A metallic cross microstrip patch of varying length placed beneath the DRA to act as the phase shifter to tune the phase and give smooth variation in slope with a large phase range. The proposed cross hybrid DRA unit cell provides a high reflection phase range of 342◦ and 1.8 dB reflection loss. The computed results are compared with experimental results revealing reasonable agreement, thereby confirming the viability of the design.

Index Terms **─** DRA reflectarray, phase range, reflection loss, reflection phase, unit cell.

I. INTRODUCTION

Reflectarray antennas are the combination of some capabilities and some advantages between phased array antennas and parabolic reflectors [1,2]. It comprised of an array of element radiators illuminated by a feed antenna (usually a horn antenna). The feed antenna provides the feeding mechanism to the array, in order to eradicate the need for a complex and lossy corporate feed network. Therefore, the losses in reflectarray antenna can be easily optimized due to its simple feeding mechanism. The feeding is located at the focal distance of the reflectarray. Usually, the focal distance is evaluated in focal-length-to-diameter (f/D) ratio. The distance of the reflectarray and the feed represented by *f*, while the longest dimension of the reflectarray represented by D [3,4]. The occurrence waves coming from the feeding are reradiated and scattered back with electrical phases that are required to form a planar wave front in the far-field distance towards the desired direction. One vital component of the reflectarray performance investigation is the unit cell elements have been designed and characterized accurately [5]. The unit cell element's dimensions are responsible to accurately predict the phase shift required for planar wavefront. The radiation patterns of the reflectarray antenna can only be estimated after the unit cell element and the full reflectarray has been fully characterized and designed. Reflection phase and reflection loss are two major important parameters to analyse the performance of reflectarays unit element. The reflectarray unit element's reflection loss will have an impact on the gain of a full reflectarray antenna, whilst the reflection phase or phase range of the unit cell corresponds to the bandwidth of the reflectarray antenna [6]. A complete cycle of phase swing with 360° is normally considered adequate to design any size of reflectarray with a good performance [7].

Initially, microstrip unit elements are widely used to develop reflectarrays antenna due to their good criteria such as low profile, light weight, flatness, easy deployment in space, beam steering capability as well as their low manufacturing cost [8]. Nevertheless, the conductor loss of the microstrip reflectarray antenna becomes worse. The reflectarray antenna's competency at mmW frequencies of the microstrip unit cell also may drop markedly. Reflectarray made by dielectric resonator (DRA) that has small losses and large phase range is

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presented to overcome this problem [9-11].

DRA has been investigated for designing various reflectarray antennas to obtain high reflection phase range, and small reflection loss by changing the length of the DRA or any other one of its geometrical parameters to present phase variation s to the radiating unit cells [12]. But the fabrication process will be more complex when the reflectarray antenna made by different DRAs sizes. For that reason, the unit cells of DRA reflectarray also able to be combined alongside several strip elements like patches, slots as well strips. The purpose of that is to produce wide band reflectarray or specifically to expand the bandwidth and concurrently to ensure the easy fabrication [13-15]. As a consequence, a full reflection phase range with smooth variation in slope will be able to be produce practicably. However, a problem faced by a slot loaded DRA reflectarray was an electric field that can leak through the under-loading slot that may lead to a growing back lobe radiation problem. Meanwhile, the top-loaded microstrip patch DRA element has a risk of gain reduction due to misalignment between patch and DRA that may arise because the microstrip has to install by manual at the upper of the DRA surface. In another study, a transparent rectangular DRA reflectarray element with beneath-loaded strip have been proposed giving a phase range of 316° with reflection loss of less than 3 dB [16]. Another approach to enhance the reflectarray element's bandwidth with large reflection phase range is by implementing dual-polarized technique [17-19]. The option of the polarization be able to accomplish by using square shapes or rectangular shapes for linear polarization. Whereas circular polarization or dual polarization can be attained by using circular shapes or crossed shapes.

Inspired by the mentioned foregoing studies of the unit elements, the goal of this study is to introduce a new DRA reflectarray element with a microstrip patch incorporated underneath the DRA as a phase tuning mechanism for 5G applications. For the ease of fabrication purpose, the size of each DRA is always the same. The only change is made on the microstrip length (L_m). The focus has been given specifically on attaining large phase range which is greatly associated to the low reflection loss and substantial operational bandwidth performance. The aim is to design a DRA-based reflectarray element with low reflection loss, wide bandwidth and ease fabrication for 5G applications.

II. RESEARCH METHOD

In this work, the frequency band from 24 GHz to 28 GHz has been chosen for design specifications based on several 5G frequency bands that have been suggested in [20]. 26 GHz as a resonant frequency has been selected to design the reflectarray unit element.

The unit elements of the reflectarray nominated in this paper made of DRA. The dielectric constant of the DRA is ε_r = 10. The cross shaped DRA consists of two rectangular DRA (RDRA) with the same size. The cross microstrip patch on the other hands is formed by two identical rectangular patch elements. The resonant frequency, f_0 for the RDRA has been calculated by using the equation (1) that derived from the Dielectric Waveguide Model (DWM) [21]:

$$\boldsymbol{k_z} \tan\left(\frac{\boldsymbol{k_z h}}{2}\right) = \sqrt{(\boldsymbol{\varepsilon_r} - 1)\boldsymbol{k_0^2} - \boldsymbol{k_z^2}} \;, \quad (1)$$

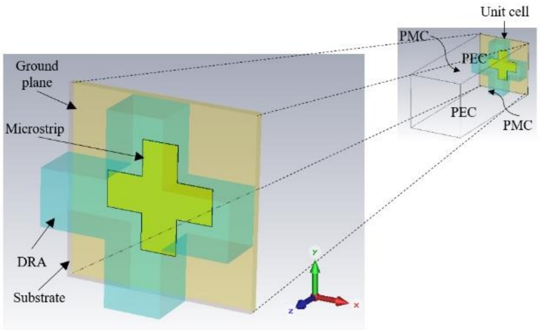
where k_0 is the free space wave number, h represents the width in the z-direction and k_z represents the wave propagation number in the z-direction.

The DRA width (W) has been set at 2.40 mm whilst the DRA length (L) has been set at 8.00 mm. The cross microstrip patch acts as a phase shifter to adjust the phase of the unit cell element. On the other hand, the microstrip length (L_m) is varied from 1.50 mm to 4.50 mm as the phase shifting mechanism while the width of microstrip patch (W_m) has been set at 1.50 mm. Table 1 summarizes the optimized unit cell design dimensions.

Table 1: Parameters of dielectric resonator reflectarray antenna unit element

Parameter	Value (mm)
L	8.0
W	2.4
H	2.2
L_m	Varies from 1.50 to 4.50
W_m	1.5

Figure 1 (a) shows the setup of waveguide simulation for the unit cell element. The proposed unit cell element is placed at one end (bottom) of the waveguide and the incident wave from the wave port is positioned from another end of the waveguide (top). The unit cell element is simulated with proper boundary conditions to imitate an infinite periodic structure. The top and bottom surfaces of the waveguide setup are interpreted to be perfect electric conductor (PEC) walls, whilst the other two side walls (left and right sides) are interpreted as perfect magnetic walls (PMC). The geometry of the unit cell which is the cross hybrid DRA is demonstrated in Fig. 1 (b). The unit element's substrate is made of a Rogers RT5880 with dielectric constant 2.2 and thickness 0.381 mm with its ground laminated on the back surface. This unit cell is a coalition of a cross shaped DRA and a cross shaped microstrip patch. The bottom loading patch was chosen as the tuning mechanism because it can be simply etched using the technology of standard printed circuit board (PCB). This method can provide high dimensioning accuracy and simplifies the tuning process. Moreover, it can also avoid misalignment problem and fabrication complexity at once. The. Fig. 1 (c) shows the fabricated cross hybrid DRA unit cell elements.



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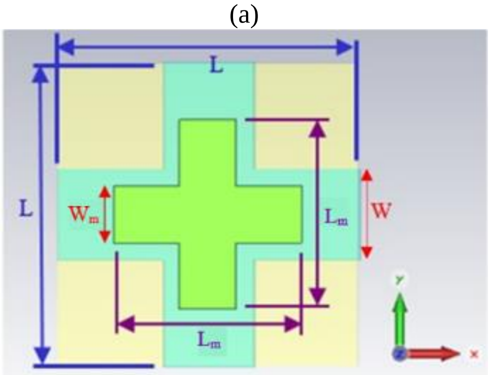

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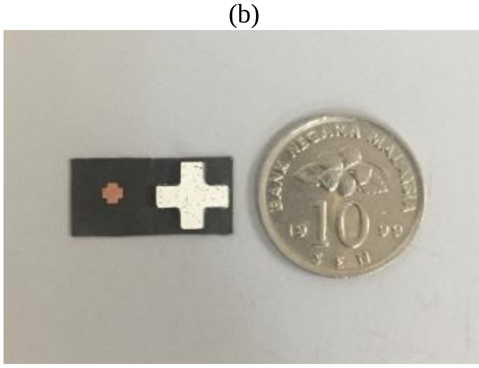
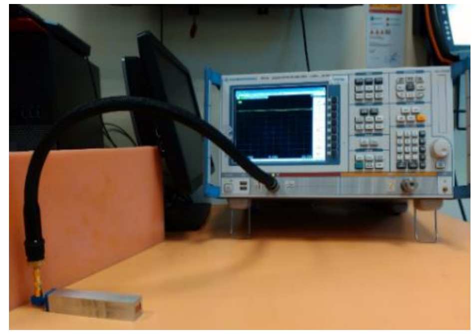


(c)

Fig. 1. (a) The simulation of unit element in periodic boundary condition and the zoom in for the proposed Cross hybrid DRA unit element geometry. (b) Top view of the proposed Cross hybrid DRA unit element. (c) Photograph of the fabricated Cross hybrid DRA unit element.

The overall measurement setup is shown in Fig. 2 (a), where the open ended waveguide is used to carry the parameter measurements of the unit cell elements. The unit cell under test is placed at one end and the other end is connected to WR-34 waveguide adapter. The reflection phase and reflection loss of the unit cell elements are measured using VNA (Vector Network Analyzer), which is connected to the waveguide using coaxial to waveguide adapter of WR-34 adapter as shown in Fig. 2 (b). Two unit cell element reflectarray is fixed into the other aperture of the waveguide simulator as shown in Fig. 2 (c).



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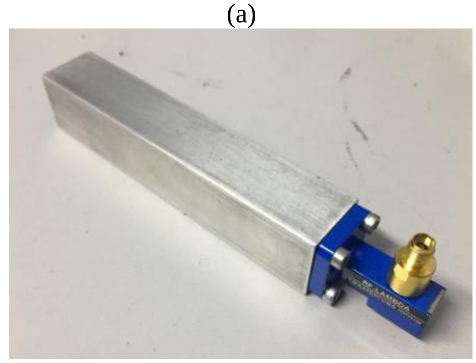

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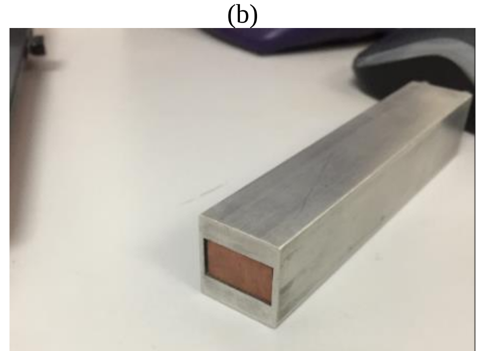
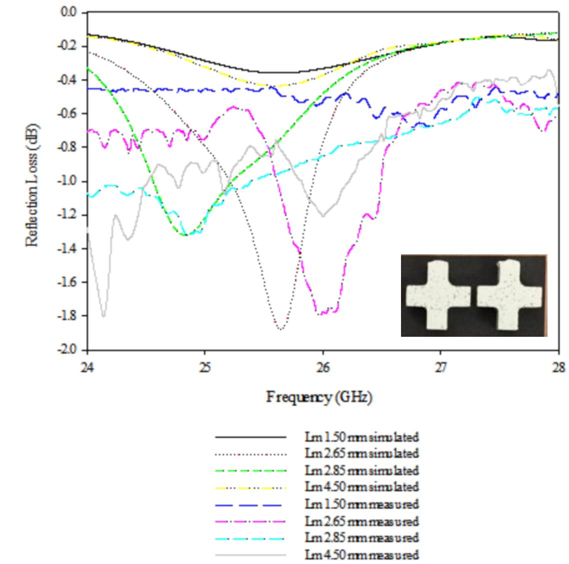


(c)

Fig. 2. (a) Scattering parameter measurements of measurement setup. (b) Coaxial to waveguide adapter WR-34 connected to waveguide. (c) Unit cell elements in waveguide aperture.

IV. RESULTS AND ANALYSIS

The proposed cross hybrid unit cell elements with microstrip patch dimensions underneath the DRA are constructed and validated as shown in Fig. 1 (c). The simulated and measured reflection phase and reflection loss of the cross hybrid DRA reflectarray elements are as presented in Fig. 3. The unit cell came with various cross microstrip lengths (L_m). The length is varied to tune the phase. Based on the results, it is found that 342° phase variations can be obtained at 26 GHz. The reflection loss is reasonably small at 1.8 dB.



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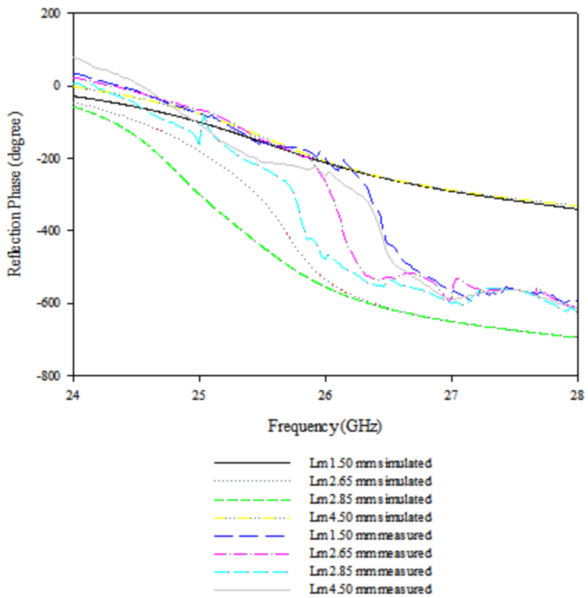
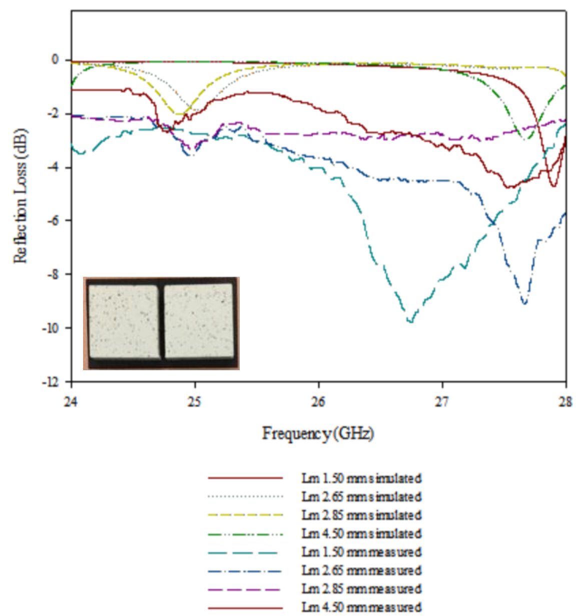


(b)

Fig. 3. (a) Simulated reflection loss and measured reflection loss of cross hybrid DRA unit cell, and (b) simulated reflection phase and measured reflection phase of cross hybrid DRA unit cell.

In order to show the advantage of the proposed cross hybrid DRA unit cell, the performance of the cross hybrid DRA unit cells is compared with similar size of full substrate unit cells which hold same DRA height and dielectric constant. This was done to confirm the function of the cross microstrip patch and the DRA in determining the resonant frequency and operating principle of the unit cell. The result comparisons are as shown in Fig. 3 and Fig. 4. The full substrate configuration is acquired by extending the cross DRA size until the walls of the PEC and PMC unit cell's waveguide setup. The tuning mechanism of the full substrate unit cell is the same as the cross hybrid DRA. To further confirm the advantages of cross hybrid DRA reflectarray elements, a set of four full substrate unit cells has also been designed and fabricated at the same frequency.



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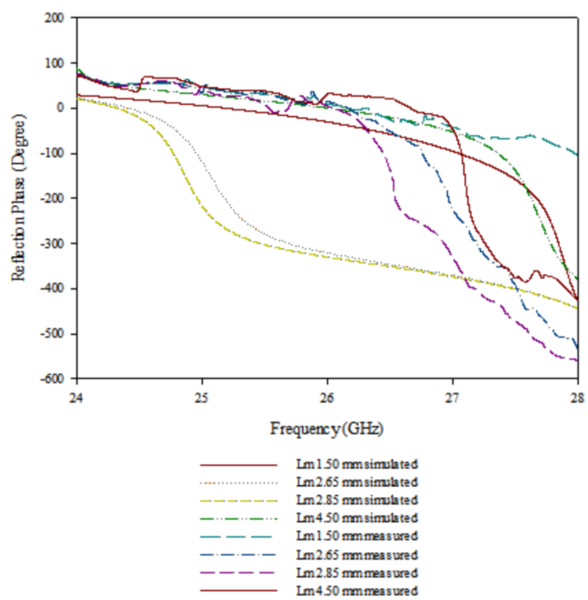


(b)

Fig. 4. (a) Simulated reflection loss and measured reflection loss of the full substrate DRA unit cell, and (b) reflection phase and measured reflection phase of the full substrate DRA unit cell.

Figure 3 (a) and Fig. 4 (a) depict the comparison between the reflection loss of the cross hybrid DRA elements and full substrate DRA elements. The hybrid DRA shows significantly lower reflection loss compared to full substrate DRA with difference of almost 5 dB between both. In term of phase range, the cross hybrid DRA produces 342° while full substrate DRA produces slightly lower range of 330°. This can be viewed in Fig. 3 (b) and Fig. 4 (b) respectively. It is proved by phase range results that cross hybrid DRA unit cell can provide wider bandwidth than full substrate unit cell. Because, the resonant frequency of cross DRA is already combined with the resonant frequency of the cross microstrip patch. Thus, higher phase range is achieved as compared to the full substrate structure. The wider phase range correlates with the enhancement of bandwidth performance of the cross hybrid DRA.

In summary, the reflection loss of cross hybrid DRA unit cells is much lower compared to full substrate DRA unit cells as shown in Fig. 5. A slightly frequency shift perceived between measured and simulated results. This may be caused by the adhesive glue used to bond the DRA and the substrate, which was not considered earlier in the simulation. The extra loss that clearly unavoidable at the measurement results is also closely related to the waveguide simulator, cable and connectors losses.

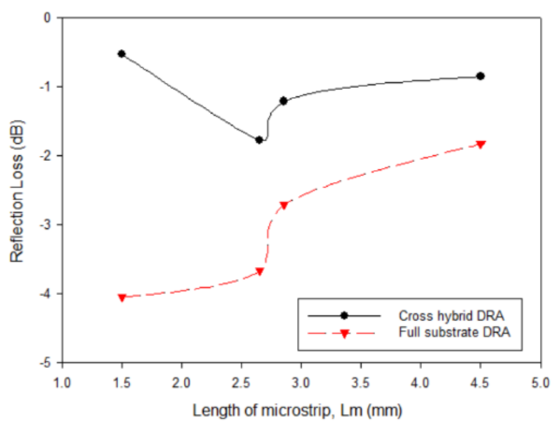


Fig. 5. Reflection loss of cross hybrid DRA unit cell and full substrate DRA unit cell at variable microstrip lengths (microstrip length as the tuning mechanism).

The bandwidth performance of the reflectarray unit element can be analyzed from the curves of the reflection loss. Figure 6 shows the reflection loss curves of cross hybrid DRA and full substrate DRA unit cells in frequency range between 24 GHz to 28 GHz. To clarify the bandwidth of the unit cell, it is determined by moving 10% above the maximum reflection loss value [22]. Table 2 tabulate the 10% bandwidth for the cross hybrid DRA and full substrate DRA. The table display the cross hybrid DRA unit cell element gives broader bandwidth of 498 MHz compared to full substrate DRA unit cell with narrower bandwidth of 122 MHz.

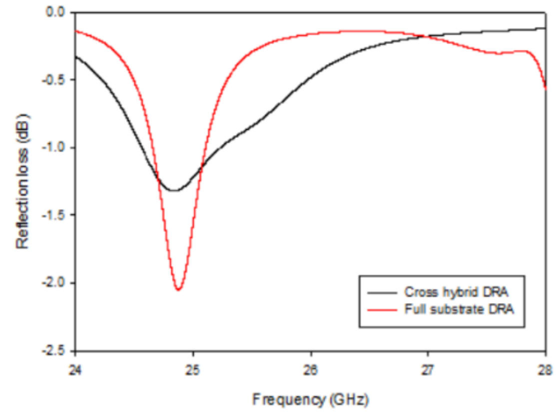


Fig. 6. Reflection loss curves of cross hybrid DRA unit cell and full substrate DRA unit cell in frequency range between 24 GHz to 28 GHz.

Table 2: 10% Bandwidth and reflection loss of unit cells

Unit Cell	***10% Bandwidth (MHz)***	***Reflection Loss (dB)***
Cross hybrid DRA	498	1.32
Full substrate DRA	122	2.05

Figure 7 shows that the phase variation curves for two different polarizations are almost identical. It proves that these unit cell elements provide dual polarization operation. It seems that, only one phase variation is illustrated in the graph, the other one being symmetric because of the symmetrical antenna design [1].

Finally, Table 3 summarized comparison between the proposed approach and previous works. The proposed cross hybrid DRA unit cell offers better bandwidth performance, reflection loss and simpler design compared with other DRA element based structures as listed in Table 3.

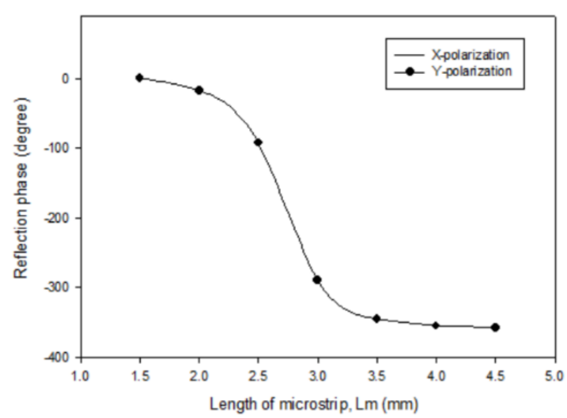
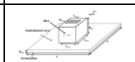
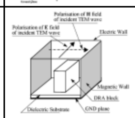
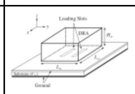
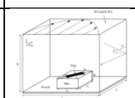
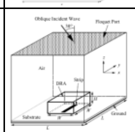
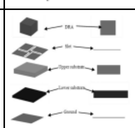
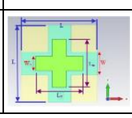


Fig. 7. Reflection phase versus microstrip length at x- and y-polarization directions of cross hybrid DRA unit cell.

Table 3: Comparison between the proposed approach and previous works

Ref.	Design	Freq. (GHz)	Unit Cell Reflection Loss (dB)	Unit Cell Phase Range (°)	Design Complexity
[9]		30	-	330	Mode-rate
[13]		30	-	360	High
[14]		7.5	Moderate	313	Low
[16]		6	Low	147	Mode-rate
[17]		6.5	High	316	Low
[18]		9.3	-	400	Low
Cross hybrid DRA		26	Low	346	Low

IV. CONCLUSION

A cross hybrid DRA unit cell with microstrip patch, which is placed underneath the DRA, aim for easy implementation and fabrication, has been proposed as a reflectarray element in order to realize the 5G requirements of wideband operation. The unit cell offers low reflection loss and a phase range of almost 360° at 26 GHz, which indicates wide bandwidth performance. The phase of each unit cell can be adjusted by varying the length of the cross microstrip. It was also demonstrated that the cross hybrid DRA structure exhibits better performance compared to the full substrate configuration. The further investigations on the use of proposed DRA unit cell element for high gain reflectarray operation is under progress.

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