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A Review of High Gain and High Efficiency Reflectarrays for 5G Communications

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ABSTRACT The future adaptability of reflectarray antenna requires a thorough investigation of its main conventional features for expected improvements. Its existing design featuring at microwave and millimeter-wave frequencies can be considered as a basic platform for further studies. In this paper, a thorough review of reflectarrays on some selected areas is presented. Its design implementations involving gain and efficiency improvement are discussed in details. Various design approaches have been critically analyzed at the unit cell and full reflectarray levels for a plausible enhancement in the featured parameters with 5G compatibility.

INDEX TERMS Reflectarrays, gain, efficiency, unit cell, microwave, millimeter wave, 5G.

I. INTRODUCTION

The high data rate precision in the order of Gbps is required for current communication systems to evolve into future 5th Generation (5G) technology. These high data rates will mainly be supported by fast switching mechanisms which are possible to achieve at short wavelengths of millimeter waves. Additionally, the enhanced bandwidth and efficiency features of antenna systems are also required to meet the high data rate requirements [1]. The stated antenna features are also attainable at mm-wave frequencies. Considering the importance of mm-waves [2], recently in World Radiocommunication Conference (WRC-15) 5G frequency bands were allocated on a primary basis for possible future developments [3]. Various frequency bands between the frequencies of 24.25 GHz and 86 GHz were proposed for 5G communication systems. However the plausible operation of 5G at lower frequencies was also not completely neglected. The main challenge associated with mm-wave propagation is its short communication distance with high path loss [4]. A suitably selected 5G antenna can overcome these propagation issues related with mm-waves. The two dimensional array antennas with large electrical apertures and narrow beamwidths are good candidates for 5G operation [4]. The large electrical apertures just marginally affect the physical profile of the antenna due to short wavelengths of mm-waves.

As depicted in Figure 1, the main architecture of reflectarray antenna consists of an array of radiating elements on a flat surface to reflect the incident signals coming from a properly distant feed [5]. Plane and light weighted reflectarray antenna can perform the reflection of the incident signals like a parabolic reflector with additional feature of beam scanning. Unlike phased arrays, the beam scanning reflectarrays can work without the aid of any phase shifter or power divider [6]. The bulky and curvy design of parabolic antenna is not a good candidate for high frequency applications [5]. On the other hand, a reflectarray antenna can readily be designed at frequencies ranging from Microwave [7], [8] to Terahertz [9]–[11]. The adaptability of reflectarray to high frequencies makes it suitable for high gain and high bandwidth operation. The design procedures of reflectarray play an important role in its performance improvement [5]. In relation to its design architecture a reflectarray antenna can offer different expected outputs, such as a narrow reflecting element is good for wide phase range, but at the cost of high loss performance [12], [13]. The basic architecture of a microstrip reflectarray antenna with square patches is shown in Figure 1.

The reflectarray antenna can be analyzed by a full wave technique [14] considering its resonant element as a unit cell, as depicted in Figure 1. The mutual coupling effect of

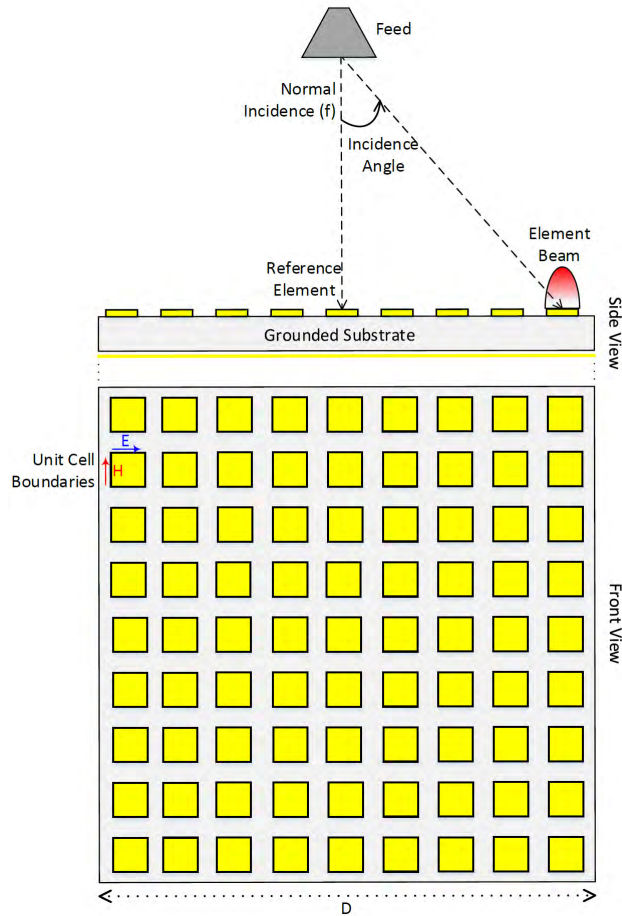


FIGURE 1. Basic architecture of a microstrip reflectarray with a prime feed.

surrounding elements [15], [16] can be taken into account by putting proper boundary conditions. The main performance parameters of the unit cell element are its reflection loss, reflection phase and beamwidth [5]. The bandwidth of a reflectarray depends on its reflection loss and reflection phase performance. Alternatively, its gain can be handled by its size which is governed by the beamwidth of the unit cell elements. As shown in Figure 1, a wide beamwidth is required by a corner element of reflectarray to properly accumulate the incident signals from a distant feed. A progressive change in the reflection phase on a reflectarray occurs as the distance increases between a selected and the reference element with normal incidence. Therefore a proper progressive phase distribution is required for each element on a reflectarray to acquire high gain performance in a required direction [17]. These reflection phase variations can be achieved by elements with variable size [18], elements with variable rotation angle [19], the length of the stub attached to the elements [20] and by same size elements with variable slots [21]. The distance of the feed (f) from reflectarray defines the angle of incidence it carries to an element. The proper accumulation of corner elements can be ensured with a large feed distance, but it also increases the antenna profile and produces spillover

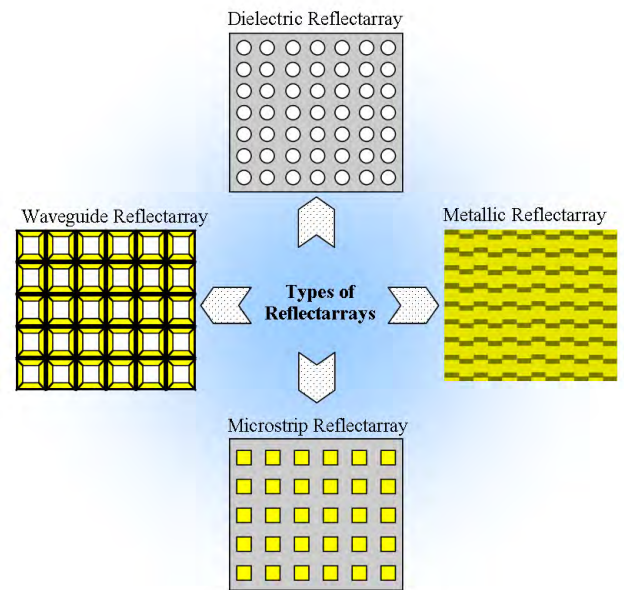


FIGURE 2. Different reflectarray configurations.

losses. The f/D ratio defines the feed distance where D is the longest dimension of reflectarray. The offset feed technique [22] in reflectarrays can be selected to avoid the feed shadow created due to a center feed.

A. REFLECTARRAY STRUCTURES

The nature and the type of the elements of a reflectarray antenna also defines its performance characteristics based on its classification. The response of the reflectarray antenna mainly depends on the type of material used to develop its resonant elements. Figure 2 classifies four different types of commonly used reflectarray antennas for performance improvement. A dielectric reflectarray is used to remove the conductor losses from its resonant behavior [23]. Its most common type is Dielectric Resonator Antenna (DRA) reflectarray [24], [25]. The same tactic can be applied to create a full conductor based reflectarray [26]. It can improve the gain performance by eliminating the dielectric loss effects, especially at millimeter wave frequencies [27].

Another type of metallic reflectarray is the variable depth waveguide reflectarray [28]. Its progressive phase distribution is associated with the lengths of its waveguide elements [29]. The most common type of a reflectarray is microstrip reflectarray [30]. It provides the best variety of design diversity by combining the conducting and dielectric features together. Electronic beamsteering is the main advantage this type holds over other types. The pros and cons of each type associated with the gain and efficiency improvement will be discussed later in coming sections.

B. ANTENNAS IN 5G COMMUNICATIONS

The main candidates for 5G communications are massive MIMO systems due to their possible integrity with small

cells [1], [4], [31], [32]. However, their design complexity and less adaptability with shorter wavelengths restrict them to attain the level of array antennas. Some types of antennas have already been recommended in [33]–[38] for 5G operation. However, enhancing only the bandwidth of proposed antenna does not solve all issues regarding 5G compatibility [39]. Some other important parameters like gain, efficiency, polarization diversity and adaptive beamsteering also require significant improvements [4], [40]–[42].

An improved gain performance can ensure the strong transmission capabilities for antenna [40]. In the case of 5G when antenna systems are required to work at mm-waves, their communication distances significantly decrease due to short wavelengths. In this case a high gain antenna can radically improve the path loss performance [33], [43] without disturbing its original power consumption. A high aperture efficiency of antenna systems ensures the best utilization of maximum gain value for the reduction of path loss [41]. On the other hand, data rate can also be increased by enhancing the spectral efficiency of antenna systems [1].

The nearest possible competitor of reflectarray antenna for 5G is phased array antenna. However, the main problem associated with phased array is its efficiency lacking at millimeter wave frequencies due to its additional loss performance [44]. Moreover, its design complexity and power consumption are also major issues at millimeter wave frequencies. On the other hand, the discussed antenna parameters for possible 5G application are inevitable with reflectarray antenna. Its bandwidth is a function of its unit cell design and substrate thickness [45]. Its gain can be improved by increasing its physical aperture to produce sharp beams [5]. Its efficiency depends on its loss performance and feeding mechanism used for the operation. Different design configuration of patch elements can be utilized for various polarization combinations. The adaptive beamsteering can be achieved by dynamically tuning its reflection phase response [46].

A vast variety of works can be found in the literature for the improvement of each parameter needed for 5G compatible reflectarray. A detailed review about the broadband features of the reflectarray antenna for 5G communications has already been presented in [47]. It has been mentioned in this article that, the bandwidth of a reflectarray can be improved by creating extra resonances in the same structure. It can be done by designing multi-resonance or dual band designs. A fractal element is the best example for multi-resonance design while it can also be done by the combination of two or more elements on a same surface. Design complexity increases with the frequency while mutual coupling could also be an issue for combination of elements. On the other hand, dual band designs can also be constructed on dual layers, representing their separate resonances. However, the attachment of two layers is a difficult task to perform at shorter wavelengths. A rather easy way to increase the bandwidth of a reflectarray is by increasing its reflection phase range by putting an extra phase tuning stub to its elements. But if not handled properly, the extra tuning stubs

can produce leakage currents which can alter the polarization of the reflected signal. The detailed information regarding each bandwidth enhancement technique, their possible issues and solutions to counter those issues can be found in [47].

In this work, the emphasis has been given specially on the design configuration needed for reflectarray gain and efficiency enhancement. Some selected works at microwave and millimeter wave frequencies have been taken into account for the detailed analysis. The analysis of design techniques has been categorized in the unit cell and full reflectarray designs. Section II comprises high gain approaches in reflectarrays by explaining the importance of different design mechanisms for its performance improvement. Section III contains the information regarding techniques for high efficiency reflectarrays.

II. HIGH GAIN REFLECTARRAY DESIGN TECHNIQUES

Along with bandwidth, the gain of a reflectarray antenna is also an important factor when a higher data rate with large throughput for wider coverage area is required. The reflectarray is a directional antenna therefore, its gain in a particular direction is normally higher than an ideal isotropic radiator. Its gain depends on its aperture size, a large aperture size is essential for high gain applications. A two dimensional reflectarray with a pencil beam acquires higher gain than a linear reflectarray with fan beam patterns. The spillover and ohmic losses are the main contributors for the degradation of the gain performance. Spillover losses depend on the electric aperture of reflectarray along with the position and the type of the feed used, while the ohmic losses are generated due to the dissipation of energy within the material used in its fabrication. Other factors like element type, element features and its position can also affect the gain of the reflectarray. Element gain and its beamwidth play an important role in gain enhancement. It is highly necessary to have high gain and narrow beam elements in the middle of the array while wide beam elements at the corners for high gain reflectarray. It is because the middle elements can easily accumulate the incoming feed signals due to normal incidence which is not possible for corner elements. However, this may increase the design complexity of the reflectarray antenna. A low side lobe level with negligible level of cross polarization is also essential for high gain value [5]. The gain and efficiency of reflectarray are correlated to each other however in this section the main emphasis has been given to the gain enhancement techniques and approaches regarding efficiency enhancement will be discussed later in the next section.

The very common and simple approach to increase the gain of a reflectarray antenna is to increase its aperture size. A large two dimensional aperture can achieve high gain values due to a pointed pencil beam [15]. However a large physical aperture can degrade the performance of the reflectarray antenna in a way that the signals coming from feed may not coincide with the edge elements. This effect has been explained in Figure 3(a) where feed signal is not reaching the edge elements and reducing the electrical aperture of the reflectarray by causing illumination losses. Increasing

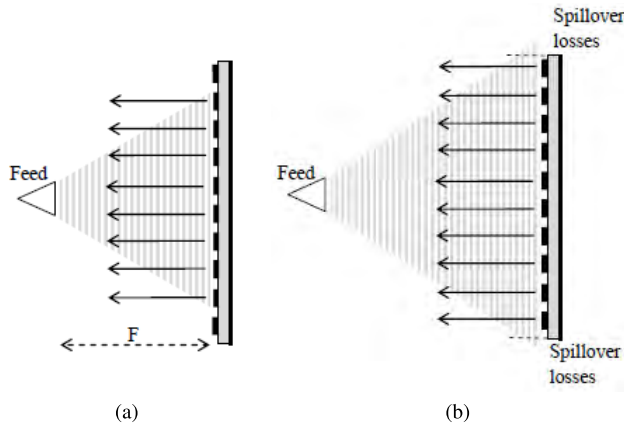


FIGURE 3. Reflectarray antenna with (a) electrical aperture less than its physical aperture (b) spillover losses.

the f distance of the feed can somehow eliminate this issue, but a large f distance also has its own consequences. Another issue depicted in Figure 3(b) where feed signals are exceeding the physical aperture of reflectarray and generating the spillover losses due to the diffracted waves from the edges [5]. The signals coming from the feed are not fully utilized due to the spillover losses. This shows that the illumination and spillover losses are complementary to one another. The beamwidth of the feed antenna can be properly adjusted to control the illumination and spillover losses. Additionally, these losses can also be controlled and gain can be improved by an additional sub-reflector with reflectarray [48]. The sub-reflector can be properly designed to reflect the signals from a feed to exactly pointing them to the aperture of the main reflectarray. This tactic eliminates the drawback of positioning the feed at larger distances from reflectarray to accumulate the physical aperture. However the designing efforts can be doubled with increment in the complexity and cost of the system. Another way to increase the gain of the reflectarray antenna is to decrease its ohmic losses contributed by the conductor and dielectric materials. This can be done at the unit cell level where the reflection loss can be optimized by various design parameters [49]–[51]. However, low loss and wide bandwidth unit cells can contribute to large phase errors [18], [52], making it difficult to get low side lobe levels for high gain performance. Some advanced techniques have been discussed in following sections based on the unit cell and full reflectarray level for gain enhancement.

The aforementioned basic gain enhancement approaches for reflectarray can further be evolved into various advanced techniques for a single unit cell or a full reflectarray. The gain of a full reflectarray can be governed by giving the emphasis on its unit cell design parameters. The type of its patch elements, dielectric material and its scattering parameters can drastically affect the performance of a full reflectarray. Additionally, a high gain full reflectarray can also be analyzed by its profile, type (full metal, full dielectric or conventional) and feeding mechanism. Various tactics involving the

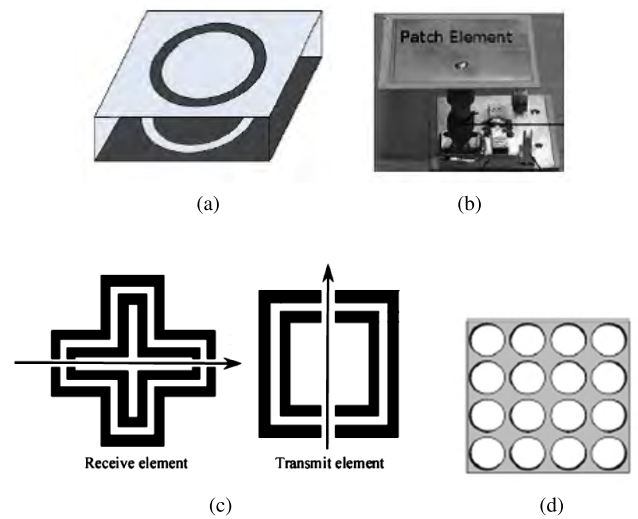


FIGURE 4. Reflectarray unit cell elements for high gain operation (a) ring element with slot on ground plane [17] (b) amplitude and phase controlled element [53] (c) dual band elements [54] (d) air holes with grounded substrate [23].

advancement of reflectarray at a unit cell or a full reflectarray level have been discussed in coming sections.

A. DIFFERENT ELEMENTS WITH HIGH GAIN REFLECTARRAY OPERATION

The design of a unit cell reflectarray element plays an important role when it comes to the performance improvement. A notable work based on unit cell with a slot in ground plane was presented in [17] for the performance improvement of reflectarray antenna. A ring element was used with a same type of slot in the ground plane as shown in Figure 4(a). The ground slot was used to modify the surface currents and electric fields of the unit cell, due to this modification a higher bandwidth was offered as compared to the unit cell without ground slot. Additionally, the leaky waves generated from the ground slot were also essential to produce a higher gain. A gain of 33.4 dB was obtained at 22 GHz by combining 1056 such elements together on a 24×23 cm reflectarray surface. The ground slot was also responsible for producing a 4 dB higher back radiations than a conventional reflectarray without ground slot. The back radiations were generated due to the discontinuity of the ground plane.

In another proposed work, the amplitude and reflection phase of the unit cell reflectarray element was electronically controlled [53] to achieve desirable results. The task was performed by an impedance transform unit which was governed by an electronic circuit consisting a varactor diode. The circuit was connected to the square patch element through a coaxial probe as shown in Figure 4(b). Bias voltage was applied to the circuit to modify the reflection parameters of the unit cell patch element by transforming its impedance. The proposed technique is useful for the designing of a full reflectarray with a desirable gain without the need of the variable size patches. The complexity of the unit cell and its

transformation to a full reflectarray is the main issue while working on high frequencies.

The gain enhancement strategy can also be performed on single layer dual band reflectarray antenna with two different types of patches. A similar work was proposed in [54] where two different open loop elements were selected for transmit (13.7–14.5 GHz) and receive (11.4–12.8 GHz) operation in different bands. Double square open loop and double cross open loop for transmit and receive signals respectively, were differentiated by two different polarizations as depicted in Figure 4(c). The gain of 40.6 dB was obtained with a 120×120 cm reflectarray constructed with both elements. This approach shows that, in order to achieve a high gain value with dual band operation a large physical aperture of reflectarray is required. The large size of the reflectarray is due to the compensation of dual frequency operation on a single surface.

The ohmic losses of the reflectarray can be reduced and its gain can be increased by removing the metallic patches with drilled holes [23]. The proposed work shows the circular holes were drilled in the substrate to make it non-homogeneous grounded substrate. The unit cell with drilled holes has been shown in Figure 4(d) where the size of the holes was varied to form a full reflectarray. 2929 such unit cells were combined together to construct the reflectarray antenna for 34.7 dB gain at 30 GHz. This design is suitable to be used at higher frequencies, but drilling the holes in the thin substrate could make it difficult for the micro-level fabrication. However, the number of air holes per unit cell can be reduced by optimizing their performance at different frequencies.

B. FULL REFLECTARRAY BASED TECHNIQUES

The gain of reflectarray antenna is actually governed and analyzed by the operation of a full reflectarray antenna. The combine effects of patch elements, substrate, feeding strategy and type of reflectarray can significantly control its gain behavior. The effects of unit cell patch element on the gain performance of reflectarray have already been discussed in the previous section. A similar tactic was adopted in [55] where the gain of a reflectarray was improved by combining the effects of different elements on a same surface. The reflectarray has been shown in Figure 5, where a square patch (SP) was used together with a square ring (SR) and ring loaded patch (RLP) at 15 GHz. Through this configuration the gain was improved up to 29.1 dBi, which was 1.9 dB higher than the conventional RLP reflectarray. Additionally, the side lobe level was also improved by 3.8 dB as compared to RLP reflectarray. The properties of the substrate material also have an impact on gain performance. In a notable work [56] a substrate material named Benzocyclobutene (BCB) was used for the performance improvement of reflectarray antenna. The selected material had low dielectric losses with strong stability at higher frequencies. A 21×21 reflectarray of square patched was tested with proposed substrate material at 60 GHz for a 29 dB gain. This work shows that, the optimized

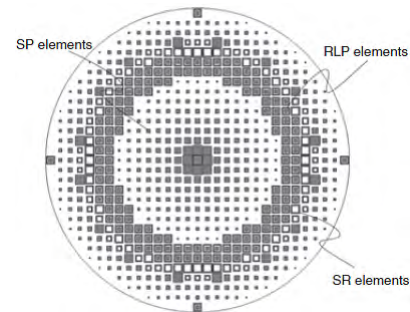


FIGURE 5. Reflectarray with combination of three types of elements [55].

dielectric losses can significantly improve the gain performance at higher frequencies while sticking with least number of elements. The other aforementioned parameters of gain improvement in reflectarrays are discussed separately below for the clarification of each concept.

1) REFLECTARRAY WITH A SUB-REFLECTOR

As earlier explained before the sub-reflector with a main reflectarray is used mainly to compensate the losses generated from conventional feed horn antenna during the illumination. These losses have an immense impact on the gain performance of the reflectarray antenna while controlling its cross polarization and side lobe level performances. A dual reflectarray antenna was recommended in [48] for the stated advantages where one reflectarray served as a sub-reflector for the other main reflector. The design architecture of the proposed reflectarray antenna has been shown in Figure 6(a). Figure 6(a) depicts that, both reflectors were placed in near-field to each other by eliminating the effects of far-field of sub-reflector. Conventional square patches were used for the fabrication of both reflectarrays. The sub-reflector was designed on a dual layer substrate while the main reflectarray was placed on a single substrate. The dimensions of the patches of both reflectors were carefully optimized for the reduction of the cross polarization level, which was reduced up to -37.12 dB level. An almost same reduction in the side lobe level was also observed and a maximum gain of 35.18 dBi was achieved at 15 GHz.

The advancement of the sub-reflector concept can be stretched for the higher frequencies. In a similar scenario a parabolic antenna was fed by a reflectarray sub-reflector at 94 GHz [57] as depicted in Figure 6(b). The main purpose of this task was to improve the gain performance of the parabolic reflector with a tilted beam. The high gain antenna pattern was tilted 5° by controlling the progressive phase distribution of reflectarray sub-reflector. A very thin quartz wafer was used to construct the 28×28 element reflectarray with conventional square patches. A maximum gain of 37.44 dBi was achieved, which shows the feasibility of using parabolic reflectors at higher frequencies with a reflectarray sub-reflector. However, at such a high frequency a small error in the reflection phase of sub-reflector can considerably affect the gain performance of the main reflector.

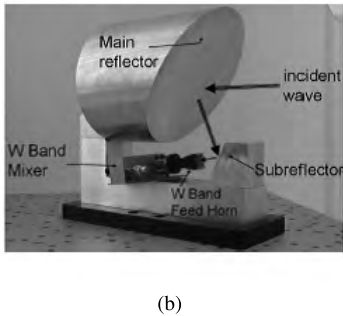
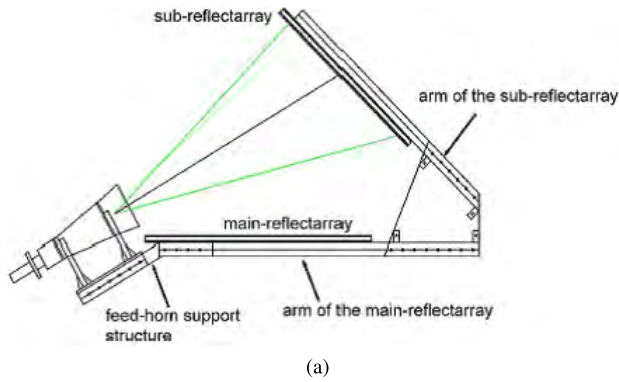


FIGURE 6. (a) Reflectarray antenna with a reflectarray sub-reflector [48] (b) reflectarray sub-reflector for a parabolic reflector [57].

2) FEEDING MECHANISM

The effect of feed movement has been already analyzed for bandwidth improvement. The same technique was also used for the optimization of the gain performance of reflectarrays [58]. A unit cell with three rectangular loops was proposed for the construction of a full reflectarray. Three feed positions of 33 cm, 40 cm and 47 cm were selected for the examination of the reflectarray performance. It was observed at a frequency of 15 GHz that, as the feed moved from 33 cm to 47 cm the gain performance was improved from 26.8 dBi to 33.2 dBi. But the same effect was reversed for a lesser frequency of 10 GHz where gain was reduced from 31.6 dBi to 26.7 dBi for the selected increment in the feed distance. The reflectarray was actually designed at 10 GHz and the shifting in frequency was caused by the feed movement. Therefore an increasing feed position was also increasing the operating frequency with gain increment, in the same way lower frequencies were facing gain degradation.

The gain enhancement requires a significant increase in the aperture area of reflectarray with a large focal length of feed. These two limitations of the high gain reflectarray antenna were significantly reduced by a technique defined in [59]. The directional feed was replaced with an Omni-directional dipole antenna feed by reducing the f/D ratio up to 0.3λ without compromising on reflectarray performance. The schematic of the design has been shown in Figure 7 where a direct wave from dipole feed was combined with the reflected wave to increase the gain performance of reflectarray. The reflectarray was made of variable size rectangular patches, operating

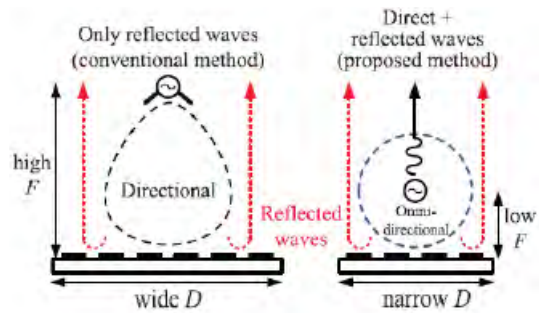


FIGURE 7. The conventional method of feeding and the proposed method with high gain performance [59].

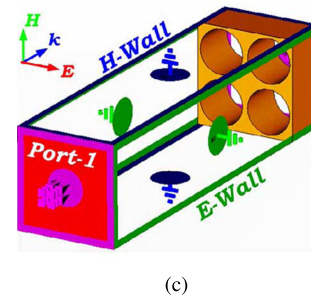
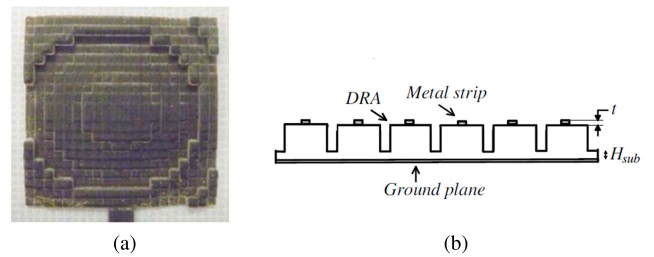


FIGURE 8. Dielectric reflectarrays (a) variable height dielectric reflectarray [60] (b) DRA reflectarray [24] (c) Discrete dielectric reflectarray unit cell [61].

at 1.84 GHz. The measured gain of 11.2 dBi was achieved through this approach which was 3.38 dBi higher than the predicted gain of the reference reflectarray antenna.

3) TYPE OF REFLECTARRAY

The gain of a reflectarray can also be optimized based on its type. In this sub-section some types of reflectarray antenna other than the conventional microstrip reflectarray have been discussed for the gain enhancement purpose. Dielectric reflectarrays and metallic reflectarrays are two common types that are mostly used for the gain enhancement purposes at higher frequencies. These both types possess three dimensional structure and require immense accuracy for the fabrication.

A dielectric reflectarray with a metallic ground was proposed in [60] for 100 GHz high gain operation. The progressive phase was obtained by the variable height of the dielectric surface as depicted in Figure 8(a). A high precision 3D technology was used to perform this task. A gain of 24.7 dB was achieved with 20×20 elements. A dielectric

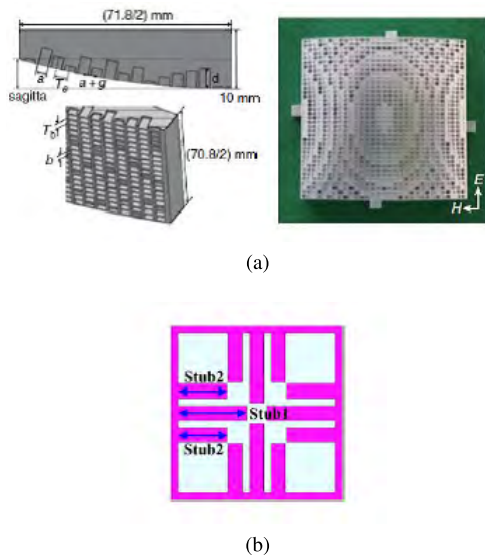


FIGURE 9. Metallic reflectarrays (a) Metallic grooves reflectarray [62] (b) unified slot element for metal only reflectarray [26].

resonator antenna (DRA) reflectarray was also reported in [24] for high gain millimeter wave operation. The DRA reflectarray has been shown in Figure 8(b) where a narrow metallic strip was used on the top of DRA to control the reflection phase of reflectarray. This reflectarray offered a 28.3 dBi gain at 31 GHz frequency. A discrete dielectric reflectarray [61] was also recommended for E-band frequency operation. It was a perforated surface reflectarray antenna with drilled air holes of different radii to control the reflection phase as shown in Figure 8(c). 40×40 such elements were combined together to form a full reflectarray with 32 dB gain. The main problem with dielectric reflectarrays is their limited efficiency performance due to lack of the conducting material in resonant structure.

A metallic reflectarray with planted grooves in a curved platform [62] as shown in Figure 9(a) was also proposed for high gain and high frequency operation. The absence of dielectric material in the proposed design eliminates the chances of high dielectric loss which is essential for high gain performance. This reflectarray achieved a maximum gain of 32.4 dBi at 95 GHz. However, its miniaturized design with curved surface makes it difficult to be fabricated for high frequencies. Another type of metallic reflectarray was proposed in [26] with unified slot elements operating at 12.5 GHz. The slots were deposited in a square patch element to make a unit cell as shown in Figure 9(b). 1380 such elements were used to form a circular aperture reflectarray with a ground plane separated by an air gap. The measured gain of the proposed reflectarray was 32.5 dB. The metallic reflectarrays offer good gain performance with negligible dielectric losses, but their design complexity for fabrication is much higher than their counterparts.

TABLE 1. Summary of the main gain enhancement approaches (Symbols refer as H=High, N=Neutral and L=Low).

Parameters	Gain enhancement by				
	Sub-reflector	Feeding tactic	Type		
			Microstrip	Dielectric	Metallic
Gain	H	N	N	H	H
Loss	N	N	N	L	L
Complexity	H	L	L	H	H
High frequency compatibility	L	N	L	H	H

C. CRITICAL ANALYSIS

Each of the ways of improving gain performance of reflectarray antenna that has been discussed in this section, can also significantly affect some other reflectarray parameters. Table 1 summarizes the performance of all major techniques used for the gain enhancement in reflectarrays. The gain enhancement performance of sub-reflector method is quite impressive due to the diminution of the phase errors. The reduced phase errors make it a potential way to achieve high gain with less side lobe level and low cross polarization. The reflection loss of this technique totally depends on the architecture of main and sub reflectors. The suitable selection of the patches and substrate material is important for less loss performance. However, due to the involvement of dual reflectors this technique is quite complex in terms of designing implementation. This also makes it less compatible for higher frequencies which are required for 5G operation. The gain of reflectarray antenna can be well improved by the selection of its feeding mechanism with less design complexity. The position and type of the feed are important when expecting an improved gain performance. However, the dependency of resonant frequency on the feed mechanism can entirely change the desirable output of the reflectarray. The gain performance of three different types of reflectarrays has also been discussed in details. The gain and loss performance of a conventional microstrip reflectarray antenna totally depends on its design parameters. On the other hand, due to the availability of various design approaches for its performance improvement, it offers less complexity for designing which is essential for high frequency operation. However, at high frequencies the conventional methods are less reliable to attain best performances. Dielectric and metallic reflectarrays on the other hand, are handy at higher frequencies, but at the cost of high design complexity. A special mechanism is required to fabricate the dielectric or metallic reflectarrays. The absence or reduction of conducting material in dielectric reflectarrays and dielectric material in metallic reflectarrays makes them suitable for optimized loss performance. The miniaturized designs of dielectric and metallic reflectarrays could become good candidates for future 5G communication if their design complexity is somehow reduced.

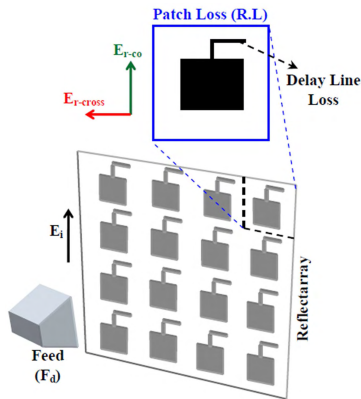


FIGURE 10. Representation of the sources of losses for a reflectarray antenna.

III. TECHNIQUES FOR HIGH EFFICIENCY REFLECTARRAYS

The efficiency of reflectarray antenna is directly related to the difference between its directivity and gain performance. This difference is actually called the overall loss of the reflectarray antenna. The total efficiency of reflectarray accounts all the losses of the system, including spillover loss, illumination loss, patch loss, delay line loss (if attached), feed loss and cross-pol loss [6]. The aperture efficiency accumulates illumination and spillover losses as it is shown earlier in Figure 3. These losses are related to the aperture size of the antenna and governed by a proper f/D ratio. The aperture efficiency is in direct proportion with the aperture size of the reflectarray when a proper feed position is selected. But a large aperture size can limit the performance of the reflectarray antenna by introducing large phase delays to the corner elements with slight change in frequency. The remaining sources of losses have been highlighted in Figure 10 where \vec{E}_i is the direction of the incident electric field from the feed. The feed loss (F_d) is associated with the feed of the reflectarray antenna. The patch loss or reflection loss ($R.L$) is the summation of conductor and dielectric losses of the patch element. The cross-pol loss is related with $\vec{E}_{r-cross}$ component of the reflected field, which is normally lower in magnitude than the \vec{E}_{r-co} component. The delay line and feed losses are mostly neglected, however patch and cross-pol losses are related to the performance of reflectarray unit cell element. Patch loss is the reflection loss of the element and cross-pol loss can occur due to dissimilarity or asymmetry in the design of the unit cell element. The efficiency of reflectarray antenna is largely affected by its phase error and cross polarization performance [5], [22]. The reduction in the phase errors is linked with higher efficiency performance with low side lobe levels while the unwanted reflections from reflectarray surface can be minimized by controlling its cross polarization level. These factors can significantly increase the efficiency of reflectarray. The high efficiency reflectarrays can be analyzed with various types of unit cell elements or by different techniques implemented to its full structure. The reflection phase range of unit cell element can be increased to reduce the phase errors and hence increase the efficiency. On the











other hand, a full reflectarray antenna can be set to reduce its cross polarization level by optimizing its design mechanism in various ways.

A. DIFFERENT ELEMENTS WITH HIGH EFFICIENCY REFLECTARRAY OPERATION

The progressive phase distribution of the unit cell element of a reflectarray antenna is responsible for the optimized gain and efficiency performance. Some resonant elements have inability to acquire a full 360° phase swing, which increases the amount of phase errors while designing a full reflectarray antenna. An enhanced phase range performance is responsible for an efficient operation of reflectarray antenna. In this section, various unit cell elements with wide phase range have been discussed which are used with high efficiency reflectarray operation.

Various elements used with high efficiency reflectarrays are summarized in Table 2. In each element a different technique was used to perform the phase enhancement strategy. It can be seen from Table 2 that, the wide phase range is also a reason behind the good efficiency ($\geq 50\%$) of a reflectarray antenna. The main reasons behind the high efficiency of the mentioned designs, which are the aperture size and f/D ratio are also summarized in Table 2. All listed reflectarray designs were fed by horn antennas except the reflectarray containing Fractal elements [63], which used a low gain rectangular waveguide. This is the reason behind its very low f/D ratio that was used to accumulate its whole aperture with a wide beam feed. As mentioned earlier, the aperture size and feed type can affect the aperture efficiency of reflectarray. However, in order to analyze the total efficiency a thorough investigation to its unit cell element is also required. The Hexagonal element with crossed slots [64] was selected for a full 360° reflection phase swing with variation in its dimensions. The slop of the reflection phase was controlled by the separation between the crossed slots. The wideband Bowtie element [65] had the ability to be used for dual circular polarization with high efficiency. The counter-clockwise rotation of this element was used to get the progressive phase distribution. In a different scenario, two concentric open rings were used with an I-shaped element [66] for the same purpose. Its reflection phase was controlled by varying the distance between the open rings while the width of I-shaped element was also optimized for a better phase performance. The combination of two or more elements can also be utilized for the efficiency improvement of reflectarrays as reported in [67] and [68]. In [67] a circular ring was used with a concentric square ring and the dimensions of both structures were varied for the removal of phase errors. In the second design [68], three parallel dipole elements were used as a single unit cell, and their lengths were varied to get an optimized reflection phase range performance with high efficiency. The efficiency of reflectarray antenna can be improved even without achieving a full 360° reflection phase swing. It can be seen from [69] and [70] where a slotted hollow ring element and a fragmented element were

TABLE 2. Selected elements with high efficiency reflectarray antenna operation.

Element shape	Design	Frequency (GHz)	Phase swing (°)	Aperture Size (λ^2)	f/D	Efficiency (%)
Hexagonal [63]		12.5	360	69.4	1	60
Bow-tie [64]		30	360	39	0.59	57
I-shaped [65]		13	360	75.7	2.35	50
Dual rings [66]		16	360	250	0.9	52.36
parallel dipoles [67]		9.5	360	180	0.83	65
Hollow ring [68]		12	333	3318	0.7	66.13
Fragmented [69]		11.2	300	245.5	1.1	65.5
Fractal [70]		10	700	54.5	0.33	66
Concentric rings [71]		13.5	500	207.6	0.75	66
Dual band [72]		20/30	360/300	784/1765	0.618	66.5/50

exploited for the efficiency enhancement. The slotted hollow ring element had a reflection phase range of 333° and it was achieved by its different angular rotations. The overall dimensions of the elements remained same over the surface of the fabricated reflectarray due to the angular rotation. This tactic was used to reduce the cross polarization level with high efficiency performance. On the other hand, a single reflection phase value was possible to obtain with many different shapes of the fragmented element [70]. Through this method the variations in the shape of the fragmented element were minimized over the surface of the reflectarray with improved efficiency performance even with a reflection phase range of 300° . The efficiency enhancement can also be performed with multi-resonant elements like Fractal element [63] and Concentric square rings [71], as mentioned in Table 2. The Fractal shape was used to obtain a 700° reflection phase range, which was enough to reduce the phase errors and improve the efficiency up to 66%. The three concentric square rings also offered the same amount of efficiency with a 500° phase range. The dual band elements such as proposed in [72] can also perform efficiency enhancement at two different frequencies by enhancing their respective phase ranges. The dual band element shown in Table 2 was used to operate at 20 GHz and 30 GHz with 360° and 300° of reflection phase range respectively. The modified Malta cross element was used with a surrounded split ring element. The rotation angle of split ring was varied for the phase variations at 20 GHz, whereas the same was obtained by the variable size of the Malta cross element at 30 GHz. The optimization for

each element was performed to get a lower cross polarization for the full reflectarray. The efficiencies of 66.5% and 50% were achieved at the upper and lower band of frequencies respectively. The reduction in the efficiency at the lower band was due to the narrow reflection phase range at that frequency.

B. FULL REFLECTARRAY BASED TECHNIQUES

The unwanted cross polarization reflections of reflectarray antenna can be controlled with various approaches used by researchers. The proper arrangement of the elements on the surface of the reflectarray and its feed mechanism can be used to optimize its cross polarization and hence efficiency performance. Likewise a potential work was reported in [73] where the cross polarization of the reflectarray antenna was controlled by the proper arrangement of the elements on its surface. A circular element with two open ended phase tuning stubs was used for this purpose. The elements were arranged in such a way that each element was set by mirroring the design of its adjoining element, as shown in Figure 11(a). This approach was proposed to reduce the dissimilar reflections from the reflectarray surface and hence enhance its performance in terms of gain and efficiency. A 21×31 reflectarray was tested with the proposed configuration and significant improvement in cross polarization level was achieved compared to conventional arrangement of elements, as listed in Table 3. It can be observed from Table 3 that, the cross polarization level can be reduced from 1 dB to 12 dB in E and H planes at different frequencies. This approach was also used to enhance the gain performance by 1.3 dB as

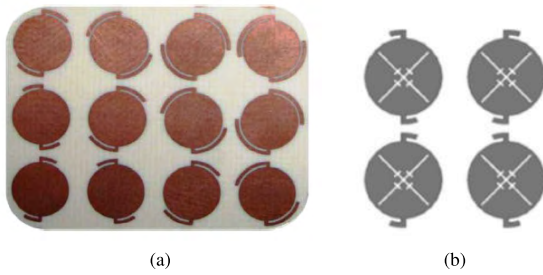


FIGURE 11. Mirroring of elements for cross-polarization reduction (a) single band design [73] (b) dual band design [74].

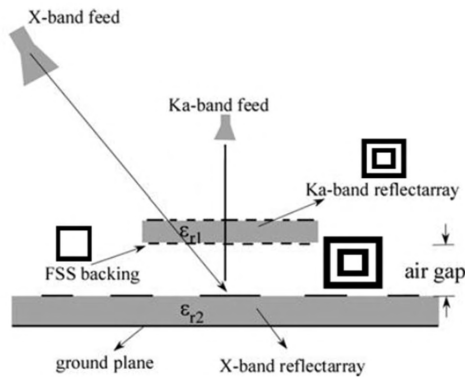


FIGURE 12. Dual layer reflectarray with Ka/X-band of operation [75].

compared to conventional design. The same approach for cross polarization reduction was also applied to a dual band design [74] where a circular element with cross slot and two phase tuning stubs was proposed for X-band and K-band operation as depicted in Figure 11(b). It offered 47% efficiency at 10.2 GHz with a cross polarization level of -25 dB. However the K-band operation at 22 GHz was less efficient (25%) due to the higher cross polarization level of -16 dB. Another dual band design for X-band and Ka-band operation with two different layers of reflectarray and dual feed was proposed in [75]. The Ka-band reflectarray placed above the X-band reflectarray separated by an air gap has been shown in Figure 12. It was shown that the FSS backed Ka-band reflectarray attained an efficiency of 42%, compared to a solid grounded X-band reflectarray which offered 60% efficiency. The FSS ground was used in the Ka-band reflectarray in order to reduce the blockage of the signals reflected from X-band reflectarray. Additionally, the FSS ground plane could also introduce some back radiations which were the main reason behind the less efficiency of Ka-band reflectarray. Some other types of reflectarrays like full conductor reflectarray [27] and Dielectric resonator reflectarray [76] were also tried to get high efficiency. Their main aim was to reduce the reflection losses for an efficient performance. The conductor cell reflectarray offered a higher efficiency of 50% as compared to a DRA reflectarray which offered 47%. Another advantage of conductor reflectarray was its millimeter wave operation at 95 GHz while DRA reflectarray was designed at a lower frequency of 12 GHz.

TABLE 3. Cross-polarization level of conventional and proposed designs in E and H-planes [73].

Frequency (GHz)	E-plane (dB)		H-plane (dB)	
	Conventional design	Proposed design	Conventional design	Proposed design
10.7	-23.5	-29	-18	-28
11.7	-17	-21	-13	-25
12.5	-19	-20	-9	-20

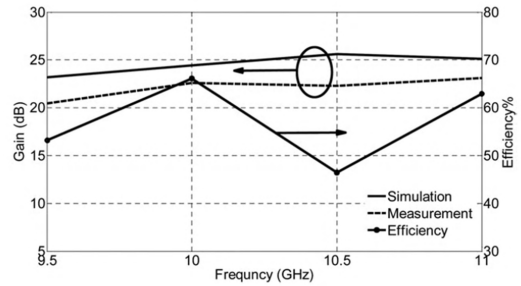


FIGURE 13. Gain and efficiency with respect to frequency of the reflectarray with $\lambda/2$ element size [63].

As it has been mentioned earlier, the feed mechanism can also affect the gain and hence the efficiency performance of reflectarray antenna. In a proposed design of a reflectarray antenna feed distance from reflectarray was varied [63] along with some other amendments to get an optimized gain and efficiency performance. The resonant patch elements were also tested with two different sizes of $\lambda/2$ and $\lambda/3$ at 10 GHz frequency. The reflection phase value of the center element with respect to a center feed was taken as a phase reference value. That phase reference value was varied between 0° , 60° and 120° with a variable f/D ratio of 0.25 to 0.5 for the investigations. As it is depicted in Figure 13, the maximum gain performance with an efficiency of 60% was obtained at an element size of $\lambda/2$ with 60° phase reference and $0.33 f/D$ ratio. The stated work actually demonstrated that, the gain and efficiency performance of a reflectarray antenna can be evaluated based on its element configuration, reflection phase and feeding mechanism.

Another useful technique regarding the feeding of a reflectarray antenna was proposed in [59] where a dipole antenna was used instead of a conventional feed horn antenna. Due to the Omni-directional characteristics of dipole antenna the f/D ratio was drastically reduced to 0.3λ at a frequency of 1.87 GHz. But this reduction in the f/D ratio also reduced the efficiency performance of the reflectarray antenna. As described in Figure 14, the efficiency of the proposed reflectarray antenna was improved by combining the reflected waves of reflectarray and radiated waves of the dipole antenna together. Through this tactic a gain of 11.2 dB was obtained with an efficiency of 52.6%. The feed distance variations can also be performed in an offset feed reflectarray antenna as reported in [58]. The feed was moved

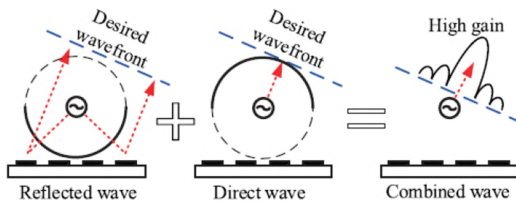


FIGURE 14. The combination of radiated and reflected waves for efficiency improvement of reflectarray [59].

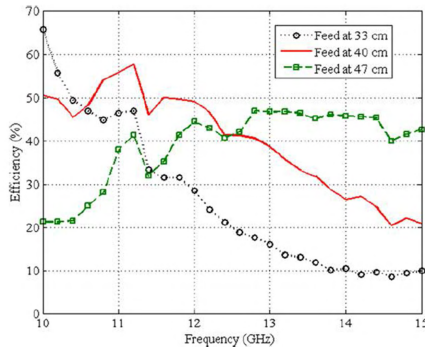


FIGURE 15. The effect of different feed positions on the efficiency of reflectarray antenna [58].

from 33 cm to 40 cm and then to 47 cm in order to observe the performance of the reflectarray antenna. It was shown that the resonant frequency of the reflectarray antenna was shifted from 10 GHz to 15 GHz with the prescribed feed movement. Figure 15 depicts the effect of feed movement on the efficiency performance of reflectarray. It can be observed that, when the feed was positioned at 33 cm from reflectarray, it attained a maximum efficiency of 65% at 10 GHz. On the other hand, a maximum 42% efficiency was achieved with a feed position of 47 cm at 15 GHz. This was because of the change in the resonant frequency of reflectarray due to the feed movement. This work shows that, while the design of reflectarray remains same, its efficiency can be optimized by changing its feed position.

C. CRITICAL ANALYSIS

The unit cell element or the whole reflectarray antenna characteristics can be taken into account for the enhancement of its efficiency performance. A unit cell can contribute through a wide phase range element for the performance improvement of the full reflectarray made of it. This task requires a lot more efforts than just a conventional design approach. Some new design approaches as mentioned in Table 2 can actively perform the task. However, some complex derivations of the resonance behavior along with its detailed analyses are required for each novel design of the unit cell element. Additionally, each design holds its own pros and cons for the performance improvement. It is an efficient but a time consuming approach which can contribute negatively to the designing of a 5G reflectarray antenna. On the other hand, controlling the characteristics of a full reflectarray antenna for the optimization of its efficiency performance is much easier to perform. Considering the analysis of a reflectarray

antenna as a whole, reduces the designing efforts and time for the performance analysis. The main disadvantage of this tactic is that, while improving one parameter of reflectarray antenna it can also marginally affect its other parameters.

IV. CONCLUSIONS

The possibility of the enhancement in the gain and efficiency features of reflectarrays has been thoroughly studied. The unit cell design of a reflectarray is the initial factor to be considered for any expected changes in its conventional parameters. The full design architecture of reflectarray is also an important factor to be analyzed for the required improvement in the stated features. Different types of reflectarrays also play their role in the performance improvement of reflectarrays at various required frequencies. Additionally, the cost effective and less complex design requires some extraordinary experimental efforts to be made. It has been concluded that, the design complexity increases with the resonant frequency of reflectarrays, which is the main issue highlighted for the 5G communications. This work sets an initial platform for further studies on the enhancement of gain and efficiency of reflectarrays. Further analysis can also be performed by considering the other important parameters of reflectarrays, such as electronic beam scanning and beam forming. The effect of each parameter over the performance of other parameters is also a crucial factor to be considered for further investigations. The future research can be made more comprehensive by including some other features like cost, material properties and power consumption related to high frequencies.

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