Polarization Diversity and Adaptive Beamsteering for 5G Reflectarrays: A Review

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ABSTRACT The growing demands of advanced future communication technologies require investigating the possible enhancement in the current features of a reflectarray antenna. Its design and experimental features need a thorough investigation before a plausible transition towards millimeter wave frequencies. This paper provides a detailed review covering various fundamental and advanced design tactics for polarization diversity and beamsteering in the reflectarray antenna. The diversity in the polarization has been discussed for linear and circular polarized designs in reflectarrays. The importance of electronically tunable materials and different lumped components for adaptive beamsteering in reflectarrays has also been highlighted. Each design has been critically analyzed and possibilities of its compatibility with future 5G systems have been provided.

INDEX TERMS Reflectarrays, unit cell, polarization, beamsteering, tunable materials, lumped components, 5G.

I. INTRODUCTION

Reflectarray consists of the array of properly spaced resonating elements on a planar surface used to reflect the incoming signals with a much higher strength [1]. The reflection towards the desired direction can be performed with the help of a suitably placed feed. The low profile reflectarray antenna can be designed with a much lesser complexity than a phased array antenna which requires electronic power dividing and phase shifting mechanism [2]. The flat and light weighted surface of the reflectarray can perform the reflection of the signals just like a parabolic reflector. However, a parabolic antenna is not a good option for high frequency operation due to its bulky design [1]. On the other hand, reflectarrays can be optimized to work from microwave [3], [4] to millimeter wave frequency ranges [5]–[7]. The performance of a reflectarray antenna at any selected frequency depends on its design characteristics. The basic design architecture of a square patch reflectarray antenna has been shown in Fig. 1. A reflectarray antenna can be properly analyzed using full

wave technique [8], by considering its single element as a unit cell with finite or infinite boundary conditions. The infinite boundary conditions of a unit cell element [9], as shown in Fig. 1, are used to accumulate the mutual coupling effects of surrounding elements [10], [11]. Another way to analyze the reflectarray antenna is to transform it into an equivalent circuit of lumped components [12]. It reduces the amount of processing time for a large reflectarray antenna.

The performance parameters of a unit cell are essential to design a full reflectarray antenna with required outputs. The frequency of operation and the output gain mainly depend on the reflection phase range of the unit cell element. Additionally, the aperture size of the reflectarray is governed by the beamwidth of its unit cell element. As depicted in Fig. 1, a wide beamwidth is required by an element of reflectarray to properly accumulate the incident signals coming from a distant feed. Moreover, each element of the reflectarray needs to be designed with proper progressive reflection phase to attain high gain performance in the direction of interest [13]. This
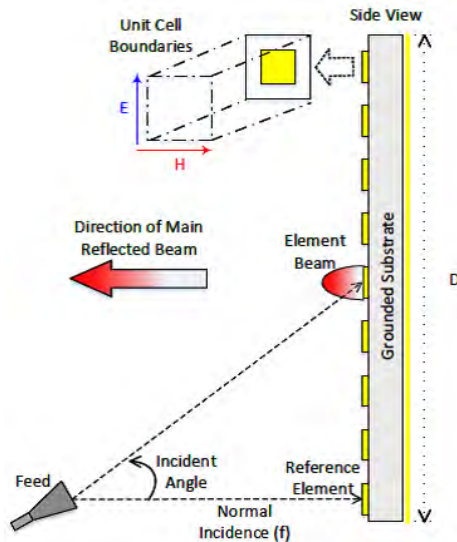
FIGURE 1. Basic design architecture of a microstrip reflectarray with an offset feed.

progressive reflection phase can be distributed over the entire reflectarray surface either by variable size elements [14], by different element rotations [15] or by adding an extra phase tuning stub to the elements [16]. The distance of the feed (f) from the reflectarray, which is normally defined in f/D ratio, is also an important factor to define the expected reflectarray performance. A large f/D ratio ensures the proper accumulation of corner elements, but at the cost of a larger antenna profile with the possibility of spillover losses.

The losses and the performance of the reflectarray antenna can also be optimized by the type of material used to design it. The most widely referred microstrip reflectarray antenna [17] contains both dielectric and conducting materials in its structure. It attains excessive material losses but with the ease of designing and optimizing. These material losses can be countered by designing either a full metallic [18], [19] or a full dielectric [20], [21] reflectarray antenna. The array of variable depth based reflecting waveguides [22], [23], is also a type of metallic reflectarray to counter the dielectric losses. The main disadvantage associated with the single material based reflectarrays is their lack of capability to attain electronic beamsteering. The dielectric reflectarray is a frequency resonant reflectarray, but it does not have any resonating metallic part to tune the surface currents for electronic beamsteering. On the other hand, a metallic reflectarray works on the principle of non-resonant reflecting structures. Therefore, in this case, a change in the frequency or phase of the reflected signal will not change its direction.

The inevitable high data rate goals of 5th Generation (5G) mobile networks require fast switching mechanism which is possible to attain at millimeter wave frequencies. A vast number of 5G frequency bands are recommended for initial considerations by the World Radiocommunication Conference (WRC-15), ranging from 24.25 GHz to 86 GHz [24]. The

actual 5G frequency bands will be finalized in the 2019 version of the same conference. The main limitations associated with the millimeter waves which need to be tackled are the path loss issue and the shorter communication distance [25].

Antenna is one of the main components in the physical layer, which requires significant improvements in its performance parameters to acquire the 5G targets [26]. The array antennas with narrow beams and high gains can be a possible solution to the issues related to millimeter waves [25]. Massive MIMO arrays are recently gaining some considerations for a possible 5G operation [25]–[27]. However, the design complexity at shorter wavelengths is always an issue with Massive MIMO. Some other wideband antennas have also been proposed for 5G operation [28]–[32]. All these 5G antennas are recommended to be used at the user end level. On the other hand, a reflectarray antenna can easily be deployed at the 5G base station due to its profile and characteristics. Apart from bandwidth the other parameters of the antenna also need considerable importance for a possible 5G compatibility. High gain and efficiency can solve the problems related to path loss at millimeter waves [28], [33]. The ability of using the same antenna for different polarizations can emulate the concept of frequency reuse in 5G. The electronic beamsteering is an important aspect for a 5G antenna to overcome the flaws of signal blockage with narrow beams [25], [34].

The main performance competitor for reflectarray antenna is the phased array antenna, which can also be recommended for 5G operation. However, its higher design complexity, higher losses and efficiency lacking at millimeter wave frequencies limit its chances for a possible 5G compatibility [35]. On the other hand, the performance parameters of a reflectarray antenna can be optimized and improved for the 5G communications. A detailed analysis regarding the techniques involving in its bandwidth enhancement for 5G communications is presented in [36]. It was stated in [36] that, the unit cell and full reflectarray design parameters are equally important for bandwidth enhancement at millimeter waves. The possibilities of the enhancement of gain and efficiency of the reflectarray antenna for 5G communications are discussed thoroughly in [37]. The effects of the losses in reflectarray and the importance of its feeding mechanism over its gain and efficiency performance were thoroughly reviewed and some possible solutions were also proposed. Therefore, now it is the need of time to analyze the remaining two important parameters of the reflectarray antenna for 5G communication systems. In this article, the emphasis has been given entirely to the design configurations needed for the polarization diversity and adaptive beamsteering for a 5G reflectarray antenna. Various designs of dual linear and dual circular polarized reflectarrays have been discussed in Section II. A concept for the polarization diversity for 5G reflectarrays has also been defined in this Section. Section III comprises some selected techniques to acquire adaptive beamsteering in reflectarrays. The importance of electronically tunable materials and lumped components in reflectarray beamsteering has been analyzed for 5G requirements. Each described

technique has also been critically analyzed and a hypothesis has been developed for 5G reflectarrays.

II. POLARIZATION DIVERSITY IN REFLECTARRAYS

The direction of the orientation of the reflected electric field from reflectarray represents its polarization. It can be divided into Horizontal Polarization (HP), Vertical Polarization (VP), Right Handed Circular Polarization (RHCP) and Left Handed Circular Polarization (LHCP). HP and VP are collectively called as Linear Polarization (LP) whereas RHCP and LHCP can be represented as Circular Polarization (CP). Some conventional patch elements, like dipoles and rectangular patches can easily be utilized for HP or VP, depending on their orientation to the incident field. On the other hand, CP can be achieved by using elements with angular rotation [38]. The CP is composed of two orthogonal components of the propagating electric field. The ratio of the larger component to the smaller one is called the axial ratio, which determines the performance of the CP [39]. A large value of axial ratio represents the eliptical polarization, whereas a small value (ideally 1) is essential for good performance with CP. The CP is widely used for satellite communications due to its robustness towards environmental losses. Some common types of elements for CP used in the literature are split rings [3], [40], rotated crossed dipoles [38], [41], aperture coupled patches [42] and circular patch [43]. In a recent work mechanical rotation technique was utilized by motors attached to loaded split rings for wide band CP operation [44]. CP can also be achieved with a linearly polarized feed by performing polarization transformation. A double layer T-shaped element [45] and a circular patch with two elliptical cross slots [46] were used to convert a linearly polarized incident wave to circular polarized reflected wave.

The polarization diversity is a state of operation when a single reflectarray can be used for more than a single polarization. By doing so, it can be used for multiple applications at the same time. Reflectarrays with dual linear polarization and dual circular polarization can be designed using various techniques. A novel approach of getting four different polarizations from a single reflectarray by the rotation of feed horn, was proposed in [47]. A single reflectarray consisting of rectangular elements with 0.3λ element spacing was used for HP, VP, RHCP and LHCP respectively. Vertical and horizontal polarizations were obtained rotating the feed position by 90° as shown in Fig. 2. The linear polarization of the feed was then set parallel to the diagonal line of the patch element. In this way the linearly polarized wave was decomposed into two orthogonal components parallel to the surface of reflectarray to generate a circularly polarized wave. As shown in Fig. 2, RHCP was obtained by rotating the feed by 45° counter clockwise to horizontal polarization and LHCP was attained by orienting the feed by 45° counter clockwise to vertical polarization. This method provided a simple way to achieve polarization diversity with a single and conventional reflectarray antenna. However, only a single polarization can be obtained at a time and two or more polarizations cannot
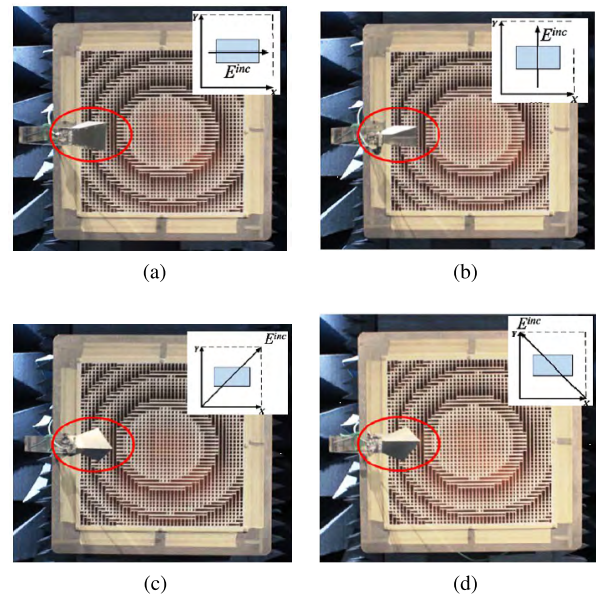

FIGURE 2. Different orientations of feed horn with same reflectarray for (a) Horizontal polarization. (b) Vertical polarization. (c) Right hand circular polarization. (d) Left hand circular polarization [47].

occur simultaneously through this tactic. Moreover, changing the orientation of the feed horn antenna can also degrade the performance of the reflectarray antenna in terms of its gain and efficiency. Various approaches utilized by many researchers to obtain dual linear or dual circular polarization simultaneously are summarized in this section. In this regard, the main emphasis has been given to the design of the unit cell element of the reflectarray antenna for polarization diversity.

A. DUAL LINEAR POLARIZED DESIGNS

The dual polarization of reflectarray antenna consisting of HP and VP requires unit cells with orthogonal identical shapes. The similarity in orthogonal direction allows them to reflect the same frequency signals with dual linear polarization. Fig. 3 depicts some of the selected elements used for dual linear polarization. Two orthogonal sets of cross dipole elements working at 11.95 GHz [48] as shown in Fig. 3(a) were placed on two different substrates respectively. The first and second layers were used to reflect the signals with VP and HP respectively. A similar strategy was also utilized in [49], where four co-planar dipoles were used instead of three to increase the reflection phase range performance. The dual layer structure was used to transmit and receive in dual linear polarization at Ku-band for satellite applications. The cross loop element [50] shown in Fig. 3(b) was also used for dual linear polarization at Ka-band frequency range. The unit cell was comprised of a solid cross surrounded by a cross loop to achieve a wide phase range performance. The unit cell shown in Fig. 3(c) consists of two orthogonal dipoles surrounded by a square metallic waveguide [51]. The unit cell was used for the orthogonal polarization at X-band frequency range. Fig. 3(d) shows, double cross loop element [52] for dual
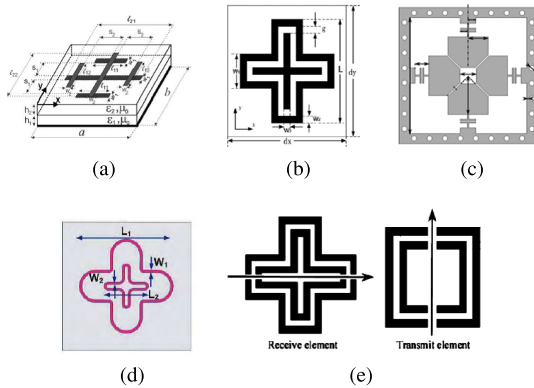
(a)   (b)   (c)

(d)   (e)

FIGURE 3. Dual linear polarized elements. (a) Crossed dipoles [48]. (b) Cross loop [50]. (c) Two orthogonal dipoles [51]. (d) Double cross loop element [52]. (e) Transmit-receive elements [53].

band operation with dual linear polarization. The outer loop was fixed to work at X-band frequency range, whereas the inner loop was set for the K-band operation. The dual band operation proposed in [53] used for two different elements to transmit and receive purpose as depicted in Fig. 3(e). Two multi-open loop elements were selected for the dual linear polarization at two different bands of frequencies. The double cross loop element with a horizontal slot was used for the receive band (11.4-12.8GHz) with HP. On the other hand, a double square loop element with a vertical slot in it was used for transmitting purposes (13.7-14.5GHz) with VP. Both elements were printed on the same surface where the incorporated slot determined the direction of the propagated E field.

The conventional rectangular and square patch elements were also suggested for dual polarization operation [54] at 13.285 GHz. Two different feeds were proposed for each orthogonal polarization with dual beam operation. This work showed that rectangular element had two degrees of freedom (length and width) for the optimization of its performance as a dual polarized reflectarray unit cell whereas square element only had one degree of freedom (length). In another notable work various types of designs of unit cell elements were used to form a dual linear polarized reflectarray [55]. Different unit cell designs were selected for every single value of the reflection phase on the surface of reflectarray. Each design had the capability to reflect the incident signals with dual linear polarization while maintaining the desired reflection phase value. A portion of the mentioned reflectarray has been shown in Fig. 4. Four different synthesized combinations of selected elements were also tested for the best possible outputs. A DRA reflectarray [56] was also suggested for dual polarization operation in X-band frequency range with a windmill slot element as shown in Fig. 5. The windmill slot had the capability to reflect the signals with dual linear polarization due to its identical orthogonal structure. Additionally, the windmill slot was also used to eliminate the phase errors from the conventional design of the DRA reflectarray.
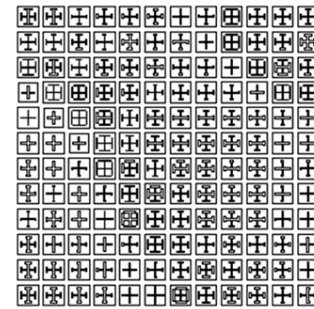

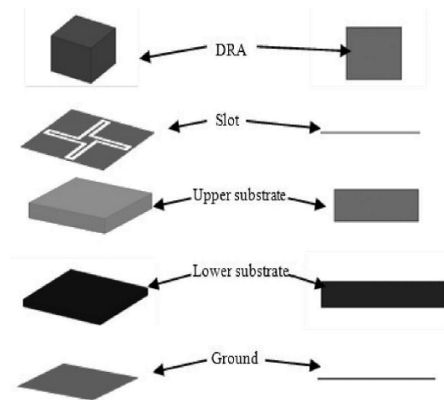**FIGURE 4.** Reflectarray with dual linear polarization consisting of various designs of unit cell elements [55].

FIGURE 5. Unit cell element of a DRA reflectarray with dual linear polarization [56].

B. DUAL CIRCULAR POLARIZED DESIGNS

Similar to the linear polarization, circular polarization also depends on the basic architecture of the unit cell element of reflectarray. The circularly identical orientation in the design of the unit cell element is required in order to reflect the circularly polarized signals. However, some other patch elements that have been discussed in this section are also tested with circular polarization for the sake of polarization diversity. In order to get RHCP and LHCP simultaneously from a single reflectarray structure some extraordinary efforts are required to be made in the design of reflectarray. A dual reflector antenna made of a reflectarray backed by a parabolic reflector was proposed in [57] for dual circular polarization in Ku-band. The design setup of the proposed architecture has been shown in Fig. 6. It was actually a polarization transformation design where the feed illuminated RHCP/LHCP, which were converted into linear polarization by a polarizer layer. Then the reflectarray was set to reflect the HP signals while allowing VP signals to pass through it and get reflected by the parabolic reflector. Then the reflected signals were again converted back to RHCP and LHCP by the polarizer layer. The polarizer was composed of a three layer structure with printed meander lines while the reflectarray implemented with rectangular patches with horizontal metallic traces on the back side. Apart from its high design
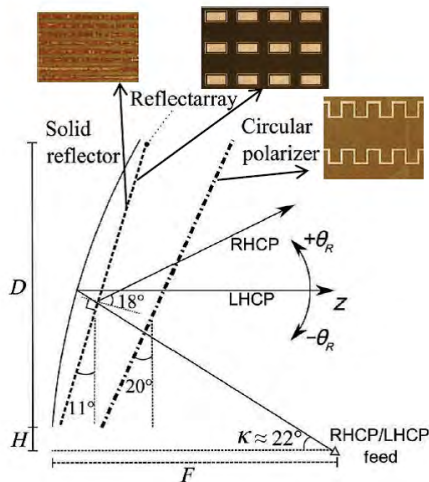
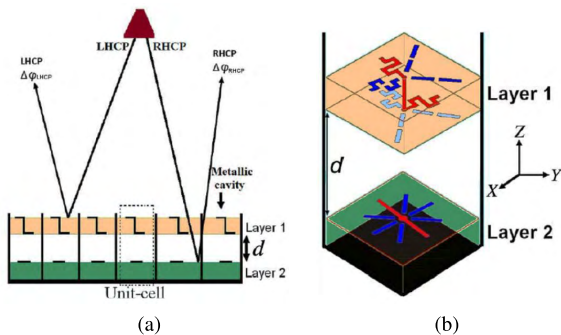**FIGURE 6.** Prototype of the dual surface circularly polarized reflectarray [57].

FIGURE 7. (a) Dual CP reflectarray. (b) Unit cell element with lego type patch element [58].

FIGURE 8. Single layer dual band and dual CP reflectarray operating at: (a) Ku-band and K-band [60]; and (b) C-band and Ku-band [61].

complexity and bulkiness the proposed design was well set to be used for the dual CP operation.

The lego type elements were also used for the dual CP operation in reflectarrays [58]. The proposed design as shown in Fig. 7 was used for the independent control of RHCP and LHCP signals in X-band frequency range. The reflectarray was made of two layers, each one was controlling its respective CP signal. The two layers were separated by a distance (d) to provide mechanical support and to reduce the mutual coupling between the layers. The structure was illuminated by a CP feed and the first layer of the reflectarray was designed to reflect LHCP signals while RHCP signals were reflected by the second layer. The same concept of independent control of dual CP by dual layer design was also reported in [59]. The advantage of using double layer designs is to generate both desired polarizations at the same resonant frequency. However, the cranked metal strips used to from the lego like element are less likely supported for higher frequencies due to their small dimensions.

The single layer designs provide dual polarization at two different frequencies as compared to dual layer designs which attain single frequency operation. A single layer design was
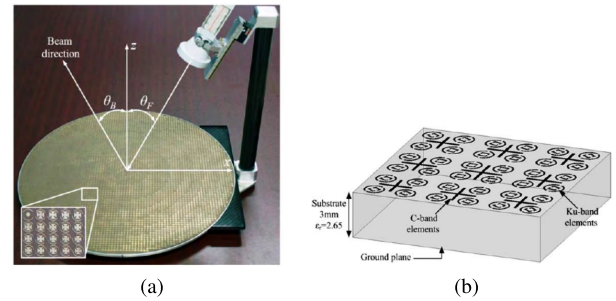
proposed in [60] where LHCP and RHCP operation was obtained at 20 GHz and 30 GHz respectively. It was achieved with a patch element which can simultaneously support dual band and dual polarization operation of reflectarray. Fig. 8(a) shows the structure of the proposed reflectarray for dual CP polarization. The novel element was comprised of a malta cross operating at 30 GHz surrounded by a split ring operating at 20 GHz. The malta cross element was set to reflect RHCP signals while the LHCP signals were reflected by the split ring. The separation in the resonant frequencies of each polarization reduced the risks of lower efficiencies. Moreover, due to the dual band operation, the cross polarization level can also be controlled easily. Another dual band single layer design was reported in [61] for C-band and Ku-band operation with the combination of two resonant elements together. As shown in Fig. 8(b) the split rings were set to operate in Ku-band frequency range and cross loop element had a resonance in C-band frequency range. LHCP was the dominant polarization for both bands as compared to RHCP. A helix feed was used here instead of a conventional horn antenna in order to generate a CP wave for the reflectarray. The dominant polarization was actually dependent on the characteristics of the feed used for the operation. A shared aperture reflectarray antenna was proposed in [62] for a dual CP transmit and receive operation in L-band and Ka-band respectively. The structure of the reflectarray as shown in Fig. 9 comprised of dual split ring elements backed by an FSS ground plane with dual concentric rings. The purpose of using an FSS ground was to allow the transmitted L-band signals coming from a 22 element patch array antenna. The dual split rings of reflectarray allowed it to operate at 20 GHz and 29.8 GHz with a dominant LHCP and RHCP respectively. Due to the wide separation of frequencies for both polarizations, a very low cross polarization level was obtained.

C. CRITICAL ANALYSIS

The polarization diversity in reflectarray can be achieved by double layer designs with two different patch elements on each layer or with single layer designs with the combination of elements. Similarly, it can be obtained at a single frequency or at two different bands of frequency. The main problem with single frequency dual polarized designs is their
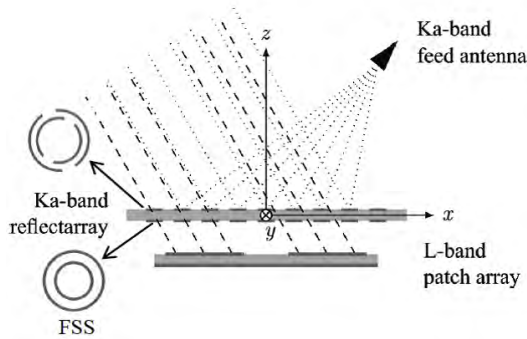
(a)   (b)

FIGURE 10. Beam scanning reflectarray by lateral displacement of feed: (a) design of reflectarray; and (b) radiation patterns of proposed reflectarray [66].

higher cross polarization level due to the double polarized reflections. The higher value of cross polarization limits the reflectarray performance in terms of its efficiency, which is not good for a 5G reflectarray. This issue is more severe in double layer designs while this effect can be reduced by single layer designs. However, the double layer designs can operate at a single frequency for both desired polarizations whereas single layer designs support each polarization with a different operating frequency. The reflectarray operation at two different frequencies eliminates the concept of frequency re-use for 5G communications. Producing polarization diversity in reflectarrays requires some extraordinary efforts for the design and realization of its unit cell element. It can possibly increase the design complexity along with the processing time for its completion. Moreover, the testing procedures of a reflectarray antenna with polarization diversity are also more challenging than that of a single polarized reflectarray. A special kind of measurement setup is required for the scattering parameter measurements of a dual polarized unit cell reflectarray element. Additionally, the radiation pattern measurements of full reflectarray also require special considerations for each individual polarization.

III. ADAPTIVE BEAMSTEERING IN REFLECTARRAYS
The fixed beam reflectarray with high gain and wide bandwidth is flexible to be used for many applications. However, its usefulness can increase to a new degree of freedom if its main beam can be steered in various directions. The coverage area can also be increased by pointing its beam in different directions. The conventional way of performing beamsteering by an antenna is to physically rotate it, which is called mechanical beamsteering [9]. The mechanical beamsteering can also be performed with reflectarray antenna, but basically reflectarray is not made for it. Alternatively, its counterpart parabolic antenna can easily attain beamsteering linked with its mechanical movements [63]. The beamsteering in reflectarray antenna can be divided into passive and active beamsteering. Passive beamsteering is not very common and it involves in the physical orientation of its whole structure or a
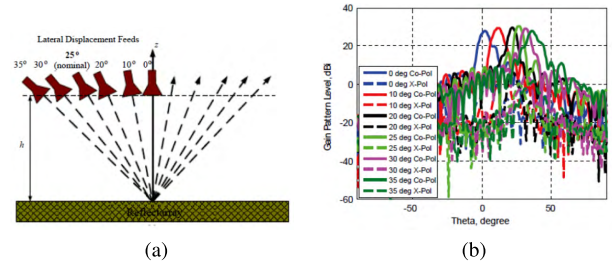
part of its structure. On the other hand, reflectarrays are well known for their capability of acquiring active or electronic beamsteering.

The beamsteering in reflectarrays totally depends on the reflection phase characteristics of its unit cell element. The variation in the reflection phase can make its main beam to move towards a certain direction. The reflection phase of the unit cell reflectarray element can be tuned by rotation of elements [15] or by manually modifying effective dielectric constant of the substrate [64]. The effective dielectric constant and hence the reflection phase of a unit cell reflectarray can also be controlled by fluidic reactive loading [65]. Apart from this, the direction of the main beam of reflectarray antenna also depends on the position and placement of its feed [66]. As shown in Fig. 10(a), the proposed strategy was used to enhance the scanning range of the main beam of the reflectarray antenna by lateral displacement of its feed horn. The main beam of reflectarray antenna was scanned up to 35° while physically moving the feed horn from 0° to 35°. The main advantage of this tactic was that the same reflectarray can be utilized for various beam positions with the same design strategy. However, the movement of the feed also generated some unwanted reflections which were caused to increase the side lobe levels for various scanned beam positions, as it is shown in Fig. 10(b). Moreover, as the feed moves from its normal position, its signals cannot fully align to the aperture of reflectarray and as a result its efficiency degrades.

The main purpose of beamsteering is to acquire a wide coverage area, which can also be done by increasing the number of main beams of a single reflectarray antenna. This idea was suggested by creating four multiple beams from a single reflectarray with single feed [67]. Two different methods were proposed to attain the required beam patterns. First one was the geometrical method, in which the reflectarray was divided into four sub-arrays to form four different beams. In the second method the aperture fields of reflectarray were superimposed for each reflected beam by optimizing the reflection phase distribution of the reflectarray elements. As shown in Fig. 11, each generated beam was 60° apart from each other. On the other hand, the generation of four different beams can degrade the reflectarray performance by introducing gain loss and high side lobe levels. It is because,
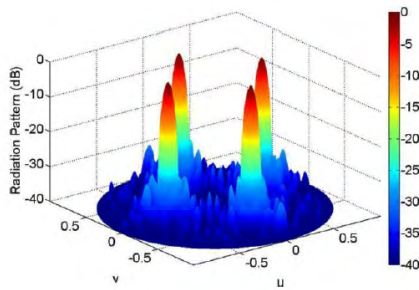
FIGURE 11. Radiation pattern of four beam reflectarray antenna [67].

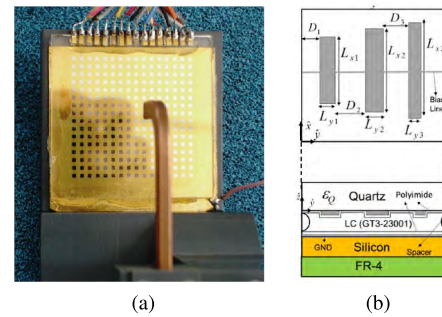(a)   (b)

FIGURE 12. (a) Design of a liquid crystal based reflectarray antenna [73] and (b) liquid crystal based multi-resonance reflectarray unit cell element [74].

the amplitude of each reflectarray element cannot be controlled while it was linked with the feed.

The beamsteering in reflectarrays can also be performed electronically, which is called active beamsteering. The direction of the main beam can be controlled by an external biasing source. The amount of that biasing is usually minimal to affect the radiation parameters of the reflectarray. The active beamsteering in reflectarrays can be performed either by controlling its material properties or by imposing capacitive or inductive loading to its radiating part [35]. The properties of dielectric or conductor part of the reflectarray can play important role in its resonant characteristics. The amplitude and reflection phase of the reflectarray depend on the behavior of its material properties. Subsequently, its radiating characteristics can also be controlled by optimizing the surface currents on its patch element.

A. BEAMSTEERING USING ELECTRONICALLY TUNABLE MATERIALS

Reflectarrays can be designed with fixed or variable properties materials [68], [69]. The variable properties of these materials can be tuned by the means of an external field which can affect them. The commonly used tunable dielectric materials for beamsteering purpose are Liquid Crystals and Ferroelectrics. Additionally, the conductive Graphene has recently been introduced as a potential candidate for beamsteering antennas due to its tunable conductivity.

1) LIQUID CRYSTALS

Liquid crystals are temperature dependent materials and hold an intermediate state between solids and crystals. Their dielectric constant and dissipation factor can be tuned between two extreme values by applying an external electric field across them [70]. The change in the dielectric constant can be used to tune the reflection phase of the reflectarray elements which can be further realized for beamsteering [71]. The patch and ground plane of reflectarray element can act as biasing electrodes for encapsulated liquid crystal substrate [72]. When a higher voltage is applied across the electrodes the rod like molecules of liquid crystal tend to change their orientation and acquire a higher dielectrhigher dielectric constant value. A millimeter wave reflectarray antenna with

conventional square patches was proposed with the beamsteering realization at 77 GHz by tunable liquid crystal substrate [73]. The design of the reflectarray antenna is shown in Fig. 12(a). The bias lines were used to provide an external voltage up to 15 V to the elements of reflectarray in order to tune their reflection parameters. An electronic beamsteering of $\pm 25°$ was achieved through this approach. The beamsteering capability of reflectarray antenna can be increased by increasing the phase tuning range of its unit cell element. The same strategy was proposed in [74] and [75] by selecting three parallel dipole elements to enhance the reflection phase range of reflectarray antenna at millimeter waves. Fig. 12(b) shows the schematic of its unit cell element comprised of an encapsulated liquid crystal layer. The full reflectarray antenna was designed at 96 GHz, 100 GHz and 104 GHz respectively to attain a maximum beamsteering up to 55° with a maximum bias voltage of 14 V. The multi-resonance strategy was also useful to reduce the side lobe level up to −13 dB. The main problem linked with liquid crystals is their high loss performance, which can lead them to limit the performance of the reflectarray antenna in terms of its gain requirements.

2) FERROELECTRICS

Ferroelectric is another form of dielectric non-linear materials. They possess a molecular property called ferroelectricity, by which they can store or release the energy inside them with and without an external biasing voltage respectively [76]. This phenomenon of storing the energy implies to tune their dielectric constants for acquiring phase shifting characteristics [77]. Ferroelectrics acquire higher dielectric constant value as compared to liquid crystals [78]. Subsequently, a higher biasing voltage is also required to tune their dielectric properties [76], [79]. Ferroelectric materials are normally used as thin films or thin layers in electronic circuits in order to compensate their high effective dielectric constant values and high loss effects. A dual band (X-band and Ka-band) phase shifting reflectarray unit cell was proposed in [80], based on a Ferroelectric material called BST (Barium Strontium Titanate). Fig. 13 shows the design of the proposed reflectarray unit cell with 400 nm thick BST layer in between the patch elements to create capacitive loading. The dielectric
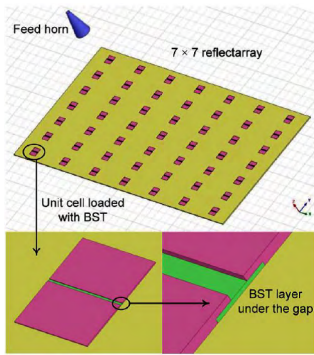
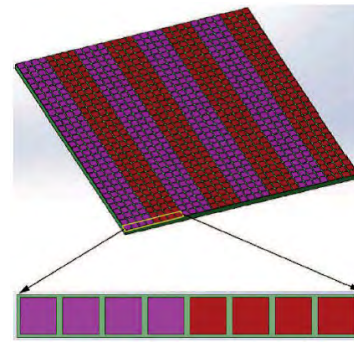**FIGURE 13.** BST based capacitive loaded reflectarray antenna [80].

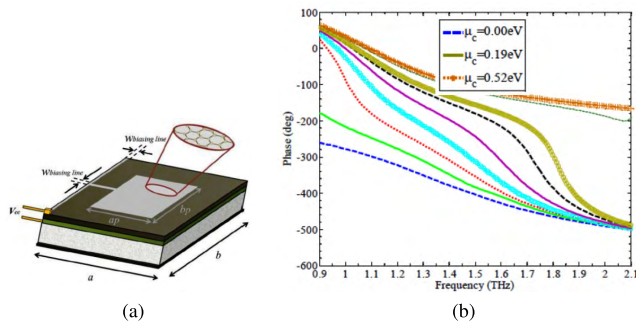**FIGURE 14.** (a) Graphene based reflectarray patch element (b) dynamic reflection phase range of Graphene based patch element [81].

FIGURE 15. Graphene based reflectarray with two different chemical potentials for dual beam operation [82].

constant of BST was varied from 500 to 250 and 600 to 300 for X-band and Ka-band respectively, with a maximum bias voltage of 35 V/μm. The variable permittivity acted as a tunable capacitance between the patches and realized them as a tunable capacitor. A maximum dynamic phase range of 250° was obtained for both selected bands of frequencies.

3) GRAPHENE

Graphene has emerged as a good candidate for future smart antennas at millimeter and THz frequencies [6]. It holds a variable chemical potential that can be used to tune its conductivity by giving minimal biasing. Moreover, it can ideally be produced in very thin layer configuration which is suitable for THz based fabrication requirements. Graphene based antennas are still in their initial phase of developments, but a few works have been recently proposed for its possible future applications in reflectarrays [5], [7]. Tunable features of Graphene have also been proposed for beamsteering realizations in THz reflectarrays. A frequency tunable patch element was proposed in [81] for beam reconfigurable reflectarray antenna. The structure of the patch has been shown in Fig. 14(a), which was placed on a Quartz substrate. The electronically tunable features of Graphene were varied by applying an external E-field via bias line for dynamic phase behavior from 0.9 THz to 2.1 THz. As it has been shown in Fig. 14(b) that, a 300° of reflection phase tunability was obtained by applying an E-field of 0 eV to 0.52 eV.

In the same way the variable chemical potential of Graphene was used to generate dual beam reflectarray antenna at THz frequencies [82]. Two types of patch elements with different chemical potentials and altered by 180° in phase were proposed for the stated application. The altered phase was produced by two different bias voltages given to the selected patch elements as shown in Fig. 15. Moreover, the beam scanning was also suggested by providing controlled bias voltages for a required beam in a certain direction. However the process of fabricating a Graphene layer with its maximum conductivity is quite complex and thus expensive.

B. BEAMSTEERING USING LUMPED COMPONENTS

The lumped elements in reflectarrays are used to modify the flow of surface currents by virtue of their tunable electronic features. The modified electric behavior of reflectarray elements, then leads it to attain tunable response for beamsteering realization. The lumped components are not part of the resonant structure of the patch and can be placed at any optimized position to control its reflection characteristics. The commonly used lumped components in the design of reconfigurable reflectarrays are PIN diodes, Varactor diodes and Radio Frequency Micro-Electromechanical Switches (RF-MEMS). Tunable electronic features of these components allow them to be independently used for frequency reconfigurable reflectarrays by means of an external bias source.

1) PIN DIODES

The digital biasing nature of PIN diodes makes them suitable for the beam switching realization in antenna design. It acts like a two state switch with an ON and OFF state, providing two different values of capacitances while its inductance remains constant [83]. The change in the capacitance can regulate the flow of the currents between two conducting points of the resonating structure. This can change the resonance behavior and hence the reflection characteristics of a reflectarray patch element. PIN diodes have been used in various ways of designs for reconfigurable reflectarrays. A surface mounted PIN diode in a multi-layered unit cell reflectarray element [84] has been shown in Fig. 16(a). The PIN diode was mounted between the patch and phase tun-
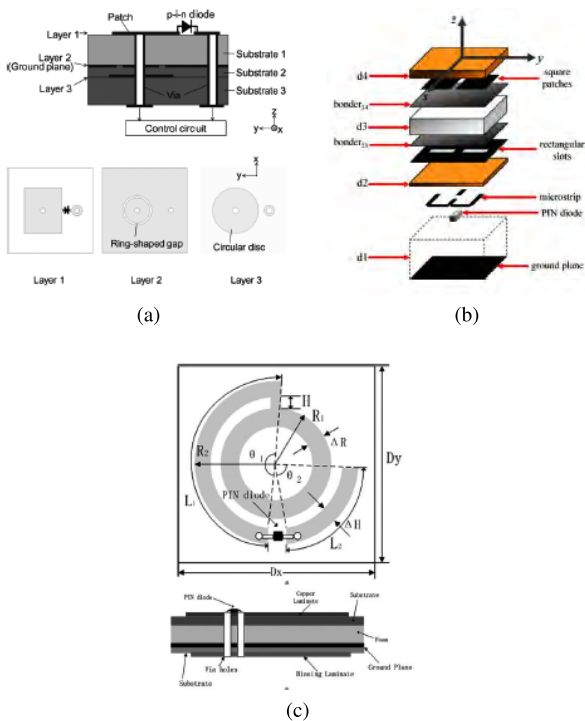
FIGURE 16. Reflectarray unit cell elements with PIN diodes: (a) multi-layer design with surface mounted PIN diode [84]; (b) aperture coupled PIN diode [85]; and (c) single layer design [88].

FIGURE 17. Varactor diode based tunable reflectarray unit cells: (a) aperture coupled element [92]; (b) surface mounted Varactor [94]; (c) dual resonance element with 6 Varactors [96]; (d) dual resonance element with single Varactor [97]; and (e) amplifying and tunable element [98].

ing stub in order to receive uninterrupted reflections from patch element. 25600 such elements were used to form a full reflectarray antenna with a $\pm20°$ azimuth and elevation beam scanning capability at 60 GHz. The multi-layered design utilized to provide the bias voltage to the PIN diode from the back side of the element through a control circuit. However, the introduction of phase tuning stub limits its performance in terms of efficiency. Another type of multi-layer unit cell reflectarray design with aperture coupled PIN diode [85] has been depicted in Fig. 16(b). A $\pm5°$ of beam switching was offered by a reflectarray of 244 such elements in X-band frequency range. The maximum beam switching in a particular direction was achieved by setting half of the reflectarray elements of that particular direction on forward bias. The $0°$ state of beam position was achieved by setting all diodes with reverse bias. The aperture coupled design was used to increase the capacitive coupling between the layers to ensure a wide variation in the reflection phase of the element. The single layer designs have also been widely used for the beam switchable reflectarrays with surface mounted PIN diodes [86], [87]. These single layer designs can reduce the design complexity with a reduction in the profile of the reflectarray antenna. As shown in Fig. 16(c), a single layer surface mounted PIN diode reflectarray design was proposed for beam switching in [88]. A circular ring element with a variable length arc delay line was used to make an 88 element reflectarray at 4 GHz. The biasing circuit was placed behind the ground plane to avoid its coupling with the resonant
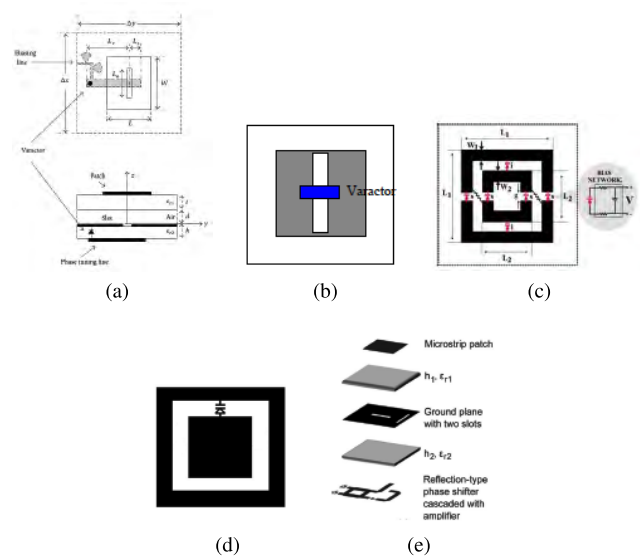
structure. A $10°$ of beam switching was obtained with design configuration by forward biasing the selected PIN diodes of the reflectarray.

2) VARACTOR DIODES

Varactor diodes possess the characteristic of variable capacitance depending on two potential differences of bias voltage. Varactor diodes work in a reverse bias state and an increasing bias voltage is used to gradually decrease its capacitance. The tuning capacitance is then used to provide dynamic reflection characteristics for beamsteering reflectarrays. The Varactors are made to use between two conducting parts of the unit cell element in order to create a change in the flow of the currents. The most common and conventional design to hold a Varactor for reconfigurable purpose is the aperture coupled unit cell element [89]–[91]. The aperture coupled element has the capability to achieve wide bandwidths while it can easily attain the full reflection phase swing by the use of a phase tuning slot. An aperture coupled element with tunable characteristics by using a Varactor diode [92] has been shown in Fig. 17(a). The proposed aperture coupled unit cell element was made to enhance the beamsteering feature of the reflectarray antenna by providing a $330°$ dynamic phase range at 11.5 GHz. The electronic beamsteering of the full reflectarray antenna was extended up to $\pm45°$. A wide beamsteering is achievable through aperture coupled elements, but their design complexity and fabrication sensitivity are the two main issues to restrict them to operate at higher frequencies. The single layer reflectarray designs have also been used for tunable purposes with a Varactor diode. As a conventional method the Varactor diode can be placed between the patch and the ground plane [93]. This design provides ease

of fabrication and biasing where patch and ground plane can be utilized as two electrodes for applying an external voltage to the Varactor. In order to overcome the flaw of design complexity the Varactor diode can also be used as a surface mounted lumped component with patch element [94] as depicted in Fig. 17(b). It can be seen that, the Varactor was mounted in the center of the patch element within a vertical slot, this ensures the maximum passage of surface currents through the Varactor and can enable it to provide wide reflection tunability. The same approach can also be utilized with other patch elements just like a dipole element proposed in [95]. Dipole element acquires higher reflection phase variations compared to a patch element which can be used to achieve wider beamsteering.

The main problem with single resonance elements, such as patches and dipoles, is their narrow reflection phase range, which can be increased by introducing more resonances in a single structure. A dual resonance element with double square rings was proposed in [96] for a wider dynamic phase range. A single bias voltage was used to tune 6 different Varactors mounted on the surface of unit cell as depicted in Fig. 17(c). A wider reflection phase swing of 380° was obtained from this unit cell, but at the cost of a higher design complexity due to an increase in the number of Varactors. The number of Varactors were reduced to 1 in another proposed F-band and S-band dual resonance reflectarray design [97]. Its unit cell consisted of a square patch with a loaded ring connected by a single Varactor through a gap as shown in Fig. 17(d). Due to the dual resonance behavior of unit cell element an extended ±60° beamsteering was obtained in both bands while bias voltage varied from 0.5 V to 28 V for a 100 element reflectarray.

A combination of electronically amplifying and tunable reflectarray antenna was proposed in [98] to overcome the flaw of scanning loss. The unit cell element was comprised of aperture coupled transmission lines which were used for the amplification and phase shifting purposes. The structure of the unit cell has been shown in Fig. 17(e). It was designed to receive a linearly polarized signal, amplified and re-radiated it in the desired direction with an orthogonal polarization. Its phase shifting strategy was composed of four Varactor diodes situating behind the ground plane separated by a second substrate. The dynamic phase range of 362° was used to get a beamsteering of ±20° with 48 element reflectarray along with an active obtained gain of 24.6 dBi. However, the extra power and bias lines were needed to bias the amplifier in each unit cell of reflectarray.

3) RF-MEMS

The discrete electrat provide variable switching mechanism for electronic circuits are known as RF-MEMS. Their structure is comprised of tiny sub-millimeter sized components that work at radio frequencies. Each variable digitized level of switching provides a different value in terms of capacitance when it is connected between two conductors [99]. This nature of RF-MEMS is essential when it is used for beam
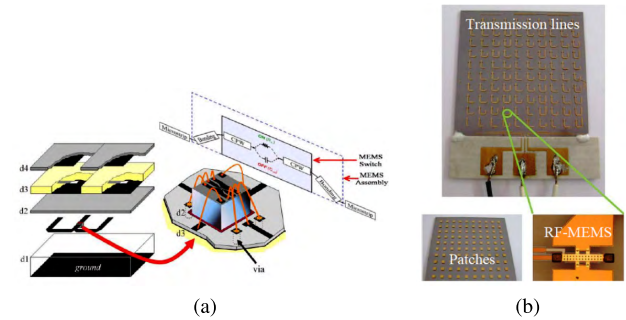

FIGURE 18. (a) Aperture coupled element with integrated RF-MEMS [104]. (b) Monolithically integrated RF-MEMS in transmission lines [105].

reconfigurable reflectarrays [100]. They can be used for beam switching in reflectarrays just like a PIN diode. However, unlike a PIN diode they can possess more than one state of switching. The multi-state switching of RF-MEMS has been utilized for reflection phase variations of unit cell reflectarray at millimeter and microwave frequencies by many researchers [101]–[103]. An aperture coupled element with a phase reconfigurable characteristic by an ohmic RF-MEMS was proposed in [104] at X-band frequency range. As shown in Fig. 18(a), two patches were aperture coupled with a common phase tuning delay line. The RF-MEMS was embedded with the delay line to electronically control its electric length, its equivalent circuit is also shown in Fig. 18(a). In the ON state the switch allows the current pass through it while a potential difference was created by a capacitance when the switch was in OFF state. The described two electric states of RF-MEMS used for the reflection phase switching in the unit cell element. The functionality of RF-MEMS for beam switching reflectarrays was also examined at a high frequency, such as 26.5 GHz in [105]. A total of 90 RF-MEMS were monolithically integrated to a 10 × 10 reflectarray antenna as depicted in Fig. 18(b). The length of the open ended transmission line was electrically varied by RF-MEMS to produce two different reflection phase values for a beam switching of 40° from broadside direction. Apart from the cascaded aperture coupled elements, RF-MEMS were also proposed as surface mounted structures by creating a slot in the patch element [102]. The surface mounted structures have the advantage of holding low profile single layer designs for reconfigurable performance. However, the coupling between the patch and tuning circuit is its major drawback.

C. CRITICAL ANALYSIS

The electronic beamsteering in reflectarray antenna is a need of time, but usually it comes with drawbacks of high SLL and scan loss. As the main beam of the reflectarray antenna steered from its broadside direction the SLL increases due to the undesired reflections from a portion of the reflectarray in the direction of generating side lobes. Moreover, the magnitude of the steered beam also deteriorates with beamsteering due to the reduction of reflection energy in the direction of

TABLE 1. Summary of adaptive beamsteering techniques (symbols refer as C = Continuous, A = Analog, D = Discrete/Digital, H = High, N = Neutral and L = Low).

Parameters	Tunable Materials			Lumped Components		
	Liquid Crystal	Ferroelectric	Graphene	PIN	Varactor	RF-MEMS
Beam Control	C	C	C	D	C	D
Biasing	A	A	A	D	A	D
Loss	H	N	L	L	L	H
Complexity	N	N	H	H	H	H
High frequency compatibility	N	L	H	N	N	L

beamsteering. These issues can be optimized by employing an amplifying circuit or by extending the range of progressive phase distribution of the elements. The first technique may increase the cost, profile and complexity of the system while the second requires an extra amount of time for designing.

Beamsteering techniques have usually been employed in the conventional microstrip reflectarray antenna due to its ease of creating a current transition in the resonant structure. Other high gain designs such as DRA reflectarrays and full metallic reflectarrays are still under development for beamsteering realization. Moreover, the aperture coupled reflectarray element designs are more liable to achieve electronic tunability with integrated lumped components as compared to a single layer design. They provide wide bandwidth, low loss and high isolation between resonant and tuning structures, but at the cost of high design sensitivity. Alternatively, single layer designs are easy to fabricate with surface mounted lumped components, but with a high possibility of extra reflection losses with limited bandwidth. Table 1 briefly compares the performance of major beamsteering techniques used in reflectarray antenna design. PIN and RF-MEMS are used for beam switching instead of a continuous beamsteering due to their digitized nature. The number of PIN diodes or switching states in RF-MEMS increases in the unit cell reflectarray with an increasing demand of more switchable beam positions. On the other hand, the analog nature of other beamsteering tactics allows them to be biased collectively in a combined manner. High loss is always an issue with RF-MEMS and liquid crystal based reflectarrays which can significantly affect the gain performance of a 5G reflectarray. The complex nature of RF-MEMS and the high value of dissipation factor of liquid crystal material are the main reasons behind that issue. Due to the fabrication and testing issues the design complexity of lumped components embedded reflectarray unit cells is always high. It is also a challenging work to produce a Graphene based reflectarray antenna. The fabrication of a single Graphene layer with high conductivity is a difficult task to achieve, but due to this reason it also holds a high compatibility with millimeter wave or even with THz frequencies. Due to this reason Graphene could be a potential candidate for future 5G communications.

The complex electronic nature of RF-MEMS makes it difficult to be integrated with reflectarrays at higher frequencies such as millimeter waves. In order to compensate the high effective dielectric constant values the Ferroelectrics are used as thin films below the patch elements which also restrict its use for shorter wavelengths at higher frequencies.

IV. CONCLUSIONS

The reflectarray antenna has the capability to work within a very vast range of frequencies including microwave and millimeter waves. Based on its structure and profile it can be recommended as a base station antenna for future 5G communication systems. The aspects involving the polarization diversity and adaptive beamsteering in reflectarrays have been discussed in details for a possible integrity with 5G communications. It is easier to acquire dual linear polarization in reflectarrays than dual circular polarization. A single layered single element with some design modifications can provide dual linear polarization. Alternatively, two different elements are required for dual circular polarized operation in reflectarrays. The polarization and physical orientation of the feed are also important factors for reflectarray polarization diversity. The electronic beamsteering in reflectarray can be introduced by integrating it either with tunable materials or with lumped components. Among tunable materials, graphene has the potential to become a good candidate for electronic beamsteering in 5G communication systems due its fast switching ability. The Varactor and PIN diodes can also be optimized for a relatively fast beamsteering in 5G reflectarray. However, design complexity is always an issue for millimeter wave beamsteering reflectarrays, which opens the doors for more research possibilities. Some other parameters like cost, power consumption and material properties related to 5G reflectarrays can make it more interesting as potential future research aspects.

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