IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 15, 2018, accepted March 20, 2018, date of publication March 30, 2018, date of current version April 25, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2821358

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

**MUHAMMAD HASHIM DAHRI[1], MOHD HAIZAL JAMALUDDIN[1], (Member, IEEE),
MOHSEN KHALILY[2], (Member, IEEE), MUHAMMAD INAM ABBASI[1],
RAGHURAMAN SELVARAJU[1],
AND MUHAMMAD RAMLEE KAMARUDIN[3], (Senior Member, IEEE)**
[1]Wireless Communication Centre, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[2]Institute for Communication Systems, Home of the 5G Innovation Centre, University of Surrey, Guilford GU2 7XH, U.K.
[3]Centre for Electronic Warfare, Information and Cyber, Cranfield Defence and Security, Cranfield University, Defence Academy of the United Kingdom, Shrivenham SN6 8LA, U.K.

Corresponding author: Mohsen Khalily (m.khalily@surrey.ac.uk)

This work was supported in part by the Ministry of Education Malaysia, Ministry of Science Technology and Innovation and in part by the Universiti Teknologi Malaysia under Grants 4J211, 03G33, 4S134, and 13H26.

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

2169-3536 © 2018 IEEE. Translations and content mining are permitted for academic research only.
Personal use is also permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

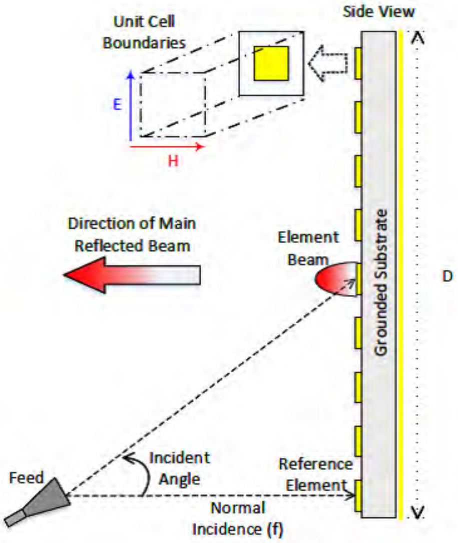


FIGURE 1. **Basic design architecture of a microstrip reflectarray with an offset feed.**

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].

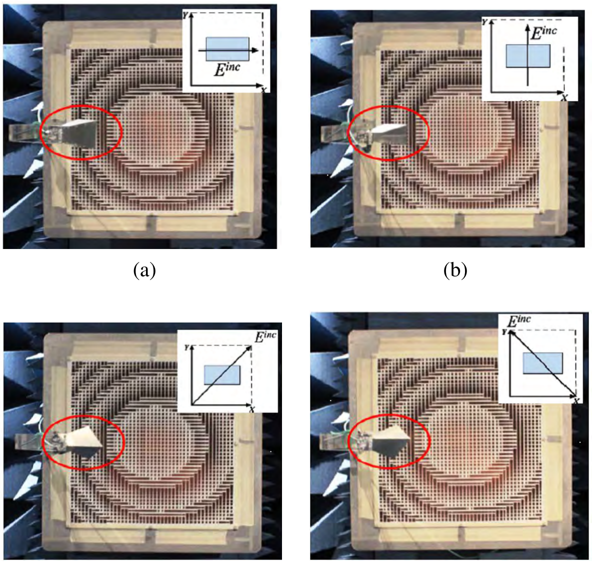
Antenna is one of the main components in the physical layer, which requires significant improvements in its performance parameters to acquire the 5G targets [26]. The array antennas with narrow beams and high gains can be a possible solution to the issues related to millimeter waves [25]. Massive MIMO 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 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.



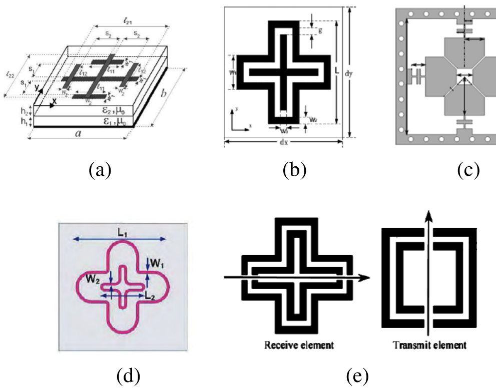
(a) (b)

(c) (d)

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].

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.

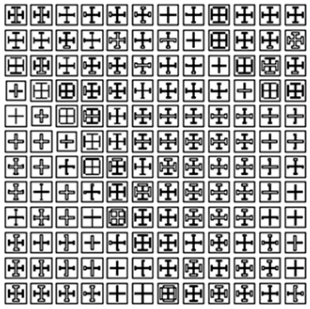


FIGURE 4. Reflectarray with dual linear polarization consisting of various designs of unit cell elements [55].

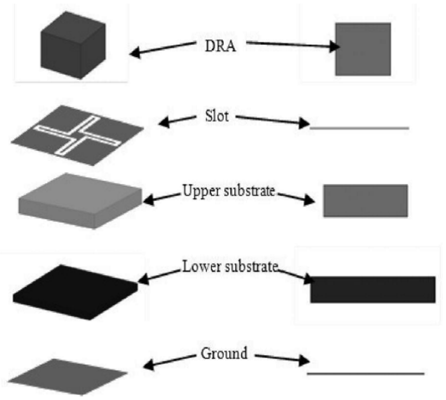


FIGURE 5. Unit cell element of a DRA reflectarray with dual linear polarization [56].

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

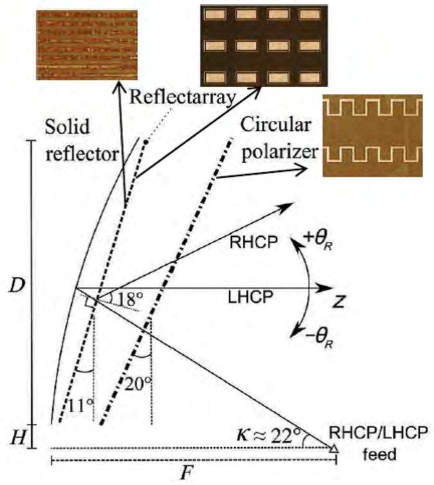
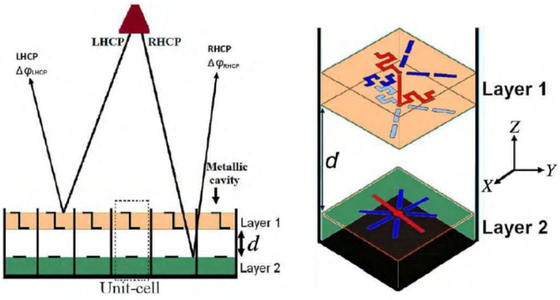


FIGURE 6. Prototype of the dual surface circularly polarized reflectarray [57].



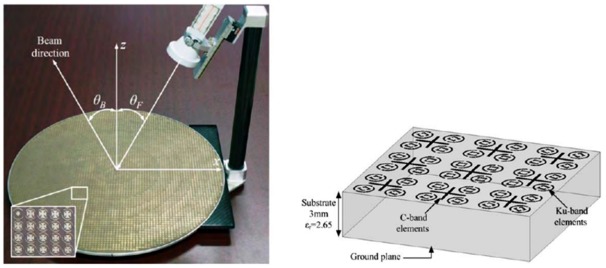
(a) (b)

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

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.



(a) (b)

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].

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

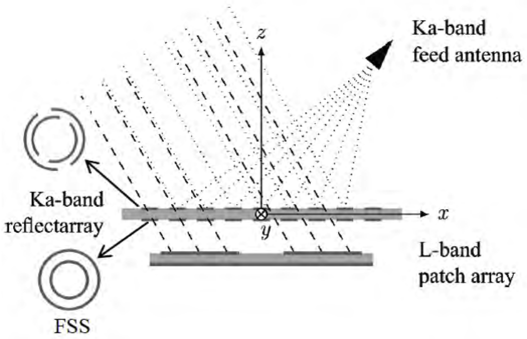
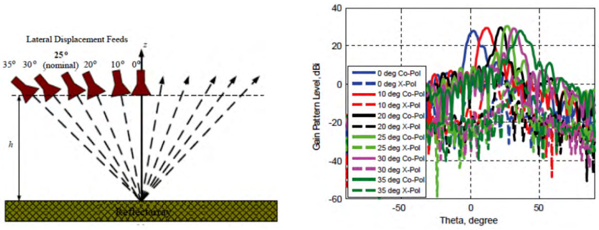


FIGURE 9. An FSS backed reflectarray for dual CP operation in L-band and Ka-band [62].

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.



(a) (b)

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

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,

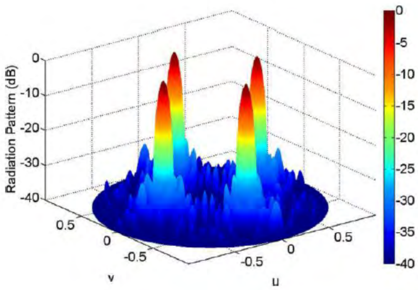


FIGURE 11. **Radiation pattern of four beam reflectarray antenna [67].**

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

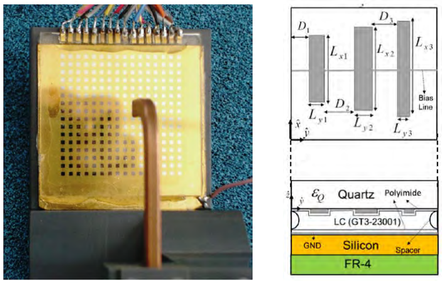
The beamsteering in reflectarrays can also be performed electronically, which is called active beamsteering. The direction of the main beam can be controlled by an external biasing source. The amount of that biasing is usually minimal to affect the radiation parameters of the reflectarray. The active 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 ±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.



(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].**

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

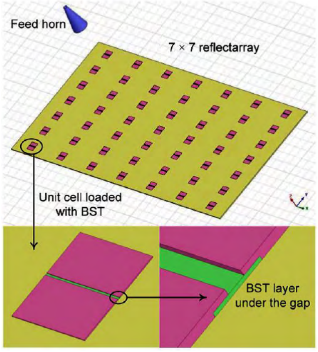
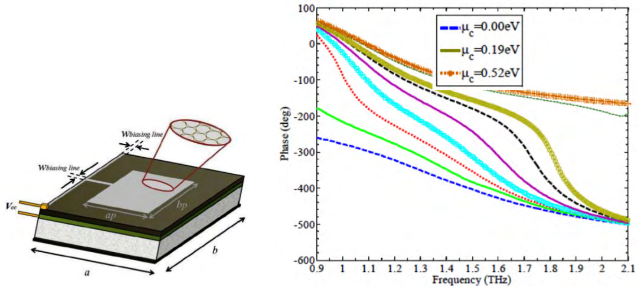


FIGURE 13. BST based capacitive loaded reflectarray antenna [80].



(a) (b)

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

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.

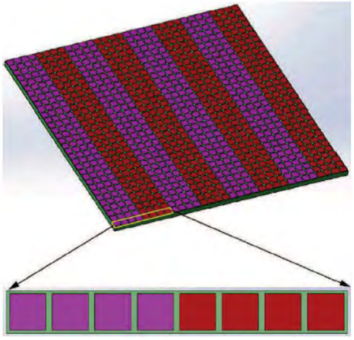


FIGURE 15. Graphene based reflectarray with two different chemical potentials for dual beam operation [82].

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-

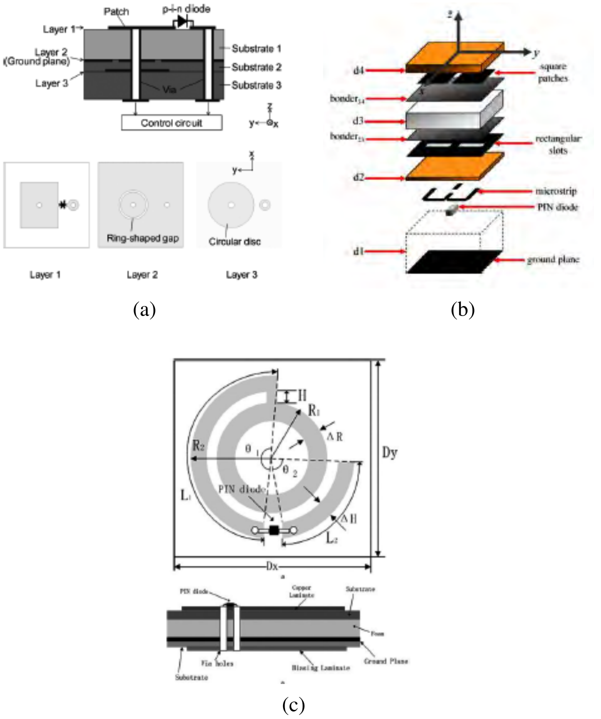


FIGURE 16. Reflectarray unit cell elements with PIN diodes: (a) multi-layer design with surface mounted PIN diode [84]; (b) aperture coupled PIN diode [85]; and (c) single layer design [88].

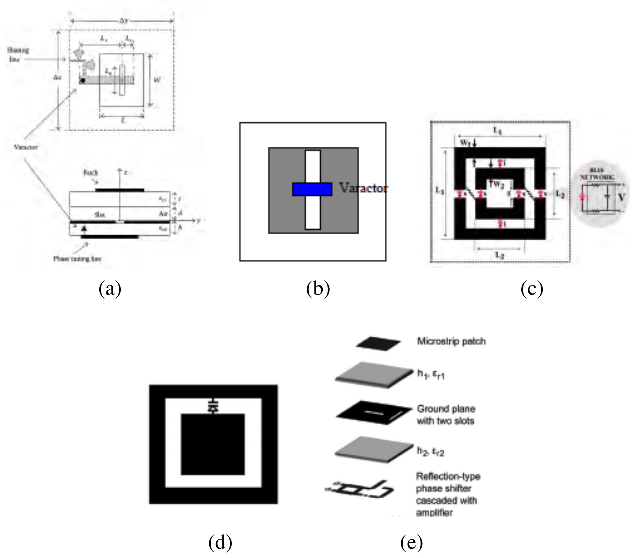


FIGURE 17. Varactor diode based tunable reflectarray unit cells: (a) aperture coupled element [92]; (b) surface mounted Varactor [94]; (c) dual resonance element with 6 Varactors [96]; (d) dual resonance element with single Varactor [97]; and (e) amplifying and tunable element [98].

ing stub in order to receive uninterrupted reflections from patch element. 25600 such elements were used to form a full reflectarray antenna with a ±20° 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 multilayer unit cell reflectarray design with aperture coupled PIN diode [85] has been depicted in Fig. 16(b). A ±5° 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

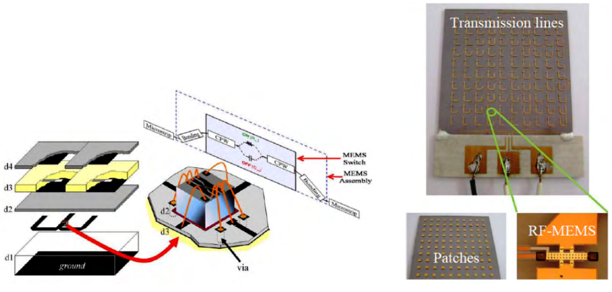
Varactor diodes possess the characteristic of variable capacitance depending on two potential differences of bias voltage. Varactor diodes work in a reverse bias state and an increasing bias voltage is used to gradually decrease its capacitance. The tuning capacitance is then used to provide dynamic 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 ±45°. 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 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.



(a) (b)

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

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.

REFERENCES

[1] J. Huang and J. Encinar, *Reflectarray Antennas*. Hoboken, NJ, USA: Wiley, 2007.

[2] J. Huang, "Analysis of microstrip reflectarray antenna for microspacecraft applications," Jet Propuls. Lab., California Inst. Technol., Spacecraft Telecommun. Equip. Section, Pasadena, CA, USA, Tech. Rep. N95-21541, Feb. 1995, pp. 153–173.

[3] A. Yu, F. Yang, A. Z. Elsherbeni, J. Huang, and Y. Kim, "An offset-fed X-band reflectarray antenna using a modified element rotation technique," *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1619–1624, Mar. 2012.

[4] M. Y. Ismail, M. Inam, N. H. Sulaiman, and M. A. Mugha, "Slotted tunable reflectarray antenna," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, 2011, pp. 1322–1325.

[5] Z. Chang, L. S. Wu, M. Tang, Y. P. Zhang, and J. F. Mao, "Generation of THz wave with orbital angular momentum by graphene patch reflectarray," in *IEEE MTT-S Int. Microw. Symp. Dig., Adv. Mater. Process. RF THz Appl. (IMWS-AMP)*, Jul. 2015, pp. 1–3.

[6] E. Carrasco and J. Perruisseau-Carrier, "Reflectarray antenna at terahertz using graphene," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 253–256, 2013.

[7] Z. Chang, B. You, L. S. Wu, M. Tang, Y. P. Zhang, and J. F. Mao, "A reconfigurable graphene reflectarray for generation of vortex THz waves," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1537–1540, 2016.

[8] D. M. Pozar and T. A. Metzler, "Analysis of a reflectarray antenna using microstrip patches of variable size," *Electron. Lett.*, vol. 29, no. 8, pp. 657–658, Apr. 1993.

[9] H. J. Visser, *Array and Phased Array Antenna Basics*. Chichester, U.K.: Wiley, 2005.

[10] D. Liu, U. Pfeiffer, J. Grzyb, and B. Gaucher, *Advanced Millimeter-wave Technologies: Antennas, Packaging and Circuits*. Hoboken, NJ, USA: Wiley, 2009.

[11] M. H. Jamaluddin, R. Gillard, R. Sauleau, and M. A. Milon, "Perturbation technique to analyze mutual coupling in reflectarrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 697–700, 2009.

[12] S. V. Hum, M. Okoniewski, and R. J. Davies, "Modeling and design of electronically tunable reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 55, no. 8, pp. 2200–2210, Aug. 2007.

[13] S. W. Oh, C. H. Ahn, and K. Chang, "Reflectarray element using variable ring with slot on ground plane," *Electron. Lett.*, vol. 45, no. 24, pp. 1206–1207, Nov. 2009.

[14] D. M. Pozar, D. Targoski, H. D. Syrigos, S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 45, no. 2, pp. 287–296, Feb. 1997.

[15] J. Huang and R. J. Pogorzelski, "A Ka-band microstrip reflectarray with elements having variable rotation angles," *IEEE Trans. Antennas Propag.*, vol. 46, no. 5, pp. 650–656, May 1998.

[16] D.-C. Chang and M.-C. Huang, "Multiple-polarization microstrip reflectarray antenna with high efficiency and low cross-polarization," *IEEE Trans. Antennas Propag.*, vol. 43, no. 8, pp. 829–834, Aug. 1995.

[17] J. Huang, "Microstrip reflectarray," in *Antennas Propag. Soc. Symp. Dig.*, 1991, pp. 612–615.

[18] M. Yi, W. Lee, Y. J. Yoon, and J. So, "Non-resonant conductor reflectarray element for linear reflection phase," *Electron. Lett.*, vol. 51, no. 9, pp. 669–671, Apr. 2015.

[19] W. An, S. Xu, and F. Yang, "A metal-only reflectarray antenna using slot-type elements," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1553–1556, Jul. 2014.

[20] M. H. Jamaluddin *et al.*, "A dielectric resonator antenna (DRA) reflectarray," in *Proc. 39th Eur. Microw. Conf. (EuMC)*, Sep./Oct. 2009, pp. 25–28.

[21] M. Abd-Elhady, W. Hong, and Y. Zhang, "A Ka-band reflectarray implemented with a single-layer perforated dielectric substrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 600–603, 2012.

[22] D. Berry, R. Malech, and W. Kennedy, "The reflectarray antenna," *IEEE Trans. Antennas Propag.*, vol. AP-11, no. 6, pp. 645–651, Nov. 1963.

[23] S. V. Polenga, A. V. Stankovsky, R. M. Krylov, A. D. Nemshon, Y. A. Litinskaya, and Y. P. Salomatov, "Millimeter-wave waveguide reflectarray," in *Proc. IEEE Int. Siberian Conf. Control Commun. (SIBCON)*, May 2015, pp. 1–4.

[24] *Final Acts WRC-15 in World Radiocommunication Conference*, document 190-15, Geneva, Switzerland, Apr. 2016.

[25] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

[26] J. G. Andrews *et al.*, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[27] F. W. Vook, A. Ghosh, and T. A. Thomas, "MIMO and beamforming solutions for 5G technology," in *Proc. IEEE MTT-S Int. Microw. Symp. (IMS)*, Jun. 2014, pp. 1–4.

[28] O. M. Haraz, A. Elboushi, S. A. Alshebeili, and A. R. Sebak, "Dense dielectric patch array antenna with improved radiation characteristics using EBG ground structure and dielectric superstrate for future 5G cellular networks," *IEEE Access*, vol. 2, pp. 909–913, 2014.

[29] R. Elsharkawy, A. R. Sebak, M. Hindy, O. M. Haraz, A. Saleeb, and E. S. El-Rabaie, "Single layer polarization independent reflectarray antenna for future 5G cellular applications," in *Proc. IEEE Int. Conf. Inf. Commun. Technol. Res. (ICTRC)*, May 2015, pp. 9–12.

[30] W. Hong, K. Baek, Y. Lee, and Y. G. Kim, "Design and analysis of a low-profile 28 GHz beam steering antenna solution for future 5G cellular applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2014, pp. 1–4.

[31] Z. Chen and Y. P. Zhang, "FR4 PCB grid array antenna for millimeter-wave 5G mobile communications," in *IEEE MTT-S Int. Microw. Symp. Dig., RF Wireless Technol. Biomed. Healthcare Appl. (IMWS-BIO)*, Dec. 2013, pp. 1–3.

[32] O. M. Haraz, M. M. M. Ali, S. Alshebeili, and A.-R. Sebak, "Design of a 28/38 GHz dual-band printed slot antenna for the future 5G mobile communication networks," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 1532–1533.

[33] D. T. Phan-Huy, M. Sternad, and T. Svensson, "Making 5G adaptive antennas work for very fast moving vehicles," *IEEE Intell. Transp. Syst. Mag.*, vol. 7, no. 2, pp. 71–84, Mar. 2015.

[34] W. Roh *et al.*, "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 106–113, Feb. 2014.

[35] S. V. Hum and J. Perruisseau-Carrier, "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 183–198, Jan. 2014.

[36] M. H. Dahri, M. H. Jamaluddin, M. Inam, and M. R. Kamarudin, "A review of wideband reflectarray antennas for 5G communication systems," *IEEE Access*, vol. 5, pp. 17803–17815, Aug. 2017.

[37] M. H. Dahri, M. Inam, M. H. Jamaluddin, and M. R. Kamarudin, "A review of high gain and high efficiency reflectarrays for 5G communications," *IEEE Access*, vol. 6, pp. 5973–5985, Dec. 2017.

[38] X. J. Zhong, L. Chen, Y. Shi, and X.-W. Shi, "A dual-frequency single layer circularly polarized reflectarray with frequency selective surface backing," *Prog. Electromagn. Res. C*, vol. 51, pp. 87–93, 2014.

[39] E. H. Lim and K. W. Leung, *Compact Multifunctional Antennas for Wireless Systems*. Hoboken, NJ, USA: Wiley, 2012.

[40] X. Zhong, L. Chen, Y. Shi, and X. W. Shi, "Single-layer broadband circularly polarized reflectarray with subwavelength double-ring elements," *Electromagnetics*, vol. 35, no. 4, pp. 217–226, May 2015.

[41] X. J. Zhong, L. Chen, Y. Shi, and X. W. Shi, "A dual-band single-layer circularly polarized reflectarray composed by elements having variable rotation angles," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 25, no. 1, pp. 39–47, Jan. 2015.

[42] M. Albooyeh, N. Komjani, and M. S. Mahani, "A circularly polarized element for reflectarray antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 319–322, 2009.

[43] R. S. Malfajani and Z. Atlasbaf, "Design and implementation of a broadband single layer circularly polarized reflectarray antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 973–976, 2012.

[44] L. Martinez-Lopez, J. Rodriguez-Cuevas, A. E. Martynyuk, and J. I. Martinez-Lopez, "Wideband-reconfigurable reflectarrays based on rotating loaded split rings," *J. Electromag. Wave Appl.*, vol. 29, no. 2, pp. 218–232, Jan. 2015.

[45] L. S. Ren, Y. C. Jiao, F. Li, J. J. Zhao, and G. Zhao, "A dual-layer T-shaped element for broadband circularly polarized reflectarray with linearly polarized feed," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 407–410, 2011.

[46] F. Ahmadi, A. Namiranian, and B. Virdee, "Design and implementation of a single layer circularly polarized reflectarray antenna with linearly polarized feed," *Electromagnetics*, vol. 35, no. 2, pp. 93–100, Feb. 2015.

[47] L. Guo, P. K. Tan, and T. H. Chio, "A simple approach to achieve polarization diversity in broadband reflectarrays using single-layered rectangular patch elements," *Microw. Opt. Technol. Lett.*, vol. 57, no. 2, pp. 305–310, Feb. 2015.

[48] R. Florencio, J. A. Encinar, R. R. Boix, and G. Perez-Palomino, "Dual-polarisation reflectarray made of cells with two orthogonal sets of parallel dipoles for bandwidth and cross-polarisation improvement," *IET Microw., Antennas Propag.*, vol. 8, no. 15, pp. 1389–1397, 2014.

[49] R. Florencio, J. A. Encinar, R. R. Boix, V. Losada, and G. Toso, "Reflectarray antennas for dual polarization and broadband telecom satellite applications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1234–1246, Apr. 2015.

[50] Q. Wang, Z. Shao, P. Li, L. Li, and Y. Cheng, "A dual polarization, broadband, millimeter-wave reflectarray using modified cross loop element," *Microw. Opt. Technol. Lett.*, vol. 56, no. 2, pp. 287–293, 2014.

[51] R. Pereira, R. Gillard, R. Sauleau, P. Potier, T. Dousset, and X. Delestre, "Four-state dual polarisation unit-cells for reflectarray applications," *Electron. Lett.*, vol. 46, no. 11, pp. 742–743, May 2010.

[52] A. M. Abbosh, "Design of dual-band microstrip reflectarray using single layer multiresonance double cross elements," *Prog. Electromagn. Res. Lett.*, vol. 13, pp. 67–74, 2010.

[53] M. R. Chaharmir, J. Shaker, N. Gagnon, and D. Lee, "Design of broadband, single layer dual-band large reflectarray using multi open loop elements," *IEEE Trans. Antennas Propag.*, vol. 58, no. 9, pp. 2875–2883, Sep. 2010.

[54] S. R. Rengarajan, "Reflectarrays of rectangular microstrip patches for dual-polarization dual-beam radar interferometers," *Prog. Electromagn. Res.*, vol. 133, pp. 1–15, 2013.

[55] L. Marnat, R. Loison, R. Gillard, D. Bresciani, H. Legay, and H. Legay, "Comparison of synthesis strategies for a dual-polarized reflectarray," *Int. J. Antennas Propag.*, vol. 2012, pp. 1–10, May 2012.

[56] F. Ahmadi, K. Forooraghi, Z. Atlasbaf, and B. Virdee, "Dual linear-polarized dielectric resonator reflectarray antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 635–638, 2013.

[57] M. A. Joyal, R. E. Hani, M. Riel, Y. Demers, and J. J. Laurin, "A reflectarray-based dual-surface reflector working in circular polarization," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1306–1313, Apr. 2015.

[58] S. Mener, R. Gillard, R. Sauleau, A. Bellion, and P. Potier, "Dual circularly polarized reflectarray with independent control of polarizations," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1877–1881, Apr. 2015.

[59] S. Mener, R. Gillard, R. Sauleau, C. Cheymol, and P. Potier, "Design and characterization of a CPSS-based unit-cell for circularly polarized reflectarray applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 2313–2318, Apr. 2013.

[60] R. Deng, Y. Mao, S. Xu, and F. Yang, "A single-layer dual-band circularly polarized reflectarray with high aperture efficiency," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 3317–3320, Jul. 2015.

[61] X. J. Zhong, L. Chen, Y. Shi, and X. W. Shi, "A novel design of dual broadband, single-layer circularly polarized reflectarray," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 25, no. 4, pp. 364–369, May 2015.

[62] T. Smith, U. Gothelf, O. S. Kim, and O. Breinbjerg, "An FSS-backed 20/30 GHz circularly polarized reflectarray for a shared aperture L- and Ka-band satellite communication antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 2, pp. 661–668, Feb. 2014.

[63] M. I. Skolnik, *Radar Handbook*, 3rd ed. New York, NY, USA: McGraw-Hill, 2008.

[64] M. E. Cooley, J. F. Walker, D. G. Gonzalez, and G. E. Pollon, "Novel reflectarray element with variable phase characteristics," *IEE Proc.-Microwa., Antennas Propag.*, vol. 144, no. 2, pp. 149–151, Apr. 1997.

[65] S. A. Long and G. H. Huff, "A fluidic loading mechanism for phase reconfigurable reflectarray elements," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 876–879, 2011.

[66] L. Guo, P. K. Tan, and T. H. Chio, "Investigations on beam-scanning improvement of reflectarrays using single-layered sub-wavelength elements," *Prog. Electromagn. Res. C*, vol. 51, pp. 139–147, 2014.

[67] P. Nayeri, F. Yang, and A. Z. Elsherbeni, "Design and experiment of a single-feed quad-beam reflectarray antenna," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 1166–1171, Feb. 2012.

[68] D. Askeland, P. Fulay, and W. Wendelin, *The Science and Engineering of Materials*, 6th ed. Stanford, CA, USA: Cengage Learning, 2010.

[69] N. Ida, *Engineering Electromagnetics*, 3rd ed. Cham, Switzerland: Springer, 2015.

[70] S. M. Kelly and M. O'Neill, "Liquid crystals for electro-optic applications," in *Handbook of Advanced Electronic and Photonic Materials and Devices*, H. S. Nalwa, Ed. San Diego, CA, USA: Academic, 2000, pp. 1–66.

[71] M. Y. Ismail and M. H. Dahri, "Tunable reflectarray resonant elements based on non-linear liquid crystals," *J. Adv. Mater. Res.*, vol. 746, pp. 357–362, 2013.

[72] S. Bildik, S. Dieter, C. Fritzsch, W. Menzel, and R. Jakoby, "Reconfigurable folded reflectarray antenna based upon liquid crystal technology," *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 122–132, Jan. 2015.

[73] A. Gaebler *et al.*, "Liquid crystal-reconfigurable antenna concepts for space applications at microwave and millimeter waves," *Int. J. Antennas Propag.*, vol. 2009, pp. 1–7, Jan. 2009.

[74] G. Perez-Palomino *et al.*, "Design and demonstration of an electronically scanned reflectarray antenna at 100 GHz using multiresonant cells based on liquid crystals," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3722–3727, Aug. 2015.

[75] G. Perez-Palomino *et al.*, "Design and experimental validation of liquid crystal-based reconfigurable reflectarray elements with improved bandwidth in F-band," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1704–1713, Apr. 2013.

[76] H. Chan, "Smart ferroelectric materials for sensors and mechatronic device applications," in *IEDM Tech. Dig.*, Hong Kong, Jun. 1999, pp. 68–71.

[77] G. Velu *et al.*, "A 360° BST phase shifter with moderate bias voltage at 30 GHz," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 2, pp. 438–444, Feb. 2007.

[78] M. Y. Ismail, M. H. Dahri, and W. N. Zaihasra, "Characterization of material properties for tunable reflectarray antenna design," in *Proc. Nat. Conf. Phys. Amer. Inst. Phys. (AIP) Conf. (PERFIK)*, 2013, pp. 237–242.

[79] T. R. Shrout and S. L. Swartz, "Processing of ferroelectric and related materials: A review," in *Proc. 8th IEEE Int. Symp. Appl. Ferroelectrics (ISAF)*, 1992, pp. 80–88.

[80] K. K. Karnati, Y. Shen, M. E. Trampler, S. Ebadi, P. F. Wahid, and X. Gong, "A BST-integrated capacitively loaded patch for Ka and X-band beamsteerable reflectarray antennas in satellite communications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1324–1333, Apr. 2015.

[81] E. Carrasco, M. Tamagnone, and J. Perruisseau-Carrier, "Tunable graphene-based reflectarray element for reconfigurable beams," in *Proc. 7th Eur. Conf. Antennas Propag. (EUCAP)*, Gothenburg, Sweden, 2013, pp. 1779–1782.

[82] X. B. Li, W. B. Lu, J. Wang, B. H. Huang, and H. Chen, "Dual-beam scanning using graphene-based reflectarray," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, vol. 2. Dec. 2015, pp. 1–3.

[83] S. Montori *et al.*, "A transportable reflectarray antenna for satellite Ku-band emergency communications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1393–1407, Apr. 2015.

[84] H. Kamoda, T. Iwasaki, J. Tsumochi, T. Kuki, and O. Hashimoto, "60-GHz electronically reconfigurable large reflectarray using single-bit phase shifters," *IEEE Trans. Antennas Propag.*, vol. 59, no. 7, pp. 2524–2531, Jul. 2011.

[85] E. Carrasco, M. Barba, and J. A. Encinar, "X-band reflectarray antenna with switching-beam using PIN diodes and gathered elements," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5700–5708, Dec. 2012.

[86] Y. Li and A. Abbosh, "Electronically controlled phasing element for single-layer reconfigurable reflectarray," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 628–631, 2012.

[87] M. Y. Ismail and M. Inam, "Resonant elements for tunable reflectarray antenna design," *Int. J. Antennas Propag.*, vol. 2012, pp. 1–6, Jun. 2012.

[88] Y. Li and A. Abbosh, "Reconfigurable reflectarray antenna using single-layer radiator controlled by PIN diodes," *IET Microw., Antennas Propag.*, vol. 9, no. 7, pp. 664–671, May 2015.

[89] F. Venneri, S. Costanzo, and G. Di Massa, "Reconfigurable aperture-coupled reflectarray element tuned by single varactor diode," *Electron. Lett.*, vol. 48, no. 2, pp. 68–69, Jan. 2012.

[90] F. Venneri *et al.*, "Beam-scanning reflectarray based on a single varactor-tuned element," *Int. J. Antennas Propag.*, vol. 2012, pp. 1–5, 2012.

[91] F. Venneri, S. Costanzo, and G. Di Massa, "Design and validation of a reconfigurable single varactor-tuned reflectarray," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 635–645, Feb. 2013.

[92] F. Venneri, S. Costanzo, G. Di Massa, F. Venneri, S. Costanzo, and G. Di Massa, "Tunable reflectarray cell for wide angle beam-steering radar applications," *J. Elect. Comput. Eng.*, vol. 2013, pp. 1–7, Jul. 2013.

[93] F. Venneri, L. Boccia, G. Angiulli, G. Amendola, and G. Di Massa, "Analysis and design of passive and active microstrip reflectarrays," *Int. J. RF Microw. Compu.-Aided Eng.*, vol. 13, no. 5, pp. 370–377, 2003.

[94] M. Hajian *et al.*, "Passive and active reconfigurable scan-beam hollow patch reflectarray antennas," *ISRN Commun. Netw.*, vol. 2012, pp. 1–10, Jan. 2012.

[95] K. Hasan, M. Khaliel, M. El Hadidy, and T. Kaiser, "Design an adaptive electronically beamsteering reflectarray antenna for RFID systems," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 2157–2158.

[96] C. Liu and S. V. Hum, "An electronically tunable single-layer reflectarray antenna element with improved bandwidth," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 1241–1244, 2010.

[97] A. Tayebi, J. Tang, P. R. Paladhi, L. Udpa, S. S. Udpa, and E. J. Rothwell, "Dynamic beam shaping using a dual-band electronically tunable reflectarray antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 10, pp. 4534–4539, Oct. 2015.

[98] K. K. Kishor and S. V. Hum, "An amplifying reconfigurable reflectarray antenna," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 197–205, Dec. 2012.

[99] E. Carrasco *et al.*, "Recent developments of reflectarray antennas for reconfigurable beams using surface-mounted RF-MEMS," *Int. J. Antennas Propag.*, vol. 2012, pp. 1–12, Jun. 2012.

[100] Y. Radi, S. Nikmehr, and A. Poorziad, "A novel bandwidth enhancement technique for X-band RF MEMS actuated reconfigurable reflectarray," *Prog. Electromagn. Res.*, vol. 111, pp. 179–196, 2011.

[101] C. C. Chieh and A. Abbaspour-Tamijani, "Evaluation of a novel topology for MEMS programmable reflectarray antennas," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 12, pp. 3333–3344, Dec. 2009.

[102] F. A. Tahir, H. Aubert, and E. Girard, "Optimisation of MEMS-controlled reflectarray phase shifter cell," *IET Microw., Antennas Propag.*, vol. 5, no. 3, pp. 271–276, Feb. 2011.

[103] S. Mäkelä *et al.*, "Near-field measurements of a millimeter-wave reflectarray at 120 GHz," in *Proc. 42nd IEEE Eur. Microw. Conf. (EUMC)*, Amsterdam, The Netherlands, Oct./Nov. 2012, pp. 807–810.

[104] E. Carrasco, M. Barba, B. Reig, C. Dieppedale, and J. A. Encinar, "Characterization of a reflectarray gathered element with electronic control using ohmic RF MEMS and patches aperture-coupled to a delay line," *IEEE Trans. Antennas Propag.*, vol. 60, no. 9, pp. 4190–4201, Sep. 2012.

[105] O. Bayraktar, O. A. Civi, and T. Akin, "Beam switching reflectarray monolithically integrated with RF MEMS switches," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 854–862, Feb. 2012.

MUHAMMAD HASHIM DAHRI received the B.E. degree in telecommunications from the Mehran University of Engineering and Technology, Pakistan, in 2010, and the master's by research degree in electrical engineering from Universiti Tun Hussein Onn Malaysia in 2014. He is currently pursuing the Ph.D. degree with the Wireless Communication Centre, Universiti Teknologi Malaysia. He has authored over 20 research papers in various indexed journals and conference proceedings. His research interests include reflectarray antennas, planar printed antennas, and tunable materials for antenna design.

MOHD HAIZAL JAMALUDDIN received the bachelor's and master's degrees in electrical engineering from Universiti Teknologi Malaysia, Malaysia, in 2003 and 2006, respectively, and the Ph.D. degree in signal processing and telecommunications from the Université de Rennes 1, France, in 2009, with a focus on microwave communication systems and specially antennas such as dielectric resonator and reflectarray and dielectric dome antennas. He is currently an Associate Professor with the Wireless Communication Centre, Faculty of Electrical Engineering, Universiti Teknologi Malaysia. He has authored over 25 papers in reputed indexed journals and conference proceedings. His research interests include dielectric resonator antennas, printed microstrip antennas, MIMO antennas, and DRA reflectarray antenns.

MOHSEN KHALILY (M'13) has been with the Home of 5G Innovation Center, Institute for Communication Systems, University of Surrey, U.K., as a Research Fellow on antenna and propagation since 2015. Before joining 5GIC, he was with the Wireless Communication Center, Universiti Teknologi Malaysia, as a Senior Lecturer and a Post-Doctoral Research Fellow from 2012 to 2015. He has authored almost 70 academic papers in international peer-reviewed journals and conference proceedings. His research interests include: dielectric resonator antennas, MIMO antennas, phased array antennas, and millimeter-wave antennas and propagation.

MUHAMMAD INAM ABBASI received the B.Sc. degree in electrical engineering majoring in telecommunication from the Centre for Advanced Studies in Engineering, University of Engineering and Technology, Taxilla, Pakistan, in 2008, and the master's by research and Ph.D. degrees in electrical engineering from the Wireless and Radio Science Centre, Universiti Tun Hussein Onn Malaysia, in 2011 and 2016, respectively. He joined the Wireless and Radio Science Centre, Universiti Tun Hussein Onn Malaysia, as a Graduate Research Assistant in 2009. He is currently a Post-Doctoral Research Fellow with the Wireless Communication Centre, Universiti Teknologi Malaysia. He has published one book and over 40 research papers in internationally indexed journals and conferences. His recent research interest lies in high performance planar and printed antenna design, passive and reconfigurable reflectarray and planar reflector antennas, novel materials for the design of enhanced performance antennas.

RAGHURAMAN SELVARAJU was born in Gandarvakottai, Tamilnadu, India, in 1989. He received the bachelor's degree in electronics and communication engineering and the master's degree in wireless communication systems from Periyar Maniammai University, India, in 2011 and 2014, respectively. He is currently pursuing the Ph.D. degree with the Wireless Communication Centre, Universiti Teknologi Malaysia. He is currently a Researcher with the Wireless Communication Centre, Universiti Teknologi Malaysia. His research interests include microstrip patch antennas, dielectric resonator antennas, MIMO antennas, beamforming array antennas, mutual coupling analysis, metamaterials, and split ring resonators.

MUHAMMAD RAMLEE KAMARUDIN (M'08–SM'13) received the degree (Hons.) majoring in electrical and telecommunication engineering from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 2003, and the M.S. degree in communication engineering and the Ph.D. degree in electrical engineering from the University of Birmingham, Birmingham, U.K., in 2004 and 2007, respectively, under the supervision of Professor P. H. Dr. Kamarudin. He has been a Senior Lecturer with the Centre for Electronic Warfare, Information and Cyber, Cranfield Defence and Security, Cranfield University, U.K., since 2017. Prior to this appointment, he was an Associate Professor with the Wireless Communication Centre, Universiti Teknologi Malaysia. He holds an H-Index of 20 (SCOPUS) and over 1500 citations (SCOPUS). He has authored a book chapter of a book entitled *Antennas and Propagation for Body-Centric Wireless Communications* and has published over 215 technical papers in journals and proceedings including the IEEE Transaction on Antenna and Propagation, the IEEE Antennas and Wireless Propagation Letter, the IEEE *Antenna Magazine*, the IEEE Access, the *International Journal of Antennas and Propagation*, *Progress in Electromagnetics Research*, *Microwave and Optical Technology Letters*, and *Electronics Letters*. His research interests include antenna design for 5G, wireless on-body communications, in-body communications (implantable antenna), RF and microwave communication systems, and antenna diversity. He is a Member of IET, an Executive Member of Antenna and Propagation, Malaysia Chapter, and a Member of the IEEE Antennas and Propagation Society, the IEEE Communication Society, the IEEE Microwave Theory and Techniques Society, the IEEE Electromagnetic Compatibility Society, an Associate Editor for *Electronics Letters* and *IET Microwaves, Antennas and Propagation*, and an Academic Editor for the *International Journal of Antennas and Propagation*.

• • •