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Beam Scanning and Efficiency Requirements of Reflectarray Antennas for Modern Day Applications: A Review

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Abstract – **Reflectarrays' many advantages make them appealing options for enhancing 5G and 6G networks. As such, a set of requirements must be followed while developing antennas for modern day communication systems. Benefits of reflectarrays include bandwidth, reconfigurability, high gain, beam shaping, beam scanning, efficiency and multi-beam capabilities, which imply their high potential with 5G/6G networks. This study thoroughly examines the current state of reflectarray antennas by assessing and categorizing them based on 5G/6G communication system requirements. Various works that presented beam scanning and efficient reflectarrays are classified according to several factors, such as operating frequency, range of reflection phase, substrate structure and material, size of aperture, aperture efficiency (AE), distance of focal point, performance in cross-polarization, gain, and levels of side lobes.**

Keywords – **Reflectarray, 5G/6G, Beam Scanning, reflectarray antenna efficiency, Reconfigurable reflectarray antenna**

I. Introduction

Advancements in technology have led to the development of fifth generation (5G) communication technologies, with data rates that might be up to a thousand times faster than 4G current systems. Antenna designers are encountering challenges in developing antennas capable of supporting wide bandwidth, high gain, high efficiency, polarization diversity, and adaptive beam steering [1]. Therefore, substantial changes to the structural architecture of existing communication networks are required to include 5G technology [2], [3], [4].

5G is planned to operate across frequency ranges ranging from 24.25 GHz to 86 GHz, accommodating various uses [5]. High gain antennas may be used as a viable method to offset losses. The parabolic dish antenna is renowned for its high gain and efficiency, making it a popular choice in wireless communication systems as a directional antenna. Nevertheless, it has constraints including the need for mechanical motion to scan the primary beam and a nonplanar surface, which complicates its installation on various structures [6]. Moreover, its substantial bulk takes up more room in comparison to a flat antenna [7]. To address these problems, one may use a dual-layer architecture or a single-layer design with two specific resonant structures customized for separate frequency ranges. Moreover, its substantial size leads to taking up more area compared to a flat antenna. It has been proposed to create a dual-band, single-layer circularly polarized reflectarray antenna. Among the several types of reflectarray antennas in use are band-loaded dielectric resonator antennas [8]. Several configurations of reflectarray antennas have been suggested for millimetre-wave and 5G communication systems [8], including the use of band-loaded dielectric resonator antennas [9]. The appropriateness of several antenna architectures for millimetre-wave and 5G communication systems has been studied. These include single-layer designs, designs that employ variable capacitance, and designs that use Micro Electromechanical Systems on the resonant components [10], as well as utilizing the variable capacitance [11], have been explored for their suitability in millimetre-wave and 5G communication systems [12].

The aim of this manuscript is to investigate the beam scanning and efficiency performance of reflectarray antennas (RAs) from the perspective of 5G/6G communication systems. Maintaining high efficiency over a wide operating frequency band is crucial for RAs to be considered as candidates for future systems. The paper categorizes and evaluates efficient reconfigurable RA architectures based on various design techniques, including liquid crystal-based electronically scanned reflectarray antennas, mechanical rotation of cylindrical unit cells, and dual-frequency beam steering arrays. Section II elaborates the basic requirements and characteristics of antennas for 5G and 6G Communication systems focusing on the performance attributes. Section III provides a detailed discussion about the potential of employing reflectarray antennas for modern day communication systems with main focus on the characterization of the beam scanning and efficiency aligned with the application requirements.

II. Design of Antennas for 5G and 6G Users

The model and combination of antennas into a 5G/6G communication scheme that meets the criteria presents several challenges from an electromagnetic perspective. Whether the antennas are being integrated into fixed terminals or mobile devices, the same problems still arise. A 5G/6G system's effective bandwidth is mostly dictated by the relevant frequency range, which falls into one of three categories: sub-

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6 GHz (FR1), mm-Wave (FR2), or THz. For example, an operating bandwidth of around 400MHz is required within the FR1 range, shown in Figure 1. On the other hand, the operational bandwidths may reach 3.25GHz or 10-100GHz in the FR2 or THz bands, respectively [13].

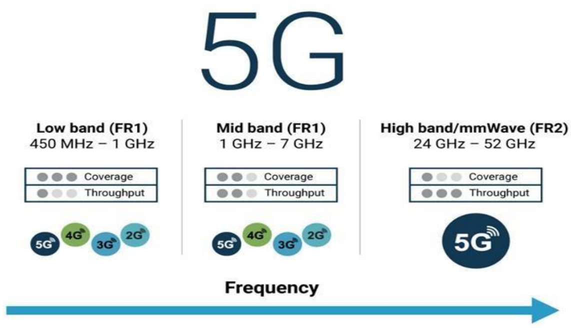

Fig. 1. Frequency Bands for 5G communications

Electromagnetic waves may experience severe deterioration in the higher frequency mm wave/THz bands, including obstruction, reflection, and attenuation in route loss. If a high-gain antenna system is not employed, the aforementioned problems might lead to a decrease in the Signal-to-Interference-plus-Noise ratio (SINR) of the connection [14]. When highly directional antennas are deployed, the advantage of wide user coverage is compromised unless multibeam antennas are considered. Therefore, it is essential to use highly directional antennas with Multiple Input Multiple Output (MIMO) and adaptive beamforming capabilities. Tracking base stations or user needs also presents a big difficulty for mobile terminals with high velocities, such trains or aircraft, in efficiently handling different 5G/6G traffic [15]. As a result, antenna topologies with beam steering and beamforming become essential for 5G and 6G communication systems [16][8]. Moreover, the beams' adaptive steering capability is required to respond to quickly altering traffic patterns and the need for on-demand beam coverage because of the users' spatial development [17][5]. As a result, antenna topologies with beam steering and beamforming become essential for 5G and 6G communication systems [18], [19]. Because of this, 5G and 6G antennas need to have better gain bandwidth performance and a programmable radiation pattern [2].

Furthermore, null-steering control may be employed to reduce resource-sharing-induced interference while preserving gain bandwidth and appropriate impedance matching for beam scanning. Furthermore, establishing a polarization A variable antenna system with a wide axial ratio bandwidth and outstanding polarization purity may boost the overall system throughput by sending signals at the same frequency but different polarizations.

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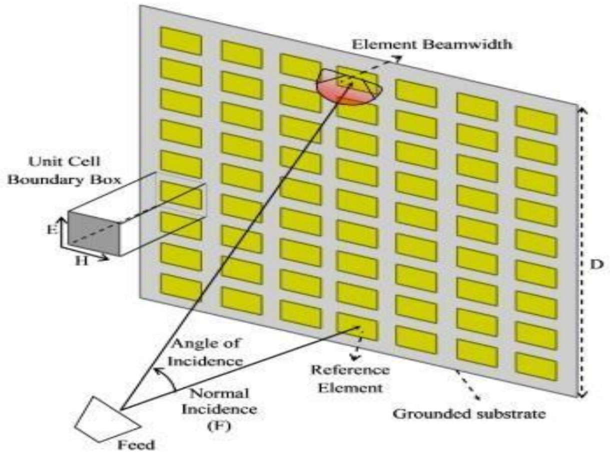


Fig. 2. Reflectarray Antenna [5].

RAs have several advantages, such as high gain, beam shaping, scanning, multi-beam potentials, radiation pattern reconfigurability, and beam shaping [5],[23]. RAs may reach higher aperture efficiencies due to lower losses since they do not need the same complex and lossy feeding network as phased arrays [13]. The low profile and lightweight design of planar RAs is another benefit [21]. For a variety of space tasks, big satellite platforms have historically used reflectarrays to create pencil- or shaped-beams [24], [25], [26], [27], [28].

Furthermore, RAs are seen as ingenious solutions for enormous Low Earth Orbit (LEO) constellation-facilitated future Non-Terrestrial-Networks (NTN). These RAs may provide users shaped-beam isoflux patterns at Ku-band with a bandwidth of 2 GHz [29]. Retrodirective antennas have been used in small satellite projects like the Integrated Solar Array and Reflectarray (ISARA) initiative, demonstrating high-gain Ka-band communication capabilities for CubeSats. Furthermore, RAs were used in NASA's Jet Propulsion Laboratory's deep space CubeSat MarCO project [30], [31]. Moreover, RAs have been suggested as potential antennas for CubeSat circularly polarized intersatellite connections, where the antenna's weight and profile are crucial [32]. Reflectarrays, which provide mechanical and electrical beam steering in the FR1 and FR2 frequency bands, respectively, have lately drawn attention in 5G and 6G communications [33]. They may also be used for dual band and dual polarization [34], [35]. Resonant phase gradient elements have been used to show beam steering at THz frequency [36].

Furthermore, research has looked at reflectarrays as a possible option for Reconfigurable Intelligent Surfaces (RIS), which would allow change of the communication channel for 5G and 6G [37]. The use of RAs for 6G RIS has been investigated; a liquid crystal 108GHz RA was used to demonstrate beamforming, guiding, and splitting for 6G [38]. A solitary 10-30GHz RA aperture may cover six different frequency bands on the Internet of Vehicles, which presents another 5G/6G use case for Ras [39]. Studies have looked at the feasibility of employing RAs as indoor and outdoor 5G Ka-band fronthaul base stations, showcasing the antenna's near- and far-field capabilities [13]. Finally, a 400GHz quartz-based RA with polarization diversity has been suggested for high-density base station high-speed 6G lines [40]. These studies demonstrate reflectarrays' noteworthy qualities, making them excellent choices for 5G and upcoming 6G applications. It is crucial to remember that reflectarrays do have some drawbacks, such as a small bandwidth (less than 10%), the need for active components to be able to scan beams, and a high cost of fabrication since low loss tangent dielectric substrates are used [21], [41].

In conclusion, reflectarray antennas offer a versatile and high-performance solution by combining the advantages of both parabolic reflectors and phased arrays. Their planar geometry, phase control capabilities, and simplified feed ystem make them a promising technology for various applications, including satellite communications, radar systems, and 5G networks. Additionally, advanced features such as polarization control and reconfigurability further enhance their functionality. However, challenges like limited bandwidth and feed blockage remain areas of active research, as efforts continue to optimize performance and expand their practical applications. Figure 3 summarizes various components that affect the reflectarray efficiency.

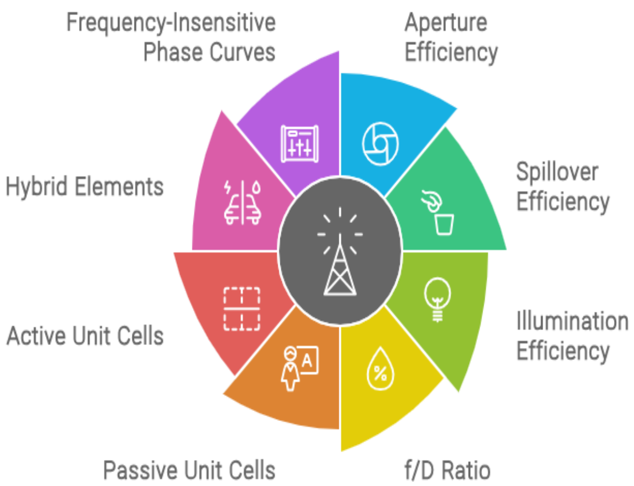


Fig. 3. Components influencing reflectarray antenna efficiency

III. Reflectarray Related Works

In this work, we assess Reflectarray Antennas (RAs) appropriate for 5G/6G applications. As far as we are aware, no other research has made a distinctive contribution in this manner. As of right now, the corpus of literature has no study or review of the research on employing existing RAs as the enabling technology for 5G/6G networks. Therefore, the aim of this work is to examine the beam scanning and efficiency performance of RAs from the perspective of 5G and 6G systems. When RAs are considered as possible candidates for upcoming 5G/6G systems, this analysis is very important since it is necessary to keep the high beam and efficiency performance across a large range of operating frequencies within reasonable bounds. This study specifically reviews architectures for RA. Beam scanning and design configuration, which includes single and multilayer structures, are used to categorize the wideband performance. Furthermore, design methodologies are examined from the perspective of a unit cell, and the reflectarray system's overall performance is assessed thereafter. The amount of reflection loss, the phase of reflection, the aperture efficiency (AE), the gain, the aperture size, the substrate material, the number of layers, the type of polarization, the phase reflection range, and the operating frequency band are all metrics that are considered when assessing the system's overall performance.

TABLE 1
Summary of Beam Scanning and Performance of Various Reflectarrays

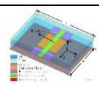
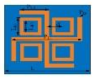
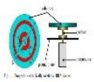
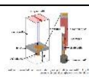
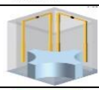
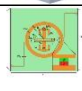
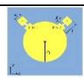
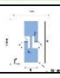
Ref. No	Freq. (GHz)	Design Configuration	Beam Scan	Aperture Efficiency (%)
[43]	23.7-24.2		± 60°	5.8
[54]	6.5 to 9.5		20°-58°	55
[55]	8.3		± 60°	51.8
[46]	5.8 & 10		±40°	32.9/50.6
[47]	7		60°	60.4
[56]	10.1		±50° continuous, dual plane	25.42
[57]	7.6–15.9		-20° tilt	58.3
[58]	9.5–10.5		Reconfigurable	2.95
[59]	24		±45°	29.47
[60]	10		25° tilt	67

Table 1 illustrates the many evaluations that RAs have been subjected to. A thorough analysis of several methods and strategies for creating reconfigurable RAs was carried out in [21], with an emphasis on beam formation and beam steering. They also investigated reconfigurability using frequency-agile and polarization-flexible unit cells. The study also looked at active RAs that have boosters built in, which could give a reflection coefficient value greater than 1. A review by Nayeri [36], categorized various beam-scanning methods and supporting technologies into two primary groups: aperture phase-tuning techniques and feed tuning approaches. Additionally, the authors focused on active RAs and explored many approaches, including digital, analogue, and subarray techniques, to achieve phase control. Afterwards, a large number of review papers that addressed RAs from a 5G viewpoint were published in [41], [5], [23] & [16] explored this topic. Their studies concentrated on several methods of wideband 5G RA bandwidth augmentation, considering different element geometries for each method [5]. They also looked into how the RA was fed, how it worked with sub-reflectors, and the materials that were used to make the RA so that they could look at high gain and high efficiency RAs from both an element and a system point of view [23]. The same authors did a bigger study than the one in [23] and [42], looking at different element designs, feeding methods, and opening sizes to see how efficiency and measurement accuracy improved or decreased in RAs. Finally, the study in [22] looked at the different types of polarization in RAs by putting them into two groups: dual linear and dual circular. The researchers also looked into RAs that could change the direction of the beam. They divided their study into two groups: lumped components and electronically changeable materials.

A. Beam Scanning Capability of Reflectarrays

As shown in Figure 4, an electronic scanned reflectarray antenna based on liquid crystals (LC) is presented in [43]. Parallel H-shaped polygons are regularly loaded onto two metal layers to create the reflectarray element. A varactor-based, 8 μm-thick LC layer is used in place of a substrate in order to provide a tuneable reflection phase and lessen the inhomogeneity impact of LC. Based on simulations, it is shown that the suggested element provides a 180◦ changeable reflection-phase range in the 21–21.5 GHz frequency range. The design concept is validated by building a prototype reflectarray with 26 rows of the basic components. Also designed and manufactured is a biasing control circuit with 32 channels. The experimental results provide a reasonable phase range of 150◦ at 23.8 GHz; nevertheless, we do highlight and resolve a number of discrepancies with the results from the simulations. A test approach is proposed to address these discrepancies.

As a demonstration of the design's high beam-steering performance, the reflectarray's primary beam is steered to 0◦, −40◦, and −60◦ in a single plane, with measured gains exceeding 18 dB at 23.8 GHz. This study offers useful information for LC-based reflectarray antenna design and evaluation. An additional 18.9 dBi at 26 GHz and 20% bandwidth from 24.7-30 GHz are achieved by the mechanically rotating cylindrical unit cells in the reflectarray proposed in [42], which is suitable for 5G millimetre-wave communication. The unit cells may rotate up to a maximum of 60°, which is the beam steering angle.

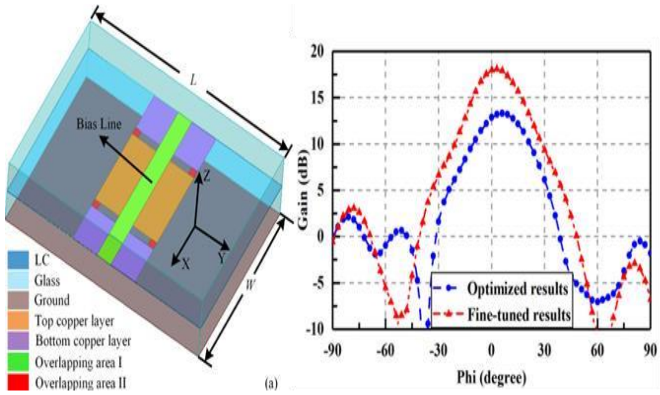


Fig. 4. Geometry of the reflectarray cell & measured far-field patterns for main-beam +60° [43]

The proposed reflectarray in [44] using mechanical rotation of cylindrical unit cells achieves gain of 18.9 dBi at 26 GHz with 20% bandwidth from 24.7-30 GHz, suitable for 5G millimetre wave communication. A maximum beam steering angle of 60° is demonstrated using the rotational capability of the unit cells shown in Figure 5.

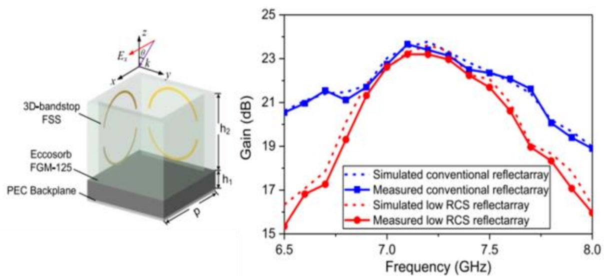


Fig. 5. Using mechanical rotation of cylindrical unit cell & simulate and measured realized gain versus frequency for conventional reflectarray and proposed low-RCS reflectarray [44]

In [45], The design and analysis of active reflectarray antennas utilizing slot embedded patch elements within the X-band frequency range are presented in this study. The researcher’s study two different forms of active reflectarray technologies, namely digital frequency switching using PIN diodes and analogue frequency tuning enabled by liquid crystal substrates, as depicted in Figure 6. A waveguide simulator is utilized to almost equate the performance of reflectarrays designed with these two approaches. The PIN diode-based unit cell is shown to offer 0.36 GHz of frequency tune-ability with a substantial 226° dynamic phase range. In contrast, the liquid crystal design achieves slightly lower 0.20 GHz tune-ability but only 124° phase range. Furthermore, the liquid crystal approach exhibits higher reflection loss and slower tuning compared to the PIN diode design. Slot embedded patches are identified as a promising element for improved passive and reconfigurable reflectarrays, providing an extra tuning parameter in the slot dimensions. While the PIN diode approach provides advantages in tuneability, phase range and loss, the liquid crystal technique enables analogue control for continuous tunability over a frequency range. There is thus a trade-off between performance metrics and continuous tunability. Further research should focus on enhancing the t tunability and reducing loss in reconfigurable reflectarrays, by investigating advanced materials and electronic components. In summary, this work presents a valuable comparative study of two active reflectarray technologies using slot embedded patch elements. The findings reveal the superior discrete tuning performance of PIN-diode designs, while continuous analogue control can be realized using liquid crystals despite higher losses. This investigation provides important insights that can guide the development of improved active reflectarray antennas.

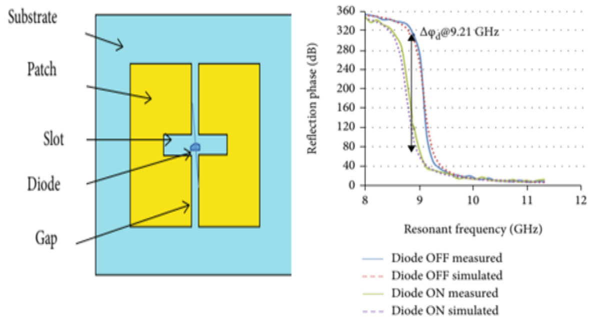


Fig. 6. Unit Cell shape & Comparison between simulated and measured reflection phase curves of PIN diode-based active reflectarrays [45]

In [46], a novel dual-frequency beam-steering array (DBSA) antenna is presented as shown in Figure 7, integrating a height-adjustable reconfigurable C-band reflectarray with an X-band phased array. Each antenna element can achieve arbitrary 0° - 360° phase shifts at 5.8 and 10 GHz by controlling the height-adjustable device and digital phase shifter, respectively. This enables independent feeding of the two arrays to simultaneously steer beams at arbitrary angles for the two frequencies.

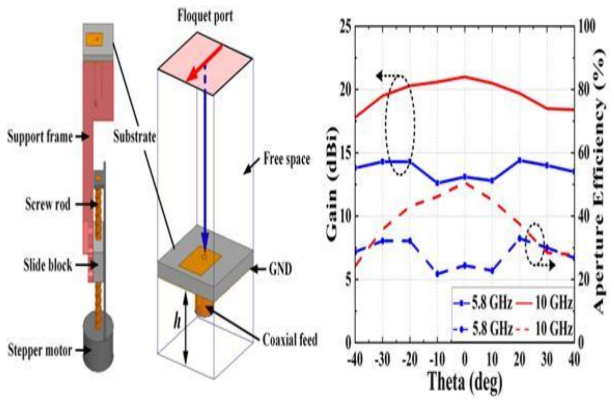


Fig. 7. Structure of the height-adjustable device and full-wave simulation & measured gains and aperture efficiencies of the scanned beams at 5.8 and 10 GHz, respectively [46]

An 8x8 DBSA prototype is designed and fabricated, demonstrating beam scanning from -40° to 40° in the XOZ plane at 5.8 and 10 GHz. Measured peak gains are 14.4 and 21 dB with aperture efficiencies of 32.9% and 50.6% at 5.8 and 10 GHz, respectively. The proposed DBSA holds promise for satellite communications, providing simultaneous airto-ground and inter-satellite links.

Research work in [47] presents a wideband, high-efficiency reflectarray antenna with low radar cross section (RCS) enabled by an absorptive frequency-selective reflector (AFSR) incorporating metal pillars shown in Figure 8. The AFSR utilizes bent resistor-embedded metal strips, exploiting multimode resonances to achieve wideband absorption-reflection absorption characteristics. Importantly, the compact AFSR lattice spacing improves antenna radiation efficiency. Variable-height metal pillars inserted into the AFSR serve as phase shifters, providing flexible reflection phase control over the wide reflection band. Simulated and measured results demonstrate the reflectarray antenna produces a pencil-beam pattern from 6-8 GHz with an aperture efficiency up to 60.4%. Additionally, two RCS reduction bands are attained over 66.7% and 32.3% fractional bandwidths.

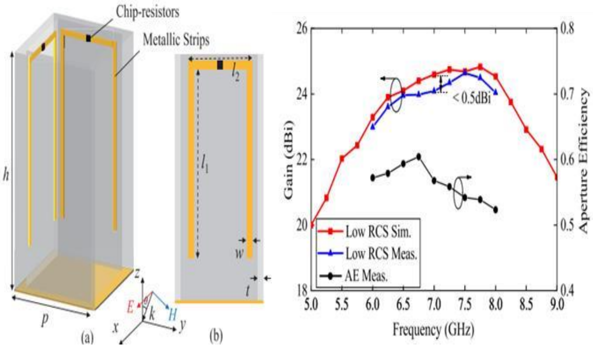


Fig. 8. Unit cell structure of AFSR backed with the PEC plane & Simulated and measured gain of the proposed low RCS reflectarray antenna versus frequency [47]

In summary, the bent resistor-embedded metal strip AFSR provides wideband RCS reduction and reflection control. Inserted metal pillars of various heights enable in-band beam focusing. The resulting reflectarray antenna combines wideband operation, high radiation efficiency and dual RCS reduction bands suitable for high-efficiency, low-observable systems. This communication makes important progress in wideband reflectarray antennas using absorptive frequency-selective surfaces.

B. Aperture Efficiency of Reflectarrays

The attainment of high aperture efficiency is crucial in order to maximize the gain of a reflectarray that is of limited size and is suitable for 5G base stations. Most designs achieve reasonably efficient results, with efficiencies ranging from 25 % to 60 % shown in Table 1. However, a small number of designs are able to achieve efficiencies close to 70 %, as mentioned in references [3] and [33]. It is possible to achieve further enhancements in efficiency through the implementation of denser element spacing and the mitigation of performance-reducing factors such as phase errors and losses. Given the constraints imposed by the LINK budget, I consider a minimum baseline efficiency of 60% to be acceptable for 5G reflectarrays. However, in order to compete with other fabricated antennas, our target should be at least 80% efficiency. Challenges arise from increased spill over around the edges of the array and diffraction at higher frequencies, which can be addressed through the improvement of modelling and simulation techniques. Additionally, as the frequency increases, power losses originating from conductor and dielectric materials also increase, necessitating careful optimization of subcomponents. In theory, the densities of unit cells can approach 100% by sufficiently reducing the size of the elements below half wavelength sizes. However, it is important to note that fabrication tolerances impose limitations, resulting in greatly diminishing returns. Therefore, it is likely that the practical maximum efficiency will hover around 90%.

A technique closely related to mutual coupling between components and subwavelength periodicity is that of tightly coupled reflectarrays. The concept of tightly coupled RAs was first presented in reference [48]. This approach utilizes the ultra-wideband operating features of closely linked antenna arrays and connected arrays to improve bandwidth performance. The operation of arrays depends on the antenna components being near to one another or on the usage of inductors and capacitors to improve the electromagnetic interaction between them. A typical resonance antenna has components spaced half the wavelength of the operating frequency apart. In the tightly coupled RA described in [49], this gap is decreased to λ/10 of the wavelength of the lowest working frequency. As seen in Figure 9, the authors used closely spaced printed dipoles positioned perpendicular to two metallic surfaces.

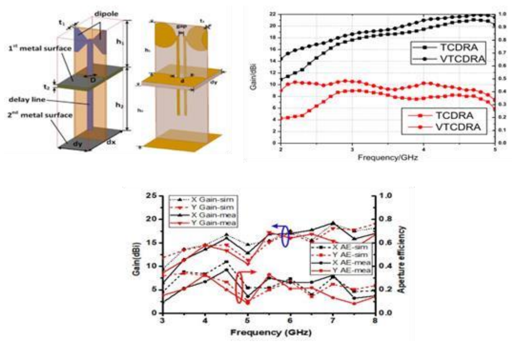


Fig. 9. Geometry of the proposed unit cells simulated and measured gains and AE [49], [50]

The guided wave methodology was used in the phase tuning procedure. Printed bowtie dipoles with a real-time delay line connected compensate for spatial phase delay caused by distance from reflecting surface to feed antenna. The delay line's height was chosen to suitably modify the reflected wave's phase. Recently, a paper cited as [48] built on the studies on closely related RAs. Figure 9, depicts an improved rectifier antenna (RA) that makes use of real time delay line and variant-coupling capacitance techniques; this topic is covered in reference [50]. The element is created using an elliptical printed dipole. As mentioned in reference [36], the overlapping of adjacent components in this design may cause the coupling capacitance to fluctuate. In order to obtain a reflection phase range of about 5000°, consideration is given to the coupling capacitance and time delay line length during the construction of the unit cell.

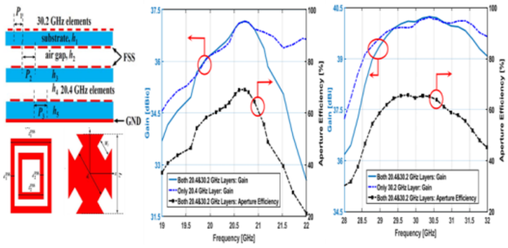


Fig. 10. Unit cell configurations. (a) Proposed FSS-backed element Measured gain and efficiency across the band of interest, Lower & upper frequency [51]

Present a highly efficient dual-band, circularly polarized reflectarray antenna supported by a wide frequency selective surface (FSS), as mentioned in reference [51],[64],[66]. Refer to Figure 10. Their phasing approaches reduce mutual coupling and increase antenna efficiency by varying the element size and rotation angle. Between the 20- and 30-GHz element layers, a double layer Frequency Selective Surface (FSS) is used to reduce phase errors and streamline the design process. An experimental confirmation of the reflectarray antenna with a 400 mm circular aperture has been made. The results showed that the aperture efficiencies exceeded 47% in the receiving band and 59% in the transmitting band, with gains of 36.7 dB at 20.4 GHz and 40.2 dB at 30.2 GHz.

Applications for commercial satellite communication in the Ka-band are possible with this particular antenna design. Figure 9 shows a unit cell with a λ/5 dimension made up of two meandering square loops, as described in more detail in reference [52]. By varying their length, the meander lines enable the subwavelength element to attain a reflection phase range of 420^0 .

By using square loops with λ/5 frequency, the (AE) is increased by 56.5%, or 120^0 . In [53], an effort was made to lessen the reflection phase's sensitivity by using concentric ring components. As seen in Figure 11, the unit cell is made up of rings with different widths spaced at λ/3 periodic intervals. The aperture phase distribution's usage of a phase constant produced the desired result.

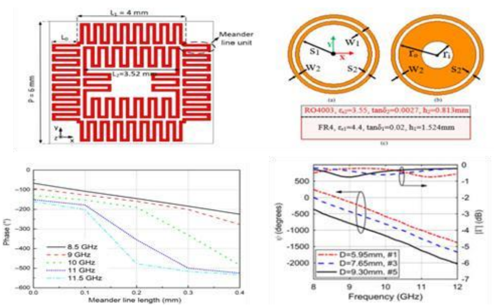


Fig. 11. Unit cells geometry and measured reflection characteristics [52], [53]

IV. Conclusion

Reflectarray antennas have great potential for 5G wireless systems because of its notable advantages such as high gain, beam scanning flexibility, lightweight design, and cost-effectiveness. This study presents a detailed comparison of several wideband reflectarray topologies, showcasing their ability to attain gains greater than 25 dBi and bandwidths surpassing 10%. These antennas have the ability to function across a wide range of frequencies, namely from X-band to Ka-band. Additionally, they possess the capability to scan beams up to 50° for designs that can be reconfigured. However, further progress is required in areas such as dynamic range, efficiency, and integration in order to facilitate practical applications. However, more research and development are necessary to enhance the bandwidth, gain, and beam steering performance for practical applications.

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