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TOPICAL REVIEW

State-of-the-Art Passive Beam-Steering Antenna Technologies: Challenges and Capabilities

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ABSTRACT This article reviews the latest developments of beam steering antennas that are entirely passive to realize interference-free, power-efficient, and highly secured end-to-end wireless communication. We briefly introduce metamaterials and metasurfaces, a timely advanced topic in electromagnetics (EM) and optics. Mathematical formulas associated with the design of beam steering metasurfaces have been numerically explained. In addition, reflect and transmit array antennas are also discussed for an in-depth understanding of beam scanning principles in elevation and azimuth planes. We then provide intuitive design examples and discuss three broad classes of the latest beam scanning antenna systems, namely 1) Reflectarrays (RAs); 2) Transmitarrays (TAs); and 3) Near-Field Meta-Steering (NFMS) antennas that are available in up-to-date literature. The third category's unprecedented scanning performance and aesthetically compact size are elucidated compared to previous antenna systems, such as reflector dishes or large phased arrays. Alongside the working principles, the trade-offs for the scanning techniques, operation, and physical size of each antenna type are also discussed. Towards the end, an evaluative conclusion with a comparative discussion on the beam-steering antenna systems is provided. Future research directions considering mass-market demands are also indicated.

INDEX TERMS Antennas, arrays, beam-scanning, beam-steering, feed-tuning, global connectivity, high-gain, metamaterials, metasurfaces, near-field meta-steering, phase gradient, phase correction, phase transformation, reflectarrays, satellite communication, high-power, space, transmitarrays, CubeSat.

I. INTRODUCTION

Beam-steering antenna systems have been at the pivot of an extensive range of applications from the Ocean to Earth and Space communications [1], [2], [3], [4], and some are shown in Fig. 1. The ability of beam-steering antenna systems to offer interference-free, power-saving, and highly secured end-to-end communication has caused incredible interest. Moreover, through technological advances and multi-billion-dollar investment from the private sector, satellite communication (SatComm) has been reviewed as a cornerstone in satisfying high-speed, heterogeneous, ultra-reliable, and low-latency communications. Alongside its preexisting popularity in defense, SatComm has recently garnered significant interest in many non-military and civilian applications. The key element in the success of this satellite-based technological solution is a highly directive beam-steering antenna that can transmit energy in a focused beam towards the satellite seamlessly, even when both the satellite and ground stations are non-stationary. Satellite-based communication systems also need simultaneous dual-band beam-steering capability for the front-end antenna to support uplink and downlink data streams. In addition, the antenna system must be lightweight, low-profile, low-power driven, and easy to manufacture for mass-market production. Besides physical constraints, the associated cost (more than 90%) of deploying antenna technology for SatComm-on-the-Move (SOTM) terminals is one of the prime issues [5], [6], which poses intense R&D challenges for antenna engineers to shape and fit the antenna system for consumer and industrial grade applications.

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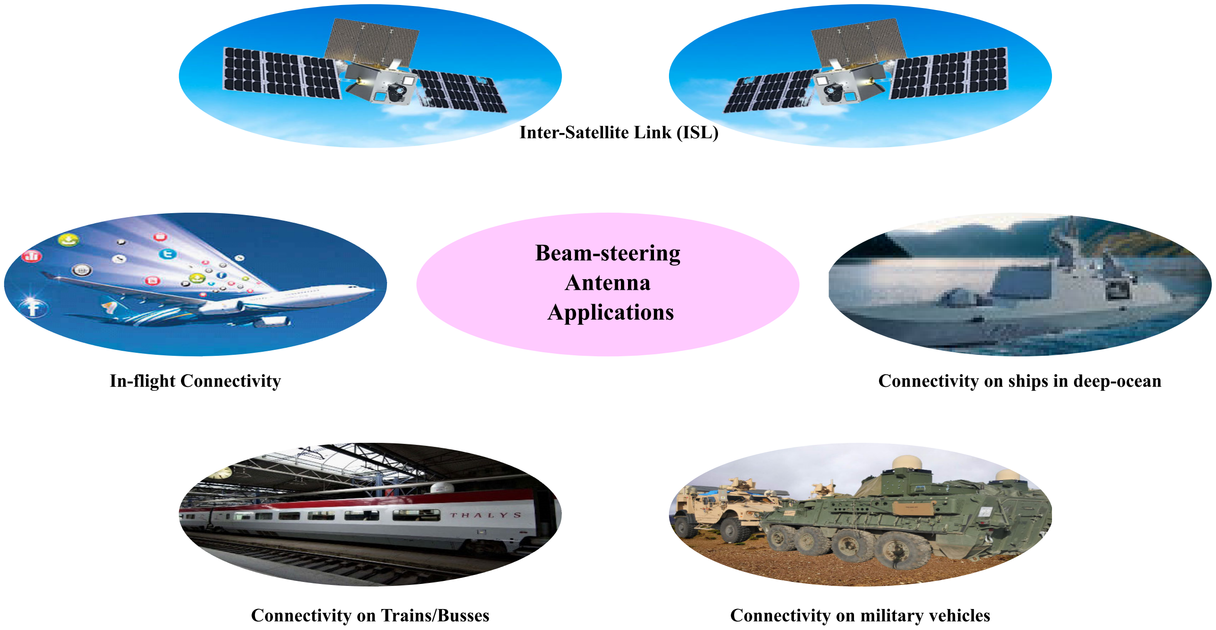


FIGURE 1. **A few potential areas of applications for the beam-steering antenna technologies.**

Over time, antenna research communities have devoted their time and thought to developing beam-steering antenna systems to fulfill the current demands of civilian and defense mass markets. The most conventional solutions are to use mechanical beam-scanning antenna systems, popularly called parabolic reflectors (dishes) [7], [8], [9] that have a large aperture, or electronic beam-scanning antenna systems, usually called phased arrays [10], [11], [12], [13], [14]. Notwithstanding the design aspects, both antenna systems have excellent beam-steering performance, as demonstrated by their widespread use in real-life applications such as cruise ships for satellite TV reception, defense vehicles for satellite communication, and in-flight connectivity [15], [16], [17]. However, parabolic reflectors' design architecture comes at the cost of tall and bulky systems, requiring high-powered, complicated mechanical control devices or expensive advanced feed clusters [18]. On the other hand, the complex feed networks, numerous antenna elements, and the phase shifters used in the design of phased arrays are prohibitively complex and expensive [19]. Besides, thermal management of the array in the active phased array is another practical limitation for high-power applications [16]. A beam-steering approach using antenna arrays without phase shifting circuits has also been demonstrated in [20], but the feed circuit uses Wilkinson power dividers, and each antenna element uses resistors. At higher frequencies, such as Ku-band and beyond, the transmission lines of the power divider will incur heavy losses, and the resistors will behave parasitically. Besides, the feed circuitry will become more complex with the increasing number of antenna elements in the array. Another approach in [21] discusses beam steering using an electrowetting-driven liquid prism. The liquid prism is fabricated using a simple dip-coating method, thereby avoiding the need for the complex and expensive laboratory setup usually required for liquid prisms. Despite the simplicity of fabrication and high beam-steering performance, the highest reported steering achieved is approximately 20°, significantly less than other more popular methods such as parabolic dishes and electronically steered phased arrays. These physical and economic challenges restrict the applications of such technologies to scenarios with cost and space constraints, such as satellite communication on-the-move terminals. Therefore, improving the traditional beam-scanning antenna system demands a new perspective.

Refelectarray (RA) [22] and transmitarray(TA) [23] antennas have several promising merits over reflectors and phased arrays, such as design simplicity and ease of manufacturing, good efficiency, relatively lightweight and high gain. These features have attracted a large antenna research community and led to excellent research outcomes over the years. Metamaterial and metasurface-based antennas have recently been used actively in satellite communication, radar, and telecommunication applications [24], [25], [26]. Modern satellite communication systems widely use modulated metasurface antennas based on surface wave interactions. In these antennas, the cylindrical wavefront interacts with the metasurface's boundary conditions, creating a leaky wave transformation. The surface wave technology has been implemented to achieve several functionalities, including monopulse radar using multi-port duplexing [27], dual-frequency control by superposition of surface impedance with different periods [28], extreme beam-shaping by changing holography [29] and shared aperture multi-beam antennas [30]. In addition, a seven-beam transparent TA antenna was reported in [31], and a conformal seven-beam TA antenna was recently proposed in [32].

Metasurfaces have been implemented from a completely different perspective as an add-on device to steer the high-gain antenna beam passively, using the principle of the Risley prism. This beam-steering approach offers a more pragmatic and cost-effective solution than the conventional antenna systems mentioned above. These antennas have simple design features and passive beam scanning capability and do not require power-hungry complicated active RF components. Hence, the research on these antenna systems is advancing faster to fulfill the new mass-market demands for low-cost and low-profile beam-steering front-end devices.

Several beam-steering antenna systems with different beam-scanning approaches are discussed in the literature, including mechanical, electronic, hybrid, and electrowetting techniques. Each method has some limitations, including bulkiness, power loss, a non-planar profile, or a low scan range. Passive solutions are inexpensive, less lossy, easily scalable, reproducible, and thermally stable. They do not affect the performance of active RF front-end components and hence are the most sought-after. This review article is an scientific resource compiling the state-of-the-art passive beam-steering technologies that would be helpful to the industry, academia, and research organizations to make an educated decision when selecting/designing consumer-grade beam-steering antenna systems. A comparative analysis of the electrical performance and technical features of traditional beam-steering approaches based on TAs and RAs with respect to modern metasurface-driven beam-steering technology is an essential feature of this study as it serves as a precursor to understanding beam-steering principles in general. To this aim, the article provides an in-depth review of three broad classes of the latest passive beam-steering antenna systems, namely: i) Reflectarray, ii) Transmitarray, and iii) Near-Field Meta-Steering antenna systems. Unlike other available survey papers that discuss beam-steering mechanisms either in general [33], electronic [34], TA or RA-based beam-steering technologies [35], [36], [37], [38], [39], this article is focused explicitly on future shaping passive technologies that are key enablers for affordable global connectivity.

Section II presents a basic understanding of RAs, RAs, metamaterials, and metasurfaces. The available beam scanning methods in elevation and azimuth planes and their associated mathematical derivations are presented for in-depth knowledge of beam steering concepts. Building upon these fundamental insights, Section III provides an intuitive discussion of three major beam-scanning antenna systems available in the up-to-date literature. Each category is further sub-grouped and discussed based on the beam-steering principle they have used. The trade-offs governing each class's design and operation to find more research gaps in this domain are identified. Section IV draws a comprehensive comparison to predict future research openings considering new mass-market demands and summarizes the article with critical concluding remarks.

II. BACKGROUND

The attempt to gain unprecedented control over EM waves using thin subwavelength interface discontinuities is an ongoing endeavor and, in the process, has elicited several other technologies such as RAs, TAs, and metasurfaces. This section will briefly discuss the definitions and technical distinctions underlying RA, TA, and metasurface. Various beam-steering technologies that are followed to realize passive beam scanning in medium-to-high gain antennas are discussed in the next section.

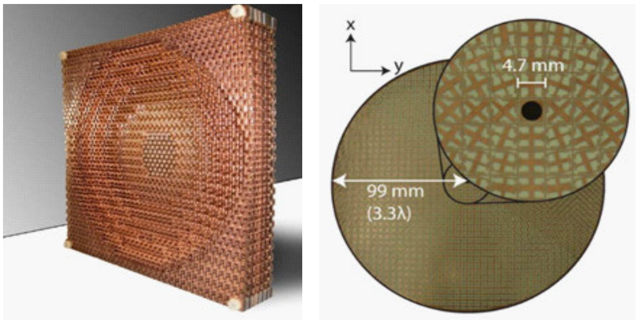
A. REFLECT AND TRANSMIT ARRAYS

Reflectarrays [22] and transmitarrays [23] are spatially fed high-gain planar antennas composed of subwavelength arrays of metallic patches and typically function as flat parabolic reflectors and flat lenses, respectively. In these antennas, the field radiated by a feed source located at the focal point reaches the array elements on the aperture with different phases due to different path lengths. Each TA/RA element is designed to compensate for this phase difference, and an in-phase field is re-radiated in a desired direction. The RAs redirect the waves in the same side as the source, whereas the TAs re-transmit the waves in the opposite direction from the source. A hybrid transmit-reflect array induces bidirectional radiation [40].

The TAs/RAs offer a balanced solution between the bulky parabolic dishes and lossy active phased arrays. Despite their limited scanning capability, TAs/RAs have several advantages over active phased arrays when a high-power amplifier is connected to the feed source. TAs/RAs are excited spatially by a primary feed source and hence do not have a bulky or dissipative feed network, which considerably reduces insertion loss compared to parabolic reflectors and phased arrays.

B. METAMATERIAL AND METASURFACE

Metamaterials are bespoke materials artificially engineered to provide control of EM wave properties, including phase, amplitude, and polarization. The concept of metamaterial was first explored back in 1898 [41], and since then, a series of significant contributions [42], [43], [44], [45], [46], [47] have expanded the capabilities of metamaterials and enriched the field to its maturity. There has been a recent surge in the commercialization of metamaterials due to the advancements in additive manufacturing (3D printing) technology. Metamaterials are composed of many subwavelength scattering elements arranged in a strategic sequence to achieve predefined desired properties. The scattering elements are made of metals, dielectrics, plastics, or any compound form. Most importantly, metamaterials can tailor the wave properties by arranging their constituent elements (also called meta-atoms or unit cells) appropriately with proper physical attributes, including geometry, shape, size, and orientation. Recent advancements have enabled the application of metamaterials in critical areas such as cloak devices [48], [49], super-lens [50], [51] and antennas [52],



(a) (b)

FIGURE 2. **Photos of (a) Metamaterial [55] and (b) Metasurface [56] Lenses.**

[53], [54]. Despite their favorable properties, their applications are limited due to space constraints, especially at micro- and nano-scales since they are bulky 3D structures, as shown in Fig. 2(a).

Metasurfaces (MTSs) have emerged as a planar alternative (2D surface) to metamaterials. As such, they are lightweight, easy to fabricate, and more versatile in applications [57]. Metasurfaces are also created using a periodic or aperiodic repetition of subwavelength unit elements like metamaterials. They can uniquely manipulate the transmitted, reflected, and refracted waves in microwave and optical domains. Due to their thin profile and other attractive features, MTSs have a wide range of applications [58], [59]. However, the major challenge of metasurface-based antennas is that the constituent elements of MTSs are narrow-band due to their resonant nature, restricting their application in a wideband application. A photo of a conventional metasurface lens is shown in Fig. 2 (b). MTSs are also called Metafilms and Metascreen [59], [60], [61].

III. BEAM-STEERING METHODS

Several beam-steering techniques have been proposed to steer the main beam in the desired direction. The three main approaches that can efficiently realize passive beam-steering antenna systems are shown in Fig. 3. They are (i) aperture phase-tuning, (ii) feed-tuning (or translation), and (iii) near-field meta-steering or hybrid approaches. However, none of the techniques could be a single, supreme choice – every method has pros and cons.

In the phase-tuning approach, each element's phase can be controlled individually either by a delay-line microwave network, by changing the geometrical dimensions of the scattering elements, or by rotating the elements on the aperture of the metasurface [62], [63], [64], [65]. The dimensional changes or rotational orientation of the elements can be further realized either electronically, mechanically, or passively.

In the feed-tuning approach, the main beam is scanned by changing the feed's phase center via feed translations [68], [69], [70]. Feed translation can be performed either by in-plane (lateral) displacement or circular-arc displacement of the feed [71] or by using multiple feeds and exciting them one after another [72]. In-plane rotation of the RA/TA or rotation of the whole antenna assembly can also steer the main beam in the off-broadside direction [39], [73]. In some cases, beam steering has also been achieved by using a tiltable ground plane in RA antennas [73]. In a nutshell, a combination of mechanical movement techniques in elements, arrays, and feed levels can be used to scan the beam of RAs and TAs, such as by combining feed displacement and array rotation.

In the third category, the beam can be scanned in the elevation, azimuth, or both planes just by mechanically rotating a pair of phase-gradient metasurfaces based on the concept of the Risley prism [67]. The feed antenna is entirely fixed, and a pair of identical (but not mandatory) metasurfaces are placed in the near-field region of the feed. The main beam's projection can be determined based on the Risley prism concept discussed here briefly to better understand the near-field meta-steering approach. Since the 1960s [74], the Risley prism has been dominantly used as a beam steering technique in the optical domain. A Risley prism system, as shown in Fig. 4 (a), is typically made of two prisms, Π_1 and Π_2, which are independently rotatable about the direction of propagation (along the z-axis). If an incoming ray passes through the prisms, the final beam pointing position (θ, ϕ) will be varied and defined based on the refractive indices ($n1$, $n2$) and orientation angles (θ_1, θ_2) of the two prisms.

The same approach is useful to steer the beam in the microwave domain by rotating two metasurfaces mimicking prisms. The beam deflection angles can be determined using a first-order paraxial approximation method discussed in [66] and [75]. TM1 and TM2 denote the two independently rotatable metasurfaces atop a fixed beam antenna, as shown in Fig. 4 (b). ψ_1, ψ_2, δ_1, and δ_2 are the corresponding orientation angles and individual beam tilting angles of the two metasurfaces, respectively. Here, it is essential to mention that the beam tilting angle, δ_i for each metasurface can be defined at the design level of MTSs following (1), where $\Delta\phi$ and Δd are the progressive phase delay and center-to-center distance between adjacent cells, respectively. However, the magnitude and direction of the resultant vector OC (Fig. 5) define the antenna's beam position (θ, ϕ). The elevation angle θ and azimuth angle ϕ of the beam can be computed using equations (2) – (6).

$$\delta_{i/j} = \sin^{-1}\left(\frac{\Delta\phi}{2\pi} \times \frac{\lambda_0}{\Delta d}\right) \tag{1}$$

$$\theta = \sqrt{\left(\delta_i^2 + \delta_j^2\right)} = \sqrt{\delta_1^2 + \delta_2^2 + 2\delta_1\delta_2\cos\left(\psi_1 - \psi_2\right)} \tag{2}$$

$$\angle OC = \tan^{-1}\left(\frac{\delta_j}{\delta_i}\right) = \tan^{-1}\frac{\delta_1\sin\left(\psi_1\right) + \delta_2\sin\left(\psi_2\right)}{\delta_1\cos\left(\psi_1\right) + \delta_1\cos\left(\psi_2\right)} \tag{3}$$

$$\phi = \begin{cases} \angle OC, & \delta_i \geq 0, \delta_j \geq 0 \\ \angle OC + 180^\circ, & \delta_i < 0 \\ \angle OC + 360^\circ, & \delta_i \geq 0, \delta_j < 0 \end{cases} \tag{4}$$

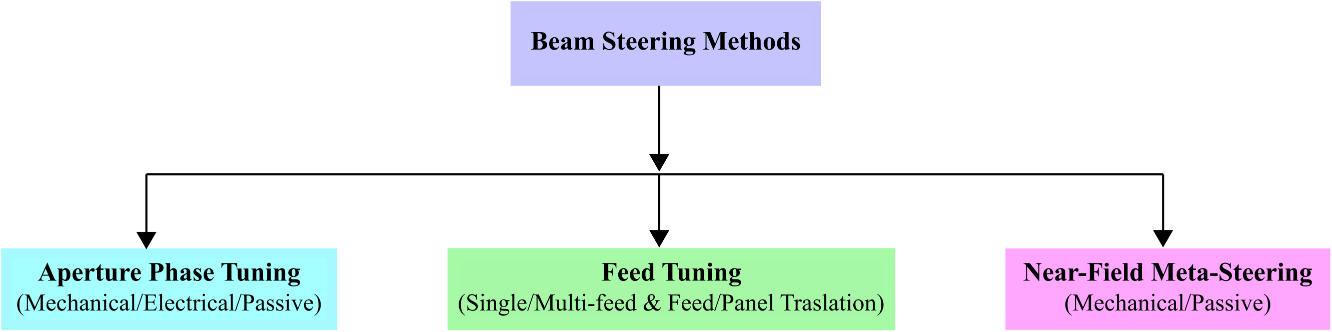
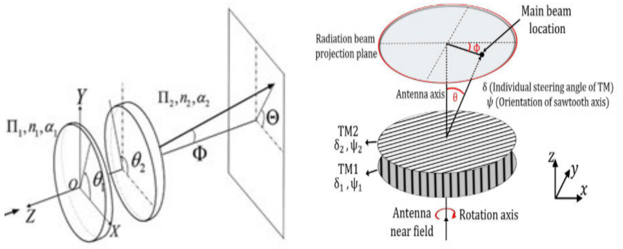


FIGURE 3. Three main categories of passive beam-steering techniques widely accepted to design beam-scanning antenna systems for emerging and future wireless networks.



(a) (b)

FIGURE 4. Notations and coordinate systems for (a) Risley prism system [66] and (b) Near-field meta-steering system [67].

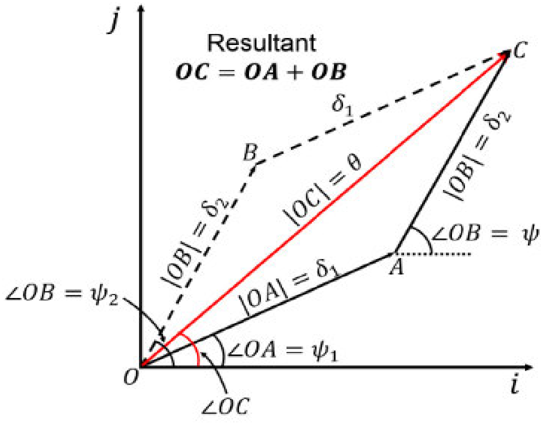


FIGURE 5. Beam pointing system based on the first-order paraxial approximation method [67].

When the two MTSs have equal beam-tilting angle, i.e. $\delta_1 = \delta_2 = \delta$, (2) and (3) can be further simplified as follows:

$$\theta = \sqrt{2\delta^2 \left(1 + \cos\left(\psi_1 - \psi_2\right)\right)} \tag{5}$$

$$\angle OC = \tan^{-1} \frac{\sin\left(\psi_1\right) + \sin\left(\psi_2\right)}{\cos\left(\psi_1\right) + \cos\left(\psi_2\right)} \tag{6}$$

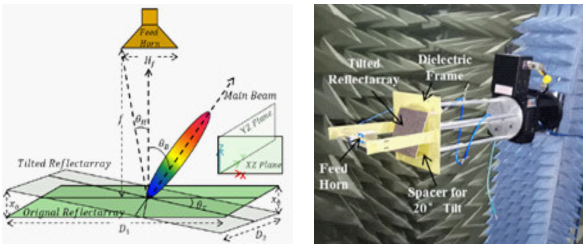
Using equations (2) – (6), one can calculate the beam position (θ, ϕ) of an antenna system in terms of synchronous co-rotation or counter-rotation of metasurface pair or only by rotating one while the other is fixed. However, the first-order paraxial approximation method cannot predict the beam pointing position accurately as expected when the beam deflection angle is large enough [66]. This phenomenon was further explained and verified more intuitively in [76], where the authors suggested a new phase method to predict the steering angle more accurately in case of a larger beam deviation in the elevation plane.

Modulated metasurface antennas, as demonstrated in [29], have piqued the interest of space scientists. A modulated metasurface antenna can generate a high-gain pencil beam in the broadside direction or at a desired offset [77]. Multiple beams can also be created from a single aperture of modulated metasurface antenna by using multiple feeds and implementing the principle of superposition [78], [79]. However, a complete 3D beam-scanning has not been realized yet in such modulated metasurface antenna. Near-field meta-steering technology can be implemented to overcome this limitation, and the modulated metasurface antennas can be used in conjunction with a pair of phase-gradient metasurfaces to achieve dynamic beam-steering in a large conical volume.

A. BEAM-STEERING REFLECTARRAY ANTENNAS

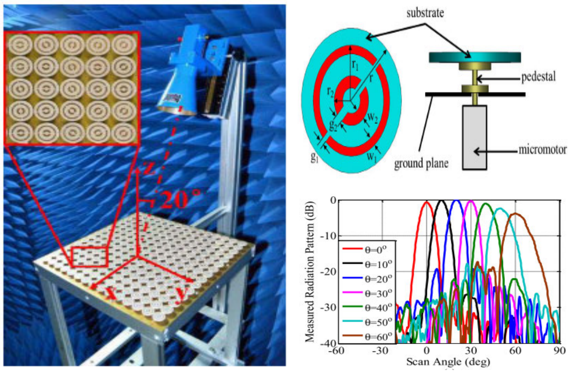
Technically, RA antennas combine the positive features of reflectors and phased arrays. They are low-profile, relatively lightweight, and easy to prototype compared to parabolic reflectors or dishes. Most importantly, RAs have both passive and electronic beam-steering capabilities without the need for any power dividers or additional phase shifters [80]. Furthermore, the independent phase control capability of each element on the aperture of RA has added an extra degree of freedom to the design of high-gain beam-steering RA antennas. Besides, the phase can be manipulated by in-plane feed translation, feed rotation, or tuning the spatial delay. This section presents and discusses promising design concepts and techniques to realize beam-steering RA antennas. Associated pros and cons are also indicated for further research directions.

The beam-steering RA antenna systems using the feed-tuning technique are investigated and presented in [68], [69], [71], [72], [81], and [82]. The study reveals that the feed translation approach is preferable only for limited field-of-scanning systems [68]. It is also observed that the gain loss is severe when the beam is scanned far away from its broadside direction. The performance can be enhanced by



(a) (b)

FIGURE 6. **A 20 × 20 element beam-steering RA antenna (a) a schematic representing tilting panel and coordinates, (b) prototype in a chamber measurement setup [85].**



(a) (b)

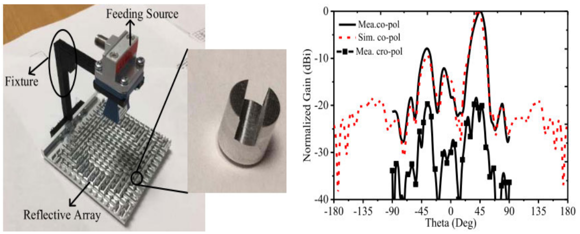
FIGURE 7. **A 15 × 15 element beam-steering RA antenna (a) prototype, (b) mechanically rotatable element and far-field pattern cuts [86].**

improving the F/D ratio, but it also increases the antenna profile. Later, wide-angle beam-steering RA antennas were reported based on hybrid approaches [69], [81], [82]. In [69], ±60° scan coverage with 30 dBi gain, minimum scan loss, and low side-lobe level (below 15 dB) was achieved using a feed displacement and bifocal aperture phase distribution method. The measured results also confirm that the beam-scanning performance is better due to bifocal aperture phase distribution than the parabolic aperture phase method. Besides, a bifocal RA with an optimized phase distribution function can further improve the beam-scanning range and gain performance [83]. In addition to the bifocal design method, the offset feed structure further eliminates the feed blockage problem and improves the scanning performance significantly by achieving a maximum gain of 36.4 dBi, aperture efficiency of 51.4% and scan loss of about 1 dB within ±15° scan angles [84]. The major limitation of this design approach is that the feed (horn) needs to be rotated mechanically [71], [84], which requires a high-powered motor and may also degrade the scanning speed.

The scan angle was further improved up to ±70° by combining feed displacement and in-plane rotation of the RA panel [82]. However, the main beam can be steered in one plane (1D) only, and scanning loss is around 4.9 dB in the worst-case situation. The radiation pattern will be degraded due to the phase alteration caused by defocusing feed, which is the major limitation of feed tuning approaches. On the other hand, the 2D beam-steering RA can be realized only by rotating the flat RA panel while the feed is fixed at its focal point [85]. In this design approach, the panel is first designed using the ray tracing method and tilted to a certain angle in a plane (here in *xz*-plane) to overcome the feed blockage problem, as shown in Fig. 6, and this tilting effect steers the beam in the azimuth plane. Then, it is rotated mechanically along the orthogonal plane (here in *yz*-plane) to steer the beam in the elevation plane. Using this scanning approach, authors in [85] have demonstrated a wideband (7% to 13.1%) wide-angle (±60°) beam-scanning RA having a maximum gain of 26.47 dBi with 6.62 dB scan loss. However, the technique has a limited scanning speed and is unsuitable for space-limited applications as it requires a large volume to rotate the panel vertically. The panel rotation is also sensitive to F/D; hence, it might change the phase progression and degrade the scanning performance.

The rotating elements approach was demonstrated in [62] and [63]. Each element is rotated mechanically using low-powered micro-motors and acts as a localized spatial phase shifter. A 10° beam defection from its broadside direction was observed when each disc was rotated 45° with respect to the adjacent disc. However, the proposed system has limited scanning performance as well as low scan rates. A broadband wide-angle beam-steering RA antenna realized by mechanically rotating phase elements or controlling the height of the phase elements was demonstrated in [87], [88], [89], and [90]. A 15 × 15 rotatable elements beam-steering RA was fabricated, and its performance was investigated in [86] and [89]. Excellent performance was achieved in terms of wide-angle scanning (±60°), aperture efficiency (51.8%), and operating bandwidth (28.6%). The maximum gain is 25.6 dBi, whereas the scan loss is 3.7 dB in the worst-case scenario. A schematic model of the rotatable unit element, a fabricated prototype, and scanning far-field pattern cuts are shown in Fig. 7.

An alternate design approach was presented in [90], where the phase shift range of up to 324° was achieved by mechanically tuning the height of the slotted patch of the unit cells of RA. The antenna prototype having a 528 mm ($8.5\lambda_0$) diameter circular aperture was fabricated and tested. The measured results indicate an excellent scanning performance up to ±60° within the 3.4 dB scanning loss while maintaining the maximum gain of 25.7 dBi, aperture efficiency of 48.6% and 1 dB gain bandwidth of 6.2%. The merit of this approach is that the phase can be controlled in real-time. However, it also has its inherent cons, such as feed blockage issues, and requires numerous microcontrollers or actuators to control the height of individual unit cells, which increases the prototyping cost and complexity, especially when the RA size is considerably large. Each microcontroller or actuator must have precise tuning capability to avoid positioning errors in the unit cells. Most notably, it should have a minimum height variation of the phasing elements to achieve the desired phase



(a) (b)

FIGURE 8. (a) Fabricated prototypes of all-metal beam-steering RA and (b) far-field pattern cuts at $\theta = 45°$, $\phi = 45°$ [64].

shift; otherwise, it will negatively impact blockage effects caused by adjacent unit cells.

The authors of [64] have recently presented mechanically rotatable, fully metallic elements to construct an efficient wideband beam-steering RA antenna system. The proposed unit element can achieve a 1-bit reflection phase (0 and π) both for TE and TM normally incident waves, and hence, fit for dual-polarized feed antenna as well. The main beam can be scanned easily by adjusting the rotation of every corresponding unit element. The measured results validated the design concepts successfully. A prototype was fabricated, and performance was measured for six different main beam directions. It was observed that the maximum gain variation is 2 dB when the main beam is at 60° off-broadside. The photos of the fabricated prototype and unit element are shown in Fig. 8. The proposed antenna system does not require any active RF components to steer the main beam. The lack of dielectric substrates also ensures the antenna system's high efficiency and high-power handling capability. However, bulkiness might be a bottleneck for this type of metallic phasing element.

In a recently published article, a hybrid design technology is used, and a combination of 3D printed lens antennas with retro-directive feed and microstrip patches is used to design the reflective surface [91]. Each lens antenna is four times the size of the microstrip patch, and the inter-lens distance is more than one wavelength. Thus, replacing microstrip patch elements only at the edge of the reflecting surface with lens antennas reduces the required number of phase shifters and does not limit the beam scanning performance, which is essentially a limitation of lens antennas. Like conventional RA, the edge elements (lens antennas) are fed with low power. The assembly of this reflecting surface with a feed horn results in a low-cost passive beam-steering RA antenna when microstrip delay lines replace the phase shifters.

B. BEAM-STEERING TRANSMITARRAY ANTENNAS

Transmitarray antennas also possess the same positive attributes as RA antennas over reflectors and phased arrays. Unlike RAs, TAs are free from feed blockage problems due to the location of feed sources behind the radiating aperture and the highly transmissive nature of TA. Recently, beam-steering TA antennas have been an alternative in many modern wireless communications systems as front-end RF devices. This section presents the remarkable performance of passive beam-steering TA antennas by providing promising design examples. Wherever possible, the inherent design and technical pros and cons will be discussed in order to broaden the scope of future research.

The beam-steering TA antenna using the feed-tuning technique has been investigated in [92]. By exciting the selected two out of eight patches (as a feed source) placed beneath a transmitting metasurface, the beam can be steered to a maximum angle of ±40° in the elevation plane only. This approach is typically limited to narrow-band with 1D selected/small-angle scanning performance. In [70], [93], [94], [95], [96], and [97], a hybrid approach was investigated to develop two-dimensional beam-steering antenna systems. The in-plane translation (in the lateral axis) of a thin flat lens over a fixed primary feed is used to rotate the beam into the elevation plane. In contrast, either in-plane rotation of the lens or rotation of the whole antenna system provides full azimuth beam steering. A circular polarized Ka-band beam-steering TA was proposed in [70] to achieve an outstanding gain of 27.3 dBi with 2.8 dB scan loss and wide-scan angle of ±50° in the elevation plane. A new auxiliary-lens-feeding technique was introduced, which reduces the F/D ratio to 0.55 and hence lowers the overall antenna profile significantly. However, a common challenge of this approach is having a larger lateral dimension for translation. The lens displacement also increases the level of pattern aberrations and scan losses, which were further resolved by developing bi-focal planar lenses [94].

The first attempt to demonstrate a dual-band circularly polarized beam-steering TA antenna for Ka-band satellite-on-the-move terminals was presented in [95]. The authors have developed a generalized formula and strategy to design dual-band phase delay cells, which are the most critical component to realizing dual-band beam steering TAs. The mechanical beam-steering strategy was followed to steer the beam in the 2D plane. A ±50° beam deflection in the elevation plane is obtained through in-plane feed translation, whereas the azimuth plane scanning requires in-plane rotation of the entire assembly. The measured maximum gain is 24 dBi within the scan loss of 3.6 dB at 20 GHz and 27 dBi within the scan loss of 3.3 dB at 30 GHz. The photographs of the fabricated TA and its unit element are shown in Fig. 9. Later, the dual-band beam-steering performance of two independent linearly polarized feeds was investigated in [98]. The TA is made of interleaving unit cells and shares the same physical radiating aperture. The prototype demonstrated a high gain of 25.9 and 29.0 dBi at 19.5 and 29 GHz, respectively, with an aperture efficiency of more than 20%. However, it has a limited beam scanning range of ±20° due to the increase of spill-over losses while the feed is translated off the TA's center.

The beam-steering performance of a circularly polarized (CP) feed was presented in [97] based on two different TAs comprised of phase delay (PD) and phase rotation (PR) scattering elements. The study reveals that the PD cells

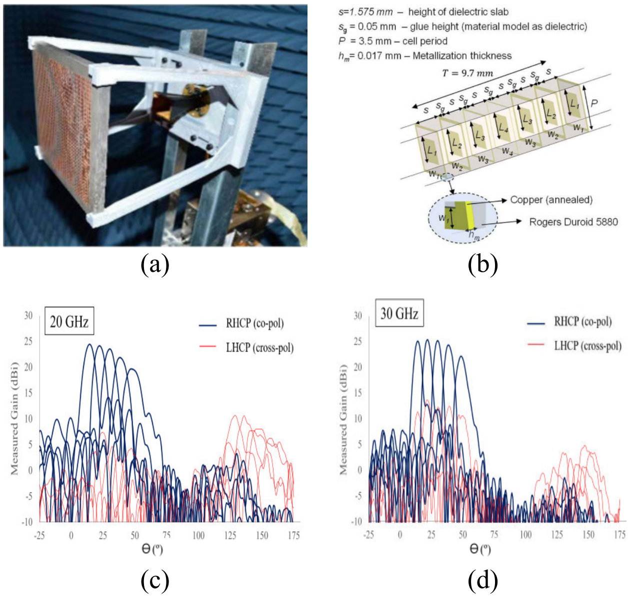


FIGURE 9. The photographs of (a) fabricated TA, (b) constituent unit element, and (c)–(d) far-field pattern cuts of the scanned beam [95].

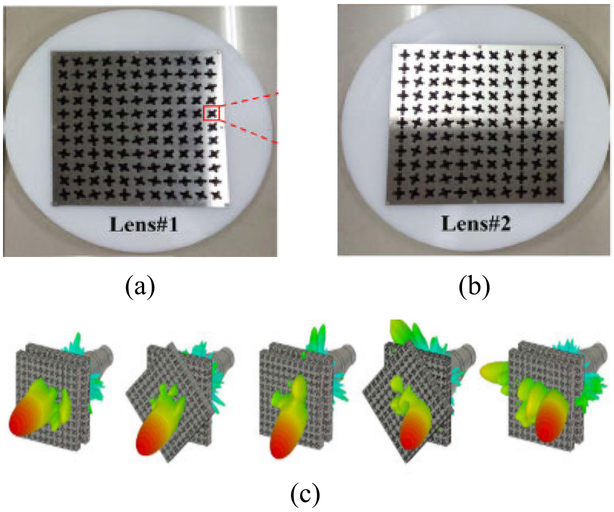


FIGURE 10. Cross-slot-based all-metal TA. (a) lens-1, (b) lens-2 and (c) 3D view of steered beam patterns showing feed antenna and lenses [65].

also correct the phase of the cross-polarized transmission coefficient like co-polar components, which increases the cross-polar level and degrades the axial ratio of the main beam. On the other hand, unlike PD cells, PR cells do not refract the cross-polar components. Hence, the TA with PR outperforms the TA with PD in terms of better axial ratio (AR) and 3 dB AR bandwidth, as the PR cell can filter the cross-polarization effect significantly. In contrast, PD cells have greater design flexibility, a wider operation bandwidth, and less sensitivity to feed polarization. Nevertheless, both cells reflect the back lobe at $(180^\circ - \alpha^\circ)$, where α° is the direction of the main beam of the feed to be deflected by the TAs. However, both TAs have the same beam scanning performance from 17° to 50° at 30 GHz. The scan losses are less than 2.8 dB and 3 dB up to 50° tilt angle for TAs with PD and PR, respectively. The 3 dB gain bandwidths of PR and PD TAs are 1.9 GHz and 2.2 GHz, with a maximum gain of 29.1 dB and 29.5 dB, respectively. Later, the authors proposed a dual-band beam-steering TA using a linear-to-circular polarization converter instead of an actual CP feed [99].

Interestingly, based on the Risley prism concepts discussed in Section II, several beam-steering TAs using meta-steering principles were also developed and presented in the literature [65], [100], [101], [102]. In [100], two linear phase progressive phase-shifting surfaces (LPP-PSSs) were rotated mechanically over a fixed beam feed (horn) to achieve 2D beam steering at 30 GHz. Excellent scanning performance was achieved with a scan angle of ±70° and a maximum realized gain of 24.5 dBi. The concept was further explored by designing an all-metal metasurface-inspired 2D beam-steering circularly polarized TA at X-band [65]. The unit element was made of cross slots drilled into metal plates and several metallic waveguides. The total phase-shift range from $0^\circ - 360^\circ$ was achieved by manually rotating each element. The two lenses are placed at the focal point of a primary feed (i.e., horn) and rotated mechanically to steer the beam in both the elevation and azimuth planes. The proposed TA shows narrow-band performance and higher SLLs but has an excellent power-handling capability of about 4 GW for a 1 m^2 TA. The all-metal lens and its 3D view are shown in Fig. 10.

Recently, the idea of mechanically rotatable metasurfaces to steer the beam to an off-broadside direction was further demonstrated in [102] to design a dual-band TA operating in linear polarization at 8 GHz (X-band) and 14 GHz (Ku-band). In this design, an anisotropic lens was used to transfer the spherical phase front into the nearly uniform phase front. Two standard x- and y-polarized horns were used as the feeds. The 1^{st} MTS was placed at 10 mm above the lens, and the 2^{nd} MTS was placed 5 mm atop the 1^{st} MTS. While these two MTSs are rotating independently, the main beam can be scanned around ±52.7° at 8 GHz and around ±49.5° at 14 GHz in the elevation plane. The scan losses are about 5.3 dB at 8 GHz and 5.4 dB at 14 GHz when the beam is at the extreme elevation angle.

A hybrid metal-plasma TA antenna with beam-scanning capabilities is presented in [103]. A novel low-cost wide-angle beam-scanning TA using lens-loaded patch elements is presented in [104]. A hybrid combination of lenses and patches in the TA reduces the number of phase shifters, thereby reducing overall cost. Quite recently, the authors in [105] introduced the concept of offset unifocal phase symmetry to improve the performance of mechanically beam-steerable TA antennas, which is also applicable to mechanically beam-steerable RA antennas. The beam-steerable TA antenna enabled by the offset unifocal phase symmetry achieved a smaller gain roll-off than that of the unifocal beam-steerable TA antenna, higher realized gains than the counterparts of the bifocal beam-steerable TA antenna and outperformed both the unifocal and bifocal beam-steerable

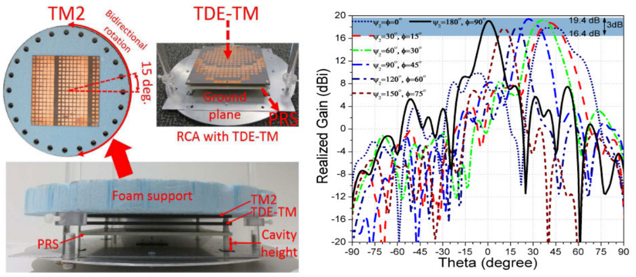
TA antennas in terms of the side-lobe levels of all scanning beams.

C. NEAR-FIELD META-STEERING ANTENNA SYSTEMS

Low-profile antennas are considered the primary feed in the third category of beam-steering antenna systems, such as resonant cavity antennas (RCAs), patch antennas, and continuous transverse stub (CTS) arrays. The horn can also be used as a feed to demonstrate the NFMS antenna system, but most importantly, the near-field phase transforming structures or metasurfaces are placed just above the feed (typically $< \lambda/2$) in its near-field region. Hence, it reduces the antenna profile significantly compared to RAs and TAs. Moreover, the F/D ratio need not be obeyed even when the horn is used as a primary feed. In this framework, the low-profile beam-steering antenna system can be realized either by i) in-plane translation and rotation of metasurface(s) and feed tuning approach [106], [107], [108], [109], [110] or ii) near-field meta-steering approach where a pair of phase gradient structures/metasurfaces is rotated along the axis of propagation while the feed antenna is fixed [67], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120]. The first approach has limited scanning ability, whereas the latter has a sophisticated design and excellent 3D beam-steering performance. Some of the most relevant design examples based on both approaches are outlined in this section.

A hybrid phase gradient metasurface (PGM) was proposed and demonstrated to steer the beam of a patch antenna [107]. The PGM is made of two different phase profiles varying radially and linearly; hence, it works as a phase-correcting lens. However, the PGM is placed at $0.43\lambda_0$ away from the feed, and the in-plane translation and rotation of the PGM can steer the beam in both elevation and azimuth planes, respectively. The proposed antenna is low profile but has a narrow band and poor scanning performance (only ±18°). Rather than the in-plane translation of MTS, the beam can be scanned in the upper hemisphere by rotating a planar semi-circular metasurface atop a patch antenna in [108]. In [109], the low-profile beam-steering antenna was developed based on the feed-tuning technique. Here, the beam-steering concept involves the excitation of slots with a varying phase difference, which essentially excites each element of MTS sequentially with a progressive phase delay; hence, beam-steering functionalities are observed. However, the major limitation is that the beam can be scanned only in the elevation plane (1D) with a maximum scan angle of ±30°.

Flat-topped beam antennas provide improved link budget and uniform coverage in a certain angular space; hence, they have potential applications in wireless communication as well as radar and microwave wireless power transmission applications. A flat-topped beam-steering antenna was presented in [110] comprising of a linearly graded index metasurface (LGIMS) and a radially graded index metasurface (RGIMS) placed over a microstrip patch antenna (MPA). The fundamental unit cell of metasurfaces is made of a double-sided, double-circular ring resonator, and the required transmission characteristics are obtained by varying the radius of the inner and outer CRRs. The unit cells of LGIMS and RGIMS are fashioned in such a way that they can provide the negative graded refractive index region along the x-axis and radial direction. In this design, the 2D beam-steering concept is achieved by moving the LGIMS and RGIMS in linear (along the x-axis) and angular axes (clockwise rotation), respectively parallel to the primary radiator, MPA (feed) or vice versa. Hence, its deployment is relatively difficult in a space-confined, fixed-volume application domain. The proposed antenna has a maximum gain of 14.82 dBi and a scanning angle of ±50° within 1 dB gain variation. At the design frequency of 10.1 GHz, the excellent flat top response was achieved in the case of linear and angular motion of the metasurfaces. However, the antenna operates in linear polarization and shows extremely narrow-band performance.



(a) (b)

FIGURE 11. Low-profile beam-steering antenna (a) 3D view of antenna prototype and (b) far-field pattern cuts at 11 GHz [67].

Besides the low-profile beam-scanning approach, 3D beam-steering antenna systems using the meta-steering concept have been successfully demonstrated. The authors in [67] have proposed a passive, low-profile, and low-cost method to steer the linearly polarized antenna beam in elevation and azimuth planes inspired by metasurfaces. An RCA was used as a feed, and phase gradient metasurfaces were placed in the RCA's near-field region, resulting in a novel low-profile and planar beam-steering antenna system. The main beam was scanned both in elevation and azimuth planes by rotating the two MTSs independently. It achieves ±51° scanning angle within the 3 dB gain variation over the elevation plane with full azimuth coverage. The measured maximum peak gain is 19.4 dBi at 11 GHz. In the worst-case scenario, the scan loss is 1.9 dB while the beam is at ±46° from its broadside direction. The 3D view of the antenna prototype and far-field pattern cuts are shown in Fig. 11. However, the beam-steering performance is excellent for a linearly polarized antenna system at a single frequency only, which is the bottleneck of this prototype. Later in 2021, the same authors demonstrated the continuous beam-steering solution for radial line slot array (RLSA) antennas [113]. The system comprises stationary Ka-band circularly polarized (CP) RLSA and a highly transmitting pair

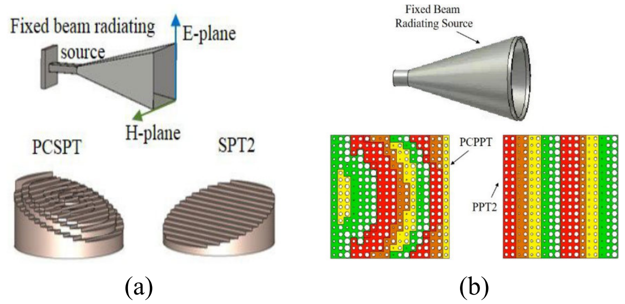


FIGURE 12. **Photo of feed and 3D printed all-dielectric phase-transforming structures to form meta-steering antenna systems, (a) non-planar [115] and (b) planar model [116].**

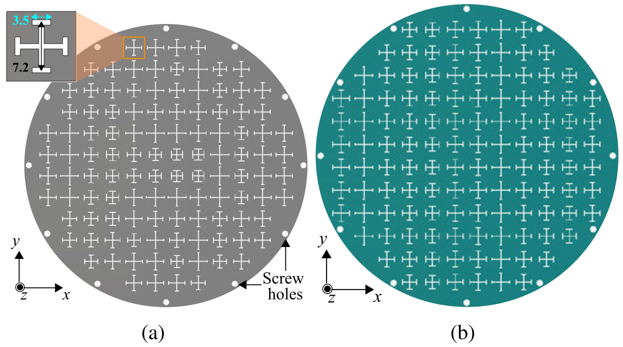


FIGURE 13. **The front view of (a) dual-mode metallic metasurface and (b) phase-gradient metallic metasurface [121].**

of Hybrid Metasurfaces. The metasurface was composed of through-holes drilled in the three stacked layers of dielectric substrates, and four layers of metallic patches sandwiching three layers of dielectric substrates and hence were called Hybrid metasurfaces. They are placed above RLSA in the near-field region and rotated independently to perform beam steering at any azimuth and elevation angle within a large conical region.

In order to improve the spectral efficiency and channel capacity, a dual-polarized (DP) 2D beam-steering antenna system was presented in [114] based on the NFMS concept. The proposed beam-steering antenna system is composed of two main components, namely i) DP CTS array including a line source generator (LSG) and ii) two rotatable flat linear phase progression phase-shifting surface (LPP-PSS). The two LPP-PSSs are placed just above the DP-CTS array and rotated independently, which results in a novel low-profile and planar beam-steering antenna system. The main beam can be steered about ±40° in the elevation plane with a maximum gain of 17.8 dBi and a maximum scan loss of 3.3 dB. However, the operational bandwidth of the antenna system is extremely narrow, which is 1.62% (12.25 to 12.45 GHz). The feed is compact and excites plane waves. However, it possesses significant fabrication challenges due to its numerous metallic reflectors, radiators, and vias, especially for the large array.

Recently, a pair of 3D-printed fully dielectric or metal-dielectric composite near-field phase transforming structures was proposed to realize the beam-steering antenna systems [115], [116], [117], [118], [119]. This literature has resolved the bandwidth issues and demonstrated a good example of low-cost and fast prototyping aspects. The first attempt to overcome the bandwidth issue for a beam-steering antenna in millimeter-wave (mmWave) applications was demonstrated efficaciously in [115] using the meta-steering concept. A pair of stepped-dielectric phase transformers (SPTs) was placed in the near-field region over a fixed beam antenna. Then, both SPTs were mechanically rotated independently around the antenna axis to steer the beam in the elevation and azimuth planes. The complete antenna system, feed, and SPTs are shown in Fig. 12. The excellent steering angle of ±52° was achieved with a maximum scan loss of 3.6 dB over an operational bandwidth of 40.6% (26.5 - 40 GHz). Although the horn is used as a feed source, the overall antenna profile is significantly lower than RAs/TAs as phase correcting stepped-dielectric phase transformer was placed only 1 mm away from the horn, yet the overall antenna height is 14.6λ_0.

Unlike two-stepped dielectric structures developed in [115], a single-stepped dielectric and dielectric wedge were proposed in [117] to demonstrate the beam-scanning performance at mmWave band. The other significant system-level difference is that an RCA fed by a WR28 coaxial to waveguide adapter was used instead of a commercially available WR28 horn, which ensures a 40% reduction of the antenna height compared to the previous design reported in [115]. The proposed antenna shows an excellent beam scanning performance from 29.2 GHz to 30.8 GHz (5.33%) within the 3 dB scan loss while maintaining a maximum measured gain of 16 dBi. The antenna beam can be steered effectively in both azimuth and elevation planes within a maximum apex angle of 68°. Yet, both systems are likely to be bulky and heavy due to the thick all-dielectric phase transformers. Moreover, due to thick dielectric edges, there is a possibility of additional power losses due to lateral propagation and electric field leakage from the sides of the antenna systems, which need to be taken care of at the design level. An updated solution to the issues above was presented in [116], where a pair of planar perforated dielectric phase transforming surfaces were used for beam scanning. The same research group that introduced NFMS further advanced its technology by developing a low-cost, all-metal, 2D beam-steering antenna system suitable for space and high-power applications [121], [122]. Unlike the heavy metallic metasurfaces in [65], the proposed phase gradient all-metal metasurfaces do not require bulky waveguides and can be used with any type of polarized feed antenna. As shown in Fig. 13, the novel Slots-in-Sheet method made the metasurface mechanically robust and kept the system lightweight. The 3-dB scanning bandwidth is at least 700 MHz, and beams can be scanned up to ±42° in the elevation plane. The side lobe level is at least 12.6 dB below the main lobe. By selectively arranging metallic cells

TABLE 1. The performance comparison of three classes of passive beam-steering antenna systems.

Ref.	Steering Technology	Frequency Band (GHz)	Elevation Scan Angle (°)	Scan Loss (dB)	Scanning plane	Maximum Peak Gain (dBi)	3-dB Gain Bandwidth (%)	Antenna Height (λ_0)	Aperture Efficiency (%)	Primary Feed	Polarization
[62]	RA	K (26)	±60	2.0	2D	18.9	20.0	8.8	51.0	Horn	DP
[81]	RA	Ku (12)	±45	1.7	1D	25.6	–	8.1	45.1	Horn	LP
[82]	RA	Ku (12)	±70	4.9	1D	26.2	–	10.12	42.5	Horn	LP
[86]	RA	X (8.3)	±60	3.7	2D	25.6	28.6*	8.4	51.8	Horn	CP
[91]	RA	Ku (12.5)	±30	3.9	2D	22.9	3.2*	–	–	MPA	LP
[63]	TA	X (9.375)	±20	–	2D	–	–	15.3	53.0	Horn	CP
[95]	TA	Ka (20,30)	±51	3.6	2D	24.0 27.0	–	8.0 12.0	23.6 20.6	Horn	CP
[101]	TA	X (8) Ku (14)	±52.7 ±49.5	5.3 5.4	2D	15.8 18.6	–	3.0 5.4	15.6 23.5	Horn	LP
[102]	TA	L (1.07)	±30	3.38	2D	10.3	–	–	–	MDP	LP
[103]	TA	Ku (12.5)	±60	3.5	2D	23.3	7.2	7.9	30.1	Horn	LP
[67]	NFMS	X (11.0)	±51	2.0	2D	19.4	–	1.3	24.5	RCA	LP
[109]	NFMS	ISM (2.45)	±35	-	2D	8.0	4.0	0.07	54.4	Slot	LP
[113]	NFMS	Ka (20)	±46	5.0	2D	30.9	–	3.0	22.0	RLSA	CP
[114]	NFMS	Ku (12.5)	±40	3.0	1D	17.8	1.6	1.17	18.5	CTS Array	DP
[115]	NFMS	Ka (35)	±52	3.6	2D	21.3	40.6	14.6	59.0	Horn	LP
[116]	NFMS	Ka (35)	±54	2.2	2D	21.6	28.6	10.2	–	Horn	CP
[117]	NFMS	Ka (30)	±39	4.0	2D	16.2	–	8.1	–	RCA	CP
[121]	NFMS	Ku (12.5)	±42	4.5	2D	18.8 (Sim.) 16.0 (Mea.)	6.4	4.9	21.35 11.21	Horn	DP

'–' Data is not available, MPA: Microstrip Patch Antenna, CTS: Continuous Transverse Stub, LP/CP/DP: Linear/Circular/Dual-polarized, MDP: Metallic dipole with plasma discharges, *1-DB gain-bandwidth,

that replicate digital bits, such a passive metallic metasurface can potentially be employed to generate multiple beams from a single radiating source [123].

The pattern reconfigurability was achieved passively by modulating the phase distribution in the near-field region of a Fabry-Perot cavity antenna (FPCA). Comprehensive design principles and beam-scanning performance of FPCA using four passive phase shifting surfaces such as wedge-shaped dielectric lens (WSDL), discrete multilevel grating dielectric (DMGD), printed gradient surface (PGS), and perforated dielectric gradient surface (PDGS) have been investigated and discussed critically [119]. By changing the material and refractive index of WSDL, the steering angle in the elevation plane can easily be controlled, whereas the lens rotation moves the beam around the azimuth plane. Hence, a single lens can scan the beam in the 2D plane but is not suitable for continuous beam scanning. Moreover, the lens thickness is proportionally increasing with the increase in scan angle in the elevation plane; hence, relatively thicker lenses are required to achieve a wide scanning range. On the other hand, in DMGD, the phase delay (or phase shifting) profile can be achieved by varying the dielectrics' permittivity or thickness. Materials with variable heights but uniform permittivity are preferable to reduce design complexity. However, this approach is also limited due to its thick and bulky 3D structures. These types of structures have also been investigated thoroughly in [115], [117], and [118]. The PGS and PDGS are well adopted due to their flat profile, low cost, and size. These metasurfaces are made of subwavelength phase-shifting scattering elements, where each element is designed with either multilayered printed metallic patterns mounted on dielectric substrates or perforated bare dielectrics. The required phase shift is achieved for the former element by varying the metallic inclusion size [67]. In contrast, for the latter one, the perforation size (diameters of holes) is changed in dielectric substrates [118]. But, in both cases, an additional bonding technique or a specialized machining facility is required for air-free layering and fine-tiny and precise perforation. However, the scanning performance for all design approaches is good enough within the 2 dB scanning loss while maintaining a maximum peak gain of around 20 dBi. Yet, undesirable SLLs and dominant grating lobes must be minimized to improve overall scanning performance. Nonetheless, the proposed design only applies to a particular frequency in the mm-Wave application. Fig. 14 shows photographs of three passive phase-shifting surfaces.

The inherent challenge with NFMSs is to control the unwanted grating lobes and side lobes which typically appear when the main beam is in the off-broadside direction due to the supercell periodicity in the metasurfaces. Several efforts have been made to address the aforementioned issue in the literature [124], [125], [126], [127], [128] by implementing

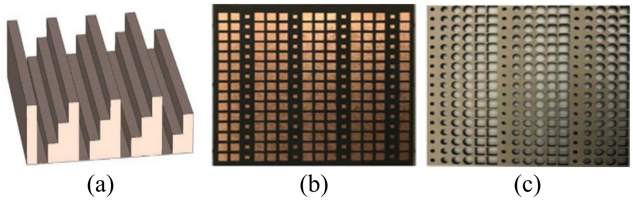


FIGURE 14. Photographs of (a) DMGD, (b) PGS - 4 metallic patches are mounted on three layers of dielectric substrates, and (c) PDGS [119].

Floquet analysis in conjunction with evolutionary algorithms. Most of the non-traditional beam steering systems that use transmitarrays or reflectarrays have narrow gain bandwidth when the beam is steered away from the broadside. The patch-based antenna intrinsically has narrower bandwidth, hence result in narrow band NFMS systems, However, waveguide-based antennas, dielectric-based resonant cavity antennas or horn antennas when combined with the wide-band metasurfaces can give efficient gain-bandwidth performance. The NFMS system designed in [115] uses a horn antenna along with a dielectric stepped phase transformer and exhibits wideband characteristics. Also, in [116] a pair of all dielectric metasurfaces are placed over a wideband horn antenna and the systems exhibits decent gain-bandwidth performance.

IV. COMPARATIVE DISCUSSION AND CONCLUSION

We observe a decent scanning performance in all three passive beam-steering technologies based on the figures of merit for some selective works mentioned in Table 1. They have stable radiation performance with minimum scan loss, even at the farthest scan angles. They are lightweight, low-cost, and low-profile. They can scan and control the beam passively without active RF components, thereby avoiding the necessity of biasing and issues related to non-linearity and RF losses. However, among the three, each antenna system has its own merits and demerits compared to each other. Some are preferable for narrow-band applications, while others have wide-angle scanning facilities. Some function with linear polarized feed sources, while others are perfect for dual and circular polarization. Some of these make an excellent choice for high-power and space applications.

Antennas using feed-tuning techniques usually suffer from pattern degradation due to phase alteration while defocusing the feed. They also have a limited scanning range over the elevation plane (1D scanning system). Simultaneous rotation of the feed and lens can provide a more comprehensive angle scan in both the elevation and azimuth (2D scanning system) planes. However, this technique involves high-powered motors for mechanical rotation and limits the scan speed. Unit elements rotation actuated by micro-motors of the RA aperture could be the alternative to low-power beam scanning systems but still requires many micro-motors.

On the other hand, in-plane translation of TA/RA needs a larger aperture in the elevation plane; otherwise, the spill-over problem will be encountered. Besides, the horn is usually used as a primary feed in beam-steering RA and TA antenna systems, and for optimal gain, the feed should be placed at the focal point of the metasurfaces (i.e., by following the proper F/D ratio) to excite the plane wave, increasing the antenna profile notably. In addition, high-powered motors are required to rotate the entire antenna system to achieve high-performance beam scanning. However, TA holds an advantage over RA by eliminating feed blockage problems and has also successfully demonstrated dual-band beam scanning capability in Ka-band. A significant research gap on dual-band beam-scanning RA has been identified in the literature, which could be an interesting avenue to be explored in the future.

In the near-field meta-steering antenna systems, the feed is fixed, and a pair of metasurfaces rotate to scan the beam in 2D planes without increasing the scanning volume. The metasurfaces are planar, thin, and light in weight; hence, they can rotate by employing low-powered stepper motors. They have a remarkably lower profile as the metasurface pair is placed in close proximity to the near-field of the feed antenna. Though comparable performance is observed in all three steering technologies in terms of gain and aperture efficiency, the NFMS provides the most compact beam-steering solution with a height of about three wavelengths. On the flip side, a dual-band beam steering antenna using the NFMS technique is not explored in the open literature and is a good indicator for future research directions. Such compact NFMS antenna operating in dual-band can be an excellent choice to enable full-duplex satellite-based communication for future heterogeneous networks, 5G and beyond. In a nutshell, a trade-off is required at the time of antenna choice based on mass-market demands, applications, and applied areas.

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