A detailed overview of various design methodologies and enabling technologies for beam-scanning reflectarray antennas is presented in this article. Numerous advantages of reflectarrays over reflectors and phased arrays are delineated, and representative beam-scanning reflectarray antenna designs are reviewed. For limited field-of-view beam-scanning systems, utilizing the reflector nature of the reflectarray antenna and the feed-tuning technique can provide a simple solution with good performance. On the other hand, for applications where wide-angle scan coverage is required, utilizing the array nature of the reflectarray and the aperture phase-tuning approach are the more suitable choices. There are various enabling technologies available for both design methodologies, making them a suitable choice for the new generation of high-speed, high-gain beam-scanning antennas.

**Mikcrostrip Reflectarrays**

Since the revolutionary breakthrough of printed antenna technology, microstrip reflectarrays have emerged as a new generation of high-gain antennas, combining many favorable features of both reflectors and printed arrays as well as offering an alternative design with low-profile and low-mass features [1], [2]. The aperture of a reflectarray antenna consists of elements arranged in a certain grid that are designed
to collimate the main beam of the antenna by controlling the phase of the reflected wave, as shown in Figure 1. The promising features of the reflectarray antenna, particularly its low weight and low profile, which are ideally suited for space applications, combined with ease of manufacturing, good efficiency, and high gain, have attracted a great deal of interest over the years. A prominent advantage of reflectarrays over reflectors is the direct phase control over every element on the aperture. This feature allows shaped-beam [3], [4] or multibeam [5]–[7] performance to be realized easily at no additional cost. In comparison with a microstrip array antenna, the main advantage of a reflectarray is the spatial feed system that eliminates the distribution losses associated with the feed network for large array antennas [8]. Owing to these advantageous features, this hybrid antenna has received considerable attention and is quickly finding applications in wireless and satellite communications [9], [10], radars [11], [12], and commercial usages.

In addition to the numerous advantages of reflectarrays over reflectors and arrays for fixed-beam applications, the reflectarray antenna can also serve as a paradigm for beam-scanning applications. High-gain beam-scanning architectures impose stringent requirements on the antenna radiation capabilities [13], [14]; therefore, very few types of antennas are capable of achieving the required performance. In most high-gain beam-scanning applications, the conventional choice is between a reflector (or lens) and a direct-radiating phased array, which is driven by factors relating to scan rate, scan volume, and cost [15]. Reflector antennas are typically more suitable when a very high-gain aperture is required and a phased array is cost prohibitive [16]. For reflectors, beam steering can be accomplished through mechanical scanning or by using sophisticated feed cluster architectures, where the latter is typically expensive [17]. On the other hand, electronically scanned phased arrays rely on phase shifter technology. For high-gain beam scanning where the antenna aperture is large, active phased arrays using transmit/receive (T/R) modules are employed [18]. While the phase shifter and T/R module technology have greatly matured over the years, and the cost of active phased arrays has dropped dramatically, they still represent a considerable portion of the overall antenna cost [19]. Typically, the primary disadvantages of phased arrays are the large hardware footprint and their high cost.

Due to its hybrid nature, the reflectarray antenna provides advantages over reflectors and arrays, and it is well suited for applications requiring high-gain beam-scanning antennas. The beam of a reflectarray antenna can be scanned by means of the reflector nature or the array nature of the antenna [20]. In addition, it is possible to utilize both approaches in a single design to improve scan performance or reduce system cost. It should be noted that, similar to reflectors, it is also possible to scan the beam of a reflectarray by mechanical movement of the aperture [21]; however, the focus here is on achieving a dynamic pattern. The aim of this article is to review the available design methodologies for beam-scanning reflectarray antennas and present a comparative study on the performance of these approaches, with the aim of providing guidelines for antenna engineers to select a suitable design for their system.

**BEAM-SCANNING REFLECTARRAY ANTENNAS**

**DESIGN METHODOLOGIES**

To realize a dynamic radiation pattern, the phase distribution on the reflectarray aperture has to be tuned corresponding to the direction of the scanned beam. Let us consider the reflectarray system shown in Figure 1, which consists of a single reflector and a single feed. The phase distribution for each element on the reflectarray aperture consists of two components:

\[ \phi(x, y) = -k_0 R_i + \phi_R(x, y). \]  

(1)

In this equation, the first term corresponds to the spatial delay, which is the electrical distance between the phase center of the feed and the element position on the array, i.e., \( R_i \). Here, \( k_0 \) is the free space wavenumber. The second term is the reflection phase of the \( i \)th element on the aperture. Since one can control these two components almost independently in a reflectarray antenna, different approaches are available for beam-scanning reflectarray antennas. These techniques can be categorized as follows:

- **feed-tuning techniques:** change \( R_i \)
- **aperture phase-tuning techniques:** change \( \phi_R(x, y) \)

In the feed-tuning technique, one takes advantage of the feed system and changes the phase on the reflectarray aperture by tuning the spatial delay. To address the system design requirements such as scan speed, coverage, and resolution, proper selection of the reflector and feed system is of paramount importance. In general, scan coverage typically depends on the choice of reflector, while scan speed and resolution depend on the feed system. For beam-scanning applications with these systems, the phase center of the feed antenna should be displaced. The ideal displacement path (or focal arc) depends on the system design and is typically determined using ray-optic analysis. In any case, the feed phase center has to move along this path. An illustrative diagram showing the various design methodologies for beam-scanning reflectarrays is given in Figure 2. For feed tuning, movable feeds provide continuous scan coverage; however, they generally have a slow scan.

**FIGURE 1.** The geometry of a reflectarray antenna and vector coordinates.
speed. Multiple feed arrays can provide fast beam switching, essentially on the basis of one feed per beam but not a continuous scan. Phased-array feeds are typically considered the best choice, and, although they are quite expensive, they can provide continuous high-speed scanning. Various designs of planar array and cluster feeds have been developed for reflector antennas [22]–[25], and, in general, these designs are applicable for beam-scanning reflectarray antenna systems. However, to our knowledge, very little has been done to design feed arrays specifically for beam-forming reflectarrays. The focus in this area has primarily been on the scan capabilities of different reflectarray systems, which will be discussed in the “Classifications Based on Reflector Type” section. Recent developments in beam-scanning reflectarrays that utilize the feed-tuning technique will be reviewed in the “Feed-Tuning Techniques” section.

In the second approach, the elements on the reflectarray aperture are equipped with a phase-tuning mechanism [26], essentially utilizing the array nature of a reflectarray antenna. This is similar to a phased-array antenna design [13], [14], with the added advantage of replacing the feed network, which is a major challenge in phased-array design, by a space feed system. This feature is particularly advantageous for high-gain beam-scanning arrays, since small phased arrays can be designed by using only phase shifters for each element, and large phased arrays require the use of T/R modules to compensate for the distribution losses in the feed network. These active phased arrays [18] can achieve a high-gain beam-scanning performance; however, the main disadvantage of these designs is the high cost of the system. With the spatial feed system of a reflectarray antenna, not only the challenging part of designing a feed network is removed but also the space feed reduces the cumbersome distribution losses associated with large array antennas. With low-loss phase shifters [2], an aperture phase-controlled reflectarray can eliminate the need for T/R modules. It is worthwhile to point out that while there are some distribution losses in a reflectarray antenna due to spillover losses [27], in most cases, for large arrays, a spillover efficiency above 90% can be achieved.

In the phase-tuning technique, the system typically relies on the enabling technology, as shown in Figure 2. Various designs of aperture phase-tuned reflectarrays with micromotors [28], diodes [29], microelectromechanical systems (MEMS) [30], and functional materials [31] have been demonstrated over the years. In the “Aperture Phase-Tuning Techniques” section, we will review the recent advances in these dynamically reconfigurable reflectarray antennas. It should be noted that generally for these beam-scanning reflectarrays, apart from the spatial feed network, a control board has to be placed behind the array to supply control voltages to each element, and a microcontroller is used to interface the system with an external computer that synthesizes the array.

CLASSIFICATIONS BASED ON REFLECTOR TYPE

The choice of single- or dual-reflector configuration, in addition to the choice of aperture phase distribution, or, in other
words, the reflectarray system design, plays a major role in the beam-scanning performance of these antennas. This is particularly more important for the feed-tuning technique since the array has no phase-tuning capability in these configurations. For single-reflector configurations that use a single-feed architecture, a parabolic-phase distribution cannot typically realize a good scan performance. In these cases, nonparabolic phase distributions can help to improve the scan capability of the antenna.

Dual-reflector antennas have evolved from their counterparts used in optical telescopes. In comparison with single reflectors, one of the most advantageous features of dual-reflector systems is to provide additional degrees of freedom to optimize a particular characteristic of these reflectors, e.g., to reduce cross polarization [32], [33]. They also have some mechanical advantages since they allow the feed to be placed near the main reflector. In addition, they can provide a higher accuracy for beam pointing, thus they are quite suitable for high-gain beam-scanning applications. Configurations such as bifocal dual reflectors [34] and Gregorian corrected spherical reflectors [35] provide wide-angle scan coverage with higher aperture efficiency. As far as the reflectarray technology goes, they can be designed as the subreflector, main reflector, or both in these dual-reflector configurations [36]. In addition, oversized apertures, such as spherical reflectors that are partially illuminated for any given beam direction, are well suited for wide-angle scan coverage with a passive reflectarray. In the next section, we will take a closer look at some of these beam-scanning reflectarray antennas that utilize the capabilities of different reflector classes in the feed-tuning context.

FEED-TUNING TECHNIQUES

As discussed in the previous sections, in the feed-tuning technique, scan coverage typically depends on the choice of reflector. In the following, we will review some of the different reflector configurations that have been developed for beam-scanning reflectarray antennas.

SINGLE-REFLECTOR CONFIGURATIONS

PARABOLIC-PHASE APERTURES

Conventionally, the phase on a reflectarray antenna aperture is designed based on the phase compensation of a comparable parabolic reflector antenna with the same subtended angle [1]. The main beam of a parabolic reflector can be scanned by displacing the phase center of the feed antenna. However, the primary concern is that, due to the phase aberration introduced by the defocused feed, the far-field pattern can be substantially degraded, the level of which depends on the focal length over diameter ratio, i.e., $F/D$, and scan angle in terms of number of beamwidths scanned. Similar observations have been made for parabolic-phase reflectarray antennas [37], [38]. In [37], it was shown that the beam-scanning performance of a reflectarray by means of feed displacement is limited to a few beamwidths, and it is slightly inferior to a parabolic reflector. The scan performance of reflectarrays is found to improve with $F/D$ ratios, as is true for paraboloids. In addition, the scan performance is poorer for an offset system compared to a symmetric system. The scanned beam patterns of a reflectarray antenna studied in [37], with a diameter of 21.354 and an $F/D = 1$, is given in Figure 3.

It can be observed that while for beams scanned further from broadside the pattern degradation is significant, i.e., high gain loss and a higher level of coma lobes for small beamwidth scans, the performances of these designs are quite acceptable. In another study on the scanning capability of parabolic-phase reflectarrays, it was shown that the scan performance can be improved by using subwavelength elements [39]. Scanning properties of piecewise planar parabolic (PPP) reflectarrays were also studied in [40]. PPP reflectarrays were proposed in [41] to overcome the bandwidth limitations of large reflectarray antennas [42]. While various broadband techniques have been developed for reflectarrays over the years [43]–[49], PPP reflectarrays are still desirable for high-gain applications. The study in [40], however, revealed that the scan performance of tilted PPP reflectarrays is poor, even for one beamwidth scan, which is due to the fact that the radiation from the outer panels peak at different directions compared with that from the central panel. Despite the fact that reflectarrays with parabolic-phase apertures are limited in scan capability, they are still quite desirable for applications that do not require wide scan coverage, e.g., limited field-of-view systems. A practical implementation of this approach is a multifed reflectarray with four beams for X-band synthetic aperture radar, which was demonstrated in [2]. A 1.6-m offset reflectarray with four feeds and $F/D$ around one was designed to generate four beams, SS1, SS2, SS3, and SS4, in the directions of 20.91°, 18.41°, 15.91°, and 13.41°, respectively. The reflectarray is designed for one beam (SS3), and the scanned beams (with about 7.5° of angular coverage) are achieved by feed displacement.

NONPARABOLIC-PHASE APERTURES

One prominent feature of the reflectarray antenna is that it allows for individual phase control of each element in the array. Because of this feature, any phase distribution can be attained for an offset system compared to a symmetric system. The scanned beam patterns of a reflectarray antenna studied in [37], with a diameter of 21.354 and an $F/D = 1$, is given in Figure 3.
on the aperture, and one is not bound to use a parabolic-phase distribution. In other words, one can design an aperture that provides a better phase compensation for the scan range required.

Based on the concept of single-reflector multifocal apertures, different aperture phase distributions were proposed in [38]. The basic idea of these designs is that a reflectarray antenna designed to compensate for multiple focal points will have a better scan performance than a unifocal design. In [38], a pattern synthesis optimization technique to design bifocal and quadrufocal phase distributions for a single-reflector configuration is used to improve the scan capability. These optimized phase distributions are shown in Figure 4.

The experimental results showed that these nonparabolic-phase reflectarrays achieved a scan performance far better than parabolic-phase designs; however, this comes at the expense of antenna gain. The measured scanned gain patterns for both these designs are shown in Figure 5, where it can be observed that a good scan performance is achieved. Both of these reflectarray antennas can realize 60° scan coverage in one plane; however, the quadrufocal design achieves a better side-lobe performance.

It is worthwhile to point out that some other designs for nonparabolic reflectarray phase distribution have been reported, such as the power combining multifeed single-beam reflectarray antenna in [50], although these are not in the beam-scanning context.

PARTIALLY ILLUMINATED APERTURES

Most reflectarrays are designed for a fully illuminated aperture, typically realizing a taper of about -10 dB at the reflector rim. The optimized multifocal-phase reflectarrays can improve the scan capability to some degree, but wide-angle and two-dimensional scanning is generally not possible with conventional designs. On the other hand, spherical reflector antennas have been recognized for years as a suitable design for applications requiring high-gain, wide-angle, full-azimuth scan coverage [51]. In spherical reflectors, a portion of the reflector surface, known as the illuminated aperture, is excited for any given beam direction. This restricted aperture approach minimizes the effects of spherical aberrations and the inherent poor collimating properties of spherical reflectors.

A similar concept has recently been introduced for reflectarray antennas [52], where a planar oversized aperture reflectarray was designed based on the phase compensation of a comparable spherical reflector. The spherical-phase reflectarray has a physical diameter of 48 m at a center frequency of 32 GHz, and the illuminated aperture size is 15 m. The reflector is designed for a 30° elevation coverage. The simulated scanned gain patterns for this design are shown in Figure 6. Note that an almost similar scan performance is achieved in all the azimuth planes.

While the spherical reflector is an ideal candidate for wide-angle scanning, the primary drawback is its slow scan speed. Typically, for spherical reflectors, the feed moves along a spiral path where all the points on the spiral path have an equal distance from the center of the sphere [53]. Consequently, this requisite mechanical movement limits the scan speed of these reflectors. Nonetheless, for many applications, such as radio astronomy [54], that do not require a high scan speed, a spherical-phase reflectarray can be a suitable choice.

**FIGURE 4.** The phase distributions on the aperture of optimized reflectarray antennas. (a) Bifocal phase. (b) Quadrufocal phase. (Reprinted with permission from [38].)

**FIGURE 5.** The measured scan patterns of multifocal reflectarray antennas designed for a 60° scan coverage. (a) The bifocal phase. (b) The quadrufocal phase. (Reprinted with permission from [38].)
Another beam-scanning reflector configuration worth mentioning is the parabolic torus [55]. The torus reflector is a parabola rotated about an axis perpendicular to the axis of the parabola, and it can be used for wide-angle one-dimensional (1-D) scanning. Similar to the spherical-phase reflectarray, it is possible to design an oversized reflectarray based on the phase distribution of a parabolic torus; however, to our knowledge, no such design has yet been reported.

**DUAL-REFLECTOR CONFIGURATIONS**

**PARABOLIC REFLECTOR/REFLECTARRAY**

In these configurations, beam scanning is typically achieved by tuning the subreflector. This can be done mechanically, which will be discussed here, or by using reconfigurable subreflectors, which will be reviewed in the “Frontiers in Beam-Scanning Reflectarray Antenna Research” section. A 3-m dual-band Cassegrain reflectarray (X/Ka-band) with a reflectarray main reflector was demonstrated in [56]. At the X-band (8.4 GHz) and the Ka-band (32 GHz), 19,000 and 275,000 annular ring elements provided the phase shift on the reflectarray aperture, respectively. The feed antenna was a microstrip array that was moved mechanically to scan the beam. A 10-cm movement of the feed translated to more than 1.5° scan for the main beam at both bands. A Ka-band Gregorian reflectarray with a parabolic subreflector was also studied in [56], where a similar beam-scanning performance was observed.

A 94-GHz parabolic reflector with a reflectarray subreflector was also demonstrated in [57]. The initial design used mechanically rotated flat metal subreflectors to scan the beam. A 28 × 28 element patch reflectarray fabricated on a metal-backed quartz wafer was designed to replace the metal subreflectors, and the reflectarray-phase control capability was used to scan the beam 5° without rotating the subreflector plate. A photo of the prototype is shown in Figure 7.

**NONPARABOLIC REFLECTOR/REFLECTARRAY**

For passive reflectarray designs, a notable improvement in scan coverage can be realized with nonparabolic configurations. One of the best configurations is that of the bifocal dual-reflector antenna [34]. In contrast to the single-reflector bifocal design discussed in the previous section, which cannot achieve two perfect foci, the dual-reflector configuration allows for two degrees of phase control, thus enabling a perfect bifocal performance.

A bifocal folded dual-reflectarray antenna using a seven-element feed array placed on the focal arc was presented in [58]. In this design, the subreflector also acts as a polarizer, thus no blockage effects are observed. The prototype was designed for a multibeam performance, but it can be used to scan the beam by switching from one feed to the next. The scan range for the design was about 27° (±13.5°); however, this was further improved to 49° (±24.5°) by designing a system with restricted apertures. A photo of the fabricated antenna and a figure of the measured scanned beam patterns are shown in Figure 8. Recently, a dual reflectarray with dual-offset feeds has also been demonstrated in [59].

**FIGURE 6.** The simulated scanned gain patterns for a spherical-phase reflectarray antenna designed for a 30° elevation and full-azimuth coverage. (Reprinted with permission from [52].)

**FIGURE 7.** A beam-scanning dual-reflectarray antenna. The subreflectarray is designed for 5° beam scan. (Reprinted with permission from [57].)

**FIGURE 8.** The bifocal dual-reflectarray antenna for 27° scan coverage. (a) The prototype. (b) The measured scanned beam patterns. (Reprinted with permission from [58].)
Dual reflectors with a spherical main reflector are also a very practical choice for wide-angle scanning. The subreflector provides a degree of freedom to minimize the effects of spherical aberrations, although this generally reduces the scan coverage. A 35.5-m Ka-band spherical reflector antenna with a 0.3-m subreflectarray was demonstrated in [60]. The main beam is scanned 4° (approximately 200 beamwidths) by rotating the feed 4°. The scanned beam patterns for this antenna are given in Figure 9, where it can be observed that a stable radiation pattern is obtained across this very wide scan area.

In summary, a multitude of reflector configurations are available for beam-scanning reflectarrays that can be effectively utilized with the feed-tuning technique. The primary advantage of this technique is the ease of fabrication for passive arrays. This feature also allows for very high-gain and high-power operation with low cost. Some of the key characteristics of this beam-scanning technique are as follows:

Advantages:
- ease of fabrication (passive array)
- very high-gain operation
- high radio-frequency (RF) power handling.

Limitations:
- Depending on the design, it may have a slow scan speed.
- The feed array may be complicated and expensive.

APERTURE PHASE-TUNING TECHNIQUES

BASICS OF APERTURE PHASE TUNING

As discussed in the previous sections, the aperture of a reflectarray antenna consists of phasing elements that are designed to realize a certain reflection phase response. Different approaches are available for tuning the phase of reflectarray elements, which, in general, can be categorized into three groups:

- elements with phase/time delay lines
- variable-size elements
- rotated elements.

In the first group, the incident wave is initially received by the element, then phase shifted using a delay-line microwave network, and finally reradiated. This methodology is known as the guided-wave technique and is essentially the concept Berry [61] used when introducing the first reflectarray antenna in 1963, which utilized short-circuited waveguide elements. With the second group, variable-size elements, the phase of the scattered field is controlled by changing the dimensions of the element, e.g., the patch length. The last group, which is applicable only to circularly polarized (CP) designs, takes advantage of the unique property of an incoming CP wave, i.e., the 90° phase difference between the two orthogonal electric field components. It is shown that, by rotating the element on the aperture plane by $\varphi'$, the phase of the reflected field will be rotated by $2\varphi'$; hence, this approach is known as element rotation. While there is a fundamental difference in the principal of operation between the second and third groups, both approaches directly modify the radiating structure and the phase-shifting mechanism is directly integrated with the element.

In passive (or fixed) reflectarray configurations, such as the ones reviewed in the “Feed-Tuning Techniques” section, the...
Reflection phase for each element is a fixed quantity. For dynamic phase apertures, however, a tunable phase-shifting mechanism must be incorporated into the elements. The three general approaches for passive reflectarray elements can also be realized in a dynamic form. For a detailed discussion on the operating mechanisms of these dynamic phase-tuning approaches, refer to [62]. This article provides a brief overview of the enabling technologies for the aperture phase-tuning technique.

**Enabling Technologies**

Similar to phased-array antennas, and regardless of the choice of element phase-tuning approach, a primary challenge is how the element is integrated with the phase-tuning mechanism. Here, we discuss various enabling technologies that have been used in designing phase-tuned reflectarray antennas. Tuning techniques based on mechanical actuation are presented in the “Mechanical Actuators/Motors” section. In the “Electronic Devices” and “Functional Materials” sections, various electronic devices and functional materials that can achieve discrete or continuous phase tuning are briefly summarized. In each given class, the tuning mechanisms share common attributes, e.g., low scan speed with mechanically actuated designs or limited RF power handling with electronic devices. A summary of the advantages and limitations of various tuning methods is presented at the end of each section.

**Mechanical Actuators/Motors**

In this approach, phase agility is achieved by means of a mechanical actuation that ultimately changes the physical dimension or orientation of the elements. For reflectarray elements, both linear (translation) and rotary (rotation) motions can be utilized to achieve aperture phase tuning. For high-frequency designs, microactuators and motors, typically fabricated using micromachining techniques, with maximum dimensions in the order of a few millimeters are available. While various types of actuators such as electric, magnetic, electromechanical, thermal, hydraulic, pneumatic, and chemical are available in the market [63], only a handful of designs using electrostatic and electromechanical-type actuators have been experimentally demonstrated for reflectarray antennas. The following sections take a closer look at some of the mechanically actuated beam-scanning reflectarray designs that have been developed over the years.

**Mechanical Rotation**

Utilizing the element rotation technique, mechanical phase-tuning can be achieved by placing micromotors beneath each element as proposed in [26], [64], and [65]. This element design approach is applicable for CP elements and is capable of achieving a full phase range. The experimental results were demonstrated in [28] for a small prototype, achieving 10° of beam scan. A schematic model of the design concept and a fabricated prototype are shown in Figure 10.

**Mechanical Translation**

Microelectrostatic actuators were proposed in [66] to adjust the height of each patch element in the reflectarray over the ground plane. The electrostatic fields are generated through an applied dc voltage bias between the patch and the ground plane, which moves the patch vertically and changes the fringing fields, allowing for phase control of the reflected fields by controlling the dc bias. In general, however, a full phase cycle cannot be achieved with this design. A schematic model of this reflectarray element is shown in Figure 11(a).

Linear-motion mechanical actuation was demonstrated in [67] with a multilayer configuration where the entire middle layer, consisting of two sets of slots, was displaced with a digital caliper to change the relative position of slots and collimate the beam at −30°, 0°, and +30°. It should be noted that, with this design, the elements do not have independent phase control, and this approach is more suitable for beam-switching applications. A photo of the fabricated prototype is shown in Figure 11(b).

In general, the primary drawbacks of mechanical phase-tuning techniques arise from the requisite physical displacement. As such, these configurations have received very little attention and only a handful of designs have been demonstrated. Some of the key characteristics of these types of beam-scanning reflectarrays are as follows.

Advantages:

- High RF power handling
- Potentially offer low-loss continuous phase tuning

Limitations:

- Slow scan speed (milliseconds)
- Typically require high bias levels
- Low reliability (due to mechanical motion).
Electronic phase tuning provides the highest scan speed and, therefore, is a subject of great interest for beam-scanning applications. Thanks to the recent advances in packaging and miniaturization, a variety of electronic devices are commercially available that can be integrated (as either lumped or distributed components) with reflectarray elements. These devices can be divided into two classes: 1) switches providing discrete phase states (digital phase control) and 2) devices with continuous phase tuning (analog phase control). The p-i-n diodes and field-effect transistors (FETs) are examples of electronic switches, and varactor diodes are an example of an electronically tunable device. MEMS devices can provide both discrete (MEMS switch) and continuous (tunable MEMS devices) phase control; however, digital MEMS devices are typically more reliable [68].

The promising capabilities of these electronic devices have opened a new frontier in reconfigurable reflectarray designs, and several prototypes using various electronic devices have been demonstrated. In the following sections, we will briefly review some of the electronic beam-scanning reflectarray antennas that have been developed over the years.

### P-i-n Diode Switches

The p-i-n diode switch is a semiconductor device that can be made to behave as either a short (on state) or open circuit (off state) by controlling the biasing dc voltage across its terminals. This characteristic makes it a very good candidate for delay line phase shifters. Phase-shifting reflectarray antennas that use a series of half dipoles connected to the periphery of a circular metal layer by means of diodes were proposed in [69]. A 60-GHz electronically reconfigurable reflectarray with 160 elements using p-i-n diode switches, as shown in Figure 12, was experimentally demonstrated in [70]. A number of other designs using a similar 1-b phase-control mechanism have also been demonstrated. A wideband reconfigurable reflectarray element consisting of a circular patch aperture coupled to a phase-shifting circuit was demonstrated in [71]. A dual-polarization operation and a flat phase-shift response over a 50% relative bandwidth were obtained with this element. A 244-element beam-switching X-band reflectarray antenna using p-i-n diodes was also demonstrated in [72]. Another very interesting application of p-i-n diodes is in electronic element rotation that was initially proposed in [73], where selective activation of the lumped elements of the rotationally symmetric geometry mimics a rotation of the reflected electromagnetic wave [74]–[76].

### FET Switches

FET devices, particularly metal–semiconductor FETs (MESFETs), can be used as microwave switches for reflectarray elements. The FET switch draws almost no dc current in either the on or off state, which gives it an advantage over the p-i-n diode switch in terms of a lower dc power consumption. However, a comparative study between p-i-n diodes and MESFETs for Ka-band patch elements with 2-b delay line phase shifters [77] showed that, while the beam-scanning performances for these two designs were quite similar, the p-i-n diode design showed a better performance in terms of RF insertion loss. As such, FET switches are seldom used for electronic beam-scanning reflectarrays.
MEMS SWITCHES

MEMS RF switches show a momentous promise for reconfigurable reflectarray antennas [78]–[80]. In comparison with p-i-n diodes or other solid-state switches, MEMS RF switches have a lower insertion loss, high linearity, very low dc power consumption, and higher power-handling capability. Moreover, they can be readily integrated with antennas in a monolithic fabrication process. These integrated electronic devices use micromachined beams or membranes that can be deflected to provide an open or short for an RF circuit. MEMS devices can be designed for either direct (ohmic) or capacitive-coupled contact with the RF circuit. Different techniques can be used for beam actuation in MEMS, such as electrostatic, electromagnetic, and piezoelectric, where electrostatic beam actuation is the most common technique.

A patch element loaded with two slots controlled by a set of ten MEMS devices was demonstrated in [30] and [81]. Another reconfigurable reflectarray element consisting of a patch and variable length slots using MEMS switches was demonstrated in [82]. A 2-b X-band reflectarray element with electronic phase control implemented by ohmic MEMS switches was also demonstrated in [83]. The first functional MEMS reflectarray prototype operating at 26.5 GHz was recently demonstrated in [84] using aperture-coupled microstrip patch elements. This 100-element beam-switching reflectarray antenna is monolithically integrated with 90 RF MEMS switches. The series RF MEMS switches provide only two states, corresponding to a broadside and 40° scanned beam in the H-plane. The schematic model of the element and photos of the fabricated prototype are shown in Figure 13.

Reflectarray elements integrated with MEMS capacitors are also a practical application of MEMS technology for beam-scanning designs. Most MEMS variable capacitors have been developed as digitally switched capacitors; however, analog MEMS designs have also been explored. It is important to point out that, while MEMS switches seem to have many advantages over p-i-n diodes and FET switches, they typically have a slower switching speed. In addition, they are usually more expensive than other electronic switches.

MEMS TUNABLE DEVICES

Tunable MEMS capacitors have significant potential in addressing the loss and linearity issues with these devices, and, if built correctly, they exhibit very high quality factors [85]–[87]. For these analog designs, the continuous tuning range is limited in some simpler designs, which is the result of the pull-in phenomena due to the imbalance between the squared increase in

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**FIGURE 13.** A beam-scanning reflectarray antenna using MEMS demonstrating a scan range from 0° to 40° off-broadside. (a) The element model. (b) The 100-element prototype. (Reprinted with permission from [84]).
electrostatic force compared to the linear increase in restoring force with displacement. However, advanced designs such as two-layered bridges with dual-gap heights can avoid the pull-in tuning limitation by separating the capacitance plate gap from the electrostatic electrode gap and increase the tuning range. A two-layered bridge dual-gap-height MEMS capacitive reflectarray element was experimentally demonstrated in [87].

VARACTOR DIODES

The varactor diode is a semiconductor p-n junction device that can provide variable junction capacitance by a controlled applied bias voltage. Integrated with the phasing element, varactor diodes can provide the means to control the capacitance of the elements [88], [89]. A phase-agile reflectarray element using two varactor diodes that serially connect two halves of a microstrip patch was demonstrated in [90]. Another C-band reconfigurable reflectarray using varactor diodes was demonstrated in [91]. In [92], a single varactor diode was used to load a transmission line stub in an aperture-coupled patch configuration. Capacitive loading of hollow patches with varactor diodes was studied in [93]. More recently, the focus has been on a performance improvement of these configurations. In [94], a study revealed that a single patch with a shunt-connected varactor diode can be designed to attain the full phase-tuning range. Bandwidth improvements of varactor diode-tuned reflectarrays were studied in [95]. It is also important to point out that, in the same context, tunable impedance surfaces have also been demonstrated to redirect an impinging plane wave [96].

Integrated electronically phase-tuned reflectarray antennas show a momentous promise for wide-angle beam-scanning applications, and a myriad of electronic devices and design configurations are available. The designs reviewed in this section are just some examples of integrated electronic devices that have been proposed for use in electronically reconfigurable reflectarray antennas. In general, the choice of switch or tunable devices strongly depends on the application. In comparison with mechanical designs, their primary advantage is a fast scanning speed. On the other hand, their primary drawback is their low power-handling capability, which limits their application as a transmitter. Advantages:

- fast scanning speed
- discrete or continuous phase tuning
- low to moderate dc power consumption.

Limitation:

- low to moderate power handling.

FUNCTIONAL MATERIALS

The integrated electronic devices studied in the previous section provide the means for high-speed scanning; however, with the current technology, the majority of these devices cannot operate efficiently at the high microwave spectrum. A promising approach to address the growing demands in millimeter-wave and terahertz frequencies is based on the use of functional or exotic materials. These relatively newer technologies are based on the reconfiguration of the material, e.g., via distributed control of the dielectric constant of the substrate in the case of liquid crystals (LCs). Other technologies based on thin-film ferrolectrics, ceramics, plasma, and, more recently, graphene have also been explored.

A beam-scanning reflectarray antenna using nematic LCs was experimentally demonstrated in [31]. The cell consists of a carrier substrate with a printed metallic patch on the lower side and an LC cavity beneath the patch. The applied voltage changes the effective relative permittivity of the LC from 2.62 to 3.04, enabling some adjustment of the phase of a reflected wave. A 16 × 16 reflectarray prototype, as shown in Figure 14(a), with unidirectional bias control was demonstrated for Ka-band operation. Two other similar designs operating at 102 and 130 GHz were also demonstrated in [97]. Another design combining LCs and multilayer technology of low-temperature cofired ceramics was also demonstrated in [98], and a 256-element array prototype operating at 77 GHz was demonstrated. The prototype is shown in Figure 14(b). Due to the limited tunability of the material properties in LCs, most of these designs exhibit some limitations in the phase agility of the elements. To mitigate these problems, a multiresonant unit cell made up of three parallel dipoles in the same cell and a tunable LC as substrate was proposed in [99].
and [100]. The multiresonant element configuration also demonstrated an improved bandwidth.

Thin-film ferroelectric-based devices [101] have matured greatly over the past decade. While ferrite phase shifters are still considered the main workhorse in military phased arrays, interest in ferroelectric-based devices is mounting because of their high power-handling capability, negligible dc power consumption, and potential for low loss and low cost [19]. In particular, the high power-handling capability of these devices cannot be matched with any of the other designs presented in this section. A 19-GHz reflectarray with 615 elements using a ferroelectric thin-film device was demonstrated in [102]. Reconfigurable unit cells using thick-film ceramic materials were also studied in [103]. A very new and highly promising material for terahertz beam-scanning applications is graphene [104]. In contrast to LC design, the substrate material is fixed and resonance is achieved by changing the complex conductivity of the graphene patch [105]. Plasma-based phase control is also a very interesting approach for designing beam-scanning reflectarray antennas. In [106], surface p-i-n diodes are proposed, which generate plasma on the diode surface due to the injected carriers. In another design, a laser is used to induce plasma [107]. More recently, fluidic phase tuning has also been explored [108]. Also, effective material implementations using metallic conductors have recently been proposed, which seem to provide wide scanning ranges [109].

Addressing the challenges at high frequencies is still a fundamental concern for researchers in this field. While these new technologies are very encouraging, they are certainly not mature enough yet for practical applications. Moreover, they exhibit losses that are significantly higher than RF electronic devices. Nonetheless, with the potential capabilities that these new technologies can offer, it seems that they will be the state of the art for terahertz and optical beam-forming applications in the near future. Some key characteristics of these functional material beam-scanning reflectarrays are as follows.

Advantages:
- potential for terahertz and infrared applications
- potential to offer low-loss continuous phase tuning

Limitations:
- technology is not mature
- expensive prototyping

FRONTIERS IN BEAM-SCANNING REFLECTARRAY ANTENNA RESEARCH

In the previous sections, the basic design methodologies and enabling technologies for beam-scanning reflectarrays were outlined, and some recent examples were reviewed. However, in comparison with the very mature technology in beam-forming reflector systems and phased-array antennas, the reflectarray technology is still in its developmental stage, and many advanced design concepts are only recently being explored. The following sections review some of these advanced concepts.

ACTIVE DESIGNS

Integration of active devices, mainly amplifiers, with reconfigurable reflectarray elements is an area of considerable interest that has recently been explored [62]. The concept is similar to active phased-array antennas. In the case of reflectarrays, however, the primary motivations are increasing the overall gain of the antenna or compensating for phase-shifter losses. The first active reflectarray antenna was demonstrated in [110], where the X-band amplifying elements were designed using FET transistors. In the same work, the authors demonstrated another design for active spatial power combining. A few other designs for active reflectarrays have also been demonstrated [111], [112]. The first active reconfigurable design was demonstrated in [113], where a 48-element beam-scanning reflectarray prototype operating at 5.7 GHz was demonstrated. While these active designs have great potential, very little work has been done on active reconfigurable reflectarrays. In comparison with active phased arrays that use a very mature T/R module technology, active reconfigurable reflectarrays are still in the developmental stage.

ANALOG OR DIGITAL PHASE CONTROL

In aperture phase-tuned designs, scan resolution and pattern control typically depend on the phase range and available phase states of the elements, i.e., phase quantization effects in array antennas [13], [14]. As such, the choice of analog or digital phase control (and the number of bits) is generally a primary concern. While continuous phase tuning is certainly advantageous for small array configurations, in most cases of large arrays (such as reflectarrays), discrete phase control provides satisfactory results due to the phase front averaging of the collimated beam. Moreover, low-bit discrete phase control is generally less complicated to implement, which is quite advantageous for large arrays. In the same context, increasing the number of bits (or phase states) in digital phase shifters increases the complexity of the design. As a result, in practice for a specific application, one must determine the minimum requirements of the element before selecting the optimal enabling technology.

To quantitatively illustrate these design considerations, we study the performance of a reflectarray antenna with a diameter of 20\(\lambda\) with ideal phase-tuned elements. The edge taper is set to −10 dB for this reflectarray system. Broadside and scanned patterns are obtained as described in [114] and are shown in Figure 15 using different phase-control capabilities. The radiation patterns show that, while the performance of the 1-b design is rather poor, 2- and 3-b configurations can provide acceptable performances [115]. For wide scan-angle capability or better side-lobe level control, an increase in the number of bits is generally desirable; but for large arrays, 3-b phase control provides a performance comparable to that of the analog case over all the scan angles. Combined with the practical issues of cost, volume, and manufacturability for large arrays, it is expected that, similar to phased arrays, digitally controlled designs with three or four discrete bits [14] will be more desirable for electronically reconfigurable reflectarrays. More discussion on scan loss due to phase errors and the influence of number of bits is given in [116]. It should be noted that, in comparison with switched-pattern designs that provide only
two states for each element, a 1-b phase-shifter-based design provides two different phases for each element, which allows for much more pattern flexibility.

**SUBARRAY TECHNIQUE AND NUMBER OF CONTROL BITS**

Organizing an array into equally spaced subarrays is a well-known concept in phased-array antennas. The primary advantage of this technique is the reduction of the number of control bits, which are a considerable portion of the array cost. A number of beam-scanning reflectarrays using the subarray technique have recently been demonstrated. In contrast to phased arrays, reflectarray elements have to compensate for the spatial delay in addition to providing the progressive phase on the aperture for a scanned beam. Consequently, implementing the subarray technique for beam-scanning reflectarrays is more complicated and could require more control bits.

Recently, two reconfigurable reflectarray designs using the subarray technique were demonstrated [72], [83]. Each subarray consisted of a pair of elements. A more advanced subarray technique was proposed in [117], where delay lines were used to compensate for the spatial delay from the feed. A 400-element prototype with only 40 control elements was demonstrated with this design; however, only a static case was experimentally studied. The prototype is shown in Figure 16.

**HYBRID CONFIGURATIONS**

In the “Beam-Scanning Reflectarray Antennas” section, it was mentioned that one can take advantage of the hybrid nature of the reflectarray and combine both scanning methodologies to improve the scan performance. While very little work has been done in this context, a dual-reflector configuration using a phase-tunable subreflectarray has been proposed. Dual-reflector/array configurations with a phase-tunable subreflectarray can be a suitable choice for beam scanning, since the use of subreflectarray reduces the number of control elements. A beam-scanning 1.5-m parabolic reflector antenna using a subreflectarray at 11.95 GHz was studied in [36]. In this work, the scanning was achieved by introducing a progressive phase shift along the reflectarray subreflector, which allows for 1-D scanning. The simulated results were given using ideal phase shifters, which showed a scan range from $-2^\circ$ to $+2^\circ$ with a gain reduction under 1 dB in all of the cases. In general, for these configurations, the control at row or column level (and the subarray level) significantly reduces the scan capability. A fully controlled subreflectarray configuration was studied in [118], which demonstrated beam scanning in the range of $\pm 6^\circ$ using 3-b ideal switches. While, in this case, quantization effects did not result in a significant pattern distortion, in general, a higher number of bits would be required for reconfigurable subreflectarrays due to their smaller aperture size.

The myriad capabilities that beam-scanning reflectarrays offer will encourage continuous development and diversified applications in the future. In addition to the advanced concepts introduced in this section, dual-polarization cells, polarization-flexible cells, dual-band cells, and frequency-agile reflectarray elements have also been investigated [62], [119]. As such, it is expected that this field will remain an active area of research and development for some time.

**CONCLUSIONS**

A technical overview of various design methodologies in beam-scanning reflectarray antennas along with the state of the art in enabling technologies has been presented. High-gain beam scanning can be achieved by reflectarray antennas using two distinctive approaches: feed tuning and aperture phase tuning.
It is revealed that, for limited field-of-view beam-scanning systems, utilizing the reflector nature of the reflectarray antenna and using the feed-tuning technique can provide better performance. On the other hand, for applications where wide-angle scan coverage is required, the aperture phase-tuning approach that utilizes the array nature of the reflectarray antenna is the suitable choice. Several promising enabling technologies, such as p-i-n diode switches, digital MEMS capacitors, LCs, and thin-film ferroelectric phase shifters, were also reviewed in this context. Some of the key innovations in this field along with the present limitations have also been discussed.

In summary, various design methodologies and enabling technologies are available for beam-scanning reflectarray antenna design. By proper selection of the design method and enabling technology, a reflectarray antenna can offer several advantages over conventional reflectors and phased-array antennas, which makes it a suitable choice for high-gain beam-scanning applications.

ACKNOWLEDGMENT

This work was supported in part by the NASA EPSCoR program under contract number NNX09AP18A and by the Tsinghua National Laboratory for Information Science and Technology.

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AUGUST 2015


