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SURVEY

Pattern Reconfigurable Antennas at Millimeter-Wave Frequencies: A Comprehensive Survey

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ABSTRACT Millimeter-wave bands (around 28, 38, 60, and 73 GHz) are anticipated to play a decisive role in the hosting of future wireless systems. The necessity of smart antennas to adaptively meet the requirements of the wireless links calls for new pattern reconfiguration antennas with beam-steering and/or beam-shaping capabilities. This paper reviews the latest research contributions on pattern reconfigurable antennas at mm-Wave frequencies, proposing an original classification according to the reconfiguration technique and technology. The analyzed systems are divided into two main groups: Reconfigurable and non-reconfigurable feeding antennas. Phased-arrays antennas are the main component of the first category, whereas other reconfigurable means such as the use of metasurfaces or advance materials like liquid crystal or graphene form the second group, devoted to non-reconfigurable feeding antennas. Furthermore, some insights and theoretical background are provided to help the reader understand and appreciate the uniqueness of every solution. Similarly, the beam-scanning and beam-shaping performance of some of the discussed works is analyzed. Finally, some instructive remarks and open research challenges are discussed, with the aim of providing some guidelines for potential new works on the field.

INDEX TERMS Active tuning, antennas, artificial materials, beam scanning, beam shaping, beam steering, beamforming, metamaterial, millimeter wave, pattern reconfiguration, phased-array, reconfigurable, transmitarray.

I. INTRODUCTION

Recently, the exponential growth of wireless data traffic, together with the exigent demands of future communication generations in terms of latency, reliability and speed, have driven to the exploration of new unused frequency regions in the radio spectrum to meet the projected requirements. As reported by Rappaport *et al.* [1], there are some spectral regions that undergo less atmospheric attenuation. In particular, the regions between $40 - 50$ GHz and $70 - 80$ GHz have been noticed as attractive for extended range millimeter-wave (mm-Wave) data links. Irradiating systems that operate at those wavebands could represent an advance for the development of future communications networks. Four different frequency bands around 28, 38, 60, and 73 GHz have been considered as candidates for indoor and outdoor communication at mm-Wave frequencies [2]–[4].

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Due to the high path and penetration losses at millimeter wavelengths, antenna beam-forming assumes a pivotal role in establishing and maintaining a robust communication link. Reconfigurable antennas (RAs), capable of dynamically altering their characteristics according to the operation environment, constitute a practical solution to avoid multiple radiating structures and fulfill the performance requirements.

Under this scenario, the design of RAs has gained popularity among the research community. According to the type of reconfiguration, RAs are often divided into three different categories: frequency, polarization, and pattern reconfiguration structures. Some efforts have been conducted in the literature to provide a compilation of state-of-the-art RAs according to their category [5]. In the same way, there have been multiple attempts to classify RAs according to other different criteria. In [6], RAs are separated into four groups with regard to the adopted design strategy to achieve reconfiguration (switch-based, nonswitch-based, graph modeling, software control, neural networks). Similarly, other works focus on a specific antenna type or technology, such as liquid-based RAs [7] or microstrip patch antennas [8]. Hong *et al.* propose an application-oriented classification in [9], collecting works on multibeam antennas for 5G communication systems, which imposes also some restriction on the operating frequency of the selected antennas. This work is an attempt to go one step further and focus only on pattern reconfigurable antennas (PRAs) operating on high-frequency mm-Wave bands. To the best of our knowledge, this is the first time that a compilation of the state of the art in this particular topic is done. Moreover, we propose an original classification in which PRAs are sorted out according to their reconfiguration mechanisms.

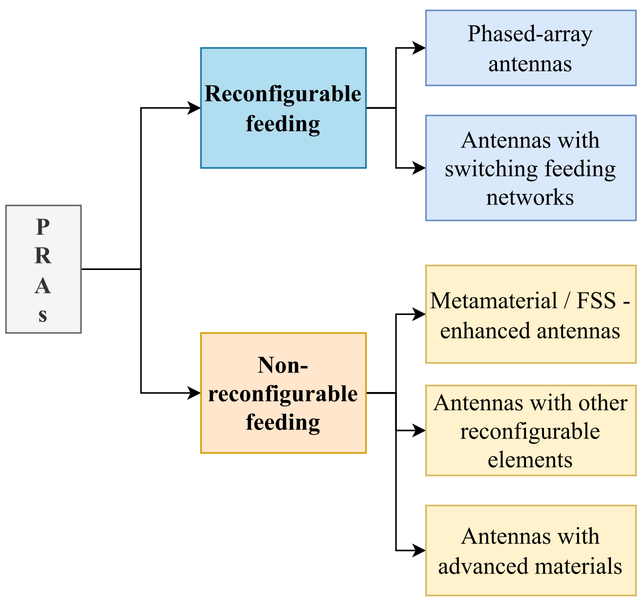

FIGURE 1. Proposed classification of PRAs.

Figure 1 includes the proposed classification criteria. Two main groups of antennas are distinguished: On the one hand, reconfigurable feeding antennas contain the reconfiguration engine as a part of the antenna feeding network, while preserving an invariant radiating structure. Phased-array antennas are the main constituents of this group, but other designs presenting different kinds of switching mechanisms integrated into the feeding network can also be found. On the other hand, non-reconfigurable feeding antennas contain the reconfiguration engine as part of the antenna radiating structure. In this group, reconfigurability can be achieved via many different means. For example, electrical switches such as PIN diodes or varactors can be integrated into metamaterials or frequency selective surfaces (FSS), an then combined with a fixed radiating source to build a PRA. Another important group is the one constituted by antennas in which reconfiguration is achieved by exploiting some changing properties of special materials like graphene or liquid crystal (LC).

The rest of the paper is organized as follows: Section II contains a background on pattern reconfiguration modalities and switching techniques, which will allow the reader to better understand the rest of the paper. Next, Sections III and IV are devoted to reconfigurable and non-reconfigurable feeding antennas, respectively. Finally, Section V summarizes some of the common conclusions of the work and introduces some future challenges.

II. BACKGROUND

In the following, some general concepts, agreements and distinctive features about pattern reconfiguration modalities and switching mechanisms are included.

A. TYPES OF PATTERN RECONFIGURATION

Beamforming has been classically defined as a spatial filtering operation that typically uses an array of radiators to capture or radiate energy in a specific direction over its aperture [26]. However, the scope of this work is not restricted to antenna (phased) arrays, but they are only a group of the antenna beamforming technologies presented. In order to provide a narrower and more meaningful definition than the one of beamforming mentioned before, two main pattern reconfiguration modalities are distinguished in this paper. These are beam-steering and beam-shaping, and they are illustrated in Figure 2.

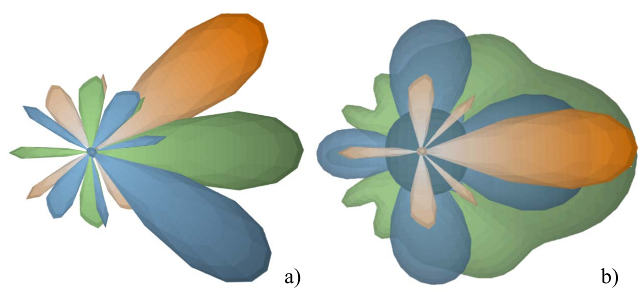

FIGURE 2. Illustration of the two different pattern reconfiguration modalities. (a) Beam-steering and (b) beam-shaping.

TABLE 1. Compilation of state of the art beam-steering antennas at mm-wave frequencies. Sorted by increasing operating frequency.

Ref.	Reconfiguration mechanism	Centr. freq.	Scanning range	Cont. scanning	Prototype
[10]	Conformal phased-array	20.7 GHz	$30°, 150°$ (E-plane) / $60°, 120°$ (H-plane)	✓	✓
[11]	Reflectarray, PIN diodes	26 GHz	$0°, 60°$ (E-plane) / $0°, 60°$ (H-plane)	✗	✓
[12]	Pixel antenna, PIN diodes	27 GHz	$-60°, +60°$ (H-plane)	✗	✗
[13]	Phased-array, PIN diodes	28 GHz	$-50°, +50°$ (E-plane)	✓	✗
[14]	Transmitarray, PIN diodes	29 GHz	$-60°, +60°$, RHCP and LHCP	✓	✓
[15]	Phased-array, PIN diodes	29 GHz	$-47.2°, +47.2°$ (E-plane) / $-60°, +60°$ (H-plane)	✓	✗
[16]	Phase delay line	30 GHz	$-50°, +50°$ (E-plane)	✓	✓
[17]	Adaptive lens array	32 GHz	$0°, +60°$ (E-plane)	✗	✓
[18]	Phased-array, PIN diodes	35 GHz	$-75°, +75°$ (E-plane)	✓	✓
[19]	Phased-array with lens antennas, PIN diodes	38 GHz	$-37.5°, +37.5°$ (E-plane)	✓	✓
[20]	Moving lens	40 GHz	$-50.5°, +50.5°$ (E-plane)	✓	✓
[21]	Lens antennas array, Variable feeding	60 GHz	$0°, +360°$ (E-plane)	✗	✓
[22]	Reflector with multi-feed sources	60 GHz	$-18°, +18°$ (E-plane)	✗	✓
[23]	Reflectarray, PIN diodes	60 GHz	$-20°, +20°$ (E-plane) / $-20°, +20°$ (H-plane)	✓	✓
[24]	Gap waveguide, Mechanical system	60 GHz	$-60°, +60°$ (H-plane)	✓	✓
[25]	Moving lens	69 GHz	$-45°, +45°$ (E-plane)	✓	✓

Beam-shaping consists on the ability of an antenna system to switch between multiple radiation patterns of different nature. Multi-beam antennas are an example of this category. Conversely, beam-steering reconfiguration implies the change of the direction of the main lobe of the radiation pattern. Depending on the steering capabilities and side lobes configuration, we distinguish various types of beam-steering. The term continuous beam-steering (also often referred as beam-scanning) refers here to the ability of tilting the antenna main lobe to any possible direction within the scanning range. On the contrary, non-continuous beam-steering antennas often present a limited number of states within the scanning range, each one associated to a particular direction of the main lobe. Phase-arrays are a good illustration of systems often capable of implementing continuous beam-steering (beam-scanning), whereas switched-beam antennas (often build upon a multiport feeding network) are examples of non-continuous beam-steering PRAs.

A more powerful technique is adaptive beam-steering, since it has the ability to adapt the radiation pattern in real-time. Moreover, adaptive techniques can place nulls to undesired signals, as shown in Figure 3. This avoids interference by minimizing the gain in unwanted directions, and improves spectral efficiency by orientating the main lobe adaptively to the intended direction.

A compilation of some recent representative works on beam-steering antennas is included in Table 1, considering the scanning range and the frequency bandwidth as the main performance indicators. In the same way, a distinction has been made between continuous and non-continuous beam-steering. According to the performance indicators depicted in the table, we can affirm that phased arrays are the most solid approach to achieve wide-range continuous scanning. However, other alternative techniques like mechanical systems, transmitarrays or the utilization of lenses provide a competitive performance, specially at higher frequency bands (around 60 GHz).

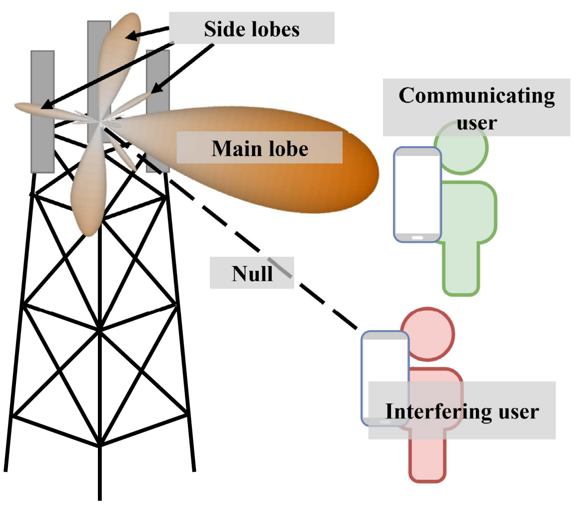

FIGURE 3. Communication between base station and users, where the adaptive beamforming principle is applied by the base station antenna.

B. SWITCHING MECHANISMS

The selection of the most suitable switching mechanism is directly correlated to the constraints imposed by the application for which the antenna is designed. For the targeted frequency range and applications addressed in this work, electrical switching and material-based reconfiguration elements (sometimes combined with mechanical systems) are the preferred reconfiguration mechanisms.

1) ELECTRICAL SWITCHING

Table 2 provides a brief performance comparison between some of the most used electrical switching mechanisms in the millimeter wave frequency range. These are: PIN diodes, radio frequency microelectromechanical systems (RF MEMS), radio frequency field-effect transistors (RF FETs) and varactor diodes [28].

A PIN diode is a special diode composed by an intrinsic semiconductor region ("I") sandwiched between a p-type semiconductor ("P") and an n-type semiconductor region ("N"). For RF circuits, a PIN diode behaves as a variable resistor. Figure 4 includes the equivalent circuit for a PIN diode when it is operating in both ON and OFF states.

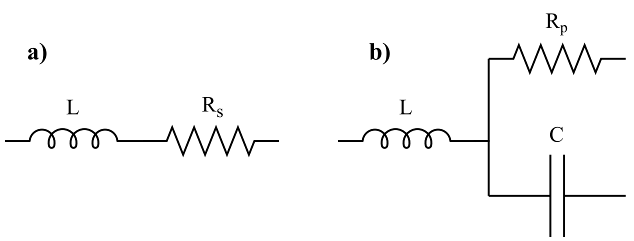

FIGURE 4. Equivalent circuit of a PIN diode. (a) ON state (b) OFF state.

The value of the inductance L is the same for both ON and OFF configurations. However, a small value of the series resistance R_s (around 1 Ω) allows for current flow in the ON state, whereas a large value of the parallel resistance R_p (around 1 MΩ) produces an open circuit behaviour in the OFF state. This can be modelled as a lumped RLC boundary in full-wave simulation [29].

Moreover, PIN diodes present some advantages compared to other switching mechanisms, including lower cost, shorter switching time and higher supply voltage. This positions PIN diodes as the most used electrical switching technique in the

TABLE 2. Comparison of electrical switching mechanisms at millimeter wave frequencies. Data extracted from [27].

Parameter	PIN-diode	RF MEMS	FET
Voltage (V)	±3-5	20-80	3-5
Current (mA)	3-20	0	0
Power consumption (mW)	5-100	0.05-0.1	0.05-0.1
Switching time	1-100 ns	1-300 μs	1-100 ns
Isolation	Medium	High	Low/none
Loss (dB)	0.3-1.2	0.05-0.2	0.4-2.5
Power handling (W)	< 10	< 1	< 10

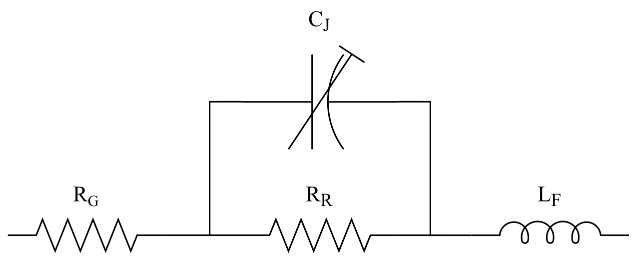

FIGURE 5. Equivalent circuit of a varactor diode.

mm-Wave frequency range. However, there are some other options that might result more convenient in certain cases.

Among the alternatives to PIN diodes, RF MEMS use mechanical movement to achieve a short or open circuit configuration through electrostatic force. Compared to PIN-diodes, MEMS switches present lower insertion loss, higher isolation, higher linearity and lower power consumption.

Varactors consist of a p-n junction diode whose capacitance varies as different bias voltages are applied to the diode. The equivalent circuit of a varactor is depicted in Figure 5. Typical values of a varactor capacitance C_J range from tens to hundreds of picofarads. Although they are widely referenced, varactors have a low power handling capability, which might sometimes restrict their use for reception antenna devices.

It is worthy to mention that the simulation of the performance of electrical switches is often perform using theoretical equivalent models (like the ones provided above). However, it can be sometime crucial to consider a more realistic model in order to simulate the real performance of the device and the impact it might have in other components of the system. For example, in the case of PIN diodes, parasitic effects at mm-Wave frequencies can induce significant uncertainty and imprecision to the simulation of the simple performance. In order to tackle this, some more realistic circuits models have been proposed, like the one depicted in Figure 6.

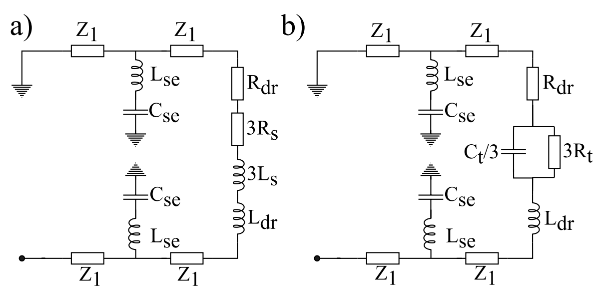

FIGURE 6. Equivalent circuit of the directors and the dc feeding lines. (a) PIN diode ON and (b) PIN diode OFF.

Using this model, an interesting analysis on the parasitic effect of PIN diodes is performed in [13], coming to the equivalents circuits of the directors and dc feeding lines for both ON and OFF states of the PIN diode.

2) MATERIAL-BASED SWITCHING

The activation of electrical switches often requires biasing lines, which may affect negatively the antenna radiation pattern and, adding extra losses. Moreover, the incorporation of such switches increases the complexity of the antenna structure due to the need for additional bypass capacitors and inductors which will increase the power consumption of the whole system [30]. This has motivated the interest of new reconfiguration means based on special materials with variable properties. Example of these materials are graphene, liquid crystal and phase change materials (PCM). A more detailed explanation of the use and properties of these materials is included in Section IV-C.

III. RECONFIGURABLE FEEDING ANTENNAS

This section is dedicated to include PRAs in which the reconfiguration capabilities are achieved within the feeding network. In many works, authors use the term beamforming feeding network (BFN) to refer to the reconfigurable feeding network. Phased-array antennas, Butler matrix networks and multiport systems including lenses are examples of designs within this group.

A. PHASED-ARRAY ANTENNA SYSTEMS

Phased-array antennas consist of several antenna elements and a reconfigurable feeding network that provides variable phase or time-delay control at each element, which allows for beam-steering capabilities. Sometimes, the amplitude of the feeding is also modified to enable beam-shaping. The utilization of antenna arrays provides more precise control of the radiation pattern, which results in lower side-lobes. Similarly, arrays contribute to produce a directive beam, that is then re-positioned electronically [31].

In the traditional phased-array configuration, one phase shifter is connected to every of the antennas forming the array, which allows for the individual control of the phase of the feeding signal of each element. Multiple techniques have been adopted to produce the feeding weights of the phased array [32]. The selection of the most appropriate method depends on many factor such as the type of array, the number of antennas or the distribution of incoming signal, and it is out of the scope of this paper. However, in order to illustrate the basic principle of operation of such schemes, a basic example of a radiation pattern produced by a linear phased-array is depicted in Figure 7. The weights of the feeding signals have been computed using the null-steering beamforming (NSB) algorithm.

Following these strategies, a very good scanning performance has been achieved multiple times in the literature. However, when it comes to the case of realistic antenna arrays, the particular radiation pattern of the antenna in use has to be considered, as well as the coupling between the antenna elements. Moreover, these designs often imply the use of very complex circuitry and a large number of phase shifters. This translates into high power consumption when

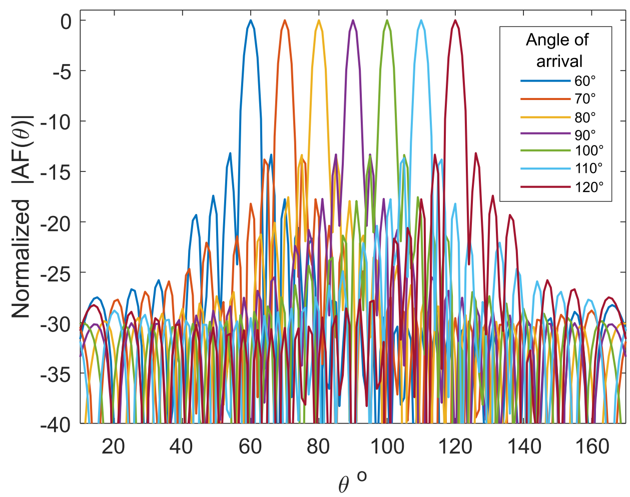

FIGURE 7. Simulated radiation patterns for different angles of arrival (main lobe). Feeding weights computed with the NSB beamforming algorithm for a linear array of 32 point sources. Two interference signals (nulls) are considered at ±20° from the angle of arrival in each case.

the number of elements of the array becomes large, which is often the case when multiple interference signals close to the direction of arrival of the desired signal are considered.

To tackle this issue, some efforts have been done to reduce the number of phase shifters. This is the case of the design proposed in [19], where lenses are used to group antennas into lens antenna subarrays (LASs), each one forming a switched-beam array. In this way, LASs are interfaced with phase shifters to realize a similar beamwidth performance that the one produced by a traditional phased-array with a similar number of antenna elements.

Another key issue when it comes to the design of phased-arrays is to determine the most suitable antenna element. Leaky-wave antennas are a popular alternative for the design of PRAs. They provide high-gain pencil beams to be scanned over broad angular ranges and can be integrated into systems including phased-arrays and partially reflective surfaces (PRS) [33]. Nevertheless, the large bandwidths associated with mm-Wave frequency bands introduce some problems to maintain impedance matching, making its utilization difficult in this frequency range [34].

In [18], microstrip antennas are combined with PIN diodes to build a reconfigurable feeding network in which three different radiation sub-spaces are created. Through this technique, a PRA at 35 GHz is achieved by using only four antenna elements. A similar principle is adopted in [15], in which strips lines and PIN diodes are integrated into every antenna element, forming then a 16-elements planar array that is able to perform beam scanning from −60° to +60° at a center frequency of 28.85 GHz. The idea of miniaturization and reduction of the number arrays and transmit-receive components is taken one step further in [13], where directors and PIN diodes are employed to design a four-elements planar array with a clearance of only 4 mm, what makes it suitable for its use in future 5G mobile terminals.

Two reconfigurable directors loaded with three PIN diodes each allow for pattern reconfiguration. In this way, the proposed antenna implements three different radiation patterns corresponding with three switching modes: two broadside modes and one endfire mode. With this mechanism, wide-angle beam-scanning is achieved, from -50° to 50° for the two broadside modes and from -40° to 40° for the endfire mode.

Another interesting solution proposed in the literature is the one configured by conformal phased-arrays. The first obvious advantage of these conformal arrays relies on the fact that they are compatible with non-planar surfaces. In addition to this, they often achieve a wider field-of-view compared to planar phased-array antennas. Among the different existing designs of conformal phased-arrays, CYCLON conformal arrays are the most fundamental and popular.

Despite of their facility of performing beam-scanning along the circumferential direction, it is still a challenge to realize full solid angle scanning. An interesting analysis of possible solutions to achieve full solid angle scanning based on cylindrical and conical CYCLON phased-arrays is provided in [10]. In this work, an integrated phased-array antenna is proposed and fabricated, combining conical and cylindrical microstrip antennas. Beam-scanning is thus achieved in the regions of $0^\circ \leq \theta \leq 30^\circ$, $30^\circ \leq \varphi \leq 150^\circ$ and $30^\circ \leq \theta \leq 180^\circ$, $60^\circ \leq \varphi \leq 120^\circ$.

Before closing this section, it should be stressed that many other designs in the literature have been integrated into a phased-array to implement beam-scanning. An example of this is the array proposed in [16], where a phased delay feeding line is combined with a binary metasurface to achieve 100° scanning performance from 21.8 to 33.2 GHz.

B. ANTENNAS WITH RECONFIGURABLE FEEDING NETWORKS

It was shown previously that phased-arrays can provide quasi-continuous steering at mm-Wave frequencies. However, they often suffer from high losses (typically coming from phase shifters and feed distribution network), delay and gain variations, and elevated cost [20]. In order to alleviate these problems, multiple alternatives have been proposed. Amid them, the use of a reconfigurable (multiport) feeding network allows to achieve beam-steering and/or beam-shaping by a different technique to that of phase shifting.

Under these premises, creative proposals for reconfigurable feeding networks can be found in the literature, using electrical switches and or multi-layer structures [35]–[38]. Some designs use the block cell antenna (BCA) concept to perform reconfigurability. The unit BCA consists of two ports, and the weighting matrix is used to selectively excite the ports for operation modes. As the unit BCA is expanded two-dimensionally, a $N \times N$ BCA structure can be obtained. This idea is exploited in [39], [40] to produce four different radiation patterns at 28 GHz by modifying the weights of the feeding signals that feed the four connected monopole loop antennas forming the radiating structure.

However, these designs seem to be isolated proposals and often they do not reach a competitive performance. On the contrary, antennas with a Butler matrix (BM) feeding network and multiport lens antennas have emerged as attractive solutions for both beam-steering and beam-shaping purposes, and have been widely explored recently in the literature.

1) BUTLER MATRIX FEEDINGS

First proposed by J.Butler and R.Lowe back in the 60s [41], a BM typically consists of hybrids, phase shifters and cross couplers, forming a multibeam-array antenna system capable of providing spatial orthogonal beams [42]. In order to provide high directivity scanning in the 2-D space, the conventional BM has been substituted by other designs, including cascaded BM topologies.

In [43], a planar 4×4 cascaded BM is introduced, with the aim of reducing the complexity of 3-D stacked structures. A 16-ports prototype is manufactured, resulting in a 16-beams system capable of performing beam-scanning from -37.8° to 39.6° in the elevation plane and from -66.6° to 70.2° in the azimuthal plane.

At high mm-Wave frequencies (around 60−70 GHz), some challenges such as antenna miniaturization, cost reduction and on-wafer integration arise [44], [45]. In order to address these issues, some solutions like the utilization of highly reproducible, thin wafers [46] or waveguide-based antenna solutions [47], are adopted in the literature.

Another important challenge of BM designs is the reduction of the sidelobe level (SLL), which is a key aspect in the mitigation of interference. In this way, some works propose the substitution of the classic $N \times N$ by other configurations [42], like the 4×8 BM. However, this results in a more complex structure that also covers a larger area. To solve this problem, some efforts have been made on the reduction of the number of crossover to provide a better compactness [48].

With the same intention of reducing the transmission loss and the processing cost of the antenna, BM designs based on substrate integrated waveguide (SIW) technology have gained a lot of attention recently. Among them, multi-folded BMs provide with a better compactness [49]. In [50], a compact SIW design with end-fire circularly-polarized antennas is proposed, which allows for a flexible orientation angle between transmitting and receiving antennas.

Both the advantages of a double-fold 7×8 BM and the SIW technology are exploited in [51], where a multibeam antenna with the three-layer configuration is proposed. In order to reduce the antenna size, the 7×8 BM is folded twice. The transition between each of the three layers is realized by slot coupling. The antenna is also fabricated and measured obtaining a good scanning performance at 30.5 GHz, keeping the SLL below −7.7 dB for all beams.

Zhu and Deng went a step further in [52], where they combine a BM feeding network with 8 different ports, 4 of the which dedicated for vertical polarization, and the other 4 for vertical polarization. In this way, dual-polarization is achieved, which results in an increase of the channel capacity through polarization diversity.

Despite the numerous advantages, BMs designs require a large number of components (phase shifters, crossovers, and 90° hybrid couplers). Moreover, as the number of beams increases, the required number of components grows significantly, leading to a much more complicated layout. Therefore, it is of great research significance and practical value to design new multi-beam antennas with simpler architectures. As an alternative to BM designs, [53] proposes a modularized interchangeable multibeam slot array antenna consisting of a port deck and an antenna deck (composed of a parabolic lens and a slot array) that are made of different substrates.

2) MULTIPORT LENS ANTENNAS

The utilization of integrated lens antennas is a very attractive design option to achieve beam-steering capabilities at mm-Wave frequencies with wide scan angle and high gain. Lens antennas use the refraction of electromagnetic waves at the lens surfaces to transform the radiation pattern of a primary feed into a prescribed otput radiation pattern. Due to their flexible design and good performance at mm-Wave frequencies, they have become an attractive alternative to design PRAs. Lately, different designs including numerous lens topologies and technologies have been registered in the literature.

Saleem *et al.* [21] integrated 15 hemispherical lenses (around microstrip patch antennas) into an antenna array, achieving full 360° beam-scanning in the azimuth plane. Despite of offering a constant level of the beam through the whole scan range, this solution implies the use of a large number of antennas and lenses.

In [54], the Rotman lens is used, which provides true-time-delay (TDD), steering the beam independently of the operating frequency. However, BFNs including Rotman lenses require different delay lines, and need to be designed for a fixed maximum beam-steering angle and a fixed number of radiating elements. A good solution to mitigate these disadvantages relies on the involvement of Lunenburg lenses. By including a Luneburg lens in the BFN, it is enough to change the feeding position in order to provide beam steering. Moreover, it does not require additional delay lines. Since the early 2000s, multiple works that use Luneburg lenses for beam-steering applications at mm-Wave frequencies have been registered [55]. An example of a BFN including a Luneburg lens is given in [56]. An open-ended SIW is adopted to launch the feeding signals into the circumference of the lens. When only one-axis beam-scanning is required, a planar implementation of the Luneburg lens can be implemented. Liao *et al.* use a parallel plate waveguide to emulate the behaviour of a Luneburg lens with a rotational symmetry in [57]. In this work, the feeding network is composed of eleven cascaded coaxial ports, achieving a total scanning range of 125° and a total efficiency above 90% between 28 and 36 GHz. Finally, in [58], a parallel-plate configuration is achieved with holes to form a low-loss fully metallic lens, while metallic pins are placed into the unit cell in a glide-symmetric configuration with the objective to increase the refractive index produced by the holes.

IV. NON-RECONFIGURABLE FEEDING ANTENNAS

In contrast to the works discussed previously, this section is devoted to antennas in which reconfigurability is not achieved by means of an adaptive/variable feeding network. Alternatively, reconfigurable metasurfaces, artificial materials with changing properties and other kind of creative designs including electrical and mechanical switching are some of the techniques used to accomplish reconfigurability.

A. METAMATERIAL/FSS-ENHANCED ANTENNAS

Metamaterials and metasurfaces (2-D periodically-arranged metamaterial structures) are well-known for presenting some properties that are not attainable with ordinary materials, such as a negative permittivity and permeability, and a negative refractive index. These extraordinary properties are derived from their physical structure, and not form their chemical composition [59]. This gives multiple extra degrees of freedom, since geometrical parameters are easier to tune than chemical ones. Hence, metamaterials offer fullness of novel options for the design of almost any kind of RF device [60]. Metamaterials have been already used for antenna design at microwave and mm-Wave frequencies [61], [62]. To achieve reconfigurability, multiple advanced materials and/or switching techniques are integrated into the metasurface design [63], [64]. At mm-Wave frequencies, the most used tuning technologies are PIN diodes, MEMS, mechanical, microfluidics and liquid crystals [65].

Furthermore, metamaterials and frequency selective surfaces (FSS), acting as phase transformation devices when placed in the near-field region of the source, have proven to be an interesting alternative to phased-arrays to achieve wide-range 2-D beam-steering. The typical configuration of such a system consists on placing the metasurface within a fraction of a wavelength from the aperture of a fixed-beam antenna, thus reducing significantly the overall height of the whole system [66].

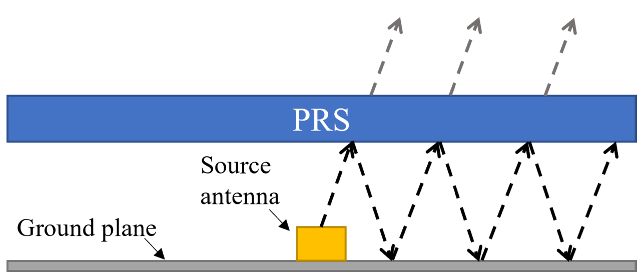

FIGURE 8. Schematic model of a conventional PRS antenna.

Recently, PRS antennas have gained popularity thanks to their compact structure and their facility to attain high directivity. Figure 8 illustrates the configuration of a conventional PRS antenna. A source antenna is embedded between the ground plane and a metallodielectric periodic array. Thus, multiple reflections and transmissions will take place within the cavity between the ground plane and the PRS, and ray theory can be applied to calculate the maximum directivity and profile of the antenna [67]. Multiple strategies have been adopted to realize pattern reconfigurable PRS. Among them, the incorporation of PIN diodes or the utilization of a phased-array source are of great interest, specially for the sub-6 GHz bands. However, the aim to avoid using switches and phase shifters at mm-Wave frequencies creates a big interest for passive systems.

In [66], two turning metasurfaces are placed in the near field of the antenna, achieving a spatially sawtooth time delay and thus transforming the phase distribution of the near field, which permits to change the beam direction of the antenna system. Adopting this mechanism, a reconfigurable beam-steering resonant cavity antenna (RCA) is proposed. Comite *et al.* go one step further in [68], combining a multilayer design of Fabry–Pérot cavity antennas (FPCAs) with a multi-source feeding network, forming thus a phased-array capable of steering the beam.

Despite of the low-cost and high-gain performance RCAs and FPCAs, they can easily suffer from narrow-bandwidth. In order to tackle this shortcoming, some approaches comprising the generation of multiple resonant modes or the utilization of multilayer PRSs have been proposed in the literature. An example of an innovative technique for bandwidth enhancement by the utilization of a quasi-curve reflector on a FPC antenna wth beam-steering capabilities at 60 GHz is provided in [22].

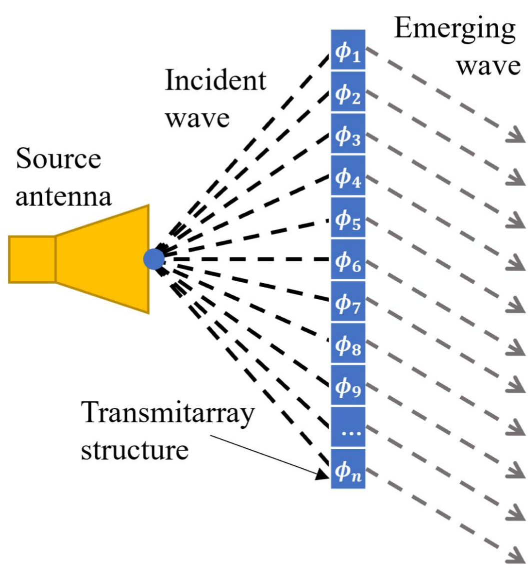

FIGURE 9. Illustration of the transmitarray principle.

Similar to RCAs with PRSs, transmitarray antennas are based on a thin periodic array placed in the near-field region of a transmitting antenna, capable of implementing receiving, transmitting and/or phase shifting functions. Reconfigurable transmitarrays can be obtained by changing the transmission phase of each unit cell electronically. An schematic of the working principle of a reconfigurable transmitarray is presented in Figure 9. In contrast to reflectarrays, that re-radiate all the power regardless of the frequency and cell design, transmitarrays rely on the impedance matching between the structure and the free-space. Therefore, it is desirable to make the transmittarray as ‘‘transparent’’ as possible, minimizing the losses induced by the structure, thus maximizing the radiation efficiency [69]. There are several ways of realizing phase reconfiguration electronically in order to achieve beamforming capabilities within a transmitarray. Amid them, active devices such as MEMS switches [17], [70] or PIN diodes [14], [23], [71], [72] have been used to fabricate beam-steering antennas at from C- to Ka-band frequencies in transmitarray and FSS unit-cell designs.

As an alternative to the utilization of active components, a mechanically reconfigurable transmitarray based on binary phase unit cell is presented in [11].

Other designs exploit FSSs in a creative way to achieve reconfigurability. In many cases, the periodic structure is placed around a dielectric resonator antenna (DRA) to achieve beam steering and/or patter diversity. DRAs have proven to be a good alternative to metallic antennas at the mm-Wave band due to their good radiation characteristics, provoked by their minimum conductor losses and the absence of surface waves. Moreover, they present a really high flexibility to control their radiation pattern and/or polarization by inducing the desired mode(s) of operation [73]. A reconfigurable FSS by means of a PIN diode is placed in the surroundings of a cylindrical DRA antenna both in [34] and [74] to produce different radiation patterns, which provides beam-steering capabilities over the whole scanning range.

B. ANTENNAS WITH OTHER RECONFIGURABLE ELEMENTS

The smart integration of reconfigurable and/or movable elements into an antenna structure is also employed to realize PRAs. Despite of not using metamaterial unit cells or periodic arrangements of scatterers, many of the designs presented below rely on the behavior of individual resonators, and can be thus seen as ‘‘metamaterial-inspired’’ antennas [75].

Reconfiguration is often accomplished by means of electrical switches. This is the case of the work presented in [76], where beam-steering is achieved at 28 GHz by means of four inverted F antennas (IFAs) controlled by PIN diodes. Similarly, a two-states RA at 26 GHz using planar IFAs is achieved in [77]. Endfire and broadside radiation patterns are achieved by switching ON and OFF diodes. Tang *et al.* also use PIN diodes, this time integrated into a pixel antenna, and combined with the utilization of a dipole as a radiator, to design an RA at 27 GHz. Despite of the creative designs included in these works, they are far from offering a competitive performance in terms of beam-steering or beam-shaping capabilities. Most of the antennas with high performance in this group can be grouped in one of the following two categories: electromagnetic bandgap (EBG) structures, and antennas with other mechanical systems.

1) ELECTROMAGNETIC BAND GAP STRUCTURES

EBG structures prevent/enable the propagation of electromagnetic waves in a particular frequency band for all incident angles and all polarization states. It has been proven that EBGs can improve/alter electrical properties of an antenna [78]. This principle is adopted in [79], where a 6-sectors EBG is combined with switching diodes and placed around a DRA operating at 60 GHz.

The circular-shaped mushroom-like structure is designed to create a stopband around 60 GHz when the diodes are ON, producing a passband around the same frequency when they are OFF. This allows to achieve a 360° beam-steering capability by playing with different combinations of the states of the diodes.

2) ANTENNAS WITH MECHANICAL SYSTEMS

In spite of the development of numerous promising technologies to achieve pattern reconfigurability, sometimes they imply high cost and complexity. Under this scenario, mechanical schemes are still a valid alternative, and we still see many works on the literature in which the reconfiguration engine is based on a mechanical system. Actually, it might be enough to use a lens antenna and vary the position of the illuminator to achieve beam-scanning. This is attained using a hemispherical dielectric lens antenna centered at 60 GHz in [80]. Also a moving lens antenna is employed in [25], but in this case it is dielectric lens the element that is pivoted by the mechanical system, while a circular horn feed remains fixed acting a radiating source. In this way, a good beam-scanning performance is achieved by keeping the structure compact.

However, other more advanced solutions have shown to be more beneficial due to their lower profile, higher performance and easier fabrication. Among them, slotted waveguide arrays configure an attractive solution for the mm-Wave range. They offer the possibility to be manufactured in printed circuit board (PCB), which has allowed the utilization of SIW solutions, like the one presented in [81], [82]. In [83], a 16-element array of continuous transverse stubs (CTS) is proposed in which a pillbox transition is used to create the line source needed to excite the CTS array. The system achieves a scanning range of ±40° in the H-plane with $> 90\%$ around 29 GHz.

An innovative design is proposed in [24], where the popular gap waveguide technology is used to achieve beam-steering capabilities with a rotating system. The system is comprises two layers: a quasi-TEM corporated-feed-ridged waveguide and a periodic arrangement of slots acting as radiating unit. Developed in hollow waveguide technology, the two parts do not touch each other, which allows for an easier rotational movement to generate phase gradient across the radiating part. The beam can be scanned up to ±60° in the H-plane with remarkable performance at 60 GHz.

C. ADVANCED MATERIALS ANTENNAS

It has been shown throughout this document that some reconfigurable designs including PIN diodes and other electrical switching techniques present often some difficulties to be scaled to mm-Wave frequencies, due to its losses and large packaging volume in terms of wavelength in this frequency range. On top of that, these elements sometimes require bias circuits, which notably enlarges the size of the antenna. Reconfiguration by mechanical means is another option that has been widely exploited. However, mechanical systems suffer from wear-out failures and are maintenance-intensive. To overcome these drawbacks, new artificial materials with amorphous properties configure an attractive alternative for reconfigurable mm-Wave antenna systems. In the following, some state of the art materials and their utilization for the design of PRAs are presented. Specifically, the selected works are divided into three groups: Liquid crystal, graphene, and phase change materials.

1) LIQUID CRYSTAL

LC is a well-known technology for the design of tunable microwave and optical devices. In the mm-Wave regime, the anisotropic behaviour of LC is exploited, taking advantage of the variable effective permittivity of the material. Particularly, thermotropic calamitic nematic LCs are used as mixtures for microwave applications, and the anisotropy present in the nematic phase is used for electrically tunable RF circuit/devices [84].

Based on this property, electric biasing is used to induce an electric field and produce an alignment of LC molecules, thus adjusting the permittivity. The permittivity range that can be achieved depends on the type of LC crystal used. In [85], permittivity is varied from $\varepsilon_{r,low} = 2.4$ to $\varepsilon_{r,low} = 3.2$, which is exploited to design a reconfigurable lens antenna operating at the V-band and with a beam-steering range of ±30°. The same principle is adopted in [86], using a similar material to produce a dielectric beam-steering lateral wave antenna. In [87], LC is used as substrate of a microstrip line. In this design, a change in the LC permittivity produces a phase difference, which permits to re-shape the radiation pattern of the antenna array. LC is integrated in a SIW structure by adding a rectangular metal ground to SIW in [88], producing a beam-steering antenna at 28 GHz. Dual polarized PRA at 28 GHz exploiting the anisotropic characteristics of liquid crystal in [87].

2) GRAPHENE

First synthesized by Novoselov *et al.* [89], graphene has recently gained the interest of the whole research community due to its promising mechanical, thermal and optical properties, which include good electrical and thermal conductivity, high optical transmittance and elevated Young's modulus, among others [90]. The potential of graphene is specially usable for THz applications, which has already been employed to design beam-steering antennas [91]. In the mm-Wave regime, graphene is not specially dispersive i.e.

its conductivity does not change significantly with frequency. However, considerable changes in the conductivity are appreciated for different electrical bias values. According to the demonstration in [92], the real part of σ_d can range from a couple of mS to values over 60 mS when the applied bias electric field is varied from 0 to 20 V/nm. This principle is used in [93] for the design of a reconfigurable (3-states) Vivaldi antenna at 30 GHz via graphene nanoplates. In this work, the resistance of graphene is varied by an external bias, thus controlling the amount of electromagnetic energy that passes through the feeding line to the radiation part of the antenna. This permits gain manipulation, which allows to achieve beam-shaping capabilities.

Due to their scalability and easier fabrication, multilayer forms of graphene are an attractive solution for mm-Wave applications. Among the different synthesis methods of graphene, bottom-up techniques (in which pristine graphene is constructed from simple carbon molecules) are proven to be time-consuming and non-scalable, which makes them inconvenient for industrial applications. In this regard, top-down methods, in which layers of graphene derivates are extracted from a carbon source (typically graphite), have gained attention within researchers. In particular, the promising properties and synthesis simplicity of graphene oxide (GO) and reduced GO (rGO) open new possibilities for an easier and more feasible fabrication of reconfigurable antennas using graphene. In [94], graphene oxide (GO) films are used to build a graphene microstrip antenna array that is fed by a microstrip feeder followed by a SIW Butler matrix to configure a multi-beam antenna array at 30 GHz.

These alternative forms open new research ways in which graphene pads can be integrated into complex systems like periodic structures or 3D designs. This is exploited in [95], where a 3-D reconfigurable intelligent surface controlled by graphene pads performing beam-steering capabilities at 28 GHz is proposed.

3) PHASE-CHANGE MATERIALS

Phase-change materials (PCMs) possess the ability to absorb energy when the phase-changes from solid to liquid, and release energy when the phase changes from liquid to solid. This has been exploited for RF reconfiguration purposes.

TABLE 3. GeTe properties between 24 and 31 GHz. Data extracted from [96].

GeTe state	Conductivity (S/m)	Relative permittivity
Amorphous	4.1×10^{-5}	1
Crystaline	10	63

GeTe materials can act as a bi-stable switch at mm-Wave frequencies due to the change on its properties from the amorphous to the crystaline state. The transition from one state to the other (in any of the two possible directions) is accomplished by a laser pulse consisting of a beam of a few squared millimeters. In this manner, the conductivity (and thus the relative permittivity) of the material in the mm-Wave range can be modified according to the values included in Table 3. This has been exploited by Wong *et al.* [97], [98] to design PRAs with switched beams around 30 GHz.

Paraffin (also known as alkane) is another PCM that presents a density change over the solid-to-liquid phase transition [99]. This property can be utilized to construct a PCM-based variable capacitor in the mm-Wave frequency range. Thus, if the temperature of the material is changed (by applying a dc voltage, for example), a phase change from solid to liquid will be triggered, resulting on a volume expansion of the paraffin, which provides the force to move to the top plate of the capacitor.

Lastly, [100] presents a number of works on high-frequency RAs using paraffin-based MEMS capacitors. Despite of the fact that this material has not been used yet for pattern reconfiguration, it is another example of the potential that PCMs might have for PRA designs.

V. CONCLUSION AND FUTURE CHALLENGES

Pattern reconfigurable antennas will play a significant role for a number of future radiofrequency and communication technologies. The targeted functionalities and frequency range are determining factors for the design of the antenna. In this survey, a comprehensive review of different design strategies and technologies is given to the reader, with an special emphasis on beam-steering and beam-shaping antennas at mm-Wave frequencies. Also, a brief theoretical background of each of the presented technologies and reconfiguration mechanisms is offered. Moreover, the working principle and performance of some selected works are illustrated along the paper.

This review points out the following key aspects for the design of future PRA systems at mm-Wave frequencies:

- There is no unique solution to achieve pattern reconfiguration. However, the adopted strategies can be separated into two main categories, depending on weather the reconfiguration mechanism is part of the feeding network or not. A common reality for both of the groups is the necessity of a switching element that implements reconfiguration. Electrical switching is the most popular solution, but other solutions relying on multiport and phased-array networks are also widely adopted in the literature. Finally, the use of mechanical systems and the exploitation of special material properties configure interesting alternatives to electrical systems and beamforming feeding networks.
- Despite of the high popularity of electrical switches, it is worthy to highlight that the use of active components at mmWave is impeded by its scarce availability, long lead-time, and expensive bill of material costs. This, together wit the increase of complexity that the utilization of such components implies, has led to multiple attempts to find other alternatives, specially for compact systems that might be installed on mobile terminals. A simple but illustrative practical example of the negative impact of the utilization of PIN diodes on the device

performance is given in [12]. With different states of hardwired connection, the proposed antenna can achieve a beam scanning range of 240° in the azimuth plane with $6.6 - 8.9$ dBi realized gain. When all hardwired connections are replaced by PIN diode switching, the scanning range and realized gain reduce to 120° and $4.5 - 7.5$ dBi, respectively.

- Due to the strict constraints imposed by mobile applications, the reduction of the number of electrical switches has been the main concern of many works on PRAs recently. In the same way, the small footprint of antennas on-chip positions them as a key technology to take into account for the near future. Typically, on-chip antennas are handicapped by narrow bandwidth. To circumvent this issue, a wide range of possible solutions including the utilization of metasurfaces or SIW technology arises for future compact and high-performance PRAs operating at mm-Wave frequencies [101].
- The use of advanced materials with changing properties such as graphene or liquid crystal has brought many advances to the electromagnetics research community recently. However, their optimal fabrication, characterization and utilization for antenna purposes at mm-Wave frequencies is still an open question. Thus, the synthesising of new phase change material and their application to microwave reconfigurability might be a powerful strategy for the upcoming PRAs.
- Despite of the remarkable importance of pattern reconfigurability for future radiofrequency networks, it is not the only key requirement imposed for antenna systems. We are moving to a new paradigm for wireless communications, based on the adaptive reconfiguration of the antenna systems to fulfill the needs of the wireless links among users. This might imply the necessity of a hybrid reconfiguration in which pattern reconfiguration is combined with frequency and/or polarization reconfiguration. Although some works on hybrid reconfiguration have been already found [102], they are still isolated attempts, which opens the door for new research on combined reconfiguration antennas at mm-Wave frequencies.

Finally, it is worth noting that the need for a RA design should be considered as part of a beamforming system. This is specially crucial when it comes to adaptive/real-time reconfiguration, since both the computation time and the hardware reconfiguration time are critical aspects playing a major role for many applications.

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