

Review

Recent Developments and State of the Art in Flexible and Conformal Reconfigurable Antennas

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Abstract: Reconfigurable antennas have gained tremendous interest owing to their multifunctional capabilities while adhering to minimalistic space requirements in ever-shrinking electronics platforms and devices. A stark increase in demand for flexible and conformal antennas in modern and emerging unobtrusive and space-limited electronic systems has led to the development of the flexible and conformal reconfigurable antennas era. Flexible and conformal antennas rely on non-conventional materials and realization approaches, and thus, despite the mature knowledge available for rigid reconfigurable antennas, conventional reconfigurable techniques are not translated to a flexible domain in a straight forward manner. There are notable challenges associated with integration of reconfiguration elements such as switches, mechanical stability of the overall reconfigurable antenna, and the electronic robustness of the resulting devices when exposed to folding of sustained bending operations. This paper reviews various approaches demonstrated thus far, to realize flexible reconfigurable antennas, categorizing them on the basis of reconfiguration attributes, i.e., frequency, pattern, polarization, or a combination of these characteristics. The challenges associated with development and characterization of flexible and conformal reconfigurable antennas, the strengths and limitations of available methods are reviewed considering the progress in recent years, and open challenges for the future research are identified.

Keywords: flexible antennas; frequency reconfigurable; microfluidic antennas; pattern reconfigurable; polarization reconfigurable; reconfigurable antennas; wearable antennas

1. Introduction

Reconfigurable antennas have received a lot of attention in modern communication systems due to their versatile applications by offering extra functionality. A reconfigurable antenna is defined as a single structure that is capable of switching between one and a combination of characteristics such as frequency, pattern, and polarization [1]. These structures with their flexible and multi-operation characteristics offer compact and cost-effective antennas for modern communication systems such as cellular radio systems, satellite communication, airplane, health care systems, and unmanned airborne vehicle (UAV) systems [2–4]. There has been extensive research and substantial advancements demonstrated in the various types of reconfigurable antennas made from rigid and conventional materials in the last few decades. New and modern communication systems are moving toward wearable technology and system [5]. Wearable technology and systems include flexible electronics and displays, conformal consumer electronic gadgets and devices for body area networks (BANs) [6–8].

The requirements for flexible and reconfigurable antennas as a key component of the wearable systems have been increased because wearable devices must cope with the dynamics of the various surfaces.

Antenna reconfigurability is achieved by changing the antenna's current path, physical structure, or electrical properties. As Figure 1 shows, there are various methods to achieve reconfigurability in the four main categories. The progress in the development and realization of the flexible reconfigurable antennas was not as fast as their rigid counterparts. There are various existing challenges for the realization of these types of antennas. Figure 1 presents the existing reconfiguration techniques, which include: the PIN diode, the microelectromechanical systems (MEMS) switch, the varactor from the electrical category, the microfluidic-based method and the origami-based antenna. The photoconductive switch is made of semiconductor materials and uses bias lines instead of metallic wires [9]. The reason for not having a flexible reconfigurable structure with this switch is because of the challenges of integrating it with unconventional and flexible materials. Moreover, the limited range of flexible materials and permittivity restricts researchers in this area in employing reconfiguration techniques based on smart materials. These are based on reconfiguring the substrate of the antenna through changing its permittivity or permeability under different levels of voltage [10].

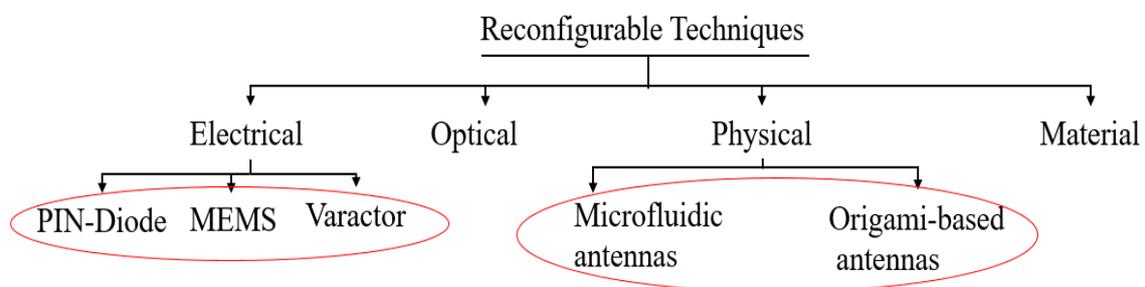


Figure 1. Categorization of reconfiguration techniques for all types of antennas.

A comprehensive review papers focusing exclusively on simulation [11], a specific reconfigurability method [10,12], antenna types [2,13], and other [14–16] of rigid antennas have been presented. Despite great efforts for comprehensive reviews of rigid antennas, there are no comprehensive review papers for the flexible reconfigurable antennas. In this review paper, we summarize recent developments in flexible pattern, frequency, and polarization reconfigurable antennas, as well as antennas with two feature reconfigurability. The purpose of this paper is to review the reconfiguration techniques, the challenges and limitations for design and fabrication, the achieved results and a comparison of the materials used in flexible and rigid structures. This leads to the recognizing of the current gap in this field and identifying of the possible future work in this area.

In the following sections, we discuss reconfigurable antennas in different categories:

- Frequency-reconfigurable antenna;
- Pattern-reconfigurable antenna;
- Polarization-reconfigurable antenna;
- Multiple reconfigurable features in an antenna.

2. Frequency-Reconfigurable Antennas

Frequency reconfigurable antennas have attracted researcher and industry communities' attention due to its capability to reduce the size of the front end systems and minimize interference with other wireless systems and maximize throughput [1]. The resonance of a proposed flexible antenna can be switched through the change of the effective length of radiator and the modification in the ground plane and feeding networks with the help of an electrical switch [17–25], by microfluidic-based antenna [26,27] and the use of a conductive fluid as a switch for a main radiating element [27], changing the antenna's permittivity [28,29] or the antenna's shape or type [30–53].

2.1. Antennas Based on Electrical Switches

Electrical switches are employed for the interconnecting of adjacent elements of the antenna patches [18–21] or varying the length of the slots on the patch or ground plane [1,22], modification on feeding networks [23] or switching between feeding ports [17] in order to realize frequency reconfigurability. Reconfigurability is limited to specific frequencies by employing a pin diode and MEMS switch, whereas continuous ranges of frequency reconfigurability are obtained by using varactor diodes.

In some research, the frequency reconfigurable antennas performance is analyzed through simulation [19,23] or it is verified through fabrication of prototypes that employ a 1 mm stub as an ideal diode. This is due to the challenges in the realization of the antenna with electrical switches such as placing diodes on unconventional materials, the need for a large RF bias network, and the effects of the nonlinearity of diodes and harmonics parameters. In other research, the conductive parts of the antenna where the diodes are placed are made of conventional materials to make the integration process easier [20,22,54].

In Reference [18], the microstrip patch antenna is placed on the Indigo blue jeans. A diode placed between two rectangles on the patch creates the reconfigurability between 2.4 GHz and 2.5 GHz for Bluetooth and WiMAX applications. In other research [23], two diodes are placed across a T-slot developed on the feed line of the rectangular patch antenna to reconfigure its frequency bands between 1.8 GHz, 2.3 GHz, and 2.4 GHz. In simulation analysis, ShieldIt Super is employed for the antenna conductive parts and it is placed on a Felt substrate with $\epsilon_r = 1.44$. In Reference [19], dual-band reconfigurability is achieved through the connection of the two rectangular patches by eleven switches. An antenna is placed on the denim jeans textile and reconfiguring, between its two frequency bands 2.44 GHz (Wi-Fi) and 3.54 GHz (WiMAX).

Further investigation has been done by fabricating designed flexible reconfigurable antennas, employing DC circuits, and the measurement. The diodes are placed on the antenna, and in some cases, DC circuits are integrated as well. In Reference [20], the proposed textile antenna reconfigures between 2.45 GHz and 5 GHz. The copper tape is used for the patch and ground plane, and a denim material is used for the substrate. The diode is integrated on the copper tapes and connects two adjacent patches to create these two frequency bands. For the proposed antenna, the DC is connected to the antenna by means of two wires. In Reference [22], the proposed antenna is placed on a flexible polyethylene terephthalate which reconfigures between two states: a single band structure at 2.42 GHz and dual-band with different polarizations at 2.36 GHz and 3.64 GHz. The structure is composed of a folded slot and the radiation characteristics of the stub is altered by a PIN diode placed on the stub. The antenna is fabricated with inkjet-printing technology. Further study has been done on this antenna in [54]. An artificial magnetic conductor (AMC) surface is added to this structure in order to improve its radiation performance and to reduce the specific absorption rate (SAR). The performance of both antennas has been measured for the flat and curved positions. To control the diodes, DC voltage is applied with the RF signal through the input connector to eliminate the need of complex DC biasing circuit, thus preserving the antennas flexibility.

The same approach for biasing of the diode is employed in [24], but more challenges arise in the design process when unconventional materials are employed for the conductor and ground plane of the antenna.

The proposed antenna in [24] is fabricated by embedding conductive fabric into the flexible polydimethylsiloxane (PDMS) polymer [55–57] and all the active and passive elements of the antenna are fully encapsulated in the structure (Figure 2). To realize the antenna reconfigurability, two varactors are placed between a rectangular patch and a parasitic patch (made of conductive fabric) and are biased with same DC voltage. The frequency resonance is tuned continuously between 2.3 GHz and 2.65 GHz. The antenna in [21] consists of a rectangular-grounded loop which is excited by a monopole antenna fed by a coplanar waveguide. A U-shaped slot is loaded to the monopole to achieve dual-band operation.

This dual polarized antenna operates within 2.21 GHz to 2.69 GHz and 3.14 GHz to 3.55 GHz bands. The resonance of the higher band is tuned by switches placed within the U-slot.

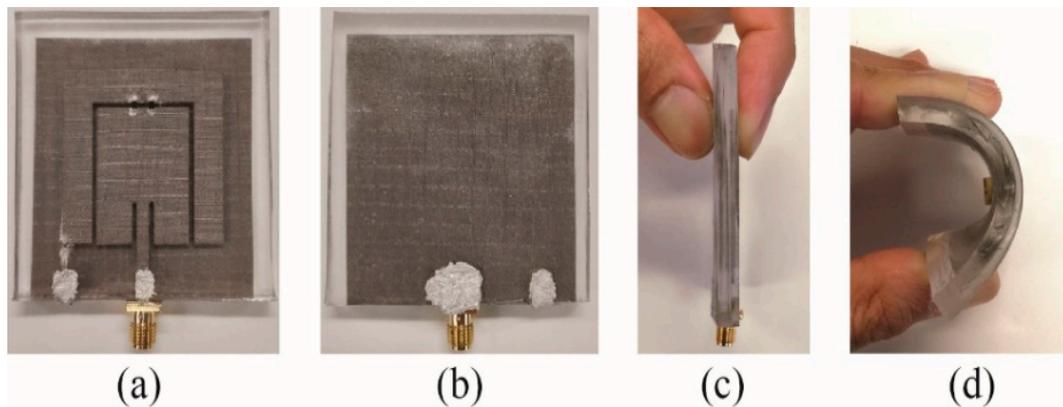


Figure 2. The fabricated frequency-reconfigurable antenna on polydimethylsiloxane (PDMS) substrate in [24]: (a) front view; (b) back view; (c) side view; (d) bending position.

Another approach for designing a reconfigurable antenna is by switching between two modes of the antenna through two-port excitation [17]. The proposed graphene conductive ink printed textile-based microstrip antenna in [17] can switch between 3.03 GHz and 5.17 GHz. The frequency reconfigurability is achieved by exciting the two modes of TM_{02} and TM_{20} through two-port excitation. A challenge of the switching between these two ports is addressed by introducing a single pole single throw switch to the structure.

DC circuits are integrated in different parts of antenna such as ground plane [1,58] or within the structure. In References [25,59], DC control circuits are integrated within commercial snap-on buttons. The snap-on reconfigurable wearable antennas are proposed to address the challenge of connection between rigid components to textile materials. This dual-band reconfigurable textile patch antenna is fabricated and the measurement results are reported showing a tuning range of 32.8% and 8.8% at 2.45 GHz and 5.8 GHz ISM bands, respectively [25].

The methods discussed so far have all been based on pin diodes and varactors. RF MEMS switches are also widely employed by researchers for realization of reconfigurability due to their low loss and distortion, small size, and high isolation [60]. The MEMS switch geometry and materials can be tailored to meet a specific size requirement and the desired actuation voltage, respectively [60,61]. While in most published literature, MEMS switches are integrated on the rigid substrate and one switch topology is used, great effort in integrating MEMS switches on flexible substrate is demonstrated in [62]. A multiband Sierpinski fractal antenna is proposed in [60], which is realized on a liquid crystal polymer (LCP) substrate, with three sets of used RF MEMS switches. Each switch has a different actuation voltage. The antenna operates at four frequencies between 2.4 GHz and 18 GHz without the need of extra lines to bias the switches.

As shown above, the main challenges for realizing frequency reconfigurable antennas with the electrical switches are based on the need for a DC-bias, and the adverse effects of rigid components on the antenna's flexibility. Moreover, in reconfigurable antennas based on electrical switches, antenna performance is degraded. The harmonics and intermodulation distortion is generated because of diode nonlinearities and gain compression.

2.2. Mechanically Frequency-Reconfigurable Antennas

Aside from the aforementioned challenges, the mechanical stability and rigidity of the frequency reconfigurable antennas based on electrical switches (PIN diodes and varactors) are not sufficient for some applications such as wearable antenna for gadget [63]. The high strength fields in MEMS switches limit the antennas with this type of switch to low-power applications [27]. To overcome these

issues, the new categories of stretchable antennas such as microfluidic antennas, antennas based on micromesh structures, and origami-based antennas have been introduced. In the following sections, different categories of the mechanical frequency reconfigurable antennas with their existing challenges are presented.

2.2.1. Microfluidic Antennas

Recent development in the composite structure manufacturing creates the ability to embed microvascular networks in flexible materials and enables conductive or dielectric fluid to be injected into these materials. To reconfigure the antenna's frequency, the conductive fluid is used as a switch [27], the reactive loading effects of the fluid metal are used in [64,65], antenna fabricated by injecting alloys is elongated via stretching [66,67], the permittivity range of substrate is changed [28,29].

In microfluidic antennas in which conductive fluid is used as a switch, PDMS and styrene ethylene butylene styrene (SEBS) are usually used to produce microfluidic channels. The examples of liquid metals are mercury and eutectic gallium indium alloy (EGaIn). There is no need for electrical actuation switches in these types of the antenna which leads to enable efficient power handling. In the first microfluidic reconfigurable antennas with simple geometry, the liquid metal conductor is used in the PDMS channel [26]. In the presented frequency reconfigurable dipole antenna, for the microfluidic channels, SEBS with the $\epsilon_r = 2.3$ and loss of 0.07 is employed and the channels are filled with EGaIn. The proposed antenna reconfigures from 2 GHz to 5.5 GHz by increasing strain up to 120% [68]. In Reference [27], the liquid metal is employed as a shortening switch. The frequency of the proposed antenna shifts between 4.6 GHz, 3.84 GHz and 5.34 GHz by emptying and filling the liquid metal to the microchannel to the lengths of $\lambda/2$ and 4λ . The antenna is placed on an S-glass composite substrate with $\epsilon_r = 3.4$ at 4.6 GHz. A copper-tape and an EGaIn is used for the ground plane and the fluidic conductor, respectively.

In other research, the reactive loading effect of the fluid metal is used for tuning of a coplanar waveguide (CPW) folded slot antenna and miniaturization as well [64,65]. Two pairs of microfluidic channels are used as a switch to reconfigure between 2.4 GHz, 3.5 GHz, and 5.8 GHz [64]. The antenna is placed on Taconic TLY substrate with $\epsilon_r = 2.2$, $\tan \delta = 0.0009$, with a thickness of 1.53 mm and two separate PDMS structures are used for two channels. The same approach is employed in [65], where liquid metal is also used as a reactive load on top of the antenna to achieve tuning and miniaturization as well.

In other types of microfluidic antennas, the frequency is tuned mechanically by elongating the antenna via stretching [66,67]. In Reference [66], a dipole antenna is fabricated by injecting EGaIn into microfluidic channels placed in PDMS substrate. The antenna frequency is tuned from 1850 MHz in a relaxed position (54 mm length) to 1600 MHz in the elongated position (66 mm length). In Reference [67], a stretchable frequency reconfigurable antenna is fabricated by injecting liquid metal alloy into a flexible substrate. Galinstan and silicone TC5005 are used for alloy and substrate, respectively. Instead of a microchannel, a square reservoir is fabricated in the flexible substrate. The frequency of the antenna is tuned from 1.3 GHz to 3 GHz by stretching up to 300% and varying the electrical length of the patch from 31 mm to 87 mm.

Despite the presented works [26,27,64–67] in which conductive fluid is used for radiating element, in [28,29], a microchannel is employed for adding different dielectric liquid materials to the antenna. The frequency shift is achieved in [28,29], by changing the permittivity range by inserting different fluids (air, acetone, and de-ionized (DI) water) into the existing channels.

As mentioned previously, fluidic-based antennas resist various or long time deformation compared to conventional antennas. In addition, the higher conductivity of conductive liquid compared to conductive fabrics, makes the design of an antenna with higher efficiency possible. On the other hand, there is a limitation for realizing the complex patterns for patch with this method. For antennas in which reconfigurability is achieved by changing the permittivity, the limited range of liquid dielectric, does not allow the researcher to have a wide range of reconfigurable antennas and frequency bands.

Moreover, their ability for stretching up is only in one direction for complex geometries, or in some cases the accurate mechanical control of antenna is difficult [69].

2.2.2. Antennas Based on Metallic Micromesh

In Reference [63], a semitransparent and flexible antenna which consists of a series of tortuous micromesh structures is presented. The proposed antenna can be stretched up to 40% without any problem. The mesh parts are made of copper and are placed on PDMS. The antenna's frequency reconfigures from 2.94 GHz to 2.46 GHz by increasing the tensile strain through mechanically elongating the meandering line of the antenna.

2.2.3. Kirigami and Origami-Based Antennas

In the class of mechanically reconfigurable structures, Kirigami and Origami-based antennas demonstrate RF characteristics that can be self-tuned by shape reconfiguration.

These antennas with their unique features are able to change the shapes and sizes of the 3-D structures or transform 2-D shapes into other 2-D and 3-D shapes by employing flexible materials [70,71]. This leads to the changing of the effective lengths [30], size [31] and type of antenna [32,33]. Various types of frequency reconfigurable origami-based antennas such as helix antennas [31,34,35], microstrip [32], yagi [36], dipole [37–39] and monopole [40] antennas have been presented in the literature.

In most of the existing 3-D origami helical antenna [41–49], accordion antenna [51], and spring structure [50], the frequency reconfigurability is achieved by changing the antenna's height. In [49], the proposed helical antenna is fabricated by copper foil on a paper, which switches between 1.82 and 2.14 GHz in folded state ($H = 38$ mm), and 860 MHz in the unfolded state ($H = 255$ mm). The same approach is presented in [43], in which origami quadrifilar helical antenna reconfigures between the normal mode at frequencies of 0.83 GHz, 1.17 GHz, or 1.5 GHz with $H = 371$ mm and axial mode at frequency of 1.23 GHz with circular polarization with $H = 200$ mm. In Reference [31], the frequency is tuned in the 3-D origami bifilar helical antenna by applying a force at its top and controlling its height. The antenna is made of copper tape on a sketching paper substrate with $\epsilon_r = 3.2$. The frequency can be reconfigured among seven frequencies from 0.86 GHz to 3 GHz for three heights of 273 mm, 154 mm, and 25 mm. Another origami quadrifilar helical antenna is presented in [44]. The resonance frequency is tuned between 2.07 GHz, 3 GHz and 4.45 GHz by varying the height of antenna to 120 mm, 75 mm and 105 mm. Unlike the previously presented origami helical antenna, an origami reflector is used around this antenna to enhance its gain. This design is modified and an origami reconfigurable quadrifilar helical with circular polarization for higher frequency bands is presented [72]. The proposed antenna reconfigures between K, Ka, and extremely high-frequency bands by varying the height of antenna to 364 mm, 345 mm and 181 mm, respectively. Beside the helical origami structures, in spring antenna, the frequency can be tuned by changing the height of structure. In Reference [50], a tunable origami spring antenna with continuous frequency shifting from 1.1 GHz to 1.4 GHz is presented. The antenna is folded and unfolded with the help of an actuation system to the various heights from 60 mm to 145 mm. The actuation system is also employed in multi-radii monofilar helical antenna [73]. The antenna reconfigures between three bands of 1.22–1.84 GHz and 1.78–3.54 GHz and 3.64–4.04 GHz, with circular polarization. The antenna consists of a combination of two helical antennas with different radii and is fabricated from Kapton and copper trace.

Frequency reconfigurability based on converting 2D structure into 3D shape is presented in [30,32,37]. In References [30,37], reconfigurable origami-based dipole antennas with mechanically robust and durable structures have been introduced. In Reference [37], an E-textile accordion-dipole is fabricated on an Organza fabric. The frequency is reconfigured from 760 MHz to 1015 MHz range through changing the effective lengths by placing the antenna on a series of four Styrofoam fixtures which provide the changing angles of inclination from 0 to 60 degrees. A self-folding origami antenna that converts 2D structure into 3D shape is proposed in [32]. The antenna is a polystyrene subassembly that reconfigures between a microstrip patch antennas with a bandwidth of 1.5 GHz to 3.5 GHz to a monopole antenna with a bandwidth of 2.0 GHz

to 2.3 GHz. The reconfigurability is realized by the concept of light activation and the bending of the polymer sheet assembly toward the light and away from the second port of the microstrip transmission line. The antenna is fabricated using RT/duroid 5870 with $\epsilon_r = 2.33$.

The transformation from a planar structure to a 3-D structures for frequency reconfigurability is employed in [33,38,40,74]. A frequency switchable monopole antenna which is designed on an origami magic cube is proposed in [40]. The antenna reconfigures between 850 MHz to 1000 MHz and 1.3 GHz to 1.6 GHz for the unfolded and folded states due to the change in the length of the antenna. The same approach is used in [74] to design a dual-band antenna operating at 1.57 GHz and 2.4 GHz in the folded state and 900 MHz and 2.3 GHz in the unfolded state. The proposed antenna consists of a meandered monopole that is loaded by a microstrip open-ended stub. The open-ended stub controls the second resonance of antenna by changing its length (Figure 3). In Reference [38], a frequency-reconfigurable dipole antenna using an origami flasher is proposed. In this structure, the dipole length is increased in the folded state into a cube. The antenna frequency is switched between 750–800 MHz (folded) and 1.19–1.26 GHz (unfolded). The transformation from a dipole structure to a 3D conical spiral structure is made in a proposed morphing Nojima origami antenna in [33]. The antenna operates at 0.48 GHz and 2.5 GHz in unfolded (dipole antenna) and fully folded state (conical spiral antenna), respectively.

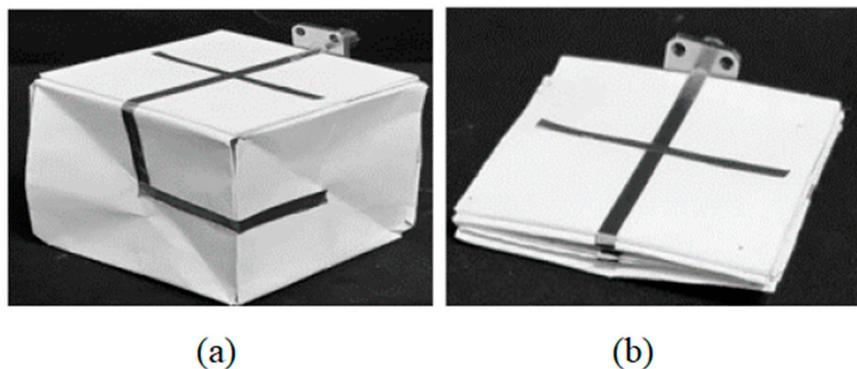


Figure 3. The frequency reconfigurable antenna based on changing the antenna shape (Origami Magic Cube): (a) unfolded; (b) folded [74].

Most origami-based antennas are designed using paper which creates poor durability and performance stability [75]. Moreover, to accurately control the change in the antenna dimensions and shape is not easy due to the high flexibility nature of paper. This also limits the range of the frequency reconfiguration to a couple of points. Therefore, in [75], a dipole antenna based on multi-material 3D printing technology is proposed, which can provide a continuous frequency reconfigurability from 0.95 GHz to 1.6 GHz through a precise structure manipulation by a robot.

In Reference [76] a frequency reconfigurable monopole antenna based on kirigami technique is presented. A three-story tower kirigami is used for this antenna. This technique provides a more stable structure compared to a free-standing structure, as well as a volume reduction. In this antenna, a horizontal monopole antenna is designed on a two dimensional flat PET film with a frequency of 0.42 GHz, which can be stretched to the three-storey tower to operate at a frequency of 0.53 GHz.

Most of the origami-based antennas use paper in their structure due to its high foldability, high thermal stability and lightweight. Despite the advantages of using paper in origami antennas, the roughness on the surface of paper creates some electrical properties of the conductive patterns. This can be addressed by coating the paper with polymers, but the folding of antenna will be affected. Therefore, in [77], a nonpaper approach with higher transparency and a smoother surface is presented for a foldable frequency reconfigurable antenna. The frequency of V-shaped silver nanowire antennas on nonpaper is switched between 2.3 GHz to 3.0 GHz in unfolded and folded states, respectively.

One of the challenges of this type of antenna is its limited durability. The conductive parts of these antennas such as copper tape and conductive inks are prone to delamination and deterioration in

conductivity due to the extensive mechanical stress. In addition, substrates such as paper and memory polymers are not robust to extensive folding [37]. Although origami-based antennas are not practical for communication systems yet, they have the potential to be used with advances in material and actuator technologies [38].

In Table 1, the presented flexible frequency-reconfigurable antennas are listed. The table presents the antenna types, reconfigurability method, number of states, radiation performance and the materials that were used in these antennas to give a general overview on this category.

2.3. Antennas at Millimetre-Wave

The millimeter-wave (MMW) spectrum addresses the challenges of the demands for high bandwidth to cover high data rates and extends capacity to facilitate the services and applications for 5G. An adaptable and flexible antenna at wireless front-ends is required for the realization of 5G mm wave architectures [78].

As mentioned earlier, one of the challenges in designing flexible reconfigurable antennas is the choice of the substrate. This becomes more challenging in mmW because of the higher dielectric loss [55]. LCPs and polyethylene terephthalate (PET) which feature low loss-tangent, good flexibility, conformity, and surface adhesion are presented as great candidates for the substrates at higher frequency bands [79]. In addition, the inkjet-printing as a cost-effective, and precise fabrication method is a promising candidate due to its sensitivity of dimensions (very low wavelength) in mmW and its capability of fabricating of thin conducting layers. In Reference [78], a slotted T-shaped radiating patch embedded in a rectangular aperture cut inside the ground plane is inkjet-printed on a PET for operating frequency bands between 26.5–40 GHz. Four ideal switches, open/short metal contacts are employed in the middle of slots to generate the four modes of reconfigurability in this antenna.

In Reference [79], a flexible frequency reconfigurable antenna in 20.7–36 GHz with four different switches configurations for 5G networks is presented. The antenna is placed on LCP and consists of a radiating fork shaped-patch and two stubs which are connected to the main patch by means of two PIN diodes. The inkjet printing for the conductive parts of the antenna which include the patch, stubs, and matched coplanar waveguide (CPW) feeding structure are employed. The efficiency of the antenna is reported to be in excess of 65% across the entire bandwidth.

Table 1. Comparison of methods and materials used in different kinds of flexible frequency-reconfigurable antennas, along with corresponding performance.

Ref.	Antenna Type	Reconfigurability Method	No of States	Used Materials	Freq. (GHz)		Gain (dBi)		Eff. (%)		BW (%)		Dimension ($\lambda_{min} \times \lambda_{min}$)	Height (λ_{min})
					Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.		
[1]	patch	electrical switch/slot modification on ground	6	ShieldIt Super and Felt	1.57	2.55	0.2	4.8	17	47	2.9	19	0.59 × 0.51	0.006
[20]	patch	electrical switch/connecting two patches	2	copper tape, Denim	2.45	5	3.17	3.55	N/A	N/A	2.5	5.85	0.40 × 0.19	0.008
[21]	loop/monopole	electrical switch/geometry morphing	3	transparent PETP	2.4	3.4	1.9	3.2	82.8	97	12.25	20.94	0.264 × 0.4	0.001
[27]	dipole	physical/microfluidic based	2	S-glass, copper-tape, EGaIn	3.84	5.34	N/A	N/A	N/A	N/A	N/A	N/A	1.8 × 1.8	N/A
[24]	patch	electrical switch/parasitic patch	Continuous	Polymer, Conductive fabric	2.3	2.68	2.9	3.3	40.3	46.1	0.3	0.4	0.4 × 0.43	0.042
[28]	slot antenna	physical/change of permittivity by injection	3	FR4, PDMS, copper	3.05	7.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.015
[31]	helical	physical/height of structure	3	copper tape, sketching-paper	0.86	3	4.69	6.79	N/A	N/A	N/A	N/A	0.13 × 0.13	0.07, 0.44, 0.78
[32]	monopole/microstrip	physical/changing the type of antenna	2	copper-clad RT/duroid 5870	1.5	3.5	N/A	N/A	N/A	N/A	13.9	80	N/A	N/A
[50]	Spring Antenna	physical/height of structure	6	Copper tape, paper	1.1	1.4	9	~10	N/A	N/A	N/A	N/A	N/A	0.22 to 0.53
[66]	patch	physical/based on injection alloys, reconfigurability by stretching up	Continuous	EGaIn, PDMS	1.6	1.85	N/A	N/A	N/A	N/A	12.5	16.5	0.053 × 0.29 to 0.053 × 0.35	0.005

3. Pattern-Reconfigurable Antennas

Pattern reconfiguration is an interesting characteristic of antennas and is often used of changing the coverage from one area of interest to another one, switched operation between two or more wireless nodes, determining direction of arrival, increasing or decreasing the coverage area of a wireless node, or more generally, to adapt the performance of a wireless node in response to varying conditions in surrounding environment. Thus, our discussion of pattern reconfiguration includes antennas that can reconfigure the radiation pattern to two (a special case often also referred to as “switchable antennas”) or more states. In the presented flexible pattern reconfigurable antennas, the reconfigurability was achieved by using an electrical switch by changing the ground or radiator shapes [80–84], switching between two types of the antenna combined in a main structure [85], shorting the radiator to the ground plane [86,87], switching between feeding ports [88] or physical reconfiguration by changing the antenna’s shape or type [89–95].

3.1. Pattern-Reconfigurable Antennas Based-On Electrical Switches

For pattern reconfigurable antennas based-on electrical switches, the reconfigurability is achieved by connecting the adjacent radiators or parasitic elements to the main patch, switching between two types of the antennas combined in the main structure. In Reference [81], the four-element circles are located at $0^\circ/+360^\circ$, $+90^\circ$, $+180^\circ$ and $+270^\circ$ and are connected by four arms to the center. The antenna’s patterns are reconfigured to four different directions of 0° , $+90^\circ$, $+180^\circ$, and $+270^\circ$ by using four RF switches which are placed on the arms between the center and the radiation circles. The antenna’s conductive parts are made of ShieldIt Super textile and are placed on Felt as a substrate. A similar approach has been used with the same research group in [96]. The antenna consists of a centre patch and four radiating elements located at $0^\circ/+360^\circ$, $+90^\circ$, $+180^\circ$ and $+270^\circ$ which are connected to the center by four PIN diodes. The same material in [81] is employed in this antenna as well. The radiation pattern of antenna is doughnut-shaped and the maximum gain is at $0^\circ/+360^\circ$, $+90^\circ$, $+180^\circ$ and $+270^\circ$ based on switches’ statuses. The antenna in [82] comprises of a circular monopole patch, three parasitic patches, and two parallel symmetrical parasitic branches embedded with two PIN diodes which operates between 2.40 GHz and 2.48 GHz. The antenna’s pattern is reconfigured to the beam in the direction 30° , 330° in the azimuthal planes by controlling the two diodes. The antenna is fabricated on Rogers 5880 substrate with $\epsilon_r = 2.2$ and a thickness of 0.127 mm.

In Reference [85], a bent dipole and a loop are combined in one structure and the radiation patterns of the two antennas are canceled or compensated by using two diodes. This antenna was fabricated on flexible polyimide with $\epsilon_r = 3.6$ and loss of 0.01. The beam direction is steered to $+50^\circ$, 0° , and -50° in the azimuth direction at 2.5 GHz (Figure 4). In Reference [97], a top-loaded monopole antenna and a loop antenna are combined in a one structure. Three antennas with different top-loading angles are proposed and two diodes are placed on antenna. For antenna with angle of 90° , the beam is steered to two directions of -90° and $+90^\circ$. The antenna is fabricated on FR-4 substrate and operates at 2.4 GHz for Fitbit Flex Wristband.



Figure 4. Fabricated prototype of the pattern-reconfigurable antenna on flexible polyimide in [85].

3.2. Mechanically Pattern-Reconfigurable Antennas

Mechanically pattern reconfigurable antennas are presented in response to disadvantages of using electrical switches, which were discussed in previous section. A pattern reconfigurable origami quasi-Yagi helical antenna using a copper film on DNA shaped PET substrate is presented in [91]. The pattern is reconfigured between four states at 2.2 GHz by changing the role of the DNA reflector and the DNA based director. In this antenna, three origami DNA geometries are used. Besides the reflector and the director, the antenna has a DNA shaped driven element. In States 1 and 2 of the antenna, the beam is directed to 30° and -30° where a parasitic director is designed by folded origami DNA and parasitic reflector is made of unfolded origami DNA for State 1 and vice versa for State 2. In State 3, the beam is directed to 0° and in State 4 it is directed at -50° and 50° , where both the parasitic elements are folded in State 3 and unfolded in State 4.

A thermally reconfigurable antenna based on origami reflectors with ability to switch the beam direction and beamwidth is presented in [92]. The proposed antenna comprises of a single monopole antenna and four origami reflectors made of copper-clad FR4 substrate. Smart shape memory polymer hinges are used to stimulate the reflectors. The beam of antenna is switched between omnidirectional pattern in State 1 (all reflectors are folded), directional pattern in the 45° , 135° , 225° , and 315° in State 2 (by unfolding various reflector pairs) and directional beam in 0° , 90° , 180° , and 270° in State 3 (by unfolding each origami reflector). In addition, the 3 dB beamwidth is changed from 52° (State 2) to 140° (State 3).

The antenna's half-power beamwidth (HPBW) is changed from a 360° to 40° in a bi-directional pattern with a loop antenna array based on magic cube origami in [95]. The antenna is an array which consists of three single cubes with a single loop antenna, in serious form. The array can be folded and unfolded due to the nature of structure. The single antenna on a single cube was designed at 1.39 GHz with 4.03 dBi gain and 360 degrees HPBW. The series of two and three loops by using two and three cubes is increased to 5.2 dBi (HPBW = 60) and 5.53 dBi (HPBW = 40), respectively. Figure 5 shows the fabricated antenna for three states. In another quasi-Yagi monopole antenna based on origami magic spiral cubes, the pattern is reconfigured between omnidirectional radiations and three other broadside patterns at 1.9 GHz [93]. The antenna consists of a stacked L-shaped driven monopole, an L-shaped reflector on the first origami magic cube, and two L-shaped directors on the Cube 2 and 3, all are fabricated on paper. In the first state, the monopole antenna has omnidirectional pattern with 1.9 dBi peak gain, which is increased to 5.7 dBi by adding L-shaped reflector. By adding first and second directors to this antenna the gain is increased to 6.8 dBi and 7.3 dBi, respectively.

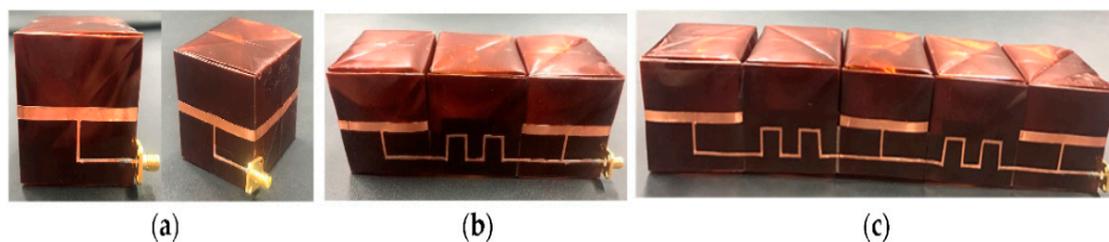


Figure 5. Fabricated proposed antenna array based on magic cube origami for: (a) single antenna and cube (b) two antennas and (c) three antennas [95].

One of the challenges in origami-based pattern reconfigurable antennas is to maintain the shape after being folded or unfolded. In Reference [98], a suitable Kresling conical is presented for a spiral antenna. This antenna shape can be kept by its internal tension after unfolding. The pattern of this antenna is reconfigured between omnidirectional (folded) for planar spiral and unidirectional for conical spiral shape (unfolded) with circular polarization at 2.5 GHz to 3.2 GHz. This challenge is also addressed in [94]. A pattern-reconfigurable axial-mode helix antenna by controlling the height of helix is presented. The height is controlled by applying a direct current to the SMA spring, which is an actuator.

In Table 2, the flexible pattern-reconfigurable antennas are listed. The table presents the antenna types, reconfigurability method, number of states, the radiation performance and the materials that were used in these antennas.

3.3. Dual Mode Antennas

Recent advances in communication technology have led to the advent of antennas for body area networks (BANs) applications. The suitable radiation pattern for connecting nodes that are placed on-body is monopole-like patterns and connecting nodes that are placed on-body and off-body are broadside patterns [88]. New types of the flexible dual-mode antennas which reconfigure between on-body and off-body radiation patterns have been presented [88–90,99,100].

In Reference [88], a flexible reconfigurable dual-mode microstrip antenna operating at 2.45 GHz is presented. A ring and a meandered patch with two different feeding ports and the same ground plane are combined in one structure for the on-body and off-body modes, respectively. The pattern of the antenna is changed by switching between two feeding ports, the monopole-like of the ring pattern and a broadside pattern of the meandered patch. The pure copper polyester taffeta fabric is used for the conductive parts of the antenna and it is placed on felt with $\epsilon_r = 1.17$ and loss of 0.016. The effects of the body tissue on antenna performance is investigated by placing an antenna on a phantom.

The dual-mode feature by having broadside radiation pattern at 2.5 GHz and a conical-like radiation pattern at 5.8 GHz in the triangular patch antenna is achieved [99]. A conductive textile is used for the patch and the ground plane and antenna is placed on the substrate with $\epsilon_r = 1.63$ and loss tangent 0.04. The reconfigurability is achieved by using three vias and two symmetrical open-ended slots. The proposed flexible microstrip patch antenna in [100], reconfigures between on and off-body communications at 2.45 GHz by employing two PIN diodes. The textile material felt and a conducting fabric pure copper taffeta is utilized for dielectric layers and metallic layers, respectively.

As it is mentioned before, mechanical tuning techniques including physical deformation, stretching, or folding for pattern reconfigurable are presented as an alternative to electronic tuning [90]. A mechanical pattern reconfigurable antenna based on liquid metal and microchannel inside a polymer is presented in [90]. This antenna comprises a 9×5 array of metal dipoles which are inside platinum-cured thermoset silicone with $\epsilon_r = 2.2$ and loss of 0.016. To form the dipoles, EGaIn is injected into the channels inside the substrate. Pattern reconfigurability is achieved through elongation from 0 to 53% to theta 0 to $\pm 55^\circ$ and surface reshaping to 0, ± 37 and ± 58 for flat, convex and concave, respectively. In a fully textile reconfigurable ultra-wideband (UWB) antenna, the pattern is switched between a monopole-like shape from 2.62 GHz to 10.1 GHz and a microstrip-like shape from 2.73 GHz to 10.1 GHz [89]. The reconfigurability in this antenna is achieved by raising and lowering a textile flap which is the main radiator. As Figure 6 shows, when this textile flap is parallel to the ground plane, the structure behaves like a microstrip antenna with a unidirectional pattern. When in the orthogonal position to the ground plane, the structure acts as a monopole antenna with an omnidirectional pattern.



Figure 6. The measurement set-up for proposed fully textile reconfigurable UWB antenna with two monopole-like and a microstrip-like patterns ([89], reproduced courtesy of The Electromagnetics Academy).

Table 2. Comparison of methods and materials used in different kinds of flexible pattern-reconfigurable antennas, along with corresponding performance.

Ref.	Antenna Type	Reconfigurability Method	No of States	Freq. (GHz)	Used Materials	Gain (dBi)		Eff. (%)		BW (%)		Dimension ($\lambda_{min} \times \lambda_{min}$)	Height (λ_{min})
						Min.	Max.	Min.	Max.	Min.	Max.		
[81]	patch	electrical switch/connecting parasitic patches to the main patch	4	2.45	ShieldIt Super, Felt	N/A	N/A	N/A	N/A	N/A	N/A	0.72 × 0.72	0.016
[82]	monopole	electrical switch/connecting surrounding elements to the main patch	2	2.40–2.48	Rogers5880	0.5	0.7	77	78	N/A	3.2	0.28 × 0.2	0.001
[85]	dipole, loop	electrical switch/combination of the pattern of two antennas	3	2.47–2.53	Polyimide	1.96	2.48	N/A	N/A	N/A	2.4	0.2 × 0.35	0.004
[86]	patch	electrical switch/connecting patch to the ground	2	2.4	Felt, conductive textile	2	3.9	38	49.5	4.8	8.5	0.78 × 0.78	0.023
[88]	patch	electrical switch/switching between feeding ports	2	2.45	felt and Copper Polyester Taffeta	2.9	5.2	65	72	4.1	4.9	0.64 × 0.64	0.03
[90]	array of dipoles	Physical/elongation of patch which is based on liquid metal	3	12.5	EGaln, platinum-cured thermoset silicone	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
[91]	helical	Physical/folding and unfolding	4	2.2	copper film, PET	7.5	9.5	N/A	N/A	N/A	N/A	N/A	N/A
[92]	monopole	Physical/folding and unfolding origami reflectors	8	2.4	copper-clad FR4 substrate	4.5	11	86	98	16	30	2.2 × 2.2 to 0.73 × 0.73	~0 to 0.73
[93]	monopole	Physical/folding and unfolding two other directors on magic cube	4	1.9	copper film, paper	1.9	7.3	64	N/A	N/A	21	0.24 × 0.24	0.06 to 0.72
[95]	loop	Physical/magic cube origami	3	1.39	Copper tape, Kapton	4.03	5.53	89	97	10	18	0.21 × 0.21 to 0.21 × 0.63	0.21

4. Polarization-Reconfigurable Antennas

The polarization mismatch between antennas in receivers and transmitters in communication systems creates power loss. The mismatch is because of the alteration of position and orientation of the two antennas. The polarization reconfigurability is a feature that compensates this power loss by matching the antenna's polarization [101]. Polarization reconfigurability can be achieved by changing the shape of the radiating patch [101], switching between different radiators [102] and changing the antennas shape [103–107].

In Reference [101], three polarization modes are created by controlling the truncations on the patch by using four diodes at 2.4 GHz. The proposed textile-based antenna is placed on felt substrate. The performance of the antenna over a phantom is analyzed to verify its suitability for BAN applications. In another proposed textile-based substrate-integrated waveguide (SIW) circular ring-slot antenna [108], the inclination of the linear polarization is controlled in the range of angles 30° by changing the position of the short strip to three places on the slot ring.

In Reference [102], by switching between four sector radiating elements located at 0° , 360° , 90° , 180° , and 270° , which are interconnected by pin diode switches to the center, the antenna exhibits dual-polarization with a combination of vertical and horizontal polarizations with an omnidirectional radiation pattern. The proposed antenna is placed on felt and conductive textile (E-textile) and is used for the ground plane and radiating elements. The polarization of the antenna is reconfigured between two circular states at 1.85 GHz to 2.75 GHz (unfolded, $H = 106$ mm) and a linear state at 1.4 GHz and 3.7 GHz (folded state, $H = 53$ mm) in an origami conical spiral antenna [107]. Another mechanical polarization reconfigurable antenna based on origami and skeleton scaffoldings is presented in [103–105]. The proposed bifilar segmented helical antennas reconfigure between right-hand circular polarization and left-hand circular polarization by retaining around their central axis (Figure 7) [103]. Paper with $100 \mu\text{m}$ thickness is used as the origami base for this structure. In other mechanical polarization reconfigurable textile patch antennas, the conductive Velcro tape and zip fastener is used separately to switch between linear to circular polarizations at 2.3–2.5 GHz [106]. Both antennas are made of felt and conductive cloth. Two antenna's axial ratio repeatability ability to interchanging polarization modes are compared in this research. The primary advantage of this research is its ability to adjust the antenna characteristics.

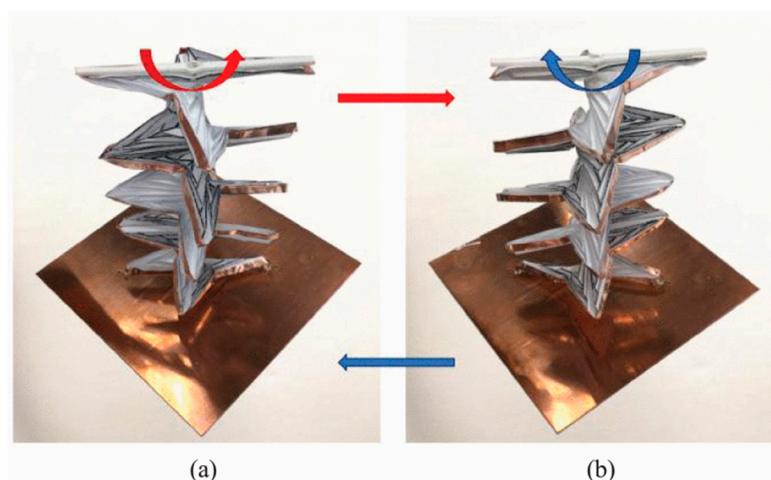


Figure 7. The prototype of the bifilar segmented helical antennas at (a) left-handed and (b) right-handed angles [103].

5. Multiple Reconfigurable Features in Antennas

In multi-reconfigurable antennas, the two features of the antenna can be switched independently. These antennas are listed in a couple of categories:

- Frequency and polarization;
- Frequency and pattern.

The advantages of reconfigurability of these two features compared to the one feature of the antenna is having more flexibility and diversity which leads to a new domain of research.

5.1. Frequency and Polarization Reconfigurability

In Reference [109], an L-shaped stub is introduced in the ground plane of a disc monopole antenna and a parasitic arc is placed around the main radiator. Two-pin diodes are placed between the main radiator and the parasitic arc to switch between two frequencies of 2.45 GHz and 0.92 GHz. The L-shaped stub is also connected to the ground plane with the help of two diodes. Through optimization of the diodes positions on the patch and the connecting and disconnecting the stub to the ground, four states of right-handed circular and left-handed circular polarizations are generated for both frequency bands, separately. The antenna is placed on jeans substrate with $\epsilon_r = 1.7$ and an adhesive copper tape is used as a radiating element and ground plane (Figure 8). In References [1] and [58], the frequency reconfigurability is achieved by manipulating the slot size at the ground plane of the truncated edges of the rectangular patch textile antenna. In Reference [1], three diodes are integrated on a slot at the ground plane of a textile antenna to switch between six frequencies: 1.57 GHz, 1.67 GHz, 1.68 GHz, 2.43 GHz, 2.50 GHz, and 2.55 GHz. ShieldIt Super and felt with $\epsilon_r = 1.22$ at 1.575 GHz is utilized for conductive parts and substrate, respectively. To bias these three diodes, four vertical slots at the edge of the ground plane are added to the structure. Capacitors are employed on vertical slots to preserve the RF current flow on the ground plane. Four wires are connected to the antenna to provide voltage and to switch the diodes (Figure 9).

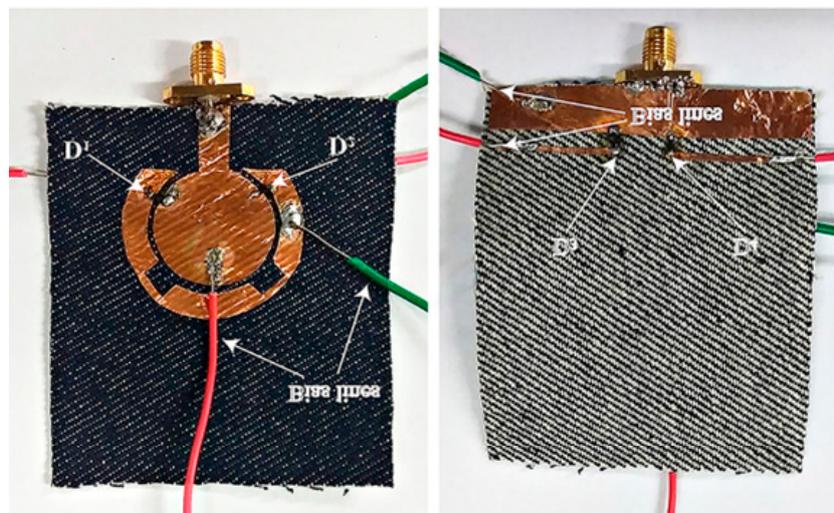


Figure 8. Fabricated prototype of the frequency and polarization-reconfigurable antenna on jean substrate in [109].

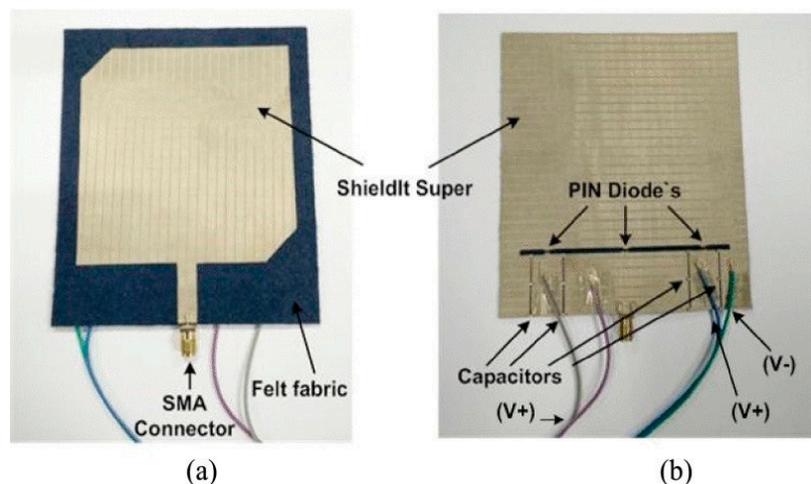


Figure 9. The fabricated frequency-reconfigurable antenna based on textile in [1]: (a) front view; (b) back view.

Polarization reconfigurability between right-handed and left-handed circular polarization at 5 GHz, and linear polarization at 4.7 GHz or 5.2 GHz is presented with a textile antenna based on snap-on buttons in [110]. The polarization is controlled by rotating the module through opening and closing the flap (the slot placed on the circular patch antenna). The metalized nylon Ripstop fabric and Cuming Microwave C-Foam PF-4 foam with $\epsilon_r = 1.06$ are used for conductive parts and substrate, respectively.

5.2. Frequency and Pattern Reconfigurability

The proposed antenna in [111] consists of two symmetrical radiating elements, with a shared feedline and a ground plane which is fabricated on a Rogers5880 substrate. Each radiation element comprises a circular monopole branch, a regular hexagonal open ring, and two other branches added to the ring. The frequency of the antenna reconfigures between two bandwidths 1.84–2.00 GHz and 2.27–2.49 GHz. It is able to steer the beam in two directions (60° and 300° for the lower band and 34° and 326° for the higher band) by employing 8 PIN diodes loaded on the symmetric hexagonal split ring and monopole branches. An ultra-wideband flexible frequency and pattern reconfigurable antenna that uses two fabrication methods of conductive thread embroidery on the textile substrate and cutting the thin sheet of copper with and sticking it on the substrate is presented in [112]. The frequency and pattern of the antenna are reconfigured for six frequency bands in a range between 2 GHz to 10 GHz and three radiation patterns modes by using 10 stubs on the front part and two semi-elliptical stubs located on the back part, respectively. In Reference [113], the antenna with both frequency and pattern reconfigurability is proposed. To achieve the pattern reconfigurability in this structure which can be changed between a straight line and helix with 1.1-turn, liquid crystalline elastomers and heating effects are employed on their shape. This material phase transition to an isotropic state happens through heating. By using the behavior of liquid crystalline elastomers and adhering thin metal, a reconfigurable antenna is designed. At 30°C , the antenna is straight (Figure 10a) and has an omnidirectional pattern at 4.9 GHz. The frequency and pattern are shifted to 14.04 GHz and directional by increasing the temperature to 92°C and having 1.1-turn helix (Figure 10b). This antenna has a capability of reconfiguring the frequency from 12 GHz to 10.7 GHz as well by changing the shape of antenna from a 0.5-turn loop to a 1.5-turn helix.

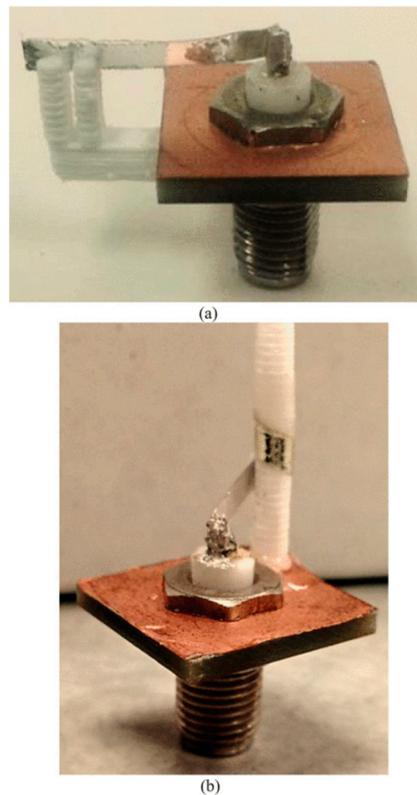


Figure 10. Pattern and frequency-reconfigurable antenna based on liquid crystalline elastomers: (a) straight status; (b) helix structure with 1.1-turn [113].

Most of the origami-based antennas reconfigure frequency due to the nature of mechanical tuning which is based on changing antenna's dimension. The Nojima wrapping for origami-based structure was proposed for the first time in [114]. It provides the various models based on the shape of central hub, which is a square shaped in this paper, and different angles between the segments as well. In Reference [115], a dual-mode origami Nojima antenna which reconfigures between directional mode at 1.61 GHz for folded state and omnidirectional mode at 0.66 GHz for unfolded state is presented.

6. Comparison between Proposed Techniques for Flexible Reconfigurable Antennas

Table 3 shows a list of materials that are mostly used for flexible and conformal reconfigurable antennas is shown. The table provides the available materials for each fabrication method and their suitability for bending/folding and sustained bending/folding (repeating deformation) for better comparison. For all of frequency, pattern, polarization, or a combination of these characteristics, the reconfigurability methods can be divided into three categories: electrical switch, antenna based on liquid metal/dielectric and Origami-based antennas.

Among the presented techniques, antennas based on electric switches employ a much wider range of materials compared to microfluidic and origami-based antennas. Their frequency can be tuned to a couple of states or even a continuous range, whereas limitations exist for the other techniques. However, if actual diodes are employed instead of ideal stubs, a DC-bias and a controlling system are required. Therefore, the flexibility of the antenna will be affected by the integration of the antenna with rigid components. The strong connection between the rigid components and unconventional materials electrically and mechanically is also challenging. For this technique, the nonlinearity effects of diodes on antenna performance should be considered. Furthermore, the efficiency of these types of antennas is usually lower compared to their rigid counterparts. As Table 3 shows, this is due to the lower conductivity of the flexible materials compared to the conventional materials e.g., copper layer with conductivity of 5.96×10^7 S/m.

In liquid metal-based antennas, power handling is more efficient and highly linear because electric switches are not used. Therefore, this technique is recommended for high-power applications. The antennas based on this technique are more flexible and durable compared to other techniques, due to the use of soft materials. In addition, their efficiency is higher compared to antennas based on electrical switches due to higher conductivity and lower dielectric loss of the materials. On the other hand, there are more limitations in the range of materials that can be used. It is very challenging to design a complex structure with this technique especially compared to their rigid counterparts. In an antenna which uses conductive fluid as a switch, the reconfigurability is mostly limited to two states.

Origami based antennas as a flexible structures do not use electrical switches. They offer a complexity reduction due to their method of reconfigurability based on changing the antenna's shape. The efficiency of these antennas is higher compare to textile or fabric-based antennas with electrical switches. This is primarily due to employment of copper tape, and other solid conductors in their structures. As they primarily use paper or copper in the form of thin foil in their structure, they are not robust or durable for continuous deformation compares to the other presented methods. In addition, there is a challenge of holding the antenna's shape upon folding and unfolding, therefore in some cases, an actuator is employed in the antenna structure. Furthermore, in some types of origami-based structure such as a magic cube, the reconfigurability is mostly limited to two states.

7. Conclusions

We critically reviewed the state-of-the-art in flexible and conformal reconfigurable antennas, categorizing of the developments with respect to frequency, pattern, polarization reconfigurability, as well as a combination of these features. Performance requirements and realization challenges that are unique to flexible and conformal reconfigurable antennas are discussed. Materials utilized in development of flexible and conformal reconfigurable antennas were considered critically, taking into account the applicability of these materials in niche applications, in the light of their electrical and mechanical characteristics. With an ever-increasing interest in flexible and conformal reconfigurable antennas nowadays, we conclude with identifying the following open research topics and potential directions for future research:

- Characterization of new flexible materials with low-moderate loss at mm-wave and terahertz frequencies;
- Robust integration methods to combine switching elements with flexible materials;
- Development if switch-less reconfiguration approaches;
- Integrating MEMS switches on flexible materials to realize this type of antenna;
- Integrating optical switches on flexible materials to realize this type of antenna;
- Employing reconfigurable microfluidic antennas for complex patch structures.

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