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Lightweight and Low-Cost Deployable Origami Antennas–A Review

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ABSTRACT The art of paper folding also known as Origami plays an important role in various research areas of different scientific fields. Origami structures possess many useful characteristics such as reconfigurability, flexibility, deployability, compactness, and multi-functionality. These attributes are inevitable for modern communication systems. Additionally, they provide antenna engineers an extra degree of freedom while blueprinting next-generation designs. One of the desirable features of origami is its folding capability. Using this property, it can be transformed into a two-Dimensional (2D) sheet from a three-Dimensional (3D) structure and vice versa through external stimulus. In recent years, researchers have proposed numerous smart materials to optimize folding behavior. These smart materials extend the functionality of origami technology for designing self-folding structures required in space systems, small scale devices, and self-assembly systems. Origami structures feature many useful characteristics pertinent to modern day design challenges of communication systems such as reconfiguration, flexibility, compactness, and multifunctionality. In this work, a state of the art review is presented on conceptualization, design challenges, and fabrication of light-weight and low-cost deployable origami antennas. Furthermore, to provide critical insights deployment challenges and possible solutions are also provided. It is believed that this work will not only help peers to understand the basic working principles of different origami structures but will also lay the foundation for future research in the evolving field of origami-based antennas. Moreover, the design methodology proposed in this paper will also provide pragmatic solutions for origami antennas suitable for the harsh and rigid environments.

INDEX TERMS Origami antenna, deployable, lightweight, low cost, self-actuation.

I. INTRODUCTION

Origami is the ancient "Japanese" paper folding technique. This technique enables construction of three-dimensional (3D) functional structures from two-dimensional (2D) planar structures. Using this capability, a 3D origami structure can also be transformed into a compact 2D structure through the act of folding in different patterns, and thus offers a unique method to fabricate, assemble, store, and morph structures to get an optimal response. The principles of this ancient art have inspired various products and emerging technologies engineered for applications far beyond art and aesthetic. It has caught attention for space applications such as mirror/solar panels, human lunar bases, and other deployable structures. Though the use of origami works starts from large-scale structures, many researchers are recently proposing ideas for the development of engineering applications with small-scale structures whose size ranges in even micro/nanometer scale for biomedical applications, Since conventional patterning methods are well developed, this simple yet innovative origami structures are readily adopted using computer aided cutting lithography/etching process, and direct-printing process. The mechanical, electrical, and optical properties of any kinds of materials are easily tunable via the origami approaches. Many researchers have exploited this capability to design compact deployable [1], [2] and reconfigurable structures [3]. In [4] GaAs based mirror was fabricated using micro origami technique. This technique

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used the stored energy as strain between semiconductor layers to create self-positioning 3D structures with robust hinges. Origami based paper folding techniques have been used to design compact and high energy density Li-ion batteries [5]. Fuel cells were prepared using current collectors consisting of folded paper coated with carbon nanotubes. The folded cells showed 14 times increase in energy density as compared to the planar versions. A deformable wheel robot using a well-known ball-shaped water bomb origami pattern was proposed in [6]. The origami pattern can change its shape from long cylindrical tube to a flat circular tube. Thus, a wheel can be designed having mechanical functionalities with few mechanical parts. Origami inspired folding has been used in wing system of morphing aircrafts [7]. The folding wing system with out of plane motion can adjust flight performance from a cruise configuration to a high-speed configuration. Origami inspired structures have been used to build rapidly deployable shelters for military applications [8]. The folding behavior of origami is used to adjust the separation between rings of split ring resonator to design a tunable metamaterials [9], microelectromechanical systems (MEMS) intraocular coil was designed using strip fold and wound origami coil [10]. The proposed origami coil is more flexible, biocompatible, and electrically efficient as compared to a traditional wire wound coil. Hinge based self-folding techniques have been explored to design 3D biomedical devices [11]. An origami technique was developed to fold microscopically thin silicon into different 3D shapes that could be used to design efficient solar cells [12].

For many origami-engineered applications, it is not feasible to apply external stimuli to produce the desired folding operations. For instance, underwater robots, space structures, and invasive biomedical devices. One possible solution for such limitation is to use a material with self-folding capabilities. A self-folding structure has the capability of folding/unfolding to the desired shape without external manipulations. Among developed self-folding systems, one approach is to use active or smart material. Active materials are materials that act as transducers to convert various forms of energy into mechanical work [13], and allow the folding mechanism via the application of a thermal, electrical, optical, or chemical procedure [14].

Origami structures possess many desirable features such as reconfiguration, flexibility, compactness, deployability, and multi-functionality. These attributes are very vital for modern radio frequency (RF), antenna, and microwave systems. In [15], a frequency reconfigurable origami spring antennas was proposed. The reconfigurability was attained by folding or unfolding it to different heights. Later, this work provided a background for novel designs of reconfigurable origami-based spiral and helical antennas [16], [17]. In another study, a similar procedure was followed to design reconfigurable circular and linear polarized conical spiral antennas [18].

The ability of an object to unfold itself is termed deployability. In satellite communications applications, this is highly desirable due to fast mobility and deployment. The conventional antennas used for military and satellite communications are usually quite large and bulky. Figure 1-a shows some conventional military and satellite antennas. Due to their weight and portability, these antennas need dedicated vehicles for mobility. Therefore, it is one of many challenges for antenna engineers to design light-weight and portable antennas for satellite applications.

Due to wide and secure communication coverage ensured by satellites, hundreds of nanosatellites are being launched for assets tracking and environmental monitoring. The main component of the satellite payload is the antenna which is quite large as compared to the spacecraft's antenna and consequently increases the size of the satellite. One viable solution is a deployable antenna that can be stowed into a small volume during transportation and then deployed fully when spacecraft reaches the orbit.

A deployable helical UHF antenna that can stow in a 4'' by 4'' package and then deploy to 54'' by 14'' for operation is reported in [19]. Fiberglass strips were used as a deployable structure to provide necessary stiffness and flexibility. Another helical antenna design with an opposite winding sense of composite strips was proposed in [20]. The active deployment of the helical antenna using shape memory alloy was reported in [21]. In order to compress the diameter along with the height of the helix, another innovative idea was proposed using a flexible composite membrane driven by a step motor [22]. A thin membrane deployable antenna was proposed for air-borne applications with low mass and low profile [23]. A compact deployable parabolic reflector antenna with a shape inspired by an umbrella was presented in [24]. The design was built by flexible carbon fiber reinforced silicone. In [25], a dual linearly polarized deployable log periodic dipole antenna (DLPDA) is presented. The antenna is comprised of foldable dipoles made of collapsible steel tape springs and stretchable zigzag double-sided parallel strips as the boom. The stowed volume was reduced to 2% of the fully deployed state. However, all of the deployable antennas mentioned above are still quite bulky and utilizes solid rigid materials. Also, the antenna design in stowed and deployed states need to be optimized in a lab before it can be used reliably in the field. An antenna design that can be folded into and expanded out allows for space-saving is needed. However, it comes at a cost of extra weight due to the requirement of motors and actuators. Therefore, paper-based origami antennas can be the best possible solution because these antennas can easily be folded/unfolded without requiring bulky rotating systems. Moreover, they are quite lightweight and require only paper sheets and copper tape to be fabricated on-field instantly. This idea allows scientists to come up with designs that are simple, compact, lightweight, and transportable. Also, these structures can be expanded to a deployable state when they are in the field.

A high gain with a large front-to-back ratio deployable origami yagi loop antenna for space communication systems is proposed in [26]. The antenna is equipped with a self-fold

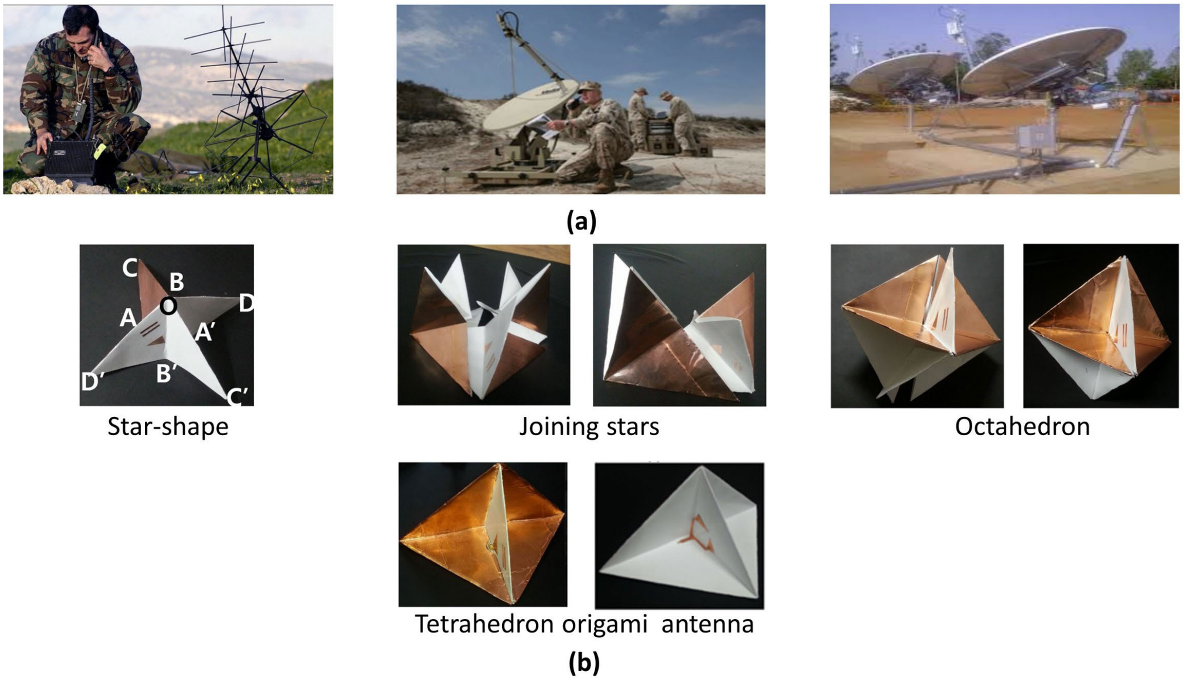


FIGURE 1. **(a) Conventional military and satellite antennas (b) fabrication steps of the tetrahedron origami antenna.**

capability that in the folded state, helps to reduce the volume of the antenna by 70%. In [27], a frequency reconfigurable dipole antenna inspired by an origami flasher was presented. In another study [28], a circularly polarized high gain origami antenna for warfare technologies is presented. The antenna exhibited a peak gain of 9.2 dBi. In another study, a low-cost tetrahedron origami antenna was built [29]. The antenna was fabricated on a paper substrate using copper tape as shown in Figure 1-b. Moreover, effects of folding on key performance parameters of the antenna such as input impedance and beamforming were investigated. It was observed that folding in different manners significantly affects the performance of the antenna.

Conventional Yagi antennas have been used in many wireless communication systems due to their simple structure, low-cost, ease of fabrication, and high gain. However, the size of yagi antennas can be quite large for low microwave frequencies. Therefore, it is reasonable to research the performance of this class of antennas using origami structures. In [30], a high gain origami-based traditional yagi antenna was proposed. The antenna was operating within the 2 GHz to 4 GHz frequency range with 66% bandwidth of 10 dB, and a peak gain of 9.5 dBi. However, the design was not robust and could not sustain repeated folding/unfolding operations. In a similar study [31], a deployable quasi-Yagi monopole antenna using origami magic spiral cubes was presented. The design of the reflector, director, and driver elements is based on L-shaped structures. The origami cubes were stacked using thin adhesive film and can easily be folded and unfolded many times without altering the performance of the antenna. As a result, a 6% reduction was achieved as compared to folded state occupying a small space for transportation and deployment.

For satellites to survive in the extreme environment of outer space, sometimes it is desirable to use rigid materials for antennas. However, the use of such materials makes the system complex, large, and challenging. A reconfigurable Yagi-Uda antenna was proposed in [32]. The antenna was designed using a rigid foldable cylinder. The antenna had four directing and a reflecting element, providing a maximum gain of 8 dB and operates in a 698 MHz to 806 MHz frequency band with a compact size as compared to the conventional antenna.

In this work, a survey of origami-inspired antennas is provided to identify and define the state-of-the-art in the evolving field of origami-based antenna design for modern communication systems, where space and weight are critical constraints. All the studies presented here, discuss theoretical principles as well as experimental results. Furthermore, this work offers an understanding of different attributes of antennas to provide readers a bigger and clearer picture while designing future origami-based applications and systems. It is believed this work will also discuss the challenges and risks involved while designing such antennas for modern wireless systems. Moreover, the design methodology followed in this paper will also provide pragmatic solutions for origami antennas suitable for harsh and rigid environments.

II. MATERIAL SELECTION FOR THE CONSTRUCTION OF ORIGAMI ANTENNAS

A. SUBSTRATE MATERIAL OF THE ORIGAMI ANTENNAS

The selection of the dielectric material plays an increasingly important role in designing origami antennas.

Many different materials have been used in the past such as conventional printer paper, photo paper, Kapton sheets, PET sheets, or polylactic acid. However, each material has its own advantages and drawbacks. A detailed review of each material is presented below.

When origami technology was first implemented for antenna design, conventional printer paper sheets were used as a substrate [16], [18], [27], [32], [33]. Paper substrates are simple, low-cost, and convenient to fold and unfold. However, they are frail, and the study shows that due to continuous folding/unfolding, the antenna becomes unstable. Therefore, these antennas can only be used for a limited time and for the indoor environment only.

To overcome the problem of instability, researchers have proposed several solutions such as utilizing multiple paper sheets to obtain a stable response. One such robust antenna based on tetrahedron shape is presented in [28]. The proposed design was achieved by joining four stars, each constructed from a single sheet of photo paper as shown in Figure 1-b. In a similar study, a circularly polarized origami antenna was proposed [34]. The tetrahedron shape was designed by using four sheets of conventional paper. A deployable quasi-Yagi monopole antenna using magic spiral cubes was proposed in [31]. This design used three sheets of paper. In [35], a frequency reconfigurable accordion origami antenna with a stable response was proposed. Also, a deployable origami Yagi loop antenna and frequency reconfigurable origami spring antenna were proposed in [26], [15]. In conclusion, the use of multiple paper sheets solved the problem of instability, but the proposed antennas were still frail. In addition, the performance of the paper-based origami antenna degrades in the outdoor environment due to humidity [36].

To solve the problem of robustness, studies show that Kapton and polyethylene terephthalate (PET) sheets are one of the suitable options. These materials are versatile, cheap, and robust. To show this, a polarization switchable origami antenna designed on Kapton Sheet [37] and a DNA-inspired pattern reconfigurable Quasi-Yagi origami antenna designed on a PET sheet [38] were proposed. Although, the use of Kapton and PET sheets in designs seems to resolve the robustness problems but their fabrication is somewhat time-consuming as compared to paper sheets due to their reduced flexibility. Therefore, a 3D printing technique was used.

Polylactic acid, which is used in 3D printing is another good choice of substrate material for origami antennas. Polylactic acid is a low-cost material that can be shaped to design desirable origami antennas. Antennas designed using this substrate are mechanically robust and suitable for outdoor use. In [39], a deployable origami antenna has been proposed, which converts a single antenna to a series array using the push/ pull phenomenon. In literature, researchers have utilized some hard substrates to design origami antennas. A thick foldable 1×4 patch antenna array realized on the FR4 substrate is proposed in [40]. The foldability of the design is achieved using a surrogate hinge architecture that allows the array to fold in a range of almost 360°. In a similar study, a foldable multifunctional planar antenna array realized on FR4 substrate is proposed in [41]. A reconfigurable and deployable origami-inspired circularly-polarized patch antenna array realized on Rogers RT-Duroid 5870 substrate was proposed [42]. In [43], a capacity reconfigurable multimode origami MIMO antenna was proposed. The proposed antenna is realized on an origami accordion structure made of 1.5mm thick FR4 substrate.

In summary, the selection of the substrate material for origami antenna systems plays an increasing vital role in the application of the antenna. For instance, paper substrate is more suitable for indoor applications while for outdoor environments, robust substrates are desirable. Next, a detailed literature study is presented for various different conducting materials used in origami antenna systems.

B. MATERIALS FOR CONDUCTIVE PATTERN OF THE ORIGAMI ANTENNAS

In order to realize the conductive material for origami antennas, there are two options: copper film or inkjet printer silver nanoparticle (NP) ink. Most origami antennas are realized using copper film as it shows better efficiency [38]. The copper film is suitable for origami antennas, which undergo extensive folding and unfolding. However, the cutting of copper film according to the particular design is rather difficult as it has to be cut manually. The inkjet printing technology is the solution to this problem [44]. Silver NP ink can be printed on a paper sheet using a traditional inkjet printer.

To print a high-resolution conductive pattern on robust substrates like Kapton or PET, a material printer is required. The material printer offers very high resolution and a broader range of substrates but they are somewhat expensive and the printing speed is very slow. For thermal sintering, the printed pattern should be passed through a heating oven that might increase the conductivity of the conductive pattern. Thus, the material selection for the conductor pattern depends on the application of the antenna. The Copper film is the best choice for a low-frequency indoor antenna, while for making complicated conductor patterns on paper sheet inkjet printer is the best option. On the other hand, to design robust antennas for outdoor applications a high-resolution material printer is a feasible solution. Figure 2-b shows different conductive materials that are used in the construction of conductive patterns in origami antennas.

In the next section, different novel origami antennas are studied. These studies are categorized based on robustness and durability.

III. IMPLEMENTATION OF DEPLOYABLE ORIGAMI ANTENNAS SINGLE PAPER ORIGAMI ANTENNAS

A. SINGLE PAPER BASED FLEXIBLE ORIGAMI ANTENNAS

In [32], a deployable and reconfigurable origami antenna operating between 698 MHz to 806 MHz frequency range is proposed. The antenna design consists of a Yagi-Uda dipole antenna, a reflecting element, and four directing elements. The reconfigurability and deployability of the antenna are

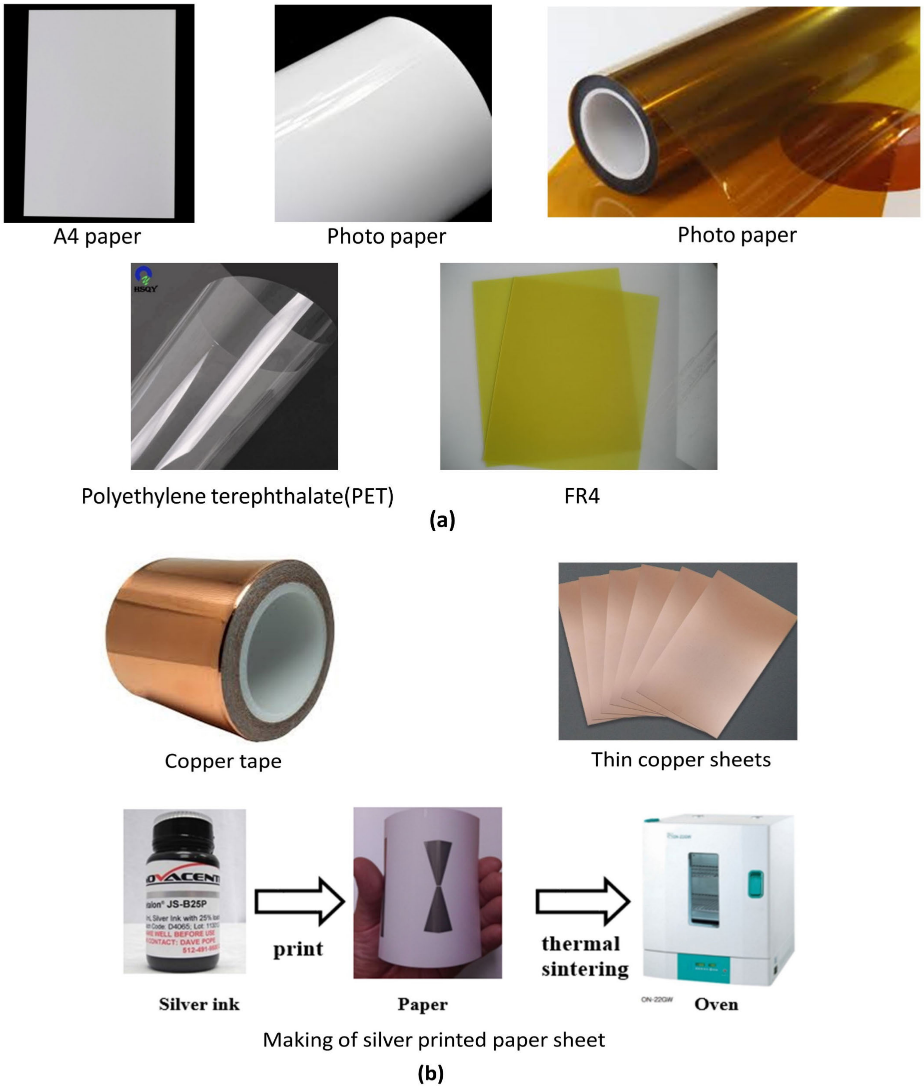


FIGURE 2. Materials suitable for the construction of origami antennas (a) for substrate (b) for conductive patterns.

achieved by mounting the antenna elements on a periodic origami structure. Analysis of different parameters is carried out to understand the behavior of the system. The frequency reconfigurable response has been achieved by changing the fold angle which results in varying inter-element responses. As expected, the resonance frequency increases when radiating elements are brought closer to each other. A change of 10% is observed within the 686 MHz to 760 MHz frequency range for 1° to 75° variations in the fold angle. Moreover, after a certain compression limit, the reflection coefficient starts to degrade. The realized gain of the proposed antenna is in the range of 4 dB to 8 dB with an unchanged 3 dB beamwidth for the whole operating range.

In another study [33], a frequency reconfigurable quasi-taper helical antenna was proposed. The reconfigurability was achieved by varying the height of the antenna. The antenna operates between 1.28 GHz and 4.12 GHz. The proposed design comprises two helices in series. A 3-turn larger monofilar is placed at the bottom while a 3-turn smaller monofilar is placed at the top, which is half in size as compared to that of a larger monofilar. The two series-connected helices are bonded using a copper tape that varies from 15 mm to 7.5 mm, and the diameter of the helix changes between 50 mm to 25 mm. Also, the two helices are placed on a 200 mm square ground plane.

The key performance elements of the proposed antenna were analyzed for three different states i.e. unfolded state, semi folded state, and the folded state. The operating bandwidths for the unfolded, semi-folded, and folded states are 1.28 GHz to 1.64 GHz (25%), 1.64 GHz to 3.56 GHz (74%), and 3.56 GHz to 4.12 GHz (14.6%), respectively. Similarly, the simulated realized gain for the unfolded, semi-folded, and folded states are 6 dB, 8.5 dB, and 5 dB, respectively. For each frequency band, a variation of around 3 dB is observed.

The proposed antenna showed a right-hand circularly polarized (RHCP) behavior in the semi-folded state for the frequency range between 2.04 GHz and 3.56 GHz, while for the other two states, it showed either linear or elliptical polarization behavior.

In a similar study, a frequency reconfigurable origami antenna is presented [16]. The reconfigurability is obtained by varying the height of the antenna using folding and unfolding capability. The analytical model of helical antennas can be used to obtain the equivalent model of such antennas. Therefore, the design parameters of the proposed antenna are obtained using an analytical model. The antenna is consisting of 6 sides with each side having 18 steps. The proposed antenna is fabricated on a paper substrate with a relative permittivity of 3.2 and the radiating element is built using a 0.2 mm copper tape that is glued and creased to ensure attachment while folding/unfolding phenomenon. The total height of the antenna is 273 mm when it is in the unfolded state.

Like the previous study [33], to understand the working principle of the antenna, studies have been conducted for three different states i.e. unfolded ($H = 273$ mm), semi-folded ($H = 154$ mm), and folded ($H = 25$ mm). The proposed antenna can operate in axial mode at different frequencies by changing its height. Furthermore, the antenna exhibits optimum performance for the following heights and corresponding frequencies; $H = 273$ mm for 0.86 GHz, $H = 154$ mm for 1.27 GHz, 1.7 GHz, and 1.98 GHz, and H = 25 mm for 2.49 GHz, 2.81 GHz, and 3 GHz. For these frequencies, each state exhibits a higher gain for its corresponding frequency rather than at the frequencies of other states.

In another study [27], the design and performance of a frequency reconfigurable dipole antenna inspired by an origami flasher are discussed. The proposed antenna design consists of the main dipole and two isolated patch poles printed on a flat paper with relative permittivity 1.8 and loss tangent 0.06, respectively. The size of the proposed system is 182 mm × 182 mm × 0.09 mm, and the antenna is fed using a 50-ohm coaxial cable as shown in Figure 3. In the unfolded state, the main dipole is half-wavelength in length and consists of a radiator and two dummies patch poles. On the other hand, the origami flasher technique is used to fold the antenna. Therefore, when the paper is folded into the origami flasher cube the dipole length increases due to the patch pole.

The antenna operates at 1.23 GHz with a return loss of 11.6 dB in its unfolded state. While in the folded state, as the dipole length increases because the patch pole gets connected to the main pole due to this the resonance frequency decreases and the antenna starts resonating at 0.77GHz with a return loss of 13.9dB. The fractional bandwidths obtained for the unfolded and folded state of the antenna are 5% (1.22-1.29 MHz) and 2% (750-770 MHz) respectively. The peak gains of the antenna are observed to be −0.48 and −3.41 dBi, and efficiencies are 90 and 20% at the resonance frequency for the unfolded and folded states respectively.

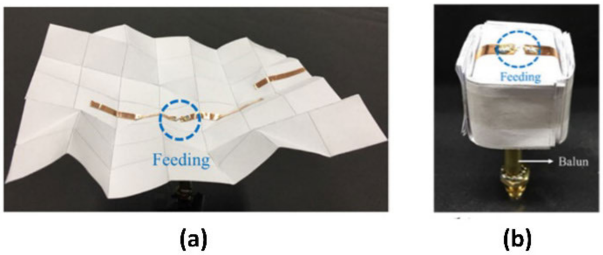


FIGURE 3. Frequency reconfigurable dipole antenna inspired by origami flasher (a) unfolded state (b) folded state.

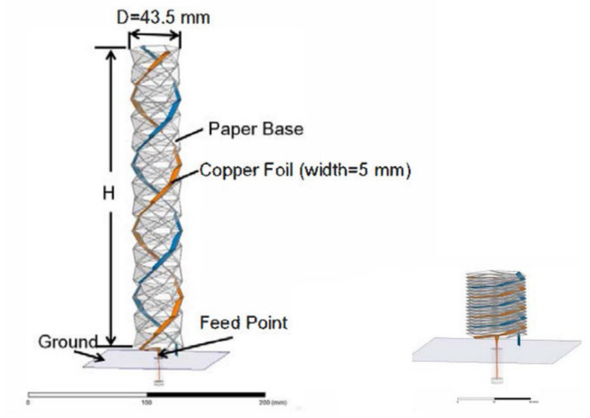
In [18], a reconfigurable origami conical spiral antenna for GPS, radar, and satellite applications is proposed. The antenna is designed on a 0.2mm thick paper substrate. It consists of two conductive arms based on an origami cone. The two arms are fed by 50 Ohm SMA ports that are 1800 out of phase. The antenna can be compressed to 6% of its unfolded volume. The proposed antenna was analyzed for two states i.e. unfolded state (H = 106 mm) and the folded state ($H = 53$ mm). The antenna shows circular polarization in its unfolded state with an operational bandwidth from 1.85 GHz – 2.75 GHz while in the folded state the antenna shows a linear polarization at 1.4 GHz and 3.7 GHz. The realized gain of the antenna for the unfolded state varies from 9.9 dB – 12.4 dB for the operational band while for the folded state the realized is observed to be 7dB at 1.4 GHz and 7.8dB at 3.7 GHz.

In [45], a frequency reconfigurable axial mode helical antenna is proposed. The antenna is designed on a paper substrate which is in the form of a helical origami structure with a copper foil on it. Figure 4 shows the geometry of the proposed helical antenna in the unfolded state, the height of the antenna is 255 mm while in the folded state it reduces to 38 mm. As a result, a reduction of 83% is achieved. It is observed that the antenna operates at 1.82 GHz and 2.14 GHz in the folded state while in the unfolded state it operates at 860 MHz. Thus a frequency reconfigurability up to 1.28 GHz is achieved. The gain differences between the unfolded and the folded state along the helical axial direction shows that for the unfolded state at the operating frequency i.e. 860 MHz, the gain difference is maximum. While for the folded state at resonant frequencies i.e. 1.82 GHz and 2.14 GHz the gain difference is minimum.

In conclusion, origami antennas based on a single paper as a substrate provide fast deployability. However, they are frail. Therefore, scientists have used multiple papers as an alternative to craft robust origami antennas.

B. MULTIPLE-PAPER SHEETS BASED RIGID ORIGAMI ANTENNAS

A high gain tetrahedron origami antenna and its circularly polarized version is proposed for military satellite applications [28]. The origami tetrahedron antenna is designed on a 0.25mm thick paper substrate, with a dielectric constant of 2.2 and a dielectric loss tangent of 0.02. Figure 5-a depicts the geometry of the proposed antenna. It consists of



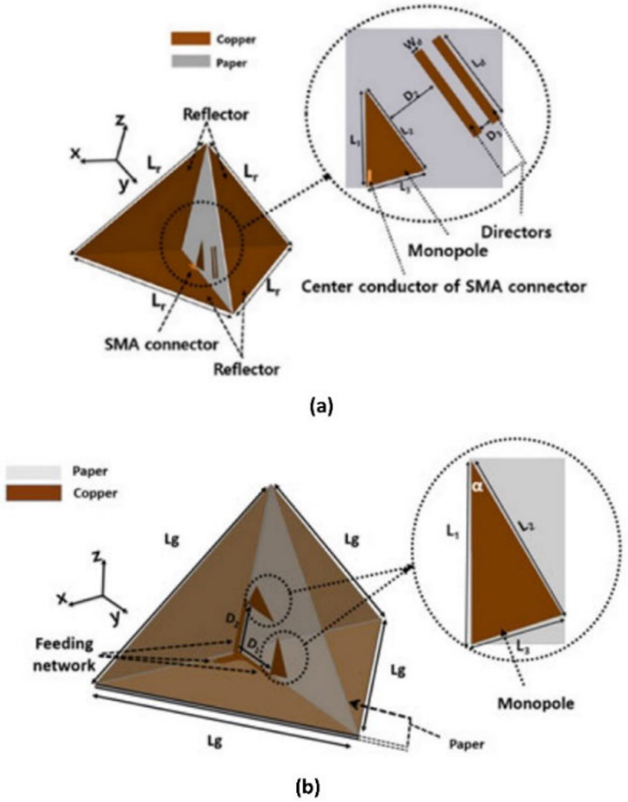
(a) (b)

FIGURE 4. **Origami helical antenna in (a) unfolded (b) folded state.**

a triangular monopole, a reflector, and two strip directors. The reflector and strip directors are used to increase the gain of the antenna. The antenna achieves a peak gain of 9.6dBi at 2.6 GHz with an impedance bandwidth of 66% (2-4 GHz). To achieve circular polarization, two triangular monopoles are used which are orthogonal to each other. Figure 5-b shows the geometry of the circularly polarized tetrahedral origami antenna. The two monopoles are excited simultaneously using a T-junction divider with a phase difference of 900. It achieves a 3-dB axial-ratio bandwidth of 8% (3.415 to 3.7 GHz) and an impedance bandwidth of 70.2% (2.4 to 5 GHz).

In [34], a circularly polarized tetrahedral origami antenna resonating at 3.5 GHz was proposed. The antenna achieves circular polarization characteristics by using two orthogonal triangular monopoles, which are excited with equal magnitudes but with a phase difference of 90°. A T-junction divider is used to feed the monopoles. Also, the length of one of the arms is of a quarter-wavelength ($\lambda/4$) to maintain the 90° phase difference between the monopoles. The antenna is fabricated using a conventional paper with a dielectric constant of 3.2 and loss tangent of 0.06, respectively. The tetrahedron shape of the antenna is achieved by folding paper in various directions. The physical size of the antenna in its unfolded state is $270 \times 135 \times 135\ \text{mm}^3$, while in the folded state the size reduces to $70 \times 70 \times 16\ \text{mm}^3$.

It was observed that the antenna exhibits an impedance bandwidth of 70.2% (2.4 to 5 GHz), a 3 dB axial ratio bandwidth of 8% (3.415 to 3.7 GHz). The left-hand circular polarization (LHCP) gain was observed to be in the range of 5.2 to 5.7 dBi within the 3 dB circular axial ratio bandwidth. The main beam of the antenna is in the direction toward $\theta = 70°$ and $\Phi = 35°$. This is because of the position of the monopole with respect to the ground plane. In the same direction, the LHCP gain is observed to be 28 dB higher than the RHCP gain. This origami-based design of the antenna is fast and easily deployable, which makes it a desirable choice for military applications.



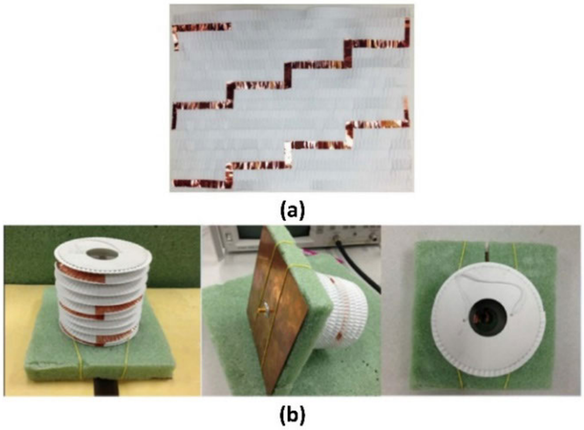
(a)

(b)

FIGURE 5. **Stable origami antenna (a) tetrahedral configuration (b) circularly polarized tetrahedral origami antenna.**

A deployable quasi-Yagi monopole antenna using origami magic spiral cubes is presented [31]. The magic cubes are constructed from 0.1 mm thick paper substrate and stacked using thin adhesive film. The driven element of the antenna is an L-shaped monopole. To enhance the gain of the antenna an L-shaped reflector and two L-shaped directors are also used. The driven monopole and the reflector are realized on the bottom magic cube while the two reflectors are realized on the two upper magic cubes. The dimensions in the unfolded state are 44 mm × 44 mm × 132 mm while the dimensions in the folded state are 44 mm × 44 mm × 8 mm. Thus, in the folded state, the antenna occupies only 6% of the unfolded volume. The simple monopole antenna without reflector and directors exhibits an omnidirectional radiation pattern with a 1.9 dBi peak gain at 1.9 GHz. The monopole antenna with reflector achieves a peak gain of 5.7 dBi while when loaded with two directors achieves a peak gain of 8.3 dBi. Both configurations successfully obtained a broadside pattern.

In [35], a frequency reconfigurable accordion origami antenna for airborne and space borne applications is proposed. The antenna is realized on a paper substrate. It consists of a 7-level origami accordion with a 0.1 mm metal strip pasted on it. The metal strip is pasted on the accordion such that the strip goes around the base of the accordion paper on the first level and then after a quarter round it moves into the next level as shown in Figure 6-a. Due to this unique configuration, the metals on different levels remain isolated from


(a)

(b)

FIGURE 6. **The origami accordion antenna (a) flat paper with copper strip (b) fabricated prototype.**

each other when the antenna is fully folded. A 20 mm thick polystyrene foam layer is used as a substrate between the radiating element and the ground, while the ground is realized using a 160 × 160 mm^2 copper sheet. The antenna is fed by a 50-ohm coaxial cable. Moreover, as the accordion structure is hollow from the inside thus it provides space where other components can be mounted as shown in Figure 6-b. In the unfolded state, the height of the antenna is 160 mm, and in the folded state, it reduces to 40 mm. The antenna in its unfolded state operates at 650 MHz with a realized gain of 6.5 dB while in the folded state it operates at 1800 MHz and 1400 MHz with realized gains of 8 dB and 7.3 dB, respectively. Therefore, it is concluded that by exploiting folding/unfolding capability, frequency reconfigurability can be achieved.

In another study [26], a deployable origami Yagi loop antenna is proposed. The antenna is designed to operate at 1.31 GHz. The proposed antenna can be compressed to a length of 5 cm using a servo motor, which reduces almost 70% of the array volume. The body of the antenna is 20.5 cm long when it is fully extended. The antenna is realized on a paper substrate which is in the form of a dodecagon. The proposed antenna uses five dodecagons which are arranged in the form of an array. However, only the second loop is excited. The loop beneath the driven loop acts as a reflector while the three loops above the driven loop act as directors. The proposed antenna in its working state shows a directional realized gain of 10.4 dBi.

In a similar study [15], a frequency reconfigurable origami spring antenna was proposed. The antenna can change its operating frequency by folding and unfolding phenomenon. The antenna can be compressed by applying pressure on the top and it can be deployed by releasing the pressure. The height of the antenna in the unfolded state is 100 mm while its height becomes 40mm when it collapses. Like previous studies, this antenna is also realized on a paper substrate. It consists of an origami spring with copper tape printed at the edges of the origami structure. The copper tape has a width of 5 mm and a thickness of 0.1 mm. The antenna is fed from the bottom by a 50-ohm coaxial cable. In the folded state, it resonates at 2560 MHz while for unfolded state, it resonates at 2190 MHz. A significant larger gain is observed for 2190 MHz and 1820 MHz for the unfolded state.

In [46], an origami-based dual-polarized antenna suitable for 5G wireless technologies is presented. The proposed antenna possesses important attributes such as broadband, dual-polarization, high-gain, and foldability. It consists of a pair of orthogonally placed magneto-electric (ME) dipole, a pair of corresponding orthogonally placed η-shape feed-lines, and a defected ground plane. The ME dipoles are realized on origami cubes, made of 0.1 mm thick paper substrate with a dielectric constant of 2.2 and loss tangent of 0.06, respectively. By folding the origami cubes the antenna dimension can be reduced from 125.3 × 125.3 × 31.5 mm^3 to 125.3 × 125.3 × 4 mm^3. The antenna operates at a wide bandwidth of 64.7% (1.85 to 3.62 GHz) and 65.68% (1.82 to 3.60 GHz) for the two ports. Due to the defected ground reflector, the antenna achieves a high isolation of 26 dB between the radiating elements. larger than 26dB. For the entire bandwidth, a high gain of 9.2 dBi is observed.

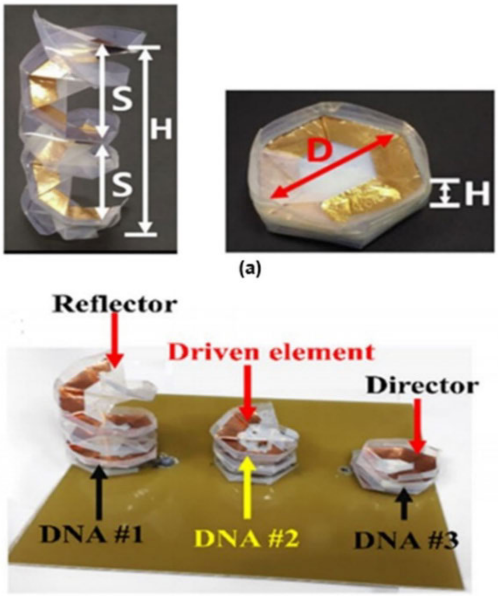
In [46], a tri-band frequency reconfigurable origami helical antenna array suitable for satellite radio and WiMax applications is proposed. The antenna can be reconfigured to operate in three different bands by changing its height. The antenna is realized on 0.1651mm thick sketching paper. It consists of 7 helical origami structures with 0.0762 mm thick copper tape glued on them. To maintain the circular polarization a small helical structure is placed at the top of each helix. To enhance the gain of the antenna, a reflector element fabricated with 0.1016mm thick copper foil glued on 0.3302mm thick cardboard is placed at the bottom of each structure. This antenna was analyzed for three different states i.e. unfolded, semi-folded, and folded. It was observed that the antenna maintains an LHCP behavior in all three states. The antenna resonates at 2.07 GHz, 3 GHz and 4.45 GHz for the unfolded, semi folded, and folded states with realized gains of 9.7dB, 13dB, and 14.7dB, respectively.

The aim of the multiple papers used as a substrate was to provide robustness but it was observed that using multiple papers the performance of the system degrades after a certain number of sheets and folding. Therefore, PET sheets were utilized to address this concern.

C. PET SHEETS BASED FLEXIBLE AND ROBUST ORIGAMI ANTENNAS

In the previous section, we have reviewed origami antennas that were realized on a paper substrate. Since the antennas fabricated on the paper substrate are not durable, therefore scientists have come up with a solution in the form of PET sheets. PET sheets are robust than paper and, they do not suffer from humidity too.

In [38], a bio-inspired Pattern Reconfigurable quasi-Yagi helical antenna operating at 2.2 GHz is presented. It consists of a DNA shaped driven element, a DNA based reflector, and a DNA based director realized on polyethylene terephthalate (PET) substrate. The ground plane of the antenna is made from an FR4 substrate backed by a conductor. Figure 7 shows a fabricated prototype of the proposed antenna. The radiation pattern of the antenna can be reconfigured by switching the role of reflector and director.



(a)

(b)

FIGURE 7. **Bio-inspired Quasi-Yagi helical antenna (a) origami DNA (b) pattern reconfigurable origami antenna.**

The antenna can operate in four different states based on the role of the reflector and the director. In state 1, a parasitic director is designed by folding the origami DNA and a parasitic reflector is designed by unfolding the origami DNA. In this state, the main beam of the antenna is directed towards 30°. In state 2, the main beam is directed toward −30° by switching the role of reflector and director. In state 3, both parasitic elements are folded to serve as directors. In this state, the main beam of the antenna is directed toward 0°. Then, in state 4, both elements are unfolded to serve as reflectors and the antenna achieves a dual-beam radiation pattern directed toward 50° and −50°. The proposed antenna design is suitable for space technology.

In [47], a low-cost, high-gain, and vertically polarized deployable antenna using kirigami pop-up geometry is proposed. The kirigami geometry is produced by utilizing a foldable polyethylene terephthalate sheet. The antenna consists of a rectangular monopole as the driven element, two reflectors, and a parasitic strip director as shown in **Error! Reference source not found.**. The folding and unfolding of the antenna is achieved using electromechanically excited shape memory alloy (SMA) actuators. The antenna achieves an impedance bandwidth of 48.8% (1.7 GHz to 2.8 GHz) and has a peak gain of more than 10 dBi at 2.45 GHz. The antenna shows a tilted radiated beam with a significantly wider beamwidth (900) in the azimuth plane as compared to (400) in the elevation plane.

In summary, the use of PET sheets provides the necessary robustness but limits the folding capability of the antenna systems. Therefore, it is reasonable to design robust and stable deployable antennas using materials, such as, FR4 and Rogers substrates.

D. ROBUST AND STABLE ORIGAMI ANTENNAS

An intensive amount of study has been conducted on reconfigurable antennas and antenna arrays over the years. Numerous reconfiguration techniques have been used to design frequency, pattern, polarization, and hybrid reconfigurable antennas. Another approach to achieve reconfigurable properties is the mechanical reconfiguration. In [40], the same approach is used to design a foldable thick-origami based 1 × 4 patch antenna array. The array is designed on a 1.5 mm thick FR4 substrate with overall dimensions of 250×102 mm^2. The foldability of the design is achieved using a surrogate hinge architecture that allows the array to fold in a range of almost 360°. The four patches are separated by the surrogate hinge at the center of the array (with two antennas on each side of the hinge). In order to verify the reliability and robustness of the proposed design, a fatigue test was conducted which showed that the antenna can withstand beyond 5000 folding without suffering through any mechanical or electromagnetic failure.

The array was fed using a dual-feed (differential) excitation which improves the radiation pattern and reduces the mutual coupling. Figure 8 depicts the geometry of the proposed antenna fed differentially using a single excitation. The proposed antenna was analyzed in its unfolded state as well as in the folded state for different fold angles. It was observed that the coupling between adjacent radiating elements to the hinge decreases as the patch array fold angle increases. The radiation characteristics of the patch array are also studied for different fold angles. It was observed that the peak gain of the antenna array varies for different fold angles i.e. the peak gain of the folded array becomes larger than that of the flat array when the scan angle is larger than 35°. It was observed that the H-plane gain of the bent array at a fold angle of 45° and a scan angle of 55° is 2.12 dB higher than the flat case, with the same side lobe level. Thus, it verifies that the array provides an improved beam steering upon folding when the scan angle is larger than 35°. Furthermore, the antenna shows a packing efficiency of 50% in its folded state. Moreover, the antenna is designed using standard PCB materials which resolves the issue of robustness that arise in origami antennas with thin substrates.

In [41], a foldable multifunctional planar antenna array is proposed. The proposed antenna can operate in two modes; diversity mode and directivity mode. The switching of modes is achieved by folding and unfolding the antenna array. The antenna operates in diversity mode in its unfolded state by acting as a MIMO antenna while it operates in directivity mode in its folded state by acting as a Yagi-Uda antenna.

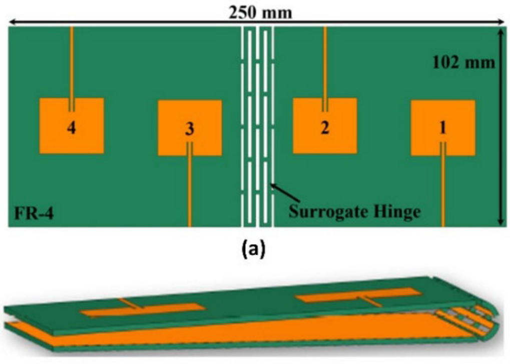


FIGURE 8. Four-element patch array antenna (a) unfolded state (b) fully folded state.

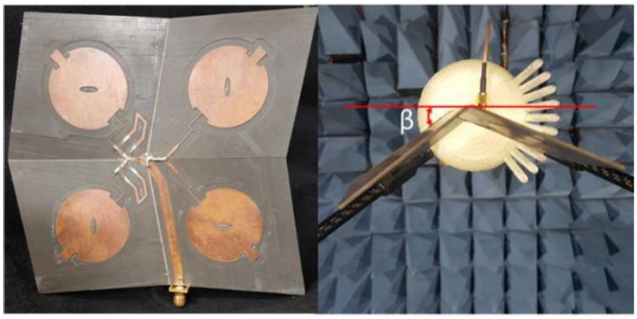


FIGURE 9. Fabricated prototype of origami-inspired robust foldable patch antenna array.

The antenna is designed to operate on 2.4GHz. The antenna design consists of four circular patches arranged in a 2 × 2 array, placed on FR4 substrate with a thickness of 1.6mm, a loss tangent of 0.002, and a dielectric constant of 4.4. The array is divided into four parts which can be folded and stacked. Layer-1 consists of a circular patch, a feed line, a quarter-wave transformer for impedance matching, and a ground plane. The ground plane of this layer acts as a reflector in directivity mode. The other three layers use the coplanar waveguide technique which does not require a ground plane. These layers' act as directors in the directivity mode of operation. The patches are arranged orthogonally to reduce mutual coupling in the unfolded state. The analysis of the antenna in diversity mode shows that the antenna achieves a reasonable isolation between layer-1 and other layers due to the orthogonal arrangement of the four elements and achieves a peak gain of 3dBi at 2.4GHz. On the other hand, in directivity mode, the antenna operates like a yagi-Uda antenna and achieves a peak gain of 8dBi at 2.4GHz.

In [42], the reconfiguration and deployment of an origami-inspired circularly-polarized folding patch antenna array was investigated. The antenna in [29], endured a graceful deterioration in electromagnetic performance as the folding angle was increased. In this study, an enhanced antenna design with circularly polarized patch elements is investigated. Using circular polarization eliminates the need to study the changes in polarization at intermediate folding phases. The antenna is designed on Rogers RT Duroid 5870 substrate with a thickness of 62 mil (1.5748 mm). The antenna operates at 3GHz. Circular polarization of the antenna is achieved by inserting an elliptical slot oriented at 45° at the center of the patch. The patch impedance is matched to a 50Ω feed line using a quarter-wave transformer. An open circuit stub is also added at the opposite side of the feed for impedance matching. The antenna is folded based on the Miura-ori fold pattern.

To evaluate the impact of physical reconfiguration, the performance of the antenna was investigated over a broad range of angles. The antenna was investigated for the fold angles of 0°, 20°, $40^{0,}$ and 60° as shown in III-E. The antenna showed a LHCP behavior. The performance of the array with bend angle 0° (unfolded) was considered as the optimum performance. The impedance matching and the antenna gain decreases due to the loading effect caused by the bending of the feed network and the mutual coupling between the patches. The analysis shows that the antenna performance degrades as the fold angle increases. However, the circular polarization of the antenna has brought significant enhancement to the antenna design as it eliminates the need to study the polarization changes as the antenna folds.

In [43], a capacity reconfigurable multimode origami MIMO antenna is proposed. The proposed antenna is realized on an origami accordion structure made of 1.5 mm thick FR-4 substrate. the antenna consists of a seven-element linear MIMO array, with each element operating simultaneously in two orthogonal modes. All the elements are uniformly spaced by a distance d. Each element of the antenna is fed by two microstrip feed lines, one for each operational mode. The radiating element is consisting of a wide slot. The first mode of operation resonates at 2.33 GHz, while the second mode of operation resonates at 2.91 GHz. The capacity and the peak gain of the antenna for the two operational modes can be varied by changing the inter-element spacing. The spacing between the elements can be varied by folding and unfolding the accordion structure. It was observed that the first mode operates efficiently when $0 \cdot 28\lambda \leq d \leq 0 \cdot 75\lambda$, while the second mode operates efficiently when $0.24\lambda \leq d \leq 0 \cdot 93\lambda$. The capacity of the antenna for the first mode varies from 15.94 bits/s/Hz to 18.4 bits/s/Hz (15% variation) while the peak gain varies from 1 dB to 12 dB for different inter-element spacing. Similarly, for the second mode, the capacity of the antenna varies from 16.98 bits/s/Hz to 19.14 bits/s/Hz (13% variation) while the peak gain varies from 1 dB to 11.66 dB for different inter-element spacing. The mutual coupling between the adjacent elements is observed to be less than -10dB for any practically achievable inter-element spacing.

In [48], an origami MIMO antenna operating in two high order modes is proposed. The antenna is realized on an origami water-bomb structure. It consists of a square ring patch fed by 4 feedlines (one at each side of the patch). The substrate material of the antenna has a dielectric constant of 2.2 and a thickness of 3 mm. The characteristic mode analysis of the antenna shows that the antenna can operate in two higher-order modes with desirable radiation characteristics in useful frequency bands. The first operational mode was observed at 1.92 GHz while the other was observed at 3.12 GHz. The two operational modes are obtained by different excitations of the four ports. The first mode is obtained by exciting two opposite ports with a phase difference of 180°. The phase difference between excited ports results in a current null at the center of the antenna which swirls due to the slight offset to the right of the line of symmetry of the patch. The second mode is obtained by exciting all four ports with a phase difference of 180° between the adjacent ports. In this case, the current null appears between the adjacent ports and is relatively unaffected by the offset of feed lines. The resonant frequencies of the modes can be reconfigured by folding and unfolding the antenna. It was observed that the resonance frequencies of the two modes decrease as the fold angle of the antenna increases.

The frequency reconfiguration and deployment of an origami-inspired deployable microstrip patch antenna array is investigated in [29]. The impact of folding on the electromagnetic performance of the antenna were studied. The antenna under investigation is a foldable 2 × 2 corporate fed microstrip patch antenna designed on a 0.75 mm thick polypropylene substrate. The antenna operates at 2.4 GHz. The inset feeding technique is used to match the patch impedances to the 100-ohm feed lines. The antenna is folded based on the Miura-ori fold pattern.

The performance of the antenna was investigated for different fold angles. Considering the flat antenna (unfolded) as a reference, the fold angle was taken as the angle that the array makes upon folding with the plane of the unfolded antenna. The antenna was investigated for the fold angles of 0°, 10°, 30°, 60°, and 75°. The performance of the unfolded array was considered as a benchmark. The analysis shows that as the bent angle increases, the array experiences elegant deterioration. The bending of the feed line causes a loading effect which degrades the impedance matching. An increase in the beamwidth in the yz-plane was also observed when the antenna was folded through high bend angles. Thus, it shows that the performance of the antenna degrades significantly due to folding.

A foldable circular polarized microstrip antenna array was proposed in [49]. The antenna operates in the frequency range from 1.98 GHz to 2.2 GHz. The antenna uses circular driven elements with a multi-layer dielectric to achieve a wide impedance bandwidth. The antenna design consists of two layers. The top layer consists of a 1 × 2 array of circular patches placed on polytetrafluoroethylene substrate with a dielectric constant of 2.2 and a thickness of 1.5 mm. The bottom layer consists of a 1 × 2 array of circular patches placed on a substrate with a dielectric constant of 2.65 and a thickness of 1.5mm. The air gap between the two layers is 5mm. The antenna can operate only in its unfolded state.

The antenna covers a frequency band from 1.98 GHz to 2.2 GHz with a VSWR less than 1.5 and an axial ratio of less than 2 dB. The simulated gain of the proposed antenna is greater than 10 dBi in the over the frequency band of 1.98 GHz to 2.2 GHz. The peak gain is observed to be 12.6 dBi at 2.2 GHz. The proposed antenna due to its foldability and easy deployability is suitable for satellite mobile communication system.

In studies, it was found that the systems design using the aforementioned substrates can provide stable and robust performance in harsh outdoor environments. However, there is a rising challenge to achieve foldability, hence requiring more efforts.

E. INKJET PRINTED BASED ORIGAMI ANTENNA

In [50], an inkjet-printed dual-band antenna for UAV applications was proposed. The antenna is printed on a photo paper using an inkjet printer. It consists of a semicircular radiation patch with a rectangular slot at the center and a coplanar waveguide feed line. The semicircular patch provides the wider bandwidth required for the higher frequency bands. The photo paper used as the substrate has a dielectric constant of 3 and a thickness of 0.177mm. The impedance bandwidth of the antenna spans from 2.3 GHz to 2.8 GHz with a resonance at 2.4 GHz and from 4.1 GHz to 7 GHz with a resonance at 5.2 GHz, while the measured results showed slightly shifted resonance frequencies with impedance bandwidths spanning from 2.3 GHz to 3.2 GHz and 4.2 GHz to 7 GHz, respectively.

The substrate of the antenna was then extended to make it foldable so that it can attain the shape of a paper airplane. The size of the extended paper substrate was 210 mm × 282.5 mm. The overall performance of the antenna was not affected by increasing the size of the substrate. The antenna was then folded into an origami paper plane. The resonance frequencies shifted slightly toward the right in the folded state and the bandwidth decreased as well. However, the impedance matching improved for the lower band but slightly degraded for the higher band. In a folded state, the antenna becomes more directional, especially at a higher band. The antenna showed a peak gain of 3.74 and 4.96 dBi at 2.4 GHz and 5.2 GHz, respectively.

Ideally, the radiated beam of the UAV antenna should point toward the remote controller but the designed antenna showed a radiation beam that pointed slightly upward. Thus, the antenna design was modified using a new origami folding pattern for the paper airplane. The new airplane antenna showed the same return loss as it was observed for the previously folded antenna. The antenna covered the desired 2.4 GHz and 5.2 GHz WLAN bands. In addition, the radiation beam of the newly designed antenna pointed downward which resolved the problem of controlling the UAV antenna, in case where controller is being at a lower height than the UAVs.

In [28], the investigation of the antennas integrated into disposable paper drones is presented. The drones are designed using origami techniques. Two vertical monopole antennas were proposed based on the same design principle and their performance was analyzed. The antennas were printed on photo paper using an inkjet printer with silver nanoparticle conductive ink and then folded to make a paper drone. The photo paper used is a 210 mm × 290 mm A4 sheet, with a dielectric constant of 3 and a thickness of 0.18 mm. This type of drone structure provides stable gliding even when loaded with additional aircraft control systems. Most of the additional components to control the plane are mounted on the body and wings of the airplane. To simulate this condition, the top of the wings was made conductive. The semi-circle provides impedance matching for higher frequencies whereas the T-shape element provided impedance matching at lower frequencies. The antenna was designed to operate at 2.4 GHz, 5.2 GHz, and 5.8 GHz.

The proposed antenna shows impedance bandwidths from 1.9 GHz to 2.7 GHz and from 5.1 GHz to 5.9 GHz, which cover the desired operating frequencies. The position of the antenna was varied and the effect of the position on the performance of the antenna was analyzed. The antenna covered the desired frequency bands for all positions. However, the depth of S_{11} and the bandwidth changed slightly due to the change in position. This is due to the coupling and impedances which are generated due to close proximity between the radiating element and the ground plane. To make the fabrication process simple and to evaluate the condition where the electrical components occupy a smaller region on the wing of the plane the size of the metallic ground plane was reduced. The antenna parameters were optimized for the smaller ground plane. It was observed that the antenna with a smaller ground plane covers the desired frequencies with lower S_{11} as compare to the antenna with a larger ground plane. The effects of wings deforming on the performance of the antenna were also studied. It was observed that the operating frequency and the impedance matching decreases as the wings are folded toward the body of the antenna.

The second antenna design was proposed in [51]. It consists of a vertically polarized antenna placed at the base of the paper drone. The antenna is designed using the same inkjet printing technique. The driven element of the antenna consists of a semicircle with an additional rectangular resonant element separated by a gap and connected by a small rectangular strip line. The antenna is small enough to be enclosed within the vertical portion of the aircraft. The antenna is fed using a coplanar waveguide transmission line. The proposed antenna resonates at two frequencies; first at 2.61 GHz with an impedance bandwidth from 2.3 GHz to 2.9 GHz and second at 5.57 GHz with an impedance bandwidth from 5 GHz to 6.5 GHz. The gain of the antenna at 2.4 GHz, 5.2 GHz, and 5.8 GHz is observed to be 19 dB, 2.6 dB, and 3.1 dB, respectively.

In [52], an investigation is carried out to develop antennas for origami paper flapping robots. An origami flapping robotic bird is used, which can be generated using regular A4 paper. For the small space available on the folded origami structure, two monopole antennas resonating at the 2.4 GHz and 5.2 GHz, are designed. The first antenna is positioned on the spine of the robot and the second is mounted on its back. The antennas are printed on a photo-paper substrate and then folded into an origami robotic crane. The antennas are printed using an inkjet printer with conductive silver nanoparticle ink. The photo-paper used is a 210 mm square (about A4 size) sheet with a thickness of 0.177 mm and a relative permittivity of 3. The desired operational bands for the antennas are 2.4 GHz and 5.2 GHz (WLAN/WiFi communication bands) for the flying robot application.

The antenna design for the spine of the robot consists of a leaf shaped driven element with a semi-elliptical bottom and a triangular top with a horizontal slot. The semi-elliptical radiator shows a resonance at the upper band whereas the semi-elliptical radiator with triangular monopole shows wideband characteristics with a lower frequency of more than 2.4 GHz. The lower resonance point was shifted to 2.4 GHz by adding an optimized horizontal slot across the triangle while maintaining the upper band as well as rejecting frequencies between the two bands of interest. The antenna is fed using a coplanar waveguide. The proposed antenna successfully covered the two desired bands with lower impedance bandwidth from 2.2 GHz to 2.7 GHz while the upper impedance bandwidth from 3.9 GHz to 5.5 GHz. The measured antenna gains at 2.4 GHz and 5.2 GHz were 1.4 dBi and 2.7 dBi respectively.

The antenna for the tail of the origami crane is concealed inside the tail of the antenna in order to protect it from environmental damage. The antenna shows a narrow band at 2.4 GHz but a wider band at 5.2 GHz. The gains of the antenna were 1.5 dBi and 2.5 dBi at 2.4 GHz and 5.2 GHz, respectively. This antenna was further investigated in space diversity configuration. A diversity antenna was created on the neck of the crane. Both antennas were fed separately. The diversity antenna system showed an impedance bandwidth from 2.3 GHz to 2.55 GHz for the lower band and 4.5 GHz to 6 GHz for the upper band.

In conclusion, inkjet printing can be used to design complex antenna structures which are not possible with hand using copper tapes. It is worthy to mention that the antennas fabricated using such procedure are not robust and suffers from breakage of the conducting material. Moreover, while folding the antennas, scratches are introduced. To address these issues, scientists have come up with a technique called 3D printing. Next, deployable antennas have been design using this technique are discussed.

F. ORIGAMI ANTENNAS USING 3D-PRINTING TECHNOLOGIES

The first of its kind "tree" origami antenna model, allowing multiple 3D antennas to be combined with minimal interference was proposed in [53]. The antenna allows an on-demand reconfigurability of frequency, polarization, and radiation patterns for optimum performance in dynamically changing environments. The breakage of the substrate and conductive film along the fold lines is one of the biggest challenges in origami antennas. Thus, For the first time, a Voronoi topology is applied to the substrate in order to reduce the stress of substrates along the fold lines. Whereas, for the conductive part of the antenna liquid metal alloy (LMA) is used instead of conventional hard metal conductors. LMA due to its liquid nature ensures a ''never-fail'' bending and constant self-healing, which enables the realization of robust flexible LMA antennas.

It consists of a dielectric origami in Voronoi topology and microfluidic structures additively manufactured using a 3D printer. For proof of concept, a circularly polarized helical antenna and a linearly polarized zigzag antenna were fabricated on the ''tree'' using LMA. The LMA used is Eutectic Gallium-Indium (EGaIn), with 75% Gallium and 25% Indium. Both antennas share the same feed which can be considered as the ''root'' of the tree. The zigzag antenna was designed to resonate at 5 GHz. It was observed that as the structure compresses, the radiation pattern of the antenna changes from directional to omnidirectional, and the 3 dB beamwidth (HPBW) increased from 28° to 60°. Similar behavior of radiation pattern reconfigurability was observed for the helical antenna and the HPBW of the helical antenna increased from 60° to 90°.

In [39], a push/pull origami-based transformable antenna is proposed. The antenna can transform a single antenna element to a three-element array. The dielectric material and the frame of the antenna are constructed us s 3D printer. The conducted patterns are realized on paper using an inkjet printer. Figure 10 shows the fabricated prototype of the proposed antenna. The antenna shows an impedance bandwidth from 2.5–2.65 GHz in single antenna mode while in the array mode the impedance bandwidth is from 2.48–2.62 GHz. the peak gain of the antenna is observed to be 5.8 dBi and 7.6 dBi for single antenna and array mode respectively.

In another study [54], a 3D printed ''Chinese Fan'' Bow-Tie origami antenna is proposed. The antenna was 3D printed using FormLabs Form 2 stereolithography (SLA) 3D printer, featuring 50 μm resolution. The flexible resin FLGR02 was used as the dielectric having a dielectric constant of 2.78 and a loss tangent of 0.06, featuring 80% elongation. It consists of a ''Chinese Fan'' bow-tie origami structure with an embedded microfluidic channel. To metalize the structure Liquid metal alloy (LMA) was injected in the microfluidic channel, which facilitated the folding without breakages. The LMA used was Eutectic Gallium-Indium (EGaIn) with 75.5% Ga and 24.5% In. The bow-tie antenna acts as a dipole antenna with extended bandwidth due to the triangular area. The bandwidth of the bow-tie antenna depends on the apex angle of the isosceles triangle. The apex angle of the bow-tie antenna can be easily tuned by applying the Chinese fan structure to the bow-tie antenna. Thus, the bandwidth of the ''Chinese Fan'' bow-tie antenna can be changed by folding and unfolding the Chinese fan. Also, the distance between the two folded triangles can be easily varied by folding the fan sides in different relative angles. Due to this capacitance increases and the imaginary part of input impedance is decreases which effectively leads to a higher resonating frequency of the structure. The analysis of the antenna shows that the resonant frequency of the antenna shifts from 896 MHz to 992 MHz as the antenna moves from the uncompressed state (800 apex) to its fully compressed state (200 apex).

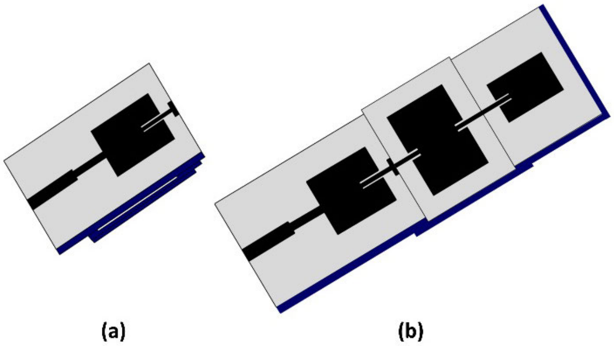


FIGURE 10. Push/pull origami-based transformable antenna (a) single antenna mode and (b) three-antenna-element array mode.

Table 1 compares different features of different origami antennas proposed in the past. In the next section, advanced origami antenna designs are discussed. This discussion is based on robustness and deployability. In literature, one of the challenges scientists have faced in origami antenna systems is self-deployability. One possible solution is to use actuators. Therefore, researchers have used actuators to achieve self-deployability in origami antennas.

IV. DEPLOYMENT CHALLENGES AND ACTUATORS AS POTENTIAL SOLUTION

The fragility of origami antennas can be compensated by making use of robust solutions discussed in previous sections, however, another remaining issue is the self-deployment of origami antennas. The earlier proposed origami antennas were deployed manually which is not viable for many practical systems as manual folding/unfolding increases system complexity as well performance. One possible solution for self-deployment is using electric motors and one such design for self-deployable origami antenna has been reported [55]. However, motors are usually quite bulky which limits the applicability of this solution. Therefore, researchers are trying to develop feasible solutions using suitable materials and actuators [56], [57].

A. SOFT PNEUMATIC ACTUATORS

Considerable interest has been devoted to developing pneumatic actuators. To reduce the overall system cost, inexpensive actuators are desirable. Therefore, an Ecoflex stretchable elastomer was mixed with non-stretchable but bendable materials like patterned paper, polyester, and polymer to produce prototype components useful for robotics and soft actuators [57]. These actuators can easily contract, expand and bend by torsion and pressure which is not achievable by hard robots. As this technology is further developed, the soft

TABLE 1. Comparison table for different origami antennas.

Ref	Substrate Material	Antenna Type	Frequency (GHz)	Gain (dBi)	Polarization	Frequency Reconfigurable	Pattern Reconfigurable	No of Modes of operation	Robust
[32]	Paper	Yagi-Uda	0.69 - 0.80	4 - 8	Linear	Yes	No	2	No
[33]	Paper	Helical	1.28 - 4.12	6, 8.5, 5	Linear, RHCP Elliptical	Yes	No	3	No
[16]	Paper	Helical	0.86 - 3	-	Linear	Yes	No	3	No
[27]	Paper	Dipole	0.75 - 1.29	-0.48 -3	Linear	Yes	No	2	No
[18]	Paper	Conical spiral	1.4 - 3.7	7-12	Linear and circular	Yes	No	2	No
[45]	Paper	Helical	0.86 - 2.14	-	Linear	Yes	No	2	No
[28]	Multiple papers	Monopole	2-4 GHz	9.6	Linear	No	No	1	Slightly
[34]	Multiple papers	Monopole	2.4-5 GHz	5.2 - 5.7	Circular	No	No	1	Slightly
[31]	Multiple papers	Yagi	0.65-1.8	6.5-8	Linear	Yes	No	3	Yes
[35]	Paper	Helical	0.650 - 1.8	6.5-8	Linear	Yes	No	2	Yes
[26]	Paper	Yagi	1.31 GHz	10.4	Linear	No	No	1	Slightly
[15]	Paper	Helical	1.8-2560	-	Linear	Yes	No	3	Slightly
[46]	Sketching paper	Helical	2.07 - 4.45	9.7-14.7	LHCP	Yes	No	3	No
[47]	PET sheets	Yagi	1.7 - 2.8	10	Linear	No	No	1	Yes
[38]	PET sheets	Yagi	2.2	-	Linear	No	Yes	4	Yes
[40]	FR4	Patch	2.45	-	Linear	No	Yes	2	Highly Robust
[41]	FR4	Array	2.4	3, 8	Linear	No	Yes	2	Highly Robust
[43]	FR4	MIMO	2.33 - 2.91	1-12	Linear	Yes	No	2	Highly Robust
[49]	PTFE	Patch	1.98 - 2.2	12.6	Circular	No	No	1	Yes
[50]	Photo paper	Monopole	2.3-7	3.7 - 4.9	Linear	No	No	1	No

actuators will play an important role to realize interesting structures for origami antenna development.

Actuation of composite Ecoflex/paper structures using PneuNets can provide relatively inexpensive, flexible, lightweight, and simple soft actuator fabrication solutions.

However, soft actuators activated by PneuNets have some limitations [57]. They are inappropriate for deploying heavy objects, are somewhat fragile, and susceptible to damage by puncture or cutting, particularly when stretched. However, they are very suitable for origami antennas due to their flexibility and lightweight, and by using tougher elastomers they can withstand strong forces and pressure.

One other issue is that these actuators need a compressed air source for continuous operation and miniaturizing the actuators below the centimeter scale is also difficult. However, most deployable origami antennas are larger than this scale, and separate compressed air sources are available, albeit somewhat larger than ideal. Therefore, this soft pneumatic actuator can be a game-changer for origami antenna deployment.

B. SHAPE MEMORY ALLOY ACTUATORS

Shape memory alloy (SMA) is one type of smart flexible material. When Direct current (DC) is passed through SMA, it heats up due to power losses and as result causing the SMA to contract. When the current source is removed, the SMA comes back to its original form. This behavior can be utilized to reduce the dimension of any reconfigurable antenna. A prototype reconfigurable helical antenna has been proposed and fabricated where the height was tuned using SMA [58]. An SMA spring was utilized to tune reconfigurable antenna at various frequencies [58], and radiation patterns [59]. The spring was thermally controlled and operated by supplying DC current or direct heating. This type of spring could be a suitable candidate for origami antenna technology, requiring simple heating for actuation as compared to pneumatic actuators. Two or more springs could be employed to provide bi-directional movement (folding and unfolding) for the origami antenna geometry. Also, antenna deployment using SMA spring is fast, which can be a critical consideration for some applications.

C. SHAPE MEMORY POLYMER ACTUATORS

Recently, shape memory polymer-based actuators are receiving significant attention for diverse applications. Shape memory polymer (SMP) has an interesting feature to transform their shape as per requirement [60], [61]. Therefore, they can be used to design reconfigurable antennas. At normal room temperature, SMP is quite stiff and remains in what is usually called as their primary shape. SMP can be temporarily softened by heating it above its specific glass transition temperature (T_g) and can then be lengthened to about 80% in this elastic and soften state. In this elastic state, it can be programmed to any desired secondary shape. This secondary shape can be maintained by subsequently decreasing the temperature lower than T_g and it will harden in a few seconds. The SMP can be restored to its primary shape upon reheating it above the T_{g}. The time taken to recover its primary shape from the secondary shape is called recovery time, which can be reduced by increasing the temperature. These SMP actuators can be used for origami antenna applications. The structure of antennas can be folded and unfolded using SMP hinges to achieve reconfigurability. For instance, a pattern reconfigurable origami antenna was designed using SMP hinges [62]. The origami reflectors were folded and unfolded using these SMP hinges to reconfigure the radiation patterns and beam-width of the antenna.

D. FOUR-DIMENSIONAL PRINTING FOR SELF-ACTUATION

Four-dimensional (4D) printing technology is another option to achieve partially self-actuated reconfigurable origami resonators and antennas. 4D printing is the process through which a 3D printed object transforms itself into another structure over the influence of external energy input as temperature, light, or other environmental stimuli. An inkjet printer antenna was proposed and fabricated using 3D printed origami packaging for harvester electronics[44].

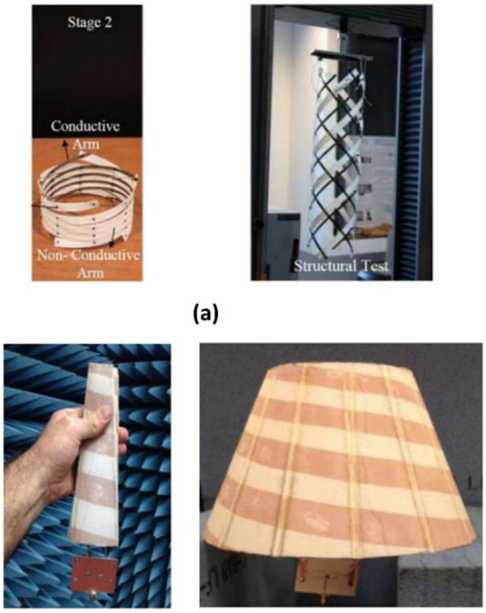
The 3D printed planar structure was joined with smart hinges realized from shape memory polymer that can be thermally folded to realize 3D format. A 3D multi-material polymer printer was utilized to fabricate an origami cube with thermoset shape memory polymers. Vero White cube faces and Grey60 hinges were selected to maximize structural strength and minimize the temperature required for folding. A similar self-actuating 3D printed packaging was proposed for deployable antennas [63], where the antenna was realized using hybrid printing technology, combining inkjet and 3D printing. Silver epoxy paste was used for the conductive pattern and polylactic acid filament for the dielectric part. The deployment mechanism was based on shape memory polymer with 60°C transition temperature to reconfigure the antenna from deployed to a permanently stored state. The deployable array antenna was demonstrated to operate within the Ka-band. Therefore, shape memory materials and 4D printing will bring innovative options for practical deployable origami antennas. **Error! Reference source not found.** compared the pros and cons of different actuators for origami antennas.

V. APPLICATION PERSPECTIVES OF DEPLOYABLE ORIGAMI ANTENNAS

Origami antennas have numerous applications in the practical field. Their significant features of foldability and deployability make them very useful in many applications including military, satellite, and energy harvesting. The applications of origami antennas in these fields are discussed below.

A. DEPLOYABLE ANTENNAS FOR CubeSat APPLICATIONS

Satellite communication due to its large and secure coverage has always received attention of the scientists. Scientists have been working on the miniaturization of the satellite antenna and have introduced the concept of nanosatellites. A great example of a nanosatellite is CubeSat which has a very small size of 10 cm × 10 cm × 10 cm. The CubeSat design has



(a)

(b)

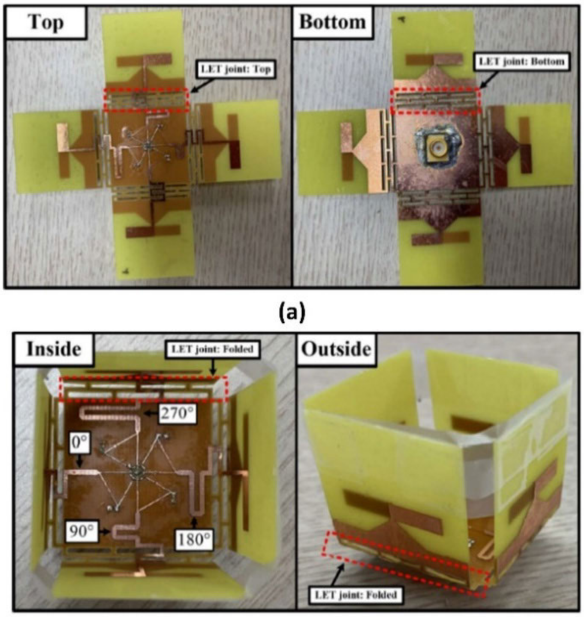
FIGURE 11. Antennas for cubesat (a) quadrifilar helix antenna (QHA) (b) conical log spiral antenna (CLSA).

forced the antenna designers to seek solutions for deployable antennas that can be stowed in the limited space of CubeSat before launch and deploy once in space.

In [20], the design of a quadrifilar helix antenna (QHA) and a conical log spiral antenna (CLSA) is presented. The antennas are designed to operate in the UHF band. The deployment for both the antennas is achieved using a helical pantograph and origami design. **Error! Reference source not found.** (a) and (b) shows the fabricated prototype of the quadrifilar helix antenna and a conical log spiral antenna respectively.

A unique reconfigurable antenna concept for CubeSat applications is proposed [64]. The proposed antenna achieves reconfigurability in terms of polarization, radiation pattern, and level of gain by changing its mode of operation from patch antenna to a monopole like antenna upon folding. The antenna is realized on a 3.175 mm thick Rogers Arlon DiClad 880 substrate having $\varepsilon_r = 2.2$. To feed the antenna a microstrip line is etched on the substrate as the first section of the feed line. The patch and second section feedlines are constructed using copper tape. A polyimide tape is placed beneath the antenna to provide rigidity to the design. Due to the inherent adhesiveness of the polyimide tape, the polyimide/patch layer attaches to the etched feed line section. The antenna operates at 2.4GHz. The actuation between two states is achieved by knotting a thin fishing line at the top edge of the monopole radiator and pulling on either end to adjust the state of the antenna.

The analysis of the antenna shows that in the patch mode the antenna has and has dominant polarization along $\hat{\phi}$ ($\phi = 0^\circ$), whereas in the monopole mode it has a dominant polarization along $\hat{\theta}$ with a significantly smaller $\hat{\phi}$ component. The operational bandwidth of the antenna for the patch state is observed to be 6.9% whereas for the monopole state it is observed to be 2.6%. the peak gain of the antenna in patch mode is observed to be 7.7dBi at $\phi = 0^\circ$ while in monopole mode the gain is observed to be 1.2dBi at $\theta = 90^\circ$.



(a)

(b)

FIGURE 12. Robust origami antenna for CubeSat (a) planar state, (b) folded state.

An origami-inspired pattern and polarization reconfigurable dipole array antenna operating in C-Band for CubeSat applications is proposed [65]. The antenna consists of a 4-way Gysel power divider, delay lines, four inside Lamina Emergent Torsion (LET) joints, and four thick planar dipole antennas integrated with balun. The antenna is printed on a 0.5-mm thick FR4 substrate with a dielectric constant of 4.4 and a loss tangent of 0.025. The antenna consists of five square boards of size 30 × 30 mm^2, interconnected through LET joints. The overall size of the antenna is 100 × 100 mm^2. The planner dipole antennas are orthogonally placed to form a 2 × 2 array with a 4-way Gysel power divider to feed each dipole antenna.

Error! Reference source not found. (a) and (b) show the fabricated antenna in planner and folded state respectively. In planner mode, the antenna achieves an impedance bandwidth of more than 33% (5 ∼ 7 GHz) with resonance at 5.8GHz. The antenna shows a monopole like omnidirectional, linearly polarized radiation pattern. At the resonance frequency, the antenna shows a gain of 0.5dBi. The overall size of the antenna in the planner mode is 100 × 100 × 0.5 mm^3. In the folded mode the S11 is values are very close to those in planar mode and the impedance bandwidth is also more than 33% (5 ∼ 7 GHz). The antenna shows an RHCP behavior in a folded state with a circularly polarized gain value of about 8.07dBic. The antenna has a measured cross-polarization suppression ratio of 25 dB, and an axial

TABLE 2. Comparison of origami antennas based on different actuators.

Reference	Actuation technique	Reconfigurability	Materials	Memory type	Advantages	Disadvantages
[66]	4D Printing	More flexibility	Costly	One way	Fast tuning	High actuation temperature
[67]	Shape memory polymer actuator	Pattern reconfigurable	fiber-reinforced composite	One way	Low cost	High actuation temperature
[68]	Shape memory alloy actuators	Frequency reconfigurable	Nickel and Titanium	One way	Low cost	Suitable for only low frequency
[69],[70], [71]	Manual	Frequency, pattern, polarization	Paper/ PET/ Nanopaper	N/A	Biasing not required	Slow tuning speed

ratio (AR) of 1.13 dB at 5.8 GHz. The overall size of the antenna in planner mode is 32.5 × 32.5 × 32.5 mm^3. The total weight of the antenna is 4.73 g.

B. DEPLOYABLE ANTENNAS FOR MILITARY FIELD APPLICATIONS

The conventional antennas used for military purposes are usually quite large and bulky and require dedicated vehicles to be moved around. The origami technology offers a practical solution to this problem by providing the feature of foldability and deployability. These antennas can be easily moved from one place to another as the military personnel can carry these antennas in their pockets. And when required these antennas can be deployed very easily and quickly. This solves a lot of the communication problems that soldiers face in areas where communication without a proper antenna setup is not possible.

C. DEPLOYABLE ANTENNAS FOR ENERGY HARVESTING APPLICATIONS

Energy harvesting is the process by which energy is obtained from external sources and stored for small, wireless sensor networks (WSNs). Power sufficiency is one of the most prominent challenges in WSN design. RF energy harvesting gives the solution to this problem and overcome the need for manual battery replacement.

Origami technology can be utilized for energy harvesting applications. As energy harvesting is the process of converting RF energy to DC which requires rectifier circuits. The origami technology can be utilized to enclosed the rectification circuit inside an origami built structure. A similar approach is presented in [44], where an origami based packaging is constructed to enclose the harvesting circuits. The origami structure is 3D-printed as a planner structure with ''smart'' shape-memory hinges that allow origami to fold to a 3D shape after heating. The conductive part of the structure is constructed directly by inkjet printing conductive inks on top of the 3D-printed surface. Figure 13, shows the 3D printed Shape memory polymer-based deployable origami antenna.

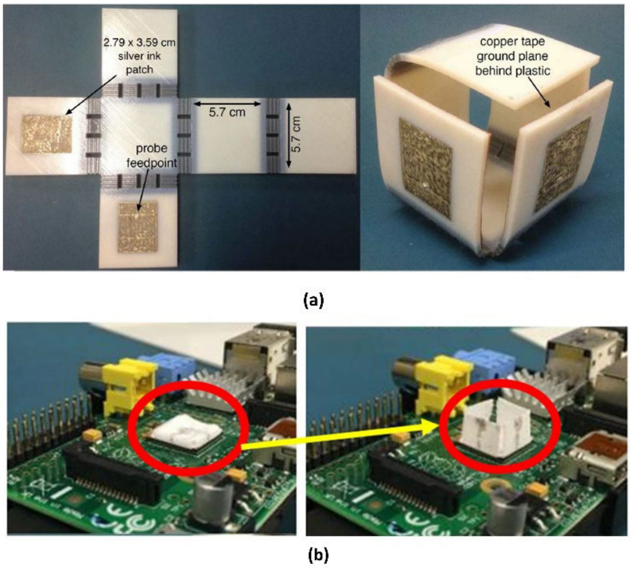


FIGURE 13. Shape memory polymer-based deployable origami antenna (a) unfolded and folded cube and origami packaging for harvester electronics, (b) implementation of monopole foldable array in temporary and permanent state.

VI. CONCLUDING REMARKS

To select an antenna for a technology is mainly depends upon the application. For instance, for indoor applications, paper-based origami antennas are favorable due to characteristics, such as, low cost and fast manufacturing procedure. Origami antennas have many advantages over traditional antennas for applications requiring mobility and quick deployment under a harsh environment. They offer a light weight and low-cost alternative to design flexible and deployable antennas as origami folding enables antenna miniaturization, making them significantly suitable for space and planetary applications. Because, such antennas are easy to transport and deployed at their desired locations and this is particularly useful for communication applications that require large size antennas.

A deployable origami antenna in the microwave frequency range can also be a suitable candidate for military communications. Traditionally soldiers use walkie-talkie-type units to communicate, which can be susceptible to tapping, and line of sight obstacles can significantly shorten their range. Satellite communication could be a suitable option in areas where cellular network is unavailable, but conventional satellite antennas are quite bulky, and transporting them to the desired locations requires relatively large vehicles or helicopters. Therefore, a lightweight deployable origami antenna offers a very suitable option, since paper sheets and copper film can be easily carried and folded to fabricate antennas at the desired location without requiring additional lab facilities. To provide stability to the paper-based antennas, multiple paper sheets can be combined to realize a stable origami antenna. If the conductor pattern of the required antenna geometry is complicated and manual cutting is challenging, for such cases inkjet-printing technology can be utilized which can print conductor pattern with higher precision. In this work, several antenna designs have been discussed that would be suitable for military and warfare applications.

Reconfigurable origami antennas are also very suitable for CubeSat applications, and deployable antennas have been developed using glass fiber reinforced epoxy with embedded copper alloy conductors [20]. Similarly, QHA helical and conical log spiral antennas offer efficient folding, packaging, and deployment for space applications [16].

In order to design a deployable origami antenna for outdoor applications, robust substrate materials like; PET sheets are a desirable choice. To further increase its stability and robustness, Rogers or FR4 substrate can also be used, where 3D printed shape memory polymer-based hinges can be incorporated to make sure its folding-unfolding procedures. This paper reviewed the state of the art lightweight and low cost deployable origami-based antennas that allow easy adoption of complex and flexible antenna structures for space systems, small-scale devices, and self-assembly systems.

Similarly, shape memory alloy-based actuators can be integrated with the origami structure, which can be advantageous to deploy the origami antenna structure remotely and electronically. Although SMA based deployable origami antennas show slow tuning speed. Nevertheless, research on SMA actuators has increased substantially, particularly in terms of their actuation speed, which can be enhanced with quick heating. Therefore, we expect that the low-switching speed of SMA actuators based deployable origami antennas will be solved in the near future.

We also provide insights into the design challenges for different possible applications. A number of antenna examples are given with theoretical and experimental results. The design methodology reviewed in the paper could provide intuition in the design of various origami-inspired antennas that are suitable for harsh and rigid requirements specified by the installation environment. The critical discussion in this paper will provide opportunities to identify the wide range of possible antenna designs using origami principles and to further develop technology in the evolving field of origami-based antennas.

REFERENCES

[1] C. Cromvik and K. Eriksson, *Airbag Folding Based on Origami Mathematics*. Semantic Scholar, Aug. 2009, doi: 10.1201/b10653-15.

[2] S. Mueller, B. Kruck, and P. Baudisch, *LaserOrigami*. New York, NY, USA: Association for Computing Machinery, 2013, p. 2851, doi: 10.1145/2468356.2479544.

[3] W. Gao, K. Ramani, and R. J. Cipra, "Reconfigurable foldable spatial mechanisms and robotic forms inspired by Kinetogami," in *Proc. 36th Mech. Robot. Conf., A B*, vol. 4, Aug. 2012, pp. 1161–1168.

[4] J. M. Z. Ocampo, P. O. Vaccaro, K. Kubota, T. Fleischmann, T. S. Wang, T. Aida, T. Ohnishi, A. Sugimura, R. Izumoto, M. Hosoda, and S. Nashima, "Characterization of GaAs-based micro-origami mirrors by optical actuation," *Microelectron. Eng.*, vols. 73–74, pp. 429–434, Jun. 2004, doi: 10.1016/j.mee.2004.03.012.

[5] Q. Cheng, Z. Song, T. Ma, B. B. Smith, R. Tang, H. Yu, H. Jiang, and C. K. Chan, "Folding paper-based lithium-ion batteries for higher areal energy densities," *Nano Lett.*, vol. 13, no. 10, pp. 4969–4974, Oct. 2013, doi: 10.1021/nl4030374.

[6] D.-Y. Lee, J.-S. Kim, S.-R. Kim, J.-S. Koh, and K.-J. Cho, "The deformable wheel robot using magic-ball origami structure," in *Proc. 37th Mech. Robot. Conf.*, vol. 6B, Aug. 2013, Art. no. V06BT07A040, doi: 10.1115/DETC2013-13016.

[7] Y. Jung and J. Kim, "Flutter speed estimation for folding wing system," in *Proc. 18th Int. Conf. Compos. Mater.*, Jan. 2011.

[8] A. P. Thrall and C. P. Quaglia, "Accordion shelters: A historical review of origami-like deployable shelters developed by the US military," *Eng. Struct.*, vol. 59, pp. 686–692, Feb. 2014, doi: 10.1016/j.engstruct.2013.11.009.

[9] K. Fuchi, A. R. Diaz, E. J. Rothwell, R. O. Ouedraogo, and J. Tang, "An origami tunable metamaterial," *J. Appl. Phys.*, vol. 111, no. 8, p. 84905, Apr. 2012, doi: 10.1063/1.4704375.

[10] Y. Zhao, M. S. Nandra, and Y. C. Tai, "A MEMS intraocular origami coil," in *Proc. 16th Int. Solid-State Sensors, Actuat. Microsyst. Conf.*, Jun. 2011, pp. 2172–2175.

[11] C. L. Randall, E. Gultepe, and D. H. Gracias, "Self-folding devices and materials for biomedical applications," *Trends Biotechnol.*, vol. 30, no. 3, pp. 138–146, Mar. 2012, doi: 10.1016/j.tibtech.2011.06.013.

[12] L. J. Fei and D. Sujan, "Origami theory and its applications: A literature review," *Comput. Sci. Eng.*, vol. 7, no. 1, pp. 1131–1135, 2013. [Online]. Available: http://www.waset.org/publications/1557

[13] J. Mohd Jani, M. Leary, A. Subic, and M. A. Gibson, "A review of shape memory alloy research, applications and opportunities," *Mater. Des.*, vol. 56, pp. 1078–1113, Apr. 2014, doi: 10.1016/j.matdes.2013.11.084.

[14] S. R. Wu, T. H. Chen, and H. Y. Tsai, "A review of actuation force in origami applications," *J. Mech.*, vol. 35, no. 5, pp. 627–639, Oct. 2019, doi: 10.1017/jmech.2019.21.

[15] S. Yao, X. Liu, S. V. Georgakopoulos, and M. M. Tentzeris, "A novel reconfigurable origami spring antenna," in *Proc. IEEE Antennas Propag. Soc. Int. Symp. (APSURSI)*, Jul. 2014, pp. 374–375, doi: 10.1109/APS.2014.6904519.

[16] X. Liu, S. Yao, B. S. Cook, M. M. Tentzeris, and S. V. Georgakopoulos, "An origami reconfigurable axial-mode bifilar helical antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5897–5903, Dec. 2015, doi: 10.1109/TAP.2015.2481922.

[17] C. D. Saintsing, B. S. Cook, and M. M. Tentzeris, "An origami inspired reconfigurable spiral antenna," in *Proc. Volume 5B: 38th Mech. Robot. Conf.*, Aug. 2014, Art. no. V05BT08A050.

[18] X. Liu, S. Yao, and S. V. Georgakopoulos, "Reconfigurable origami equiangular conical spiral antenna," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 2263–2264.

[19] D. Ochoa, K. Hummer, and M. Ciffone, "Deployable helical antenna for nano-satellites," in *Proc. 28th Annu. AIAA/USU Conf. Small Satell.*, 2014, pp. 1–7.

[20] J. Costantine, Y. Tawk, I. Maqueda, M. Sakovsky, G. Olson, S. Pellegrino, and C. G. Christodoulou, "UHF deployable helical antennas for CubeSats," *IEEE Trans. Antennas Propag.*, vol. 64, no. 9, pp. 3752–3759, Sep. 2016, doi: 10.1109/TAP.2016.2583058.

[21] C. R. Kobza, ''Space qualification testing of a shape memory alloy deployable cubesat antenna,'' M.S. thesis, Dept. Aeronaut. Astronaut., Air Force Inst. Technol., Air Force Base, OH, USA, Sep. 2016, p. 238.

[22] T. Huang, J. R. Reveles, V. Gurusamy, Q. Harrington, and V. Fraux, ''An innovative deployable VHF/UHF helical antenna for nanosatellites,'' in *Proc. 13th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2019, pp. 1–4.

[23] X.-Q. Li, Z.-P. Zhou, and Q. Gao, ''Research on thin-membrane deployable antenna,'' in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, May 2019, pp. 1–3, doi: 10.1109/ICMMT45702.2019.8992232.

[24] V. Hasanzade, S. H. Sedighy, and M. Shahravi, ''Compact deployable umbrella antenna design with optimum communication properties,'' *J. Spacecraft Rockets*, vol. 54, no. 3, pp. 782–788, May 2017, doi: 10.2514/1.A33710.

[25] A. Liu and J. Lu, ''A UHF deployable log periodic dipole antenna: Concept, design, and experiment,'' *IEEE Trans. Antennas Propag.*, vol. 69, no. 1, pp. 538–543, Jan. 2021, doi: 10.1109/TAP.2020.3004986.

[26] S. Yao, X. Liu, J. Gibson, and S. V. Georgakopoulos, ''Deployable origami Yagi loop antenna,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 2215–2216, doi: 10.1109/APS.2015.7305496.

[27] S. Lee, S. I. H. Shah, H. L. Lee, and S. Lim, ''Frequency-reconfigurable antenna inspired by origami flasher,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 8, pp. 1691–1695, Aug. 2019, doi: 10.1109/LAWP.2019.2928302.

[28] S. I. H. Shah, S. Lim, and M. M. Tentzeris, ''Military field deployable antenna using origami,'' in *Proc. Int. Workshop Antenna Technol., Small Antennas, Innov. Struct., Appl. (iWAT)*, Mar. 2017, pp. 72–73, doi: 10.1109/IWAT.2017.7915320.

[29] S. R. Seiler, G. Bazzan, K. Fuchi, E. J. Alanyak, A. S. Gillman, G. W. Reich, P. R. Buskohl, S. Pallampati, D. Sessions, D. Grayson, and G. H. Huff, ''Physical reconfiguration of an origami-inspired deployable microstrip patch antenna array,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 2359–2360, doi: 10.1109/APUSNCURSINRSM.2017.8073222.

[30] S. I. H. Shah, D. Lee, M. M. Tentzeris, and S. Lim, ''A novel high-gain tetrahedron origami,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 848–851, 2017, doi: 10.1109/LAWP.2016.2609898.

[31] S. I. H. Shah, M. M. Tentzeris, and S. Lim, ''A deployable quasi-yagi monopole antenna using three origami magic spiral cubes,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 1, pp. 147–151, Jan. 2019, doi: 10.1109/LAWP.2018.2883380.

[32] G. P. Carrara, N. E. Russo, C. L. Zekios, and S. V. Georgakopoulos, ''A deployable and reconfigurable origami antenna for extended mobile range,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Jul. 2019, pp. 453–454, doi: 10.1109/APUSNCURSINRSM.2019.8889294.

[33] X. Liu, S. Yao, P. Gonzalez, and S. V. Georgakopoulos, ''A novel ultra-wideband origami reconfigurable quasi-taper helical antenna,'' in *Proc. IEEE Int. Symp. Antennas Propag. (APSURSI)*, Jun. 2016, pp. 839–840, doi: 10.1109/APS.2016.7696128.

[34] S. I. H. Shah, M. M. Tentzeris, and S. Lim, ''Low-cost circularly polarized origami antenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2026–2029, 2017, doi: 10.1109/LAWP.2017.2694138.

[35] S. Yao, S. V. Georgakopoulos, B. Cook, and M. Tentzeris, ''A novel reconfigurable origami accordion antenna,'' in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2014, pp. 1–4, doi: 10.1109/MWSYM.2014.6848571.

[36] S. Alharbi, S. Chaudhari, A. Inshaar, H. Shah, C. Zou, R. L. Harne, and A. Kiourti, ''E-textile origami dipole antennas with graded embroidery for adaptive RF performance,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 12, pp. 2218–2222, Dec. 2018, doi: 10.1109/LAWP.2018.2871643.

[37] S. Yao and S. V. Georgakopoulos, ''Origami segmented helical antenna with switchable sense of polarization,'' *IEEE Access*, vol. 6, pp. 4528–4536, 2018, doi: 10.1109/ACCESS.2017.2787724.

[38] S. I. H. Shah, S. Gosh, M. M. Tentzeris, and S. Lim, ''A novel bio inspired pattern reconfigurable quasi-Yagi helical antenna using origami DNA,'' in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Oct. 2019, pp. 1–2.

[39] S. Shah and S. Lim, ''Transformation from a single antenna to a series array using push/pull origami,'' *Sensors*, vol. 17, no. 9, p. 1968, Aug. 2017, doi: 10.3390/s17091968.

[40] M. Hamza, C. L. Zekios, and S. V. Georgakopoulos, ''A thick origami reconfigurable and packable patch array with enhanced beam steering,'' *IEEE Trans. Antennas Propag.*, vol. 68, no. 5, pp. 3653–3663, May 2020, doi: 10.1109/TAP.2020.2963922.

[41] H. Choe and S. Lim, ''Foldable multifunctional planar antenna array,'' in *Proc. Asia Pacific Microw. Conf.*, Dec. 2012, pp. 1097–1099, doi: 10.1109/APMC.2012.6421836.

[42] S. R. Seiler, G. Bazzan, K. Fuchi, E. J. Alanyak, A. S. Gilman, G. W. Reich, A. Cook, P. R. Buskohl, S. Pallampati, F. A. Espinal, D. Sessions, and G. H. Huff, ''An origami inspired circularly-polarized folding patch antenna array,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2018, pp. 181–182, doi: 10.1109/APUSNCURSINRSM.2018.8608608.

[43] N. E. Russo, C. L. Zekios, and S. V. Georgakopoulos, ''A capacity reconfigurable multimode origami MIMO antenna,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Jul. 2019, pp. 411–412, doi: 10.1109/APUSNCURSINRSM.2019.8889073.

[44] J. Kimionis, M. Isakov, B. S. Koh, A. Georgiadis, and M. M. Tentzeris, ''3D-printed origami packaging with inkjet-printed antennas for RF harvesting sensors,'' *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 4521–4532, Dec. 2015, doi: 10.1109/TMTT.2015.2494580.

[45] X. Liu, S. Yao, S. V. Georgakopoulos, B. S. Cook, and M. M. Tentzeris, ''Reconfigurable helical antenna based on an origami structure for wireless communication system,'' in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2014, pp. 1–4, doi: 10.1109/MWSYM.2014.6848553.

[46] X. Liu, S. Yao, N. Russo, and S. Georgakopoulos, ''Tri-band reconfigurable origami helical array,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2018, pp. 1231–1232, doi: 10.1109/APUSNCURSINRSM.2018.8608197.

[47] S. I. H. Shah, A. Sarkar, and S. Lim, ''Electromechanically deployable high-gain pop-up antenna using shape memory alloy and kirigami technology,'' *IEEE Access*, vol. 8, pp. 225210–225218, 2020, doi: 10.1109/ACCESS.2020.3044522.

[48] N. E. Russo, C. L. Zekios, and S. V. Georgakopoulos, ''Origami multimode ring antenna based on characteristic mode analysis,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Jul. 2019, pp. 2037–2038, doi: 10.1109/APUSNCURSINRSM.2019.8888860.

[49] Z. Zhong, L. Xu, H. Zhang, and P. Zhang, ''A foldable circular polarized microstrip antenna array for satellite communication,'' in *Proc. 12th Int. Symp. Antennas, Propag. EM Theory (ISAPE)*, Dec. 2018, pp. 1–4, doi: 10.1109/ISAPE.2018.8634158.

[50] S. Jun, J. Heirons, and B. Sanz-Izquierdo, ''Inkjet printed dual band antenna for paper UAVs,'' in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 3452–3456, doi: 10.23919/EuCAP.2017.7928707.

[51] S. Y. Jun, A. Shastri, B. Sanz-Izquierdo, D. Bird, and A. McClelland, ''Investigation of antennas integrated into disposable unmanned aerial vehicles,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 1, pp. 604–612, Jan. 2019, doi: 10.1109/TVT.2018.2882791.

[52] P. M. Njogu, B. Sanz-Izquierdo, S. Y. Jun, G. Kalman, S. Gao, A. Malas, and G. J. Gibbons, ''Evaluation of planar inkjet-printed antennas on a low-cost origami flapping robot,'' *IEEE Access*, vol. 8, pp. 164103–164113, 2020, doi: 10.1109/ACCESS.2020.3020824.

[53] W. Su, S. A. Nauroze, B. Ryan, and M. M. Tentzeris, ''Novel 3D printed liquid-metal-alloy microfluidics-based zigzag and helical antennas for origami reconfigurable antenna 'trees,''' in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2017, pp. 1579–1582, doi: 10.1109/MWSYM.2017.8058933.

[54] W. Su, R. Bahr, S. A. Nauroze, and M. M. Tentzeris, ''Novel 3D-printed 'Chinese fan' bow-tie antennas for origami/shape-changing configurations,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 1245–1246, doi: 10.1109/APUSNCURSINRSM.2017.8072665.

[55] S. Yao, K. Bao, X. Liu, and S. V. Georgakopoulos, ''Tunable UHF origami spring antenna with actuation system,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 325–326, doi: 10.1109/APUSNCURSINRSM.2017.8072205.

[56] J. S. Ku and E. D. Demaine, ''Folding flat crease patterns with thick materials,'' *J. Mech. Robot.*, vol. 8, no. 3, Jun. 2016, doi: 10.1115/1.4031954.

[57] R. V. Martinez, C. R. Fish, X. Chen, and G. M. Whitesides, ''Elastomeric origami: Programmable paper-elastomer composites as pneumatic actuators,'' *Adv. Funct. Mater.*, vol. 22, no. 7, pp. 1376–1384, Apr. 2012, doi: 10.1002/adfm.201102978.

[58] S. J. Mazlouman, A. Mahanfar, C. Menon, and R. G. Vaughan, ''Reconfigurable axial-mode helix antennas using shape memory alloys,'' *IEEE Trans. Antennas Propag.*, vol. 59, no. 4, pp. 1070–1077, Apr. 2011, doi: 10.1109/TAP.2011.2109686.

[59] S. J. Mazlouman, A. Mahanfar, C. Menon, and R. G. Vaughan, "Square ring antenna with reconfigurable patch using shape memory alloy actuation," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5627–5634, Dec. 2012, doi: 10.1109/TAP.2012.2213053.

[60] Q. Zhang, J. Wommer, C. O'Rourke, J. Teitelman, Y. Tang, J. Robison, G. Lin, and J. Yin, "Origami and kirigami inspired self-folding for programming three-dimensional shape shifting of polymer sheets with light," *Extreme Mech. Lett.*, vol. 11, pp. 111–120, Feb. 2017, doi: 10.1016/j.eml.2016.08.004.

[61] H. J. Qi, T. D. Nguyen, F. Castro, C. M. Yakacki, and R. Shandas, "Finite deformation thermo-mechanical behavior of thermally induced shape memory polymers," *J. Mech. Phys. Solids*, vol. 56, no. 5, pp. 1730–1751, May 2008, doi: 10.1016/j.jmps.2007.12.002.

[62] S. I. H. Shah and S. Lim, "Thermally beam-direction- and beamwidth-switchable monopole antenna using origami reflectors with smart shape memory polymer hinges," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 8, pp. 1696–1700, Aug. 2019, doi: 10.1109/LAWP.2019.2928333.

[63] R. Bahr, A. Nauroze, W. Su, and M. M. Tentzeris, "Self-actuating 3D printed packaging for deployable antennas," in *Proc. IEEE 67th Electron. Compon. Technol. Conf. (ECTC)*, Orlando, FL, USA, 2017, pp. 1425–1430. [Online]. Available: https://ieeexplore.ieee.org/xpl/conhome/7998598/proceeding, doi: 10.1109/ECTC.2017.186.

[64] A. D. Johnson, V. Manohar, S. B. Venkatakrishnan, and J. L. Volakis, "Low-cost S-band reconfigurable monopole/patch antenna for CubeSats," *IEEE Open J. Antennas Propag.*, vol. 1, pp. 598–603, 2020, doi: 10.1109/OJAP.2020.3034051.

[65] M. Hwang, G. Kim, S. Kim, and N. S. Jeong, "Origami-inspired radiation pattern and shape reconfigurable dipole array antenna at C-band for CubeSat applications," *IEEE Trans. Antennas Propag.*, vol. 69, no. 5, pp. 2697–2705, May 2021, doi: 10.1109/TAP.2020.3030908.

[66] I. Kim and Y. Rahmat-Samii, "RF MEMS switchable slot patch antenna integrated with bias network," *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4811–4815, Dec. 2011, doi: 10.1109/TAP.2011.2165512.

[67] X. Bai, M. Su, Y. Liu, and Y. Wu, "Wideband pattern-reconfigurable cone antenna employing liquid-metal reflectors," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 5, pp. 916–919, May 2018, doi: 10.1109/LAWP.2018.2823301.

[68] M. Li and N. Behdad, "Fluidically tunable frequency selective/phase shifting surfaces for high-power microwave applications," *IEEE Trans. Antennas Propag.*, vol. 60, no. 6, pp. 2748–2759, Jun. 2012, doi: 10.1109/TAP.2012.2194645.

[69] R. J. Lang, T. Nelson, S. Magleby, and L. Howell, "Thick rigidly foldable origami mechanisms based on synchronized offset rolling contact elements," in *Proc. 40th Mech. Robot. Conf.*, vol. 5B, Aug. 2016, Art. no. 021013, doi: 10.1115/DETC2016-59747.

[70] R. J. Lang, K. A. Tolman, E. B. Crampton, S. P. Magleby, and L. L. Howell, "A review of thickness-accommodation techniques in origami-inspired engineering," *Appl. Mech. Rev.*, vol. 70, no. 1, Feb. 2018, Art. no. 010805, doi: 10.1115/1.4039314.

[71] J. Li, C. Fan, H. Pei, J. Shi, and Q. Huang, "Smart drug delivery nanocarriers with self-assembled DNA nanostructures," *Adv. Mater.*, vol. 25, no. 32, pp. 4386–4396, Aug. 2013, doi: 10.1002/adma.201300875.

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