Sudhakar Rao

A Design of an Origami Reconfigurable QHA with a Foldable Reflector

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This article presents a design of an origami reconfigurable circularly polarized quadrifilar helical antenna (QHA) with a foldable reflector that can operate in K, Ka, and extremely high-frequency (EHF) bands. A 10:1 scale prototype of the proposed antenna is built and validated through measurements and simulations.

EDITOR'S NOTE

Future satellites for military and commercial applications require reconfigurable payloads that could change the operational frequency band on orbit. Inspired by origami science, the authors in this issue's "Antenna Applications Corner" column describe the concept and implementation of an antenna array that could operate and reconfigure over the K, Ka, and extremely high-frequency bands. Desired frequency reconfiguration is achieved among the three frequency bands by using an origami quadrifilar helix and by reconfiguring the ground-plane shape. The design and measured unit-cell results of an array are presented in this article.

OVERVIEW OF FOLDABLE REFLECTORS

Helical antennas that operate in the axial mode are suitable for satellite applications because of their unidirectional radiation patterns. Furthermore, helical antennas with large parabolic reflectors can achieve high gains. Various designs of foldable and deployable parabolic reflectors, which can be compactly stowed, have been proposed. Specifically, a deployable Reuleaux triangle reflector and a deployable round reflector were proposed in [1] and [2], respectively. The designs of these reflectors use origami (paper folding) or kirigami (paper cutting) methods to create efficient deployment mechanisms. Also, a deployable CubeSat reflector based on a unique pantograph-like perimeter pattern for interlocking the gores of the surface was proposed in [3].

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The K, Ka, and EHF bands of the QHA employ millimeter wavelengths and can support high-bandwidth transmissions using small receiving antennas [4]. The proposed reflector and QHA are able to reconfigure themselves at three different states using origami folding. Origami was originally developed by Japanese artists, and it has been applied in various disciplines, such as aeronautics, astronautics [1]–[3], and electromagnetics [5]–[10]. A 10:1 scale model of the proposed origami QHA is manufactured and measured to validate our design.

ORIGAMI QHA WITH REFLECTOR

THE DESIGN OF ORIGAMI QHA

The QHA is designed to operate in axial mode. Empirically, the optimum circumference and pitch size for a circularly polarized helical antenna in axial mode should be $0.75\lambda_0 < C < 1.33\lambda_0$, and $S = 0.25\lambda_0$, where λ_0 is the wavelength at its operating frequency, C is the circumference of the helix, and S is the spacing between each turn [11]. Therefore, a helical antenna with fixed total length can achieve a frequency reconfigurability by changing its pitch, S. Here, an origami QHA is proposed to achieve frequency reconfigurability for K, Ka, and EHF bands.

The origami pattern used to fold the cylinder base of the QHA is shown in Figure 1. The number of sides, n, is picked to be equal to four to enable symmetric placement of the four helical arms of the QHA around the origami cylinder. The three-dimensional (3-D) QHA model is shown in Figure 2. The diameter of the origami cylinder

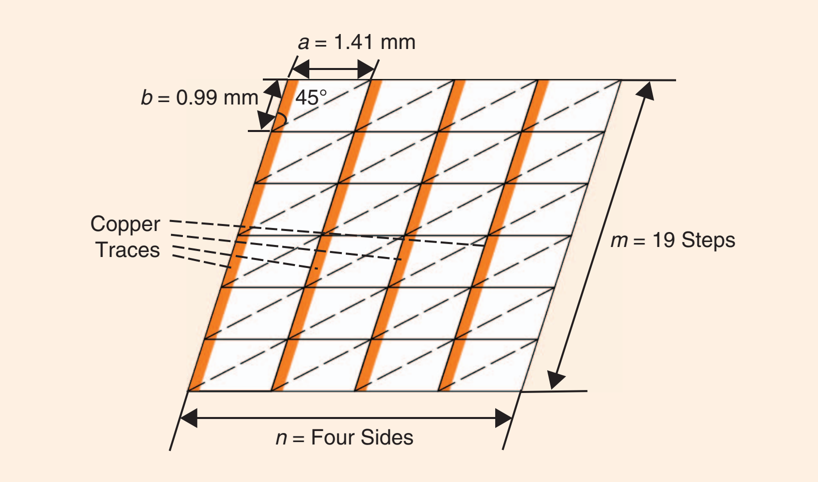

FIGURE 1. The origami folding pattern of the QHA cylinder base.

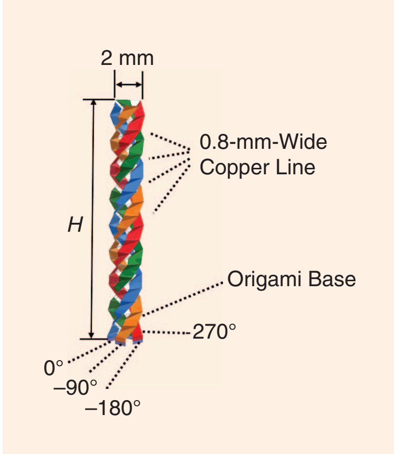

FIGURE 2. The 3-D reconfigurable origami QHA model.

is 2 mm. The QHA is fed using a progressive 90° phase difference from port to port counterclockwise (as shown in Figure 2) to achieve a right-hand circular polarization (RHCP). The total height, H, of the QHA can be adjusted to change its operating frequency from 20.7 to 30 and 44.5 GHz in K, Ka, and EHF bands, respectively. It should be noted that when H is decreased, the number of turns N is increased, as expressed in

$$N = \frac{\sqrt{m^2b^2 - H^2}}{na}. \quad (1)$$

DESIGN OF THE ORIGAMI REFLECTOR

The impact of various reflectors on the performance of helical antennas has been previously studied [12]. The truncated-cone ground provides the highest gain for helical antennas compared to square, cylindrical-cup, and conical grounds [12]. Based on the truncated-cone ground, a novel foldable truncated-heptahedron reflector is proposed in this article, which can reconfigure to cover the three operating frequency bands of the proposed QHA. The geometries of the three reconfigurable states of the reflector QHA are shown in Figure 3, along with the corresponding folding patterns of the reflector, where red dashed lines represent valleys, blue dashed-dot lines are hills, and green solid lines are outlined. The D_{max} and

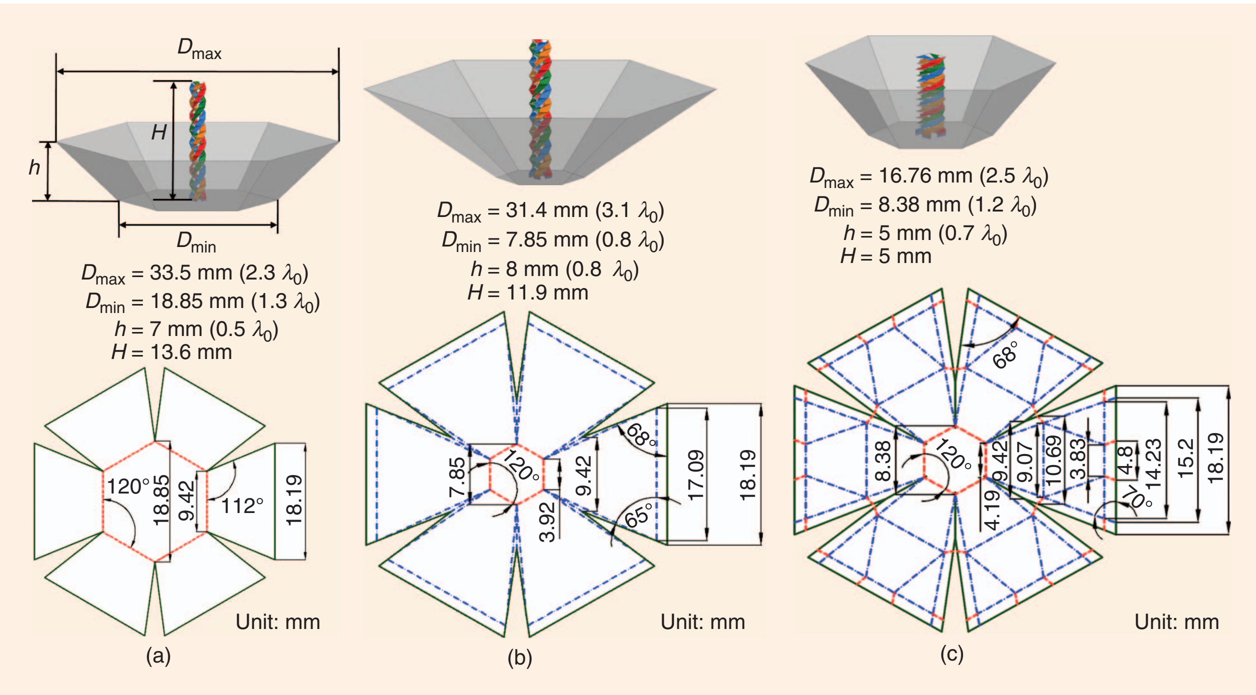

FIGURE 3. The reconfigurable origami QHA with the foldable reflector and the folding patterns of the reflector at three states: (a) state 1 (f_0 = 20.7 GHz), (b) state 2 (f_0= 30 GHz), and (c) state 3 (f_0 = 44.5 GHz).

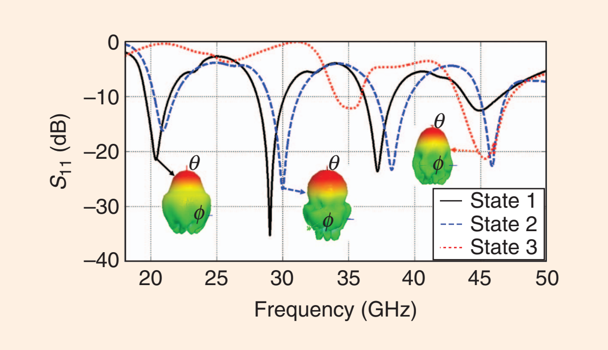

FIGURE 4. The simulated S_{11} of the reconfigurable origami QHA with the reflector at three states.

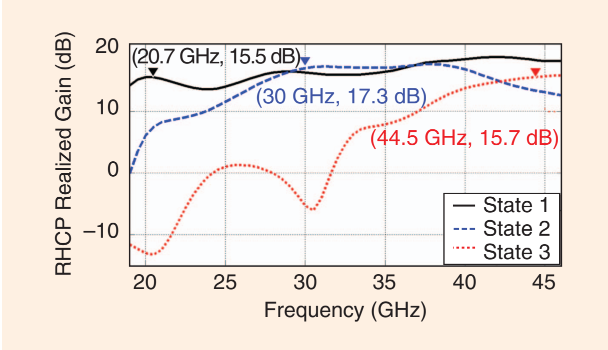

FIGURE 5. The simulated realized RHCP gain of the reconfigurable origami QHA with the reflector at three states.

D_{min} are, respectively, the maximum and minimum diameters of the 3-D foldable reflector, and h is the total height of the reflector.

SIMULATION RESULTS

This reflector QHA antenna was modeled and analyzed in ANSYS high-frequency structural simulator. The simulated S_{11}, realized RHCP gain, and axial ratio are shown in Figures 4–6. Figure 4 shows that the designed reconfigurable origami QHA with the reflector has a return loss greater than 15 dB in all three states. Also, the three states of the designed antenna are circularly polarized, and they have a realized RHCP gain higher than 15 dB at their operating frequencies, as shown in Figures 5 and 6.

Figure 7 shows that the reflector QHA exhibits the best performance in terms of gain and pattern at the operating frequency of each state compared to the other two states. It should be pointed out that Figure 5 shows that the first state (corresponding to K-band operation, $H = 13.6$ mm) exhibits approximately the same gain as the second state (corresponding to Ka-band operation, $H = 11.9$ mm) at the Ka band and a higher gain than the gain of the third state (corresponding to EHF-band operation, $H = 5$ mm) at the EHF band. However, the radiation patterns of the first state (see Figure 7) exhibit large sidelobes at Ka band (8.9 dB) and EHF band (5.2 dB) and, therefore, the first state cannot be used in the Ka and EHF bands.

To prove that three configurations of the reflector are necessary to optimize QHA performance at the three operating frequencies, simulated RHCP patterns of the QHA at three reconfigurable states of height resonating at the designated operating frequencies with one common reflector state are shown in Figure 8 for three common reflector states. Figure 8 shows that, although the QHA performance can be optimized at one of the operating frequencies with the common reflector, the radiation patterns at the other two reconfigurable frequencies cannot be as good due to larger sidelobes or lower gains. Therefore, three states of the reflector were optimized for each operating frequency, as described in the "Design of the Origami Reflector" section.

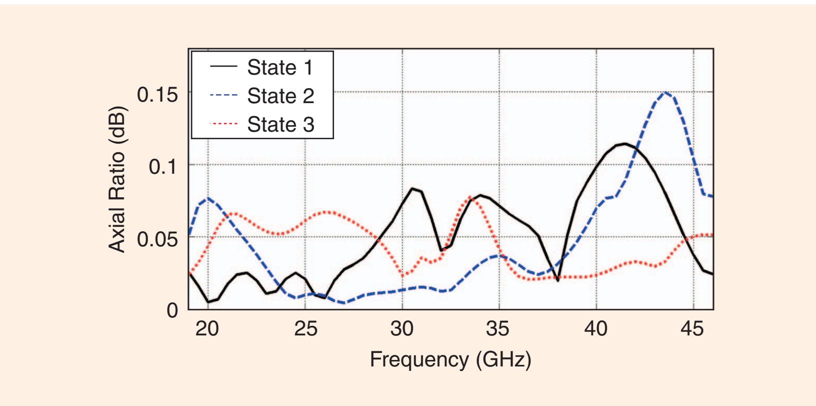

FIGURE 6. The simulated axial ratio of the reconfigurable origami QHA with the reflector at three states.

10:1 SCALE MODEL OF ORIGAMI QHA

The size of the proposed origami QHA is too small; therefore, it is difficult to build its prototype by hand, and new manufacturing techniques need to be explored. Therefore, we decided to build a 10:1 scale model of the proposed origami QHA to validate its performance. The 10:1 scale QHA will operate at the operating frequencies of 2.07, 3, and 4.45 GHz. Because the subminiature version A (SMA) connector feed slightly decreases the resonant frequencies of the antenna, the initial 10:1 scale dimensions of the origami pattern and QHA model are slightly adjusted (a increased by 1.2 mm, b increased by 0.8 mm, m decreased by 2) to compensate this effect of the SMA connector feed and tune the QHA at the scaled frequencies, as shown in Figure 9. Also, the dimensions of the 10:1 scale reflector were slightly adjusted through simulations to provide optimal performance for each state of the slightly adjusted 10:1 scale QHA, as shown in Figure 10.

The prototype of the 10:1 scale reflector of the QHA was manufactured,

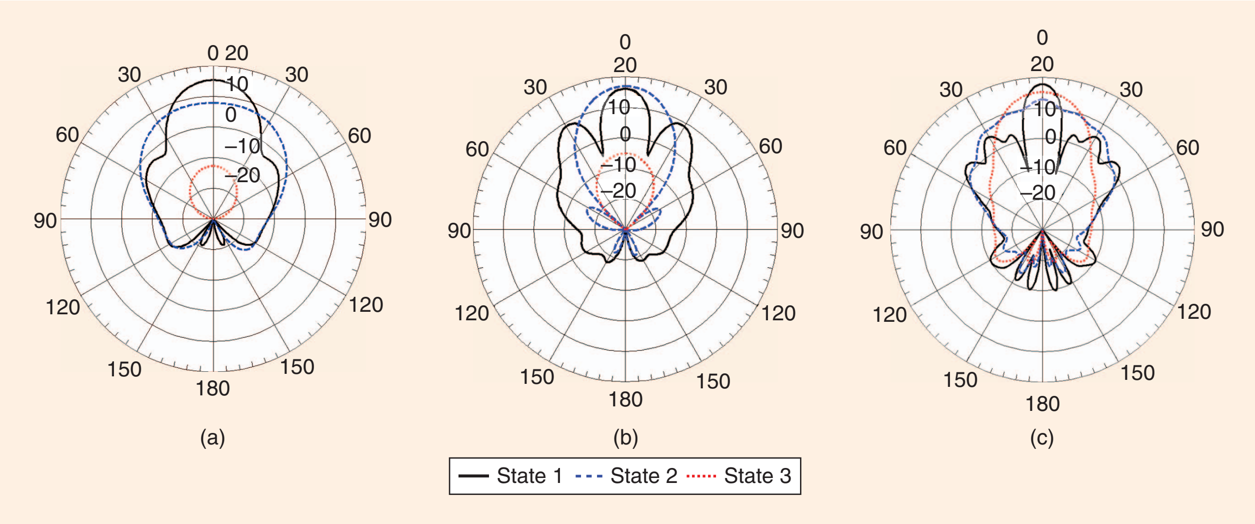

FIGURE 7. The RHCP patterns at three states of the reconfigurable origami reflector QHA at designated operating frequencies: (a) The reflector at state 1, (b) the reflector at state 2, and (c) the reflector at state 3.

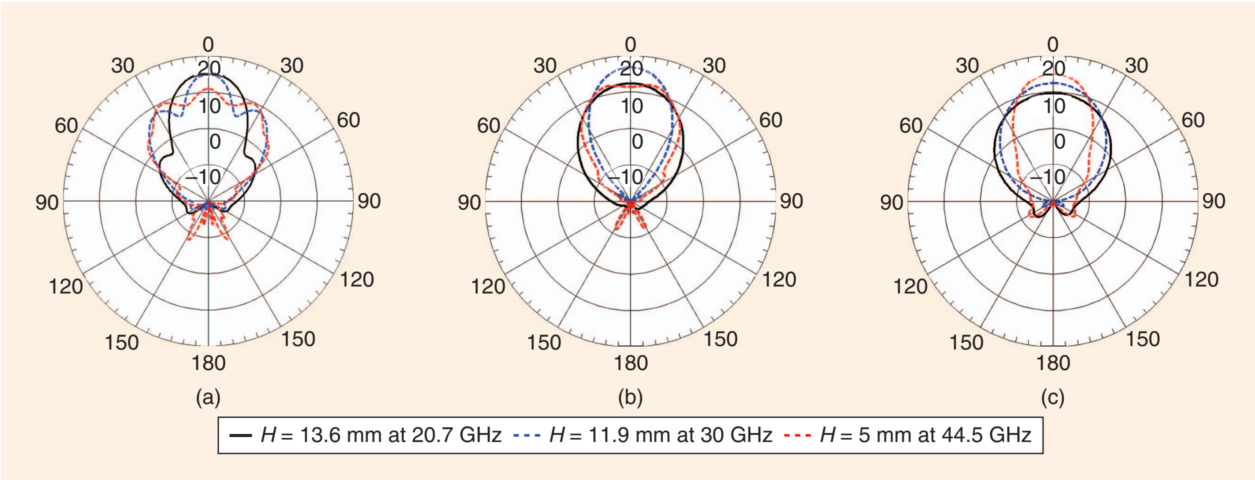

FIGURE 8. The RHCP patterns of reconfigurable QHA resonating at three designated operating frequencies with one common reflector state.

and its three states are shown in Figure 11. The 10:1 scale QHA was constructed by attaching copper tape (arms of the QHA) on sketching paper and folding the paper base into an origami cylinder, as shown in Figure 9(a). The 10:1 scale reflector was constructed by gluing copper foil on a single piece of sketching paper. This reflector can be reconfigured into three different states following the folding pattern shown in Figure 10. The QHA prototype can be reconfigured by applying a force at the top of the origami helix to adjust its height from state 1 to state 3. Also, the reflector prototype was reconfigured manually in measurements.

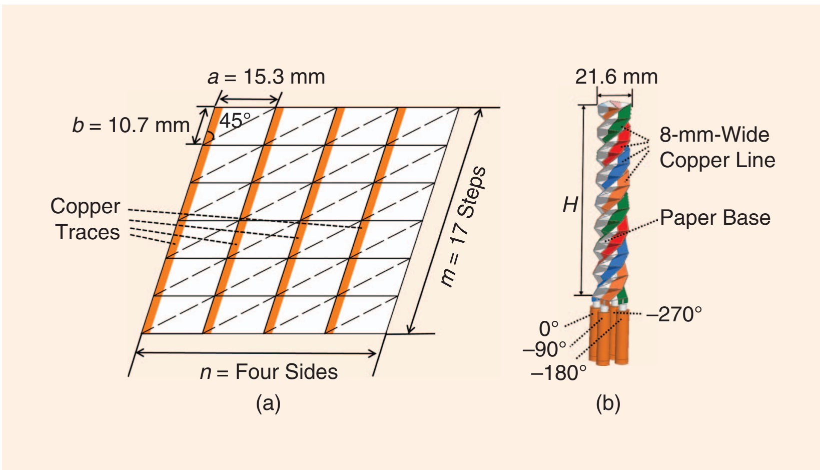

FIGURE 9. The geometry of the 10:1 scale model of the origami QHA. (a) The origami folding pattern and (b) the 3-D model.

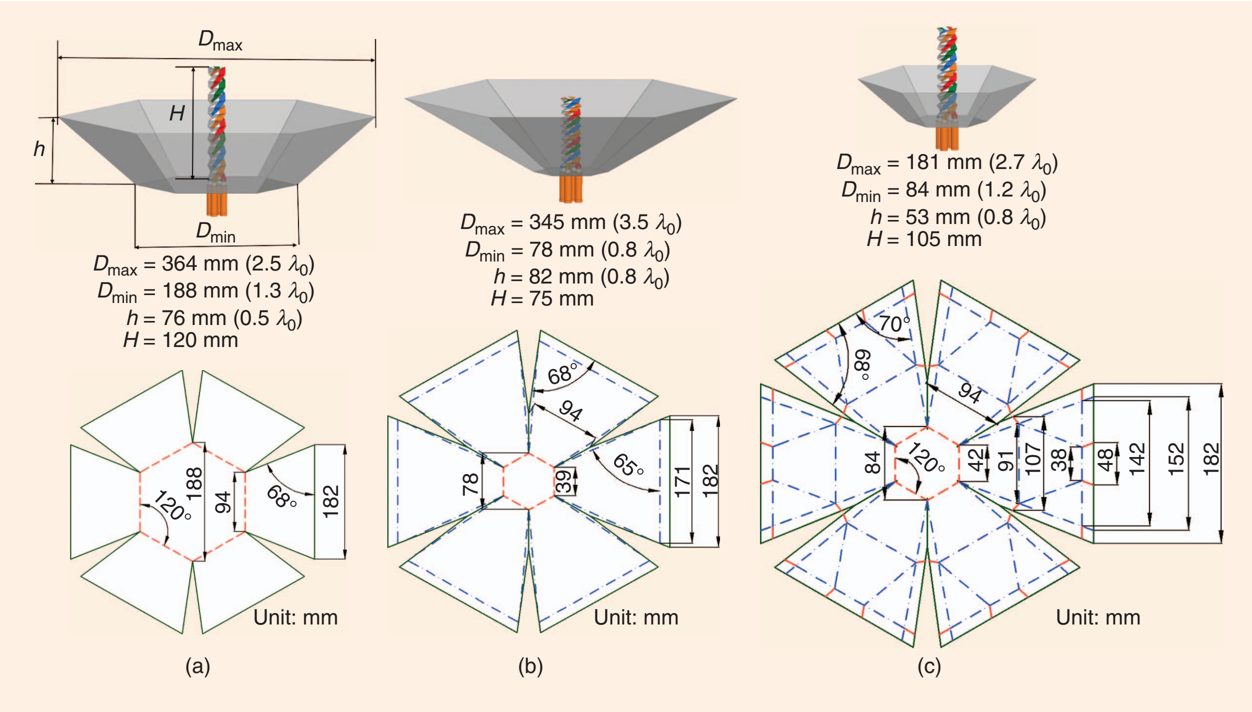

FIGURE 10. The geometry of the 10:1 scale model of the origami reflector QHA and the folding patterns of its reflector at three states: (a) state 1 (f_0 = 2.07 GHz), (b) state 2 (f_0 = 3 GHz), and (c) state 3 (f_0 = 4.45 GHz).

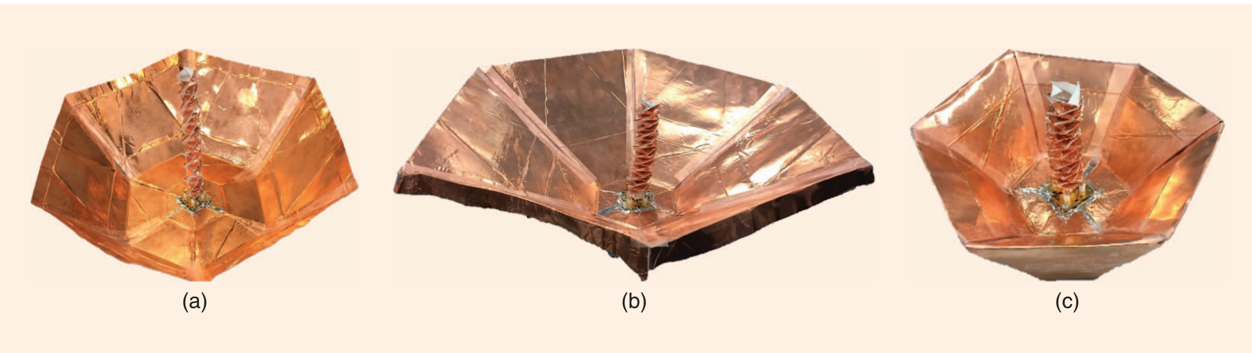

FIGURE 11. The geometry of the 10:1 scale model of the origami QHA with its reflector: (a) state 1 (operating frequency, f_0 = 2.07 GHz), (b) state 2 (operating frequency, f_0 = 3 GHz), and (c) state 3 (operating frequency, f_0 = 4.45 GHz).

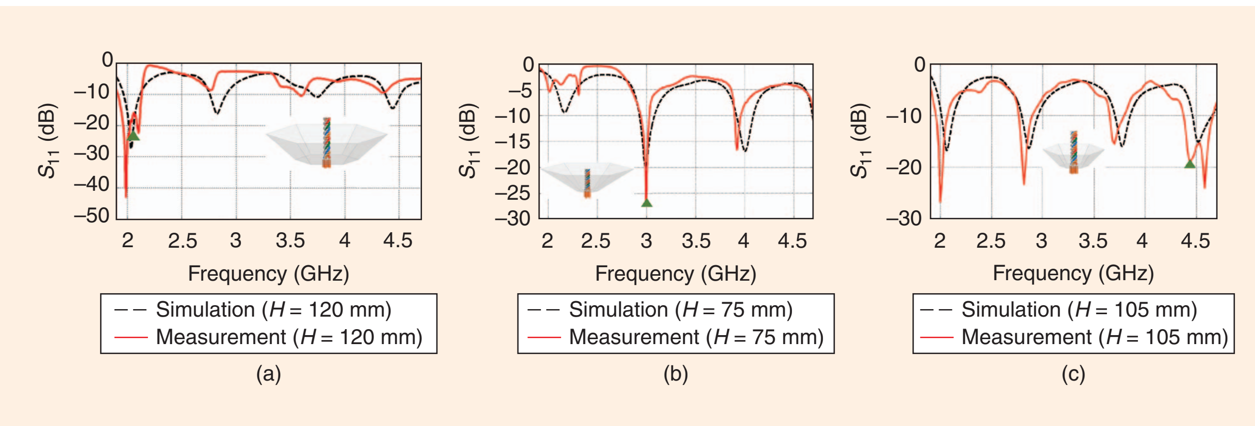

FIGURE 12. A comparison of simulated and measured S_{11} at the three states.

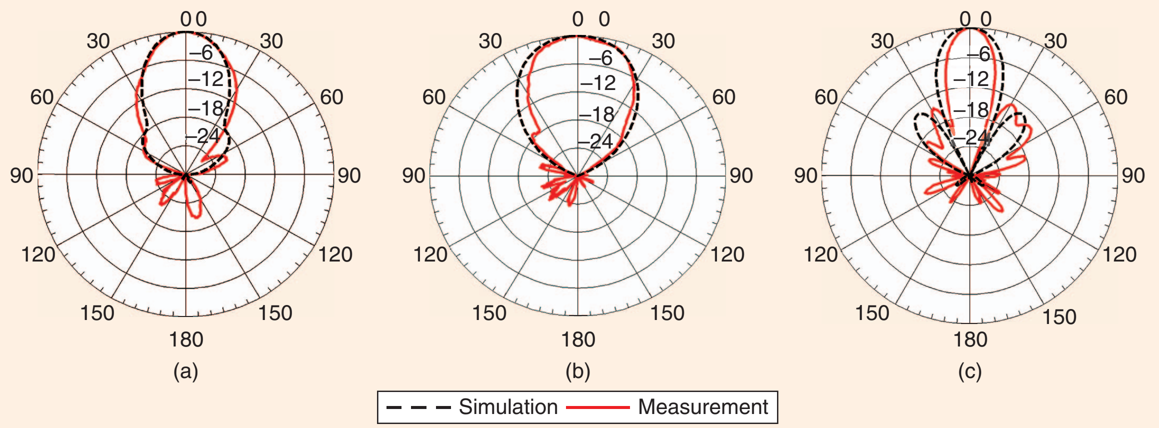

FIGURE 13. The simulated and measured normalized radiation patterns at the three states: (a) state 1 at 2.07 GHz, (b) state 2 at 3 GHz, and (c) state 3 at 4.45 GHz.

The S-parameters were measured using an E5071C Agilent network analyzer. Figure 12 compares the simulated and measured S_{11} for the three states. The feeding network is constructed using one 180° hybrid coupler and two 90° hybrid couplers. The radiation pattern and gain measurements were performed using a Diamond Engineering antenna measurement system.

The simulated and measured radiation patterns of the three states are compared in Figure 13. Also, the simulated and measured realized RHCP gains and axial ratios are listed in Table 1 at 2.07, 3, and 4.45 GHz. Figure 13 shows that the reflector origami QHA operates in axial mode at the three states, and Table 1 shows that this antenna is RHCP with measured gains over 12 dB. Compared to the proposed design in the "Origami QHA with Reflector" section, this 10:1 scale model has successfully enlarged its operating wavelength by ten times to operate at 2.07, 3, and 4.45 GHz, as shown in Table 1.

TABLE 1. SIMULATED AND MEASURED RESULTS AT DESIGNATED FREQUENCIES OF THE 10:1 SCALE ANTENNA.

State	State 1 ($H = 120$ mm)	State 2 ($H = 75$ mm)	State 3 ($H = 105$ mm)
Frequency (GHz)	2.07	3.00	4.45
Simulated realized RHCP gain (dB)	13.87	12.50	15.41
Measured realized RHCP gain (dB)	13.20	12.13	14.86
Simulated axial ratio (dB)	0.04	0.11	0.03
Measured axial ratio (dB)	0.66	0.09	0.55

CONCLUSIONS

This article presents a design of an origami RHCP QHA with a foldable reflector that can reconfigure itself to operate in three different bands: K, Ka, and EHF. Simulated and measured results of a 10:1 scale model of the QHA validated the reconfigurable performance of this antenna at the three bands. Our future work will focus on robust manufacturing of this reconfigurable origami QHA for the K, Ka, and EHF bands.

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