Design and Fabrication of an Origami Multimode Ring Antenna

Nicholas E. Russo, Constantinos L. Zekios, and Stavros V. Georgakopoulos
Department of Electrical Engineering
Florida International University
Miami, FL, US
nruss006@fiu.edu, kzekios@fiu.edu, georgako@fiu.edu

Hyeon Seok An, Anand Kumar Mishra, and Robert F. Shepherd
Department of Mechanical and Aerospace Engineering
Cornell University
Ithaca, NY, US
ha259@cornell.edu, am2877@cornell.edu, rfs247@cornell.edu

***Abstract*—In this work, a multimode multiple-input multiple-output (MIMO) ring antenna is proposed. Through characteristic mode analysis, two modes of the ring antenna are identified and excited. By mounting the antenna on an origami water-bomb pattern, the electromagnetic properties of both modes are simultaneously reconfigured through folding/unfolding. Notably, resonant frequencies at $1.91\ GHz$, $1.86\ GHz$, and $1.46\ GHz$ are attained with different radiation patterns. By exciting multiple orthogonal modes at various frequencies, MIMO operation is realized within a reduced volume as compared to designs that employ traditional spatial diversity techniques. This origami multimode antenna provides a compact and adaptive solution for next generation communication systems.**

***Index Terms*—Characteristic Modes Analysis, MIMO, Origami, Multimode, Reconfigurable**

I. Introduction

MIMO systems are critical to the success of next generation communication systems due to their ability to provide high channel capacity in a limited bandwidth. However, mutual coupling in MIMO systems, which operate in electrically small volumes, e.g. mobile terminals, deteriorates the channel capacity. Numerous designs and techniques have been proposed to overcome this problem. Notably, in [1], it has been demonstrated that an antenna utilizing higher-order modes for antenna diversity can achieve similar performance characteristics as traditional antennas which employ spatial diversity. By exciting multiple orthogonal modes on the same structure, improved capacity can be achieved in more compact terminals.

Furthermore, to meet next generation communication systems' requirements (e.g., enhanced quality of service, etc.), reconfigurable/adaptable MIMO systems have been introduced. Electromagnetic reconfiguration has been achieved by both electronic (e.g., using RF-MEMS, PIN diodes, or varactors), and mechanical (e.g., using micromotors, mechanical actuators, or origami) means. In this work, a multimode ring antenna is mounted on an origami waterbomb. Through characteristic mode analysis, [3], two radiating modes are identified and used thereby providing the desired MIMO characteristic of multi-band coverage. Also, by folding/unfolding the antenna, it is demonstrated that the resonant frequency and radiation pattern of both modes can be adjusted on demand. To fabricate a foldable antenna is extremely challenging, as both physical and electrical connectivity between the antenna pieces have to be maintained throughout hundreds of cycles of folding/unfolding, [2]. Herein, two novel fabrication techniques are proposed, and their performance will be presented at the conference.

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II. Antenna Design and Analysis

A square ring antenna with an outer edge length of 112.5 mm, and a width of 37.5 mm is placed on a 3 mm thick Rogers Duroid 5880 substrate with $\epsilon_r = 2.2$. Through characteristic mode analysis two radiating modes with complementary properties are identified. Herein, these modes are denoted as modes 1 and 2, and their current distributions are shown in Figs. 1(a) and 1(b), respectively.

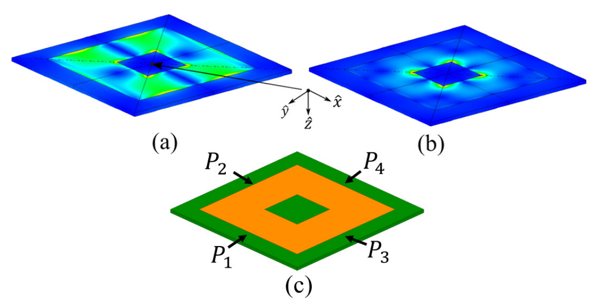

Fig. 1. Current distributions of: (a) mode 1, and (b) mode 2. Excitation locations are shown in (c).

Exploiting the current distributions of both modes, four symmetrically placed excitations, labeled as P_1 through P_4, are used to excite both modes as shown in Fig. 1(c). Mode 1 is excited using two 180^o out-of-phase excitations located on opposite sides of the antenna (P_1, and P_4), while the other two excitations (P_2, and P_3) are terminated in matched loads. Mode 2 is excited using four excitations with adjacent excitations being 180^o out-of-phase. These two excitation schemes have been implemented in microstrip lines and they have been shown in [4].

Adaptability is introduced by dividing the ring antenna into eight equal pieces to form an origami waterbomb. The

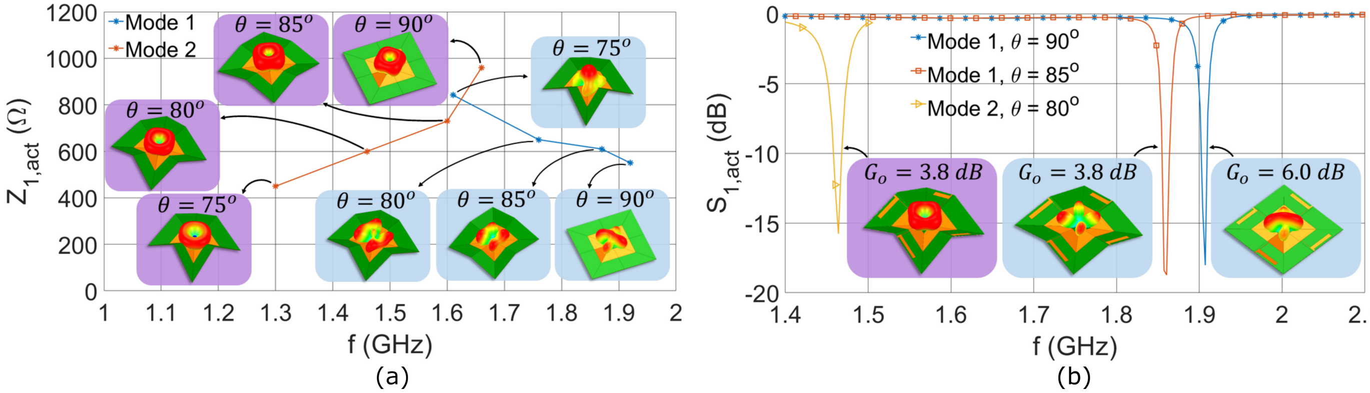

Fig. 2. (a) Simulated active input impedance, resonant frequency, and 3D radiation pattern of both modes as the antenna is folded/unfolded. (b) Simulated active scattering parameter of port 1 and 3D radiation pattern in three cases.

waterbomb's kinematics have been developed as a function of the independent fold angle θ. Variable θ represents the angle between any valley fold and the vertical axis that runs through the central vertex (refer to [5] for more details). The simulated effects of varying the fold angle, θ, on the: i) active input impedance of the first excitation, $Z_{1,act}$, ii) resonant frequency, and iii) 3D radiation pattern are presented in Fig. 2(a) for both modes of operation.

Fig. 2(a) indicates that reducing the fold angle from $\theta = 90^o$ to 75^o reduces the resonant frequency of both modes by approximately 0.3 GHz. This folding also increases the input impedance of mode 1 by nearly 300 Ω, while decreasing the one of mode 2 by nearly 500 Ω. Also, Fig. 2(a) shows that mode 1 has significant radiation along the z-axis when $\theta = 90^o$, and 75^o. Furthermore, mode 1 maintains strong radiation along the $\phi = 45^o$, and 135^o planes, scanning in elevation as the fold angle is increased. On the other hand, mode 2 radiates a conical beam which narrows as the antenna is folded.

A dual-band single stub impedance matching network, [6], is used to match the input impedance to a 50 Ω port. This network is designed to excite mode 1 when $\theta = 90^o$ and 85^o, and mode 2 when $\theta = 80^o$. Fig. 2(b) presents the: i) simulated active scattering parameters of port 1, ii) radiation patterns, and iii) peak realized gains, G_o, of these three cases. Fig. 2(b) demonstrates that by folding this antenna and operating in two modes, three complementary radiation patterns are achieved at three distinct frequencies of operation. Furthermore, there is a peak gain difference between all three cases of 2.2 dB. Also, it is seen that the bandwidth of each resonance is narrow, on the order of 10 MHz, typical of a ring antenna.

Here, two techniques are proposed to fabricate this design. In the first technique, a 3D printed flexible shell is used to hold the antenna pieces, while copper tape is used to connect the pieces, as shown in Fig. 3(a). In the second technique, liquid metal hinges encapsulated in silicon are used to maintain both physical and electrical connectivity across the folds, as shown in Fig. 3(b). Mechanical and electrical testing on this hinge is ongoing and detailed results will be presented at the conference.

(a) (b)

Fig. 3. Waterbomb antenna fabricated using: (a) copper tape and a flexible shell and (b) silicon encapsulated liquid metal hinges.

III. Conclusion

In this work, a compact dual-mode origami waterbomb ring antenna was presented. By folding/unfolding this antenna a number of operating frequencies and radiation patterns were achieved. This antenna's adaptable, compact, multimode design makes it well suited for next generation communication systems.

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