A Miniature Reconfigurable Circularly Polarized Antenna Using Liquid Microswitches

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***Abstract*— A frequency and polarization reconfigurable antenna based on electrowetting liquid metal microswitches is presented. The microswitches consist of electrostatically actuated mercury droplets that selectively connect solid metal traces. This mechanism is designed into a single-feed patch antenna configurable between two communication bands and the GPS band with different circular polarizations. The antenna topology is based on a corner truncated square patch with switched sets of extensions to achieve resonant frequency and axial ratio control. Measurements of manually reconfigured prototypes demonstrate frequency and polarization configurability.**

Keywords*— *Patch antennas, reconfigurable antenna, microswitches, electrowetting-on-dielectric.

I. Introduction

RECONFIGURABLE antennas with adaptable frequency, pattern, and polarization offer flexibility and size reduction for wireless systems that must increasingly execute multiple missions. Antennas are often reconfigured using RF MEMS switches or PIN diodes [1,2]. Disadvantages of these methods include relatively high series resistance, the constant bias required to maintain a configuration, and in the case of traditional RF MEMS, limited power handling reliability and mechanical wear [3].

The primary motive for producing a miniature reconfigurable antenna is to address the need for high performance antennas in miniature (such as portable electronic) systems. To this end, our work attempts a sophisticated antenna design that satisfies the miniaturization goals as well as the real-world performance requirements associated with high gain in three switchable bands, circular polarization appropriate to the band of interest, and implementation in an ultra-thin, single feed structure.

In this work (Fig. 1), we use liquid metal droplet based microswitches, due to their low loss and potential for integration into very thin antennas. The droplets are held in position by surface roughness and actuated electrostatically. Mechanical wear is avoided due to the fluidic nature of the moving parts, and the switch maintains its position without any bias. The prototypes discussed in this paper are manually reconfigured by applying voltages to mobile temporary electrodes composed of electrolyte solution, but simulations show that solid, permanent control electrodes can be implemented with minimal impact on antenna performance. Switching speeds have not been measured as the switches are currently manually reconfigured. Since the target application is a band-switching antenna, switching speeds on the order of tens or hundreds of milliseconds such as those achieved by other liquid metal switches [4,5] are appropriate.

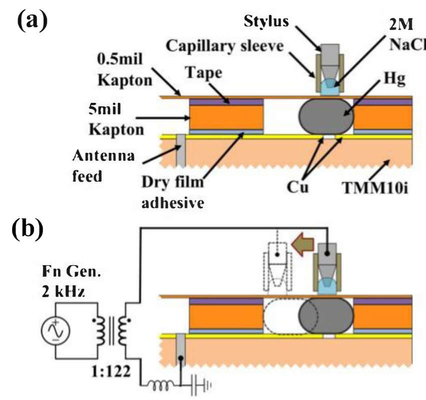

Fig. 1: (a) Illustration of Hg microswitch cross section. (b) Illustration of actuation setup. The Hg droplet is grounded relative to the actuation voltage through a bias tee on the antenna feed.

Microscale liquid metal switches with low contact resistance on the order of tens of mΩ have been examined previously [5]. Although the use of Hg is undesirable due to its toxicity, the amounts used in the proposed antenna total less than 9mg, about the same quantity of Hg present in two compact fluorescent light bulbs [7]. Antennas featuring a pressure-driven plated solid have been proposed but require tight manufacturing tolerances to enable actuation and desired antenna performance [6].

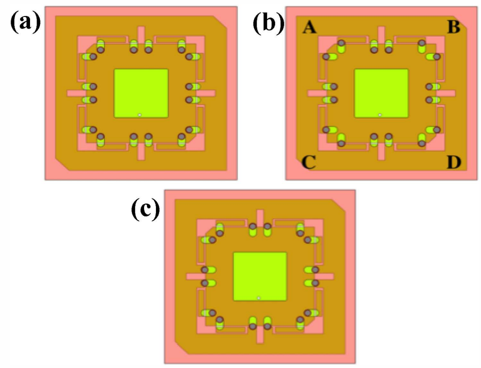

Fig. 2: Illustration of (a) ISM (b) AWS and (c) GPS antenna configurations. Grey dots represent Hg positions.

A variety of liquid-metal based antenna topologies have been demonstrated, ranging from the earliest simple patch [8] and the stunning flexible dipoles [9], to recent work using slot based designs [10-12] and more complex patches [13,14]. A key issue is the co-design of fluidic actuation for tuning with a candidate tunable antenna topology. This co-design challenge makes it particularly hard to address band-switching in circularly polarized antennas since the geometry is more complicated than monopoles and dipoles. Another key issue is the method for actuating the fluidics. Pressure [15], pneumatic [10,13,16], and more recently electrowetting [11-12] antenna tuning methods have been demonstrated with wide tuning ranges.

Our work adds to the state-of-art by contributing a switchable tri-band design with circular polarization in a thin form factor. An electrowetting actuation compatible with full integration is developed and validated.

II. Microswitch Operation

Fig. 1 shows an illustration of the proposed microswitch. A ~0.1mm^3 Hg droplet is confined within a 1.15mm wide, 2.25mm long slot defined in 5mil Kapton on top of printed metal antenna structures separated by a 250µm gap. The structure is enclosed by a 0.5mil Kapton cover and lubricated with low viscosity silicone oil. The slot is oriented such that the droplet is always electrically grounded with respect to the actuation voltage through a bias tee on the antenna feed.

During reconfiguration, a 2 kHz, 700 Vrms actuation voltage is applied between the Hg droplet and an electrode on the topside of the Kapton cover. In the fabricated prototypes, the electrode is a movable 2M NaCl electrolyte solution droplet. The electrolyte droplet is manipulated manually using a stylus, and the Hg droplet follows the electrolyte droplet when the actuation voltage is applied. By manipulating the energized electrolyte droplet along the length of the slot, the Hg droplet can be moved between two positions and selectively connect the underlying solid metal antenna structures. The stylus uses a capillary tip to ensure control

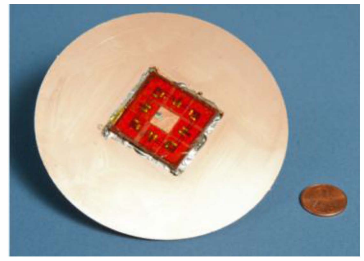

Fig. 3: Photograph of prototype antenna.

of the electrolyte droplet. The switch could also be actuated using printed electrodes on the topside of the Kapton cover for programmable control. This was demonstrated on test structures but has not yet been integrated with the antenna.

III. Reconfigurable Single-Feed CP Patch Antenna Design

A compact frequency and polarization reconfigurable single-feed circularly polarized (CP) patch antenna is presented as an application of the described microswitch. The antenna is designed to switch between three modes: right-hand circularly polarized (RHCP) operation at the GPS frequency of 1575 MHz and left-hand circularly polarized (LHCP) operation at both the Advanced Wireless Services (AWS) downlink band centered on 2132.5 MHz and the industrial, scientific, and medical (ISM) band at 2450 MHz. The antenna mode is set by 16 microswitches that selectively connect extensions to a square patch antenna.

The antenna structures are patterned in Cu on a 75 mil Rogers TMM10i substrate (ε_r = 9.8). A high permittivity substrate was selected to reduce the antenna area to within a 10.24 cm^2 area. The antenna is directly fed by a coaxial probe. The antenna's ISM mode is comprised of a square patch antenna with truncated corners as illustrated in Fig. 2(a). The AWS mode is achieved by electrically connecting the patch to the small traces positioned near its corners by means of the described Hg switches as shown in Fig. 2(b). The traces extend the resonant current path length on the antenna, thereby lowering its resonant frequency. Axial ratio control is achieved by sizing the trace lengths such that the four traces extending from corners A and D are all 4.825 mm in length and the four traces extending from corners B and C are all 4.875 mm in length. The GPS mode is achieved by opening the switches to the small traces at the corners of the square patch and closing the switches connecting the patch to the outer ring as illustrated in Fig. 2(c). The outer ring approximates a truncated corner patch antenna with the orientation of the corners chosen such that the antenna operates with RHCP.

The feed location is chosen near the antenna centerline and oriented with respect to the truncated corners such that the desired polarizations are achieved.

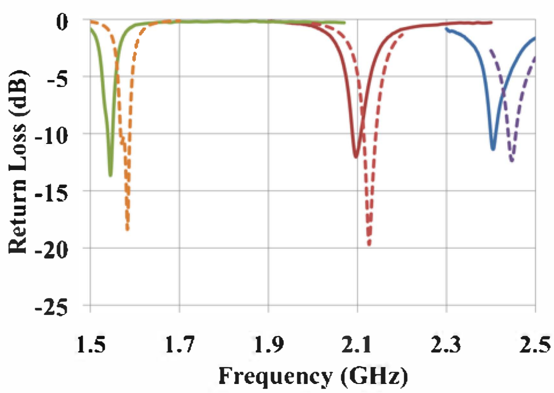

Fig. 4 Measured (solid line) and simulated (dashed line) return loss.

The chosen feed location is a compromise between the 50Ω feed points for each of the configurations.

IV. FABRICATION

The described antenna is fabricated using circuit board techniques. The Cu antenna structures are milled in 75mil TMM10i using a PCB milling machine. The 5mil Kapton fluidic layer material is backed by a 1mil dry film adhesive on one side and an adhesive transfer tape on the opposite side. The Kapton is milled with the adhesives attached on a PCB milling machine. The Kapton layer is laminated to the TMM10i substrate under vacuum at 150°C for 1 hour with the dry film adhesive. During lamination, the tape remains covered with its paper backing. After lamination, the fluidic slots must be cleaned of excess tape adhesive that flows into the slots during lamination. The antenna feed is then soldered to the central patch. For the constructed prototypes, a 4 inch diameter standard test ground plane was also soldered to the bottom of the antenna.

After soldering, the switches are filled manually with drops of Hg metered by a controlled growth mercury electrode dispenser. A small amount of 5cSt silicone oil is added to the switches to lubricate the Hg droplets. Finally, the cover is attached by removing the paper backing from the adhesive transfer tape and attaching a 0.5 mil Kapton cover to the tape. For manual switch actuation, the cover can be applied in multiple pieces, and the stylus is made from a multimeter probe tip with a cut-off plastic pipette tip attached at the end. Prototypes of the switch alone were also fabricated with the above process. A photograph of a completed antenna prototype is shown in Fig. 3.

V. MEASURED RESULTS

The measured and simulated return loss of a prototype antenna in each of its three configurations is plotted in Fig. 4. The measured resonant frequencies are at 2397 MHz, 2091 MHz, and 1535 MHz for the ISM, AWS, and GPS switch configurations, respectively. These measured

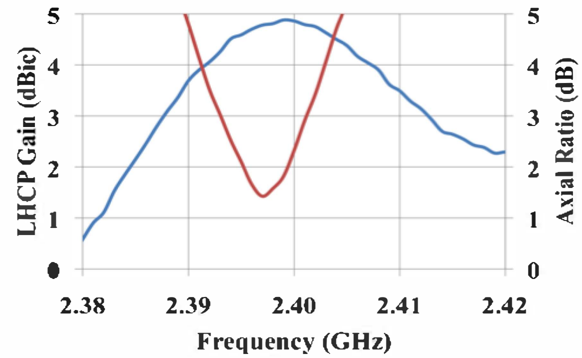

Fig. 5: Measured peak LHCP gain (blue) and boresight axial ratio (red) for ISM configuration.

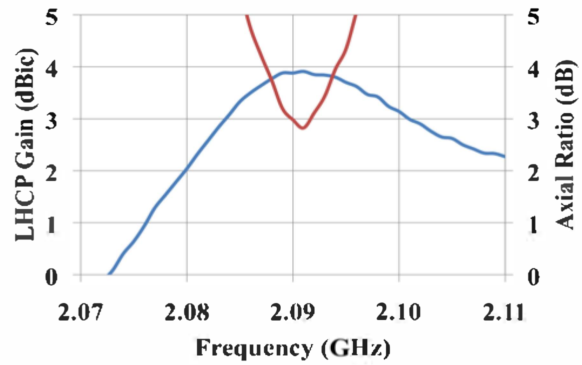

Fig. 6: Measured peak LCHP gain (blue) and boresight axial ratio (red) for AWS configuration.

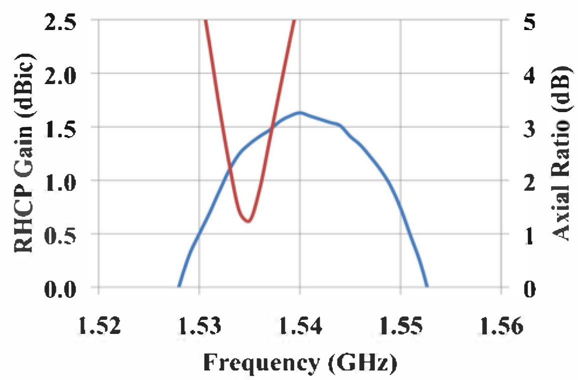

Fig. 7: Measured peak RHCP gain (blue) and boresight axial ratio (red) for GPS configuration.

resonant frequencies are lower than those predicted.. This discrepancy is likely a result of the un-modeled electrical characteristics of the adhesives. However, the reconfigurable frequency of the design is still validated by the measurements. The -10dB impedance bandwidths are 10MHz, 26MHz, and 12.5MHz for the ISM, AWS, and GPS configurations, respectively.

For the prototype antenna in the ISM mode, a peak gain of 4.9dBic was measured. In the AWS mode, a peak gain of 3.91dBic was measured. In the GPS mode, the peak measured gain is 1.63dBic. The minimum boresight axial ratios of the antenna in its ISM, AWS, and GPS modes are 1.43dB, 2.82dB, and 1.24dB, respectively, and the

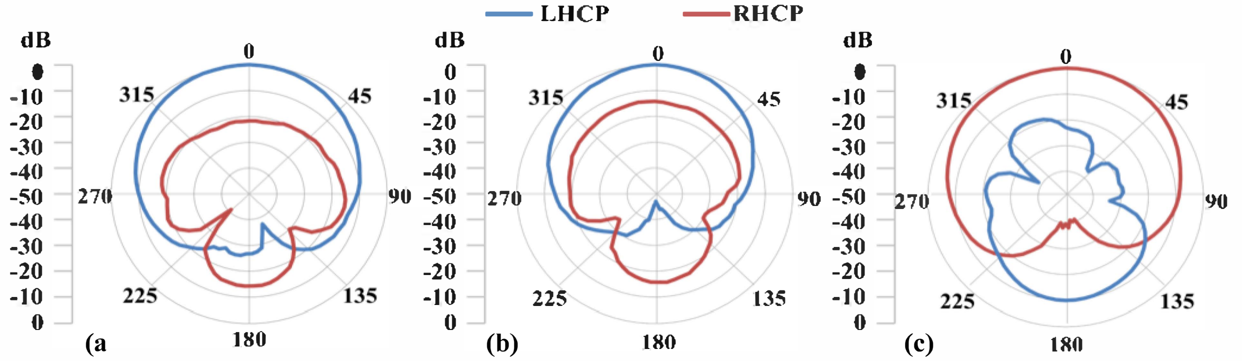

Fig. 8: Measured normalized CP radiation patterns for (a) ISM configuration at 2397MHz, (b) AWS configuration at 2091MHs, and (c) GPS configuration at 1535MHz.

axial ratio 3dB bandwidths are 0.33%, 0.08%, and 0.26%, respectively. The AWS band axial ratio can be improved by adjusting the relative dimensions of the AWS extensions. The antenna radiates with the desired polarizations in each configuration. Measured gain and axial ratio for each configuration are shown in Fig. 5–7. Radiation patterns of the antenna at resonance are shown in Fig. 8.

From four-point measurements of switch-only prototypes, the total switch series resistance was found to be 15 mΩ. Long term switching reliability has not been tested, but the amalgamation of Hg and Cu may adversely affect long-term switch behavior. This issue can be addressed by using Pt as a contact metal with the Hg instead of Cu.

VI. CONCLUSION

An electrowetting liquid metal microswitch for reconfigurable antenna applications is presented. The switch requires no bias to maintain its configuration, avoids mechanical wear due to its fluidic nature, and demonstrates a low series resistance of 15 mΩ. The described Hg microswitches are integrated with a corner truncated square patch flanked by sets of extensions to which the patch is selectively switched. The antenna achieves three narrowband operating modes between 1535 MHz and 2397 MHz with differing polarizations. The compact antenna occupies a footprint of $10.24 cm^2$ and is less than 2.1 mm thick. The low series loss of the microswitches not only maintains antenna efficiency, but also is promising with respect to power handling. Future work will explore the use of these microswitches in high power applications. Future work will also include integration of solid actuation electrodes for programmable control, alternative contact metals for long-term stability, and thinner dielectrics for lower actuation voltages. Alternative liquid metals may also lower actuation voltages and toxicity concerns.

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