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A Reconfigurable Spiral Antenna for Adaptive MIMO Systems

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We present a reconfigurable spiral antenna for use in adaptive MIMO systems. The antenna is capable of changing the sense of polarization of the radiated field. It is fabricated by using an RF-MEMS technology compatible with microwave laminate substrates developed within the author's group. The proposed antenna structure is built on a number of rectangular-shaped bent metallic strips interconnected to each other with RF-MEMS actuators. Two senses of polarization, RHCP and LHCP, are achieved by configuring the physical structure of the antenna, *that is*, by changing the winding sense of the spiral, through judicious activation of MEM actuators. The fabrication process for the monolithic integration of MEM actuators with bent microstrip pixels on RO4003-FR4 microwave laminate substrate is described. The measured and calculated radiation and impedance characteristics of the antenna are given. The operating frequency of the presented antenna design can easily be adjusted to be compatible with popular IEEE networking standards such as 802.11a.

Keywords and phrases: adaptive MIMO systems, reconfigurable spiral antenna, radio-frequency microelectromechanical systems.

1. INTRODUCTION

Reconfigurable wireless communication systems, which can dynamically adapt themselves to constantly changing environmental propagation characteristics, will be the key for the next-generation communication scenarios. A communication system, capable of changing its output dynamically through reconfigurability features, allows optimal system-level performance at all times, regardless of changing characteristics of the communication environment.

There has recently been enormous research performed on MIMO systems [1] with associated technologies such as smart antennas and adaptive coding and modulation techniques, which have been proven to dramatically increase the wireless channel capacity and improve the diversity. Although in these studies considerable attention has been given to the performance analysis of these systems in the context of coding and signal processing architectures, the investigation of the antenna aspect is mainly limited to the impact of the number of antenna elements with little consideration on their radiation and polarization characteristics as well as array geometry. Multiple antenna elements of these systems are fixed by the initial design and cannot change their properties, that is, radiation pattern, polarization, and operating frequency.

We have recently developed a microwave-laminate-compatible RF-MEMS technology [2, 3, 4] that allows fabricating multifunction reconfigurable antennas (MRAs)

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on microwave laminate substrates that best meet the antenna performance characteristics. An MRA can dynamically configure its structural architecture and thus alter its performance properties, that is, polarization, radiation pattern, and operating frequency. Therefore, an adaptive MIMO system equipped with MRAs will not be constrained to employ a fixed antenna design over varying channel conditions. This is an additional degree of freedom in adaptable parameters of an adaptive MIMO system and permits the selection of the best antenna properties and configuration in conjunction with the adapted transmission scheme with respect to the channel condition [5]. Thus the gap between theoretical MIMO performance and practice is minimized.

Motivated by the features of next-generation wireless MIMO communication systems, as stated above, we have aimed at developing innovative antenna architectures, which combine multiple functions in one single antenna. One such application example, a spiral antenna capable of changing its polarization state through microwave-laminate-compatible RF-MEMS technology, is presented in this paper. In this application example, we only reconfigure the polarization property, but there would be no process limitation to accommodate reconfigurability features in operation frequency and radiation characteristics of a more complex reconfigurable antenna design.

2. ANTENNA STRUCTURE, OPERATIONAL MECHANISM FABRICATION, AND RESULTS

Spiral antennas are attractive for communication applications where broadband characteristics with respect to both input impedance and radiation pattern are required. There have been extensive investigations regarding radiation characteristics of spiral antennas with different geometrical shapes such as circular, rectangular, and eccentric [6, 7]. These antennas are mainly used to radiate circularly polarized wave forming either an axial beam—normal to the plane of the spiral—or tilted beam pattern—off-normal to the plane of the spiral [8]. The single-arm spiral, which is used in this work, has the advantage of not requiring a balun circuit between the spiral and the feed line, which is needed for multiarm spiral antennas.

2.1. Antenna structure and operational mechanism

While the microwave-laminate-substrate-compatible RF-MEMS technology has been used in [2, 4] for monolithic integration of antenna elements with RF-MEMS switches, the role of RF-MEMS switches, which are located on antenna feed lines, has been limited to routing the RF signal feeding the antennas. In this work, we integrate a number of RF-MEMS actuators within the geometrical structure of the antenna to construct a reconfigurable spiral antenna. In other words, RF-MEMS actuators are used as part of the physical structure of the antenna, owing to the monolithic integration capability of the processing technique, providing a large degree of structural reconfigurability.

The proposed reconfigurable spiral antenna architecture is built on a number of printed rectangular-shaped metal strips interconnected by RF-MEMS actuators on a microwave-laminate printed circuit board (PCB) substrate, RO4003-FR4 ($\varepsilon_r = 3.38$, $\tan\delta = 0.002$). Shown in Figure 1 are two adjacent strips interconnected by an RF-MEMS actuator, which is made of a metallic movable membrane, suspended over a metal stub protruding from an adjacent strip, fixed to both ends of the strip through metallic posts. The optimized height of these posts was found to be 8 μm for a good tradeoff between up-position switch coupling and actuation voltage. Metal stubs are covered by silicon-nitride (SiN_x) film to prevent metallic membrane from sticking onto the stub upon contact. This film also provides a capacitive contact for actuator down state isolating RF signal from DC. A DC bias voltage of approximately 50 V applied between the membrane and the stub causes an electrostatic force that pulls the suspended membrane on top of the stub (actuator down state or actuator on) and the actuator connects the strips (see Figure 1c); otherwise strips are disconnected (actuator up state or actuator off) (see Figure 1b). Judicious activation of interconnecting actuators, that is, by keeping some of the actuators in the up position (zero bias) while activating the rest of them by applying DC bias voltages, allows the reconfigurable spiral to configure its architecture into single-arm rectangular spirals with opposite winding sense of the spiral, left or right senses (see Figure 2). Accordingly, right- and left-hand circularly polarized (RHCP and LHCP) radiation is achieved. In Figure 2, for the clarity of illustration, each configured geometry is depicted separately and actuators in the up state are shown without metallic membrane. The antenna is fed by a single coaxial probe as shown in Figure 2c. The supply voltage is connected to the proper locations on the antenna segments through resistive bias lines so as to prevent RF signal from being shorted by the DC power supply.

The proposed prototype antenna is aimed to radiate an axial beam of RHCP and LHCP fields. It is known that a single-arm rectangular spiral antenna with outermost arm peripheral length (circumference) of C,

$$1\lambda_{\text{eff}} < C < 2\lambda_{\text{eff}}, \tag{1}$$

excites only the first radiation mode giving rise to an axial beam of circular polarization [8], where $\lambda_{\text{eff}} = \lambda_0/[(\varepsilon_r + 1)/2]^{1/2}$ is the effective wavelength of the current traveling on the spiral. The strip number and size are optimized so that circumference of the antenna, $C = 42\,\text{mm} = 1.04\lambda_{\text{eff}}$, satisfies (1), and minimum number of actuators with associated bias circuitries are needed.

2.2. Fabrication and results

For reference, as a first step, conventional single-arm rectangular spiral antennas radiating circularly polarized field along their axes have been designed, fabricated, and characterized. We chose to use RO4003-FR4 ($\varepsilon_r = 3.38$, $\tan\delta = 0.002$) microwave laminated substrate [9] to realize the antennas due to its low cost and widespread use in wireless systems. The substrate is conductor-backed to ensure that the

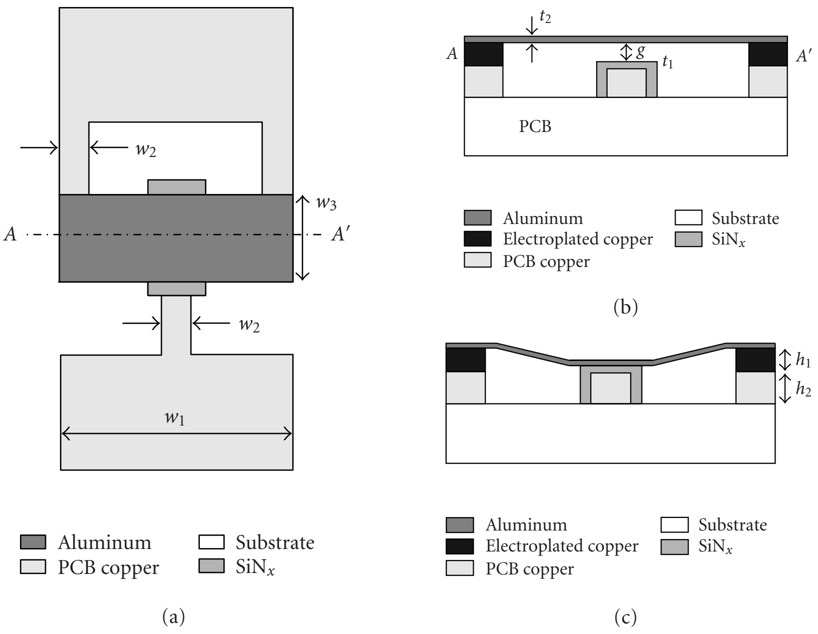


FIGURE 1: RF-MEMS actuator interconnecting two adjacent metallic strips. (a) Top view; width of metal strip $w_1 = 800\,\mu$m; width of stub $w_2 = 100\,\mu$m; width of membrane $w_3 = 150\,\mu$m. (b) Side view (up position); thickness of nitride $t_1 = 0.2\,\mu$m; thickness of membrane $t_2 = 0.5\,\mu$m; air gap $g = 7.8\,\mu$m. (c) Side view (down position); thickness of electroplated copper $h_1 = 8\,\mu$m; thickness of PCB copper $h_2 = 16\,\mu$m.

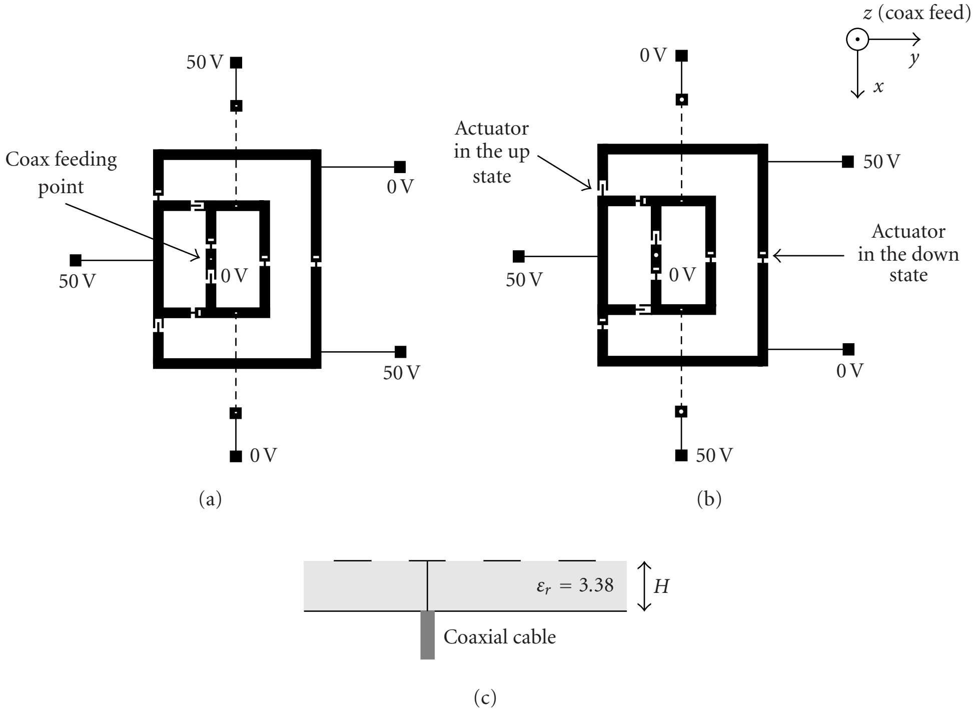


FIGURE 2: Schematics of the single-arm rectangular spiral antennas, which are reconfigured from the proposed reconfigurable spiral architecture by judicious activation of the interconnecting RF-MEMS actuators for (a) left-hand circular polarization, (b) right-hand circular polarization, and (c) side view of the antenna. The outermost dimensions of the antenna are 9 × 12 (mm), the spiral line width is 0.8 mm.

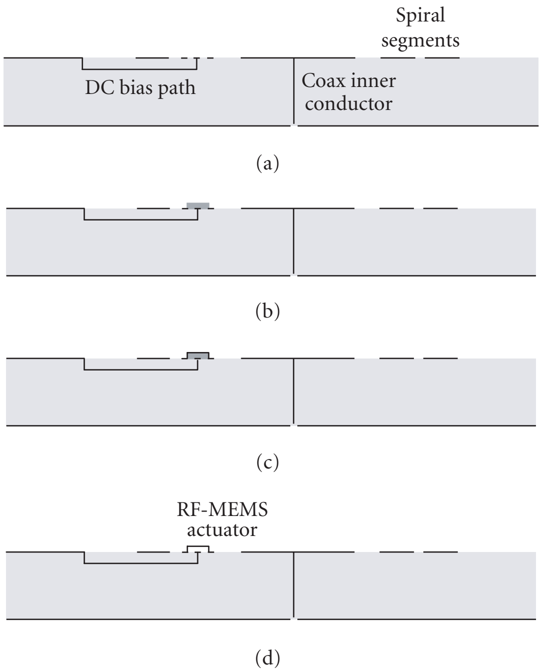


Figure 3: Fabrication sequence for monolithic integration of RF-MEMS actuators with rectangular-shaped strip segments in constructing reconfigurable spiral antenna. (a) Antenna pattern, DC bias path, and via formation. (b) Dielectric layer deposition and sacrificial layer planarization. (c) Aluminum (Al) membrane deposition. (d) Final release.

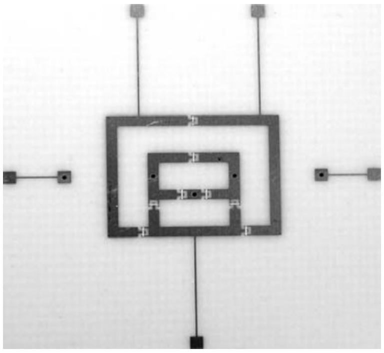


Figure 4: Photograph of the microfabricated reconfigurable spiral antenna.

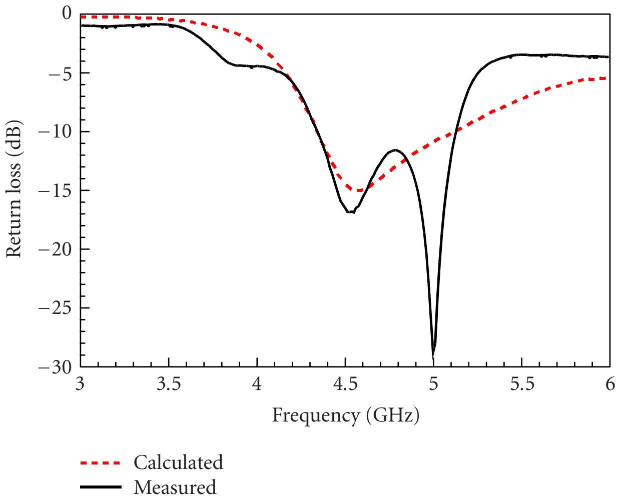
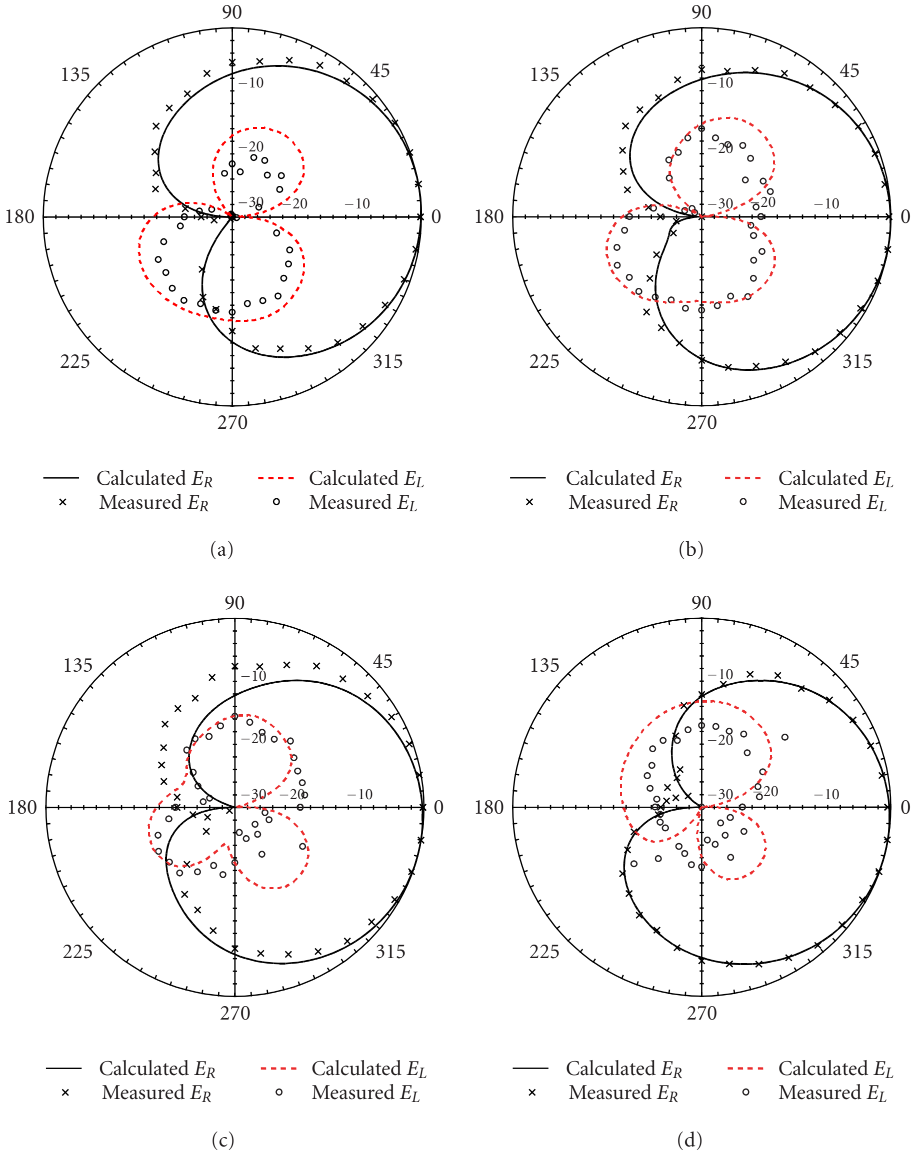


Figure 5: Return loss of the antenna for RHCP radiation.

antenna radiates broadside to the printed spiral surface. Substrate thickness is chosen to be 7.6 mm, which is one of the standard thicknesses for PCB family substrates, the closest one to the quarter wavelength at a center design frequency of 5 GHz. Theoretical characterization of the antenna structure is conducted by using Ansoft HFSS 8.5 full-wave analysis tool [10] based on finite element method which takes into account the edge effects due to finite-size dielectric and conducting plane of the antenna.

A brief fabrication sequence for monolithic integration of RF-MEMS actuators with rectangular-shaped strip segments of the spiral antenna is given in Figure 3. Details of the fabrication process can be found in [2, 3, 4], so here we only briefly explain the process. The fabrication begins with RO4003 laminate with copper layers of 16 micron on both sides. We first form the segments of the antenna and the planar part of the bias circuitry by wet-etching the copper layer. Vertical vias for bias circuitry and coax feed are created by standard PCB processes. After this step, a thin layer of HDICP CVD SiN_x is deposited and etched by reactive ion etching such that the SiN_x covers only the tips of the metal stubs protruding from the antenna segments (see Figure 1a). We continue fabricating RF-MEMS actuators following the process flow shown in Figures 3b and 3d without affecting the antenna structure. A photograph of the microfabricated antenna is shown in Figure 4, and Figure 5 shows



(a) (b) (c) (d)

Figure 6: Radiation patterns for the RHCP spiral antenna at 5 GHz in (a) $\phi = 0$ plane, (b) $\phi = 45$ plane, (c) $\phi = 90$ plane, and (d) $\phi = 135$ plane.

the return loss of the spiral antenna with counterclockwise sense of winding corresponding to the RHCP radiation. The simulated result is also validated by comparison with experimental data in this figure. Due to the symmetry between two antenna configurations, the RHCP and LHCP spirals exhibited almost identical return loss with a VSWR of less than two covering the frequency band of 4.3–5.4 GHz. The size of the antenna geometry can be scaled to change the operational bandwidth to make it compatible with popular IEEE networking standards such as IEEE 802.11a.

Measured and calculated radiation patterns at 5 GHz in four different planes of $\phi = 0°, 45°, 90°, 135°$ are shown in Figures 6 and 7 for RHCP and LHCP spirals, respectively. As seen from these figures, the antennas radiate circularly polarized wave slightly off-broadside to the plane of spiral, forming an almost axial beam pattern. This slight tilt from the z-axis is due to the asymmetry of the antenna structure with respect to the z-axis. The measured average half-power beamwidth (HPBW) is approximately 105°. The antenna radiates almost entirely circularly polarized wave in the z-direction with axial ratio value of 0.9 dB. The gain at this direction is 5.3 dB. Variations of axial ratio and gain in the z-direction with respect to frequency are shown in Figure 8. The circular polarization bandwidth over which the axial ratio is less than 3 dB is approximately 11%. Gain of the antenna with average value of 4.9 dB shows small variation over this bandwidth. The difference in performance characteristics between the RF-MEMS integrated spiral antenna and conventional single-arm rectangular spiral antenna was observed to be negligible.

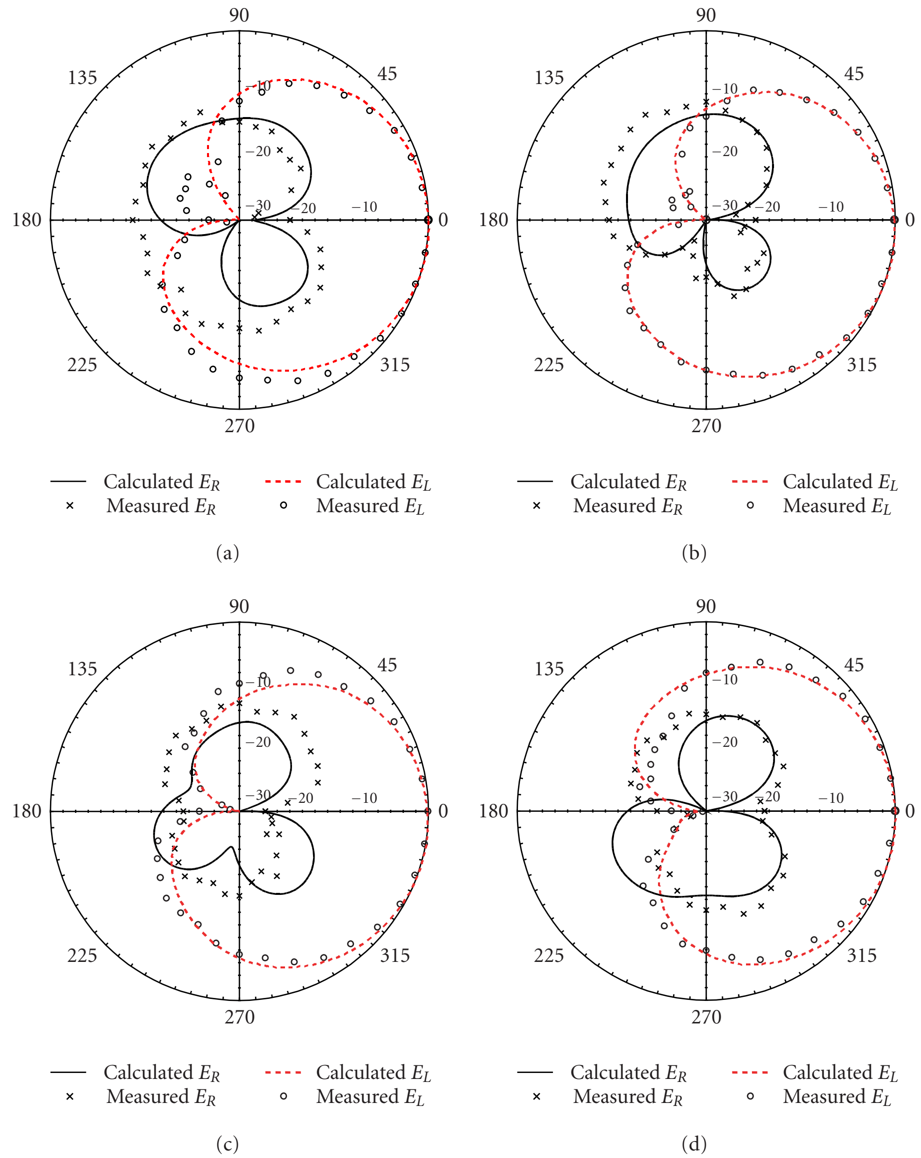


Figure 7: Radiation patterns for the LHCP spiral antenna at 5 GHz in (a) $\phi = 0$ plane, (b) $\phi = 45$ plane, (c) $\phi = 90$ plane, and (d) $\phi = 135$ plane.

3. CONCLUSION

Motivated by the fact that the antenna properties (polarization, operating frequency, and radiation behavior) can be used as additional degrees of freedom in adaptive MIMO system parameters, we presented a reconfigurable antenna architecture employing RF-MEMS as a vehicle to achieve polarization reconfigurability. The antenna builds on a number of rectangular-shaped metallic strips monolithically interconnected with RF-MEMS actuators. Its architecture is dynamically reconfigured into RHCP and LHCP single-arm rectangular spirals with opposite sense of windings by activating some of the actuators while keeping the rest in the off-state. RF-MEMS technology compatible with microwave laminate substrates is the key enabling multifunctional reconfigurable antenna systems with MEMS integration at low cost with high system-level performances. The defining feature of this technology is its capability of allowing monolithic integration of RF-MEMS, with antenna structures on any microwave laminate substrate that best meets the antenna performance characteristics. Experimental impedance and radiation characteristics of the proposed architecture are in excellent agreement with theoretical results. The results showed that the antennas radiate right-hand and left-hand circularly polarized axial beam waves with good axial ratio and gain values covering the design frequency bandwidth of 4.3–5.4 GHz. If desired, this bandwidth can be changed by scaling the size of the antenna to make it compatible with IEEE networking standards such as 802.11a. The presented application example has been intended to demonstrate an

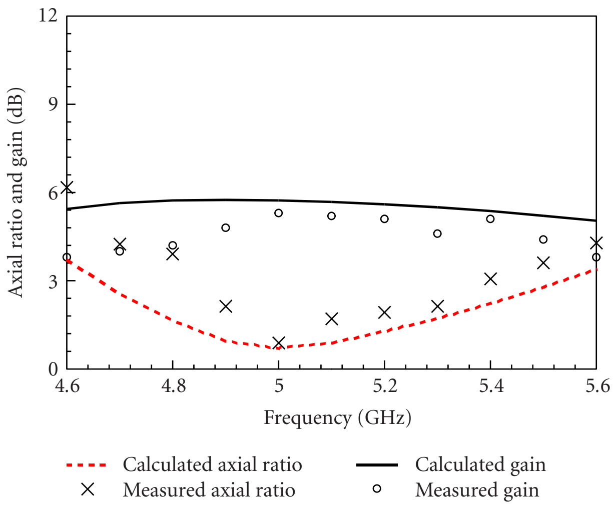


Figure 8: Frequency responses of axial ratio and gain in the z-direction for RHCP spiral antenna.

initial design and fabrication that will pave the way for novel antennas into which multifunctional features are dynamically combined by making use of large number of actuators. Multifunction reconfigurable antenna is very promising in the establishment of the next-generation multifunction highly integrated reconfigurable communication architectures.

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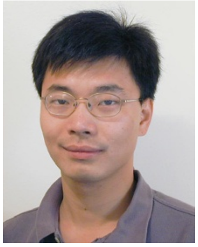
Bedri A. Cetiner was born in Gazi Magosa, Cyprus, in 1969. He received the Ph.D. degree in electronics and communications engineering from the Yildiz Technical University, Istanbul, in 1999. From November 1999 to June 2000 he was with the University of California, Los Angeles, as a Northern Atlantic Treaty Organization (NATO) Science Fellow. He then joined the Department of Electrical Engineering and Computer Science, the University of California (UCI), Irvine, where he worked as a postdoctoral researcher and Research Specialist from June 2000 to June 2004. He is currently an Assistant Professor at the Space Science Center, Morehead State University. His research interest is focused on the analysis and design of microwave circuits and RF-MEMS microwave devices and systems. He is recently concentrating on the applications of RF-MEMS to space science systems and a new class of reconfigurable antennas for use in adaptive multi-input multi-output (MIMO) systems. He is the principal inventor of microwave-laminate-compatible RF-MEMS technology. He is a Member of the IEEE Antennas and Propagation, Microwave Theory and Techniques, and Communications Societies.



J. Y. Qian received a B.S. degree in optoelectronics and an M.S. degree in optics from the University of Science and Technology of China, in 1994 and 1997, respectively, and a Ph.D. degree in electrical engineering and computer science from the University of California (UCI), Irvine, in 2004. He is currently working as a postgraduate researcher at UCI. His research interests include application of RF-MEMS switches for development of microwave devices, and small-size reconfigurable antennas for smart wireless communication systems.

G. P. Li developed a silicon silicide molecular beam epitaxy (MBE) system while being with the University of California at Los Angeles (UCLA), and then in the area of silicon bipolar developed very large-scale integration (VLSI) technology and process-related device physics while being with the IBM T. J. Watson Research Center. During his tenure as a Staff Member and Manager of the Technology Group, IBM, he coordinated and conducted research efforts in technology development of high-performance and scaled-dimension (0.5 and 0.25 μm)

bipolar devices and integrated circuits (ICs), as well as research into optical switches and optoelectronics for ultra-high-speed IC measurements. In 1987, he chaired a committee for defining the IBM semiconductor technology for beyond the year 2000. He also led a research/development team in transferring semiconductor chip technology to manufacturing in IBM. In 1988, he joined the University of California (UCI), Irvine, where he is currently a Professor of electrical and computer engineering and Director of the Integrated Nanosystems Research Facility (INRF). He has authored over 170 research papers involving semiconductor materials, devices, technologies, polymer-based bio-MEMS systems, RF-MEMS, and circuit systems. Dr. Li was the recipient of the 1987 Outstanding Research Contribution Award presented by IBM and the 1997 and 2001 Outstanding Engineering Professor Award presented by UCI.

F. De Flaviis research focused on the integration of novel materials and technologies in electromagnetic circuits and antenna systems for the realization of "smart microwave systems." He is also focused on research on novel numerical techniques enabling faster codes for the analysis and design of microwave circuits and antennas. His current research is focused on the synthesis of novel low-loss ferroelectric material operating at microwave frequency, which can be used as a phase shifters design to be employed in scan-beam antennas systems. He is also working on modeling MEMS devices to be used as analog tunable capacitors at microwave frequency, for the realization of tunable filters, tunable phase shifters, and "smart" matching circuits. Some of his research is also focused on the development of a novel numerical technique in the time domain, which will allow reduction in the memory storage and faster computation. Dr. Franco De Flaviis received his Ph.D. degree from the University of California at Los Angeles (UCLA) in 1997, and he became Assistant Professor at the University of California (UCI), Irvine, in June 1998.