Monolithic Integration of RF MEMS Switches With a Diversity Antenna on PCB Substrate

B. A. Cetiner, *Member, IEEE*, J. Y. Qian, H. P. Chang, M. Bachman, G. P. Li, and F. De Flaviis

***Abstract*—A novel process for monolithic integration of RF microelectromechanical system (MEMS) switches with three-dimensional antenna elements on a microwave laminate printed circuit board (PCB) is presented. This process calls for a low-temperature (90 °C–170 °C) high-density inductively coupled plasma chemical vapor deposition technique that allows the choice of any PCB substrate, such as RO4003-FR4 ($\varepsilon_r = 3.38, \tan\delta = 0.002$), with the desired electrical properties for antenna applications. A two-element diversity antenna system monolithically integrated with RF MEMS switches is designed and demonstrated.**

***Index Terms*—RF microelectromechanical system (MEMS) switches, monolithic integration, low-temperature process, printed circuit board (PCB).**

I. Introduction

RF microelectromechanical system (MEMS) technology is an emerging subarea of MEMS technology that is revolutionizing RF and microwave applications. RF MEMS switches are basic building blocks for a variety of new RF MEMS circuits. These switches have demonstrated outstanding RF performance, very low insertion loss, and high isolation [1], [2]. In addition, they operate at ultra-low power levels with excellent linearity and extremely low signal distortion. Such features make them very attractive for modern radar and communications applications. RF MEMS circuits such as variable capacitors and phase shifters built upon RF MEMS switches have demonstrated superiority over existing ones [3], [4].

While the manufacturing cost of a single die is very low due to batch processing, a packaged RF MEMS switch component is expensive compared to its semiconductor counterparts (i.e., FETs, p-i-n diodes). This is because packaging is still a major cost driver in current MEMS technology. We believe developing novel integrated-system fabrication processes through a system-level approach is key to reducing the cost of RF MEMS as a result of functionality enhancement. This can be achieved by integrating RF MEMS switches with other circuit elements. For example, monolithic integration of RF MEMS switches with power amplifiers on a GaAs substrate has been demonstrated [5]. Batch transfer integration and flip-chip assembly to place MEMS on different substrates have been proposed [6], [7]. More recently, integration of two-dimensional antenna elements with RF MEMS switches on a glass substrate was also presented [8]. While the RF MEMS switch systems have been demonstrated in these papers, they are still limited in RF performance due to the substrate materials used for construction, or limited in production cost due to the nonbatch process. In order to alleviate such substrate constraints and to facilitate three-dimensional (3-D) design that exploits performance limits of small size antennas [9], it is worthwhile exploring an alternative integrated system technology to address system application needs and to optimize system performance.

In this paper, we describe the monolithic integration of 3-D antenna structures with RF MEMS switches on a printed circuit board (PCB) to construct a diversity antenna. The compatible structures of an antenna element and RF MEMS switch allow monolithic batch fabrication, thus eliminating hybrid assembly. Low production cost is expected in this process by building the integrated RF MEMS-switched antenna directly on a low-cost microwave laminate PCB without requiring packaging individual components and matching impedance among various RF components. To demonstrate the integration concept on a PCB, we have chosen an RF MEMS-switched antenna that can be employed in diversity techniques and radiation pattern reconfigurability to improve receiver performance. The system is physically compact so that it can be integrated easily with portable communication devices.

II. Antenna, RF MEMS Switch, and Their Integration

A. RF MEMS Switch

In this research, RO4003-FR4 [10] was used as a substrate due to its low cost and widespread use in wireless systems. We note that any PCB substrate such as RT/Duroid5880 ($\varepsilon_r = 2.2, \tan\delta = 0.0004$) can also be used depending on the intended application. The topology of the RF MEMS switches used here is similar to the one described in [1]. The fabrication procedure[1] requires only three masks [11] due to its compatibility with PCB technology. The SiN_x layer providing capacitive contact at the switch down position is deposited by using a novel low temperature (90 °C–170 °C) high-density inductively coupled plasma chemical vapor deposition (HDICP CVD) instead of conventional PECVD. PECVD with 250 °C–400 °C process temperatures cannot be employed for many of the PCBs, which have typical operating temperatures of 150 °C–200 °C. In addition to its low-temperature nature, HDICP CVD SiN_x has higher breakdown voltage, less pinhole density, and better uniformity than PECVD SiN_x [12]. A brief fabrication sequence

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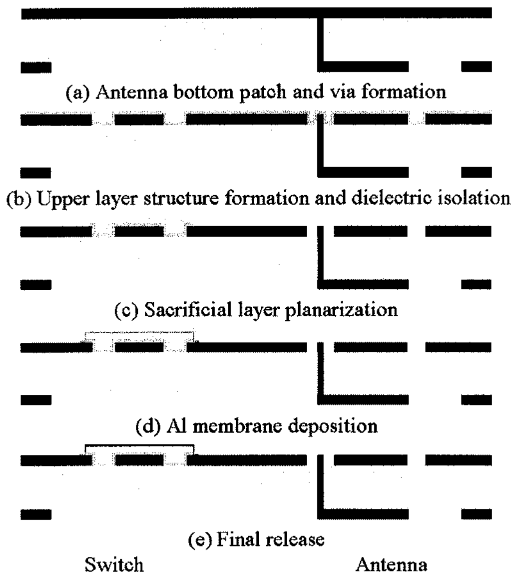

Fig. 1. Process flow of monolithically fabricated RF MEMS switched diversity antenna on RO4003-FR4 PCB.

(see Fig. 1) for the RF MEMS switch is given as the construction of the integrated antenna is described in Section II-C. Measured s-parameters of switches fabricated on RO4003-FR4 PCB showed excellent RF characteristics similar to those of switches fabricated on semiconductor substrates [11].

B. Antenna Element

The antenna structure used in this integrated system has evolved from the q-dime antenna structure [9]. In order to achieve compatibility with PCB technology and MEMS monolithic integration, we modify the q-dime antenna structure to contain only two metallization layers. In addition, this antenna structure is capacitively fed by a coplanar waveguide (CPW) line, as opposed to the coax feed of the q-dime. This allows easier integration with CPW RF MEMS switches. The schematic of the antenna geometry is shown in Fig. 2 (The bottom patch is shown as separated, in Fig. 2(b), for the sake of the illustration.) Vertical and horizontal slots radiate the electromagnetic energy from this antenna. The vertical slot is formed between two sectoral patches, namely, the upper and bottom patches, formed on the upper and bottom metallization layers, respectively, of the RO4003-FR4 laminate with copper layers of 16.5 μm and a dielectric thickness of 1.57 mm. The bottom layer of the structure is connected to the upper layer by two vertical walls. The upper layer contains the upper patch, CPW feed line, and the horizontal slot [see Fig. 2(a)].

C. RF MEMS Switch Integrated Antenna and Measurements

The fabrication of the MEMS-switched antenna starts with building its bottom layer (bottom patches) and vias to connect the bottom layer of the PCB to its upper layer, using a standard PCB process [see Fig. 1(a)]. Next, we complete the antenna structure by wet etching its upper metallization layer. In this second step, the planar sections of the RF MEMS switches (CPW lines) are also formed along with dc bias and dc block circuits [see Fig. 1(b)]. After this structure is obtained, we fab-

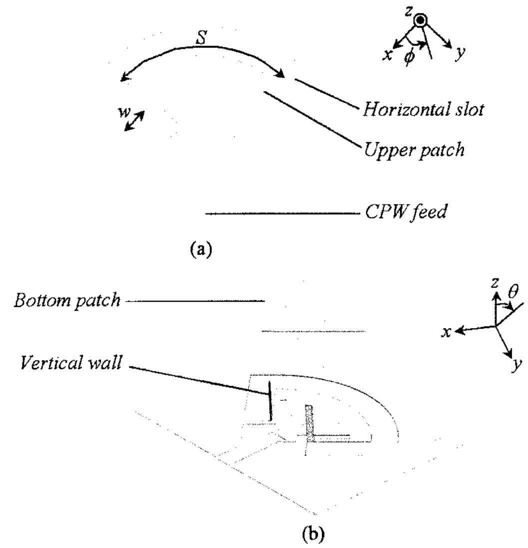

Fig. 2. Schematic of antenna geometry. (a) Top view of the upper layer ($w = 2$ mm, $S = 14$ mm). (b) 3-D schematic.

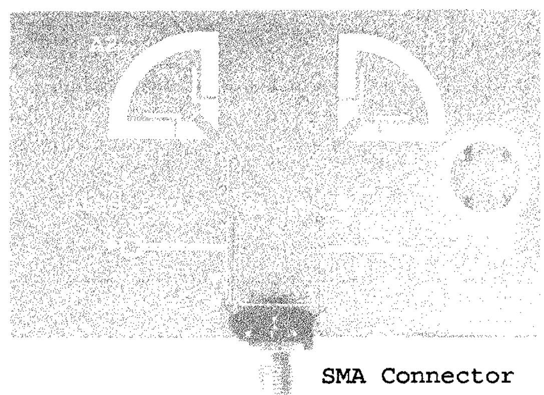

Fig. 3. Photograph of the monolithic RF MEMS switched diversity antenna.

ricate RF MEMS switches following the process flow shown in Fig. 1(c)–(e) without affecting the antenna structure.

Fig. 3 shows the monolithically fabricated RF MEMS-switched diversity antenna. The system consists of two antenna elements and two RF MEMS switches located on CPW feed lines that route the signal to the two antennas. These switches activate either the antenna element for spatial or angular diversity or operate them together to create a superposition radiation pattern for coverage reconfigurability. Antennas are placed at 90° so that, by operating either antenna, orthogonal radiation patterns are obtained. We used high RF impedance quarter-wavelength lines for dc bias to prevent the RF signal from being shorted by the power supply. Similarly, quarter-wavelength dc block circuits isolate the dc bias from the microwave signal (see Fig. 3). These quarter-wavelength dc block circuits run from the RF MEMS switches to the output ports of the tee junction. These lines transform the RF short at the RF MEMS switch locations to an RF open at the output ports of the tee junction. Therefore, when either switch is actuated, the RF signal sees an open at the output port of the tee junction on the actuated side so that it can be directed to either path to sequentially operate the antennas.

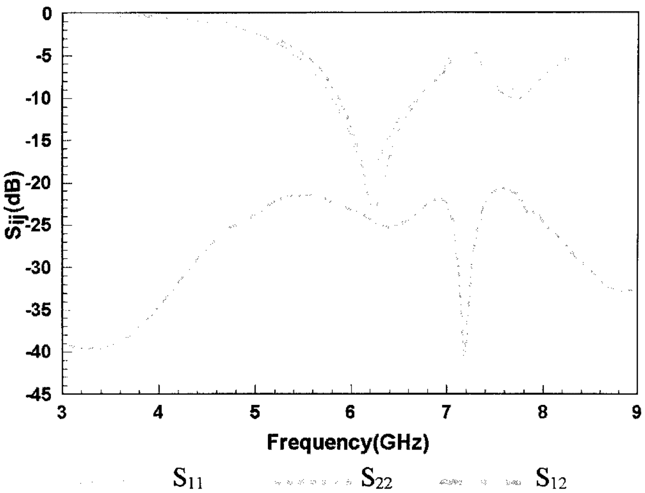

Fig. 4. Measured return loss and mutual coupling for the RF MEMS switched diversity antenna.

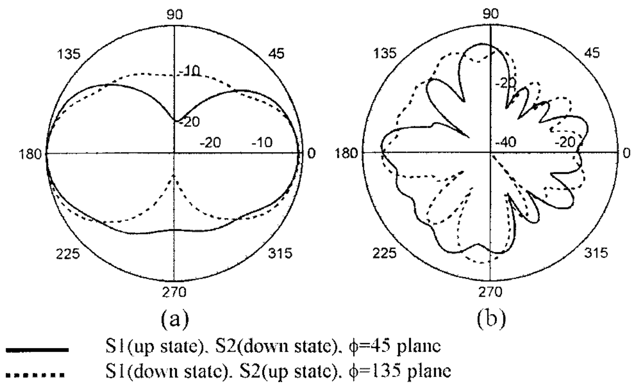

Fig. 5. Measured co-pol. radiation patterns of the RF MEMS switched diversity antenna at 6.15 GHz. (a) In elevation planes: $\phi = 45$ and $\phi = 135$ planes. (b) In azimuth plane (x-y-plane).

Fig. 4 shows the measured input impedances of the antenna elements when either switch is actuated, and inter-element coupling corresponding to the simultaneous operation of the antennas (both switches in the up state). The antennas possess 18% bandwidth for a 1 : 2 voltage standing-wave ratio (VSWR) criteria. For the frequency band of interest, mutual coupling (S_{12}) is below 20 dB, providing low correlation coefficients between radiating elements required for spatial or angular diversity techniques. Fig. 5(a) shows the radiation patterns of each antenna element measured at 6.15 GHz corresponding to the $\phi = 45°$ and $\phi = 135°$ elevation planes. The azimuth patterns of the antennas are given in Fig. 5(b). It is observed that individual operation of antennas ($S1$ in the up state, $S2$ in the down state, or vice versa) allows covering 180° sectors by switching the beam between antenna elements. These radiation patterns can be employed for spatial or angular diversity techniques to maximize the received signal while minimizing interference.

III. Conclusion

RF MEMS technology featuring a novel low-temperature fabrication process has been used to create a monolithically integrated RF MEMS switched antenna system. The system is constructed on an RO4003-FR4 PCB substrate due to its low cost and widespread use in wireless communication systems. Switching between antenna elements creates different radiation patterns that can, in turn, be employed for different diversity techniques to enhance receiving performance while mitigating multipath effects. Current and future communication systems are likely to benefit from this RF MEMS technology.

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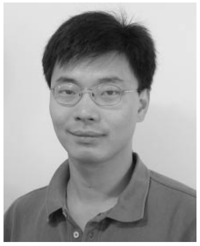

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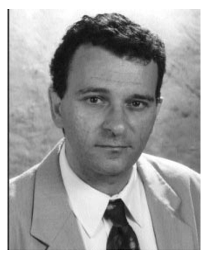

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