RF MEMS for Antenna Applications

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Abstract—**RF MEMS technology can offer enhanced performance over the conventional solid-state devices. Along with other RF MEMS components, antennas have been investigated. This paper presents a unique review and survey of RF MEMS antennas. Here, antennas can be categorized into (i) generic antennas and (ii) antenna circuits. The former employs some forms of mechanical actuation for movements of the radiation elements. With the latter, individual radiation elements are physically stationary and integrated with RF MEMS switches and/or variable capacitors to alter their electrical length and diversity. In addition, (iii) antenna subsystems incorporating RF MEMS tuneable circuits and beam forming networks should not be overlooked. Examples of these antenna categories are described and conclusions drawn.**

Index Terms— monolithic, RF MEMS, antennas

I. INTRODUCTION

Radio frequency microelectromechanical systems (RF MEMS) technology can offer enhanced performance over solid-state devices (e.g. semiconductor switches and varactor diodes), in terms of factors that can include performance figure-of-merit and RF power nonlinearity [1, 2].

There are a number of notable examples of antennas that employ RF MEMS devices. These can be divided into two distinct categories: generic RF MEMS antennas and RF MEMS antenna circuits.

The former category has radiating elements that physically move under some form of mechanical actuation mechanism. Implementing steerable antennas in this true RF MEMS technology is notoriously problematic, for at least four inherent reasons: (i) Radiating elements are very sensitive to the presence of nearby structures (e.g. feed lines, actuators and even the substrate itself; all being located in the near-field region of the antenna). As a result, antennas can easily couple electromagnetic energy into them; the resulting interactions can inadvertently distort the desired radiation patterns and cross-polarisation characteristics; (ii) mm-wave antennas have correspondingly short wavelengths, which are comparable to the physical dimensions of adjacent structures, increasing the risk of strong resonant-mode coupling; (iii) If the radiating elements are detached from the supporting substrate, they cannot exploit the size-reducing attribute offered by a non-air dielectric. Hence, this can make low-frequency microwave antennas too large to be physically displaced; and (iv) it is difficult to realise 3D radiating elements (e.g. helical antennas) that can be physically displaced over large distances.

The latter category has fixed position radiating elements that employ RF MEMS switches and/or variable capacitors to alter their electrical length [1, 2]. These antennas would not be considered generic RF MEMS because, in essence, they are resonant circuits containing non-radiating RF MEMS components. Integrating radiating (sub)elements with discrete RF MEMS switches and/or variable capacitors, to provide some form of frequency tuning, is less problematic when compared to generic RF MEMS antennas. For this reason, there are many more examples for this category of antenna being reported in the open literature.

In addition to these two distinct categories are RF MEMS antenna subsystems, which can incorporate RF MEMS tuneable impedance matching networks, variable attenuators, tuneable phase shifters or reconfigurable beam forming networks. Subsystem architectures that incorporate RF MEMS functional blocks are diverse and beyond the scope of this short survey, but one example will be given. For more detailed information on RF MEMS antenna subsystems, the reader may wish to read Chapters 10 to 13 in [2].

II. GENERIC RF MEMS ANTENNAS

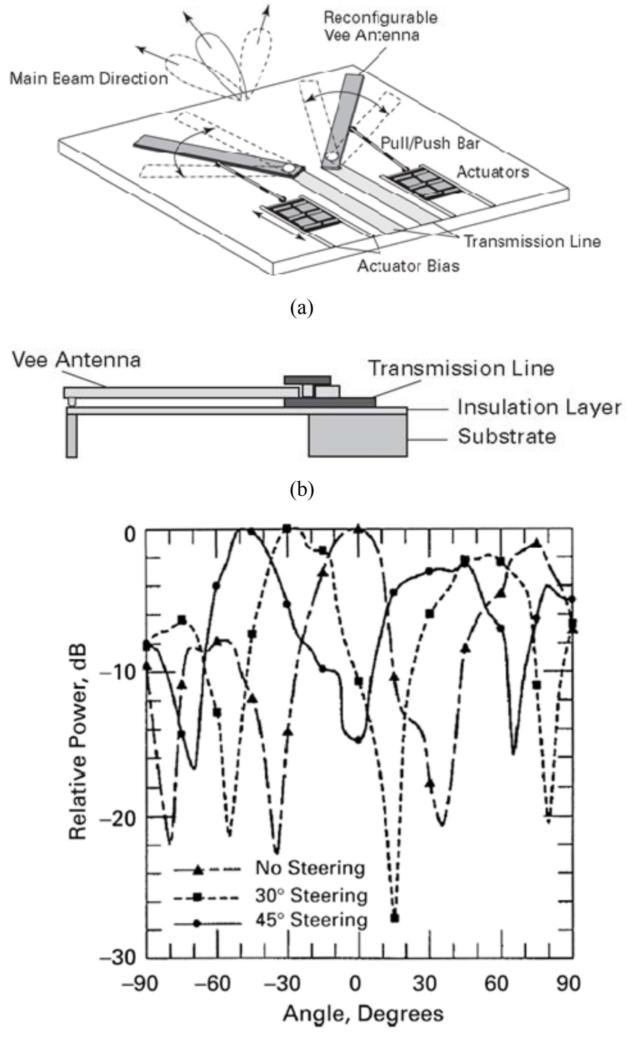
There are very few examples of generic RF MEMS antennas. Two examples will be briefly described].

A. *Half-wave Dipole Antenna*

The first generic RF MEMS antenna was reported just over a decade ago by Chiao et al. [3, 4]. Each radiating arm is capable of independent movement, giving the possibility of far-field beam steering and also beam shaping. As a result, the azimuthal pointing direction and directivity of the main beam can be controlled independently. An illustration of this 17.5 GHz antenna is shown in Fig. 1(a) and 1(b), employing a three-layer polysilicon surface micromachining process. Here, the arms are moved using linear scratch-drive microactuators. The ends of these arms are attached to hinges. Lateral movement of the actuators (20 nm per 70 V biasing pulse) is translated to in-plane rotational movement of the arms by the use of the hinges (i.e. not anchored to the substrate). The directivity for the antenna was estimated (from measured 3 dB beamwidths) to be approximately 16 dBi, while cross-polarisation levels of below 20 dB were also reported. With a fixed Vee angle of 75°, the arms were rotated to 30° and 45° off-boresight, demonstrating beam steering, as shown in Fig. 1(c). The design was further enhanced by the use of an RF MEMS impedance tuner functional block [4].

B. *2 x 2 Patch Array Antenna*

More recently, a V-band single-platform beam steering transmitter [5] was demonstrated, with an external magnetic force being used for actuation [6, 7], shown in Fig. 2. Here, a 2 × 2 array of 60 GHz patch antennas was realised on a single platform, having two degrees of freedom of motion with the aid of orthogonal benzocyclobutene (BCB) torsion bars attached to BCB frames. Here, 40 µm thick magnetic strips were placed on the edges beneath both the antenna array and outer silicon support frame. Using miniature COTS solenoids, with 700 mA bias current, a scan angle of ±20° was achieved. The side-lobe definition and radiation efficiency for this type of antenna can be quite poor because of the unwanted effects of the nickel bars and surrounding BCB/silicon frames. As such, this represents a good example of poor compatibility between the RF component and its method of actuation, because of the conflicting requirements for both.



(a)

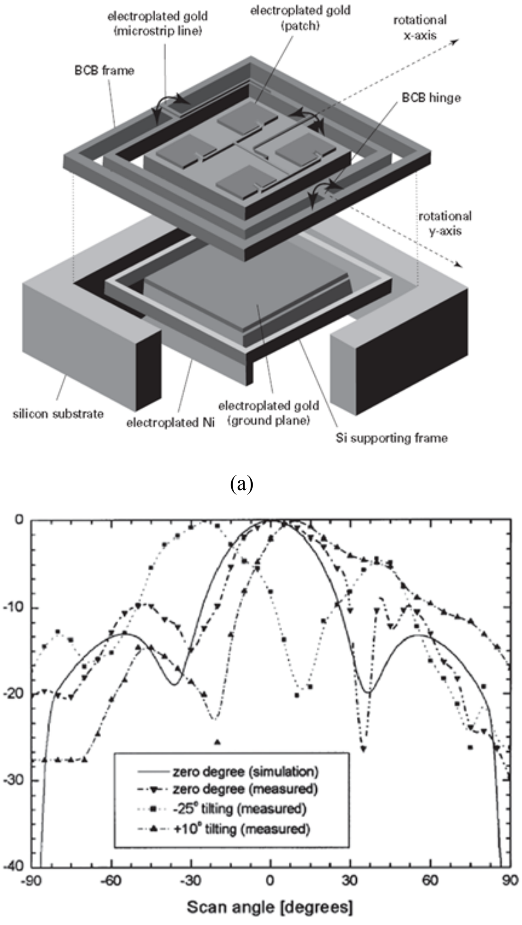
(b)

(c)

Figure 1. Scratch-drive actuated 17.5 GHz Vee antenna [2, 3] (copyright 1999 IEEE): (a) Isometric view illustration; (b) side view illustration; (c) measured radiating pattern.

III. RF MEMS ANTENNA CIRCUITS

In this category of antenna, three sub-categories will be considered: (i) multiband; (ii) space diversity; and (iii) reflect array.



(a)

(b)

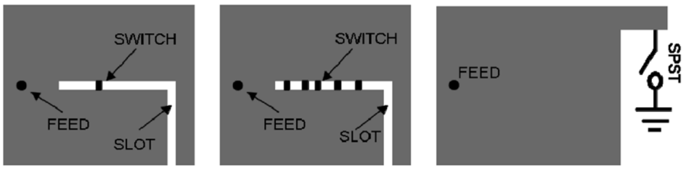
Figure 2. Magnetically driven 2D beam steering 60 GHz antenna [2, 7] (copyright 2003 IEEE):(a) simplified illustration; (b) measured radiating patterns.

A. Multiband Antennas

By far the most common type of RF MEMS antenna circuit is the multiband antenna; being implemented using a wide range of techniques. For example, multiband operation has been demonstrated using RF MEMS switches within fractal antennas [8]. Strategically placed switches can control the currents in the branches of the antenna, modifying the resonance behaviour of the entire structure and its radiation pattern. For example, using a Sierpinski Gasket design, a reconfigurable antenna was demonstrated based on this principle [8]. More recently, much simpler dual-frequency reconfigurable slot dipole arrays for X- and Ka-band [9] and Ka- and V-band [10] were reported in which RF MEMS switches were placed across the slots. Similarly, a single-arm spiral antenna with RF MEMS switches located along the line was reported for X-band operation [11]. As a low-cost solution, thermo-compression wafer bonding techniques have also been employed to realize a 3-layer tuneable coplanar patch antenna (TCPA) with RF MEMS varactor on a printed circuit board (PCB) [12, 13].

Folded antennas capable of operation in five mobile phone bands have been realised using RF MEMS solutions [14].

Ideally, as part of multiband and reconfigurable handset development, antennas should be optimised for such operation [2]. One approach is to design an antenna whereby the resonance frequencies cannot change; with each individual antenna operating within a specific frequency band. This is rather challenging when the number of frequency bands increases. Another approach is to use an antenna and switches/tuning circuits to control the antenna's resonance frequencies for adaptive, multiband operation. Fig. 3 shows examples of two planar inverted-F antennas (PIFAs) and a patch antenna [15, 16]. Switchable antenna concepts are best suited for channel- or band-switching and to compensate for finger effects. If antennas are designed to be narrowband they can also be used for filtering.



(a) (b) (c)

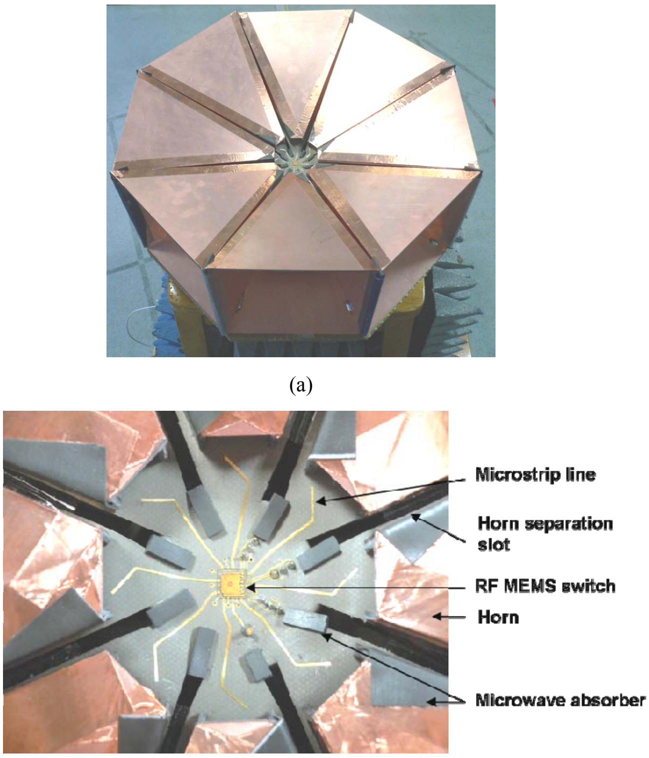
Figure 3. Possible solutions for implementing switchable, adaptive antennas for multiband radio systems [2] (copyright 2010 CUP): (a) PIFA antenna with a switch for controlling the electrical length of the tuning slot, suitable for dual-band switching; (b) PIFA antennas employing several switches for multiband switching; and (c) patch antenna with switchable short circuit for dual-band switching.

Larger telecommunications companies have also been active in developing switchable and reconfigurable handset antennas [2]. For example, LG demonstrated a switchable PIFA that is capable of hand-effect compensation [17], using a piezoelectric RF MEMS single-pole single-throw (SPST) switch. NXP has developed their prototype PIFA mobile phone antenna for 5-band operation [14]. The frequency tuning of the antenna is realised with RF MEMS switched-capacitor banks. Results show that the antenna bandwidth and specific absorption rate (SAR) can be significantly improved using RF MEMS tuning circuits. NXP has also demonstrated an antenna-matching unit for hand-effect compensation [18, 19]. The University of Tennessee and Intel Corp. have proposed a mini-maze antenna that has ohmic contact SPST RF MEMS switches for antenna reconfiguration [20]. The antenna employs two switches for switching between three frequency bands.

B. *Space-Diversity Antenna*

In general, low loss and high isolation signal routing is very important. This is also the case when implementing T/R switches within T/R modules and space-diversity sectorised antennas [21], where very high isolation is crucial.

An interesting RF MEMS antenna circuit, in the form of a sectorised X-band horn antenna, was recently presented by the authors [22], shown in Fig. 4. The circuit consists of eight Vivaldi antennas fabricated on a flexible organic substrate, with a central single-pole eight-throw (SP8T) RF MEMS rotary switch for antenna selection. Vivaldi antennas have previously employed RF MEMS. Examples include an UWB near-field imaging system [23] and a 16-element phased sub-array with Ka band phase shifters [24].



(a)

(b)

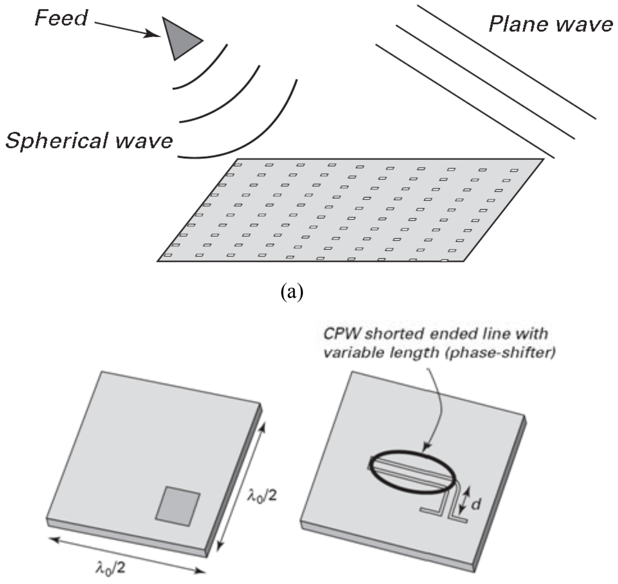
Figure 4. Assembled RF MEMS sectorised antenna array [22] (Copyright 2010 IEICE): (a) top view; (b) close-up view at the centre.

In the past single-pole multiple-throw RF MEMS switches have been realized mainly by integrating a number of SPST switches. However, as the number of bits increases, this solution can be unwieldy and result in yield and reliability issues [2]. For example, a SP8T switch may require about 15 times the real estate of an SPST switch and 8 separate moving parts. In contrast, and as a new application demonstrator, the SP8T rotary switch is relatively compact and has only one moving part [25]. This switch has also been recently employed within a 2-bit digital true time delay (TTD) phase shifter application [26].

Some applications require even larger values of throw [2]; for example, multibeam satellite communications antennas. A single-pole forty-eight-throw (SP48T) RF MEMS switching module has been reported for the measurement set-up for such antennas [27]. This module consists of a SP8T reflective RF MEMS switch that feeds into eight SP6T absorptive RF MEMS switches. Across the 18 to 40 GHz frequency band, the worst case level of ON-state insertion loss is approximately 2 dB for both the SP6T and SP8T switches. The OFF-state isolation is better than approximately 9 dB and 23 dB for the SP6T and SP8T switches, respectively [27]

C. *Reflect Array Antennas*

The reflectarray antenna [2] is receiving a great deal of attention for mm-wave beam-steering applications, because it avoids the need for having beam-forming networks that are inherently lossy at such high frequencies [28]. Fig. 5 illustrates the basic concept of operation. In principle, a double-sided substrate can accommodate the patches on one side and variable TTD phase shifters on the other. As part of the European Union's (EU's) 6th Framework Programme (FP6) Network of Excellence (NoE) on Advanced MEMS for RF and MIllimetre-wave COMmunications (AMICOM) activities, a consortium of European institutions developed RF MEMS-based reflectarray antennas; at 26 GHz for satellite communications and at 35 GHz for radiometric imaging applications. With the former, the antenna was realised on a single piece of silicon wafer, fabricated at FhG-ISiT, Itzehoe, Germany. As shown in Fig. 6(a) and 6(b), the antenna has a 10 × 10 array of patch cells individually slot-coupled to a CPW shorted variable delay line, respectively. Each shorted variable delay line has six capacitive membrane switches, shown in Fig. 6(c), to implement the seven states of operation given in Fig 6(d). The worst-case insertion loss of the shorted variable delay line is 4 dB at 26 GHz. Having 600 RF MEMS switches in total, to reduce the number of bias lines to just 60, beam steering is only performed in the E-plane. The packaging solution for this reflectarray demonstrator uses very low cost RF4 PCB technology. With one piece of PCB, having a thickness of 2 mm, a 1 mm deep cavity is created to accommodate all the RF MEMS switches. On the outermost side of the PCB, bias lines are routed and connected to those on the silicon wafer, via bond wires.



(b)

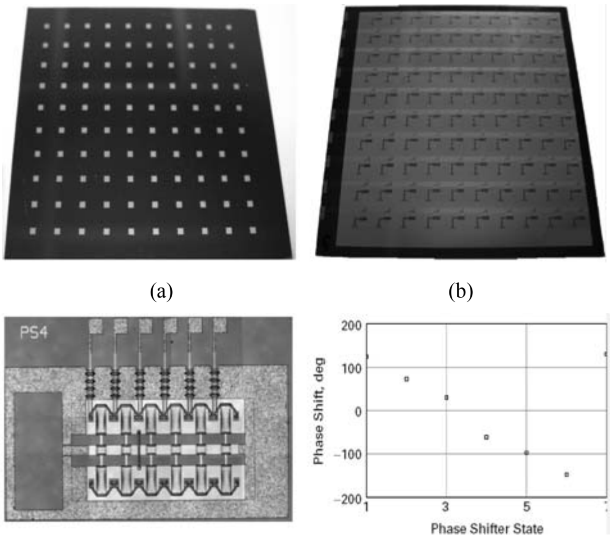
Figure 5. Reflectarray concept illustrations [2, 28] (copyright 2007 IET): (a) principle of reflectarray operation; (b) single element of the reflectarray: top view of patch radiator (left) and bottom view of shorted variable delay line (right).

IV. RF MEMS ANTENNA SUBSYSTEMS

One example of an RF MEMS functional block within and antenna subsystem will be given here. In mid-2010, mobile phone handset manufacturers started to look for signal reception enhancers, after problems emerged with the iPhone 4 antennas [29]. In conventional mobile phone architectures, multiple standards and functions coexist with multiple parallel RF paths. This architecture is not adapted to the evolution of mobile phone handsets, since it raises the number of components, size and cost, as well as the power consumption of the handsets. Therefore, reconfigurable architectures are required. For example, in terms of antenna tuning and impedance matching alone, there are multiple direct benefits of using RF MEMS for handset manufacturers and users. These include:

- Mitigate signal dropout because of hand effects (e.g. "death grip" failing with iPhone 4).
- Antenna tuning can boost data rates by 40% with LTE 4G standard phones.
- RF MEMS enables thinner antennas with greater efficiency than larger ones.

Since Nov. 2011, the Focus™ Flash smartphone from Samsung Electronics has been shipped to the US, employing RF MEMS devices supplied by WiSpry. This is the first example of a mass-produced RF MEMS-enabled wireless handset [29]. Here, an RF MEMS antenna tuning module within a die-on-LGA (low-gain antenna) package, located near the antenna connectors can be found. WiSpry's unique WS2017 Tunable Impedance Match (TIM) circuit consists of a network of low-loss inductors combined with their CMOS-based digitally-tuneable, low-loss MEMS capacitors; being ideal for 4G applications. The WiSpry single-chip design integrates logic circuits/serial interface for control, on-board high-voltage charge pump and high-voltage MEMS drivers, together with fully encapsulated digital RF MEMS capacitors on a single chip.



(c) (d)

Figure 6. Experimental 10 × 10 reflectarray demonstrator for 26 GHz operation [2, 27] (copyright 2007 IET): (a) top view of radiating layer; (b) bottom view of shorted variable delay line layer; (c) fabricated shorted variable delay line; (d) measured performance of 7-state shorted variable delay line.

V. CONCLUSIONS

RF MEMS technology has been around for almost 35 years. However, it is only in the past decade that real technological advances have been made. Indeed, the first commercial application within a consumer-based electronics application has only just been introduced in the past couple of years. For this reason RF MEMS technology is well behind other non-RF microelectromechanical systems technologies (e.g. accelerometers and digital micromirror devices). Having said this, it seems likely that RF MEMS will succeed in high performance functional blocks associated with RF MEMS antenna subsystems; for example, variable TTD phase shifters in phased array antenna systems for military and satellite applications and tuneable impedance matching networks in multiband antennas for mobile phone handsets.

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