Reconfigurable UWB Antenna With RF-MEMS for On-Demand WLAN Rejection

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Abstract—A MEMS reconfigurable ultra-wideband (UWB) antenna that rejects on-demand all WLAN signals in the entire 5.15 to 5.825 GHz range (675 MHz bandwidth) is presented. The antenna design, miniaturization procedure, and monolithic integration with the MEMS and biasing network on SiO₂ Quartz substrate are described. The integration challenges are addressed and the work is presented in a way that is useful for antenna engineers. A method to vary the rejection bandwidth is also provided. The fabricated prototype is conformal and single-sided. The antenna is measured using a custom-built platform at a university laboratory. Results indicate a successful integration and minimal interference of the MEMS and biasing circuitry with the antenna, paving the road for more integrated reconfigurable antennas on SiO₂ using MEMS technology. Such antennas can improve UWB, WLAN and cognitive radio communication links.

Index Terms—Antennas, cognitive radio, integrated components, MEMS, reconfigurable antennas.

I. INTRODUCTION

BAND-REJECT ultra-wideband (UWB) antennas can facilitate UWB systems to minimize in-band interferences within their bandwidth, extended from 3.1 to 10.6 GHz [1]. Interferences often originate from the increased use of IEEE 802.11n (and the older 802.11a) WLANs that allocate channels between 5.15 and 5.825 GHz. WLAN devices that transmit in the above range with increased signal intensity interfere with nearby UWB receivers, while in a different scenario, radiation from UWB transmitters may interfere with WLAN devices that receive a weak WLAN signal. To mitigate these interferences, UWB antennas that permanently reject WLAN bands have been developed. However rejection is not always necessary. Better UWB link efficiency requires rejection to occur on-demand and when the WLAN signal is present. Using a single reconfigurable antenna is the proposed solution to this problem. In this work we develop the needed MEMS reconfigurable UWB antenna that can reject on-demand and the 5.15–5.825 GHz 802.11n/a Wireless Local Area Network (WLAN) bands.

The design is based on a traditional uni-planar disc-shaped UWB monopole. For this development, several challenges are addressed: (a) pin diodes are difficult to bias because the design lacks a backside ground plane behind the monopole. This uni-planar structure however makes it ideal to monolithically-integrate MEMS. (b) MEMS can be biased using microstrip lines and stubs, grounded vias, or high-resistive lines. The first two typically require a backside ground plane, which single-sided monopoles do not have. The third option motivated the development of high-resistive bias lines on SiO₂ (Quartz) substrate and led to the monolithic integration of the MEMS on-wafer with the bias lines and the antenna. (c) This integration also helped avoid using bulkier pre-packaged off-the-shelf MEMS that need wire-bonds that could affect the antenna pattern and impedance.

Such on-demand and WLAN rejection antennas have not yet been realized, possibly due to difficulties in their design and integration. Here we describe the design and integration of such an antenna with MEMS, as well as the fabrication of a prototype, and measurements. A comparison with current state of the art is made in Section II and results are compared in Section V.

II. BAND-NOTCHED UWB ANTENNAS LITERATURE

During the last years, many prototypes of band reject UWB antennas have been proposed. Most are not reconfigurable antennas, so they do not include MEMS or other reconfiguration means (pin diodes, varactors, etc). Among them, some characteristic prototypes that involve permanent rejection mechanisms can be found in [2]–[12]. Most design approaches involve permanent rejection using slots [3], [5], stubs [3], [9], and feed line or ground modifications (i.e., using resonators) [11], [12]. Designs of interest include a dual-notched monopole with parasitic λ/4 resonant stubs and strong rejection especially in the
first band [10], a triple-band rejection with \( \Omega \)-shaped slots and additional slots on a defective ground plane [11], and resonant loops placed adjacent to the feed line to trap different frequencies that achieved similar levels of rejection [12]. Both [11] and [12] achieve strong rejection and with sharp roll-off, but they are not single-sided. Thus, they require double-sided etching that may impose limitations if the antenna is to be made reconfigurable, for example in a potential integration with MEMS, while the curved slots make them difficult to fine-tune. Moreover, most previous works focus on rejecting only a portion of the WLAN spectrum (i.e., either the 5.25 GHz band or the 5.75 GHz band) [2], [3], [5], [7], while prototypes that reject all WLAN usually employ multiple bands rejection [2], [6], [9], [11], [12]. In all these works, a narrowband (e.g., 100 to 200 MHz) rejection with a single resonator can indeed achieve a strong rejection level (about 10 to 20 dB). The rejection of wider bandwidths (e.g., 400 to 700 MHz) is more limited to values close to 3 or 4 dB, as in [2], [13]. The proposed antenna aims at wideband rejections of the 675 MHz WLAN band and with sharp roll-off, as in [2], [13]. Also, a method to vary the bandwidth of the rejected frequencies is mentioned in Section III. To better comprehend the significance of this work, the results, which are presented in Section V, are compared with prior studies aiming similar functionalities (i.e., UWB antennas that reject the WLAN), and the performance of the developed antenna is found comparable to or better than these prior studies of band-reject antennas that did or did not face the challenges of MEMS integration [2], [3], [5], [6], [10], [12], [13].

Successful implementations of UWB antennas with reconfigurable WLAN rejection with diodes or varactors have not yet appeared. Some implementations, however, use diodes to reconfigure rejection [14]–[16], but involve different design goals: 1) radiate from different frequencies (1.5–5 GHz [14] or 2.5–8 GHz [15]), 2) have larger antenna dimensions (e.g., 75 \( \times \) 38.85 mm [15]), 3) have larger rejected bandwidth (from 1–2 GHz [14] or up to 4 GHz [15]), 4) achieve high relative rejection (more than 10 dB [14] or up to 30 dB [15]), 5) are designs with directional patterns [14]–[16] potentially unsuitable for receivers, and most important 6) do not require the sharp roll-off imposed by the current WLAN-only rejection that approximates the ideal brick-wall filter, and therefore they cannot be directly compared to this work.

Compared to pin diodes, RF-MEMS may require two bias lines (instead of one) to actuate but provide high linearity and low losses. Their integration however up to now is limited mainly to laboratory prototypes and only one UWB antenna with MEMS reconfigurable rejection has been reported [13], which presented patterns using ideal reference prototypes. Here, measured patterns using the integrated MEMS during ‘on’ and ‘off’ actuation were made for the first time in a university setting and are presented.

This work differs also from prior MEMS antennas [17]–[22] mostly in the MEMS design, use, substrate and application which is the on-demand rejection of WLAN interference. The MEMS employ a new membrane design with dimples and can be used to reject any (one here) frequency band instead of enabling or fine-tuning additional ones. In fact, the MEMS here are not limited by a narrowband bias network, and so they can be used to reject any desired frequency. This work also presents the development of high-resistive lines on SiO\(_2\) for the first time, and complements the preliminary results of [23], by providing a) new, accurate \( S_{11} \) measurements and how they were taken, b) the antenna measurement platform and patterns measured during MEMS actuation, for the first time in a university laboratory, c) a concise antenna design and matching methodology, d) MEMS 3-D diagrams, e) a method to vary the rejection bandwidth and f) an equivalent circuit model for both MEMS’ states.

### III. Antenna Design and Matching

The base design for this antenna is a CPW-fed disc-shaped monopole with diameter 3 cm designed on SiO\(_2\) substrate with permittivity \( \varepsilon_r = 3.9 \) (Fig. 1(a)). Its lowest well-matched frequency is 3 GHz. The antenna is fed by a 50 \( \Omega \) CPW line that is tapered from a 5000 \( \mu \)m to a 100 \( \mu \)m width (CPW gaps from 150 \( \mu \)m down to 12 \( \mu \)m) for compatibility with the available 250-\( \mu \)m pitch OSC RF probe and to minimize losses throughout.

Two quarter-wave open-circuited stubs are added to the edges of the antenna to facilitate the band-notched behavior at the frequencies when they appear as short circuits connected to the antenna structure. The initially curved stubs were replaced by linear ones for easy fabrication and adjustment. Thin stubs (e.g., 200 \( \mu \)m wide) provide narrowband rejection, whereas the wider stubs (e.g., 1500 \( \mu \)m) used here reject the entire 5.15–5.825 GHz bandwidth. This happens because there is more than a single frequency at which the RF current ‘sees’ a length of one quarter-wave stub. This rule of thumb can be used to adjust or vary the rejection bandwidth. Next, the antenna edges were also linearized for the stubs to maintain a fixed distance from...
them [24]. The feed structure is then modified by narrowing the opening near the antenna and introducing two triangular slots of 250 μm each orthogonal side to reduce reactive loading and lower the input resistance. Lastly, the monopole height is further reduced by about 20% by removing metal from parts with low current density (Fig. 1(b),(c)). Fig. 1(d) shows the final design and its simulated.

IV. RF-MEMS FABRICATION AND ANTENNA INTEGRATION

The MEMS fabrication and associated 3-D layouts are shown in Fig. 3(a)–(d) with mask layouts on the right column. The process follows the general path described in [23] but contains membrane and bias line novelties. Fabrication begins with a Ti/Au 20/280 nm e-beam evaporation and standard photolithography patterning to define the antenna, stubs, bias lines and MEMS electrode. The cantilever will be anchored at the stub end (RF OUT).

For the biasing lines, simulations pertinent to their sheet resistance showed that 10 kΩ/sq suffice to suppress the 5.5 GHz RF current propagation to less than 100 μm (∼ λ/20) before attenuating by 30 dB. This led to the development of high-resistance lines on SiO₂, for the first time. The lines are defined with Tungsten deposited into W:SiO₂ silica matrix at a ratio 1:4.6 (Fig. 3(a)), and provide about 10 kΩ/sq at room temperature. The resistive part is 10 nm thick, 8 μm wide and 160 μm long and was deposited by a Discovery-22 Sputterer at 20°C, which is notably lower than the 850°C needed for the more expensive CCVD process of AZO lines [19]. This also helps avoid floating grounds that were used in replacement of these lines with LCP substrate due to its 290°C temperature limitation [22]. All remaining parts are electroplated Au.

The second novelty is the membrane design that employs dimples that are the only parts of the cantilever that contact the antenna when the switch is actuated. The dimples (0.6 μm deep holes) are patterned on the 1.2 μm thick PMGI sacrificial layer (Fig. 3(b)) that is spun and patterned to define the anchor location and create the 1.2 μm cantilever-electrode gap. After a 6 μm thick electroplating and patterning, this creates two 0.6 μm posts (dimples) under the cantilever and two 0.6 μm shallow valleys at its surface. As the membrane is 6 μm thick, the 10% thickness non-uniformity is small and does not affect the structural integrity of the switch.

Finally, the integrated MEMS switch and antenna are released in a CO₂ critical point dryer (Figs. 3(c),(d)). Fig. 4 shows photos and dimensions of the fabricated device and switches. The entire fabrication process can be completed in less than 24 hours in a commercial facility.

V. MEASUREMENT SETUP AND RESULTS

The series ohmic-contact cantilever MEMS act as relays that activate or deactivate the stubs when the 30-Volt actuation voltage is applied. The equivalent circuit of the MEMS ‘on’ is a small series inductance L₁ and resistance R₁, in parallel with a small capacitance C₁ (Fig. 5(a)). In the ‘off’ state, the MEMS present an additional (small) capacitance C₂ in series, which prevents the RF from entering the stub (Fig. 5(b)) [25]. The circuit model of the resonant stub is a parallel RLC [24] and typical values that satisfy it are: R₂ = 250 Ω, L₂ = 0.5 nH and C₂ = 1.7 pF. In Fig. 6 we see the analytical (calculated), simulated, and measured impedance of the equivalent circuit.

The antenna |S₁₁| and radiation patterns were measured with MEMS ‘on’ and ‘off’, using a 10 MHz to 67 GHz Agilent
Fig. 4. (a) The fabricated antenna with MEMS during measurements showing 
the RF and DC probes. The circular Quartz wafer is almost transparent. The 
DC bias lines can be seen in very light golden color. (b) Top view showing the 
MEMS switch, feeding taper (some wear is due to our measurements), DC bias 
pads, and antenna dimensions. First appeared in [23].

Fig. 5. Equivalent circuits: (a) RF MEMS switch ‘on’, (b) ‘off’, and (c) ideal 
UWB antenna, as a load, with the MEMS on and stub.

E8361C PNA network analyzer. The UWB antenna was measured from 1 GHz to 12 GHz (Fig. 7), and for better resolution at the rejected bands and to reduce the noise floor, it was re-measured from 4.8 GHz to 6.2 GHz using only 10 Hz IF bandwidth. This was omitted from [23] and increases significantly the accuracy of the measurement at the rejected frequencies. With MEMS ‘off’, the antenna is well-matched from 2.8 GHz to 12 GHz (Fig 7(a)). With MEMS ‘on’, a strong rejection with a 2.7 dB return loss is measured at the 5.52 GHz center WLAN frequency (Fig 7(b)), illustrating approximately 50% radiating power attenuation. Also, from 5.05 to 6.05 GHz the $|S_{11}| > -10$ dB, while from 5.13 GHz to 5.84 GHz the $|S_{11}| > -6$ dB, which shows that the other WLAN frequencies are also attenuated by more than 25%, and with sharp roll-off. A small shift from the simulated response, although minor for the number of materials and layers of the simulated, integrated unpackaged MEMS and bias lines, can be due to the proximity of the RF probe to the antenna or to fabrication inaccuracies.

The radiation patterns were measured during biasing using a custom made 1.5 GHz to 67 GHz reconfigurable antenna measurement platform (RecAMP), which was designed and built for this purpose, and can be controlled manually or through Lab-view. The platform is shown in Fig. 8 and consists of a lightweight arm counterbalanced by a mass close to the pivot to balance the gravitational forces of the assembly so that the motor can turn it wobble-free, while keeping the moment of inertia low for better start/stop response.

The measured and simulated E- and H-plane patterns are shown in Fig. 9. The 4 and 7 GHz E-plane is toroidal and the
Fig. 8. Photo of the reconfigurable antenna measurement system (RecAMP) during the pattern measurement of the reconfigurable antenna.

Fig. 9. E- and H-plane at 4 and 7 GHz, measurements and simulations.

H-plane omnidirectional, as expected for this type of antenna. The measured E-plane pattern attenuates from 130° to 180° and inevitably deviates from the (symmetric) simulations because of reflections at grazing angles by the right-angled RF probe adapter.

The measured and simulated E- and H-plane patterns are shown in Fig. 9. The 4 and 7 GHz E-plane is toroidal and the H-plane omnidirectional, as expected for this type of antenna. The measured E-plane pattern attenuates from 130° to 180° and inevitably deviates from the (symmetric) simulations because of reflections at grazing angles by the right-angled RF probe adapter.

The measured patterns with MEMS 'on' and 'off' at 5.5 GHz (center of the rejected band) are also similar to the simulations, as shown in Fig. 10. With MEMS 'on', the antenna radiation intensity is smaller on all directions and its broadside gain is reduced by more than 3 dB.

Gain measurements are reported in Fig. 11 at 5.0, 5.5 and 6.0 GHz, and confirm the 3.38 dB gain reduction at 5.5 GHz where $G_{\text{off}} = 2.8$ dBi while $G_{\text{on}} = -0.58$ dBi. The average gain of the antenna is in the range of 1.5 dBi to 3 dBi, which is good for an omnidirectional receiver, and frequencies outside the rejected WLAN band are not attenuated.

It is known that 'perfect matching' using a single resonance circuit can be achieved only at a single frequency [26]. Broader bandwidth often implies 'imperfect' matching. Similarly 'perfect rejection' over a wide range of frequencies cannot be achieved with a single-resonance structure like the resonant...
λ/4 stub. Since the objective here is the rejection of a wide range of frequencies (i.e., the entire WLAN—similar to an ideal brick-wall filter), the level of rejection cannot be very high but can reach the levels of an optimized simulated model. As an example, in [2] a 20 dB gain reduction is achieved but at a very narrow (100 MHz) bandwidth. However, here the gain reduction is more than 3 dB and it covers a six times larger bandwidth.

The measured results are very satisfactory because the rejected bandwidth (5.15 to 5.825 GHz) and maximum level of rejection (\(|S_{11}| = -2.7 \) dB) are comparable or better than prior studies of band-reject antennas aiming similar functionalities with or without facing the challenges of MEMS integration and of sharp roll-off, and that rejected significantly narrower bandwidths (e.g., \([2, 3, 5, 6, 10, 12, 13]\). As an example, the MEMS-based UWB antenna \([13]\) rejects approximately 400 MHz bandwidth with peak return loss 2.5 dB (while the proposed device rejects approximately 675 MHz bandwidth with comparable peak return loss 2.7 dB). It also compares well with fixed band-notched UWB antennas such as (for example) \([6]\) where a 600 MHz bandwidth is rejected with 4.4 dB minimum return loss, \([5]\) where 200 MHz are rejected with 5 dB peak return loss, and \([12]\) where the curved multi-band-rejection mechanism rejects 5.05–5.8 GHz with approximately 10 dB return loss and achieves a peak of 3 dB return loss in the 1st WLAN band (5.05 to 5.6 GHz) and a peak of 4.4 dB return loss in the 2nd WLAN band (5.6 to 5.8 GHz).

VI. DISCUSSION AND CONCLUSIONS

The design and successful integration of MEMS with a band-reject UWB antenna for on-demand WLAN rejection was presented. The antenna consists of linear sections and is easy to replicate and fine-tune for other applications. It is conformal, single-sided, and the MEMS are monolithically integrated on its surface.

The high-resistive lines, that were developed, were deposited at low temperature, which makes them attractive for many other temperature-sensitive substrates such as LCP (as the deposition pressure does not induce a phase change) and even paper.

This is one of the few works where a MEMS integrated antenna is completely characterized at a university facility. Measuring the antenna pattern during biasing presented interesting challenges because the RF and DC probes and the DUT cannot rotate. A measurement platform (RecAMP) was developed to enable this capability. This platform can also be used to measure other reconfigurable antennas up to 67 GHz.

The proposed antenna can be used in next generation WLAN and low-power UWB systems that will minimize interference to nearby receivers, as well as in high-performance and highly versatile cognitive radios that have low-loss. The on-demand rejection of WLAN interfering signals can lead to UWB and WLAN links with increased S/N ratio, higher capacity and throughput, and thus can improve the quality, the efficiency and the S/N ratio of UWB communication links in cognitive radio and in dense WLAN environments.

REFERENCES

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