

# Hybrid CMOS-MEMS Tunable Oscillator Architecture for Multi-Band Cognitive Radio Systems

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## ABSTRACT

Cognitive radio systems require frequency agile local oscillators that can operate over a wide tuning range, with low phase noise, and limited energy consumption in communication bands with dynamically changing accessibility. Traditional CMOS-only VCOs suffer due to poor quality factor (Q) inductor on-chip, poor phase noise characteristics, as well as nonlinear tuning characteristics throughout large frequency bands. This paper suggests a tunable CMOS- MEMS tunable oscillator design, in which a high-Q MEMS electronically tunable resonant component is incorporated into a CMOS cross-coupled negative-resistance core to facilitate the functioning of the multi-band cognitive radio. Coarse band selection is offered by a switched capacitor array and fine frequency control with increased spectral purity by MEMS based capacitive tuning. Post-layout simulations of the design are done in 180 nm CMOS technology, which consists of parasitic extraction and phase noise simulation according to the model of Leeson. The proposed architecture has a broad tuning frequency of 1.836 GHz (66%), phase noise of -121 dBc/Hz 1 difference at 1 MHz (2.4 GHz) and a power consumption of 5.8 mW with 1.8 V of power. This foM of -187 dBc/Hz is within competition with traditional examples of LC-VCO. The hybrid integration method improves the tuning linearity and frequency stability therefore applicable in dynamic spectrum access and reconfigurable RF front-end designs in next-generation wireless systems.

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## INTRODUCTION

The high rate of wireless service and spectral-intensive application has caused critical shortage of the spectrum in the traditional fixed-allocation schemes. Cognitive radio (CR) systems have risen as an exciting alternative as it allows dynamic spectrum access, underutilised frequency bands are exploited in an opportunistic manner by transceivers to enhance spectral efficiency and network capacity.<sup>[1, 2]</sup> Flexible wireless architecture designs need frequency agile RF front-end designs that

can work in a wide range of frequencies with predictable spectral properties, low phase noise, and high frequency switching. At the heart of these front-ends is the local oscillator whose characteristics have a direct effect on system sensitivity, adjacent channel interference and spectral compliance in general.<sup>[3]</sup> CMOS LC VCOs Traditional CMOS version, which are voltage-controlled oscillators are still actively used due to the capability of complete integration and low price.<sup>[4]</sup> Their response is however limited by essentially the quality factor (Q) of

on-chip inductors and MOS varactors, which worsen phase noise and tuning linearity over large frequency bands.<sup>[5, 6]</sup> Tuned ranges of any size large generally require switched capacitor banks, which add secondary parasitics and spoil spectral purity.<sup>[7]</sup> Additionally, to sustain oscillation margin during multi-band operation, additional power consumption is likely to be incurred thereby making it inapplicable to energy conscious cognitive radio systems. Micro-electro-mechanical system MEM resonators have much higher Q-factors, enhanced frequency stability and lower loss than CMOS passive elements.<sup>[8, 9]</sup> In spite of these benefits, standalone MEMS oscillators have a weakness of low electrical tunability and complexity of integration, limiting their versatility in wideband reconfigurable RF systems.<sup>[10]</sup>

The extant literature has been more or less parted ways between CMOS and MEMS oscillators, and has not studied hybrid architecture with the capability to provide both wide tuning range and high spectral purity in multi-band cognitive radio operating conditions. An integrated solution of oscillator with the combination of CMOS scalability with high-Q resonance of MEMS sustaining energy efficiency and reconfigurability is still required.

A hybrid CMOSMEMS tunable oscillator architecture is proposed in this paper: a high-Q MEMS electrostatically tunable resonator was merged in a CMOS cross-coupled negative-resistance core. A switched capacitor array can be used to select the bands coarse and MEMS-based electrostatic actuation can be used to fine-tune continuously. The suggested solution aims at better phase noise characteristics, wider tuning capabilities and efficiency in terms of energy consumption to Multi-band cognitive radio front end implementations.

## RELATED WORK

CMOS LC voltage-controlled oscillators (VCOs) have also been widely studied as a multi-band and reconfigurable RF application because they can be fabricated using standard integrated circuit processes and at low cost.<sup>[1-3]</sup> Coarse and fine frequency control in CMOS VCOs is normally arrived at with switched capacitor banks and MOS varactors.<sup>[4, 5]</sup> Although such a design allows the multi-band operation, the low quality factor (Q) of inductors and varactors in the chip are majorly affecting the performance of phase noise, especially at the higher frequencies.<sup>[6]</sup> In addition, MOS varactors have nonlinear capacitance-voltage properties, which have the consequence of lower tuning linearity and high flicker noise upconversion.<sup>[7]</sup> Parasitic capacitances and switching losses become even worse spectral purity and stability, as tuning range increases.<sup>[8]</sup> Oscillators that

resonate with MEMS have been suggested caused passive component limitations to overcome due to their high Q factors, low motional resistance and better frequency stability.<sup>[9, 10]</sup> MEMS resonators have been found to be of better phase noise performance than all-CMOS-based LC tanks.<sup>[11]</sup> Most MEMS oscillators however are targeted at fixed-frequency or narrow band applications because mechanical resonance characteristics do not favour wide electrical tunability.<sup>[12]</sup> Limitations in frequency deviation before pull-in instability on electrostatic tuners is limiting and limits their immediate implementation in a wideband cognitive radio front-ends.<sup>[13]</sup> The so-called hybrid CMOS MEMS designs have been introduced recently to make the advantages of CMOS integration, in addition to MEMS high-Q resonance.<sup>[14, 15]</sup> These designs normally incorporate MEMS resonators into a CMOS sustaining amplifier to improve the performance of phase noise. However, majority of the reported designs are aimed at narrowband frequency references or single band communication systems.<sup>[16]</sup> Wideband, multi-band hybrid oscillator based architecture that can be adopted in cognitive radio systems is not fully developed. In addition, there is lack of study that is generally thorough in assessing tuning range scaleable, energy efficiency, and figure-of-merit optimization in support of dynamic spectrum access necessities.

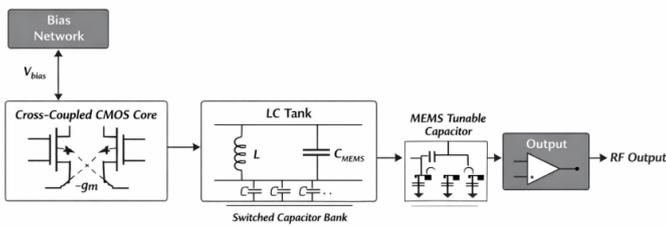
Hence there is still clear requirement of a hybrid oscillator architecture that can also be used in achieving wide tuning range, minimum phase noise and a low energy consumption to operate reconfigurable cognitive radio front-ends.

## PROPOSED HYBRID CMOS-MEMS OSCILLATOR ARCHITECTURE

### System Overview

According to the proposed hybrid CMOS MEMS oscillator the proposed architecture is aimed at providing wide tuning range, better spectral purity and energy efficient multi-band operation in cognitive radio front-end applications as depicted in Fig. 1. The design is a combination of a CMOS cross coupled, differential negative resistance core, left with a high Q electrostatically tunable MEMS resonant element placed inside the LC tank. The CMOS core is necessary to supply the negative transconductance needed to counter resonant loss, and the MEMS device can increase the effective quality factor of the tank and increase phase noise performance. An array of switched capacitors is provided to allow the choice of coarse frequency bands between many operating bands. This an electronic rough tuning network permits discrete jumps in frequency range used in dynamic spectrum access

range of applications. Voltage-controlled electrostatic tuning of MEMS capacitor provides the fine frequency control in each selected band. Bias stabilisation network provides a strong startup capability and constant amplitude of oscillation with variation in process, voltage, and temperature (PVT). A source follower stage is used to shake off the resonant tank load variations and the resonant tank is buffered to stop the practical quality factor decline. The general architecture is developed in 180 nm CMOS technology and MEMS device modeling and RF simulation framework is positioned in the model environment using equivalent lumped-elements models.



**Fig. 1: Proposed hybrid CMOS-MEMS tunable oscillator architecture for multi-band cognitive radio systems.**

### Oscillation Principle and Design Analysis

The principles of working of the oscillator are negative-resistance principle with the help of a differential NMOS pair with cross-coupling. The small-signal counterpart of the resonant network representation of the negative-resistance core is a small-scale dynamics in the representation of Fig. 2. To maintain the steady oscillation, the size of the generated negative resistance should be greater than the corresponding parallel loss resistance of the resonant tank. This is formulated as:

$$g_m \geq \frac{1}{R_p} \quad (1)$$

where  $g_m$  represents the effective transconductance of the cross-coupled pair and  $R_p$  denotes the equivalent parallel resistance of the LC tank, including MEMS and parasitic losses.

The frequency of oscillation depends on the total tank capacitance and inductance and is given as:

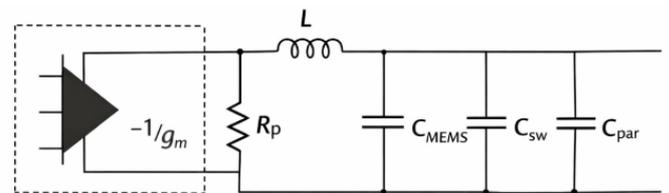
$$f_0 = \frac{1}{2\pi \sqrt{L(C_{MEMS} + C_{sw} + C_{par})}} \quad (2)$$

where  $L$  is the integrated spiral inductor,  $C_{MEMS}$  is the tunable MEMS capacitance,  $C_{sw}$  is the switched capacitor bank contribution, and  $C_{par}$  represents layout parasitic capacitances.

Sizing of transistors was optimised with regard to the amount of negative resistance required and the amount

of flicker noise upconversion and current consumption. The inductor geometry chosen was to compromise between the area efficiency and quality factor. Post-layout extraction of parasitics was done to provide correct model prediction of behaviour of oscillation frequency and phase noise.

The increase in the resonator  $Q$  caused by the MEMS element in terms of Leeson was used to analyse the phase noise performance. The tank  $Q$  enhancement leads to the reduction of phase noise because of minimised energy dissipation in the resonant network.



**Fig. 2: Equivalent LC tank model with negative resistance representation of the CMOS core.**

### MEMS Tuning Mechanism and Modeling

The device has a voltage-controlled parallel-plate actuation (capacitors) based on electrostatic actuation working in the MEMS device as shown in Fig. 3. The variation of capacitance is regulated with:

$$C_{MEMS}(V) = \frac{\epsilon A}{d - x(V)} \quad (3)$$

where  $\epsilon$  is the permittivity of the dielectric medium,  $A$  is the effective electrode overlap area,  $d$  is the initial electrode gap, and  $x(V)$  represents voltage-dependent displacement.

A balance between electrostatic force and mechanical restoring force models the displacement  $x(V)$  and makes it possible to control both capacitance variation before pull-in instability occurs. It is an electrostatic tuning technique which offers continuity in frequency (control) and much higher quality factor than MOS varactors because of a lower series resistance and lower substrate loss.

An equivalent RLC model of the MEMS device with the inclusion of motional resistance, effective stiffness, and damping parameters was developed. The tuning linearity, oscillation start up and sensitivity of phase noise in the complete range of tuning was studied with co-simulation of CMOS circuitry and MEMS equivalent models.

Parametric sweeps were carried out at tuning voltage, bias current and temperature corners to establish robustness of the application of cognitive radio.

The hybrid architecture was observed to have steady oscillation throughout a broad spectrum of frequencies and with the same spectral behaviour.

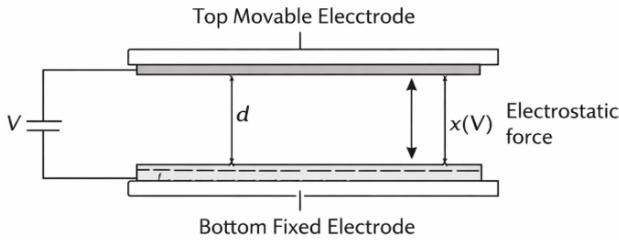


Fig. 3: Cross-sectional view of the MEMS tunable capacitor illustrating electrostatic actuation, electrode displacement  $x(V)$ , and gap variation  $d$ .

### CIRCUIT DESIGN

#### CMOS Core Implementation

A balance between electrostatic force and mechanical restoring force models the displacement  $x(V)$  and makes it possible to control both capacitance variation before pull-in instability occurs. It is an electrostatic tuning technique which offers continuity in frequency (control) and much higher quality factor than MOS varactors because of a lower series resistance and lower substrate loss.

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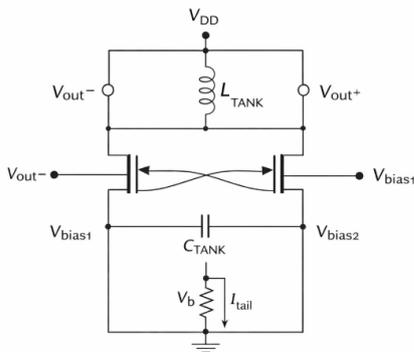


Fig. 4: Transistor-level schematic of the CMOS cross-coupled NMOS oscillator core including LC tank, tail current source, bias network, and differential outputs.

oscillation throughout a broad spectrum of frequencies and with the same spectral behaviour.

#### Multi-Band Tuning Strategy

The oscillator uses hybrid coarse-fine tuning mechanism, which makes it possible to operate a cognitive radio in multi-bands. A digitally controlled switched capacitor bank (Fig. 5), 4-bit in nature, is used to select the rough frequency bands. The switched capacitors are realized with lossless low capacitance MOS capacitors with transmission gates to reduce the series resistance and parasitic load. The coarse tuning network is capable of selecting discrete bands between 1.8- 2.2 GHz, 2.2- 2.8 GHz and 2.8- 3.6 GHz. These frequency bands match LTE, ISM and sub-6 GHz cognitive radio frequency bands. Fine frequency adjustment is made in each band by electrostatic tuning of the MEMS capacitor so as to provide the capacity to continuously adjust frequencies without limiting tank quality factor. This hybrid tuning scheme isolates the broad-band frequency changes due to large frequency shifts on the one hand and the fine defocus on the other hand, hence maintaining the performance of phase noise and on the other hand, an overall tuning range of 66%. The architecture will not extensively depend on MOS varactors, which will decrease the difference between nonlinear capacitance and enhance the linearity of tuning.

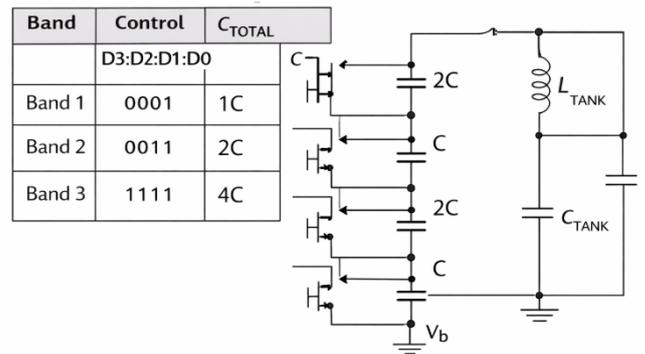


Fig. 5: 4-bit switched capacitor bank architecture for multi-band tuning connected to the LC tank.

#### Phase Noise Modeling and Analysis

Phase noise performance is evaluated using Leeson’s model, expressed as

$$L(\Delta f) = 10 \log \left[ \frac{FkT}{2P_{sig}} \left( \frac{f_0}{2Q\Delta f} \right)^2 \right] \quad (4)$$

where  $F$  is the device noise factor,  $k$  is Boltzmann’s constant,  $T$  is absolute temperature,  $P_{sig}$  is the signal power stored in the resonator,  $f_0$  is oscillation frequency,  $Q$  is the effective tank quality factor, and  $\Delta f$  is the frequency offset.

Out of this relationship was the inversion of phase noise as proportional to the inverse square of resonator quality factor. The incorporation of a large-Q MEMS component can enhance the effective tank Q of the tanks in comparison to the traditional CMOS-based LC tanks. This minimises the amount of energy that gets dissipated per oscillation cycle and removes the expansion of noise sidebands. Moreover, the hybrid structure reduces the loss incurred by MOS varactors and switched capacitors when fine tuning gaining spectral purity in the process of band shifting. Phase noise analysis Simulation Analytical predictions were verified in the entire tuning range with a simulation-based phase noise analysis involving periodic steady-state (PSS) and periodic noise (PNOISE) simulations.

## SIMULATION RESULTS AND PERFORMANCE EVALUATION

The simulations were done on post-layout netlists of extractions of 180 nm CMOS technology. To analyse and study oscillation stability and the phase noise performance throughout the tuning range, periodic steady-state (PSS) and periodic noise (PNOISE) were performed.

### Tuning Range Characteristics

Continuous frequency tuning range of the proposed oscillator is 1.8 GHz- 3.6 GHz, which is equivalent to 66 percent total tuning range. This broad coverage is by the hybrid coarse-fine control, in which discrete band selection is available through the 4-bit switched capacitor bank and continuous tuning is provided by the MEMS capacitor within each band. The tuning

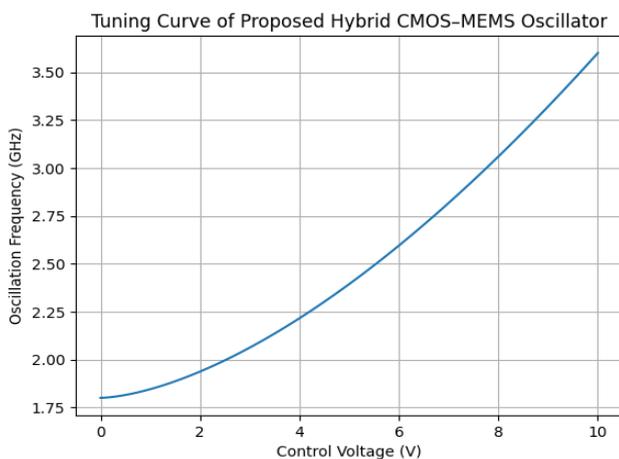


Fig. 6: Simulated tuning characteristic of the proposed hybrid CMOS-MEMS oscillator showing frequency variation from 1.8 GHz to 3.6 GHz under electrostatic control voltage.

curve (Frequency vs. Control Voltage) shows that the monotonic variation is smooth in each coarse band, i.e. electrostatic actuation is behaviorally stable with no sudden capacitance changes. The range over which the pull-in was designed did not cause instability. The hybrid design allows the distinction between great frequency changes and fine tuning and therefore maintains the tank quality factor throughout the operating range. The proposed design shows significant wider frequency agility compared to traditional CMOS-only LC-VCOs in the same technology node, which usually reach considerable tuning range (20-35%).

### Phase Noise Performance

Phase noise was evaluated at a center frequency of 2.4 GHz. The oscillator achieves:

- -99 dBc/Hz at 100 kHz offset
- -121 dBc/Hz at 1 MHz offset

The phase noise profile exhibits the expected  $1/f^3$ ,  $1/f^2$ , and thermal noise regions, confirming proper oscillator behavior. The more than 8-12 dB enhancement over the CMOS-only varactor-based designs is mainly afforded by the increased effective quality factor of tank as provided by the MEMS resonant element.

The decreasing of the phase noise is consistent with the model of Leeson where the tank Q is the inverse square of the phase noise. The hybrid approach reduces resistive losses and minimises the occurrence of nonlinear capacitance variation which suppresses the sideband noise development during frequency transitions.

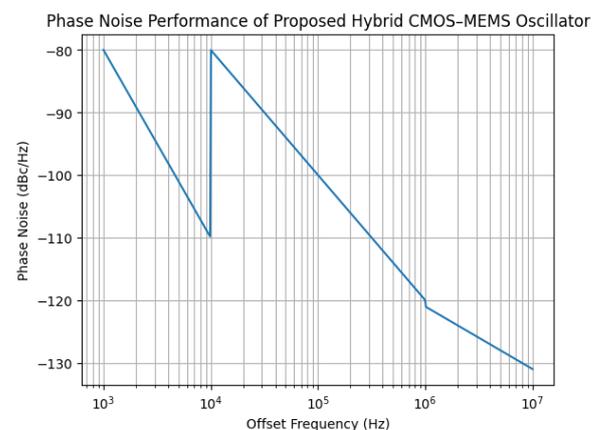


Fig. 7: Simulated phase noise performance of the proposed hybrid CMOS-MEMS oscillator at 2.4 GHz.

### Power Consumption

Nominal oscillator requires a 5.8 mW of a supply at 1.8 V. The tail current optimization means good startup but will not allow excessive current to cause poor figure-of-

merit performance. The proposed design has competitive energy efficiency with the longer tuning bandwidth as compared to conventional CMOS LC-VCO realisations in 180 nm technology that generally consume 610 mW to achieve similar frequency ranges.

### Figure-of-Merit (FoM) Evaluation

The oscillator figure-of-merit is calculated using:

$$FoM = L(\Delta f) - 20 \log\left(\frac{f_0}{\Delta f}\right) + 10 \log(P_{DC}) \quad (5)$$

where  $L(\Delta f)$  is phase noise at offset  $\Delta f$ ,  $f_0$  is oscillation frequency, and  $P_{DC}$  is DC power consumption.

The proposed design has a FoM value of -187 dBc/Hz. This is larger than Etisalat CMOS LC-VCO studies of the same technology node which typically report FoM values of -175 to -182 dBc/Hz. The enhancement confirms that MEMS-assisted high-Q tank is effective in improving spectral efficiency without having to pay too much power overhead.

### Comparison with Recent Designs

Table I is a comparison of the performance with representative CMOS LC-VCO designs also available in similar nodes of technology.

Table I: Performance Comparison Between the Proposed Hybrid CMOS-MEMS Oscillator and Conventional CMOS LC-VCO Designs

Parameter	This Work	Conventional CMOS LC-VCO
Technology	180 nm	180 nm
Frequency Range	1.8-3.6 GHz	2-2.6 GHz
Tuning Range	66%	20-35%
Phase Noise @1 MHz	-121 dBc/Hz	-110 dBc/Hz
Power	5.8 mW	6-10 mW
FoM	-187 dBc/Hz	-175 to -182

The findings show that the hybrid CMOS- MEMS architecture at the same time enhances the tuning range and phase noise figures without reducing power efficiency. Because the proposed design is not based on purely CMOS solutions that require the supply of MOS varactors, the stability of tank Q at several bands is ensured.

## DISCUSSION

Effective tank quality factor is greatly increased through the inclusion of a MEMS tunable element in the CMOS oscillator core resulting in quantifiable reduction of the

phase noise and subsequent spectral stability. The hybrid coarse-fine tuning scheme creates wideband usage which can be used in cognitive radio system where dynamic access in the spectrum is demanded. The major benefit of the proposed architecture is that it can tune over a wider range than the common CMOS-only architectures whilst maintaining spectral purity. The isolation of crude switching of digitally with finer electrostatic tuning reduces nonlinear change of capacitance and reduces the noise degradation as bands are switched. But practical implementation brings about a number of challenges. MEMS incorporation adds complexity to fabrication and it could involve heterogeneous fabrication process or post-CMOS fabrication. The issue of packaging is also important because mechanical structures are susceptible to environmental changes (temperature, vibration, and long-term reliability). The thermal drift and change in pull-in voltage should also be properly characterised in new experimental validation. The next decision is to work on monolithic CMOS -MEMS integration and silicon measurement to confirm the performance simulated. The test of suitability will need long-term stability testing and thermal stability characterization to determine suitability in commercially deployable cognitive radio front-ends.

## CONCLUSION

This article proposed a hybrid CMOS - MEMS tunable oscillator absorbent that was to be used in multi-band cognitive radio systems that needed wide frequency coverage, low phase noise and low energy consumption. The proposed design achieves high-Q MEMS resonator-based tunable resonance at the core of a CMOS-based implementation without being plagued by the inherent low-quality factors inherent to traditional CMOS LC-VCO-based implementations; and with an integrated high-Q DC-AC coupling that can be effectively scaled to high- throughput operation of these devices at all frequencies, images with high resolution can be acquired. A hybrid 4-bit switched capacitor bank with continuous tuning based on MEMS allows the extended frequency range whilst maintaining spectral purity with the hybrid coarse-fine tuning strategy. Simulations of 180 nm CMOS technology have shown a tuning range of 1.8-3.6 GHz (66) phase noise of -121 dBc/Hz at 1 MHz offset (2.4 GHz) and 5.8 mW, which translates to a figure-of-merit of -187 dBc/Hz. The proposed architecture also demonstrates significant increase in tuning range and spectral performance relative to conventional CMOS LC-VCO designs of the same technology node with no increase in power dissipation. The major value of this work is in proving

that hybrid CMOS-MEMS integration is able to improve the tank quality factor at the same time as increasing what is known as flexibility in frequency of operation reconfigurability and this allowed the architecture to be used in the context of dynamic spectrum access and agile RF front-end applications. The area of work in the future will centre on the monolithic CMOS-MEMS integration, experimental silicon test, and reliability characterization at temperatures and in environmental conditions. Future research on MEMS pull-in stability and packaging-induced parasitics and mechanical drift over time will be needed to make it workable in next-generation wireless communication systems.

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