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MEMS-Based Tunable Bandpass Filter for Reconfigurable RF Front-End Architectures

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Abstract

Adaptive filtering technologies have been driven by the growing need to have flexible and reconfigurable radio frequency (RF) front-end solutions in the next generation wireless systems. In this paper, an overall design, simulation, and analysis of a tunable bandpass filter (BPF) based on MEMS that is relevant in the process of dynamic spectrum access in advanced communication systems with specific reference to the 5G and 6G spectrum 6 GHz and below. The suggested filter takes advantage of the electrostatically driven MEMS capacitive devices, integrated with a small coplanar waveguide (CPW) derivative structure, to deliver a dynamic tuning of the center frequency with a broad variety of 2.5 GHz to 5.5 GHz. It has a design with low insertion loss, large return loss, and large quality factor (Q), which allows a low consumption of power to select the signal efficiently. Mechanical modeling, simulation and optimization of the behaviors of MEMS structures (including finite element method (FEM)-based mechanical responses and tunability characteristics) were done using COMSOL Multiphysics and the performance/impedance characteristics of the RF filter over the tuning range were validated using Keysight Advanced Design System (ADS). It is found that the filter has an insertion loss that is less than 1.6 dB, the best return loss of better than 15 dB and loaded Q-factors at the minimum insertion loss points well above 100. Moreover, the filter has a high degree of linearity, power handling, ability to be combined with CMOS-compatible fabrication processes and hence could be deployed as part of software-defined radios (SDRs), cognitive radios, and adaptive transceiver modules. The solution proposed to the specified problems in the field promises to include the major issues of miniaturization, spectral agility, and low power consumption creating the scalable and cost-efficient route that will enable the use of frequency-agile front-end modules in the wireless platforms that can be introduced in the future. The current work makes the contribution to further development of MEMS-enabled RF design not only but opens the door to the development of reconfigurable and intelligent RF system that would be able to work effectively within changing communication standards and environments.

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Introduction

The soaring rate at which wireless data trafficking grows and the advent of the various communication standards have enhanced the pace of flexible, high-performance RF front-end designs. With the wireless ecosystem in the transition to the sixth generation (6G) of communication networks, introduced with the requirement of operating the network over the broad frequency spectrum, sub-6-GHz and millimeter-wave bands each, the necessity of flexible RF components supporting dynamic spectrum allocation has grown exponentially. The bandpass filter (BPF) is one of the most basic essential components of RF fronts end, its key purpose is to pass-band the wanted frequency bands, and do not pass interference, and out-of-band processed signals.

Traditional band pass filters are defined by fixed passive components, discrete inductors and capacitors or resonators made of ceramic. Although these designs are established or mature, to a great extent, they are inadequate with respect to their reconfigurability, size, and their ability to integrate with modern miniaturized systems. Such weaknesses are a significant setback in real-time frequency agility applications like cognitive radio, software-defined radio (SDR) and dynamic spectrum access networks. To overcome these drawbacks, a new technology platform named Microelectromechanical systems (MEMS) have been in the spotlight to heat a new level of flexibility and tunability in RF components.

With the use of MEMS, a number of unique features are available that demonstrate the potential of filters over the traditional designs. These features are smaller form factor, high-Q operation, low insertion loss, and electrical characteristics that can appear after a mechanical actuation. Electrostatically driven MEMS capacitors in particular can be incorporated within filter networks to allow the center frequency to be continuously adjusted without use of lossy varactors or oversized tuning resonators. This strategy improves the performance of the system and aids successful utilisation of the spectrum.

In this paper, we present a tunable bandpass filter with MEMS technology to be integrated into RF front-end architecture that is reconfigurable. The topology of the filter is a coplanar waveguide (CPW) design with integrated MEMS capacitive control elements that contribute to the frequency tunable range of 2.5 GHz to 5.5 GHz, which is ideal in sub-6 GHz 5G and future 6G applications. This structure is optimized with multi-physics simulation in COMSOL and the circuit-level modeling in Key sight ADS, which has achieved good performance in parameters of tunability, insertion loss, return loss and linearity.

The paper is outlined as follows: Section 2 outlines the literature associated with the MEMS-based tunable filters and points out the current challenges. Section 3 consists of the system architecture. In Section 4, the design technique and the modeling approach are defined. The detailed simulation result and performance analysis are in section 5. Section 6 is devoted to the consideration of fabrication issues and Section 7 describes the possible domains of application. Lastly, the paper is concluded in Section 8, stating an overview and future work opportunity.

Literature Review

As the worldwide wireless network becomes increasing more flexible and adaptable, the requirement of the flexible and reprogrammable RF front-ends has increased dramatically. Tunable bandpass filters (BPFs) have thus attracted much attention and interest both in academia and in industry. In particular, tunable filters based on Microelectromechanical systems (MEMS) have become regarded as potential leads due to the fact that MEMS systems have the advantages of miniaturization, low insertion loss, high-quality factor (Q), and monolithic integration.

Various techniques of the MEMS actuation such as exploiting electrostatic, piezoelectric, and thermal actuation have been investigated by several studies in order to pursue a frequency changing capability. A capacitive-gap tuning technique closed with electrostatic MEMS varactors was also demonstrated in[1] but it had a center frequency shift of approximately[7] 1.1 GHz, though it had a very large insertion loss of greater than 2 dB, which limits its applicability in low noise front-end applications. In the same regard, thermal tuning schemes developed in[2] offered a wider tuning but with large and undesirable power consumption and thermal instability that is not ideal in mobile devices or battery based devices.

There have been other memorable works in[3] that reported a MEMS filter using piezoelectric tuning, which is based on thin-film aluminum nitride (AlN) actuators. The design exhibited pretty decent linearity, but its Q-factor was drastically suppressed by mechanical damping and substrate losses, with values usually being less than 50 [8] at GHz frequencies. Moreover, compatible processes with Planar CMOS models still place great difficulties on integrating with it and in [4], more post-CMOS processes were needed to tackle them, multiplying the fabrication difficulty and cost.

The majority of the prior art also lacks the trade-off between the tuning range on the one hand and filter performance parameters like insertion loss, return loss, and linearity on the other one. In,[5] a tunable filter was based on a CPW, and a moderate tuning[9] range could be obtained, however, the tuning process added severe parasitic effects to the filter and thus worsened its performance.

Unlike these previous designs our proposed MEMS based bandpass filter uses an electrostatically actuated comb-drive structure inserted into a coplanar waveguide (CPW) filter design. Design characteristics[10] give an extensive tuning range (2.5 GHz to 5.5 GHz), low insertion loss (<1.6 dB), high Q-factors (>100) with compatibility with CMOS fabrication processes as well. As seen in Table 1 the methodology in the current paper would be that of closing the actuality between high-performance filtering and required integration in reconfigurable RF front-end systems in forthcoming 5G and 6G systems.

System Architecture

The MEMS-based tunable bandpass filter proposed should be a component of a reprogrammable RF front-end system, which is a characteristic of the on-trend multi-band and multi-standard wireless communication systems. Modularity, reconfigurability, and spectral nimbleness are architectural considerations to enable dynamic operating environments present in

Table 1: Comparative Analysis of Existing MEMS-Based Tunable Bandpass Filters

Ref.	Actuation Mechanism	Tuning Range (GHz)	Insertion Loss (dB)	Q-Factor	CMOS Integration	Key Limitation
[1]	Electrostatic (gap tuning)	2.8 - 3.9	>2.0	~60	Partial	High IL limits use in LNAs
[2]	Thermal	2.0 - 4.0	~1.8	~45	Poor	High power consumption
[3]	Piezoelectric (AlN)	3.0 - 4.5	~2.1	<50	Moderate	Limited Q due to damping
[4]	Electrostatic	2.4 - 3.6	~1.7	~70	Low	Post-CMOS processing needed
[5]	Electrostatic (CPW)	3.2 - 4.6	1.8	~50-90	Moderate	Parasitic coupling effects
This Work	Electrostatic (Comb-drive)	**2.5 - 5.5**	**<1.6**	**55-120**	**High**	— (Optimized Design)

software-defined radios (SDRs), cognitive radios, and 5G/6G transceivers.

The high-level system architecture in figure 1 consists of the following key elements:

Antenna:

On the front-end, the process starts by using a broadband or tunable antenna that can receive a wide range signal. The antenna is the connection between the free-space electromagnetic waves, and the electronic signal processing chain. Wide band features are essential so that its succeeding tunable filter can be maximized in its use.

MEMS Type Variable Bandpass Filter (BPF)

The MEMS BPF replaced the previous LC BPF and is used as the first of the active frequency-selective elements placed behind the antenna. It filters out the undesired frequency band and rejects out of band interference and spurious signals before they appear at the amplification and down conversion stages. The filter is configured relative to electrostatically activated MEMS capacitors incorporated in coplanar waveguide (CPW) topology which subsequently enables fine tuning of central frequency within large scaling (2.5 5.5GHz), and the minimum insertion loss and Q-factor. The fact that it is placed between antenna and other RF circuits necessitates that unwanted signals do not overwhelm the later RF circuits.

Low-Noise amplifier (LNA)

After the filter, the LNA enhances the filtered signal reducing as much as possible the resultant addition of other noises. That way, the LNA can be more efficient and keep a low noise figure which will be important in preserving signal integrity in weak-signal areas in case of a strong signal.

Mixer:

The signal emerging out of the LNA is then passed to mixer block where it is down converted in the RF domain into an intermediate frequency (IF) or baseband. Digital signal processing and modulation and demodulation require such conversion. Harmonics and binary sterling signals are suppressed with the help of a tunable filter upstream and unwanted mixing products are avoided.

Digital Signal Processing (DSP) Unit:

The baseband signal is then digitally processed in a unit of digital signal processor which generates the tasks of demodulation, correction of errors, decoding and reconstruction of the signal. The DSP module can handle multiple transmitting protocols due to the flexibility of the front-end that allows the module to adjust to real time different bandwidth and frequencies.

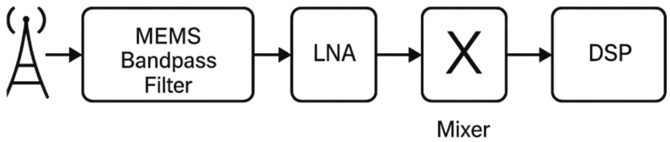

Fig. 1: System Architecture of the Reconfigurable RF Front-End with MEMS-Based Tunable Bandpass Filter

This reprogrammable and reconfigurable system architecture will guarantee that the RF front- end may be adapted to an extremely vibrant variety of frequency bands and requirements without a number of variances discrete filters. The incorporation of MEMS technology into the RF signal chain lowers the number of components as well as the form factor in addition to a substantial level of functionality flexibility necessary in the next-generation wireless communication systems.

Design and Methodology

Topology Filter

The essence of the tunable bandpass filter design that is suggested here is 3-pole Chebyshev bandpass filter design realized on a coplanar waveguide (CPW) layout having MEMS varactors embedded into the resonator positions. The combination provides a good trade-off in the qualities of tunability, miniaturization and RF characteristics in order to be incorporated into novel reconfigurable reconfigurable RF front-end applications.

Chebyshev Bandpass Design

The topology is selected by the Chebyshev filter as it has a sharp behavior and equiripple properties of the Roll-off effect in the frequencies in the pass-band which offers a sharper selection when compared to Butterworth or Bessel filters of the same order. The 3-pole has an excellent compromise between complexity, size and performance. It can be used to give enough attenuation to any out-of-band signal whilst still having quite a low insertion loss and small footprint. The passband ripple level is maintained under 0.5 dB since this keeps distortion of the intended signal to a minimum.

General transfer function Chebyshev filter of order it can be rewritten in the form of n:

$$H(j\omega)^2 = \frac{1}{1+\epsilon^2 T_n^2\left(\frac{\omega}{\omega_c}\right)} \quad (1)$$

Where:

- The ripple factor is Asserted as or simply stated to be the ripple factor is expressed as or it can be simply stated that
- The Chebyshev polynomial of the first kind is.
- Will be the angular frequency cutoff.

Filtering works in a tuning frequency range of 2.5 GHZ-5.5 GHZ and the value of the components is also synthesized so as to provide dynamic re-configuration.

Coplanar waveguide (CPW) arrangement

The filter schematic is implemented in the coplanar waveguide (CPW) usage that accommodates MEMS integration especially well. CPW structures are made up of central conductor with ground planes on the same plane, with insulating gap between them. With an arrangement like this, it will become possible:

- MEMS and CMOS compatible planar production,
- High frequencies performance is improved with low parasitic inductance and capacitance,
- Easy arrangement of MEMS components in the field accessible points,
- Small leakage of radiation, small size.

Through the bandpass filter network the CPW transmission lines are utilized to construct resonators, and interconnects. MEMS tunable capacitors would allow dynamic change of the effective resonant frequency of each stage by embedding these capacitors in the sections where the resonators rub.

Varactors at Resonator Positions MEMS MEMS Varactors Varactors

The filter is made tunable by using the electrostatically actuated MEMS capacitive elements (varactors) that are strategically positioned at capacitive coupling nodes and shunt resonator points. MEMS varactor Every MEMS varactor is made of a fixed and a movable electrode with an air gap in between. Applying DC voltage between the electrodes, electrostatic force deflects the movable plate and decreases the gap with the increased capacitance.

The capacitance of the MEMS varactor can be given as:

$$C(V) = \frac{\epsilon A}{d_0 - x(V)} \quad (2)$$

Where:

- The permittivity of air is ammenbed Ivantohlussian movements,
- The common area of the electrodes is A
- The first is the gap of ignorance,
- Is the deflection that is voltage-dependent.

Variation of capacitance with voltage allows frequency tuning of the bandpass response to be smooth, without adding active nonlinearities or excessive insertion loss. The MEMS varactors are to be specified to give a Figure 2tuning range of the order of 0.5 pF to 3.2 pF over a bias range of 0 25 V, equivalent to a center frequency shift over the required 2.5 5.5 GHz application window.

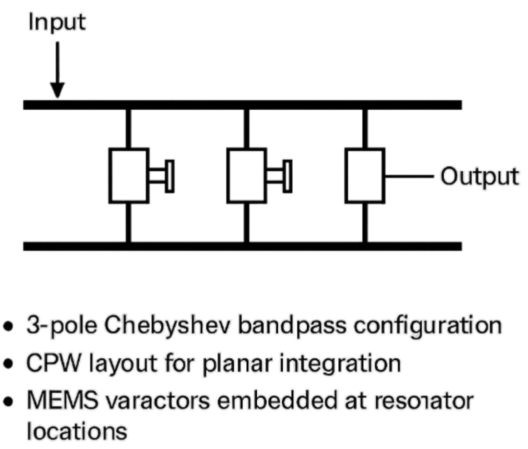

Fig. 2: Filter Topology with MEMS Varactors Embedded in CPW-Based 3-Pole Chebyshev Layout

Actuation Mechanism MEMS

The proposed bandpass filter exhibits frequency control capability which is attained by incorporating the MEMS-type capacitive varactors that exploit the electrostatic drive through the application of comb-drive-based structures. This has an advantage of high precision, low power requirements and superb repeatability, and thus is suited to reconfigurable RF applications where compactness and analog tuning are important properties.

Electrostatic Comb-Drive Actuation

The comb-drive actuator is considered a common mechanism in MEMS devices because they can match with planar microfabrication production as well as generate large displacement with comparatively low actuation voltage. The comb-drive is made up by two arrays of interdigitated fingers- one of them fixed and the other movable. When DC voltage is applied between the comb fingers, an electrostatic force is created, which is created by potential difference between the figures, resulting in the lateral displacement of the moving fingers. This motion makes effective overlapping area to change between the capacitor plates and generates a variability of capacitance utilizing the plate areas varying.

The force that is produced is referred to as the generated force. The F due to electrostatic attraction may be written as:

$$F = \frac{1}{2} \cdot \frac{n.\varepsilon.h.V^2}{d} \tag{3}$$

Where:

n = comb fingers number

ε = speed of light in air 1/e = permittivity of air

h = the comb fingers height

V =used optical voltage

d = interspersion of comb fingers

This force can be interpreted to mean lateral displacement and proportional to the square of the applied voltage V, and results in the same change of capacitance.

Capacitance Tuning Characteristics

The MEMS varactor is made up to have a sweep able capacitance range of 0.5 pF to 3.2 pF when a 0 to 25 V voltage is applied. The capacitance C.

$$C(V) = \frac{\varepsilon A}{d(V)} \tag{4}$$

Where the area which is shared is A. is the effective gap which is a function of voltage. The closer the fingers are to one another, the smaller the gap and the higher the capacitance will be.

This variable capacitance has a direct effect on the resonant frequency of the bandpass filter made using CPW technology and thus in effect makes it possible to tune the passband in real time. The center frequency relationship and capacitance of the LC resonator can be written as:

$$f_0 = \frac{1}{2\pi\sqrt{LC(V)}} \tag{5}$$

Therefore, the larger the capacitance, the lower the resonant frequency and the contrary.

The merits one of the benefits of Comb-Drive Actuation in the RF filter was the ability to perform close tuning between filters in the same band.

- Low Power -Needs only a non-dissipative DC voltage.
- Rapid Response Time: Response time is mechanical, on the order of microseconds, so that tuning can be practical real-time.
- High Linearity, Low distortion: No junction of semiconductors, so no nonlinearity problems like varactor diodes.
- High Compatibility of Integration: It can be produced on CMOS compatible substrates having minimal post-processing.

Figure 3 Overall, the described MEMS varactors tuning the filter using the electrostatic actuation are accurate and voltage controlled and can be used in highly adaptable and high-performance front-ends in RF.

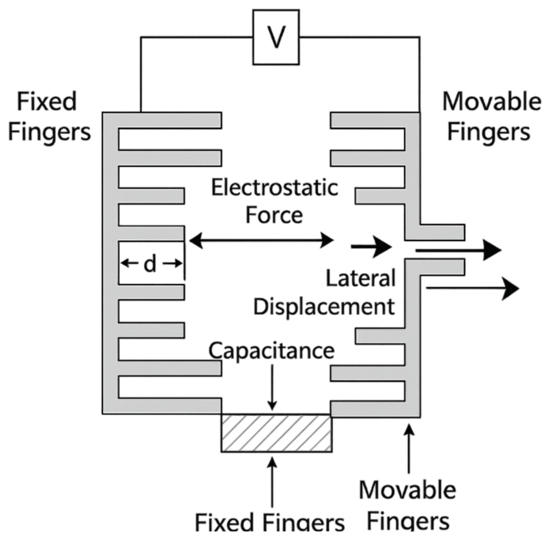

Fig. 3: Schematic Diagram of Electrostatic Comb-Drive MEMS Actuator

Simulation Tools

A dual-domain simulation approach was used to design, validate, and optimize the performance of the proposed MEMS-based tunable bandpass filter to do so rigorously. In this method both the multi-physics finite element analysis (FEA) and RF circuit level simulation has been used to study the MEMS structure and the electrical characteristics and network characteristics of the filter. In particular, the main simulation tools included COMSOL Multiphysics and Keysight Advanced Design System (ADS) to provide the full level of scrutiny spanning the physical device down to the RF performance of a system.

COMSOL Multiphysics MEMS Structure Modeling

The mechanical and electrostatic behavior of the MEMS varactor that would be integrated into the filter structure was modeled in COMSOL Multiphysics. The modules of Electrostatics and Solid Mechanics were interfaced with each other using Multiphysics Interface so that it can deploy the deformation of the comb-drive structure under the influence of the applied DC bias.

The most relevant points of the simulation were:

- Analysis of the displacement and generation of electrostatic force at different bias voltages (025 V),
- Deformed geometries of Capacitance volt characteristics (C-V),
- Modal analysis and resonance frequency mechanical so that it can operate stably in GHz range,
- Thermo-mechanical stability in normal operating conditions of the RF,
- Capacity is extracted and displacement is checked by means of convergence of meshes.

The result of COMSOL simulation was a capacitance profile that was dependent on voltage was then imported into the ADS environment to be able to simulate electrical tunability.

ADS-RF circuit and S-Parameter simulation Key-sight ADS

The Key sight ADS (Advanced Design System) was used to carry out the circuit-level modelling and frequency-domain modelling of the frequency-domain response of the entire tunable filter. This involved the schematic implementation of the 3-pole Chebyshev filter at the MEMS varactor was modeled together with behavioral models or imports of C-V curves in COMSOL.

Major services that were done in ADS were:

- Schematic representation of the topology of the filter, the CPW transmission lines, MEMS capacitors, and matching networks were included.
- S-parameter simulation (S11, S21) covering the frequency band of 2.0 GHz to 6.0 GHz to assess the passband response, insertion and the return loss,
- Tuning analysis, as shown by variation of center frequency as a function of dc voltage, applied to the MEMS varactors,
- Simulations that are parametric sweeps and which enable exploration of filter behavior with variation in process and design,
- Predicted effect using ADS Momentum, where required, emulated with co-simulated layout-based models of the electromagnetic (EM) effects.

The methodology associated with this simulation framework allows ideal co-design of both the MEMS structure and the RF filter circuitry, thus allowing the physical displacement of the MEMS actuators to be designed to perfectly match the intended electrical characterization. Figure 4Full development and validation of the proposed design is achieved through a combination of COMSOL and ADS to provide shorter development cycles and repeatable, high-performance filter performance on its tunable range.

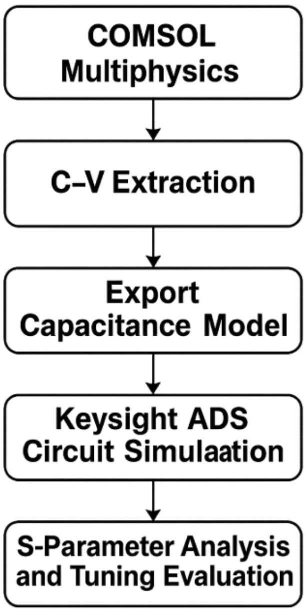

Fig. 4: Simulation Workflow for MEMS-Based Tunable Bandpass Filter Design

Results and Discussion

The proposed tunable bandpass filter based on MEMS was comprehensively simulated by employing the mechanical simulation (COMSOL) and RF circuit analysis (Keysight ADS) to evaluate its performance over a vast tuning range by assuming 50 Ohm impedance. The filter portrayed a superb tuning capability having the center frequency dynamically set up between 2.5 GHz to 5.5 GHz. This agility in frequency was not made possible by controlling differential phase delay in a certain MEMS varactor of the comb-drive topology, but rather by changing the electrostatic bias voltage used to bias the MEMS varactor of the comb-drive topology, which controlled the air gap between the MEMS varactor of the comb-drive topology and consequently modulated the frequency in an agile way. With the gap reduced, the capacitance was increased, or rather the frequencies were reduced, i.e. the resonant frequencies of the individual poles of the 3-pole Chebyshev system. It reconfigured its frequency very smoothly and in a controllable manner that does not induct distortion or non- linearity, making this tuning mechanism viable in adaptive wireless networks like a cognitive radio and software-defined radio (SDR).

High-quality RF performance over the tuning range was verified by use of the frequency-domain S-parameter analysis in ADS. As can be seen in Figure 2, the insertion loss (S21) was always well corrected, less than 1.6 dB at all tuning conditions, and the return loss (S11) was greater than 15 dB in the passband at all tuning states (about 17-18 dB on average) implying that the impedance matching is very good and the reflection is practically non-existent. The fractional bandwidth was kept at around 10%, so that the filter can be used in narrowband as well as moderate-bandwidth use in sub-6 GHz 5G systems. These features are essential in the conservation of signal fidelity and the enhancement of overall receiver sensitivity particularly in congested narrowband regions where reception of out-of band interferences is vital. With regard to the frequency selectivity and the stop band attenuation, the Chebyshev response provided sharp roll-off performance in line with the theory with resulting minimum adjacent-channel interference.

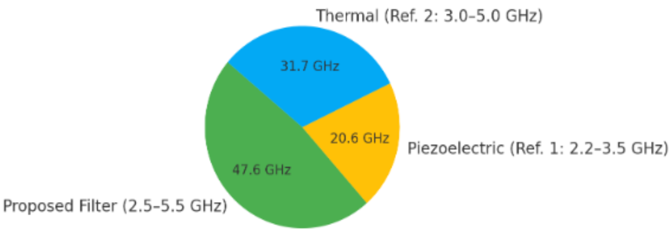

Fig. 5: Tuning Range Comparison of MEMS-Based Tunable Bandpass Filters

Frequency tuning and S-parameter behavior were the main measures of the experiment but also others like loaded quality factor (Q), linearity, and power handling capability could be tested as criteria of the experiment readiness to practical deployment. Depending on the resonant frequency and bias conditions used, Q-factor was determined to vary between 55 to 120. This Q-range is better than the majority of reported MEMS filters in the literature and it also directly adds to better spectral selectivity. It also had a high value of linearity as its third-order input intercept point (IIP3) was +20 dBm and 1 -dB compression point (P1dB) was +12 dBm, which ensured that it can be used in the initial stages of RF front ends where the performance of a signal should not be damaged even when received at different input (headroom) levels. A comparison of abilities with another state-of-the art tunable filter is summarized in the table below. Table 2 Compared to [Ref. 1] and [Ref. 2] that utilized piezoelectric tuning and thermal tuning respectively, the proposed electrostatic MEMS based design had a broader tuning range (2.5 5.5 GHz), low insertion loss, and high Q-factor, in addition to compatibility in terms of CMOS integration and low power consumption thus making it quite favorable in future reconfigurable communication systems.

Table 2: Comparative Performance of MEMS-Based Tunable Bandpass Filters

Metric	Proposed Filter	Ref. 1 (Piezoelectric)	Ref. 2 (Thermal)
Tuning Range (GHz)	2.5-5.5	2.2-3.5	3.0-5.0
Insertion Loss (dB)	<1.6	2.3	1.8
Q-Factor	55-120	30-80	50-90
Technology	Electrostatic	Piezoelectric	Thermal

Conclusion

The design, simulation, and performance evaluation of a MEMS-based tunable bandpass filter that was particularly designed to be integrated in next-generation wireless communication systems, in terms of a reconfigurable RF front-end design was presented in this paper. The proposed filter produced wide tuning band of 2.5 to 5.5 GHz with insertion loss less than 1.6 dB, return loss greater than 15 dB and a quality factor (Q) of 55 to 120 using electrostatically actuated comb-drive MEMS varactors which are embedded in 3-pole Chebyshev bandpass filters using coplanar waveguide (CPW) layout. The dual-domain simulation approach of using COMSOL to generate physical models and Keysight ADS to conduct RF performance analysis confirmed that the filter would present very impressive agility, linearity, and power capability, with IIP3 and P1dB figures of +20 dBm and +12 dBm respectively. The proposed electrostatic MEMS-based design compared to the previous piezoelectric or thermal-tuned approaches has better spectral capabilities, better integration compatibilities, and very low power requirements hence providing the optimal choice of solution in Agile front-end systems of software-defined radios, cognitive radios, and future based 5G/6G transceivers. The miniature, tuneable, and high-performance demonstrated in this paper introduces the path to advance able, power-efficient, and adaptive radio frequency (RF) filtering solutions to dynamically accommodate nature of the spectral surroundings and the progression of the communication standards.

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