

TOPICAL REVIEW • OPEN ACCESS

RF MEMS electrostatically actuated tunable capacitors and their applications: a review

To cite this article: Fahimullah Khan and Mohammad I Younis 2022 *J. Micromech. Microeng.* **32** 013002

View the [article online](#) for updates and enhancements.

You may also like

- [Synergetic Effect of 5-Methyl-1H-Benzotriazole and Sodium Dodecyl Benzene Sulfonate on CMP Performance of Ruthenium Barrier Layer in \$KIO_4\$ -Based Slurry](#)
Yi Xu, Baimei Tan, Lianjun Hu et al.
- [Lessons learned from nanoscale specimens tested by MEMS-based apparatus](#)
Mohamed Elhebeary and M Taher A Saif
- [MEMS-based platforms for mechanical manipulation and characterization of cells](#)
Peng Pan, Wenhui Wang, Changhai Ru et al.

Topical Review

RF MEMS electrostatically actuated tunable capacitors and their applications: a review

Fahimullah Khan  and Mohammad I Younis*

Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

E-mail: Mohammad.Younis@kaust.edu.sa

Received 11 April 2021, revised 9 September 2021

Accepted for publication 24 November 2021

Published 8 December 2021



CrossMark

Abstract

This paper reviews the recent developments of micro-electromechanical system (MEMS) based electrostatically actuated tunable capacitors. MEMS based tunable capacitors (MBTCs) are important building blocks in advanced radio frequency communication systems and portable electronics. This is due to their excellent performance compared to solid state counterpart. Different designs, tuning mechanisms, and performance parameters of MBTCs are discussed, compared, and summarized. Several quantitative comparisons in terms of tuning range, quality factor (Q factor), and electrodes configurations are presented, which provide deep insight into different design studies, assists in selecting designs, and layouts that best suit various applications. We also highlight recent modern applications of tunable capacitors, such as mobile handsets, internet of things, communication sensors, and 5G antennas. Finally, the paper discusses different design approaches and proposes guidelines for performance improvement.

Keywords: tuning range, quality factor, parallel plate, microelectromechanical system, tunable capacitor

(Some figures may appear in colour only in the online journal)

1. Introduction

With the rapid global advancement of technology, there is an increasing demand for reconfigurable radio frequency (RF) components. Frequency tuning, RF tunable filtering, and tunable matching impedances can be promising solutions for handling numerous telecommunication standards, and eliminating the need for complex hardware. Nowadays,

there is an urgent demand for integrated RF systems of low cost, low power, reconfigurable frequency, and operation in multiband due to the requirements of advanced technologies, such as, internet of things (IOT) applications, 5G communications, and fast data communications.

Since inception, microelectromechanical systems (MEMS) have shown great potential to replace RF solid-state devices with superior RF MEMS devices. MEMS based tunable capacitors (MBTCs) exhibit much higher Q factor, and tunability as compared to semiconductor diodes tunable capacitors. MEMS tunable capacitors are employed in today's wireless transceiver's RF front-ends [1], as shown in figure 1. They are used in voltage controlled oscillators (VCOs), low noise amplifiers (LNAs), power amplifier, tunable filters, re-configurable phase shifters, and impedance matching

* Author to whom any correspondence should be addressed.



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

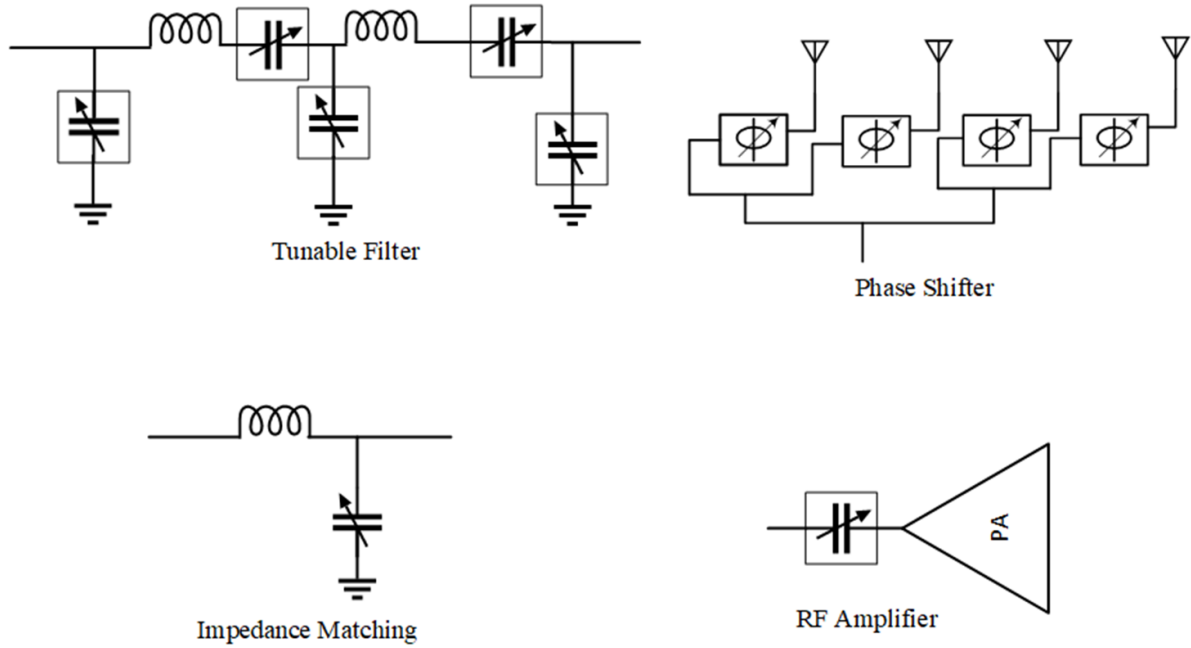


Figure 1. Block diagram of replaceable transceiver's components using RF MEMS technology.

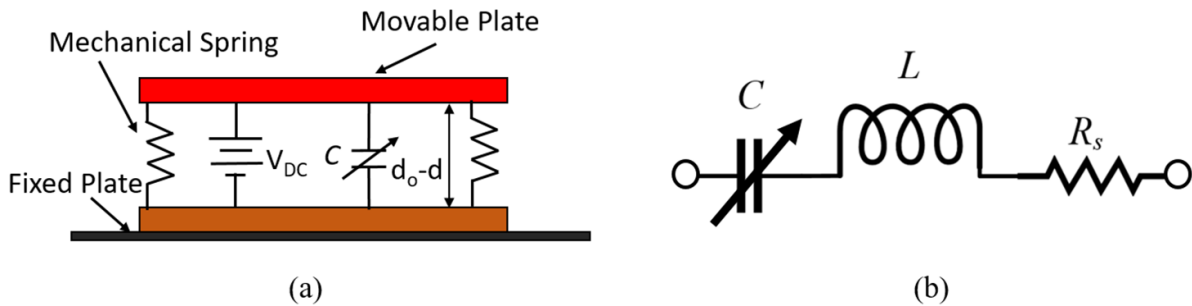


Figure 2. (a) Schematic diagram of a tunable parallel plate capacitor. (b) Electrical series equivalent model of tunable capacitor.

networks [2]. Reconfigurable passive components such as reconfigurable LC tanks, and tunable filters, not only improve the performance of the systems but also widen the reconfigurability of the systems, besides reducing the size and power consumption [3].

There are several approaches for the actuation of MBTCs, such as electrostatic, electro-thermal, magnetic, and piezoelectric. Among them, electrostatic is the most attractive and commonly employed actuation method for tunable capacitors due to the fast response, low power consumption, and compactness. However, it may require high voltages (10–50 V) [2]. Traditionally, there are three methods for tuning MBTC: the gap tuning [4–6], area tuning [7], and dielectric displacement tuning [8].

A typical implementation of a MEMS tunable capacitor is based on two parallel plate electrodes, one of the electrode is fixed and the second is movable, as shown in figure 2(a) and electrical series equivalent model is shown in figure 2(b). The capacitance is tuned by varying the air gap, by changing the electrode overlap area using electrostatic actuation, or by modifying the dielectric property of the gap between the parallel plates.

In this paper, a thorough review of electrostatically actuated tunable capacitor is presented. Advanced applications of tunable capacitors are presented in section 2. The performance figure of merits are evaluated in section 3. Different types of electrostatically tunable capacitors designs, development, and performance comparisons are presented in section 4. Finally conclusions are presented in section 5.

2. Advanced applications

RF MEMS tunable capacitors, and switches are ideal for reconfigurable circuits and systems. These systems include matching networks, RF receivers, RF filters, phase shifters, antennas, and oscillators/resonators. They have very low insertion loss, and high Q factor and can be integrated on low dielectric-constant substrates, which is important for high-performance tunable filters, high-efficiency antennas, and low-loss matching networks [2, 9, 10]. In addition, RF MEMS devices have very low intermodulation products/harmonics, which are critical for LNAs.

MBTC can be used for designing high performance RF filters. Tunable filters play important role in the communication industry, and are key part in almost every RF electronics and RF military equipment. Tunable filters are used for selection or rejection of desired channel from a wide band spectrum of RF signals. A compact tunable filter using tunable capacitor with improved stopband rejection has been presented in [11]. The 1.4–2.1 GHz filter has an insertion loss <2 dB with 1 dB fractional bandwidth of 12%–13%. This low loss is due to the high performance tunable capacitor implemented in modern communication systems. RF-MEMS tunable capacitor based tunable filters provide excellent performance in terms of tuning range and quality factor. Many other papers also reported utilizing MBTC for designing high performance RF filters [11–22].

MBTCs are also used in the development of RF phase shifters. Nowadays, for changing the radiation pattern, electronically scanned arrays have been utilized to change the phase of radiating part of the antenna, thereby guiding the radiation of the beams in space communications. The device used for creating phase differentiation among output terminal and input terminal is known as phase shifter. MEMS tunable capacitor based phase shifters have advantages over solid state counterpart due to small insertion loss, high linearity, low power, and high tunability. Several works have been reported in [23] for the development of phase shifters using MBTCs. In [24], an RF MBTC WS1042 designed by WiSpry has been used to steer the beam of an antenna using an innovative phase shifter. Simulations results confirm that considering 70° and 105° phase shift can cover more than 80° and 100° beam steering, respectively with a maximum gain of 7 dBi. Similarly, more recent works have been reported in [23, 25–30] utilizing RF MEMS tunable capacitor for the development of phase shifters.

Another common application of tunable capacitor is in matching networks. Matching networks are very critical for the design of LNA, power amplifier, VCO [31], etc. Normally, the frequency of operation in these devices remains fixed, but the power amplifier output impedance changes with time and one must tune the output matching network to get highest system efficiency. MEMS tunable capacitor based impedance matching networks are electronically tunable, provide low insertion loss, low power consumption, and good linearity. Therefore, several works have been reported [32–37], which utilize the MBTC as a basic component of the matching network.

Recently, MBTCs are used in mobile phones antennas tuning [23, 38, 39] and IOTs sensor communications [40, 41]. Tunable antennas have a great potential for enhancing the antenna bandwidth while keeping a low profile. MBTCs provides this important feature of tunability to the mobile phone antenna, 4/5G communication antennas, IOTs antenna with low insertion losses, and high quality factor [38, 42, 43]. The evolution of (4G-LTE) in smartphones resulted in the degradation of voice and data signal quality due to the integration of many electronic components with the antenna [44]. RF MEMS tunable capacitors integrated in impedance matching tuners enable impedance matching between the smart phone

antennas and RF front ends, which reduces the degradation of receiving signals. The IOTs are emerging technology through which 5/6G mobiles communicate with electronic machines, electronic sensors, robots, smart cars, and aerial drones independently. This requires high operating frequency in mmW spectrum for Gigabit (Gb) communications, large scale multiple inputs and multiple output units, and large frequency re-configurability while reducing hardware redundancy. RF MEMS technology is one of the promising candidate for IOTs and 5G technology. However, further efforts are needed in the development of RF MEMS devices operating at high frequency.

MBTCs are also utilized in tuning and impedance matching of multi-nuclear magnetic resonance imaging (MRI) coils for diagnosis, screening of bio-samples, and diseases due to their high quality and tunability [45, 46]. In addition, they have been recently utilized in tuning microwave circuits, such as half mode substrate integrated waveguide-complementary split ring resonator [47]. The resonance frequencies of 3.9 GHz and 7.35 GHz are tuned to 3.65 GHz and 6.6 GHz, respectively. The tuning range of capacitor is only 29%. Thus the resonance frequencies tuning ranges can be improved by using higher tuning range capacitors.

Table 1 shows the comparison summary of the electrostatically actuated tunable capacitors used in RF communication industry, electronics, and biomedical industry. It is clear from the table that the performance of electronic devices have been significantly improved in terms of low losses, high tunability, efficiency, and quality factor. Nonetheless, considerable research is still under way to integrate RF MBTCs in power electronics [48], sensors, and advance electronics.

Due to the evolution of modern communication technology and the advent of 5G, 6G and terahertz communication, the operating frequency of the communication systems have increasing trends [49]. Therefore, high frequency MBTC is growing in demand not only in research and development but also in the consumer markets due to clear advantages of MBTC over solid state capacitors.

3. Figures of merit

3.1. Quality factor

Quality factor (Q factor) is one of the most important figure of merit for tunable capacitors. It is defined as a measure of the loss in the microwave circuit, and mathematically is expressed as:

$$Q = \omega \frac{\text{average energy stored}}{\text{energy lost/second}}. \quad (1)$$

The tunable capacitor Q factor can be derived as:

$$Q = \frac{|\text{Im}(Z)|}{\text{Re}(Z)} = \frac{1}{\omega CR_s} \quad (2)$$

where C is the capacitance of the tunable capacitor, Im and Re refers respectively to the imaginary and real part of the impedance Z parameter, ω is the resonant frequency, and R_s is the

Table 1. Summary of tunable capacitors in recent works highlighting some modern applications.

References	Year	Type of application	Type of actuation	Frequency range	Tuning range	Performance enhancement
[11]	2016	RF filter	Transverse electrostatic parallel plate	1.4–2.1 GHz	1.1–5.5 pF	Insertion loss = 1.73–2.0 dB
[13]	2018	RF filter	Transverse electrostatic parallel plate	5.3–7 GHz	0.38 pF–0.99 pF	Q = 93–370
[14]	2017	RF filter	Transverse electrostatic parallel plate	0.4–3 GHz	0.3 pF–3.9 pF	Insertion loss = 5.3 dB
[15]	2017	RF filter	Transverse electrostatic parallel plate	1.1–1.7 GHz	0.3 pF–3.9 pF	Insertion loss = 3.2–6.8 dB
[19]	2020	RF filter	Transverse electrostatic parallel plate	800–1100 MHz	0.5–5.75 pF	Insertion loss = 1.2–2.9 dB
[49]	2020	RF Bandpass filter for 5G communication	Comb drive lateral electrostatic actuation	2.5–3.0 GHz	NA	Quality factor = 45–85
[20]	2018	RF filter	Transverse electrostatic parallel plate	25 GHz–29 GHz	150 fF–170 fF	Insertion loss = 2.8 dB
[22]	2018	RF filter	Transverse electrostatic parallel plate	400–560 MHz	1–5 pF	Insertion loss = 1.9 dB
[25]	2020	Phase shifter	Transverse electrostatic actuation	3–10 GHz	0.2035–0.4035 pF	Bandwidth tuning = 4.4 GHz
[26]	2017	Phase shifter	Transverse electrostatic actuation	1–20 GHz	0.15 pF–1.2 pF	Insertion loss = 2.3 dB
[27]	2016	Phase shifter	Transverse electrostatic actuation	110–170 GHz	NA	Phase shifts = 30°
[32]	2010	Impedance Matching	Transverse electrostatic actuation	13–24 GHz	72 fF–246 fF	Insertion loss = 0.18 dB
[33]	2010	Impedance Matching in power amplifier	Transverse electrostatic actuation	1.8–2.7 GHz	NA	Phase shift = 0–348.75°
[35]	2010	Impedance Matching	Transverse electrostatic actuation	10–16 GHz, 15–23 GHz	NA	Insertion loss = 4.18 dB@140 GHz
[50]	2019	Impedance Matching	Transverse electrostatic parallel plate	1–6 GHz	Tuning ratio = 10	Power transfer ratio = -2.84 dB@24 GHz
						Return loss $ Γ < 0.85$
						Insertion loss < 1.3 dB
						Insertion loss = 1–3 dB
						Impedance tuning = 30–100 Ω,
						Imaginary part = -10 to -50 Ω
						Return loss < 18 dB

(Continued.)

Table 1. (Continued.)

References	Year	Type of application	Type of actuation	Frequency range	Tuning range	Performance enhancement
[38]	2015	Tunable Antennas	Transverse electrostatic actuation	600–900 MHz	0.92–4.61 pF	Max. antenna efficiency = –5.5 dB
[39]	2017	Tunable Antennas	Transverse electrostatic actuation	600 MHz–2.6 GHz	0.5–11.9 pF	Max. antenna efficiency = –3.9 dB@600 MHz
[40]	2017	Tunable Antennas For IoT	Transverse electrostatic actuation	868 MHz, 1.58 GHz, 2.4 GHz	0.38 pF–1.5 pF	Max. antenna efficiency = 93%@2.4 GHz
[51]	2020	Tunable Antennas For IoT	Transverse electrostatic parallel plate	600 MHz–960 MHz	1PF–3 pF	Max. antenna efficiency = –6 dB
[42]	2016	Tunable Antennas for mobile	Transverse electrostatic actuation	700–960 MHz, 1710 MHz–2170 MHz	0.5–2.2 pF	Max. antenna efficiency = 30%@600–2690 MHz
[23]	2019	Tunable Antennas	Transverse electrostatic parallel plate	5–6 GHz	0.265 pF–1.577 pF	Max. antenna gain = 7.2 dBi, phase shift = 70 °
[46]	2019	MRI application	Transverse electrostatic parallel plate	75 MHz–298 MHz	1.76 pF–48.7 pF	NA
[47]	2020	Microwave resonators	Transverse electrostatic parallel plate	2 GHz–10 GHz	Tuning range = 26%	Tuning range of 1st resonance 7% and second resonance is 10%
[31]	2018	Voltage controlled Oscillator	Transverse electrostatic parallel plate	1 GHz–18 GHz	0.326 pF–0.730 pF	Frequency tuning = 4 MHz Phase noise = –113.65dBc/Hz
[52]	2018	Digital logics	Comb drive lateral electrostatic actuation	NA	NA	Energy efficiency = 99.1% @25 Hz Power dissipation = 1pJ per operation

series equivalent resistance. A large Q factor ensures a high selectivity in passive filters, and better performance in terms of low losses. The Q factor at microwave frequency can be measured using scattering parameters (S-parameter) obtained from a vector network analyzer. The Q factor of tunable capacitor at microwave frequency can be written as:

$$Q = \frac{|\text{Im}(Z)|}{\text{Re}(Z)} = \frac{2|\text{Im}S_{11}|}{1 - |S_{11}|^2} \quad (3)$$

where S_{11} is the input port voltage reflection coefficient.

3.2. Tuning range

The tuning range is another key parameter for designing tunable capacitors. Mathematically, it is expressed as:

$$\text{Tuning range} = \frac{C_{\max} - C_{\min}}{C_{\min}} \times 100 \quad (4)$$

where C_{\max} is the maximum capacitance and C_{\min} is the minimum capacitance. A wide tunable range for the capacitance enables a correspondingly large re-configurability of the functional block that employs it. Therefore, most of the broadband communication systems require wide tuning range.

3.3. Reliability

The performance of tunable capacitors may change over time, particularly if placed in harsh environment. In most cases, the reliability of tunable capacitors are considered better than MEMS switches. This is because unlike MEMS switches, the tunable capacitor plates do not come in contact and similarly, there is no dielectric layer between the capacitor plates, hence no issue of charging of the dielectric layers. The issue of dielectric layer charging is very common in MEMS based switches [53]. This means that the pull-in voltage is not altered by the dielectric charging of the capacitor, which is a critical issue in MEMS based switches. Similarly, MEMS tunable capacitors do not need to be hermetically sealed since they do not suffer much from charging or surface-contact problems resulting from humidity [2].

3.4. Linearity

Parallel-plate capacitors are known to have high nonlinearity governing their voltage and capacitance parameters (C - V curves). This non-linearity greatly limits the applications where accurate capacitance is crucial. In addition, it is difficult to design a controller circuit for accurate capacitance in the range in which a dramatic change occurs. For example, the phase noise in the frequency tuning of VCOs, and the bandwidth variation in phase locked loops are also caused by the non-linearity of tunable capacitors [54, 55].

Several solutions have been reported to overcome the issue of nonlinearity of parallel-plate capacitors. Lateral comb tunable capacitors were introduced in the early work of tunable capacitors for improved linearity. However, the tuning ranges were limited due to designs imperfections [56, 57]. Shavezipur

et al [58–60] introduced a linear tunable capacitor with a linearity factor of up to 99.7% along with a large tuning ratio of 68%. Similarly, parallel plate system with unconventional geometric shapes have also been investigated to improve the linearity between capacitance and voltage curve. However, the tuning range was low due to the sharp change in the capacitance values while approaching the pull-in point. Han *et al* [24] remarked that by increasing the distance between parallel plate capacitance instead of traditionally closing the gap between tunable capacitor, linearity of C - V response can be improved. They reported linearity factor of 99.1% and a large tuning ratio of 178%. Similarly, Zhuhao *et al* [61] reported a nonplanar upper plate and a side leverage electrode structure for large tuning range and high linearity. The results showed high linearity factor 99.92% and large tuning ratio of 309%. However, the size of the tunable capacitor is increased compared to traditional parallel plate capacitor.

4. MBTCs development

Next, we classify tunable capacitors into two main categories; in-plane and out-of-plane. We discuss their main features and then present a comprehensive comparison between them in section 4.3, and discuss their fabrication techniques in section 4.4. In addition, new techniques for improved tunability based on the two main categories are presented in sections 4.5 and 4.6.

4.1. In-plane laterally actuated tunable capacitors

Unlike, transverse actuated tunable capacitor, laterally actuated tunable capacitor takes the advantage of capacitance generated from the side walls. They involve interdigitated fingers (IDT) to increase the edge coupling length. The IDTs are shaped like teeth of a comb, as shown in figure 3. In comb drive systems, two set of electrodes are placed in the same plane. One set of electrode fingers is fixed, the stator, while the second set, rotor is suspended and free to move.

In 1998, Yao *et al* [7] reported a comb drive based tunable capacitor with a tuning range of 200% and a Q factor of 34 at 500 MHz. The electrical self-resonance frequency of the comb drive tunable capacitor is 5 GHz. The structure is fabricated on silicon on insulator (SOI) substrate, as shown in figure 4(a). When an electrostatic voltage is applied across the fixed and movable comb drive, it results in a change in the overlapping area. The parameters limiting the tuning range in such comb drive system are the supporting spring design and the length of comb's fingers. Similarly, Borwick *et al* [17] proposed similar variable comb drive tunable capacitor with a high tuning ratio of 8.4–1, and Q factor values of more than 100 in the 200–400 MHz, as shown in figure 4(b). The left side comb drive system was used as an actuator and the right side was used as a tunable capacitor. The high tuning ratio is due to double side metallization of silicon structure layer, which reduces the out of plane stresses and bending of the tunable capacitor. Furthermore, when implementing the tunable capacitor into a two-pole UHF filter, tuning over a 225–400 MHz range was

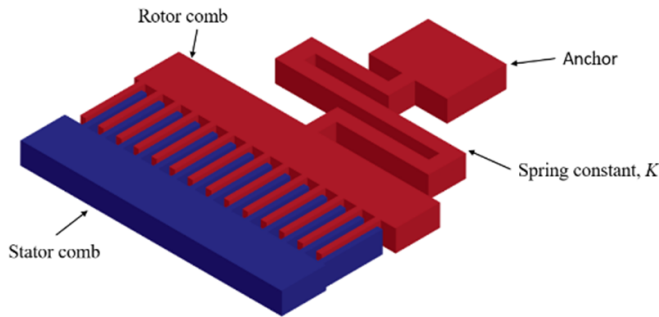


Figure 3. Laterally actuated comb drive system.

achieved with a loss below 6.2 dB. Another comb drive tunable capacitor was presented by Zhejiang [62]. They proposed a comb drive tunable capacitor with a tuning range of 242%. The comb drive system was used for actuation, whereas a parallel-plate capacitor was used for sensing, as shown in figure 4(c). Bumpers have been fabricated on the suspended springs for extending the tuning range. The capacitance increases parabolically before electrode contact with bumpers, and after contact the capacitance increases linearly.

Nguyen *et al* [63] proposed an electrostatic vertical comb drive actuator to extend the tuning range. The vertical comb drive tunable capacitor creates a large offset in comb fingers by small rotation of actuator's angle. A high tuning ratio of more than 31:1, and a maximum Q factor of 273 at 1 GHz have been reported. This is the maximum tuning range ever reported in literature. The SEM image of the vertical comb drive actuator is shown in figure 4(d).

Similarly, a new MEMS based variable capacitor using electrostatic vertical comb drive has been proposed by Saeid *et al* [64]. The proposed design was simulated in COMSOL, and Intellisuite software. In the design, an electrostatic vertical comb drive was introduced to extend the tuning range. According to the simulation results, the achieved tuning range was 285%. A detailed fabrication process was also proposed in the same paper but the design was not fabricated and the proposed fabrication process is complex.

4.2. Out of plane transverse tunable capacitors

These tunable capacitors are comprised of parallel plates with their broad side parallel to each other. In a typical capacitor, one of its plate is fixed and the other is movable. The movable plate is suspended or attached to a suspended structure, which acts as a spring, as shown in figure 2(a). Electric field lines are parallel to each other and perpendicular to plate surfaces in the overlapped region. When a DC bias is applied between the two plates, an attractive electrostatic force is induced, which deflects the movable plate toward the fixed one, and thus increases the capacitance across the plates. By increasing the applied voltage, one can further increase the displacement of the movable plate. However, this is limited to one-third of the initial air gap $d/3$ (i.e. one-third of the initial air gap), and the phenomenon pull-in, at which the electrostatic force dominates the restoring mechanical force, collapsing the suspended

plate into the fixed plate. The electrostatic force F_e and the voltage at pull-in are given by

$$F_e = \frac{\epsilon A}{2d^2} V^2 = \frac{CV^2}{2d} \quad (5)$$

$$V_p = \frac{2d}{3} \sqrt{\frac{K_m}{1.5C_o}} \quad (6)$$

where A is the cross-sectional area of the plates, d is the gap between plates, C is the capacitance across plates, K_m is the stiffness, and C_o is the initial capacitance across the plates.

The theoretical tuning range of the parallel plate capacitor is limited to 50% due to pull-in effect. However, the practical tuning range of parallel plate capacitor is much lower than the theoretical limit due to the parasitic effect [67].

4.3. Non-conventional designs of transverse tunable capacitors

To improve the tuning range, and linearity several non-conventional designs have been reported in the literature. These designs greatly improve the tuning range, quality factor and linearity of the tunable capacitors. Zou *et al* [66] proposed a new design of tunable capacitors with a tuning range of 69.8%. This range exceeds the theoretical maximum range of 50%. This is due to the higher gap between driving electrode than the gap between capacitor plates. The tunable capacitor consists of one suspended top plate and two fixed bottom plates. One of the two fixed plates, E2, and the top plate E1 form a variable capacitor, whereas the other fixed plate E3 and the top plate, E1 are used to provide electrostatic actuation for capacitance tuning, as shown in figure 5(a). The surface micromachining technique has been used in the fabrication on a pyrex glass wafer. The Q factor of 30 at 5 GHz, and self-resonance frequency beyond 10 GHz have been achieved [65]. However, this tuning range is still not enough for broad band communications as most of the broad band communication systems require high tuning range. Therefore, Dec *et al* [68] used two plates and three plates structure with tunability of 50% and 87%, respectively. In addition to this, the Q -factor of 20 is obtained at 1 GHz. The control voltage of only 4.4 V has been used, which is compatible with CMOS electronic devices. The design is shown in figure 5(b), and it is implemented in the standard PolyMUMPs process, which has three structure layers and two sacrificial layers for the prototype design.

Similarly, another parallel plate MEMS tunable capacitor has been fabricated in a thin film technology with a high tuning range [69]. A capacitance tuning ratio of up to 17 has been demonstrated with the voltage requirement of 20 V. The high tuning ratio is due to different gaps with actuator and capacitors electrodes, which assists in the utilization of greater displacement of movable electrode in the tunable capacitor. This is the second highest tuning range in parallel plate capacitors ever reported. A Q -factor of 150–500 has been demonstrated in the frequency range of 1–6 GHz. This high Q factor is due to the high resistance substrate wafer. To avoid pull-in of the

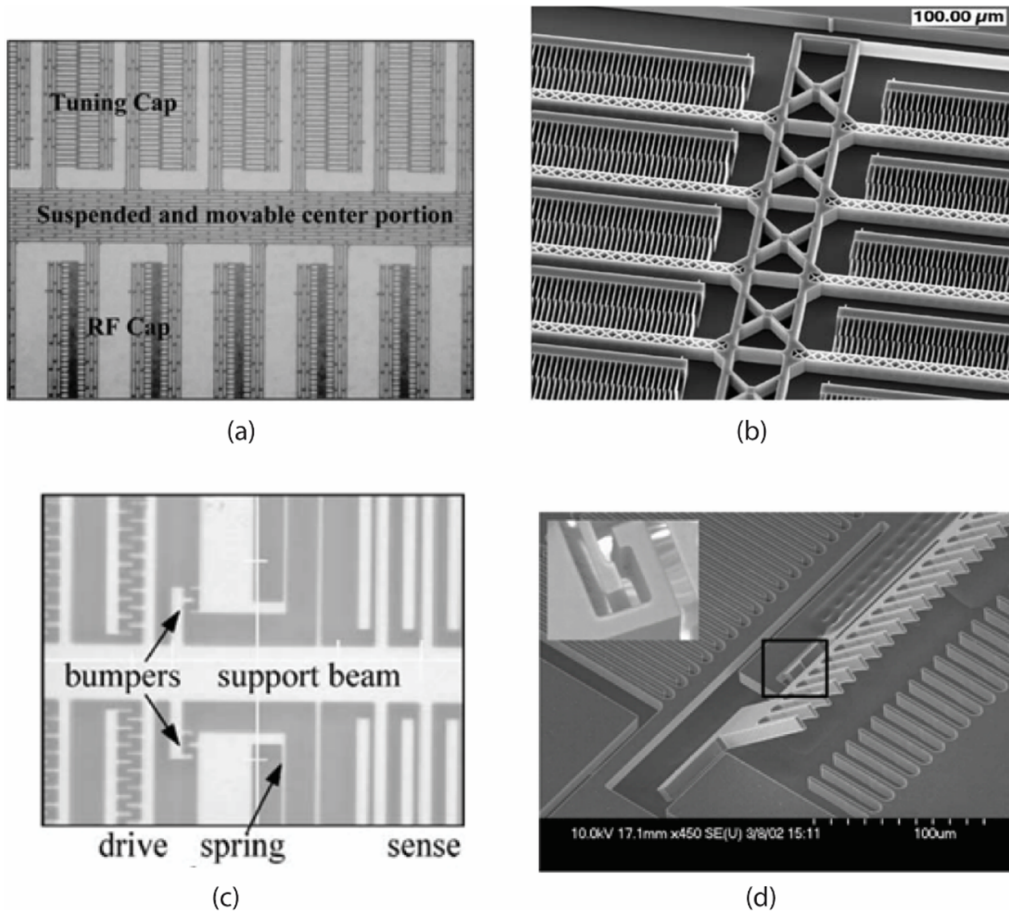


Figure 4. SEM images of (a) tunable capacitor on glass substrate [10], (b) thick laterally actuated and sensed tunable capacitor [17], (c) tunable capacitor laterally actuated and transverse sensing with stoppers [62], (d) angular lateral comb actuated tunable capacitor [63]. Reprinted from [17], Copyright (2003), with permission from Elsevier. Reprinted from [65], Copyright (2003), with permission from Elsevier. © 2004 IEEE. Reprinted, with permission, from [63].

tunable capacitor, special stoppers are designed at the edges of the structure.

Besides tuning range and Q factor, linearity of capacitance vs voltage curve is also crucial in some applications. Bakri-Kassem *et al* [12] developed a parallel-plate tunable capacitor with curled moving plate, which exhibits linear tunability of 115%. Shavezipur *et al* [58] introduced a parallel-plate capacitor with structural nonlinearity to get high tunability with a controlled plate displacement to get linear tunability of 100%. Addition of extra stiffness to capacitor's structure and design optimization increases tunability and linearity of C - V curve by creating discontinuity in the curve. In the butterfly-shape design, the moving electrode is divided into two trapezoidal segments, each one has two nodal displacements and therefore two degrees of freedom, as shown in figure 5(c). In another work, Shavezipur *et al* [60] introduced triangular shaped parallel capacitor with a maximum tunability of 71% and linearity factor of 0.943.

Majid *et al* [70] presented a parallel plate tunable capacitor in which both plates move to a distance of $d/6$, and total displacement of $d/3$, when electrostatic force is applied across the plates. The main advantage of the design is that it inhibits the pull-in of the tunable capacitor and enables

good control on the capacitance change. Secondly, it helps in structure's stress and strain reduction, thus increases the lifetime of the tunable capacitor. Thirdly, it offers the linear behavior of the capacitance change in the one-third of gap between two plates. Simulation results shows that the design can get 59% tuning at 7 V. The Q factor is 91 at 11 GHz, which is excellent for high frequency applications. However, the design is not fabricated and measurements results are not available.

Han *et al* [24] reported a novel method to achieve highly linear capacitance, and a large tuning range in a parallel-plate MEMS tunable capacitor by using leverage structure in the design to drive the movable plate to the increasing gap direction. Liu *et al* [71] proposed a similar new structure for improving the linearity of capacitance-voltage curve as shown in figure 5(d). The non-planar top electrode offers small gap for high initial maximum capacitance. When the downward electrostatic force is applied at the two drive electrodes, it moves up the middle capacitor plate to control the capacitance by deforming the torsional beams. This increases the gap between the top and bottom electrode. The tunable capacitor has a stable performance from 1 to 10 GHz and a tuning ratio greater than 10.

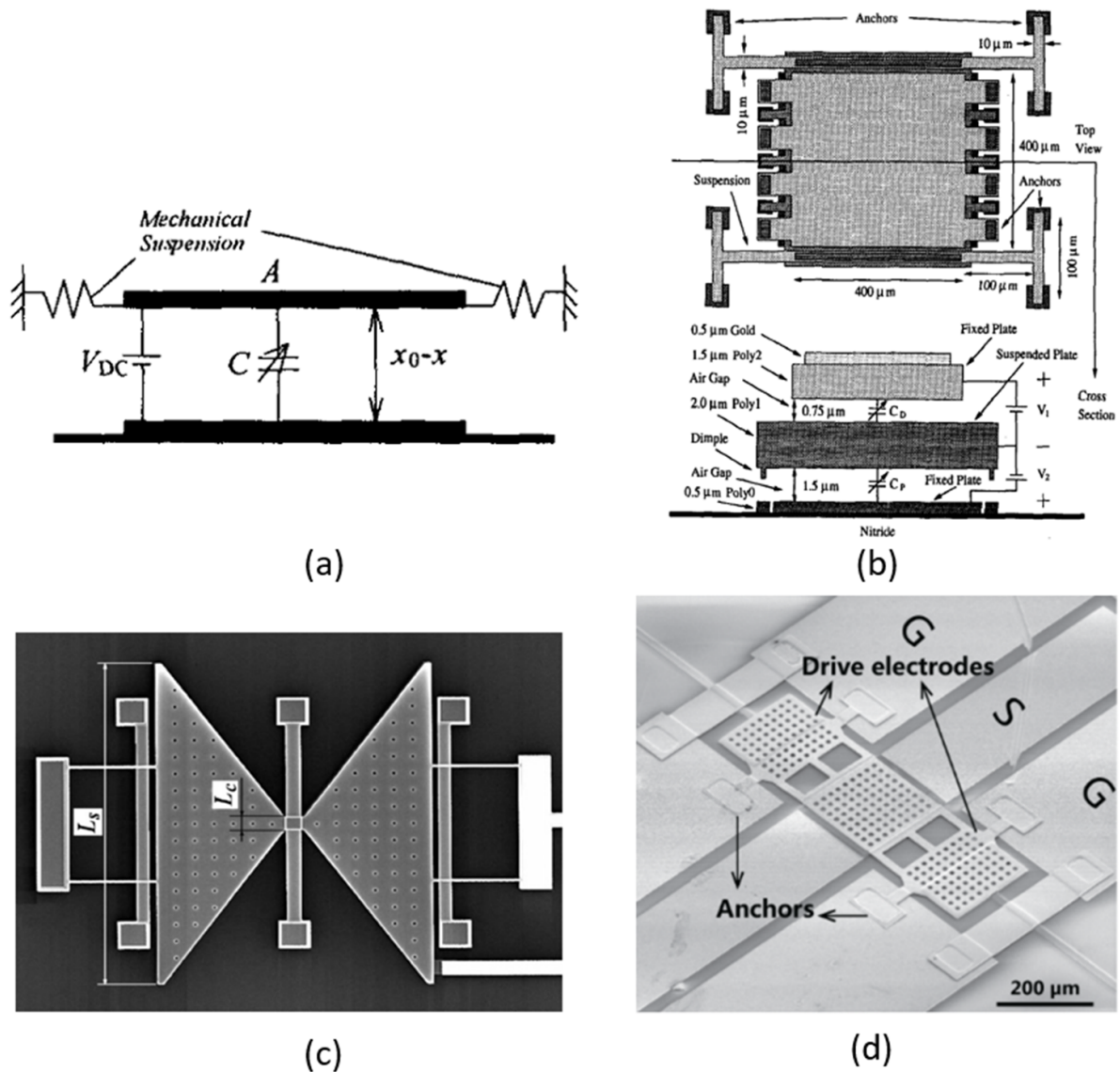


Figure 5. Out of plane transverse non-conventional tunable capacitors, (a) schematic [66], (b) top and cross-sectional view of design for high tunability [68], (c) butterfly shaped tunable capacitor for high linearity [58], (d) leverage structure tunable shunt capacitor for high tunability [71]. © 2000 IEEE. Reprinted, with permission, from [66]. © 1998 IEEE. Reprinted, with permission, from [68]. Reprinted from [58], Copyright (2008), with permission from Elsevier. © 2019 IEEE. Reprinted, with permission, from [71].

4.4. Performance comparison of lateral comb drive and transverse parallel plate tunable capacitors

Parallel plate and lateral comb drive actuated, and sensed tunable capacitors are the common electrostatic techniques for MEMS capacitor tuning. Both techniques have their advantages and disadvantages. However, the main difference between them is that in transverse tunable capacitor, there is a non-linear relation between the electrostatic force and the voltage across the plates, and the capacitance produced is inversely proportional to the gap between the plates. The capacitance of the parallel plate changes sharply with the change in separation gap. On the other hand, in lateral comb drive capacitor the relation between generated force and voltage is linear, similarly, the relation between capacitance change and overlap length change is linear.

It is clear from table 2 that laterally comb drive actuated tunable capacitors have high tuning ranges compared to parallel plate capacitors. The tuning range in lateral comb drive system depends upon the overlapping area of comb fingers and the mechanical design of spring suspension. However, they have large footprint area as compared to parallel plate tunable capacitors. On the other hand, parallel plate tunable capacitors are more attractive due to their small footprint, and fast response. The tuning range has been increased by using different techniques to suppress the pull-in effect of the parallel-plate capacitors as reported in [4, 5, 66, 72]. However, the Q factor of parallel plate actuated tunable capacitors are higher than the comb drive ones. In addition to this, comb drive tunable capacitors require high driving voltages, and lower electrical resonance frequency.

Table 2. Performance comparison of reported tunable capacitors.

Reference	Type of actuator	Type of capacitor	Tuning range	Quality factor	Tuning voltages	Electrical resonant frequency	Size
[4]	Parallel plate	Parallel plate	1:1.5	20 @1 GHz	0–1.8 V 0–4.4 V	NA	400 μm \times 400 μm
[18]	Parallel plate	Parallel plate	22:1	<20@1 GHz	30–55 V	NA	3.2 mm \times 3.2 mm \times 0.53 mm
[8]	Parallel plate	Parallel plate	7.7%	290@1 GHz	0–10 V	NA	NA
[66]	Parallel plate	Parallel plate	69%	NA	0–20 V	NA	500 μm \times 500 μm
[73]	Parallel plate	Parallel plate	46%	6.5@1.5	0–35 V	NA	1.6 mm \times 0.6 mm
[5]	Parallel plate	Parallel plate	69.8%	30@5 GHz	0–19 V	5 GHz	500 μm \times 500 μm
[56]	Lateral comb drive	Lateral comb drive	8%	NA	0–8 V	NA	876 μm \times 876 μm
[74]	Lateral comb drive	Parallel plate	1.63:1	NA	0–20 V	NA	1000 μm \times 1000 μm
[17]	Lateral comb drive	Lateral comb drive	8.4:1	100	0–14 V	NA	NA
[72]	Parallel plate	Parallel plate	325%	90@2.4 GHz	0–10 V	4 GHz	NA
[62]	Lateral comb drive	Parallel plate	600%	100 @1 MHz	0–22.6 V	NA	NA
[63]	Lateral comb drive	Lateral comb drive	31:1	273@1 GHz	0–40 V	NA	NA
[69]	Parallel plate	Parallel plate	17:1	500@4 GHz	0–20 V	NA	NA
[75]	Parallel plate	Parallel plate	41%	26.7@5 GHz	0–5.5 V	NA	NA
[58]	Parallel plate	Parallel plate	100%	NA	0–11.5 V	NA	300 μm \times 400 μm
[76]	Parallel plate	Parallel plate	5:1	45@20 GHz	0–65 V	NA	140 μm \times 160 μm
[24]	Parallel plate	Parallel plate	134%	7.3@1 GHz	10–45 V	3.4@ GHz	400 μm \times 400 μm
[77]	Parallel plate	Parallel plate	4.1:1	5@1 GHz	0–6 V	40 GHz	NA
[78]	Lateral comb drive	Parallel plate	9.42:1	14.5@1 GHz	0–12 V	6.3 GHz	NA
[79]	Parallel plate	Parallel plate	2.3:1	NA	23 V	NA	50 μm \times 40 μm
[80]	Parallel plate and lateral comb drive	Parallel plate and lateral comb drive	101%	118.5@0.8 GHz	0–90 V	NA	NA
[64]	Lateral comb drive	Parallel plate	285%	NA	0–14 V	NA	600 μm \times 800 μm
[81]	Parallel plate	Parallel plate	3:1	NA	0–40 V	>40 GHz	70 μm \times 50 μm
[82]	Parallel plate	Parallel plate	225%	1150@60 MHz	95 V	NA	1.70 \times 1.08 mm ²
[71]	Parallel plate	Parallel plate	10:1	NA	2–28 V	>40 GHz	NA

The maximum tuning ratio in parallel plate capacitor is 22:1. However, the tuning voltage is at the high side (30–55 V). Similarly, the maximum tuning range in lateral comb drive capacitor is 31:1 with voltage requirement of 40 V. The Q factor is also higher than the parallel plate capacitor operated at 1 GHz.

4.5. Fabrication processes for in-plane and out of plane tunable capacitors

There are mainly two methods for the fabrication of electrostatically actuated tunable capacitors: bulk micromachining and surface micromachining. The bulk micromachining is mostly used for the fabrication of in-plane motion tunable capacitors, whereas surface micromachining is generally incorporated for the fabrication of out-of-plane tunable capacitors.

Bulk micromachining is mainly applied on silicon, glass, and gallium arsenide wafers. Etching in bulk micromachining is categorized into wet and dry etching. For dry etching, deep reactive ion etching (DRIE) is the common technique used for fabricating in-plane tunable capacitors. It offers deep and high vertical aspect ratio, vertical wall profile, and good material selectivity. The vertical wall anisotropy is controlled by adjusting several process parameters, which include process pressure, temperature, DC bias voltage, input power, and the chemical gases used in the process.

Tunable capacitors fabricated using bulk micromachining require fewer masks than surface micromachining as reported in [56, 74]. In these works, the tunable capacitors are fabricated using silicon-glass bonding processes. The silicon wafer is etched using ICP deep etcher from bottom and top for patterning of comb fingers, and bonded to glass wafer using anodic bonded process. Another bulk micromachining silicon-glass bonding process tunable capacitor with improved performance is reported in [17]. The tunable capacitor achieved high Q factor and large tuning ratio. The improved performance is due to double sided metallization of silicon layer for comb drive system to reduce the out-of-plane bending caused by Coefficient of thermal expansion (CTE) mismatch between silicon and metal layers as, shown in figure 4(b).

Similarly, another high performance tunable capacitor fabricated using DRIE etching having angular vertical comb drive system is reported in [63]. The tunable capacitor is fabricated on glass wafer to reduce the parasitic capacitance. A SOI wafer is bonded to a Borofloat glass wafer to create a silicon on glass wafer. A DRIE etching of silicon is performed to build device structure. Photosensitive cyclotene resist benzocyclobutene hinges are patterned to physically connect the horizontal anchors with the angular comb fingers, as shown in figure 4(d).

Another common process for fabricating in-plane tunable capacitor using bulk micromachining technique is given in [62]. The tunable capacitor is fabricated on oxidized silicon wafer and a SU-8 bonding has been utilized for bonding ultra-thin silicon wafer on top, which is patterned using DRIE. The SU-8 bonding helps in replacing expensive SOI wafers and enables flexible designs.

The surface micromachining technique fabricate microstructures by adding material layer by layer on top of the substrate. The polycrystalline silicon (polysilicon) is a common material for the layers. Several two layers (two parallel plates) and three layers (three parallel plates) tunable capacitors are fabricated using surface micromachining technique in a standard PolyMUMPs process [83]. The process offers three layers of polysilicon and a gold layer on the top polysilicon layer. The tunable capacitors with three parallel plates achieved greater tunability than two plates parallel plate capacitor reported in [4, 72]. Another design of tunable capacitor is reported in [73] using bottom and top polysilicon layers of the PolyMUMPs process. Similarly, some novel geometry tunable capacitor fabricated in PolyMUMPs standard process are reported by Shavezipur [58, 60, 84].

Several other prototypes have been fabricated with surface micromachining using aluminum or copper metal layers as structural layers [8, 18, 75]. The Young's Modulus of aluminum and copper is lower than silicon. Thus, these are more flexible and require low actuation voltage with better RF performance (low ac resistance). In addition, gold is also used as a structural layer for good RF performances reported in [6, 71]. Similarly, some designs have been fabricated using polyimide as a structural layer to achieve low actuation voltages [5, 66]. The Young's modulus of polyimide is only 3 GPa [85].

4.6. Switchable tunable capacitor

Modern communication systems require high tuning range and fast response. Unfortunately, traditional parallel plate, and comb drive tunable capacitors are limited in tuning range whereas thermally actuated tunable capacitors are slow in tuning. Therefore, switchable tunable capacitors have gained increasing attention because high tunability can be achieved by selection from parallel connection of tunable capacitor through switches. The capacitance of the variable capacitor depends on the selection of actuated switches, as shown in the schematic of figure 6. However, the size of switched capacitor is relatively large due to the array of capacitors and switches integrated together on the same chip. These tunable capacitors also suffer from high parasitic effect due to the large size, and their operation is often limited to 1–10 GHz.

Goldsmith *et al* [18] proposed a bistable switchable tunable capacitor with a high tuning range of 22:1. The obtained tunable capacitance ranges from 1.5 pF to 33.2 pF. The controlled voltage is in the range of 30–55 V, and switching speed is less than 10 μ S. The fast switching speed allows quick tuning of capacitor elements. The high switching speed is related to the high mechanical natural frequency of the switch. The membrane moves from the contact position to its mechanically neutral position when there is no electrostatic force exerted on it. By neglecting air damping, Van der Waals force, bouncing effects, and contact complications, this release time can be approximated by 1/4 period of the membrane free vibration. The switching speed is even higher when electrostatic force is applied. In another work [86], they fabricated 16 state variable capacitor together with fixed capacitors and demonstrated a tunable filter for Ultra-high frequency (UHF) and Very High

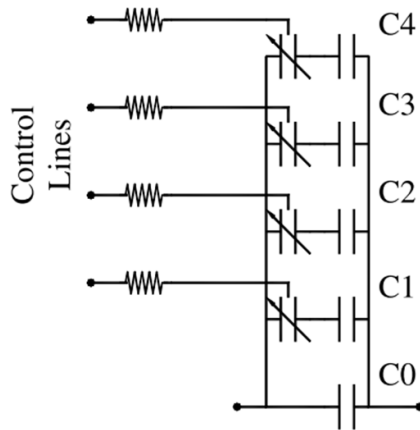


Figure 6. Schematic of four bit switched capacitors in series with fixed capacitors and parallel to each other. [86] John Wiley & Sons. Copyright © 2001 John Wiley & Sons, Inc.

Frequency (VHF) bands. To realize a tunable capacitor, a fixed capacitor is connected in series with a capacitive switch for a two state capacitance as shown in figure 6. The capacitive switch has maximum value when it is ON (down state) and minimum value when OFF (up state). The combinations of these two-state capacitance with a fixed capacitance allows construction of variable capacitor as shown in figure 7. A four bit switched capacitor can provide total of 16 capacitance values. Similarly, Belkadi *et al* fabricated switched capacitors on glass wafers. The MEMS capacitors are tuned by deflecting thin gold metal layers on dielectric layer, thus increases the capacitance 3 times to the initial capacitance, from 25 fF to 75 fF. Several high power tunable capacitor banks are reported in [87–89]. These high power capacitors are essential for impedance tuning of high power transmitters at the base station of mobile industries and satellite communications.

4.7. Dielectric tuning tunable capacitors

In this method, a dielectric material between the two fixed plates are changed to get high tunability and Q factor. Yoon *et al* [8] presented a movable dielectric tunable capacitor for attaining high Q factor of the capacitor. In the proposed design, the top and bottom plates are made stationary and the dielectric between the plates is made movable, as shown in figure 8(a). The total tunability of 40% and Q factor of 218 have been achieved at 1 GHz.

Similarly, another work is presented in [90] based on changing the dielectric medium using deionized (DI) water between the plates. DI water is injected into the SU 8 channel for changing the dielectric between capacitor plates. The initial capacitance when microfluidic channel is empty, is $C_{\min} = 0.11$ pF and when it is full, is $C_{\max} = 5.76$ pF. This allows a very wide tuning range with $T_r = 5136\%$ at 4.5 GHz. Furthermore, the resonant frequency ranges from 5.67 GHz to 19.81 GHz. The maximum Q factor value $Q_{\max} = 84.27$ is achieved when the capacitor is empty and it reduces to $Q_{\min} = 3.99$, when it is filled with DI water at 4.5 GHz. Habba-chi *et al* [91] reported the effect of dielectric liquid on the

tunability of MEMS capacitor. A wide tuning range of around 7660% can be obtained by changing the fluid position in the channel between the electrodes, which is shown in figure 8(c). The Q factor varies from 51.9 when it is empty to 1.49 when it is fully filled.

Although the tunability of dielectric liquid tunable capacitors is high but they suffer from low Q factors when filled by dielectric medium. In addition, these tunable capacitors are also bulky and occupies large area. Further, dielectric liquid tunable capacitors require microfluidic channels, which adds fabrication complexity.

4.8. Electrically floating plate tunable capacitors for high quality factor

The traditional parallel plate capacitor, and lateral comb drive systems have the disadvantage of low Q -factor. This is due to the RF losses in the suspension beams of the tunable capacitors. These suspension beams are normally made long and thin to acquire low stiffness values for low actuation voltages [4, 75]. Thus, the Q factor is low due to RF losses in the suspension beams. Lee *et al* [92] proposed a tunable capacitor actuated with an electrically floating plate. The electrically floating plate means that the suspended plate is not connected electrically and RF signal does not pass through the long beams of suspended plate, which are made long to reduce the operating voltages. A SEM image of the proposed tunable capacitor with a thick electrically floating top plate, and a thin mechanical spring beams are shown in figure 9(a). The proposed design showed 200% increment in Q factor at 5 GHz compared to the conventional parallel plate capacitor. They achieved a tuning range of 41% and a Q factor of 34.9 at 5 GHz.

Yong *et al* [93] proposed an electrically floating movable dielectric fabricated in SOI-MUMPs. The tunable capacitor is actuated with lateral comb drive system and is sensed using parallel-plate capacitor, as shown in figure 9(b). A tunability of 172% was achieved with the voltage range of -120 V to 120 V. The Q factor of 0.35 was achieved at 1 GHz. This Q factor is very low due to the RF losses in the silicon material. Another electrostatically actuated, and electrically floating plate tunable capacitor is proposed by Khan *et al* in [82]. The device is fabricated in Metal-MUMPs process. To minimize the size of the device, the tunable capacitor is designed to be actuated using the same parallel plates of the capacitor, as shown in figure 9(c). The tunable capacitor achieved a wide tunable range of 225% with the help of a stopper and a Q factor of 1150 at 50 MHz.

4.9. High power handling tunable capacitors

In some communication systems, such as radio detection and ranging, long distance communication, and satellite communication, high power handling passive devices possess great importance due to their crucial role in the performance of the systems. Electrostatically actuated tunable capacitors are known for compact size, fast response, and good performance. However, they can handle only low power signal due to

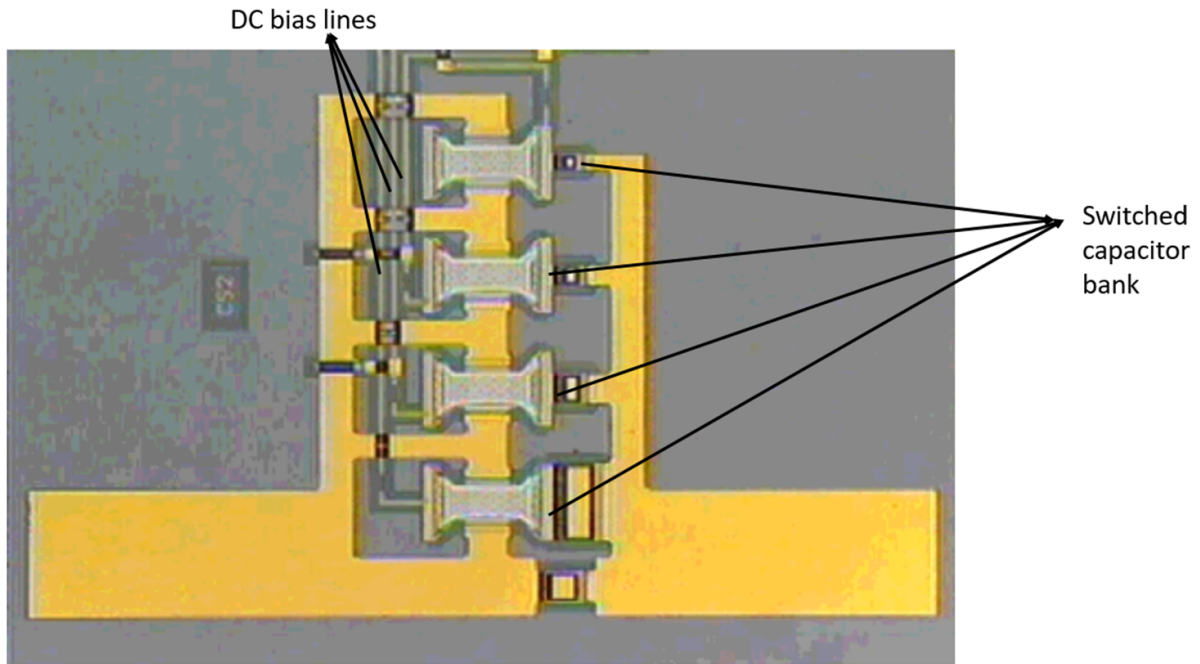
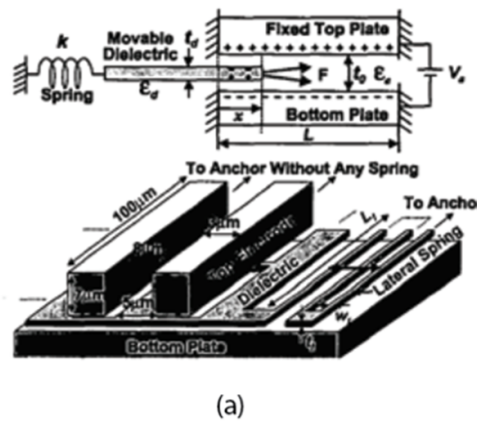
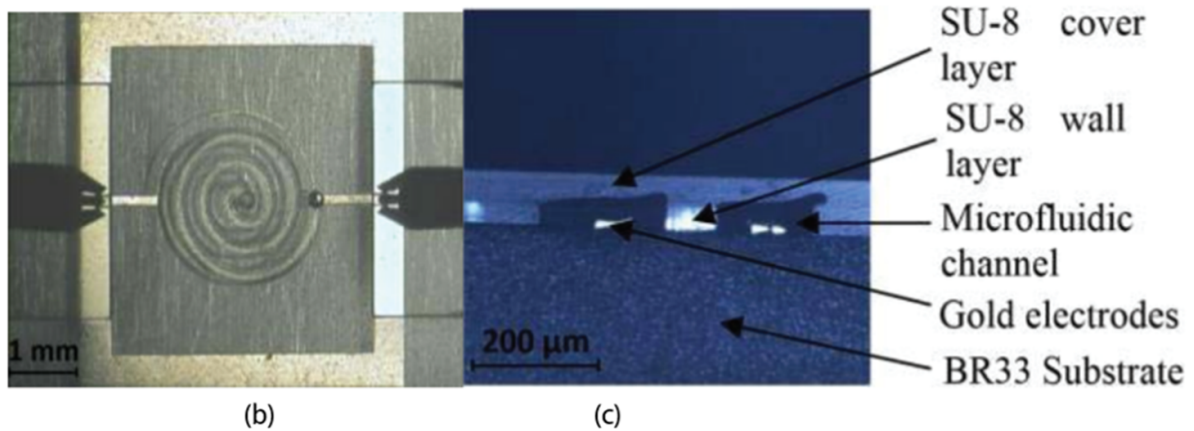


Figure 7. Photographs of switched capacitor bank tunable capacitor for UHF-VHF bands. [86] John Wiley & Sons. Copyright © 2001 John Wiley & Sons, Inc.



(a)



(b)

(c)

Figure 8. Moving dielectric based tunable capacitors, (a) schematic and 3D view of tunable capacitor [8], (b) photograph of fluid based tunable capacitor, (c) cross-sectional view of fluid based tunable capacitor [91]. © 2000 IEEE. Reprinted, with permission, from [8]. © 2016 IEEE. Reprinted, with permission, from [91].

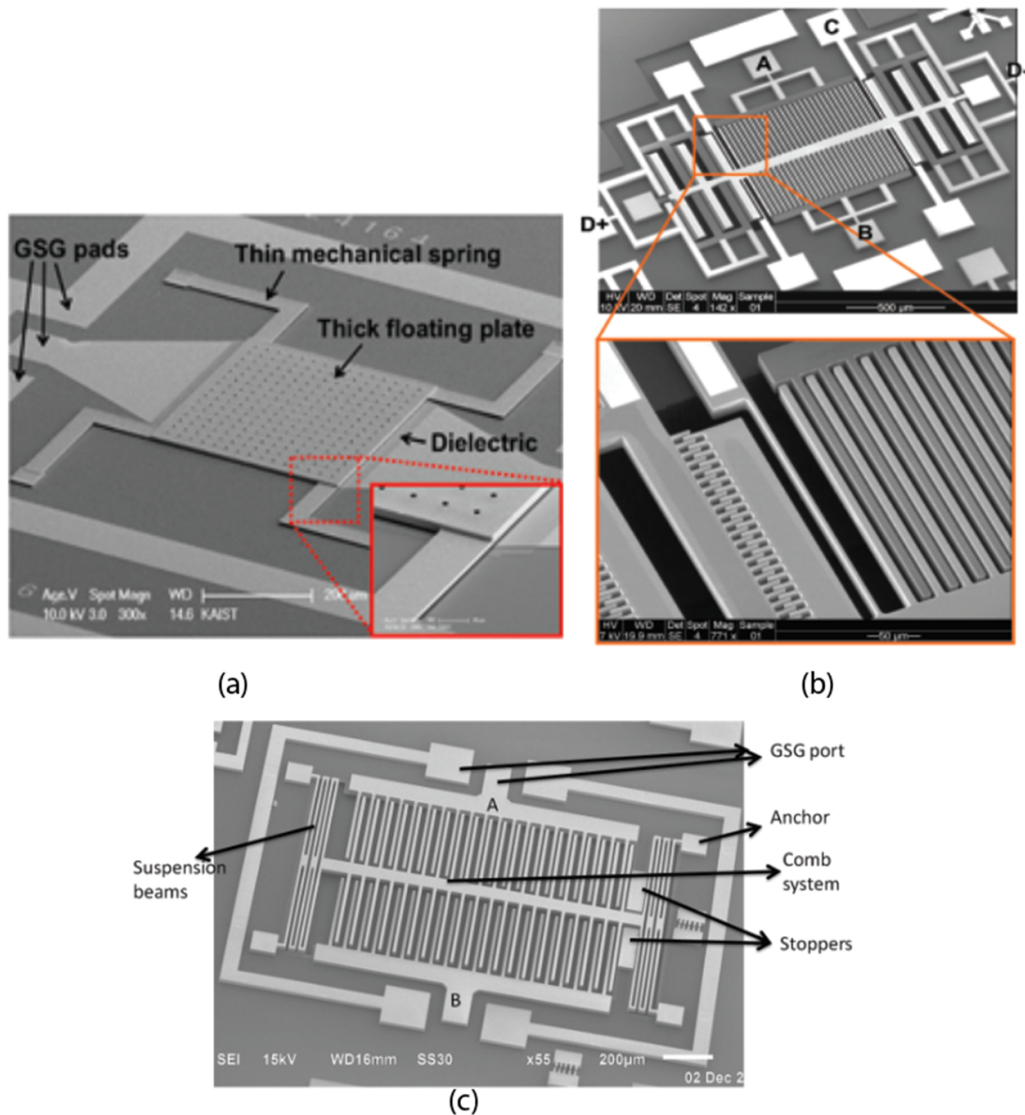


Figure 9. SEM images of electrically floating tunable capacitor; (a) transverse parallel plate [92], (b) thermally actuated transverse parallel plate comb drive system [93], (c) transverse actuated and sensed comb drive tunable capacitor [82]. © 2008 IEEE. Reprinted, with permission, from [92]. © 2009 IEEE. Reprinted, with permission, from [93]. Reprinted from [82], Copyright (2019), with permission from Elsevier.

the well-known phenomenon of self-actuation. When a high power RF power is applied to tunable capacitors, electrostatic force generated due to the signal power is so large that can induce the pull-in effect, which is a great issue in electrostatic MEMS capacitors. To avoid this issue, Reines [94] reported RF shunt tunable capacitor with large spring constant. The tunable capacitor consists of separate RF and DC electrodes, which are fabricated underneath a circular diaphragm, as shown in figure 10. The design increases both the restoring force, and the RF self-actuation voltage, resulting in improved power-handling capabilities. The prototype requires a small pull-in voltage of only 24–28 V. A ring-shaped RF transmission line is routed underneath the higher spring constant portion of the circular beam to increase both the restoring force and the RF self-actuation voltage, as shown in figure 10. Separate DC bias electrodes are placed on the either side of the RF line to result in a relatively low pull-in voltage. Similarly,

another technique is reported for the high power handling with relatively low voltage in [52]. The tunable capacitor is connected with two fixed and two MEMS tunable capacitors all connected in series. This quadruple series capacitor structure helps in reduction of the actuation voltage across the MEMS tunable capacitor. Thus the power-handling capability is greatly improved. For comparison purpose, a summary of the reported high power electrostatically actuated tunable capacitor is presented in table 3.

5. Commercial devices

Presently, there are few commercially available MEMS tunable capacitors manufactured by several companies such as Menlo micro, Cavendish Kinetics, ST Micro, WisSpry, and Nanusens. Recently in 2021, Nanusens manufactured RF

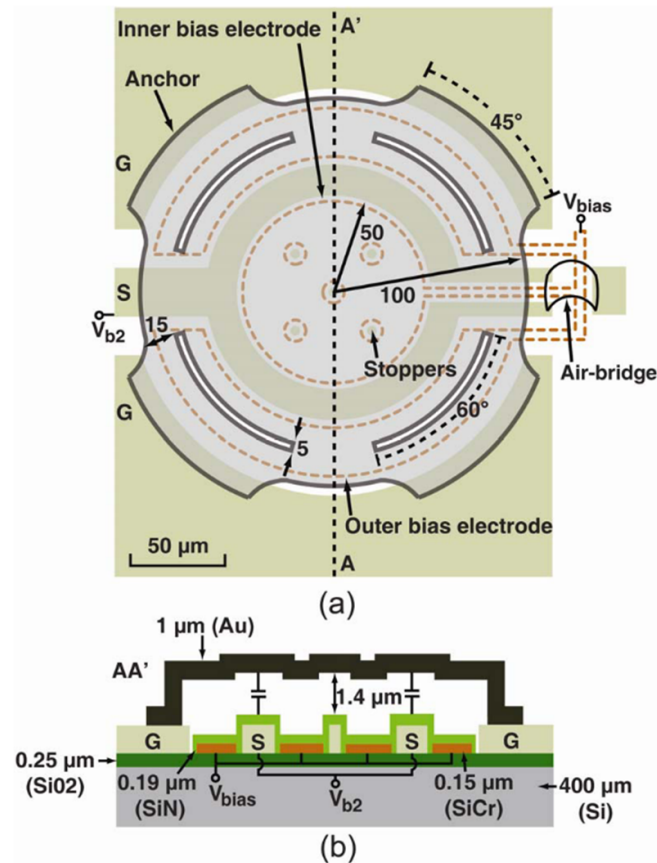


Figure 10. High power handling tunable capacitor, (a) top view, (b) cross-sectional view [94]. © 2011 IEEE. Reprinted, with permission, from [94].

Table 3. High power tunable capacitors.

Reference	Frequency	Type of actuation	Type of capacitor structure	Quality factor	Tuning range	Handling power
[95]	1–20 GHz	Electrostatic	Parallel plate	225 @ 20 GHz	1:1.90	1 W
[76]	1–40 GHz	Electrostatic	Parallel plate	90 @ 40 GHz	5.2	<1 W
[94]	1–10 GHz	Electrostatic	Parallel plate	NA	1:5.7	10–11 W
[96]	1–5 GHz	Electrostatic	Parallel plate	114 @ 1 GHz	1:1.89	36 dbm

MEMS digital tunable capacitors (DTCs) on standard CMOS technology [97]. The DTC is designed for solving the problem of 5G technologies that require more energy and higher efficiency. Cavendish Kinetics also manufactures a tunable capacitor named smarTune Antenna Tuners. The device has two different shunt capacitors with minimum capacitance of 0.50 pF or 0.75 pF and maximum capacitance of 1.65 pF or 3.10 pF, respectively [98]. WiSpry also manufactures a RF MBTC chip, WS1042, which is used in several applications. Details are given in section 2. ST Microelectronics has several variants of commercially available MEMS tunable capacitors. They are fabricated from tunable material called Parascan, which is a version of barium strontium titanate. Omron manufactures and commercializes a high performance MEMS switch based on a tunable capacitor [99]. The switch’s actuator is a parallel plate capacitor with a movable electrode. The switch is used for base station antennas in RF communications.

In 2020 Menlo micro, produced a highly reliable MEMS switch using electrostatic parallel plate actuation. The new device has super low resistance and leakage current, high linearity, and low power consumption. The switch is based on highly conductive and highly reliable alloy that can withstand billions of switching cycles. Currently, MEMS industry is working on the performance improvement of key parameters, such as reduction in parasitic capacitance, large tuning range, improved linearity, reliability, and quality factor.

6. Conclusions

MEMS tunable capacitors have become primary choice over CMOS tunable capacitors in RF industries due to their superior performance. In this paper, a review of electrostatically actuated tunable capacitors has been performed. Different designs

have been investigated and their influence on the performance improvement of tunable capacitors has been studied. Besides, many applications of tunable capacitors, and their influence on the performance of applications have been summarized. Considerable future research is expected on high frequency ranges, terahertz (THz), and 5G ranges due to excellent performance of tunable capacitors in these ranges.

In the last two decades, significant work has been reported on MEMS based electrostatically tunable capacitors. Different out-of-plane and in-plane designs with parallel-plate, lateral comb drive systems and a combination of both configurations have been reported using different types of materials and fabrication processes to maximize the tuning range, quality factor and linearity. Some of them also worked on improving the reliability of the tunable capacitors, however, the reliability is always high due to non-contact nature of the device.

The summarized performances with quantitative performance of tunable capacitors in tables 1 and 2 give guidelines for designing high performance tunable capacitors. The type of actuation, fabrications process, and design parameters, such as gaps between plates, and dimensions play very crucial role in the performance of the tunable capacitors. In addition, advanced application of the electrostatically actuated tunable capacitors have been summarized in table 3. The current state of the art RF communication industry demands high frequency, large re-configurability to cover different services, reduced power consumption and miniaturization. Therefore, MBTC has been exploited largely in modern communication industry.

Acknowledgment

This publication is based upon work supported by King Abdulah University of Science and Technology (KAUST).

Conflict of interest

The authors declare no conflict of interest.

ORCID iD

Fahimullah Khan  <https://orcid.org/0000-0001-6471-9602>

References

- [1] Nguyen C-C 1998 Microelectromechanical devices for wireless communications *Proc. MEMS 98. IEEE. Eleventh Annual Int. Workshop Micro Electro Mechanical Systems. An Investigation of Micro Structures, Sensors, Actuators, Machines and Systems (Cat. No. 98CH36176)* (IEEE) pp 1–7
- [2] Rebeiz G M 2004 *RF MEMS: Theory, Design, and Technology* (New York: Wiley)
- [3] Nguyen C T-C 2006 Integrated micromechanical circuits for RF front ends *2006 Proc. 32nd European Solid-State Circuits Conf.* (IEEE) pp 7–16
- [4] Dec A and Suyama K 1998 Micromachined electro-mechanically tunable capacitors and their applications to RF IC's *IEEE Trans. Microw. Theory Tech.* **46** 2587–96
- [5] Zou J, Liu C and Schutt-Ainé J E 2001 Development of a wide-tuning-range two-parallel-plate tunable capacitor for integrated wireless communication systems *Int. J. RF Microw. Comput.-Aided Eng.* **11** 322–9
- [6] Dussopt L and Rebeiz G M 2002 High-Q millimeter-wave MEMS varactors: extended tuning range and discrete-position designs *2002 IEEE MTT-S Int. Microwave Symp. Digest (Cat. No. 02CH37278)* (IEEE) pp 1205–8
- [7] Yao J 1998 High tuning-ratio MEMS-based tunable capacitors for RF communications applications *Tech. Digest Solid State Sensor and Actuator Workshop* pp 124–7
- [8] Yoon J-B and Nguyen C-C 2000 A high-Q tunable micromechanical capacitor with movable dielectric for RF applications *Int. Electron Devices Meeting 2000. Technical Digest. IEDM (Cat. No. 00CH37138)* (IEEE) pp 489–92
- [9] Rebeiz G M, Entesari K, Reines I C, Park S-J, El-Tanani M A, Grichener A and Brown A R 2009 Tuning in to RF MEMS *IEEE Microw. Mag.* **10** 55–72
- [10] Yao J J 2000 RF MEMS from a device perspective *J. Micromech. Microeng.* **10** R9
- [11] Alazemi A J and Rebeiz G M 2016 A low-loss 1.4–2.1 GHz compact tunable three-pole filter with improved stopband rejection using RF-MEMS capacitors *2016 IEEE MTT-S Int. Microwave Symp. (IMS)* (IEEE) pp 1–4
- [12] Bade L A, Dennis J O, Khir M H M and Wen W P 2016 Modeling and simulation of tunable band-pass filter based on metal-mumps *2016 IEEE Int. Conf. Semiconductor Electronics (ICSE)* (IEEE) pp 1–4
- [13] Lin T-W, Low K K W, Gaddi R and Rebeiz G M 2018 High-linearity 5.3–7.0 GHz 3-pole tunable bandpass filter using commercial RF MEMS capacitors *2018 48th European Microwave Conf. (Eumc)* (IEEE) pp 555–8
- [14] Motoi K, Oshima N, Kitsunozuka M and Kunihiko K 2017 A 0.4–3-GHz nested bandpass filter and a 1.1–1.7-GHz balun bandpass filter using tunable band-switching technique *Int. J. Microw. Wirel. Technol.* **9** 1279–91
- [15] Wang H, Anand A and Liu X 2017 A miniature 800–1100-MHz tunable filter with high-Q ceramic coaxial resonators and commercial RF-MEMS tunable digital capacitors *2017 IEEE 18th Wireless and Microwave Technology Conf. (WAMICON)* (IEEE) pp 1–3
- [16] Bade L A, Dennis J O, Khir M H M and Wen W P 2016 RF-MEMS tunable interdigitated capacitor and fixed spiral inductor for band pass filter applications *AIP Conf. Proc.* (AIP Publishing LLC) p 050012
- [17] Borwick III R L, Stupar P A, DeNatale J, Anderson R, Tsai C, Garrett K and Erlanson R 2003 A high Q, large tuning range MEMS capacitor for RF filter systems *Sens. Actuators A* **103** 33–41
- [18] Goldsmith C L, Malczewski A, Yao Z J, Chen S, Ehmke J and Hinzl D H 1999 RF MEMS variable capacitors for tunable filters *Int. J. RF Microw. Comput.-Aided Eng.* **9** 362–74
- [19] Khodapanahandeh M, Babaeihaseghobi A and Ghavifekr H B 2020 Design and simulation of a novel RF-MEMS tunable narrow band LC filter in the UHF band *Microsyst. Technol.* **27** 1–10
- [20] Lin T-W, Gao L, Gaddi R and Rebeiz G M 2018 400–560 MHz tunable 2-pole RF MEMS bandpass filter with improved stopband rejection *2018 IEEE MTT-S Int. Microwave Symp.-IMS* (IEEE) pp 510–3
- [21] Wang Z-J, Kim E-S, Liang J-G, Qiang T and Kim N-Y 2018 A high-frequency-compatible miniaturized bandpass filter with air-bridge structures using GaAs-based integrated passive device technology *Micromachines* **9** 463
- [22] Chaubey M K and Bhadauria A 2018 Rf mems based tunable bandpass filter for x-band applications *IOP Conf. Series:*

- Materials Science and Engineering* (IOP Publishing) p 012030
- [23] Di Paola C, Del Barrio S C, Zhang S, Morris A S and Pedersen G F 2019 Mobile phased antenna array@ 6 GHz with digitally tunable capacitor phase shifters *2019 13th European Conf. Antennas and Propagation (EuCAP)* (IEEE) pp 1–4
- [24] Han C-H, Choi D-H and Yoon J-B 2011 Parallel-plate MEMS variable capacitor with superior linearity and large tuning ratio using a leveraging structure *J. Microelectromech. Syst.* **20** 1345–54
- [25] Aziz A K A, Bakri-Kassem M and Mansour R R 2020 Design and characterization of compact digital RF MEMS capacitors and phase shifters in CMOS 0.35 μm technology *J. Micromech. Microeng.* **30** 045006
- [26] Chakraborty A and Gupta B 2017 Utility of RF MEMS miniature switched capacitors in phase shifting applications *AEU-Int. J. Electron. Commun.* **75** 98–107
- [27] Du Y, Su W, Li X, Huang Y and Bao J 2016 A novel MEMS distributed phase shifter for D-band application *2016 IEEE Int. Conf. Microwave and Millimeter Wave Technology (ICMMT)* (IEEE) pp 542–4
- [28] Jmai B, Rajhi A and Gharsallah A 2016 Conception of a tunable analog reflection-type phase shifter based on capacitive RF MEMS for radar application *Int. J. Microw. Opt. Technol.* **11** 339–46
- [29] Scardelletti M, Ponchak G E, Zaman A J and Lee R Q 2005 RF MEMS phase shifters and their application in phase array antennas *NASA Technical Reports Server* (<https://doi.org/10.1016/j.lungcan.2005.08.013>)
- [30] Ming-Shien T 2020 Tunable capacitors to control antenna radiation pattern (Google Patents)
- [31] Chatim R H, Sandhagen C and Bangert A 2018 RF MEMS tunable capacitor for voltage-controlled oscillator application in C-band range *2018 18th Mediterranean Microwave Symp. (MMS)* (IEEE) pp 365–8
- [32] Fouladi S, Domingue F, Zahirovic N and Mansour R R 2010 Distributed MEMS tunable impedance-matching network based on suspended slow-wave structure fabricated in a standard CMOS technology *IEEE Trans. Microw. Theory Tech.* **58** 1056–64
- [33] Mohamed A M M, Boumaiza S and Mansour R 2010 Novel reconfigurable fundamental/harmonic matching network for enhancing the efficiency of power amplifiers *The 40th European Microwave Conf.* (IEEE) pp 1122–5
- [34] Vähä-Heikkilä T and Rebeiz G M 2004 A 4–18-GHz reconfigurable RF MEMS matching network for power amplifier applications *Int. J. RF Microw. Comput.-Aided Eng.* **14** 356–72
- [35] Malmqvist R, Samuelsson C, Rantakari P, Vähä-Heikkilä T, Smith D, Varis J and Baggen R 2010 RF MEMS and MMIC based reconfigurable matching networks for adaptive multi-band RF front-ends *2010 IEEE Int. Microwave Workshop Series on RF Front-ends for Software Defined and Cognitive Radio Solutions (IMWS)* (IEEE) pp 1–4
- [36] Shen Q and Barker N S 2006 Distributed MEMS tunable matching network using minimal-contact RF-MEMS varactors *IEEE Trans. Microw. Theory Tech.* **54** 2646–58
- [37] Fouladi S, Domingue F and Mansour R 2012 CMOS-MEMS tuning and impedance matching circuits for reconfigurable RF front-ends *2012 IEEE/MTT-S Int. Microwave Symp. Digest* (IEEE) pp 1–3
- [38] Del Barrio S C, Morris A and Pedersen G F 2015 MEMS tunable antennas to address LTE 600 MHz-bands *2015 9th European Conf. Antennas and Propagation (EuCAP)* (IEEE) pp 1–4
- [39] Del Barrio S C, Foroozanfar E, Morris A and Pedersen G F 2017 Tunable handset antenna: enhancing efficiency on TV white spaces *IEEE Trans. Antennas Propag.* **65** 2106–11
- [40] Asadallah F, Costantine J, Tawk Y, Lizzi L, Ferrero F and Christodoulou C 2017 A digitally tuned reconfigurable patch antenna for IoT devices *2017 IEEE Int. Symp. Antennas and Propagation & USNC/URSI National Radio Science Meeting* (IEEE) pp 917–8
- [41] Rashidzadeh H, Kasargod P, Supon T M, Rashidzadeh R and Ahmadi M 2016 Energy harvesting for IoT sensors utilizing MEMS technology *2016 IEEE Canadian Conf. Electrical and Computer Engineering (CCECE)* (IEEE) pp 1–4
- [42] Bahramzy P, Jagielski O, Svendsen S, Olesen P and Pedersen G F 2016 Aspects of high-Q tunable antennas and their deployment for 4G mobile communications [antenna applications corner] *IEEE Antennas Propag. Mag.* **58** 70–81
- [43] Costa J, Carroll M, Kerr D, Iversen C, Mason P, Tombak A, Bauder R, Khlal N and Spears E 2014 Advances in SOI switched capacitors for 4G tunable antennas *2014 IEEE MTT-S Int. Microwave Symp. (IMS2014)* (IEEE) pp 1–4
- [44] Allan R 2013 RF MEMS switches are primed for mass-market applications *Microw. RF* **52** 48
- [45] McCormick D T, Li Z and Tien N 2003 Dielectric fluid immersed MEMS tunable capacitors *IEEE MTT-S Int. Microwave Symp. Digest, 2003* (IEEE) pp 495–8
- [46] Abuelhaija A, Salama S and El-Absi M Multi-tuned RF coil using microfluidically tunable RF capacitor for MRI/MRS at 7T
- [47] Saberhosseini S S, Ganji B A, Koohsorkhi J and Ghorbani A 2020 Design and simulation of a variable MEMS capacitor for tunable HMSIW resonator *IET Circuits, Devices Syst.* **14** 707–12
- [48] Guo X, Xun Q, Li Z and Du S 2019 Silicon carbide converters and MEMS devices for high-temperature power electronics: a critical review *Micromachines* **10** 406
- [49] Dey S and Koul S K 2020 Reliable, compact, and tunable MEMS bandpass filter using arrays of series and shunt bridges for 28-GHz 5G applications *IEEE Trans. Microw. Theory Tech.* **69** 75–88
- [50] Jmai B, Dinis H, Anacleto P, Rajhi A, Mendes P M and Gharsallah A 2019 Modelling, design and fabrication of a novel reconfigurable ultra-wide-band impedance matching based on RF MEMS technology *IET Circuits, Devices Syst.* **13** 1299–304
- [51] Di Paola C, Del Barrio S C, Zhang S, Morris A S and Pedersen G F 2020 MEMS tunable frame antennas enabling carrier aggregation at 600 MHz *IEEE Access* **8** 98705–15
- [52] Galisultanov A, Perrin Y, Samaali H, Fanet H, Basset P and Pillonnet G 2018 Contactless four-terminal MEMS variable capacitor for capacitive adiabatic logic *Smart Mater. Struct.* **27** 084001
- [53] Van Spengen W 2012 Capacitive RF MEMS switch dielectric charging and reliability: a critical review with recommendations *J. Micromech. Microeng.* **22** 074001
- [54] Kurachi S, Yoshimasu T, Itoh N and Yonemura K 2007 5-GHz band highly linear VCO IC with a novel resonant circuit *2007 Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems* (IEEE) pp 285–8
- [55] Wu T, Hanumolu P K, Mayaram K and Moon U-K 2009 Method for a constant loop bandwidth in LC-VCO PLL frequency synthesizers *IEEE J. Solid-State Circuits* **44** 427–35
- [56] Seok S, Choi W and Chun K 2002 A novel linearly tunable MEMS variable capacitor *J. Micromech. Microeng.* **12** 82
- [57] Dai C-L, Liu M-C and Li Y-R 2005 A linearly tunable capacitor fabricated by the post-CMOS process *Smart*

- sensors, actuators, and MEMS II* (International Society for Optics and Photonics) pp 642–8
- [58] Shavezipur M, Khajepour A and Hashemi S 2008 A novel linearly tunable butterfly-shape MEMS capacitor *Microelectron. J.* **39** 756–62
- [59] Shavezipur M, Khajepour A and Hashemi S 2008 Development of novel segmented-plate linearly tunable MEMS capacitors *J. Micromech. Microeng.* **18** 035035
- [60] Shavezipur M, Hashemi S, Nieva P and Khajepour A 2010 Development of a triangular-plate MEMS tunable capacitor with linear capacitance–voltage response *Microelectron. Eng.* **87** 1721–7
- [61] Gong Z, Liu H, Guo X and Liu Z J 2018 Optimization of a MEMS variable capacitor with high linearity and large tuning ratio *Microsyst. Technol.* **24** 3169–78
- [62] Xiao Z, Peng W, Wolffenbuttel R and Farmer K 2003 Micromachined variable capacitors with wide tuning range *Sens. Actuators A* **104** 299–305
- [63] Nguyen H D, Hah D, Patterson P R, Chao R, Piyawattanametha W, Lau E K and Wu M C 2004 Angular vertical comb-driven tunable capacitor with high-tuning capabilities *J. Microelectromech. Syst.* **13** 406–13
- [64] Afrang S and Nematkhah N 2019 A new MEMS based variable capacitor using electrostatic vertical comb drive actuator and auxiliary cantilever beams *Microsyst. Technol.* **25** 3317–27
- [65] Chen J, Zou J, Liu C, Schutt-Ainé J E and Kang S-M 2003 Design and modeling of a micromachined high-Q tunable capacitor with large tuning range and a vertical planar spiral inductor *IEEE Trans. Electron Devices* **50** 730–9
- [66] Zou J, Liu C, Schutt-Ainé J, Chen J and Kang S-M 2000 Development of a wide tuning range MEMS tunable capacitor for wireless communication systems *Electron Devices Meeting, 2000. IEDM'00. Technical Digest. Int. (IEEE)* pp 403–6
- [67] Young D J 1996 A micromachined variable capacitor for monolithic low-noise VCOs *Tech. Digest. Solid State Sensor and Actuator Workshop, 1996*
- [68] Dec A and Suyama K 1998 RF micromachined varactors with wide tuning range *1998 IEEE MTT-S Int. Microwave Symp. Digest (Cat. No. 98CH36192)* (IEEE) pp 357–60
- [69] Rijks T G, Van Beek J, Steeneken P, Ulenaers M, De Coster J and Puers R 2004 RF MEMS tunable capacitors with large tuning ratio *Micro Electro Mechanical Systems, 2004. 17th IEEE Int. Conf. (MEMS)* (IEEE) pp 777–80
- [70] Teymoori M M and Ahangarkolaie J M 2016 A tunable capacitor based on MEMS technology for RF applications *Eng. Technol. Appl. Sci. Res.* **6** 982–6
- [71] Liu H, Guo X, You Z and Liu Z 2019 Fabrication of a tunable capacitor with a non-planar plate by using titanium and polyimide as sacrificial layers *2019 IEEE 32nd Int. Conf. Micro Electro Mechanical Systems (MEMS)* (IEEE) pp 863–6
- [72] Tsang T K and El-Gamal M N 2003 Very wide tuning range micro-electromechanical capacitors in the MUMPs process for RF applications *2003 Symp. VLSI Circuits. Digest of Technical Papers (IEEE Cat. No. 03CH37408)* (IEEE) pp 33–36
- [73] Ionis G V, Dec A and Suyama K 2001 A zipper-action differential micro-mechanical tunable capacitor *Microelectromechanical Systems Conf., 2001* (IEEE) pp 29–32
- [74] Wang C-S, Yang Z-C, Cui Y-J, Fang J and Zhang D-C 2002 Design and fabrication of a novel two-dimension MEMS-based tunable capacitor *IEEE 2002 Int. Conf. Communications, Circuits and Systems and West Sino Expositions* (IEEE) pp 1766–9
- [75] Yoon Y J, Lee H S and Yoon J-B 2007 MEMS variable capacitor actuated with an electrically floating plate *Electron Devices Meeting, 2007. IEDM 2007. IEEE Int. (IEEE)* pp 431–4
- [76] Grichener A and Rebeiz G M 2010 High-reliability RF-MEMS switched capacitors with digital and analog tuning characteristics *IEEE Trans. Microw. Theory Tech.* **58** 2692–701
- [77] Elshurafa A M, Ho P, Radwan A, Ouda M and Salama K N 2012 Low-voltage puzzle-like fractal microelectromechanical system variable capacitor suppressing pull-in *Micro Nano Lett.* **7** 965–9
- [78] Baek D-H, Eun Y, Kwon D-S, Kim M-O, Chung T and Kim J 2014 Widely tunable variable capacitor with switching and latching mechanisms *IEEE Electron Device Lett.* **36** 186–8
- [79] Nadaud K, Roubeau F, Pothier A, Blondy P, Zhang L-Y and Stefanini R 2016 Compact thin-film packaged RF-MEMS switched capacitors *2016 IEEE MTT-S Int. Microwave Symp. (IMS)* (IEEE) pp 1–4
- [80] Hailu Z 2017 High quality factor RF MEMS tunable capacitor *Microsyst. Technol.* **23** 3719–30
- [81] Belkadi N, Nadaud K, Hallepee C, Passerieux D and Blondy P J 2019 Zero-level packaged RF-MEMS switched capacitors on glass substrates *J. Microelectromech. Syst.* **29** 109–116
- [82] Khan F, Lu J and Zhu Y 2019 Experimental investigation of actuation in a micromachined electrically floating tunable capacitor *Microelectron. Eng.* **213** 31–34
- [83] Cowen A, Hardy B, Mahadevan R and Wilcenski S 2011 *PolyMUMPs Design Handbook* vol 13 (Durham, NC USA: Memscap Inc.)
- [84] Shavezipur M, Nieva P, Hashemi S and Khajepour A 2012 Linearization and tunability improvement of MEMS capacitors using flexible electrodes and nonlinear structural stiffness *J. Micromech. Microeng.* **22** 025022
- [85] Allen M G, Mehregany M, Howe R T and Senturia S D 1987 Microfabricated structures for the insitu measurement of residual stress, young's modulus, and ultimate strain of thin films *Appl. Phys. Lett.* **51** 241–3
- [86] Brank J, Yao J, Eberly M, Malczewski A, Varian K and Goldsmith C 2001 RF MEMS-based tunable filters *Int. J. RF Microw. Comput.-Aided Eng.* **11** 276–84
- [87] Aziz A K A, Bakri-Kassem M and Mansour R R 2018 Reconfigurable MEMS latching-type capacitors for high power applications *J. Micromech. Microeng.* **29** 025005
- [88] Bakri-Kassem M, Aziz A A and Mansour R 2015 A high power latching RF MEMS capacitors bank *2015 SBMO/IEEE MTT-S Int. Microwave and Optoelectronics Conf. (IMOC)* (IEEE) pp 1–4
- [89] Zareie H and Rebeiz G M 2012 High-power RF MEMS switched capacitors using a thick metal process *IEEE Trans. Microw. Theory Tech.* **61** 455–63
- [90] Habbachi N, Boussetta H, Kallala M, Boukabache A, Pons P and Besbes K 2017 Design and simulation of tunable microwave capacitor based on microfluidic actuation *Int. Conf. Circuits, Systems, Control and Signals (CSCS)* p 5
- [91] Habbachi N, Boussetta H, Boukabache A, Kallala M A, Pons P and Besbes K 2016 Fabrication and modeling of a capacitor microfluidically tuned by water *IEEE Electron Device Lett.* **38** 277–80
- [92] Lee H S, Yoon Y J, Choi D-H and Yoon J-B 2008 High-Q, tunable-gap MEMS variable capacitor actuated with an electrically floating plate *Micro Electro Mechanical Systems, 2008. MEMS 2008. IEEE 21st Int. Conf.* (IEEE) pp 180–3
- [93] Zhu Y, Yuce M and Moheimani S 2009 A low-loss MEMS tunable capacitor with movable dielectric *Sensors, 2009 IEEE* (IEEE) pp 651–4

- [94] Reines I and Rebeiz G 2011 A robust high power-handling (>10 W) RF MEMS switched capacitor *2011 IEEE 24th Int. Conf. Micro Electro Mechanical Systems (IEEE)* pp 764–7
- [95] Grichener A, Mercier D and Rebeiz G M 2006 High-power high-reliability high-Q switched RF MEMS capacitors *2006 IEEE MTT-S Int. Microwave Symp. Digest (IEEE)* pp 31–34
- [96] Yamazaki H, Ikehashi T, Saito T, Ogawa E, Masunaga T, Ohguro T, Sugizaki Y and Shibata H 2010 A high power-handling RF MEMS tunable capacitor using quadruple series capacitor structure *2010 IEEE MTT-S Int. Microwave Symp. (IEEE)* pp 1138–41
- [97] *nanusens creative nano devices* (available at: https://nanusens.com/?utm_source=everythingRF) (Accessed 26 March 2021)
- [98] *RF smart tuners* (available at: www.cavendish-kinetics.com/rf-mems-products/rf-mems-smartuners/)
- [99] *Omron MEMS* (available at: <https://components.omron.com/solutions/mems-sensors/omrons-mems>)