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Experimental Investigation of Actuation in a Micromachined Electrically Floating Tunable Capacitor

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Abstract

In this paper, a tunable parallel plate capacitor with an electrically floating plate has been designed, micromachined and characterized. The device is fabricated from a single metal layer based on a low-cost standard process. The floating tunable capacitor exhibits a higher quality factor (Q-factor) compared to a traditional non-floating capacitor by eliminating the spring's resistive loss in radio frequency (RF) signal path. To minimize the size of the whole device, the tunable capacitor is designed to be actuated using the same parallel plates. Experimental results show that the capacitor has a wide capacitance tuning range of 225% and a high Q-factor of 1150 at 60 MHz. The total size of the device is $1.70 \times 1.08 \text{ mm}^2$.

Keywords: Electrically floating, tunable capacitor, Metal-MUMPs, tuning range.

Introduction

Radio frequency (RF) tunable capacitors are passive components and play an essential role in wireless communication systems such as tunable bandpass and bandstop filters, matching networks, voltage controlled oscillators (VCOs) and phase shifters. All these communication system devices require high tuning range and quality factor.

Microelectromechanical systems (MEMS) tunable capacitors inherently have higher quality factor, tunability, linearity, and lower loss compared to their semiconductor counterparts. However, in conventional MEMS tunable capacitors, suspension beams/springs have to be narrow and long to achieve high tunability and low actuation voltage [1]. However, long beams contribute significant resistive loss for RF signals. For example, several high tuning range capacitors have been presented in [1] and, [2] but

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low Q-factors were obtained.

To increase Q-factor, a tunable capacitor with an electrically floating plate is presented in [3]. However, the tunable capacitor is electro-thermally actuated by a thermal actuator which greatly increases the switching time and power consumption of the overall device. Moreover, the size of the thermally actuated tunable capacitor is also large.

In this paper, an electrostatically actuated floating tunable capacitor has been investigated using simultaneous actuation and sensing technique for the first time. The tunable capacitor is actuated and sensed from the same parallel plates of tunable capacitor. Thus, the total size of the tunable capacitor has been greatly reduced. The device is simulated in Intellisuite and fabricated through a standard Metal-MUMPs process. The testing of prototype is performed using a vector network analyzer.

Fig. 1. SEM image of the electrically floating parallel plate capacitor

Design and fabrication

Fig.1 shows the SEM image of the prototype micro-fabricated using Metal-MUMPs process. In this design, the tunable capacitor is actuated using the same parallel plate comb system. Unlike traditional designs, there is no separate actuator for actuating the movable part of the tunable capacitor. This technique greatly reduces the footprint area of the tunable capacitor. In addition, the electrically floating plate technique is used to increase the Q-factor of the tunable capacitor by eliminating the spring's resistive loss in radio frequency (RF) signal path [3,4]. To avoid the damage of the comb system due to pull-in effect, stoppers have been utilized in the proposed design, as illustrated in Fig.1.

The proposed tunable capacitor consists of transverse comb structures, including fixed and movable comb fingers. Movable comb fingers are mechanically supported by folded beams as shown in Fig. 2. The RF signal flows from plate **A** through the floating plate to plate **B**, as shown in Fig. 2(a). As RF signal does not go through the suspension beam, resistive beam loss in the traditional tunable capacitor from **A** to **C**, as shown in Fig. 2 (b), can be eliminated.

Fig.2 Schematics of electrostatic tunable capacitor design with RF signal passing through (a) floating plate; (b) suspension beam.

Electrostatic parallel plate capacitors often have limited tuning range due to pull-in effect [5, 6]. After pull-in voltage is reached, actuator beams will contact and short the circuit causing permanent damages. Therefore stoppers are used in the proposed design to eliminate the short circuit situation as shown in

Figs.1 and 2. Table 1 lists the design parameter values of proposed electrostatic tunable capacitor. The tuning range, capacitance, Q factor, and impedance can be calculated by using equations (1), (2), (3), and (4) respectively [3].

Table:1 Design parameters and values

Parameters	Design values
Tunable capacitor initial gap (μm)	10
Length of capacitor comb finger (μm)	380
Width of capacitor comb finger (μm)	12
Number of capacitors each side	20
Suspension beam width (μm)	8
Suspension beam length each side (μm)	5×450
Device thickness (μm)	20.5
Air-trench thickness (μm)	25

$$Tuning\ range = \frac{C_{\max} - C_{\min}}{C_{\min}} \quad (1)$$

$$C = \frac{1}{2\pi f (imag\{Z\})} \quad (2)$$

$$Q = \frac{1}{2\pi f C (real\{Z\})} = \frac{1}{2\pi f C R_s} \quad (3)$$

$$Z = Z_o \frac{2(1 - S_{21})}{S_{21}} \quad (4)$$

Where Z , R_s , and S_{21} are the impedance, the series resistance and the Scattering parameter of the tunable capacitor, respectively. Equation (3) implicates that the Q-factor is inversely proportional to the series resistance of the capacitor. Therefore, the series resistance has to be minimized to maximize the Q-factor.

The design is fabricated in a standard Metal-MUMPs fabrication process [7]. The structure of tunable capacitor is made of a 20 μm thick nickel layer with a 0.5 μm thick gold layer on the top as shown in Fig. 3. A 25 μm air trench is made beneath the floating tunable capacitor structure, which is able to reduce the energy loss in silicon substrate.

Fig. 3 Cross-sectional view of tunable capacitor.

Fig.4. Simulated and measured voltage requirement comparison of floating and traditional configurations.

Results and Discussions

The proposed design is simulated in the TEM module of Intellisuite. Fig. 4 shows the comparison of voltage requirement of the proposed floating and traditional non-floating tunable capacitors for the given displacements. It is clear from the figure that the floating configuration for parallel plate systems requires double voltage than the non-floating traditional configuration. Therefore, the floating technique can be used to improve the Q-factor of tunable capacitor; however the trade-off is that twice voltage is required compared to non-floating traditional tunable capacitor.

The actuation and measurement schematic of tunable capacitor is shown in Fig. 5. Bias tees were used to decouple AC and DC signals before connecting with a N9923A vector network analyzer. The impedance parameter of the tunable capacitor was obtained from vector network analyzer and capacitance and quality factor were extracted using Eq. 2 and 3.

Fig. 5. Actuation and measurement schematic for electrostatic tunable capacitor

The experimental setup for the testing is shown in Fig. 6. The GSG probes are connected to the two fixed plates, as shown in Fig. 2 at points A and B. The DC actuation voltages and RF signals are applied through the same probes. Bias tees are used to decouple the AC and DC signals to dc supply and vector network analyzer. A voltage amplifier (A400DI, FLC electronics) is used for DC voltage amplification as shown in Fig. 5. The parasitic capacitance of bias tees and capacitor's pads were de-embedded using de-embedding technique given in [8].

Fig. 6 The testing setup and placement of GSG probes on parallel plate capacitor.

Fig. 7 shows the capacitance versus voltage plot of tunable capacitor at 60 MHz. The simulated and measured capacitance show close correlation. The change in capacitance with the applied voltage is extracted from the impedance of the tunable capacitance by using Eq. 2. Tuning range of 225% is achieved from the proposed design. The measured quality factor of the proposed design is illustrated in Fig. 8.

Fig. 7 Measured capacitance versus actuation voltage.

The quality factor of 1347 has been achieved at 25 MHz, which decreases to 39 at 1 GHz. The decrease in quality factor is due to the increase in frequency as Q is inversely proportional to frequency given in Eq. 3. A comparison of Q -factor of floating and non-floating tunable capacitor for thermally actuated tunable capacitor was performed in [3].

Fig. 8. The quality factor of the electrostatic floating tunable capacitor.

Conclusion

This work demonstrates a micro-machined parallel plate floating tunable capacitor operated in VHF and UHF frequency ranges. The tunable capacitor is actuated by the same combs of the tunable capacitor, which greatly reduces the size of tunable capacitor. It has been noted that the quality factor of floating tunable capacitors is far better than the non-floating tunable capacitor. However, on the other hand floating parallel plate tunable capacitor requires twice voltage than that of the non-floating tunable capacitor. The tuning range of 225% and quality factor as high as 490 at 250 MHz have been achieved. The overall size of the prototype is reduced compared to traditional tunable capacitors and total footprint area is $1.70 \times 1.08 \text{ mm}^2$.

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Highlights

1. Electrostatically actuated floating plate MEMS tunable capacitor was investigated for the first time.
2. Floating plate capacitor requires double voltage as compared to traditional MEMS capacitor.
3. The Quality factor of floating plate MEMS tunable capacitor is higher than traditional MEMS capacitor.
4. The performance of electrostatically actuated floating plate MEMS capacitor is simulated and validated experimentally.