A MEMS Capacitor with Improved RF Power Handling Capability

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Abstract — **This paper presents a structure of MEMS capacitor providing independence of its nominal capacity and tuning range from the applied RF signal power. The capacitor includes a third parallel plate acting as an electrode to which an extra DC voltage is applied to compensate for the self-actuation effect. This means that the device can be used in many applications working under different RF power conditions, without changing its performance – nominal capacity and tuning range –. Capacitor design concept and simulations are provided. It has been manufactured using a standard surface-micromachining MEMS technology. Experimental results are presented, validating the concept and demonstrating its feasibility and advantages.**

I. INTRODUCTION

RF MEMS variable capacitors are being considered for next generations of wireless communication systems. Potential advantages of these devices are reconfigurability, capacity of integration and no DC power consumption (in the most common electrostatic actuation case). Some other characteristics, which not long time ago seemed to be a drawback (as for example tuning range [1] and reliability [2]) have demonstrated an outstanding performance. But concerning RF power handling capability, this is one of the unsolved problems in electrostatically-actuated parallel-plates MEMS variable capacitors. While some authors have theoretically studied the effects of RF power on MEMS capacitors [3], other works have considered this effect on switches [4], proposing different solutions to improve its performance, and empirically demonstrating their viability [5].

The most important property of MEMS is offering reconfigurability to the circuits. This reconfigurability is an added value when it can be fully controlled, but in the case of RF power applications, it may translate into a drawback, as the MEMS device changes its performance as a function of RF power. This unwanted behaviour can be diminished, but not completely overcome, by increasing the total stiffness (K). This solution is acceptable in capacitive switches, as the ON state capacity is in the range of fF, but it is not in MEMS capacitors, because a change in RF power can produce an important change in the nominal capacity and in the tuning range. In addition to this, increasing K means increasing the control voltage, which is not permitted in many applications. Moreover, the required K for a specific power condition in a circuit may not be the same as the one required for another power condition in a different circuit. Thus, different MEMS designs would be required, with an additional cost in terms of re-designing, manufacturing and testing.

In this paper, it is proposed to use a MEMS variable capacitor [1] with three parallel-plates to compensate for the effects of power handling on the device, making its characteristics independent of the injected RF power, with three objectives:

1) To obtain a capacitor with a constant nominal capacity versus RF power.

2) To keep the device tuning range invariable with RF power.

3) To provide flexibility: the capacitor can be used in different circuits working under different power conditions, without needing to be re-designed.

II. EFFECTS OF RF VOLTAGE ON A TWO PARALLEL-PLATES MEMS VARIABLE CAPACITOR

Two effects limit RF power handling in MEMS capacitors: self-actuation and thermal effects due to RF current. Self-actuation, the effect considered in this work, is the attractive force that appears on a mobile membrane due to the RF rms voltage [4], causing the membrane to deflect in a similar manner to an applied DC bias. If a RF signal $V_{RFrms} \sqrt{2} \, cos(\omega t)$ is simultaneously applied to the DC bias V_{DC}, the resulting electrostatic force can be written as:

$$F_e = -\frac{1}{2}\frac{\partial C}{\partial x}\left(V_{DC}^2 + V_{RFrms}^2\right) \qquad (1)$$

where C is the RF capacity and x the displacement of the mobile membrane. The consequence of this self-actuation effect is shown in Fig.1.a and Fig.1.b, where the displacement of the mobile membrane and the capacity variation of a two parallel plates capacitor are shown as a function of V_{DC} and V_{RFrms} voltages, respectively. Two consequences of the RF self-actuation can be appreciated: an increase of the nominal capacity and a decrease of the tuning range.

On the other hand, RF current results in thermal heating of the membrane causing the material to expand and the membrane to deflect. This is an effect which in low-loss devices is much less significant than self-

actuation, in spite it should be taken into account mainly under high power conditions [4], and is not considered here.
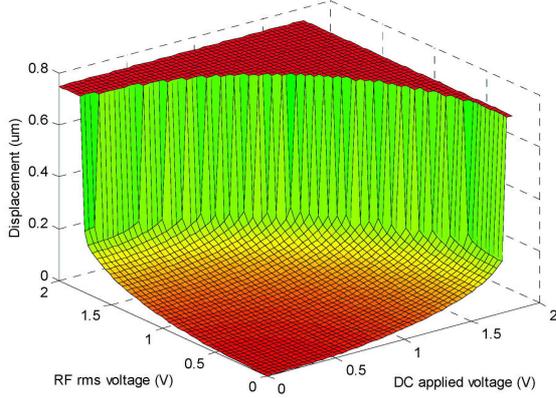
Fig.1.a. Displacement of the mobile membrane as a function of DC bias V_{DC} and of RF rms voltage V_{RFrms}.
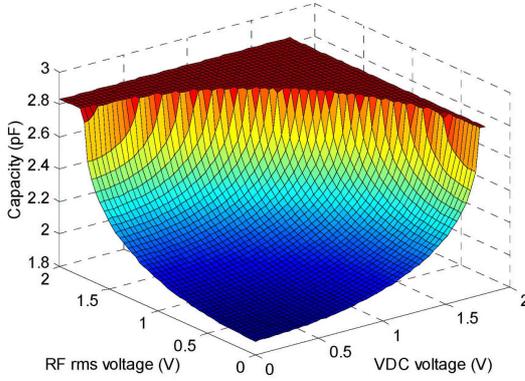
Fig.1.b. Capacity variation in a two parallel-plates MEMS capacitor as a function of DC bias V_{DC} and of RF rms voltage V_{RFrms}. Capacitor parameters: see section III.

III. CAPACITOR TOPOLOGY AND PERFORMANCE ANALYSIS

A. Capacitor Concept

The solution proposed in this paper consists of adding a third parallel plate and a second control voltage V_{DCdwn}, as shown in Fig.2, being the mobile plate the one in the middle. The two parallel-plates capacitor is built between the middle and top plates. A new electrostatic force appears between the mobile plate and the third added bottom plate. This means that any value of RF voltage causing self-actuation can theoretically be compensated by biasing the third plate. This second bias provides a suitable force in order to keep the mobile membrane in the right position x_{DC} –determined by DC biasing V_{DC}–, and making it independent from the RF voltage. The effect of adding a restoring force can be observed in Fig.3.a. In this way, the limit in RF power handling will increase up to the limit imposed by current density, much higher than the one imposed by self-actuation [4]. The latter depends basically on the materials and shape of the structures. Another important advantage of this solution

is no DC current consumption, as it is based on adding an electrostatic force –DC voltage–.
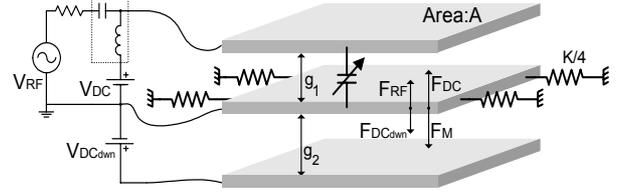
Fig.2. Schematic of the proposed MEMS capacitor to improve RF power handling.
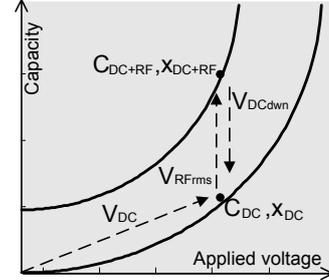
Fig.3.a. Effect of adding the restoring voltage V_{DCdwn}.
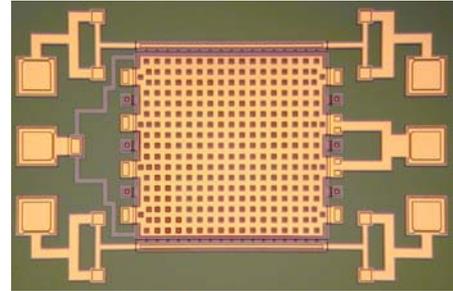
Fig.3.b. Photograph of the manufactured capacitor

The 1-D equation that rules the steady-state position of the membrane is:

$$\sum F_{electrostatic} = F_{DC} + F_{RF} + F_{DCdwn} = F_M$$

$$\frac{\varepsilon A V_{DC}^2}{2(g_1+x)^2} + \frac{\varepsilon A V_{RFrms}^2}{2(g_1+x)^2} - \frac{\varepsilon A V_{DCdwn}^2}{2(g_2-x)^2} = -Kx \quad (2)$$

being F_{DC} the force caused by the DC bias signal V_{DC}, F_{RF} the force caused by the RF signal V_{RFrms} (self-actuation), F_{DCdwn} the added compensating force caused by V_{DCdwn}, F_M the mechanical restoring force, A the area and ε the gap permittivity (air). The compensating voltage V_{DCdwn} that has to be applied to the third plate depends on the position x_{DC} where the plate has to be re-placed and on the rms value of the RF voltage signal V_{RFrms}:

$$V_{DCdwn} = \frac{(g_2-x_{DC})}{(g_1+x_{DC})} V_{RFrms} \quad (3)$$

B. Simulated Performance

Table I shows the parameters of the designed three-plates capacitor. It has been manufactured with the commercially available surface-micromachining process PolyMUMPS[TM].

The design process for this capacitor (Fig.3.b) is similar to that of a two parallel-plates capacitor [1], but adding an extra (bottom) plate placed at a distance g_2 (air gap 2) below the middle plate. The thickness of this gap g_2 is fixed by the technology. Then, using (3), the restoring voltages V_{DCdwn} are plotted as a function of RF voltages.

Area A	400x400 μm^2	E (Young	165 GPa
Gap1 g_1	0.75 μm	Modulus)	
Gap2 g_2	2 μm	K	35 N/m

TABLE I
PARAMETERS OF THE DESIGNED CAPACITOR

Fig.4 shows the displacement of the mobile membrane working as a traditional two parallel-plates (V_{DCdwn}=0), for five RF rms voltages V_{RFrms}. It is observed that the nominal capacity increases and the tuning range reduces as the RF voltage increases. The objective of the proposed capacitor topology is to obtain a displacement (and, therefore, capacity) corresponding to the trace of no RF power applied, independently of the effectively applied RF power.
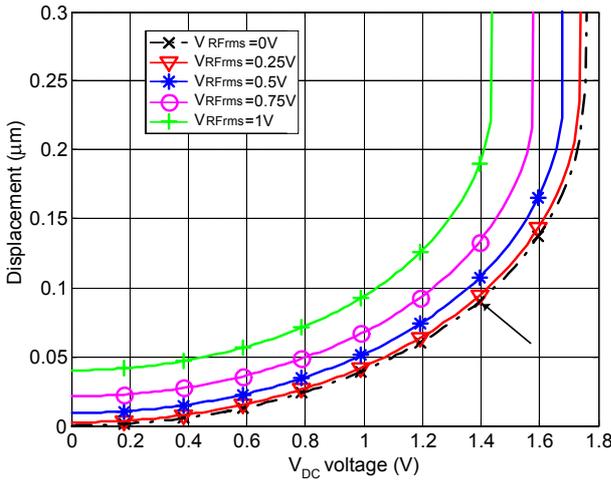
Fig.4. Simulated effect of the RF rms voltage V_{RFrms} on the mobile membrane: nominal capacity increase and tuning range decrease.

To this end, Fig.5 shows a plot of the V_{DCdwn} required for the designed capacitor, as a function of the applied DC bias voltage V_{DC} (which determines the membrane position x_{DC}), for the same five RF voltages as in Fig.4. As an example (see the arrows in Figs.4-6) assume an application requiring the capacitor mobile membrane in the position x_{DC}=0.09 μm (corresponding to an applied DC voltage V_{DC}=1.4 V) and a RF voltage V_{RFrms}=1V. From Fig. 4, the actual position of the membrane due to self-actuation is x_{DC+RF}=0.19 μm. From Fig.5, for the abscise 1.4 V and a RF voltage of 1 V, the required restoring voltage can be obtained: V_{DCdwn}=3.17 V. Applying this voltage to the third plate, provided that the capacitor is under those DC and RF conditions will restore the target position x_{DC}.

This effect can be seen in Fig.6, where the displacement for the condition of no RF voltage applied is plotted along with displacement for V_{DCdwn} = 3.17 V

and V_{RFrms} = 1 V. It can be observed that the capacity converges at a displacement of x_{DC}=0.09 μm for an applied DC voltage V_{DC} =1.4V, as expected. This means that the membrane positioning and RF voltage can be made independent. In an application for which a constant power and constant position are expected (as for instance, a capacitor in a matching network) this is the right solution, because the map of the voltages to be applied to the third membrane is perfectly known (see Fig.5) as a device characteristic. In applications requiring the membrane to work at different positions (as for instance, voltage controlled oscillators), a good solution is applying a constant V_{DCdwn} restoring voltage. In the presented example, a reasonable figure for V_{DCdwn} would be 2.7V, corresponding to the restoring voltage for V_{DC}=0V in the case of V_{RFrms}=1V. Observe in Fig.6 that, although it is not an optimum solution for all membrane positions, it is much better than not applying it, in spite of a tuning range slight reduction. In this case, the nominal capacity also remains constant with RF voltage.
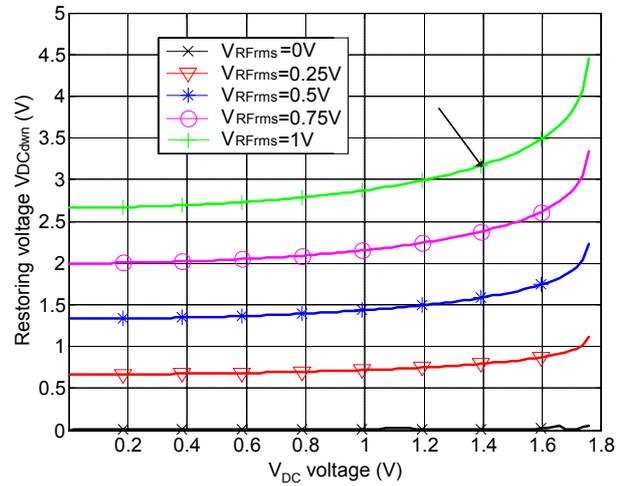
Fig.5. V_{DCdwn} voltage required to restore the mobile membrane as a function of the V_{DC} voltage (determined by the required x_{DC} position), for five RF rms voltages V_{RFrms}.
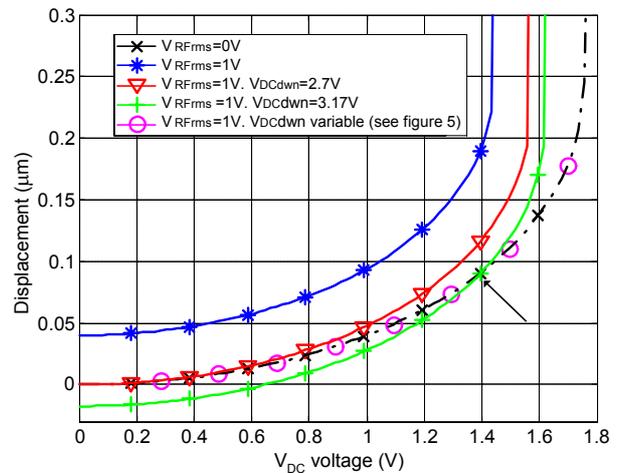
Fig.6. Simulated results of applying a variable and a constant V_{DCdwn} voltage in order to restore the mobile plate to its x_{DC} position.

IV. EXPERIMENTAL RESULTS

Measurements of RF power handling have been done at 1.5 GHz using the system proposed in [6]. It is based on I/Q demodulation of the reflected signal in RF MEMS capacitors in order to characterize dynamics and power handling. It is advantageous in terms of allowing S parameters time measurement as well as suitable for high RF power signals. Fig.7 shows the measured capacity versus applied voltage in five cases. First, the capacity is measured using a HP8510 VNA with low RF power (0 dBm), and the result is compared to the capacities obtained using the measurement system of [6] for RF powers of 14 and 16 dBm. A shift in the nominal capacity of 0.13 pF in the first case and 0.25 pF in the second can be appreciated. Finally, two more plots are shown, corresponding to the capacity excursions with an applied RF power of 14 and 16 dBm, but adding their respective V_{DCdwn} restoring voltages: 3.2 and 3.6 V. It can be seen that the nominal capacity has been restored to its correct position and the tunability made independent of the RF power. Furthermore, as it is observed in Fig.5, applying a constant voltage for a given RF power is a good option because the restoring V_{DCdwn} voltage is nearly constant during all the excursion except when the capacitor is close to the pull-in limit, where the required restoring voltage has a slight increase.
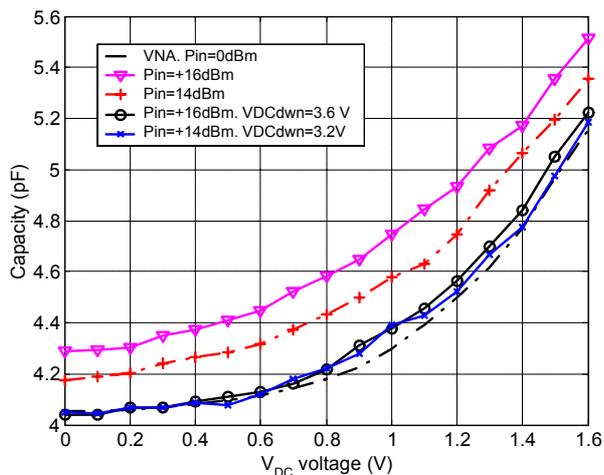
Fig. 7. Measured results. Comparison between the capacity variation at +14 and +16 dBm RF power with and without restoring V_{DCdwn} voltages, measured with the system proposed in [6]. Comparison to the measurement with low RF power using a VNA.

The plots were obtained as an average of 2730 measurements at each point. Measurements have been done up to 1.6 V (below pull-in) because the capacitor remained in stiction after pull-in collapse, as there is no dielectric layer to avoid contact between electrodes.

V. CONCLUSION

This work has presented simulated and experimental results of a MEMS variable capacitor whose topology, based on the addition of a third parallel plate, provides a solution to the issue of RF power handling, important limitation in MEMS capacitors. With the proposed structure, the nominal capacity and the tuning range have demonstrated independence from the applied RF signal power. Design equations are provided, the capacitor performances are simulated and a practical realization is designed and tested. Experimental results show that, by applying a restoring voltage to the third plate, the nominal capacity and tuning range are made independent of RF voltage, counteracting the RF self-actuation effect.

REFERENCES

[1] D.Girbau, A.Lázaro, L.Pradell, "Extended tuning range RF MEMS variable capacitors using electrostatic and electrothermal actuators". *Proceedings of SPIE Micromachining and Microfabrication 2004*, vol. 5344, pp.59-70. January, 2004.

[2] I.De Wolf, "The reliability of RF-MEMS: failure modes, test procedures and instrumentation", *Proceedings of SPIE Micromachining and Microfabrication 2004*, vol. 5343, pp.1-8. January, 2004.

[3] A.Cruau, P.Nicole, G.Lissorgues, C.-M.Tassetti, "Influence of RF signal power on tunable MEMS capacitors". *33rd European Microwave Conference*, Vol. 2, pp. 663-666, October 2003.

[4] J.R.Reid, L.A.Starman, R.T.Webster, "RF actuation of Capacitive MEMS Switches", *2003 MTT-S Digest*, Vol.3, pp. 1919-1922, June 2003.

[5] D.Peroulis, S.P.Pacheco, L.P.B.Katehi, "RF MEMS Switches With Enhanced Power Handling Capabilities", *IEEE Trans. on Microwave Theory and Techniques*, Vol. 52, Nº 1, pp. 59-68 January 2004.

[6] D.Girbau, A.Lázaro, L.Pradell, "Characterization of dynamics and power handling of RF MEMS using vector measurement techniques", *IEEE Trans. on Microwave Theory and Techniques*, Vol. 52, Nº 11, pp. 2627-2633 November 2004.