Differential Multi-Finger MEMS Tunable Capacitors for RF Integrated Circuits

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Abstract— **Several micro-electro-mechanical tunable capacitors fabricated in polysilicon surface micro-machining process are presented. These devices are based on parallel-plate and zipper actuation principles. Differential and multi-finger techniques are used to achieve higher quality factors. These devices are evaluated by direct measurements and by measuring phase noise of voltage-controlled oscillators that use these devices. A Voltage-Controlled Oscillator with a two-finger parallel-plate variable capacitor shows the phase noise of -129dBc/Hz at 600kHz offset from the carrier while outputting 1.3dBm and tuning between 1.81GHz and 1.85GHz. An experimental fractal capacitor with quality factor better than 17 at 1.5GHz and capacitance varying from 1.9pF to 6.7pF is also presented.**

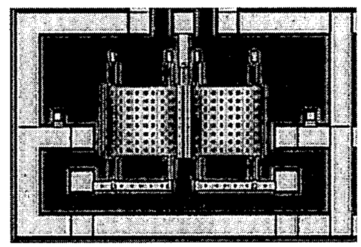

Fig. 1. Differential parallel-plate capacitor, N=1.

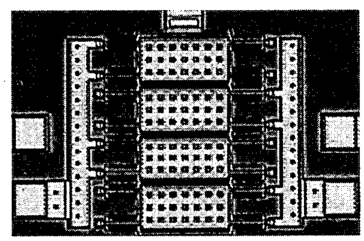

Fig. 2. Differential multi-finger parallel-plate capacitor, N=2.

I. INTRODUCTION

High-Q tunable capacitors are desirable for tunable voltage-controlled oscillators (VCOs) where they lead to lower phase noise and higher output power [1][2]. Micro-machining is a promising technology for making such devices [1][2].

Micro-mechanical tunable capacitors are often constructed of metal (aluminum or gold) to improve their quality factor [1]. On the other hand, polysilicon is a promising material for integrating such devices in standard IC fabrication processes [2]. The main disadvantage of polysilicon is its high resistivity. In this paper ways of increasing the quality factor of MEMS capacitors fabricated in polysilicon surface micro-machining technology are investigated.

Experimental devices were fabricated in the commercially available polysilicon surface micro-machining process, MUMPs [3]. This process features three layers of polysilicon and the top layer can be covered with a layer of gold (sheet resistance of 0.06Ω/sq). The capacitors considered in this paper are made of two parallel plates. Using the gold film reduces the loss in one of the plates of the capacitor. However, the other plate of the capacitor has to be made of the middle or bottom layer of polysilicon, which is lossy (with sheet resistance of 10Ω/sq and 30Ω/sq, respectively).

There are several techniques to reduce the impact of the bottom-plate resistance. One approach is to divide the capacitor into several parallel capacitors [4][5]. Another approach is to take advantage of differential topology that is common in RF integrated circuits (for example [6][7]) and use the differential capacitor [5]. These techniques can be combined to make a differential multi-finger capacitor [5][8]. This technique can be extended to realize a *fractal* capacitor which potentially has higher Q than a simpler multi-finger devices. Fractal capacitors have been proposed in [9], but for a different reason.

II. MULTI-FINGER DIFFERENTIAL MEMS CAPACITORS

The *differential multi-finger parallel-plate* device was obtained by applying both the differential and multi-finger techniques to the single-ended parallel-plate capacitor described in [2]. Devices with one, two, and four fingers are considered. The photographs of these device are shown in Fig. 1, Fig. 2, and Fig. 3, respectively. The structure of these devices is similar to the device in [2] and it uses the middle layer of polysilicon as its bottom plate.

It is not practical to make such devices with a large number of fingers, as the fingers become narrow to maintain the

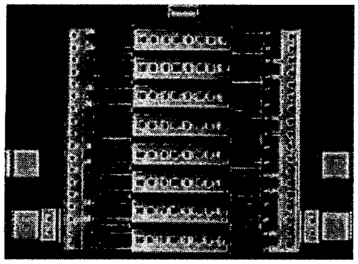

Fig. 3. Differential multi-finger parallel-plate capacitor, N=4.

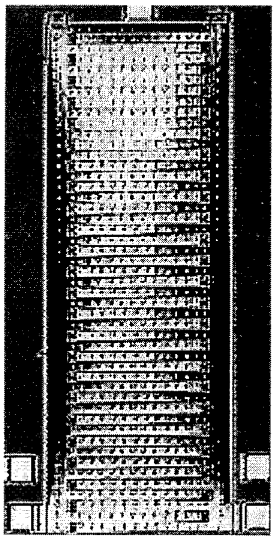

Fig. 4. Differential multi-finger zipper capacitor, N=24.

desired capacitance. A different kind of tunable capacitor was used to investigate the effect of higher number of fingers. A differential multi-finger zipper device [8] is shown in Fig. 4. This device has 24 fingers and its bottom plate is made of the bottom layer of polysilicon, which causes the device to have larger dimensions for the same capacitance.

It was shown in [10] that a two-dimensional capacitor has optimum aspect ratio that maximizes the quality factor. In the case of the proposed differential device the fingers are single-contacted on the top plate (sheet resistance ρ_1) and double-contacted on the bottom plate due to the differential operation (sheet resistance ρ_2). The optimum aspect ratio is given by

$$\left(\frac{L}{W}\right)_{\text{OPT}} = \frac{1}{2}\sqrt{\frac{\rho_2}{\rho_1}} \qquad (1)$$

and the corresponding quality factor of the N-finger device is given by

$$Q_{\text{MAX}}(N) = \frac{3N}{\omega\sqrt{\rho_1\rho_2}C} = \frac{1}{\omega R_{\text{MIN}}C} \qquad (2)$$

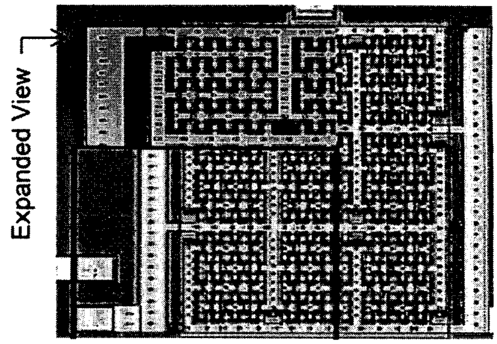

Fig. 5. Differential fractal zipper capacitor.

where $R_{\text{MIN}} = \sqrt{\rho_1\rho_2}/3N$ can be interpreted as the minimum effective resistance.

With the parameters of the MUMPs process these become $(L/W)_{\text{OPT}} = 11.2$ and $R_{\text{MIN}} = 0.45\Omega/N$ when the bottom plate of the capacitor is made of the bottom layer of polysilicon, as it is in the zipper device. While it is impractical to make parallel-plate capacitors with high aspect ratios (since fingers cannot be too narrow to be suspended properly), such multi-finger zipper devices can be fabricated.

The above argument is only valid if the fingers are connected by ideal wires, in which case the optimum topology is the structure with many fingers, each optimized individually. This is not the case in the MUMPs process, however. The best conductor available is the top layer of polysilicon with gold film whose sheet resistance is also ρ_1. Because of this the loss of the optimally-designed capacitor is dominated by the loss of the connecting wires.

Instead of making a large number of fingers, each finger can be designed differently. The first step was from a single-finger to multi-finger device. But now each pair of adjacent fingers looks like the original single-finger structure and it again can be replaced with a multi-finger structure. This procedure can be continued for as long as the design rules allow. This type of shape is called a *fractal*, and the capacitor with this topology is referred to as the *fractal capacitor* [9]. In this paper one such device is considered, depicted in Fig. 5 (the inset shows the magnified view of the corner of the device). Each element of this device operates as a zipper device. The core of the fractal capacitor (i.e. excluding the side wires) has a higher Q than simpler multi-finger devices.

III. Measurement Results

The summary of the experimental tunable capacitors and their measured capacitances are shown in Table I, together with the single-ended device from [2] for comparison. All of the differential devices were designed for 1.5pF capacitance. Fig. 6 shows the tuning characteristics of the three

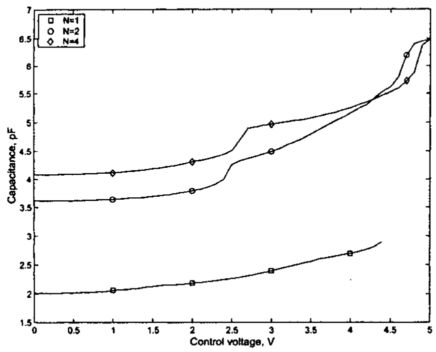

Fig. 6. Measured tuning characteristic of parallel-plate capacitors.

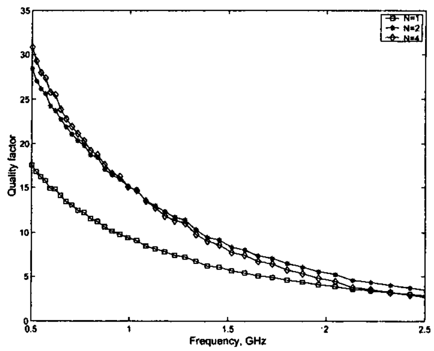

Fig. 7. Measured quality factor of parallel-plate capacitors.

parallel-plate devices. The non-linear tuning characteristics of these devices are problematic, and further work is being carried out to make it more linear. The tuning characteristic of the multi-finger zipper device is shown in [8] and is not repeated here.

The direct measurement of the quality factor of differential devices is difficult. It can be done by measuring the two-port parameters of the device and then using them to calculate the differential properties of the device. This approach was used in [5] and [8]. The quality factors obtained from this measurement are shown in Fig. 7. While this measurement confirms the expected trend (more fingers lead to higher Q), the measured quality factors are significantly lower than the values predicted by calculations. Above 1.5GHz the quality factors of multi-finger devices are almost the same, independent of the number of fingers. This indicates that there are other sources of loss present in this measurement. We speculate that this is caused by the ground ring (shown in Fig. 1) that is necessary for this measurement, but which contributes loss that cannot be easily separated from the loss of the device itself. The DC resistance of the ground ring is estimated as 0.7Ω.

A prototype fractal device was also measured. Its capacitance varies from 1.9pF to 6.7pF with 13V of control voltage. Its Q is better than 17 at 1.5GHz. However, this device shows a discontinuous tuning characteristic, and is being investigated further.

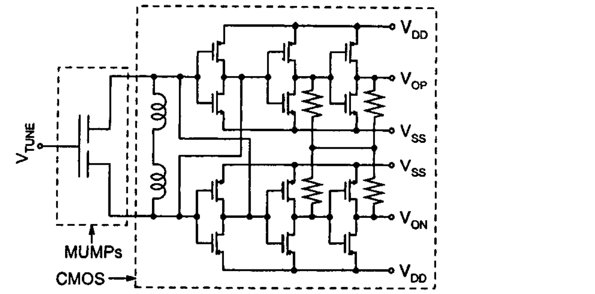

Fig. 8. VCO schematic from [2].

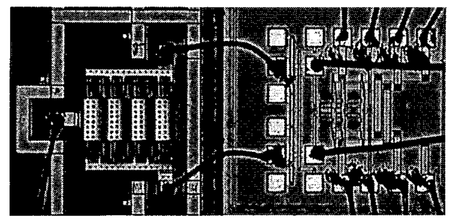

Fig. 9. Photograph of the MEMS-CMOS assembly, showing a two-finger differential parallel-plate capacitor.

IV. Micro-Machined VCOs

An indirect approach was also followed to confirm these measurement results. The same VCO as in [2] and [8] (schematic shown in Fig. 8) was used to selectively measure the phase noise when the VCO was loaded with different tunable capacitors. The power spectral density of the output of an LC oscillator is approximately given by [11]

$$S(\Delta\omega) \approx \frac{S_N}{8Q^2}\left(\frac{\omega_0}{\Delta\omega}\right)^2 \tag{3}$$

where $S(\Delta\omega)$ is the power spectral density of the output at the frequency $\omega_0 + \Delta\omega$, ω_0 is the oscillation frequency, and S_N is the power spectral density of all the noises sources in the oscillator. In all oscillators the inductors were implemeted as pairs of gold bond-wires. Therefore, by comparing the phase noise of the VCOs with different capacitors the relative quality of the tunable capacitors can be inferred.

The photograph of the VCO using a two-finger parallel-plate capacitor is shown in Fig. 9. The summary of the VCO measurements are shown in Table II. This table shows the phase noise at 600kHz offset from the carrier. This measurement confirms the conclusion that larger number of fingers leads to lower phase noise, from which it is inferred

TABLE I

CHARACTERISTICS OF DIFFERENTIAL MULTI-FINGER TUNABLE CAPACITORS

Device	Fingers	Finger size	Overall size	C_{MIN}, pF	C_{MAX}, pF	V_{TUNE}, V
Single-ended parallel-plate [2]	1	—	210μm×230μm	2.1	3.1	4.0
Differential multi-finger parallel-plate	1	240μm×240μm	0.6mm×0.5mm	2.0	2.9	4.4
Differential multi-finger parallel-plate	2	240μm×120μm	0.5mm×0.5mm	3.6	6.5	5.0
Differential multi-finger parallel-plate	4	240μm×60μm	0.6mm×0.6mm	4.1	6.5	5.0
Differential zipper [8]	24	422μm×30μm	1.6mm×0.6mm	3.2	4.6	35
Differential fractal	2×2×2×4	—	0.8mm×0.7mm	1.9	6.7	13

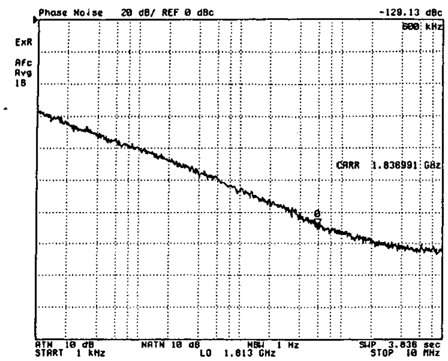

Fig. 10. Phase noise of the VCO with a two-finger differential parallel-plate capacitor.

TABLE II

SUMMARY OF VCO MEASUREMENTS

Device	ω_0, GHz	Phase noise, dBc/Hz	P_{OUT}, dBm
Single-ended parallel-plate [2]	1.77 – 1.93	-126	3.4
Differential 2-finger parallel-plate	1.81 – 1.85	-129	1.3
Differential zipper [8]	1.47 – 1.54	-131	1.6

that it also leads to higher Q. The tuning range of the VCO is smaller than expected from capacitance measurements. The tunable capacitor was wire-bonded to the VCO die. The stresses induced in the bonding process change characteristics of the capacitor and thus reduce the tuning range of the VCO.

V. CONCLUSIONS

Several differential multi-finger micro-electro-mechanical tunable capacitors were fabricated in polysilicon surface micro-machining process based on both parallel-plate and zipper actuation principles. These devices were evaluated by direct measurements and by measuring the phase noise of voltage-controlled oscillators that use these devices. A VCO with a two-finger differential parallel-plate variable capacitor shows the phase noise of -129dBc/Hz at 600kHz offset from the carrier while outputting 1.3dBm and tuning between 1.81GHz and 1.85GHz. Based in these measurements it is concluded that increasing the number of fingers can increase the quality factor of tunable capacitors. An experimental fractal variable capacitor Q better than 17 at 1.5GHz was also demonstrated. Additional research is required to make practical tunable capacitors based on these principles.

ACKNOWLEDGMENT

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REFERENCES

[1] D. J. Young, B. E. Boser, "A micromachine-based RF low-noise voltage-controlled oscillator," 1997 Custom Integrated Circuit Conference Proc., pp. 431–434.

[2] A. Dec, K. Suyama, "A 1.9GHz CMOS VCO with micromachined electromechanically tunable capacitors," *J. Solid-State Circuits*, vol. 35, no. 8, pp. 1231–1237, 2000.

[3] D. A. Koester, R. Mahadevan, B. Hardy, K. W. Markus, *MUMPs™ Design Handbook*, Revision 6.0, Cronos Integrated Microsystems, 2001

[4] C. M. Hung, Y. C. Ho, I. C. Wu, K. O, "High-Q capacitors implemented in a CMOS process for low-power wireless applications," *Trans. Microwave Theory and Techniques*, vol. 46, no. 5, pp. 505–511, 1998.

[5] A. S. Porret, T. Melly, C. C. Enz, E. A. Vittoz, "Design of high-Q varactors for low-power wireless applications using a standard CMOS process," *J. Solid-State Circuits*, vol. 35, no. 3, pp. 337–345, 2000.

[6] F. Svelto, S. Deantoni, R. Castello, "A 1.3 GHz Low-Phase Noise Fully Tunable CMOS LC VCO," *J. Solid-State Circuits*, vol. 35, no. 3, 2000.

[7] J. R. Long, "A Low-Voltage 5.1–5.8-GHz Image-Reject Downconverter RF IC," *J. Solid-State Circuits*, vol. 35, no. 9, pp. 1320–1328, 2000.

[8] G. V. Ionis, A. Dec, K. Suyama, "A zipper-action differential micro-mechanical tunable capacitor," 2001 MEMS Conference Dig., August 2001.

[9] H. Samavati, A. Hajimiri, A. Shahani, G. N. Nasserbakht, T. H. Lee, "Fractal Capacitors," *J. Solid-State Circuits*, vol. 33, no. 12, pp. 2035–2041, 1998.

[10] S. Y. Pavan, *High frequency continuous time filters in digital CMOS processes*, Ph.D. thesis, Columbia University, 1999.

[11] W. Robins, *Phase noise in signal sources: theory and applications*, Peter Peregrinus, Stevenage, UK, 1982.