MEMS-based MCM VCO for space applications

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Abstract — This paper presents the implementation and test of prototype RF MEMS based Voltage Controlled Oscillators (VCO) for space applications. RF MEMS tunable capacitors based on a dual gap architecture have been manufactured with a thin film technology on silicon and have demonstrated high tuning ratio ($C_{\text{max}}/C_{\text{min}} \sim 4$) and high Q factors (up to 100) with a good reproducibility. These tunable capacitors have been integrated as frequency tuning element in the LC tank of multi chip modules (MCM) VCO operating around 1.6 GHz with a tuning range greater than 16\% and a phase noise as low as -125 dBc/Hz at 1 MHz offset from the carrier.

I. INTRODUCTION

With the growing demand for multimedia applications and High Definition Television (HDTV), the next generation of telecommunication satellites will require higher performances and higher functionality with still stronger constraints on cost and size. At the RF transponders level, these requirements turn into higher operating frequencies (Ka band), higher flexibility, (reconfigurability, on board processing...) and further miniaturisation [1].

In that context, RF MEMS potentialities (low insertion loss, low power consumption, high linearity...) open attractive perspectives for the development of smart RF subsystems such as integrated filters, tunable LC circuits, reconfigurable antennas... [2]. In this particular paper, we will focus on the integration of MEMS tunable capacitors as frequency tuning element in the resonator circuit of Voltage Controlled Oscillators.

To achieve a low phase noise VCO, the two main requirement for a tunable capacitor are a high quality factor and a wide tuning range. However, standard parallel plates MEMS tunable capacitors with electrostatic actuation usually exhibit low tuning ratio ($C_{\text{max}}/C_{\text{min}} < 1.5$) because of the so called pull in effect which limits the tunability of MEMS based VCO reported so far in the literature [3,4].

In this work, MEMS tunable capacitors with very large tuning ratios have been designed and manufactured using a dual gap architecture. After packaging, these components have been integrated in VCO modules exhibiting RF properties (tunability, phase noise...) at the state of the art for MEMS based prototypes.

II. MEMS TUNABLE CAPACITORS

RF MEMS tunable capacitors have been designed and manufactured using the PASSI\textsuperscript{TM} process from Philips Electronics N.V. which allows fabrication of MEMS devices together with high-Q passive RF components [5]. This thin-film passive integration technology on high-ohmic silicon combines three metal layers and two dielectric layers in five mask steps: a cross section of the standard process is depicted in Fig. 1. For the realisation of RF MEMS, this standard process is slightly modified

Fig. 1: Cross-sectional view of the PASSI\textsuperscript{TM} process.

Fig. 2: Mems tunable capacitor before packaging.
and extended with surface micro-machining as a back-end module.

With this technology, relay type structures with different air gap thicknesses between the dc electrodes and the RF area could be easily achieved allowing much greater $C_{\text{max}}/C_{\text{min}}$ ratios than with standard parallel plates architectures (see ref. [6] for more details).

An example of such a dual gap MEMS tunable capacitor is illustrated in Fig. 2. This compact design operating in reflection is expected to exhibit an off state capacitance of 0.25 pF and continuous capacitance tuning for dc voltages around 15 V.

These MEMS devices have been packaged at the wafer level at IMEC according to the process described in ref [7] and finally capped components have been electrically characterised at Alcatel Alenia Space France.

S-parameters measurements have been performed between 1 and 6 GHz with a Wiltron 360B network analyser. The result obtained at 0V actuation voltage is illustrated on the Smith chart from Fig. 3 and demonstrates the nice capacitive behaviour of the device. At 2 GHz, an off state capacitance of 0.38 pF have been deduced from this measurement together with an equivalent series resistance of 2.7 $\Omega$ resulting in a Quality factor of approximately 77.

The typical C-V curve deduced from similar S-parameters measurements at 2 GHz and performed at different actuation voltages between 0 and 25 V is shown in Fig. 4. This curve demonstrated that the capacitance value continuously and reversibly increases from 0.38 pF in the off-state to 1.3 pF at 25 V, resulting in a tuning ratio, $C_{\text{max}}/C_{\text{min}}$ of 3.4. One has to note that these capacitance values which include parasitic effects from the packaging capping chip are in good agreement with the ones expected from the design. Most of the tunability is achieved for actuation voltage around 15 V as also predicted.

Similar measurements performed on other devices with the same design have demonstrated that tuning ratios between 3 and 4 could be reproducibly achieved together with Q factor between 50 and 100. Such high $C_{\text{max}}/C_{\text{min}}$ values demonstrate the benefits of the dual gap architecture which allows to overcome the 1.5 tuning ratio limitation from standard single gap MEMS tunable capacitor with electrostatic actuation.

III. MEMS BASED MCM VCO

Such high tuning ratio MEMS tunable capacitors have been integrated in hybrid 1.3-1.8 GHz MCM VCO dedicated to C and Ku band receivers frequency conversion modules in satellite payloads. A picture of such a MEMS based VCO in its whole test set-up is given in Fig. 5.

This kind of oscillator is based on a Colpitts topology and implemented on thin film alumina substrate. Here the MEMS tunable capacitor replace the standard silicon varactor diode usually used in the LC tank circuit and gold bonding wires are used as high Q inductors.

RF measurements have demonstrated VCO oscillations around 1.60 GHz as illustrated on the output spectrum from Fig. 6 with continuous tuning between 1.70 and 1.45 GHz when the MEMS tunable capacitor is actuated between 0 and 25 V (see Fig. 7).

**Fig. 3**: S-parameters of a MEMS tunable capacitor similar to the one from fig. 2 in the off-state (0V).

**Fig. 4**: Mem's tunable capacitor C-V curve at 2 GHz.

**Fig. 5**: Mem's based VCO test set-up.
This 250 MHz tunability allowed by the high $C_{\text{max}}/C_{\text{min}}$ ratio of our MEMS tunable capacitors is much higher than previously reported results (respectively 80 and 14 MHz in ref [3] and [4] for example).

Phase noise measurements were also performed with a dedicated in house test set up for different actuation voltages. The best results were achieved at 0V and actuation voltages greater than 20 V respectively, i.e. when the MEMS membrane is in its off-state or strongly hold in its down position. As an example, the phase noise measured for an actuation voltage of 20 V is shown on Fig. 8: the result is better than –100 dBc/Hz at 100 KHz and –125 dBc/Hz at 1 MHz offset from the carrier demonstrating the high quality factor of the VCO tank circuit. Such performances are comparable to the ones obtained with standard silicon varactor diodes in similar oscillators. However, degraded results were observed for intermediate actuation voltages (such as –80 dBc/Hz at 100 KHz and –115 dBc/Hz at 1 MHz at 10 V) which could be attributed to slight fluctuations of the MEMS membrane position.

IV. CONCLUSION

In summary, a prototype VCO based on a wide tuning range ($C_{\text{max}}/C_{\text{min}}$ ~ 4) and high Q factor (up to 100) RF MEMS tunable capacitor has been implemented and successfully tested with good RF performances. As a perspective, additional improvements in terms of reconfigurability and tunability could be achieved by combining such MEMS tunable capacitors with MEMS switches in the VCO LC tank.

ACKNOWLEDGEMENT

The authors would like to acknowledge the European commission for funding this work in the frame of the IST FP5 MEMS2TUNE project.

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