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A MEMS Disk Resonator-Based Oscillator

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***Abstract*— A fully integrated MEMS based oscillator using a MEMS disk resonator is presented. Parameter extraction for a circuit model of the disk resonator using ANSYS is carried out at 60.6 MHz. A PIERCE oscillator using the disk resonator is designed. The circuit simulations are presented. The different specs of the oscillator like frequency, phase noise and frequency stability are investigated. The effect of the presence of the disk resonator on the performance of the oscillator is demonstrated.**

Index Terms—MEMS, Disk Resonator, Pierce Oscillator, Phase Noise, Frequency Stability

I. INTRODUCTION

On chip integrated components (resonators and oscillators) with high quality factor are highly needed for future communication systems. A traditional oscillator is usually the off-chip quartz crystal oscillator. In a recent report [4], a MEMS disk resonator has been implemented on-chip instead of the off-chip crystal. A quality factor as a high as 48000 has been reported for the resonator which is suitable for low phase noise oscillation. The oscillator in the proposed circuit [4], however, includes several active elements which can still be a source of non-negligible phase noise.

In this work, we propose a simple fully integrated oscillator design which implements a disk resonator as well but in which the number of active elements is strongly reduced. In section II the MEMS disk resonator structure and principle of operation are reviewed. The parameters of the MEMS disk resonator are extracted using ANSYS to complete the oscillator circuit model [2]. The oscillator design and topology are described in section III. Finally, in section IV, results of circuit simulations of the integrated oscillator are presented for different specs related to frequency, phase noise and frequency stability.

II. MEMS DISK RESONATOR

A. Model

Figure 1 shows the structure of the disk resonator [1] implemented in our design. The disk is connected to a DC bias voltage, the input electrode is connected to the input ac voltage, and the output ac current is taken from the output electrode through a resistance.

The resonator is constructed as a pair of two-port electromechanical transverse transducers, one at the input and the other at the output, and a mechanical resonator. At one port the transducer mechanical variables are the force (effort) and the velocity (flow), while on the other port the electrical variables are the voltage (effort) and the current (flow) as shown in Fig.2.

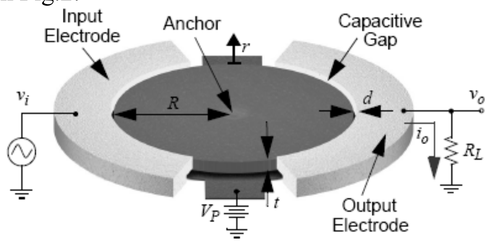

Fig. 1 Disk resonator structure [1]

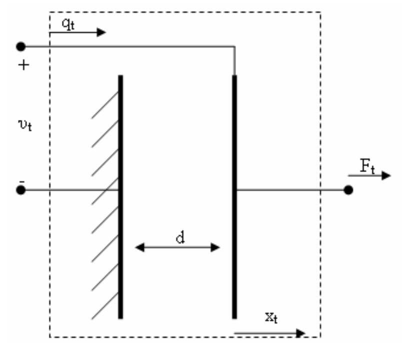

Fig. 2 Transverse Electromechanical Transducer

For small-signal variations around bias voltage the transducer behaves linearly. The small-signal equivalent electrical circuit of the transverse transducer is given by the model [2] shown in Fig.3.

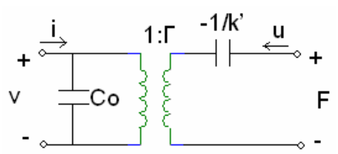

Fig. 3: Equivalent electrical circuit of the transverse transducer [2].

In the circuit sketched in Fig.3,

$$\Gamma = \frac{c_o v_o}{d + x_o} \tag{1}$$

Top

$$k' = \frac{\Gamma^2}{c_o} \qquad (2)$$

where C_o is the static capacitance between the electrodes, υ_o is the DC bias voltage between the two electrodes, d is the initial gap between the two electrodes, χ_o is the movable electrode displacement due to bias voltage, k' is the effective spring constant due to transduction, Γ is the transduction factor.

The mechanical resonator can be modeled by an equivalent electrical circuit consisting of a capacitor, a coil and a resistor representing the mass, spring constant and damper. The mechanical filter is characterized mainly by its resonance frequency and its quality factor, respectively given by:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}}\ , \quad Q = \frac{f_o}{BW} = \frac{\sqrt{k_{eff}\,m_{eff}}}{b_{eff}} \qquad (3)$$

where m_{eff} is the effective mass of the resonator, k_{eff} is its effective spring constant, b_{eff} is its effective damper, f_o is the resonance frequency, BW is the bandwidth, and Q is the quality factor. Figure 4 shows the equivalent circuit of the mechanical resonator.

Fig. 4: Equivalent circuit for mechanical resonator

B. *Disk Resonator Design*

1) *Physical design*

An equivalent electrical circuit model of the MEMS disk resonator to be used in the simulations of the integrated oscillator circuit is sketched in Fig.5.

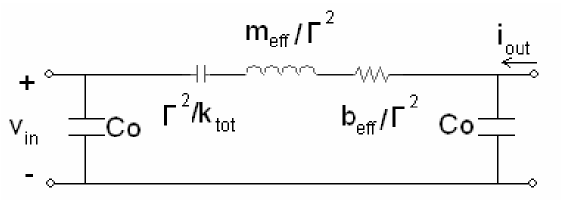

Fig. 5: MEMS disk resonator Model

where $k_{tot} = k_{eff} - 2k'$ (4)

The main parameters that affect the mechanical vibrations of the disk are its radius and the properties of its material. The disk proposed here would be made of polysilicon of material properties [3]: Young's modulus (150 GPa), Poisson's ratio (0.29), and density (2330 Kg/m^3). The radius of the mechanical disk resonator is equal to 45 µm which is designed for a resonance frequency of 60.6 MHz, Such a frequency is chosen to allow a comparison between previous work [4]. A disk thickness of 3 µm, an air gap of 0.1 µm and a DC bias voltage of 35 volts are designed to achieve a series resistance of 1.5kΩ suitable for oscillation. A quality factor of 50,000 is assumed [4]. The Anchor radius is equal to 1 µm.

2) *Model Parameter Extraction*

The parameters for the circuit model of the MEMS disk filter sketched in Fig.5 are extracted using ANSYS. In a first stage, a coupled field electromechanical static analysis is done in order to extract the radial displacement of the disk tips due to bias voltage; χ_o = 0.11848nm. An electrostatic analysis is carried out to extract the static capacitance between the electrode and the disk; knowing that this is the capacitance in pico-farads per unit thickness of the disk (in micro-meters); C_o = 0.025092pF/µm. χ_o and C_o are used in equations (1) and (2) to get Γ and k'. Finally, a harmonic analysis is done to extract effective lumped parameters at the tips region of the mechanical disk resonator.

The frequency response of the mechanical resonator is displayed in Fig. 6 with input radial force and output radial displacement.

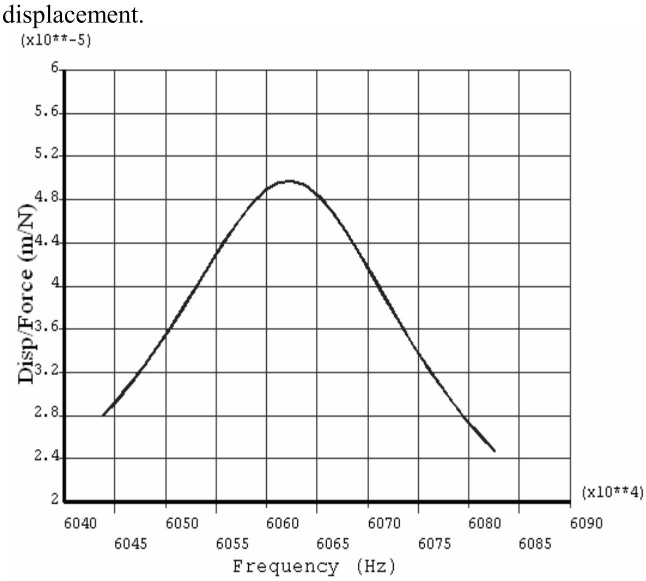

Fig. 6: Harmonic response of the mechanical disk resonator. The displacement per unit force is plotted as a function of frequency.

As a post-processing, three parameters are extracted from Fig.6, namely; the resonance frequency, the bandwidth, and the peak of the curve.

$$Peak = \frac{1}{2\pi f_o b_{eff}} \qquad (5)$$

Substituting these three parameters in equations (3) and (5) we get m_{eff}, k_{eff}, and b_{eff}.

ANSYS results in a resonance frequency f_o = 60.62 MHz, a static capacitance C_o = 0.038 pF, model capacitance C = 0.0348 fF, model inductance L = 0.2 H and model resistance R = 1.51 kΩ.

III. OSCILLATOR DESIGN

The oscillator design proposed in this work is based on the

PIERCE oscillator topology with an active current mirror PMOS transistor load which also supplies the bias current to the NMOS transistor as shown in Fig. 7. Like the crystal oscillator in the traditional PIERCE oscillator, the disk resonator is placed between the drain and source of the NMOS transistor.

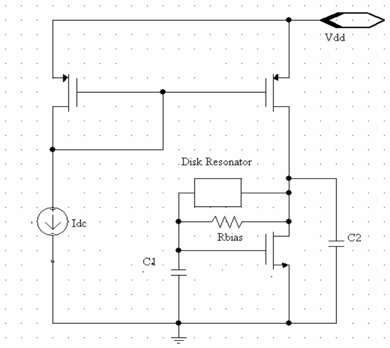

Fig. 7: Proposed PIERCE oscillator using disk resonator.

The oscillator design is carried out using AMS 0.35 µm technology with MIM capacitors. The role of the resistance R_{bias} is to give bias to the gate since the resonator is open circuit in DC due to series resonance. This resistance, however, is chosen to be 1MΩ in order to avoid loading the resonator and degrading its quality factor. It can be implemented using a MOS transistor operating in cutoff. The values for C_1 and C_2 can be much smaller than those typically used in a crystal oscillator because there are no restrictions imposed by the MEMS resonator, and are assumed to be 100 fF. This makes their integration on-chip much simpler. The output signal is taken at the gate and not at the drain to allow a larger signal head room and avoid distortion.

IV. Simulation Results

The simulation was done using Cadence Analog Design Environment and the simulator was Spectre.

A. Stability Analysis

First the circuit is simulated for stability to guarantee oscillation. The loop gain and the loop gain phase are displayed in Fig. 8.

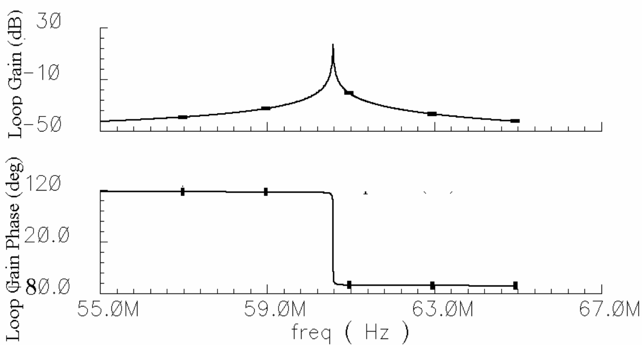

Fig. 8: Loop Gain: (Magnitude (dB) and Phase)

The circuit achieves a zero phase positive gain equal to 15.5 dB at frequency 60.573589 MHz which is the normal resonance frequency of the disk resonator. The very clear effect of the high quality factor of the resonator enhances the phase noise characteristics of the oscillator.

B. Transient Analysis

The results of the transient analysis simulations are shown in Fig. 8. The circuit shows a startup time of 50 µsec and a stability time of 450 µsec. This is roughly equivalent to 27,200 periods. This long startup is ascribed to the high quality factor.

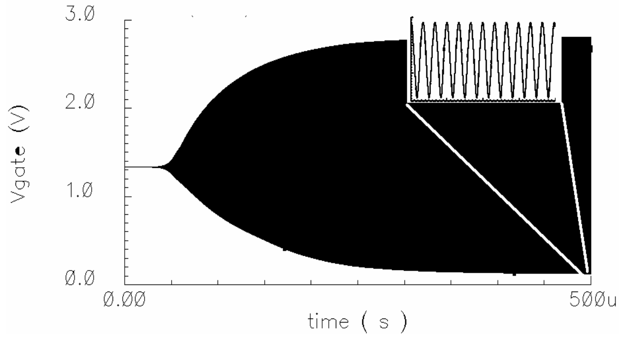

Fig. 8: Transient analysis results. Signal taken at the gate

C. Phase Noise Analysis

The results of the phase noise simulation are depicted in Fig. 9. Our Design achieves -150 dBc/Hz @ 3 KHz offset. This performance is superior to that reported by Lin *et al* [4] for instance. This is due to the fact that only three active elements are used in our design compared to at least fourteen devices in [4]. In addition, the very high quality factor of our resonator contributes to the reduction of the phase noise.

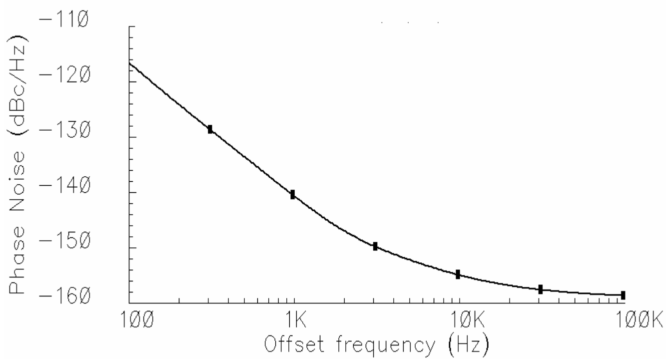

Fig. 9 Phase noise behavior

D. Frequency stability analysis

The frequency stability is measured versus all the circuit parameters using the method proposed by Adachi *et al.* [5].

1) Frequency stability versus temperature variation

The frequency deviation is plotted versus temperature in Fig. 10. The oscillator shows a very good stability versus temperature variation. For a whole range of temperature variation from -30 °C to 100°C the overall frequency deviation does not exceed ±3 ppm.

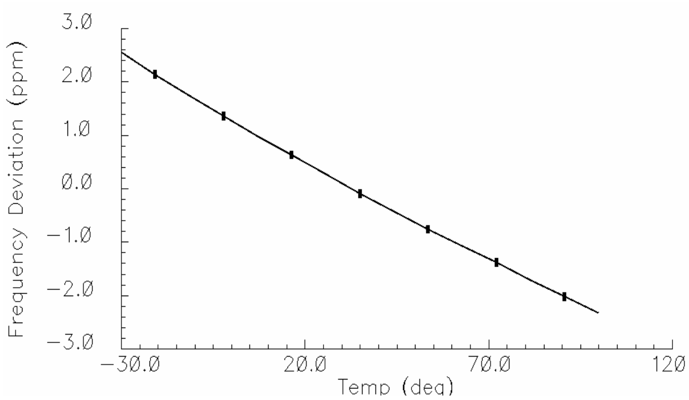

Fig.10: Frequency deviation versus temperature variation

2) Supply Pushing

The frequency variation is plotted as a function of supply voltage variation in Fig. 11. Again the oscillator shows a very good performance versus supply voltage variation since the overall deviation does not exceed ±1 ppm when the supply voltage varies from 2.5 to 5V.

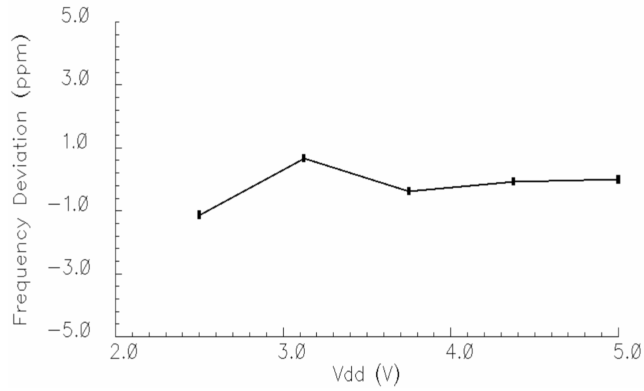

Fig. 11: Frequency deviation versus supply voltage variation

3) Frequency deviation in process corners

The circuit was simulated over the four corners of the technology. The process spread has a minor impact over oscillation frequency due to the high quality factor of the resonator. The results of this simulation are summarized in table 1.

TABLE 1
FREQUENCY DEVIATION IN PROCESS CORNERS

Process corner	Frequency Deviation (ppm)
Worst Power (WP)	-0.3
Worst Speed (WS)	-0.1
Worst One (WO)	+0.8
Worst Zero (WZ)	-0.7

V. CONCLUSION

A MEMS disk resonator based oscillator has been designed. The disk resonator exhibits a quality factor of 50,000 which enhanced the phase noise of the oscillator to achieve -150 dBc/Hz @ 3 kHz offset. The main advantage of using MEMS disk resonator is the dismissal of the bulky crystal oscillator while achieving the same high quality. The MEMS-based Pierce oscillator designed in this work showed a superior performance with respect to phase noise. The usage of MEMS disk resonator spares off chip capacitors typically used in quartz crystal Pierce oscillators.

Finally, this work explores the possibility of building a truly integrated oscillator using MEMS technology. Such oscillators show a superior performance to their crystal oscillator counterparts.

VI. ACKNOWLEDGMENT

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