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# MEMS based oscillator for UHF applications with automatic amplitude control

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ABSTRACT

This paper presents a MEMS based oscillator with automatic amplitude control. Previously demonstrated ring shape anchored contour mode disk resonator is evaluated and some of its analytical aspects are extracted as well as its equivalent electrical circuit for further transistor level simulations. Due to 180° phase change of the resonator, the sustaining amplifier should provide another 180° phase for oscillation build up. As will be shown, the motional resistance of the resonator, which determines the minimum required gain of the circuit, is very high and conventional techniques could not provide such a gain in UHF frequencies. This paper proposes a trans-impedance amplifier satisfying mentioned conditions just at the required frequency. In this case, traditional Automatic Amplitude Control (AAC) method could not be applied and therefore this paper presents a novel AAC circuitry and technique. The overall circuit including bias circuitry consumes 1128 μW from 1.8 V power supply implemented in 0.18 μm standard CMOS technology.



## 1. Introduction

Most of electronic systems from RF transceivers to on-chip atomic clocks require a reference oscillator which determines the size and cost of the overall system. Due to their high quality factor, low insertion loss, low power, integrability alongside transistors on a single chip and low fabrication costs micro-electro-mechanical resonators are excellent devices for such applications.

Recently demonstrated Ring Shape Anchored Contour Mode Disk Resonator (RSACMDR) introduced by [1] with suppressed spurious modes [2] and the ability to break GHz barrier for resonance frequency with relatively large size is an interesting device which can surmount problems of ordinary disk resonators [3], [4]. But, like the other disk resonators, since the electrostatic actuation mechanism through a capacitive gap is employed, it has a very large motional resistance which makes design of the sustaining amplifier very problematic [5]. As will be shown in the next section, electrical equivalent circuit of the RSACMDR has 180° of phase shift which puts another criterion on the sustaining circuit design.

Considering the voltage to current conversion nature of MEMS resonators, amplification circuit must work in a reverse manner and convert current to voltage for driving the resonator. One of the most popular circuits for implementing this conversion is Trans-Impedance Amplifier (TIA). But unfortunately, designing of a TIA with the required high gain (more than 100 dB Ω) for sustaining UHF oscillators requires about 10 GHz of bandwidth and is not feasible with conventional methods. Therefore, another procedure is required for implementing a TIA based oscillator.

Another problem involved with MEMS based oscillators is $1/f^3$ phase noise component as a result of device non-linearity [6–8]. This noise component degrades the very critical close-to-carrier phase noise profile. Also, power handling problem in such oscillators must be concerned [9]. The most sophisticated method to remove these problems is using the AAC circuit. This paper also introduces a novel method for implementing AAC for MEMS oscillators in UHF range. The paper is organized as follows: RSACMDR design and characterization is described in Section 2. Design procedure of core oscillator is discussed in Section 3. Proposed AAC is introduced in Section 4 followed by a conclusion in Section 5.

## 2. RSACMD resonator

RSACMD resonator is utilized in this work as the high Q tank element for the proposed oscillator. The insertion loss of such a resonator is reduced by locating the anchor at the stress-free ring area which guarantees the reliability of the device. As shown in Fig. 1, the structure is a hollow disk suspended 1 μm above the substrate and anchored at the ring shaped nodal area. In addition

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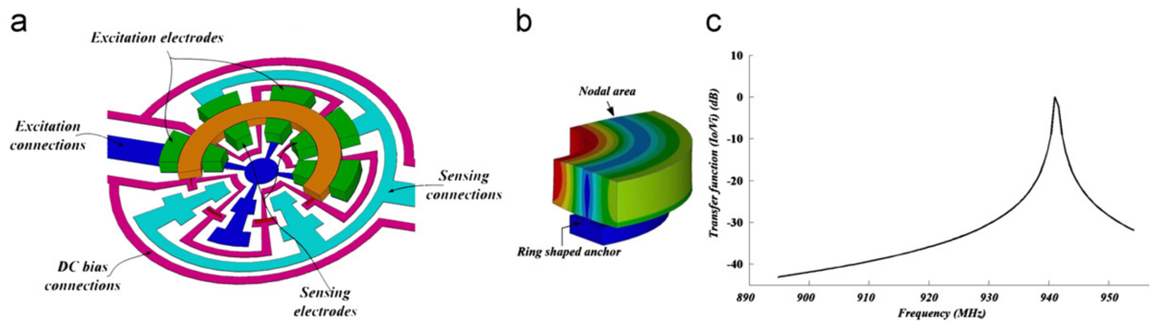


**Fig. 1.** (a) The RSACMD resonator and its electrode and anchor configuration and (b) its contour plot, (c) harmonic analysis of the resonator showing its resonance frequency.

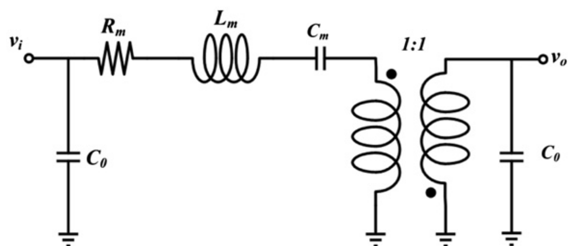


**Fig. 2.** Electrical equivalent circuit of the resonator.

to suppressing the spurious modes, the crossed ring anchor provides an excellent location for implementing low velocity coupling for much more complex mechanical UHF signal processing [10].

Fig. 2 shows the electrical equivalent circuit of RSACMDR to be used for simulation and characterization of the oscillator. Since a positive DC voltage is utilized for biasing of the resonator, when the AC exciting voltage increases, the voltage difference across the capacitive gap decreases which consequently reduces the resonance amplitude of the device and output current. Therefore the output current of the resonator has 180° phase difference with the input voltage modeled by an inverse transformer in Fig. 2.

For fabrication of the resonator, thin adhesive silicon-nitride layer is deposited over the silicon substrate. A very thin Cr/Au layer is then deposited and patterned to form interconnections of the resonator and a via is stripped for future ground plane providing a low impedance path for shunting away of the feedthrough current [11]. Then, a 250 nm thick oxide layer is deposited by PECVD as a first sacrificial layer and patterned to create proper locations for anchor segments. These regions are then filled by polysilicon and construct the anchor. After patterning, a thick polysilicon layer is deposited to form the resonator's structural body.

After deposition of the structural polysilicon mass, a 100 nm oxide layer is deposited as the sidewall sacrificial spacer in both internal and external regions of the disk to form the electrodes to resonator transducer gap by LPCVD process. A photoresist layer is placed over the sacrificial layer at the top of the structure to form the connection between internal and external electrodes in both sides of the resonator. A metal seed (Cr/Au) is then evaporated on the wafer and removed from the top of structure and sidewalls in order to prevent plating in these areas during electroplating steps. A thick photo-resist mold is then plated to determine that the electrodes confined. Au electrodes are then plated using the electroplating process. After all deposition processes the structure is released in Hydrofluoric acid to achieve the final cross-section of the resonator. For reducing parasitic and padding capacitances, a combined CMOS/MEMS chip could be achieved by flip-bond-and-tear process described in [12].

Although the precise resonance model of RSACMDR is presented in [2], it is too complicated to be used for model extraction. By neglecting the non-significant second order effects, the resonance equation of [1] could be employed:

$$r^2\frac{d^2R(r)}{dr^2}+r\nu\frac{dR(r)}{dr}+(k^2r^2-\nu)R(r)=0 \tag{1}$$

where $R(r)$ is a displacement as a function of radius, $r$ is the radius of the resonator, $\nu$ is the Poisson ratio and $k$ is

$$k=\frac{2\pi}{\lambda_s}=2\pi f\sqrt{\frac{\rho_0(1-\nu^2)}{E}} \tag{2}$$

where $f$ is the required resonance frequency, $\rho_0$ and $E$ are the density and the Young modulus of the structural material respectively. Eq. (1) is a Bessel type differential equation which could be solved by supposing a suitable value for inner radius and below boundary conditions:

$$R(r_{in}) \;=\; R_0 \quad and \quad \left.\frac{d\,R(r)}{d\,r}\right|_{r=rin} \;=\; 0 \tag{3}$$

The value of $R_0$ could be determined from Hooke's law and considering the applied voltage and excitation electrodes of the resonator.

For a resonator with about 10 nm resonance amplitude and inner and outer radii of 12 μm and 16.8 μm respectively for 940 MHz resonance frequency, the resonance equation becomes

$$R(r)=\frac{-1}{14.4}\left\{\begin{array}{l}\left[\begin{array}{l}a((k-1)Y_p(q))+3k(Y_{p+1}(q))-...\\2apY_p(q)\end{array}\right]\times\ldots\\J_p(kr)+\left[\begin{array}{l}a(\nu-1)J_p(q)+...\\3k(J_{p+1}(q))-...\\2ap(J_p(q))\end{array}\right]\times\ldots\\...Y_p(kr)\end{array}\right\}\times Cr^b \tag{4}$$

where $J_x(.)$ and $Y_x(.)$ are the Bessel functions of types 1 and 2 and in the order of $x$ and the other constants in the above equation are

$$\left\{\begin{array}{l}p=\frac{1}{2}\sqrt{5\nu^2-2\nu+1}\\q=\frac{3k}{250000}\\a=125000\\m=0.5(1+\nu)\\b=0.5(1-\nu)\\C=\frac{-(1/14.4)((1/k)3^m500^{-\nu})}{(J_{p+1}(q))(Y_p(q))-(Y_{p+1}(q))(J_p(q))}\end{array}\right. \tag{5}$$

The effective mass of the resonator could be achieved by

$$m_r=\frac{2\pi\rho h\int_{r_{in}}^{r} rR^2(r)dr}{R^2(r)} \tag{6}$$