A LOW-NOISE OSCILLATOR BASED ON A MULTI-MEMBRANE CMUT FOR HIGH SENSITIVITY RESONANT CHEMICAL SENSORS

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ABSTRACT

We present 17.5-MHz and 42.7-MHz low-noise Colpitts oscillators employing capacitive micromachined ultrasonic transducers (CMUTs), each composed of a thousand resonator cells electrically connected in parallel. The massive parallelism lowers the motional impedance, and thus, reduces frequency noise and provides better matching to low-noise oscillator topologies. The 42.7-MHz oscillator achieved a phase noise of -105 dBc/Hz and -148 dBc/Hz at offset frequencies of 1 kHz and 1 MHz, respectively in air. The performance is comparable to MEMS oscillators based on resonators with high *Q* in vacuum. The lowest Allan deviation of the oscillator was measured to be 4.7 x 10^{-9} implying a mass resolution of 0.96 attogram per membrane. In addition, using the 17.5-MHz CMUT resonator, the performance of the Colpitts topology is compared to that of the amplifier based oscillator topology.

INTRODUCTION

Resonant sensing has been widely applied to micromechanical systems to measure a variety of measurands, such as pressure, acceleration and chemical or biological agents. These sensor systems benefit from direct frequency output, high sensitivity, low noise and large dynamic range [1]. The operation principle of resonant sensing is the change of resonant characteristics in response to the effect of measurands on the spring constant or the mass of the resonant structure.

One important figure of merit for the resonant sensor system is the noise performance of the oscillator, which limits the minimum detectable signal of the sensor (i.e. resolution). Various methods have been explored in resonator design [2, 3] as well as in circuit design to improve the frequency noise. One method to further reduce the noise of an optimized single resonator is to use multiple in series or parallel to make a resonator with a lower motional resistance (R_x). Driscoll [4] demonstrated a reduction in phase noise of the oscillator by connecting multiple Quartz resonators in series. Recently, Demirci [5] and Lin *et al.* [6] reported reduction in motional resistance and phase noise by mechanically-coupling multiple microresonators.

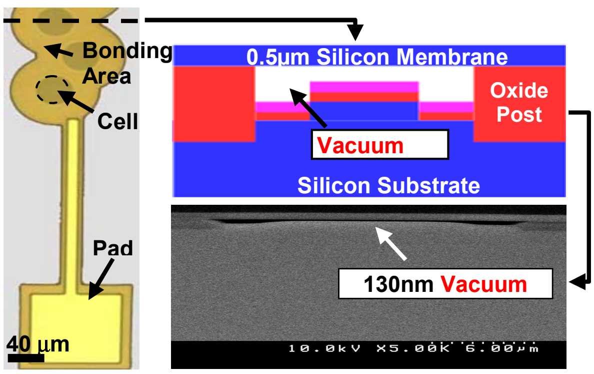


Figure 1: Schematic diagram and cross-sectional SEM of a single cell from the multi-cell CMUT resonator.

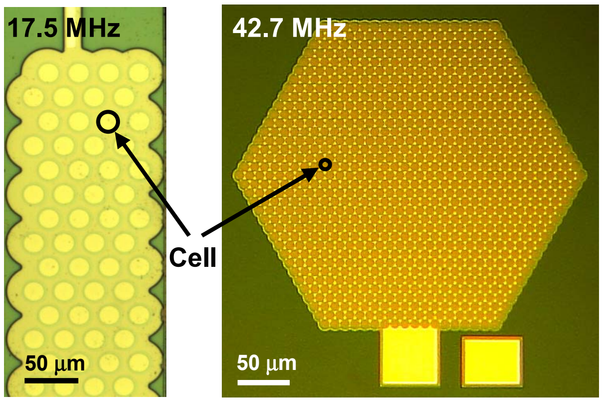


Figure 2: Photographs of the 17.5-MHz and 42.7-MHz CMUT devices with thousand resonator cells.

Connecting multiple microresonators electrically has been avoided due to the reduced *Q* resulting from the resonator-to-resonator non-uniformities. If the non-uniformities can be tightly controlled or the *Q* of a single resonator is relatively low, electrically connecting multiple microresonators is a simpler approach than that of mechanically coupling in terms of the resonator design.

We demonstrate in this work that we achieve a low phase noise by electrically connecting multiple microresonators. Motivated by the goal to improve the resolution of a chemical sensor based on the capacitive micromachined ultrasonic transducer (CMUT) technology [7, 8], we fabricated CMUTs composed of approximately 1000 resonator cells electrically connected in parallel. We first introduce design and characterization of CMUT resonators and discuss the implication of parallelism on oscillator design. Further, we demonstrate the noise characteristics of two implemented oscillators and discuss its implication on the resolution of the CMUT chemical sensor.

CMUT RESONATOR DESIGN

Operation and Structure

A CMUT with one membrane is a capacitor (Figure 1). The top and bottom electrodes are composed of a single crystal silicon membrane and a conductive substrate, respectively. These electrodes are separated by a thin vacuum gap and an insulation layer and are circularly anchored by an oxide post. When the capacitor is actuated by electrostatic (DC and AC) force, it resonates at a resonant frequency determined by the material properties and dimensions of the circular membrane resonator (1),

$$w_0 = \frac{2.98t}{r^2}\sqrt{\frac{E}{(1-\nu^2)\rho}}\,, \qquad (1)$$

where t, r, E, ν and ρ are the thickness, radius, Young's modulus, Poisson's ratio and density.

The 17.5-MHz CMUT resonator used for this work is

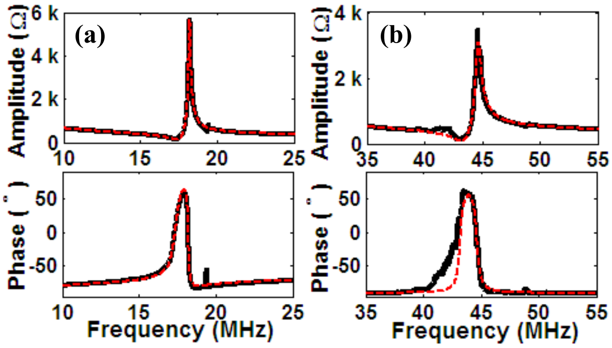


Figure 3: Measured and fitted impedance characteristics of (a) the 17.5-MHz CMUT, (b) the 42.7-MHz CMUT, in air. (Solid line: measurement, dotted lines: fitted).

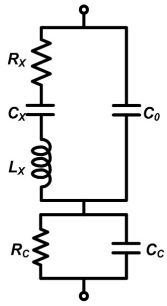
composed of 1000 circular cells with 500-nm thick silicon membranes and radii of 9 µm (Figure 1). The membranes are supported by a 0.9-µm-thick oxide post and separated from the bottom electrodes by a 130-nm vacuum gap. The 42.7-MHz CMUT is composed of 1027 circular cells with radii of 5.3 µm (Figure 2). The vacuum gap height is 50 nm and the membranes are supported by a 1-µm-thick oxide post. The details of the fabrication processes of the CMUT based on direct wafer-bonding and LOCOS techniques are described in [8].

Input Impedance Characteristics

The resonant characteristics of two CMUT resonators were measured using an impedance analyzer (Agilent Technologies, Model 4294A, Palo Alto, CA). One was biased at 41 V with a parallel resonance frequency (f_p) at 17.5 MHz and one biased at 66 V with f_p at 42.7 MHz (Figure 3). The input impedance measurements were fitted to a 6-element equivalent circuit (Figure 4), which includes parasitic effects of the substrate and the electrode contacts in addition to the conventional 4-element RLC van Dyke model [9]. The standard van Dyke circuit consists of four real circuit parameters, R_X, L_X, C_X, and C_0, which physically represent loss, mass, stiffness and electric capacitance of the resonant structure, respectively. Due to the massive parallelism, the motional resistance dropped below 100 Ω for both resonators (Figure 4).

One disadvantage of massive parallelism is the degradation of Q due to process variations. Our analysis shows that Q at the parallel resonance (Q_p) is degraded less than Q at the series resonance (Q_s) from the resonator-to-resonator non-uniformity (Figure 5). The effect of process variation on the quality factor is investigated by computing total impedance of 169 CMUT resonators placed in parallel. The radius and thickness of each resonator is given a normal distribution with a mean value of 5.3 µm and 0.5 µm, respectively. For various standard deviation values, we computed the quality factors of the overall impedance.

Q_s and Q_p are almost identical when the device variations are negligible (Figure 5). However, as the variation increases, Q_s degrades more than Q_p. The input impedance measurement also verifies that Q_s is smaller than Q_p for various numbers of microresonators connected in parallel across the operating bias voltage [10]. Therefore, instead of oscillating at the series resonance, the multi-membrane CMUT microresonators can be



	17.5-MHz	42.5-MHz
V_{DC}	41 V	66 V
R_X	50 Ω	75 Ω
C_X	1.5 pF	0.61 pF
L_X	54 µH	24 µH
C_0	21 pF	7.4 pF
R_C	154 Ω	1.6 Ω
C_C	8.8 pF	0.46 pF

Figure 4: 6-element equivalent circuit model used to fit the input impedance of the CMUT. The values for each components for the two CMUT reosonators are shown.

oscillated in its inductive region with a reasonable Q and still provide the advantages of parallelism.

CMUT OSCILLATOR DESIGN

The reduction in motional impedance has two implications in the oscillator design: better impedance matching to various oscillator circuit topologies and lower mechanical noise.

Oscillator Design for CMUT

MEMS resonator based oscillators can be largely divided into two types: transresistance amplifier based oscillators and single-stage tuned oscillators, such as Pierce and Colpitts. The open-loop gain of a transresistance amplifier based oscillator is determined by the resistive elements while that of a single-stage tuned oscillator is determined by the capacitive elements offering superior frequency stability. Further, for the CMUT resonator, the Colpitts topology is more suitable than the Pierce topology for two reasons: the constraint to ground one electrode of the CMUTs (Figure 6) and higher Q at parallel resonance than at series resonance (Figure 5). Colpitts oscillators operate at the inductive region between the series and parallel resonances while Pierce oscillators operate at the series resonance.

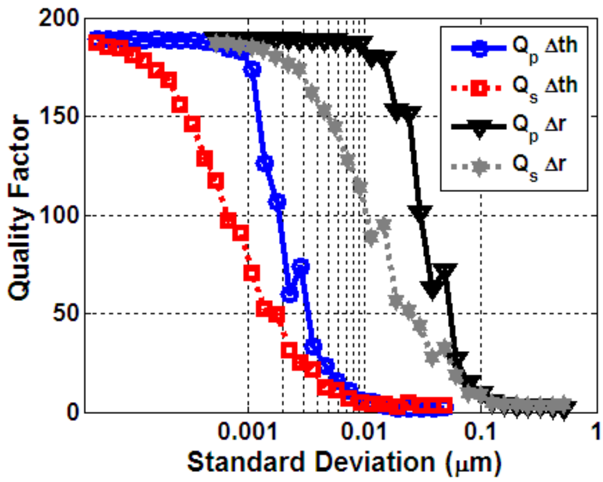


Figure 5: Simulation results showing the effect of process variations on Q_s and Q_p assuming the process variation is a normal distribution. 169 CMUT resonators are placed in parallel with mean radius and thickness of 5.3 µm and 0.5 µm, respectively. The standard deviation of the thickness (Δth) and the radius (Δr) of the membrane are varied.

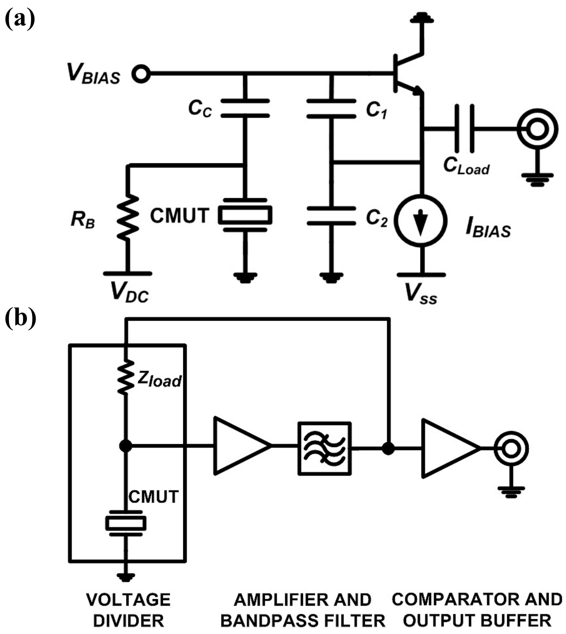


Figure 6: (a) Circuit diagram of the Colpitts oscillator with the bias circuitry of the CMUT resonator shown. (b) Block diagram of the amplifier based oscillator.

Therefore, the Colpitts topology was chosen to implement an oscillator based on the CMUT resonator.

The CMUT resonators are first modeled as a lossy inductor ($R_e + jL_e$) in the narrow frequency region between the series and the parallel resonance (Figure 6 (a)). The design values for the circuit parameters, C_1 and C_2, and the bias point for the bipolar transistor (BJT) are determined according to the start-up criteria (2) and the desired oscillation frequency (3),

$$\frac{g_m}{w_0^{\,2} R_e C_1 C_2} \geq 1 \tag{2}$$

$$w_0 = \frac{1}{\sqrt{L_e C_T}}, \tag{3}$$

where g_m is the transconductance, w_0 is the resonant frequency, R_e and L_e are the real and imaginary part of the modeled lossy inductor, and C_T is the total capacitance in parallel with the resonator [11]. In addition, the values of the biasing resistors must be large enough to avoid significant loading of the emitter-follower amplifier. Following this design method, the 17.5-MHz and 42.7-MHz CMUT Colpitts oscillators are implemented on PCBs, on which the CMUT resonators are directly wire-bonded to eliminate parasitic effects of a chip carrier.

Noise Characteristics

The stability of the oscillator is characterized in the frequency domain using a signal source analyzer (Agilent Technologies, Model E5052B, Palo Alto, CA). For the 42.7-MHz oscillator, we achieved a phase noise of -105 dBc/Hz and -148 dBc/Hz at offset frequencies of 1 kHz and 1 MHz, respectively (Figure 7). The 17.5-MHz oscillator achieved a phase noise of -97 dBc/Hz and -155 dBc/Hz at offset frequencies of 1 kHz and 1 MHz, respectively. (Figure 7). The 42.7-MHz oscillator exhibits a better close-in phase noise but a worse

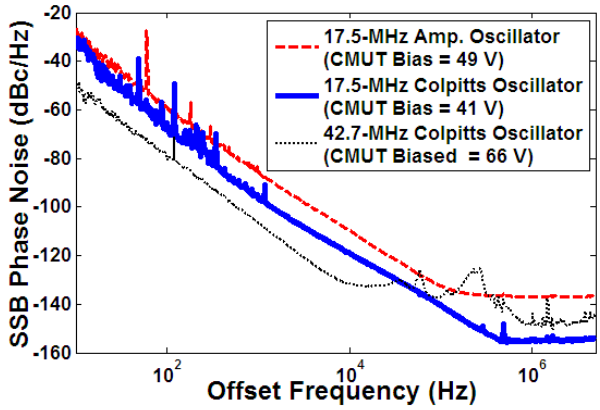


Figure 7: Single side band (SSB) phase noise of the 17.5-MHz amplifier based oscillator, the 17.5-MHz Colpitts oscillator, and the 42.7-MHz Colpitts oscillator, measured using a signal source analyzer (Agilent Technologies, Model E5052B, Palo Alto, CA).

broadband phase noise than the 17.5-MHz oscillator because 42.7-MHz resonator has a higher Q_p than the 17.5-MHz resonator.

The performance of 42.7-MHz oscillator is comparable to state of the art MEMS oscillators based on microresonators with high Q in vacuum (Table 1). For the comparison, the phase noise is converted according to (4) to incorporate the differences in the oscillation frequencies.

$$L(f)\big|_{f_0=X} = L(f)\big|_{f_0=Y} - 20\log\left(\frac{Y}{X}\right) \tag{4}$$

where X is the frequency to convert into and Y is the actual oscillation frequency.

For the 17.5-MHz resonator, we compared the performance of the Colpitts topology to that of the high-gain amplifier based oscillator topology (Figure 6 (b)). Figure 7 shows that the noise floor of the 17.5-MHz Colpitts oscillator is 19 dB smaller than that of the amplifier based oscillator. In addition, the total power consumption has decreased from 80 mW to 6 mW (Table 1). Therefore, the single-stage tuned oscillator topology is advantageous in two aspects; the gain elements are no longer noisy resistors and the required component counts are much smaller, resulting in a smaller thermal noise and potentially less power consumption.

Table 1: Comparison of the 42.7-MHz CMUT oscillator to low phase noise MEMS oscillators.

	This work	**Hsu, 2004 [2]**	**Lin, 2004 [6]**	**Lavasani , 2008 [3]**
f_0 (MHz)	42.7	70	60	467
Q	~ 300	16000	~115000	1850
Medium	Air	Vacuum	Vacuum	Air
L(1 kHz) (dBc/Hz)	-105	-117	-123	-90
L(1 kHz) (dBc/Hz) *(f_0 converted to 42.7MHz)*	-105	-121	-126	-110
Phase noise floor (dBc/Hz)	-148	-130	-136	-147
Integrated	No	No	Yes	Yes

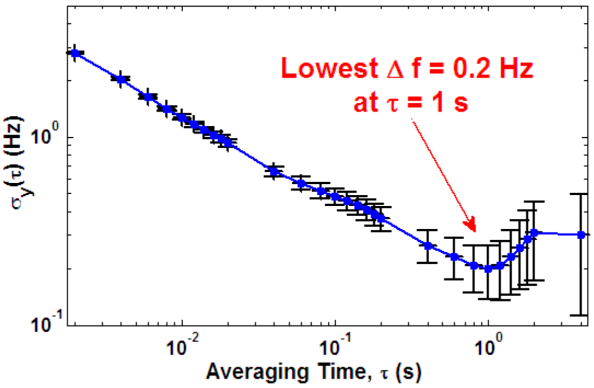


Figure 8: Overlapped Allan deviation calculated from the frequency counter data with a gate time of 2 ms (Stanford Research Systems, Model SRS620, Sunnyvale, CA). The error bars indicate the 1-sigma confidence level.

MASS SENSOR IMPLICATION

The detection limit of the mass sensor, Δm, is determined by short-term frequency stability of an oscillator (Δf). Thus, we characterized the oscillators in time domain using a frequency counter (Stanford Research Systems, Model SRS 620, Sunnyvale, CA). The 42.7-MHz oscillator exhibited the lowest Δf. The Allan deviation (σ_y) was measured as 4.7 x 10^{-9} at an averaging time of 1 s (Figure 8). Using the mass sensitivity equation, $\Delta m = -2m \cdot (\Delta f / f)$, the mass resolution was calculated to be 0.96 attogram per membrane (Table 2). For the resonant chemical sensor application, the massive parallelism has other benefits such as robustness and large sensing area required for efficient chemical detection.

CONCLUSION

By electrically connecting large number of microresonators, we demonstrated a 42.7-MHz CMUT-based oscillator with excellent phase noise. In theory, the sensor system is capable of detecting masses as low as 0.96 attogram. Using the high-gain amplifier based oscillator, we have previously demonstrated a 6-MHz CMUT chemical sensor array [12] and an 18-MHz CMUT chemical sensor with a volume sensitivity of 37 ppbv/Hz to DMMP in air [7]. Thus, with new oscillators with much smaller frequency noise, we expect a significant improvement in the volume sensitivity. In addition, we have submitted an application-specific integrated circuit chip containing oscillator circuits for future studies.

Table 2: Summary of Colpitts oscillator performance.

	17.5-MHz Oscillator	**42.7-MHz Oscillator**
CMUT Bias (V)	41	66
$\boldsymbol{R_x}$ **(Ω)**	50.2	73.7
$\boldsymbol{Q}$	127	160
Power (mW)	6	16
Output Power (dBm)	4.6	-15.7
Allan Deviation	2.8 x 10^{-8}	4.7 x 10^{-9}
Mass Sensitivity (g/Hz)	27 x 10^{-18}	4.8 x 10^{-18}
Mass Resolution (ag)	13.3	0.96
Mass Resolution per Unit Area (ag/μm^2)	0.067	0.011

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