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The effect of parallelism of CMUT cells on phase noise for chem/bio sensor applications

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***Abstract*— We investigated the effects of electrically connecting multiple microresonators on the frequency noise with a goal to improve the resolution of a chemical sensor based on the capacitive micromachined ultrasonic transducer (CMUT) technology. We fabricated twenty-two 50-MHz CMUTs with varying number of cells and measured the input impedance characteristics. The impedance measurement results show a linear increase in quality factor as the number of cells increases. Further, a phase noise simulation of Colpitts oscillators employing these CMUTs verifies that the phase noise of the oscillator in the $1/f^2$ regime are influenced by the quality factor while the phase noise in the white noise regime are primarily affected by the motional impedance. The oscillator based on the CMUT with 1027 cells has 8.8 dB and 11.4 dB lower phase noise than that based on the CMUT with 397 cells at offset frequencies of 1 kHz and 5 MHz, respectively. Therefore, we demonstrated that electrically connecting multiple microresonators is an effective technique to improve the sensor resolution.**

Keywords- multiresonators, phase noise, resonant chemical sensors, CMUT

I. INTRODUCTION

Resonant sensors based on micromechanical systems can measure a variety of measurands, such as acceleration, mass, and chemical agents. The sensing mechanism is based on the change in resonant characteristics in response to the effect of measurands on the spring constant or the mass of a resonant structure. Advantages of resonant sensing include direct frequency output, high sensitivity and large dynamic range [1].

One important performance metric of a resonant sensor is resolution, the minimum detectable signal of the sensor, which is primarily limited by the frequency noise of the system. Various techniques in resonator design and circuit design have been introduced to reduce the frequency noise [2, 3]. One method is to use multiple identical resonators in series or parallel (*i.e.* parallelism) to lower motional resistance (R_x) and to average out the independent noise contributions. Driscoll [4] reported a reduction in phase noise of the oscillator by electrically connecting multiple macro-resonators, Quartz, in series. Recently, Demirci [5] and Lin *et al.* [6] demonstrated low-noise oscillators based on mechanically-coupled multiple microresonators.

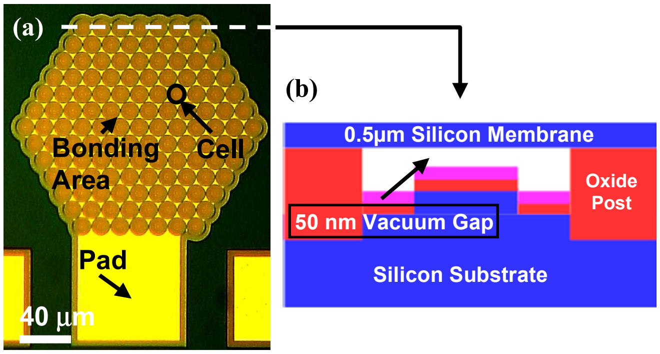

Figure 1. (a) Optical picture of a hexagonal CMUT with 127 circular cells. (b) Cross-sectional schematic diagram of a single cell.

Electrically connecting multiple microresonators has been avoided due to quality factor (Q) degradation caused from resonator-to-resonator non-uniformities. If the non-uniformities can be controlled, electrically connecting multiple microresonators is an attractive solution to reduce frequency noise, especially for resonant chemical sensors. The technique allows for a simpler resonator design than that required for mechanically coupling, while it still offers the benefits of parallelism, such as noise averaging, larger sensing area and enhanced robustness.

Motivated by the goal to improve the resolution of a chemical sensor based on the capacitive micromachined ultrasonic transducer (CMUT) technology [7, 8], this work investigates the effects of electrically connecting multiple microresonators on the frequency noise. We first introduce the structure and characterizations of the fabricated CMUTs composed of different number of cells, followed by a discussion on the implications of parallelism on Q and phase noise of a CMUT-based oscillator.

II. STRCUCTURE AND CHARACTERIZATION OF CMUT

A. Structure

We fabricated 22 hexagonal CMUT elements (Fig. 1) composed of a different number of circular cells (n) in a 2.5 mm x 5 mm single die (Fig. 2) based on direct wafer-bonding and LOCOS techniques [8]. Number of cells in each element varies from 1 to 7351. Each circular cell is composed of 500-nm thick single crystal silicon membrane with radius of 5.3 µm. The membrane is supported by the 1-µm oxide post and separated from the bottom electrode by 50-nm vacuum gap.

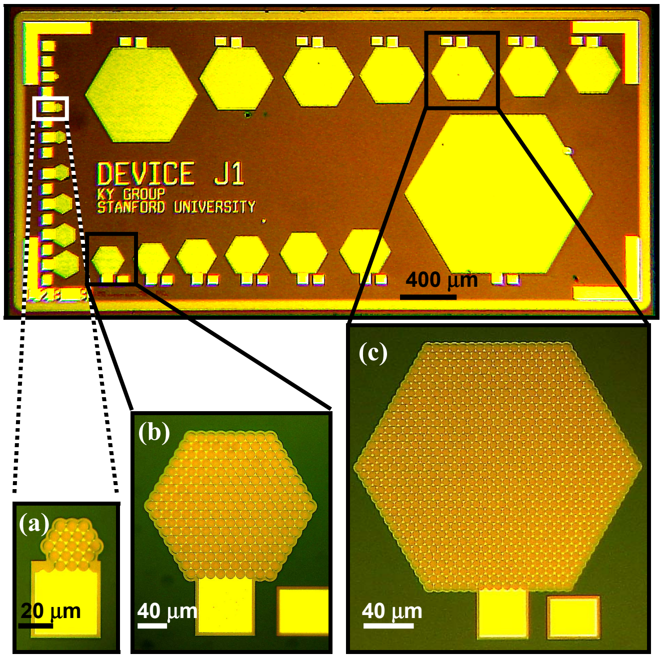

Figure 2. Optical picture of a 2.5 mm x 5 mm single die composed of 22 CMUTs with varying number of cells: (a) n = 19, (b) n = 217 and (c) n = 817.

B. *Input Impedance Characterization*

The resonant characteristics of 22 CMUTs (Fig. 3) were measured using an impedance analyzer (Agilent Technologies, Model 4294A, Palo Alto, CA). The operating bias voltage range was from 35 V to 50 V. All 22 CMUTs exhibited resonant characteristics. However, maximum phase of the first 6 elements with *n* below 100 did not exceed 0^o due to parasitic capacitance. Three elements with *n* larger than 1027 exhibited multiple peaks due to larger process variations. Thus, for data analysis, we examine 13 CMUTs with *n* ranging from 127 to 1027 (Table 1). Across the 13 CMUTs, a good match in resonant frequencies was observed (Fig. 4). For example, parallel resonant frequency (f_p) of the measured CMUT elements biased at 40 V was centered at 46.88 MHz with standard deviation of 0.32 MHz.

TABLE 1. SUMMARY OF NUMBER OF CELLS FOR 22 CMUT ELEMENTS WITH RATIO BETWEEN INNER AND EDGE CELLS.

Number of Cells (*n*)	Inner Cells	Edge Cells	Ratio
127	91	36	2.53
169	127	42	3.02
217	169	48	3.52
271	217	54	4.02
331	271	60	4.52
397	331	66	5.02
469	397	72	5.51
547	469	78	6.01
631	547	84	6.51
721	631	90	7.01
817	721	96	7.51
919	817	102	8.01
1027	919	108	8.51

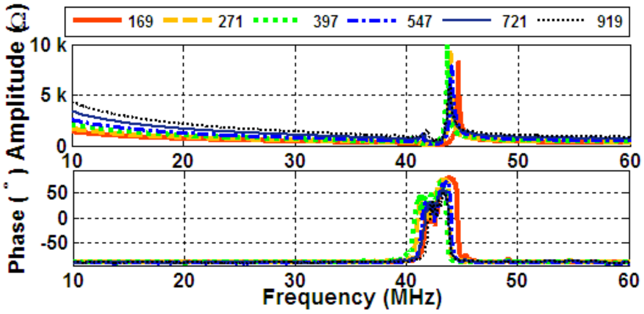

Figure 3. Measured input impedance characteristics of the CMUTs with n = 169, 271, 397, 547, 721, and 919 biased at 46 V, in air. (Characteristics of only 6 CMUTs are shown for better visibility.)

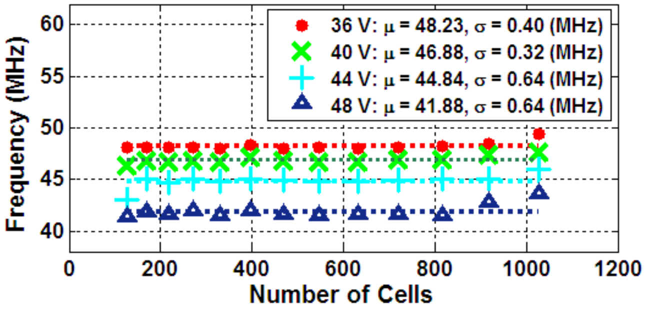

Figure 4. Plot of parallel resonant frequencies of 13 CMUTs biased at four different voltages. Mean (μ) and standard deviation (σ) values across number of cells for each bias voltage are calculated.

Two important parameters in resonant sensing applications which can be extracted from the input impedance characteristics are *Q* and R_X. Phase noise near the carrier frequency is inversely proportional to Q^2 while phase noise far from the carrier frequency is determined by thermal noise of the system, which includes the thermal noise of the resonator, R_X in addition to that of the circuit components. *Q* and R_X are extracted by fitting the input impedance measurement data to a 6-element equivalent circuit model (Fig. 5). The model includes parasitic effects of the substrate and the electrode contacts in addition to the conventional 4-element RLC van Dyke model [9].

In theory, if a single CMUT cell is modeled into the 4-element van Dyke model, a CMUT element with *n* cells connected in parallel will have *n* times smaller R_X and *n* times larger C_0. As predicted, the measured motional impedance is inversely proportional to *n* (Fig. 6). Quality factor at series resonance (Q_s) and parallel resonance (Q_p) are computed as a ratio between the resonant frequency and the 3-dB bandwidth

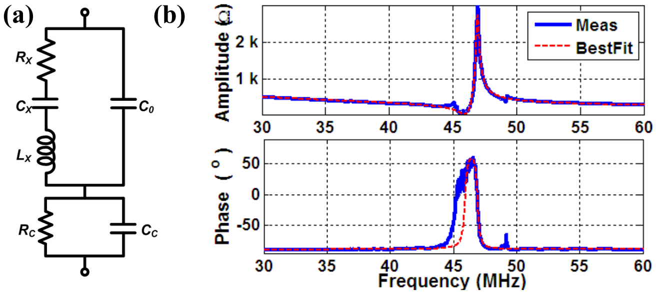

Figure 5. (a) 6-element equivalent circuit model used to fit the input impedance of the CMUT. (b) Example plot of measured and fitted impedance characteristics of a CMUT with 817 cells biased at 40 V.

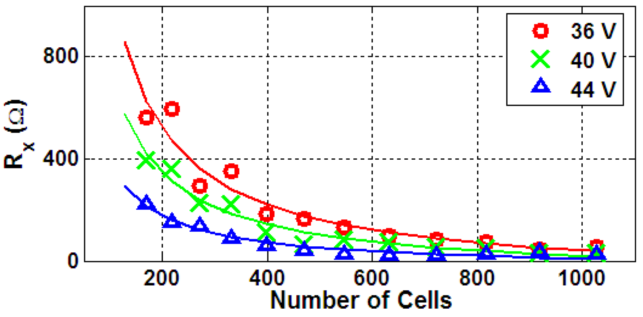

Figure 6. Plot of motional impedance (R_X) of the CMUTs biased at 36 V, 40 V, and 44 V. The solid lines are the best fit to $R_X \propto 1/n$ relationship.

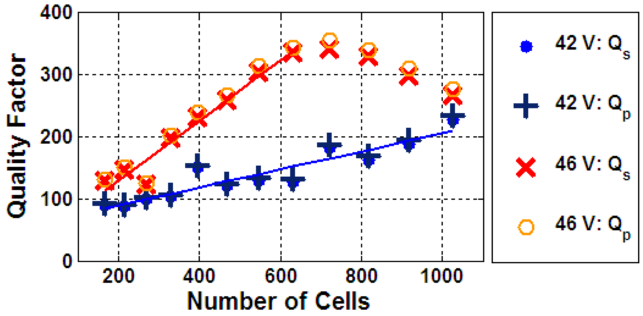

Figure 7. Plot of quality factor at the parallel (Q_p) and series (Q_s) resonances of the CMUTs biased at 42 V and 46 V.

of the fitted amplitude data. For a given CMUT, Q_s and Q_p are identical at low bias voltages and only at higher bias voltages near the collapse voltage, Q_p becomes larger than Q_s (Fig. 7). At a bias voltage below 80 % of the collapse voltage, such as 42 V, Q_s and Q_p both increase linearly with n.

III. IMPLICATIONS OF PARALLELISM ON NOISE

To investigate the effect of number of cells on oscillator phase noise, we simulated a CMUT-based Colpitts oscillator where each CMUT with different number of cells was represented as its equivalent 6-element circuit model.

A. *Theory*

Two common measures of frequency instability are the spectral density of fractional frequency fluctuation, $S_y(f)$, and phase noise, $L(f)$. By definition [10], two measures are related by

$$S_y(f) \equiv 2L(f)\left(\frac{f^2}{v_o^2}\right) \qquad (1)$$

where v_0 is the nominal oscillation frequency and f is the offset frequency. The Leeson model (2) provides a good insight into phase noise characteristics of an oscillator despite the known limitations, such as absence of $1/f^{\gamma}$ slope terms ($\gamma \geq 1$) and necessity to provide a fit parameter [11].

$$L(f) = 10\log\left(\frac{kTF}{P}\left(\frac{f_0^2}{4Q^2 f}+1\right)\right), \qquad (2)$$

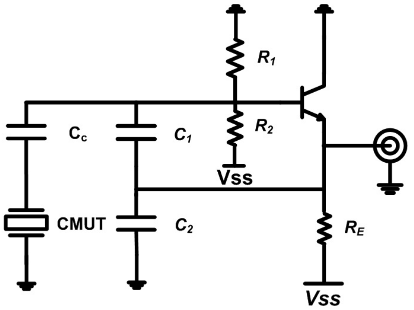

Figure 8. Circuit diagram of the Colpitts oscillator with the bias circuitry of the CMUT resonator shown.

where f_0 is the resonant frequency, f is the offset frequencies, kTF is the noise power of the amplifier and P is the resonator power delivered to the amplifier. The two additive terms in (2) corresponds to two regimes: the $1/f^2$ regime and the white noise regime. While the $1/f^2$ regime located close to the carrier frequency is inversely proportional to Q^2, the white noise regime located far from the carrier frequency depends only on the signal-to-noise ratio (*i.e.* kTF/P).

In a linear resonator model, the motional impedance, R_X, is inversely proportional to Q. Thus, if we have n number of CMUTs connected in parallel, the linear resonator model predicts n reduction in R_X, n increase in Q, and thus n^2 decrease in phase noise in the $1/f^2$ regime (2). Thus, in a system based on multiple resonators, if each resonator has a short-term instability spectrum of $S_{y,i}(f)$ that are uncorrelated from each other, the contribution of the individual instability to the total instability is reduced by n^2 due to decrease in the effective motional impedance. The total short-term instability spectrum of the multiple resonators is,

$$S_{y,total}(f) = \frac{S_{y,1}(f)}{n^2} + \frac{S_{y,2}(f)}{n^2} + \cdots + \frac{S_{y,N}(f)}{n^2} = \frac{S_{y,i}(f)}{n} \quad . \qquad (3)$$

Therefore, in theory, using n number of resonators connected in parallel, frequency stability can improve by 10 log n (in dB).

B. *Simulation*

Colpitts oscillators (Fig. 8) based on CMUTs with varying n are simulated in a circuit simulator, Advanced Design System (ADS), where phase noise is simulated based on harmonic balance method (Fig. 9). All the circuit parameters, such as C_1, C_2 and the biasing condition of the bipolar transistor, were unchanged for a fair comparison.

The simulated phase noise in the $1/f^2$ regime shows an inverse trend to Q as predicted. Q of CMUTs biased at 42 V increased monotonically with n while Q of CMUTs biased at 46 V closer to the collapse voltage increased linearly only up to n = 721 (Fig. 7). Phase noise at the offset frequency of 1 kHz, $L(f$ = 1 kHz), decreased monotonically for CMUTs biased at 42 V (Fig. 10 (a)), while $L(f$ = 1 kHz) first decreased and then began to increase at n = 721 for CMUTs biased at 46 V (Fig. 10 (b)).

In addition, the far-from-carrier phase noise simulation results show good agreement to the theory, where the phase

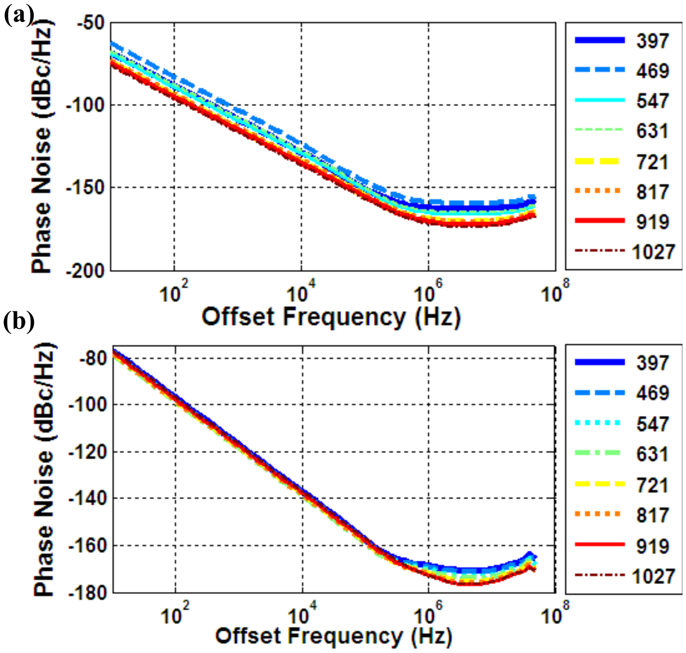

Figure 9. Simulated single side band (SSB) phase noise results of Colpitts oscillators employing the CMUTs biased at (a) 42 V and (b) 46 V.

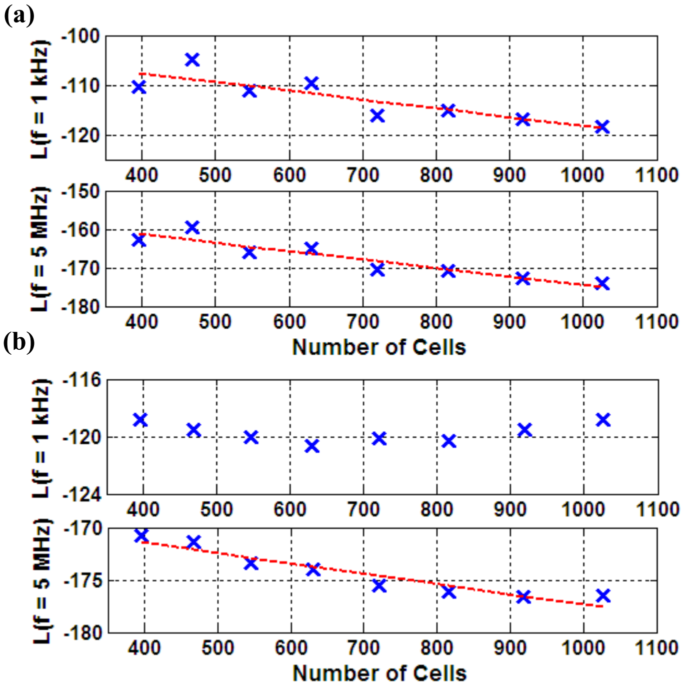

Figure 10. Simualted phase noise values at offset frequencies of 1 kHz and and 5 MHz for the CMUTs biased at (a) 42 V and (b) 46 V.

noise in the white noise regime depends primarily on the signal-to-noise ratio. While the negative resistance of the oscillator remains constant due to the same bias condition, R_X decreases as n increases, resulting in a decrease in the phase noise in the white noise regime. As n increases, the simulated phase noise at the offset frequency of 5 MHz, $L(f = 5\text{ MHz})$, decreased for both CMUTs biased at both 42 V and 46 V, independent of the trends of Q against n (Fig. 10). The oscillator based on the CMUT with 1027 showed 8.8 dB and 11.4 dB reduction in phase noise than that based on the CMUT with 397 cells at offset frequencies of 1 kHz and 5 MHz, respectively, when the CMUT is biased at 42 V.

IV. CONCLUSION

We fabricated 22 CMUTs with different number of cells to investigate the effect of parallelism on the frequency noise of a resonant chemical sensor. We demonstrated that by increasing the number of cells, a reduction in the motional impedance and hence in the phase noise in the white noise regime can be achieved. In addition, a linear increase in Q was observed against n, which improved the phase in the $1/f^{\,2}$ regime. Therefore, despite the resonator-to-resonator non-uniformities, electrically connecting multiple resonators can help to reduce the frequency noise and thus improve the resolution of resonant sensors. In addition to improvement in resolution, resonant chemical sensors can benefit from parallelism in terms of sensing area, robustness and better impedance matching to oscillator circuits.

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