A 400\(\mu\)W Differential FBAR Sensor Interface IC with digital readout

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Abstract—A low-power sensor interface IC suitable for a differential frequency measurement application is demonstrated. The circuit is used in a FBAR sensor system which includes a sensor and a reference FBAR. The sensor signal is processed and a digital output representing the sensor input is transmitted using a two wire serial interface. The architecture is entirely digital and a digital output is produced from the sensor information. The circuit is used in a FBAR sensor system which includes a sensor and a reference FBAR. The sensor signal is processed and a digital output is produced from the sensor information. The circuit is used in a FBAR sensor system which includes a sensor and a reference FBAR. The sensor signal is processed and a digital output is produced from the sensor information. The circuit is used in a FBAR sensor system which includes a sensor and a reference FBAR. The sensor signal is processed and a digital output is produced from the sensor information.

II. THEORY AND PRACTICAL CONSIDERATIONS

The operation of a FBAR sensor is very similar to any resonant frequency based sensor. The sensor variable (mass/pressure in this case) changes the resonant frequency of the FBAR which can be monitored to sense the added mass or pressure. Typically the change in the resonant frequency is monitored by an oscillator based interface.

A. FBAR as a mass sensor

An FBAR consists of a piezoelectric thin film which converts electrical energy into acoustic energy and vice versa. A resonance condition occurs if the thickness of piezoelectric thin film \((d)\) is equal to an integer multiple of a half of the wavelength \((\lambda)\). The resonant frequency of an FBAR is given as:

\[
f = \frac{v}{2t_p}
\]

where \(f\) is the resonant frequency of the FBAR membrane, \(v\) is the acoustic velocity and \(t_p\) is the thickness of the FBAR membrane. Any deposition of a foreign material on the FBAR, adds mass and changes the resonant frequency of the FBAR. The mass sensitivity is expressed by the well-known Sauerbrey equation as

\[
df = -\frac{2f^2}{NA\rho} \delta m
\]

where \(m\) is the mass per unit area, and \(\rho\) is the density of the added material. Typical sensitivities of the order of 1.7ppm/pg [3]. The higher resonant frequency of the FBAR provides a much higher sensitivity compared to a QCM [5].

B. FBAR as a pressure sensor

The phase velocity of the acoustic wave propagating in the piezoelectric membrane is related to the stiffness co-efficient, \(c_{eff}\) and the mass density \(\rho\) of the membrane as:

\[
v = \sqrt{\frac{c_{eff}}{\rho}}
\]

The effective stiffness coefficient is dependent on the stress in the FBAR membrane. Application of a pressure input on one-side of the FBAR introduces an additional stress in the membrane. This creates a pressure-to-frequency transducer. Typical sensitivities of the order of 2.2ppm/psi have been reported [4].
C. Issues in FBAR-based Sensors

FBAR provides high sensitivity to any added mass/pressure, however there are practical limitations in using an FBAR sensor. The resonant frequency of the FBAR is sensitive to environmental variables like humidity, temperature, package-level stresses etc. Temperature-compensated FBARs have a temperature dependence of 50 ppm over −20 to 100°C [3]. Additionally, the FBAR resonant frequency can drift by 100 ppm due to aging and stress. This greatly degrades the accuracy of the sensor. To cancel drift mechanisms to first order, we integrate two matched oscillator structures with two separate resonators (sensor and reference FBAR) in close proximity and use one of them as a reference to track the frequency change due to unwanted variables. The sensor input is applied to only the sensor FBAR. A differential frequency measurement then cancels the unwanted frequency drift to first order. The reference FBAR also provides a frequency reference for a communication interface.

III. Proposed Architecture

Figure 1 shows the architecture of the proposed sensor interface IC. At the core of this architecture is the presence of a reference and sensor FBAR to perform a differential frequency measurement and canceling out any measurement inaccuracies due to temperature, package stress etc. The two FBAR’s are chosen to be 628 MHz FBAR’s. The oscillator interface with the FBAR resonator directly impacts the resolution of the sensor.

The FBAR resonant frequency is monitored with a pierce oscillator structure as shown in the Figure 2. The design goal of the oscillator is to reduce the integrated jitter to improve the sensitivity of the sensor. The far-off phase noise in an FBAR-based sensor is not a concern due to the high-Q of the resonator and the relatively long sampling time in a sensor measurement.
of the order of ms. However, close-in phase noise performance dominates the total integrated noise in the system and sets the resolution of the sensor. AM-PM (amplitude modulation to phase modulation) conversion arising from non-linear device parasitic dominates the close-in phase noise generation in an FBAR oscillator. A non-linear compensation capacitor was added to reduce the close-in phase noise [6].

**Architecture description:** The sensor oscillator frequency is estimated using counter based logic. The number of edges in the sensor oscillator is counted for a fixed duration. This duration is defined by counting a set number of edges from the reference oscillator. Any common mode change results in a drift of both the sensor and the reference oscillator. The output of the counter thus remains constant. However, a differential input resulting from a sensor variable (mass or pressure) change affects only the sensor oscillator and changes the counter output. Thus a change in the output of the counter directly provides the sensor response.

The measurement window for the counting operation is fully programmable through a serial interface. The integration time trades power consumption (active duty cycle) for the minimum noise (hence resolution) in the measurement of the sensor. Typically, integration time for minimum Allan deviation is in the range of $10 – 100$ ms for FBAR oscillators. The start-up time of a FBAR oscillator ($10\mu s$) is negligible compared to the time required for minimum Allan deviation. The counting operation is run for 1/2 cycle of the counter (reference) clock and the counter output is transmitted serially for the other 1/2 cycle of the reference clock. A sync-code (EB90) is used at the beginning of the serial transmission for synchronization at the receiver.

**Asynchronous counter:** The differential frequency measurement translates to a multiple clock domain operation. A signal crossing a clock domain, appears to the circuitry in the new clock domain as an asynchronous signal. This results in a metastable state in the first storage element (flip-flop) in the new clock domain. Systems with multiple clock domains handle this with specialized synchronization circuits that greatly increases the power consumption of the system [7]. In the proposed sensor system, the total duty-cycled power consumption is of the order of a few $\mu W$.

An asynchronous counting scheme is employed to save power without synchronizing the two clocks. The sensor oscillator is followed by a chain of dividers (divide by 2) and the output of the dividers is latched as a count value at the positive and negative edge of the divided reference clock. The difference between the latched counts provides an estimate of the number of edges in the given time period from which the sensor frequency could be estimated. Figure 3 shows the block diagram of the counting operation. The design of the first divider is critical since the input frequency is high (628MHz). A True Single Phase Clock (TSPC) flip flop based divider which incorporates high speed and low power consumption is used for the first divider. The power consumption of the subsequent dividers is negligible and standard static CMOS based circuits are used.

**Quantization Error:** A digital counting scheme inherently results in a quantization error in the frequency measurement. The division ratio or the counting period dictates the quantization error. The minimum quantization error with a modulo-N programmable frequency divider in the current architecture is given by equation 4. For a $628$MHz FBAR, a divide ratio of $2^{26}$ translates to a resolution of $0.05$ppm with a $53$ms interval between successive measurements. The resolution is limited by the divide ratio rather than by the minimum noise (Allan deviation) in the proposed system.

$$Q_e = \frac{f_{sensor}}{2^N - 1}$$

**IV. Measured Results**

The sensor interface IC was fabricated in a 0.13$\mu m$ CMOS process. The IC was interfaced with a FBAR pressure sensor (Figure 4). The pressure sensor was processed as in [4] without the lid circuitry. The sensor interface IC consumes $530 \mu A$ from a $0.75V$ supply with the digital processing consuming $120 \mu A$. For one cycle of measurement and transmission (100ms), with a duty cycle ratio of 1%, the average power consumption of the IC is $4 \mu W$.

The response of the pressure sensor was characterized by mounting the chip on a measurement PCB. The PCB was placed in a pressure chamber controlled by a pressure regulator. The programmable divider was programmed for a counting window for the counting operation that translates to a multiple clock domain operation. The start-up time of a FBAR oscillator ($10\mu s$) is negligible compared to the time required for minimum Allan deviation. The counting operation is run for 1/2 cycle of the counter (reference) clock and the counter output is transmitted serially for the other 1/2 cycle of the reference clock. A sync-code (EB90) is used at the beginning of the serial transmission for synchronization at the receiver.
clock frequency of close to 10Hz. The serial output data consists of a 16-bit frame sync code $EB90$ followed by a 29-bit digital value representation of the sensor frequency.

Figure 5 shows the digital output code as the pressure inside was increased from 20psi to 80psi. The digital output codes represent the sensor frequency measurement. We observe a linear response and the pressure sensitivity is calculated to be 1.6ppm/psi.

The digital output code was then mapped to pressure values using the slope of the transfer function. Figure 6 shows the measured pressure as a function of the pressure input. The maximum error in the pressure measurement is ±0.53psi.

**Resolution:** The resolution of a FBAR sensor is determined by the minimum detectable frequency shift, which is specified by an Allan deviation measurement in an oscillator-based sensor interface. Figure 7 shows the Allan deviation measurement. The minimum detectable frequency shift is 3.9ppb at an integration time of 100ms. However, in the proposed digital sensor interface, the quantization error is limited by the measurement window. With a maximum divide ratio of $2^{26}$ and a 628MHz FBAR for deriving the counter clock, the minimum achievable resolution is 60ppb. This translates to a resolution of 0.037psi. Higher division ratios improves the resolution, however the increase in the noise of the system limits the resolution and the power consumption.

**V. CONCLUSION**

This paper demonstrated a low power digital interface circuit for operation with FBAR-based sensors. The instantaneous current consumption of the interface circuit is 530µA and operates off a 0.75V supply. The low supply voltage and the low instantaneous power consumption makes it feasible to operate the system with standard coin-cell batteries. The architecture is scalable to advanced process nodes and will benefit from process scaling. The digital output from the sensor interface IC is compatible for further digital signal processing.

**ACKNOWLEDGMENT**

The authors would like to acknowledge the efforts of Dorie Delapena for bonding services.

**REFERENCES**


