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Triple Ultra-Stable, Zero-Drift Resonators in a Single Package for BLE

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Abstract:
Quartz crystals have dominated the timing market for the last 70 years. FBAR technology is poised to replace quartz for many high frequency applications. Integration of the ultra-small form factor of the microcap'd FBAR into the SoC BGA packages currently in the market will make these applications earn the moniker, "Crystal-less". To replace crystals for non-GPS applications, the FBAR must demonstrate superb aging properties, repeatable and well-behaved temperature stability, immunity to mechanical stress, high frequency with +/- 500 ppm accuracy and small size. We will present data showing that we have met all five properties described above. Furthermore, we have integrated 3 resonators into an all-silicon 0.5 X 0.5 X 0.2 mm^3 package targeting the 3 BLE advertising frequencies: 2402MHz, 2426 MHz and 2480 MHz.
KEYWORDS — FBAR, BLE, OSCILLATORS,

I. INTRODUCTION

One of the underpinnings of IoT (Internet of Things) are small ultra-low power remote sensors that can communicate wirelessly. The most basic IoT application would be the BLE (Bluetooth Low Energy) transmitter for beacon applications [1]. BLE is an off-shoot of Bluetooth where the main differentiator is power consumption. The frequency spectrum for Bluetooth and BLE is from 2400 to 2483.5 MHz (same as WiFi). Bluetooth was originally designed to handle continuous data streams between two devices in fairly close proximity. The difference between traditional Bluetooth and BLE is that BLE focuses on low energy dissipation. One method used to reduce power is to use 'sleep mode' where the device sleeps for an extended period of time before waking up and transmitting (but, receive is always on). BLE Advertising channels are set at 3 distinct frequencies across the BT spectrum. They occupy the 2402 MHz, 2426 MHz and 2480 MHz slots. These three frequencies are far enough apart that even if one channel is blocked, the other two are available. Typical transmitting packets contain up to 37 bytes of information. This is enough to transmit a unique ID, the local temperature, battery life of the IoT device and a URL link address. Applications can be as wide ranging as pointing to a link that gives more information about a product on display, or sending out a unique identifier code that can be picked up by any Smartphone (Android or OS based) and then re-transmitted to the Cloud via the cell phone network. What is really clever about this application is that the phone can automatically assign GPS coordinates and time stamp when the unique identifier has been received. This last application has great impact on tracking stolen purses, lost dogs & cats and missing children.

One need for the IoT transmitter is size and low battery (current) consumption. Smart Pills that can continuously transmit data as it travels thru the digestive system and super small glucose monitors that are light and thin (so as to not rub against clothes or fall off or otherwise irritate the patient) can benefit the health industry. Fig. 1a gives an idea of how small an FBAR BLE transmitter is (2.56 mm^2) and also highlights that the component count inside that module is only 4 elements; the CMOS controller, the FBAR resonator, and two SMT capacitors, Fig. 1 b.

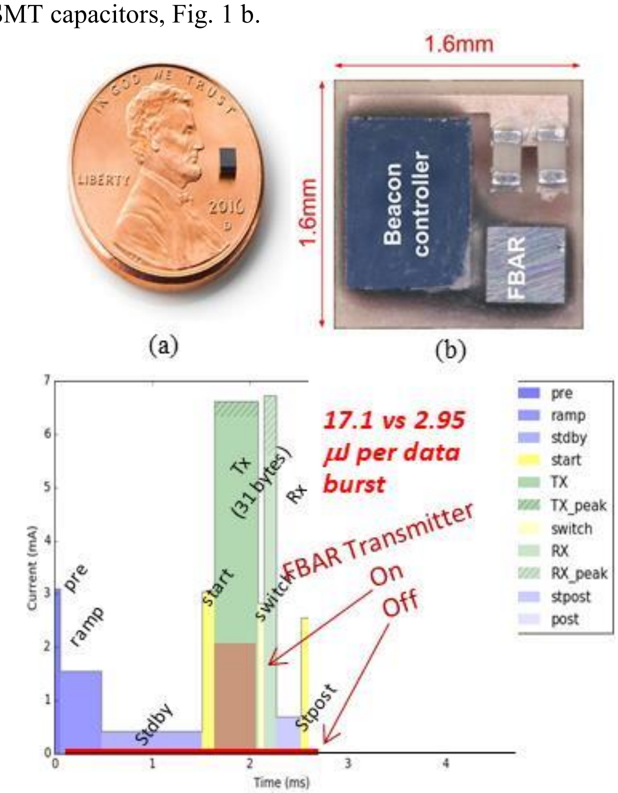


Fig. 1: a) Shows an FBAR BLE Transmitter on a penny. The total height is 0.65 mm; b) the module prior to overmold; c) The current draw per data burst of an FBAR beacon (red) vs. Nordic nR252 BLE chipset (3.3V, output power at 2480 MHz is 0 dBm).
https://devzone.nordicsemi.com/nordic/power

A BLE transmit-only device saves power by not having a receiver always on and by utilizing sleep mode (as short as 100 msec to as long as 10 seconds). Despite these power savings, there are several other sources of power dissipation:

Power Amplifier (PA), oscillator/PLL, quiescent power (during sleep mode) etc. In cases where the BLE transmitter needs to broadcast over many ten's of meters, the PA is the primary source of battery drain. However, for close-in applications (<1 meter to ~ 10 m), the PA is not the major source of the battery drain. Here, the PLL and oscillator along with crystal 'warming' start to dominate power dissipation. In order to insure that the crystal is oscillating at a stable frequency, the crystal must be allowed to 'ramp up' to its full voltage (displacement) swing. Given the high Q and low resonant frequency of the Quartz crystal compared to an FBAR, it takes several milliseconds to achieve a stable frequency output. The FBAR, in contrast, takes a few microseconds to stabilize. If one described a simple FoM – Operating frequency divided by Q –FBAR FoM will be many orders of magnitude better than quartz. Figure 1c shows the typical current draw for a Nordic BLE chipset vs an FBAR transmitter. As can be seen, there can be as much as a 5 to 7X decrease in energy per data burst.

Low current draw during broadcasting is important. Paper batteries and small silver-oxide batteries that have high input impedances do not do well with large current draw. In some cases, a 'brown out' condition on the CMOS controller can occur when there is a large voltage drop due to sudden current draw.

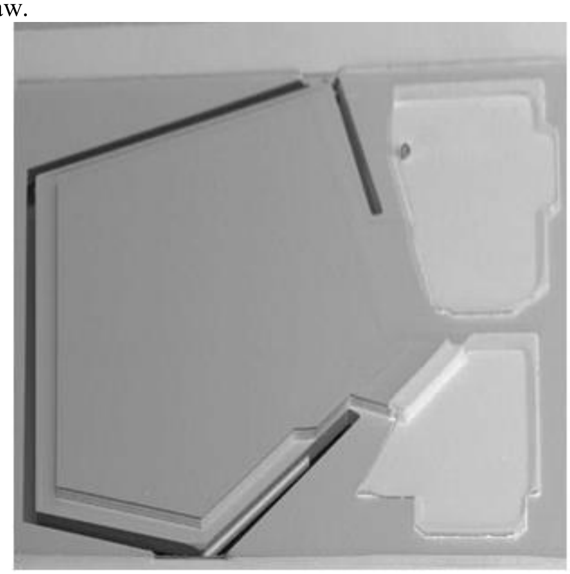
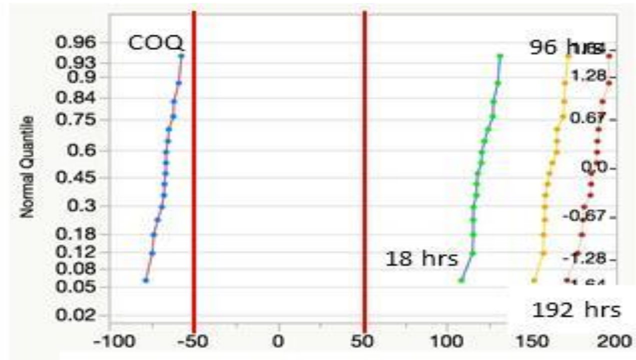


Fig.2; Cantilever type ZDR. The resonator is held at only one point (right side). This attachment point also is used for the electrical contacts to the resonator.

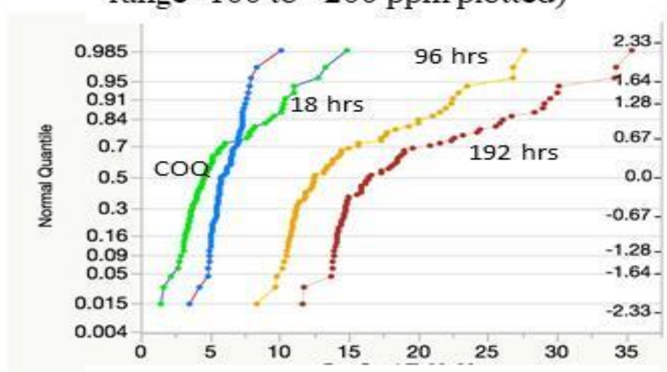
Many design challenges lie with the CMOS controller [1], but design and process challenges also exist for good FBAR design. First, using an FBAR resonator to eliminate the PLL must run at the advertising BLE frequencies. Second, having a high Rp for a given Vdd will reduce the current draw of the oscillator circuit. Third, the resonator must –at the very least- have a zero temperature coefficient of frequency (linear) these devices are called Zero Drift Resonators or ZDR [2], Fourth, the FBAR must be integrated into a hermetic package [3]. And last, the FBAR must be insensitive to external environmental stresses [4]. Integrating all 3 resonators inside a very small package that operate at the 3 BLE advertising frequencies will make the BLE transmitter even more robust in the presence of a hostile RF signals.

II. CANTILEVER ZERO-DRIFT RESONATORS

Figure 2 shows the current design of a ZDR [5] used in the BLE transmitter.



a) Standard FBAR Design (Freq range -100 to +200 ppm plotted)



b) Cantilever FBAR Design (Freq range 0 to +35 ppm plotted)

Fig. 3; Strife measurements starting with COQ, then 18, 96, 192 hours of HAST for the two ZDR designs; (a) Standard FBAR deisgn and (b) cantilever, stress-immune FBAR. Note scale difference in x-axes.

After sampling some small number of resonators, a contour ion milling step is used to bring in the frequencies of all the resonators on the 8" wafer to within ±500 ppm. The remaining ±500 ppm of 'process' variation can be tuned out using switched caps on the controller. The FBAR resonator is made 'zero-drift' by adding a thin layer of oxide near the center of the bottom electrode of the active acoustic area of the FBAR [2].

One issue that we see over and over is the sensitivity to external environmental conditions whose root cause can be traced back to poor stress relief of the resonator. Under multiple strife conditions (HAST/Autoclave, Wet High Temperature Storage, Thermal Shock, IR reflow, solder down, etc.), we see the frequency shift by unacceptable amounts for a standard FBAR layout. What is important to stress in this paper is that these shifts are erratic and irreproducible and cannot be 'calibrated out'. Figure 3 shows ~140 module builds measured for one particular stress condition (HAST). HAST is a proxy for autoclave. The first measurement is done after 'Customer Oriented Quality' (COQ) exposure (24 hr WHTS, 4X IR reflow 48 hours 120C bake). These measurements are then followed by HAST conditions after 18, 96 and 192 hours. The difference between standard autoclave and HAST is that HAST is run at 130C (vs. 120C) and a relative humidity of 85% (vs. 200%). For the stress-relieved resonator, the mean shift was about 17 ppm after ~200 hours of HAST, whereas a standard FBAR layout shows ~180 ppm shift. In many cases, the amount of frequency shift for a given strife condition will start to recover over time --but, never to the initial frequency value. The root cause is believed to be the changes in the 1.6mm^2 package that absorbs moisture and causes board warp and hence stress to the FBAR die and ultimately to the FBAR resonator.

III. TRIPLE RESONATOR/OSCILLATORS

Figure 4 is a de-cap'd die (partially damaged) with 3 cantilever stress-immune, ZDRs.

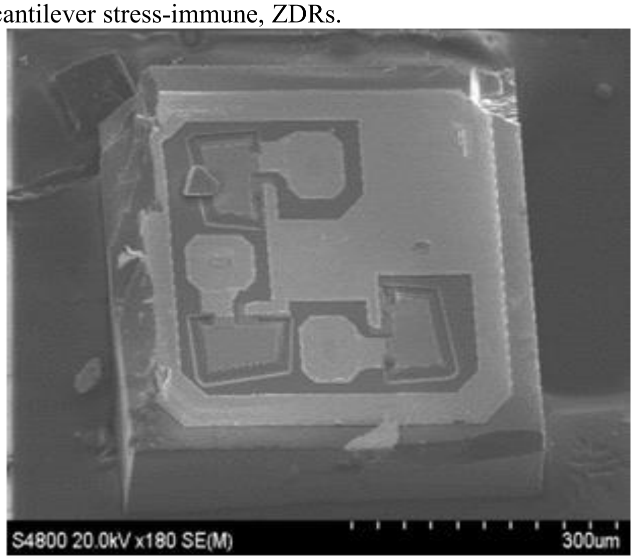


Fig.4, a Low Mag SEM Picture of the 3 ZDR (at 2402, 2426 and 2480 MHz) integrated into a single hermetic 0.25 um^2 package (lid has been removed)

The die footprint is roughly 0.25mm^2 and 0.22 um tall. Each resonator is tuned to be close to one of the 3 unique advertising bands. Each ZDR has been individually mass loaded to be in close proximity to the targeted BLE advertising channel. Absolute accuracy is not necessary as switched caps in the controller will take out any process variations. Alternatively, ion milling frequency trimming of each resonator using a photoresist mask per resonator 'flavor' can be used to bring the total offset to within ±500 ppm. As can be seen from the die photo, these die are pad limited. The actual size of the resonators (~4K um^2) takes up less than 30% of the usable die area.

Figure 5 shows the wiring configuration for the die shown in Fig. 4.

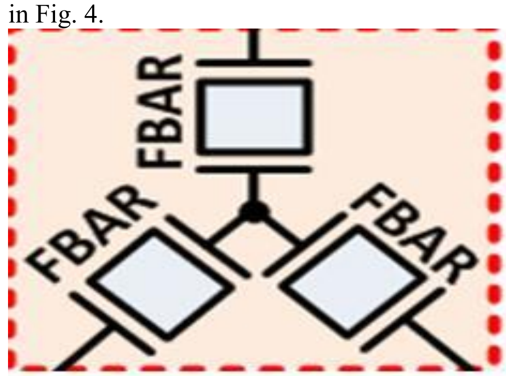


Fig. 5: Wiring Diagram of the 3 Cantilever ZDRs

IV. MEASUREMENTS

Figure 6 is a Spectrum Analyzer measurement of the three frequencies generated from the three ZDRs. We have tested over 100 units from from 10C to 90C using GFSK modulation – all meeting the BLE specifications.

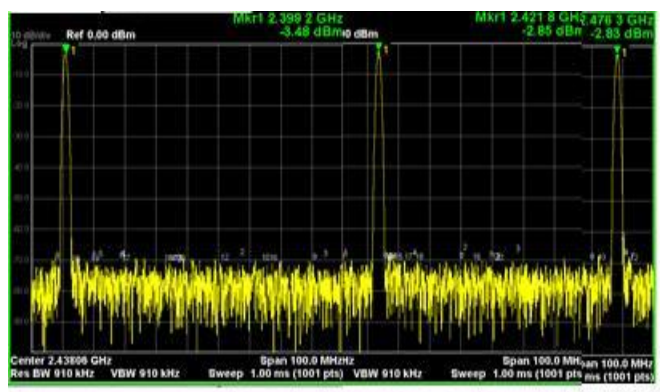


Fig. 6: Superposition of the 3 Oscillator Frequencies at 2399, 2421 and 2476 MHz The frequencies are worst case 1600 ppm from target and further frequency trimming can get to within ±500 ppm

V. CONCLUSION

We describe a 3 resonator variant than can cover the 3 BLE advertising bands in the same resonator package footprint. This resonator topology will not allow simultaneous transmission over the 3 bands. However, BLE Specifications only allow broadcasting from one of the 3 frequencies at a time. To increase the likelihood of having a beacon data burst received, one can transmit the same data serially on each of the 3 frequencies, thus, greatly reducing any interference issues surrounding any one advertising channel.

Table 1 shows a comparison of our module using the ZDR vs 3 commercial products using a crystal. As can be seen, the amount of power is 5 to 7 X smaller (using comparable transmit power at 0 dBm) and size is many times smaller. [Note: the discrepancies in energy per burst given in Figure 1 and in Table 1 reflects different Nordic part numbers and also improvements in the CMOS controller chip – Table 1 is the more up to date set of numbers.] The competing technology die size is 2 to 5 X larger than our whole PC board with mounted components, and a typical commercial module built around these silicon chips would be larger yet.

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Parameter	This Work	Nordic nRF52832	Dialog DA14580	On Semi RSL10
Tx Current (0 dBm)	3 mA	5.4 mA	4.8 mA	4.6 mA
Start-up time †	<10 us	1.5 ms	2.0 ms	1.5 ms
Supply Voltage	1.3-3.6 V	1.8-3.6 V	0.9-3.6 V	1.25-3.6 V
Total Tx Burst Energy ‡	2.3 uJ (1.5 V) 3.6 uJ (3 V)	14.8 uJ (3 V)	16.7 uJ (1.5 V)	NA >> this work
Physical Volume (mm^3)*	1.6 x 1.6 x 0.65	3 x 3.2 x 0.4	2.4 x 2.4 x 0.5	2.3 x 2.3 x 0.35
Additional BOM Count	0	12	9 (w/ dc-dc)	>8 (w/ dc-dc)

† Start-up time for 1.6mm x 1.2mm crystal. Increases for smaller crystals due to load capacitance and ESR
‡ Total to wake up from sleep, transmit one packet, and go back to sleep
* Physical volume is for the raw Silicon Die only and does not incude crystal, and SMT components

Table 1. A comparison of this work vs 3 commercial BLE transmitter modules using conventional crystals