

Optimized for Battery Life and Reliability: Quartz Crystals for IoT and Wearable Devices

This Application Note discusses how to reduce oscillator power consumption, while achieving optimal oscillation margin - using quartz crystals designed to mate with energy saving low power SoC's. Published measurements demonstrate key principles essential for the design of a reliable, low-power oscillator.

## The Need for Low Current, Reliable Crystal Oscillators

The demand for battery operated/long-life wireless devices is increasing. Demand is being driven by increasingly affordable, power efficient processors and radios. Developers commonly apply super low power System-On-Chip (SoC) radio/processors to support small devices with multi-year battery life. Often, the dominant factor in such a product's cost and size is the battery, with battery size dominated by the standby current, and standby current dominated by the low-frequency clock-oscillator.

It is an Industry known fact that very low power oscillators can exhibit start-up problems related to inadequate gain and high crystal load. To avoid start-up problems while conserving power, developers need to make well-informed design decisions on the factors that determine standby current and oscillator reliability. In other words, the oscillator needs to both draw low current and must reliably start-up over the range of production variations and temperatures.

Because of the importance of the clock's power efficiency, SoC's employ a variety of clock management methods. This application note examines the two most common clock management methods, automatic gain control (AGC) and selectable gain. Understanding how these two methods interact with the crystal characteristics will support a well-informed crystal selection and associated processor/MCU settings.

## Background: Oscillator Fundamentals

Figure 1- Pierce Oscillator Block Diagram

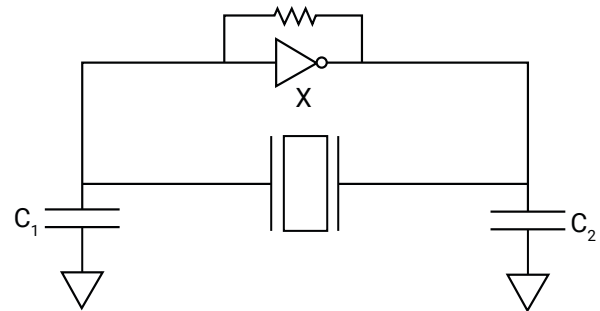
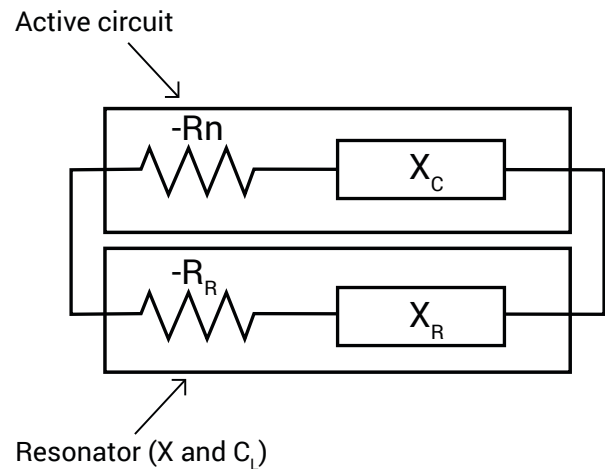


Figure 1 shows the Pierce oscillator configuration used in most SoC's. The oscillator loop consists of an inverting amplifier and feedback resistor (internal to the chip) plus a precision phase shift circuit consisting of a crystal (X) and load capacitors,  $C_1$  and  $C_2$ . When the output of the amplifier is fed back to the input, it produces negative resistance and can oscillate under the right conditions.

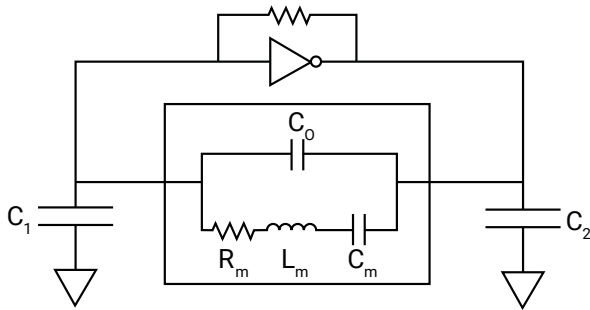
Figure 2 – Negative Resistance Oscillator Model



For further insight, Figure 2 illustrates the oscillator as the combination of negative resistance ( $R_n$ ), circuit reactance ( $X_c$ ), resonator reactance ( $X_R$ ) and resonator resistance ( $R_R$ ). The circuit will oscillate if  $R_n > R_R$  at the frequency where  $X_c = -X_R$ .

Figure 3 illustrates an oscillator with emphasis on the crystal equivalent circuit.

**Figure 3 – Oscillator Loop with Expanded Crystal Model**



$R_m$  is the crystal motional resistance  
 $C_o$  is the crystal package parasitic capacitance  
 $C_1$  and  $C_2$  are the crystal load/plating capacitors (collectively representing  $C_L$ )  
 $L_m$  is the crystal motional inductance  
 $C_m$  is the crystal motional capacitance

## Oscillation Allowance – Predicting Reliable Start-Up

Oscillation Allowance (OA), also referred to as closed-loop gain margin ( $G_M$ ) is a term used to describe the reliability of an oscillator with a figure of merit that describes how tolerant the oscillator is to added losses. It is well established that an OA of less than 5 is unacceptable and that low OA can result in production yield and temperature-related start-up problems. Desirable and robust OA is greater than 20 to account for board strays of the end-solution and, part-to-part and lot-to-lot variations at both the crystal level; as well as the SoC.

**Figure 4 – Resistor Added for Measuring Oscillation Allowance**

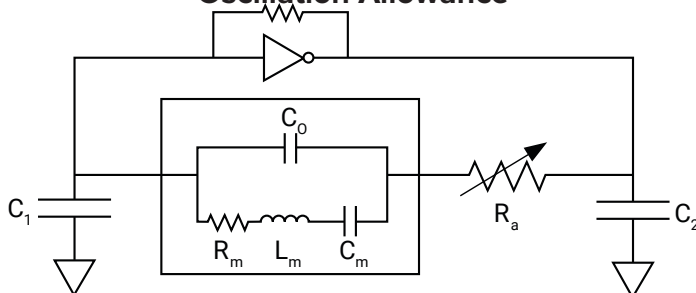


Figure 4 illustrates the practical measurement of OA and provides insight into the usefulness of the term 'OA'. Here, the oscillation loop includes an added resistor,  $R_a$ . OA is measured by increasing  $R_a$  until the oscillator will no longer start up, then OA is calculated as:

Oscillation Allowance =

$$OA = R_n / R_e$$

$R_n$  is the negative resistance

$$R_n = R_e + R_a$$

$R_e$  is the equivalent series resistance (generally referred to as ESR)

$$ESR = \text{Equivalent Series Resistance } (R_e) = R_m \times (1 + C_o / C_L)^2$$

OA has significant dependence on the quartz crystal parameters and decreases as  $R_m$  and  $C_L$  are increased. This dependency is substantially increased for very lower power oscillators where the oscillation amplitude is relatively small. Measuring OA is frequently overlooked in the development process which can lead to yield problems later.

## Power Usage Factors

Modern SOC's are designed with particular attention to achieving low-current in the oscillator circuits. They use AGC or selectable gain settings to set the amplitude of the oscillation as low as possible, while maintaining a reliable oscillator (high OA). It's fair to say that the circuit efficiency is well-optimized. However, power losses due to the crystal itself are usually overlooked, this factor can be significant. Referring to Figure 3, the motional resistance,  $R_m$  causes power to be dissipated because of current cycling through the resistor. The current increases when  $C_L$  is larger. So, lowest power usage occurs when  $R_m$  and  $C_L$  are simultaneously lowered.

## Example Crystals

To demonstrate the advantages of Abracon’s industry-leading low  $C_L$  crystals, six 32.768kHz devices were selected for comparative analysis in both an AGC-based and gain-settable oscillator realized in two different SOC’s. Table 1 summarizes the crystal characteristics. It should be noted that all crystal manufacturers provide calculated ESR rather than  $R_m$  value.

Further, the interdependency of OV ( $G_M$ ) to the crystal’s motional parameters is outlined as follows:

$$OA(G_M) = \frac{gm}{4 \times ESR \times (2\pi F)^2 \times (C_0 + C_L)^2} \dots(1)$$

- Where;
- $gm$  = Oscillator Amplifier’s Transconductance value
  - ESR = Equivalent Series Resistance [ $ESR = R_m \times (1 + C_0/C_L)^2$ ]
  - F = Frequency of resonance
  - $C_0$  = crystal package parasitic capacitance
  - CL = crystal load/plating capacitance

As is evident from equation (1),  $C_L$  is generally larger than  $C_0$  and has profound impact on OA. Additionally, ESR value greatly influences sustainability of oscillations. To achieve superior OA, the goal is to simultaneously reduce all three motional parameters ( $C_0$ , CL and ESR).

**Table 1 – 32.768 KHz Crystals Selected for Evaluation**

XTAL	Part Number	Package	$C_L$	$C_0$	ESR
		mm	pF	pF	K $\Omega$
A1	ABS07W-32.768KHZ-D-1-T	3.2x1.5x0.9	3	1.2	37.5
A2	ABS06W-32.768KHZ-D-2-T	2.0x1.2x0.6	3	0.9	61.6
M2a	Manufacture #2	3.2x1.2x0.6	6	1.0	48.5
M2b	Manufacture #2	2.0x1.2x0.6	6	1.3	59.5
M3a	Manufacture #3	2.0x1.3x0.6	4	1.3	62.6
M3b	Manufacture #3	3.2x1.5x0.9	6	1.1	31.3

Oscillation Allowance (OA) and current requirements are evaluated in the following sections.

## Gain-Selectable Oscillator

Figure 5 illustrates a gain-selectable oscillator. Here, the gain is selected in software by setting the amplifier bias current to one of four levels.

**Figure 5 – Gain Selectable Oscillator Based on Bias Adjustment**

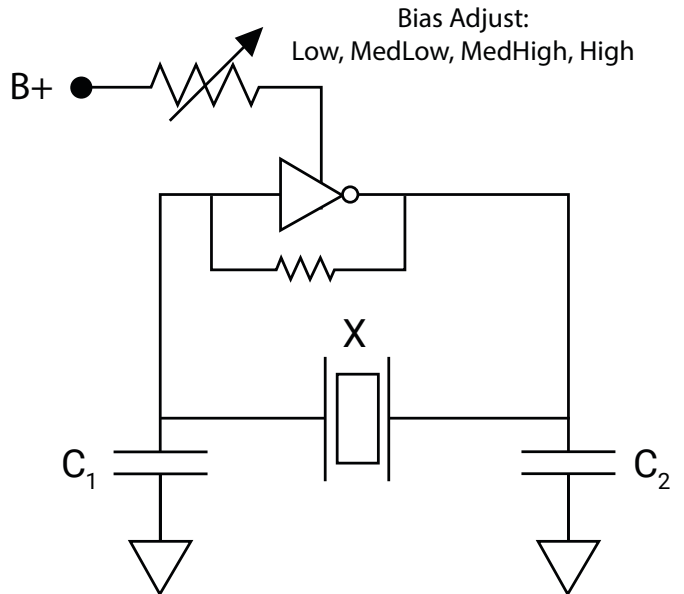
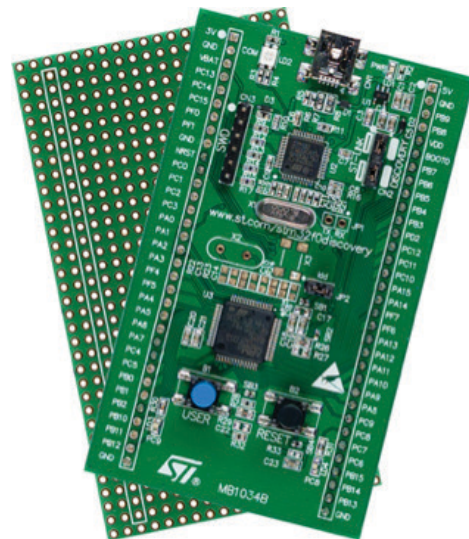


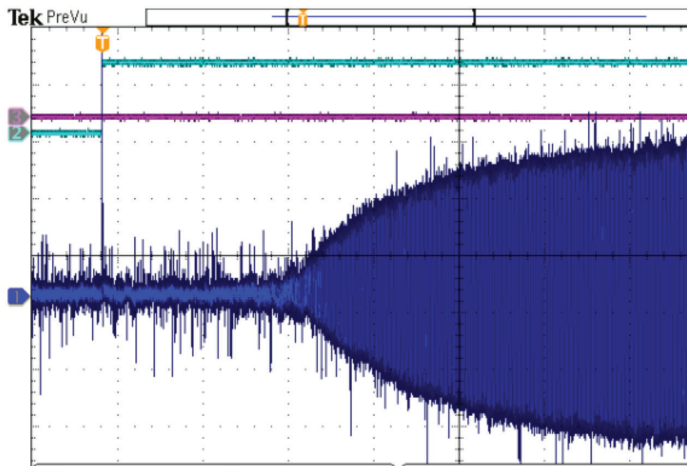
Figure 6 shows a picture of the STM320F discovery evaluation board used in the gain-settable tests. Figure 7 shows a typical start-up transient.

**Figure 6 – Evaluation Board for the Gain-Settable Tests**



This SoC includes a ‘clock ready’ signal (green trace) that is used to measure start-up time, summarized in Table 2.

**Figure 7 – Gain Selectable Oscillator Start-Up**



**Table 2 – Start up time for 32.768KHz crystals in the gain-settable circuit**

XTAL	Part Number	Package	$C_L$	$C_o$	ESR	Start-up Time
		mm	pF	pF	kΩ	ms
A1	ABS07W-32.768KHZ-D-1-T	3.2x1.5x0.9	3	1.2	37.5	172
A2	ABS06W-32.768KHZ-D-2-T	2.0x1.2x0.6	3	0.9	61.6	156
M2a	Manufacture #2	3.2x1.2x0.6	6	1.0	48.5	186
M2b	Manufacture #2	2.0x1.2x0.6	6	1.3	59.5	151
M3a	Manufacture #3	2.0x1.3x0.6	4	1.3	62.6	143
M3b	Manufacture #3	3.2x1.5x0.9	6	1.1	31.3	192

Table 2 above clearly illustrates that the Start-up time is fairly consistent across all crystals.

**Table 3 – Oscillation Allowance and Oscillator Current for the Gain-Selectable Circuits at 32.768 KHz**

XTAL	Part Number	Package	$C_L$	OA	Crystal Drive Current
		mm	pF		nA
A1	ABS07W-32.768KHZ-D-1-T	3.2x1.5x0.9	3	78	458
A2	ABS06W-32.768KHZ-D-2-T	2.0x1.2x0.6	3	52	499
M2a	Manufacture #2	3.2x1.2x0.6	6	24	508
M2b	Manufacture #2	2.0x1.2x0.6	6	6.5	457
M3a	Manufacture #3	2.0x1.3x0.6	4	19	485
M3b	Manufacture #3	3.2x1.5x0.9	6	15	496

The data shows that the oscillators based on Abracon’s low  $C_L$  design are the most reliable. Crystal M2b has an OA of only 6.5, which is marginal. Manufacture #3’s crystals also display less than desirable OA and should be evaluated over temperature as well as over part-to-part variations.

Setting the gain higher can improve OA, but it requires more current. Table 4 shows the effect of adjusting the gain for the low OA crystal “M2b”. As evident, Gain Setting affects both OA and the consumed current. Gain selection should be based on the measurement of both of these factors, especially for battery-operated designs.

**Table 4 – The Effect of Gain Settings on Oscillation Allowance and Oscillator Current for the Low OA 32.768 KHz Crystal**

XTAL	Part Number	Gain Setting	OA	Crystal Drive Current nA
M2b	Manufacture #2	Low	6.5	457
M2b	Manufacture #2	Medium Low	13	637
M2b	Manufacture #2	Medium High	22	679
M2b	Manufacture #2	High	23	757

The data shows that sufficient oscillation allowance can be achieved with the expense of about 40% more current. And, the oscillator is still not as robust as it is with the low  $C_L$  Abracon crystals.

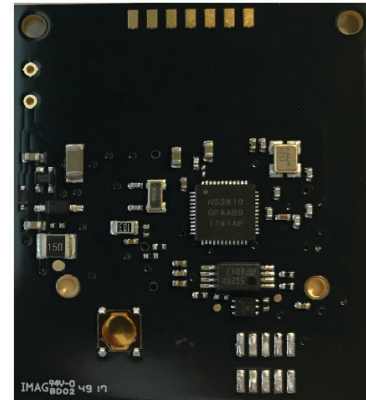
## Abracon Crystals at High Temperature

Further investigation was carried out with Abracon crystals at evaluated temperature (85°C) in the gain-settable circuit with gain set to “Low”. It was anticipated that this would be the absolute worst case. The results in Table 5 show somewhat increased OA, with robust sustained oscillations at minimal consumed current.

**Table 5 – OA for Abracon 32.768 KHz Crystals at 85°C**

XTAL	Part Number	Gain Setting	OA	Crystal Drive Current nA
M2b	Manufacture #2	Low	6.5	457
M2b	Manufacture #2	Medium Low	13	637
M2b	Manufacture #2	Medium High	22	679
M2b	Manufacture #2	High	23	757

**Figure 9 – Circuit Board Used in AGC-Based Oscillator**



### AGC-Based Oscillator – OA and current requirements

Figure 8 illustrates an AGC-based low-power oscillator. Here, the amplitude of the oscillation is held constant by adjusting the gain of the amplifier.

**Figure 8 – AGC-Based Oscillator**

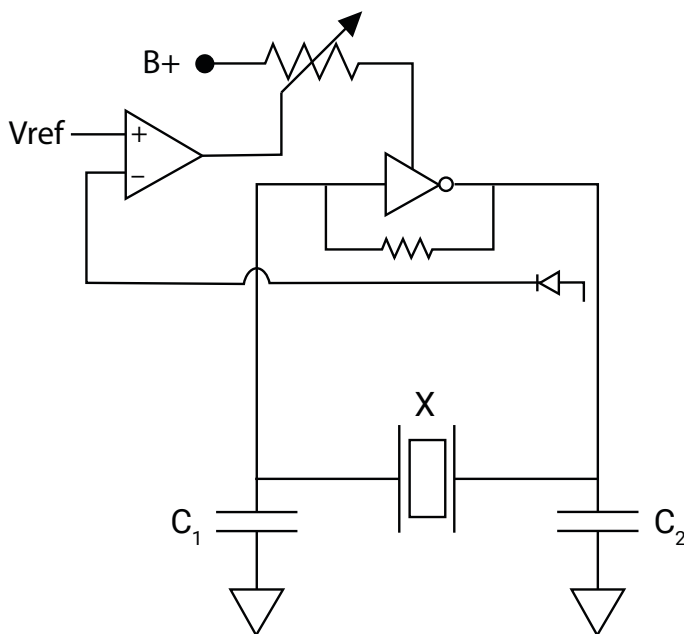


Figure 9 shows the custom circuit board with Nordic N52810 Bluetooth chip used in the AGC-based oscillator tests.

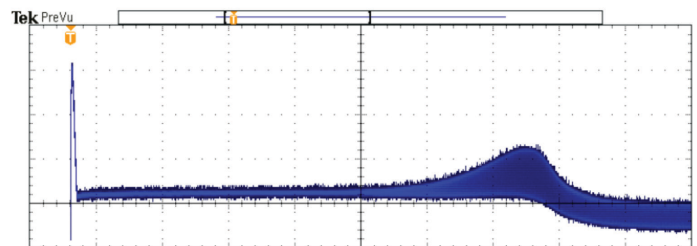
The AGC-based oscillator adjusts the bias of the amplifier according to the oscillation amplitude. As such, it can be expected that lower-loss crystals (lower  $C_L$  and ESR) will require less current and also have higher OA. The data in table 6 substantiates this assumption.

**Table 6 – Oscillation Allowance with AGC Engaged**

XTAL	Part Number	Package	$C_L$	OA
		mm	pF	
A1	ABS07W-32.768KHZ-D-1-T	3.2x1.5x0.9	3	121
A2	ABS06W-32.768KHZ-D-2-T	2.0x1.2x0.6	3	67

A typical AGC transient is shown in Figure 10. This example is for a 32.768 KHz oscillator. Notice that envelope is held constant after the start-up transient.

**Figure 10 – AGC-Based Oscillator Start-Up**



The chip also includes a ‘clock ready’ signal that is used to measure start-up time, summarized in Table 7.

**Table 7 – Start up time for 33.768kHz crystals in the gain-settable circuit**

XTAL	Part Number	Package	$C_L$	$C_o$	ESR	Start-up Time
		mm	pF	pF	k $\Omega$	ms
A1	ABS07W-32.768KHZ-D-1-T	3.2x1.5x0.9	3	1.2	37.5	313.8
A2	ABS06W-32.768KHZ-D-2-T	2.0x1.2x0.6	3	0.9	61.6	335.7
M2a	Manufacture #2	3.2x1.2x0.6	6	1.0	48.5	356.7
M2b	Manufacture #2	2.0x1.2x0.6	6	1.3	59.5	317.2
M3a	Manufacture #3	2.0x1.3x0.6	4	1.3	62.6	303.3
M3b	Manufacture #3	3.2x1.5x0.9	6	1.1	31.3	376.2

Table 7 illustrates that the measured Start-up time is fairly consistent when assessed using the Clock Ready signal.

One might anticipate that a constant amplitude results in constant consumed power. However, as is evident from table 8, consumed power actually increases as ESR and  $C_L$  are increased. In addition, OA decreases as ESR and  $C_L$  are increased. So the net effect is increased consumed power with decreased OA; when non-optimal quartz crystals are used with AGC based SoC’s.

**Table 8 – Oscillation Allowance and Oscillator Current for the AGC-Based Circuits at 32.768 KHz**

XTAL	Part Number	Package	$C_L$	OA	Crystal Drive Current
		mm	pF		nA
A1	ABS07W-32.768KHZ-D-1-T	3.2x1.5x0.9	3	80	199
A2	ABS06W-32.768KHZ-D-2-T	2.0x1.2x0.6	3	96	228
M2a	Manufacture #2	3.2x1.2x0.6	6	28	268
M2b	Manufacture #2	2.0x1.2x0.6	6	18	267
M3a	Manufacture #3	2.0x1.3x0.6	4	33	251
M3b	Manufacture #3	3.2x1.5x0.9	6	44	241

Table 8 clearly outlines the significant advantage Abracon’s low  $C_L$ , ESR Optimized crystals have in designs employing AGC based SoC’s.

## Higher Frequency Crystals: 32 MHz

Higher frequency quartz crystals were also evaluated on the Evaluation board used in this study. Both test circuits include a separate high frequency oscillator in addition to the 32.768 kHz oscillator. The high frequency oscillators use the same clock management as the low frequency (gain selection and AGC). OA, current drain and start-up were evaluated using five 32.00MHz crystals listed in Table 9.

**Table 9 – 32 MHz Crystals**

XTAL	Part Number	Package	$C_L$	$C_o$	ESR
		mm	pF	pF	$\Omega$
A3	ABM11W-32.000MHZ-4-D1X-T3	2.0x1.6x0.5	4	0.8	30.79
A4	ABM11W-32.000MHZ-4-D1X-T3	1.6x1.2x0.4	4	0.5	28.66
M2c	Manufacture #2	1.6x1.2x0.4	8	0.5	25.13
M2d	Manufacture #2	2.0x1.6x0.5 5	8	0.4	28.31
M3c	Manufacture #3	2.0x1.5x0.5	8	0.7	27.39

Table 10 shows the OA, consumed current and start-up time for the gain-settable oscillator with gain set to ”Low”.

**Table 10 – 32 MHz Crystal Results for Gain Settable Oscillator**

XTAL	Part Number	Package	$C_L$	OA	Current	Start-up Time
		mm	pF		nA	ms
A3	ABM11W-32.000MHZ-4-D1X-T3	2.0x1.6x0.5	4	56	51.53	147.9
A4	ABM12W-32.000MHZ-4-D1X-T3	1.6x1.2x0.4	4	64	51.56	188.9
M2c	Manufacture #2	1.6x1.2x0.4	8	47	51.5	459.1
M2d	Manufacture #2	2.0x1.6x0.5 5	8	52	51.53	328
M3c	Manufacture #3	2.0x1.5x0.5	8	23	51.54	194.4

Same crystals were used with AGC-based oscillator circuit to analyze the overall behavior. Results of the AGC engaged oscillator loop are outlined in table 11.

**Table 11 – 32 MHz Crystal Results for AGC-Based Oscillator**

XTAL	Part Number	Package	C <sub>L</sub>	OA	Current	Start-up Time
		mm	pF		nA	ms
A3	ABM11W-32.0000MHZ-4-D1X-T3	2.0x1.6x0.5	4	61	163.6	296.5
A4	ABM12W-32.0000MHZ-4-D1X-T3	1.6x1.2x0.4	4	62	164.9	333.5
M2c	Manufacture #2	1.6x1.2x0.4	8	29	163.6	452.5
M2d	Manufacture #2	2.0x1.6x0.5 5	8	36	163.5	470.5
M3c	Manufacture #3	2.0x1.6x0.5	8	23	163.8	346.5

Consumed Current for the high frequency oscillator loop is consistent from crystal-to-crystal and it is also about ten times higher than the 32.768kHz oscillator loop with-in the same SoC.

## Summary

Understanding how variable gain oscillators employed in modern SoC's will interact with the crystal characteristics is paramount in achieving lowest consumed power, while optimizing both oscillation allowance, as well as, start-up time.

From measured results, Abracon's IoT Optimized 32.00MHz crystals in (2.00x1.60x0.50) mm package, outperforms primary competitors' solution by 69% to 165% for Oscillation Allowance; while achieving quicker start-up by 14% to 37%. Similarly, in the (1.60x1.20x0.4) mm package, Oscillation Allowance is improved by 114%, while start-up time is reduced by 26% - while consuming almost identical total oscillator loop current with the SoC's AGC engaged.

With the Selectable Gain set to "Low", Abracon's 32.00MHz crystal in (2.00x1.60x0.50) mm package, outperforms primary competitors' solution by 24% to 55% for start-up time. Similarly, in the (1.60x1.20x0.4) mm package, the start-up time is improved by 59% over the primary competitor's device.

For 32.768kHz IoT Optimized Crystals, substantial improvement in oscillation allowance, both at room temperature, as well as elevated temperature (85°C) is realized. Abracon's IoT Optimized

(3.2x1.5x0.9) mm crystal consumed 17% to 26% less current, while improving oscillation allowance (OA) from 82% to 186%. Similarly, (2.0x1.2x0.6) mm crystal consumed 9% to 15% lower current, while improving oscillation allowance (OA) by as much as 191% to 433%.

Power optimized solutions whether IoT or wearables can greatly benefit from Abracon's IoT optimized crystals enabling faster start-up, yielding significantly higher Oscillation Allowance, while consuming less power.

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Warren is a professional consultant with 35 years of experience focusing on RF and signal processing. He holds (50) patents in diverse aspects of circuit and system design.