Optimized for Battery Life and Reliability:

Quartz Crystals for IoT and Wearable Devices

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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 System-On-Chips (SoC). 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. Increasing demand is driven by affordable, power-efficient processors and radios. Developers commonly apply super low power SoC radio or processors to support small devices with multi-year battery life. Often, the battery is the dominant factor in a product's cost and size. Battery size is dominated by the standby current and standby current is 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 reliably start up over the range of production variations and temperatures.

Due to the importance of the clock's power efficiency, SoCs 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

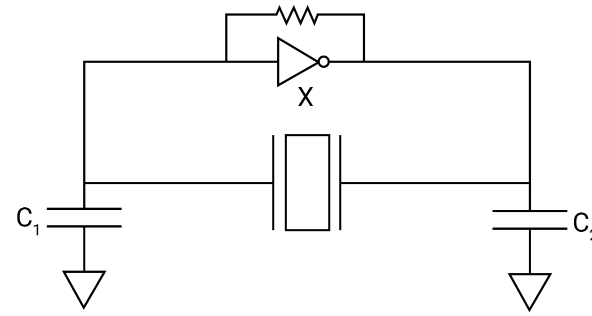
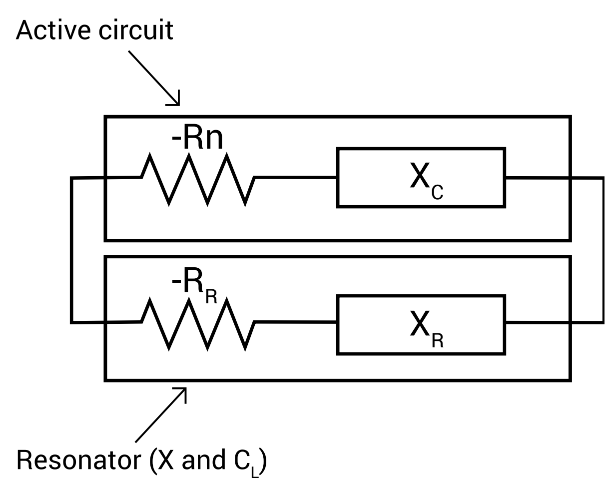


Figure 1 shows the Pierce oscillator configuration used in most SoCs. The oscillator loop consists of an inverting amplifier and feedback resistor (internal to the chip) plus a precision phase shift circuit consisting of a crystal (X) and load capacitors (C_1 and C_2). When the output of the amplifier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

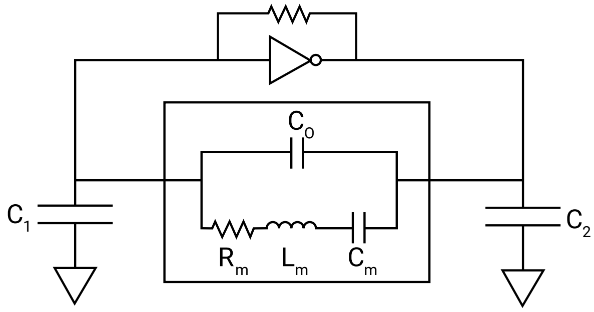
Figure 2 – Negative Resistance Oscillator Model



For further insight, Figure 2 illustrates the oscillator as the combination of negative resistance (R_n), circuit reactance (X_c), resonator reactance (XR) 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 characterize 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 IoT-to-IoT variations at both the crystal level, as well as the SoC.

Figure 4 – Resistor Added for Measuring Oscillation Allowance

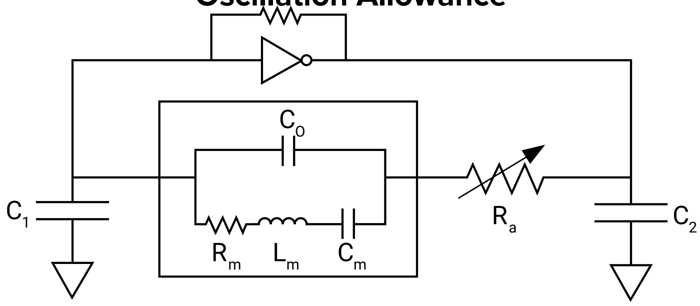


Figure 4 illustrates the practical measurement of OA and provides insight into the usefulness of the term "OA." Here, the oscillation loop includes an added resistor, R_a. OA is measured by increasing R_a until the oscillator will no longer start up. Then OA is calculated as:

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 = 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 increase. This dependency is substantially increased for very low 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 SOCs 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 is 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 dissipation as the current cycles 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 SoCs. 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:

$$\mathrm{OA}\ (G_M) = \frac{gm}{4 \times ESR \times (2\pi F)^2 \times (Co+CL)^2} \quad \text{.....(1)}$$

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

As is evident from equation (1), C_L is generally larger than C0 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 (C0, CL and ESR).

Table 1 –32.768 kHz Crystals Selected for Evaluation

XTAL	Part Number	Package	C_L	C_o	ESR
		mm	pF	pF	KΩ
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	Manufacturer #2	3.2x1.2x0.6	6	1.0	48.5
M2b	Manufacturer #2	2.0x1.2x0.6	6	1.3	59.5
M3a	Manufacturer #3	2.0x1.3x0.6	4	1.3	62.6
M3b	Manufacturer #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

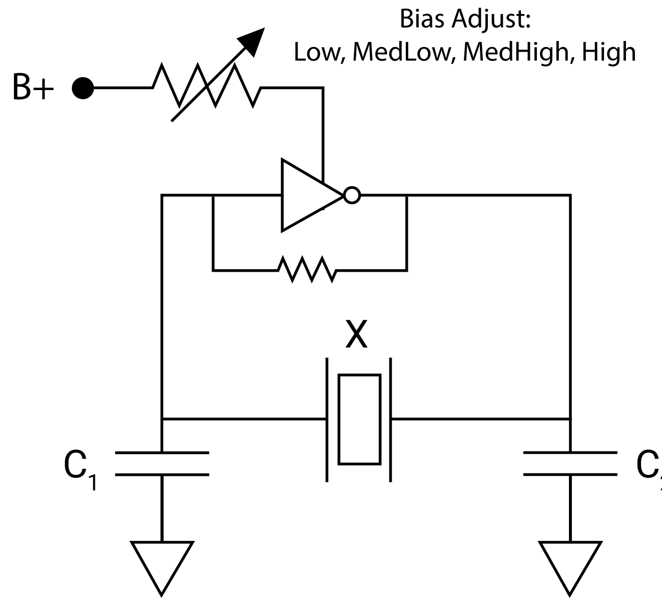
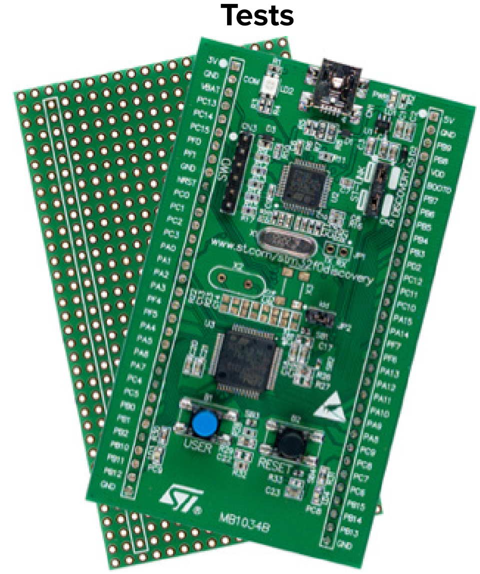


Figure 6 shows a picture of the STM320F discovery evaluation board used in the gain-settable tests. Figure 7 shows a typical start up transient.

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

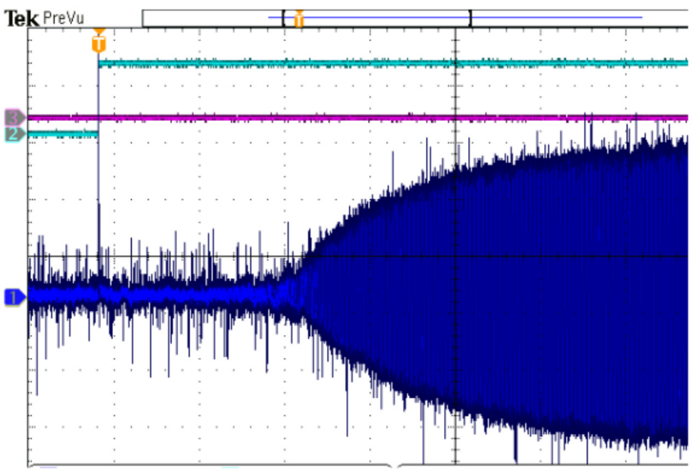


Table 2 – Start up time for 32.768kHz crystals in the gain-settable circuit

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	Manufacturer #2	3.2x1.2x0.6	6	1.0	48.5	186
M2b	Manufacturer #2	2.0x1.2x0.6	6	1.3	59.5	151
M3a	Manufacturer #3	2.0x1.3x0.6	4	1.3	62.6	143
M3b	Manufacturer #3	3.2x1.5x0.9	6	1.1	31.3	192

Table 2 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	Manufacturer #2	3.2x1.2x0.6	6	24	508
M2b	Manufacturer #2	2.0x1.2x0.6	6	6.5	457
M3a	Manufacturer #3	2.0x1.3x0.6	4	19	485
M3b	Manufacturer #3	3.2x1.5x0.9	6	15	496

The data shows that the oscillators based on Abracon's low CL 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 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	Manufacturer #2	Low	6.5	457
M2b	Manufacturer #2	Medium Low	13	637
M2b	Manufacturer #2	Medium High	22	679
M2b	Manufacturer #2	High	23	757

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

Abracon Crystals at High Temperature

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

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

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

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

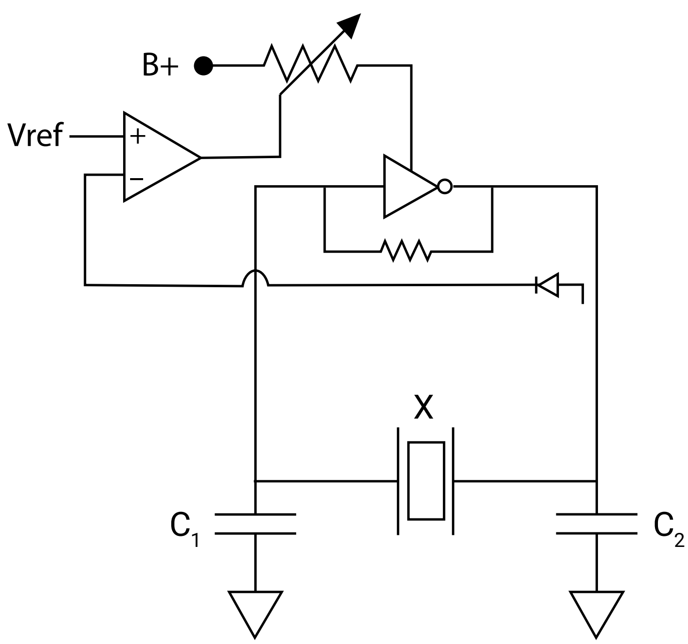
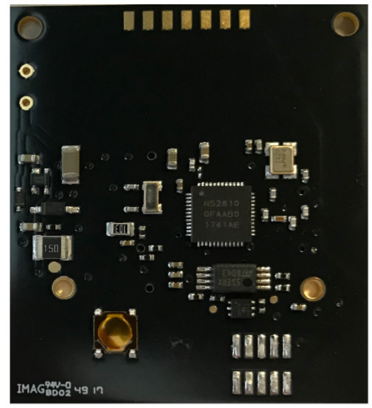


Figure 9 shows the custom circuit board with Nordic N52810 Bluetooth chip used in the AGC-based oscillator tests.

Figure 9 – Circuit Board Used in AGC-Based Oscillator



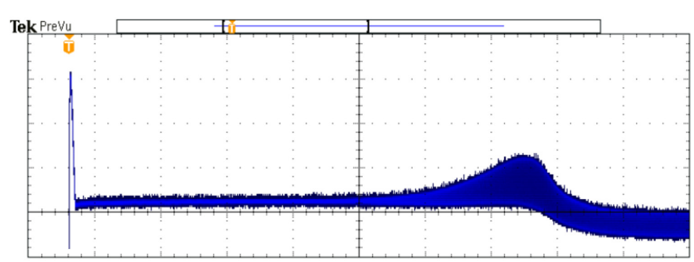
The AGC-based oscillator adjusts the bias of the amplifier according to the oscillation amplitude. As such, it can be expected that lower-loss crystals (lower C_L and ESR) will require less current and also have higher OA. The data in Table 6 substantiates this assumption.

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	kΩ	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	Manufacturer #2	3.2x1.2x0.6	6	1.0	48.5	356.7
M2b	Manufacturer #2	2.0x1.2x0.6	6	1.3	59.5	317.2
M3a	Manufacturer #3	2.0x1.3x0.6	4	1.3	62.6	303.3
M3b	Manufacturer #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 increase. In addition, OA decreases as ESR and C_L increase. So the net effect is increased consumed power with decreased OA when non-optimal quartz crystals are used with AGC-based SoCs.

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	Manufacturer #2	3.2x1.2x0.6	6	28	268
M2b	Manufacturer #2	2.0x1.2x0.6	6	18	267
M3a	Manufacturer #3	2.0x1.3x0.6	4	33	251
M3b	Manufacturer #3	3.2x1.5x0.9	6	44	241

Table 8 clearly outlines the significant advantage that Abracon's low C_L, ESR optimized crystals have in designs employing AGC-based SoCs.

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 the 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	Ω
A3	ABM11W-32.0000MHZ-4-D1X-T3	2.0x1.6x0.5	4	0.8	30.79
A4	ABM11W-32.0000MHZ-4-D1X-T3	1.6x1.2x0.4	4	0.5	28.66
M2c	Manufacturer #2	1.6x1.2x0.4	8	0.5	25.13
M2d	Manufacturer #2	2.0x1.6x0.5	8	0.4	28.31
M3c	Manufacturer #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-32.0000MHZ-4-D1X-T3	2.0x1.6x0.5	4	56	51.53	147.9
A4	ABM12W-32.0000MHZ-4-D1X-T3	1.6x1.2x0.4	4	64	51.56	188.9
M2c	Manufacturer #2	1.6x1.2x0.4	8	47	51.5	459.1
M2d	Manufacturer #2	2.0x1.6x0.5	8	52	51.53	328
M3c	Manufacturer #3	2.0x1.5x0.5	8	23	51.54	194.4

The 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_L	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	Manufacturer #2	1.6x1.2x0.4	8	29	163.6	452.5
M2d	Manufacturer #2	2.0x1.6x0.5 5	8	36	163.5	470.5
M3c	Manufacturer #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 SoCs will interact with the crystal characteristics is paramount in achieving lowest consumed power, while optimizing both oscillation allowance and start up time.

From measured results, Abracon's IoT Optimized 32.00MHz crystals in 2.00 x 1.60 x 0.50mm package, outperforms primary competitors' solution by 69% to 165% for Oscillation Allowance; while achieving quicker start up by 14% to 37%. Similarly, in the 1.60 x 1.20 x 0.4mm 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 SoCs AGC engaged.

With the selectable gain set to "Low", Abracon's 32.00MHz crystal in 2.00 x 1.60 x 0.50mm package, outperforms primary competitors' solution by 24% to 55% for start up time. Similarly, in the 1.60 x 1.20 x 0.4mm 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 3.2 x 1.5 x 0.9mm crystal consumed 17% to 26% less current, while improving oscillation allowance (OA) from 82% to 186%. Similarly, the 2.0 x 1.2 x 0.6mm 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.