AN1335: RS9116 and SiWx917 Crystal Selection Guide

Version 1.2
August 7, 2023

Table of Contents

1 Crystal Selection Guide

This Application Note provides guidelines for selecting the 40 MHz crystal oscillator needed for RS9116 and SiWx917-based designs. It also contains information on how to select the 32 kHz external clock for SiWx917 devices. This Application Note does not provide details about the external 32 kHz clock of RS9116. Check the RS9116 Data Sheet for more information.

These devices contain a 40 MHz crystal oscillator. Topics covered here include oscillator theory and some recommended crystals for these devices.

This document supports RS9116 devices, including QMS and WMS packages.

2 Oscillator Theory

2.1 What is an Oscillator?

An oscillator is an electronic circuit that generates a repetitive or periodic time-varying signal. In the context of RS9116 and SiWx917 devices, this oscillator signal is used to clock the execution of instructions and peripherals in the device. The oscillator also provides an accurate and low noise frequency reference to the transceiver for radio communication. There are multiple ways of generating such a signal, each with different properties that influence project cost, board size, and stability of the clock signal.

2.1.1 RC Oscillators

RC oscillators are built from resistors, capacitors, and an inverting amplifier. They come at a low cost and have a shorter startup time than the crystal oscillator but are generally less accurate and produce more noise. The ICs provide multiple internal RC oscillators, including one high-frequency RC oscillator and one low-frequency RC oscillator. While the internal RC oscillators can ensure proper operation of the device, they are inadequate for applications such as radio communication.

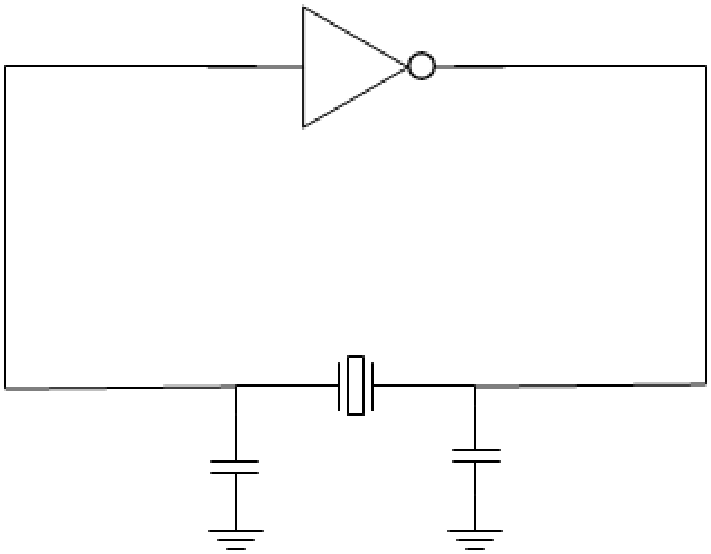
2.1.2 Crystal Oscillators

Crystal oscillators use the mechanical vibration of a crystal to generate the clock signal. Due to the molecular composition of the crystal matter and the angle at which the crystal is cut, this type of oscillator is very precise and stable over a wide temperature range. The most used crystal is the quartz crystal. Producing quartz crystals requires very stable temperature and pressure conditions over a few weeks. This makes crystal oscillators more expensive than RC oscillators.

2.1.3 Piezoelectricity

Quartz crystals hold the direct piezoelectric property. This means an applied electric field will cause the crystal to deform. Conversely, a deformation of the crystal will cause a voltage across the terminals. Once the oscillator has started, the changing voltage on the terminals of the vibrating crystal is used as the clock signal.

2.2 Basic Principle of Oscillators



The principle behind the oscillator is a positive feedback loop satisfying the Barkhausen condition: If the closed-loop gain is larger than unity and the total phase lag is 360°, the resulting closed-loop system is unstable and will self-reinforce. This is a necessary but not a sufficient condition for oscillations to be present. When the necessary conditions are met, any disturbance (noise) in the oscillator will cause oscillations to start. The frequency that fulfills the Barkhausen condition is amplified the most because it is in phase with the original signal.

The initial oscillations are very weak, and amplifying the signal to the desired magnitude takes time. When oscillations are established, only a small amount of energy is needed to compensate for losses in the circuit. Mathematically, a closed-loop gain of one is required to maintain steady-state oscillations. The IC relies on an adjustable current source controlled by an automatic gain controller to achieve and maintain the desired amplitude.

The figure above shows that the oscillator circuitry consists of two parts: an amplification stage and a filter that decides which frequency experiences a 360° phase lag. In the case of a crystal oscillator, the filter consists of the crystal and external load capacitors.

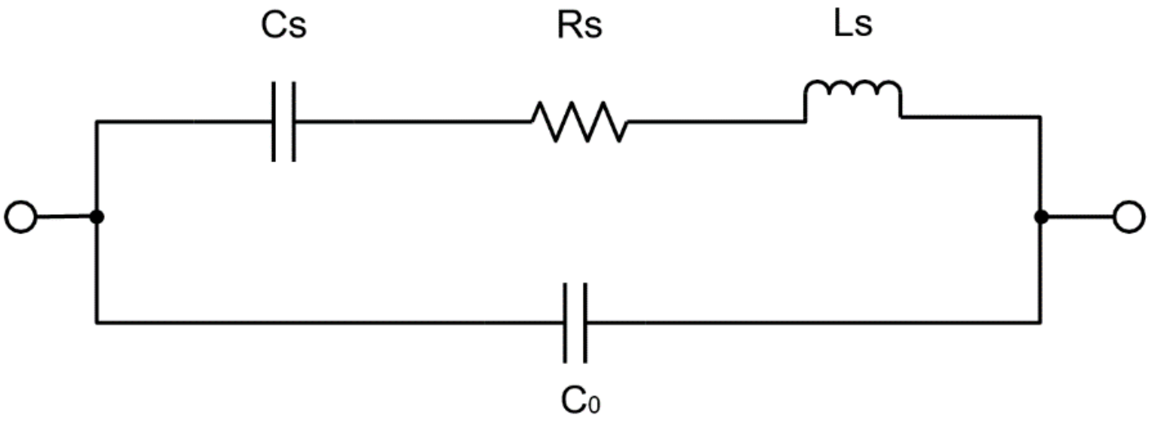
2.2.1 Startup Time

The magnitude of the closed-loop gain significantly influences the startup time. Low gain can cause excessively long startup time or failure; too high gain can also make the startup fail altogether. The ideal gain depends on the oscillator circuit's negative resistance, which is defined in the Negative Resistance in the Crystal Parameters section.

For the same reason, the oscillation frequency influences the startup time. A crystal in the kHz range would have a considerably longer startup time than a crystal in the MHz range because it takes longer to circulate the loop. Typical startup times for these devices are 300-600 µs.

2.2.2 Modeling the Crystal

The electrical equivalent circuit can describe the crystal as shown in the figure below.



- C_s is the motional capacitance. It represents the piezoelectric charge gained from a displacement in the crystal.
- Rs is the motional resistance. It represents the mechanical losses in the crystal.
- Ls is the motional inductance. It represents the moving mass in the crystal.
- C_0 is the shunt capacitance between the electrodes and stray capacitance from the casing.

For low frequencies, the electrical equivalent circuit will exhibit capacitive behavior. The presence of the inductor becomes more noticeable as the frequency increases, and thus the reactance increases. Ignoring the shunt capacitance C_0, the series resonant frequency is defined where the reactance of the inductor and capacitor cancels. At this frequency the crystal appears only resistive with no shift in phase. The series resonance frequency, f_S, therefore, determines the relationship between C_S and L_S. This can be calculated with the equation below. The series resonance frequency is the natural resonance frequency where the energy transformation between mechanical and electrical energy is most effective.

$$f_S = \frac{1}{\left(2 \times \pi \times (L_S \times C_S)^{\frac{1}{2}}\right)}$$

At higher frequencies, the equivalent circuit will appear inductive, which implies higher impedance. When the inductive reactance from the crystal cancels the capacitive reactance from shunt capacitance C_0, another resonance frequency with zero phase shift exists. This frequency is called the anti-resonant frequency, f_A. At this frequency, the impedance is 0.

$$f_A = \frac{1}{\left(2 \times \pi \times \left(L_S \times \frac{C_S \times C_0}{C_S + C_0}\right)^{\frac{1}{2}}\right)}$$

The range of frequencies between f_S and f_A is called the area of parallel resonance and is where the crystal will normally oscillate. At the resonant frequency, the phase lag in the feedback loop is provided by an amplifier with a 180° phase lag and two capacitors with a combined 180° phase lag. In practice, the amplifier provides a little more than 180° phase shift, which means the crystal must appear slightly inductive to fulfill the Barkhausen criterion.

2.2.3 Series and Parallel Resonant Crystals

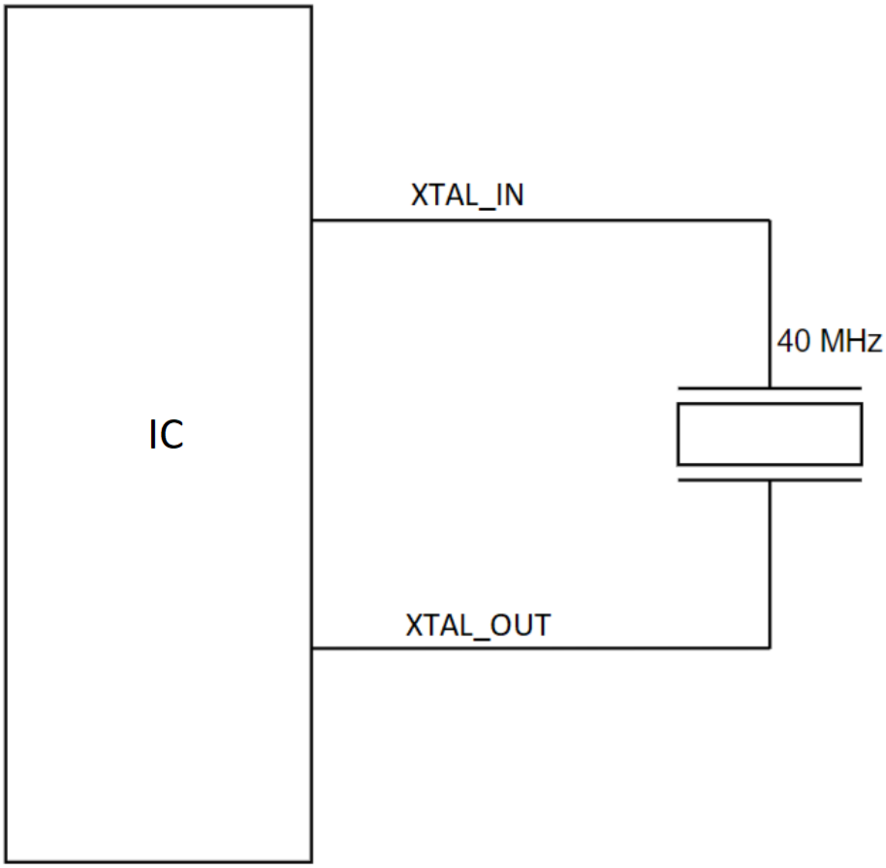
Physically, there is no difference between series and parallel resonant crystals. Series resonant crystals are specified to oscillate at the series resonant frequency where the crystal appears with no reactance. Because of this, no external capacitance should be present as this would lower the oscillating frequency to below the natural resonance frequency. These crystals are intended for use in circuits without external capacitors where the oscillator circuit provides a 360° phase shift.

Parallel resonant crystals require a capacitive load to oscillate at the specified frequency, which is the resonance mode required for most oscillators. On the ICs in question, the load capacitors are located on-chip, and their values can be controlled by firmware. Thus, they do not require external load capacitors, reducing BOM cost and saving PCB space. The exact oscillation frequency for a parallel resonant crystal can be calculated with the equation below, where CL is the load capacitance seen by the crystal. CL is, therefore, an important design parameter and is given in the data sheet for parallel resonant crystals.

$$f_P = f_S \left(1 + \frac{C_S}{(2 \times C_L)}\right)$$

3 40 MHz Crystal Oscillator Wiring

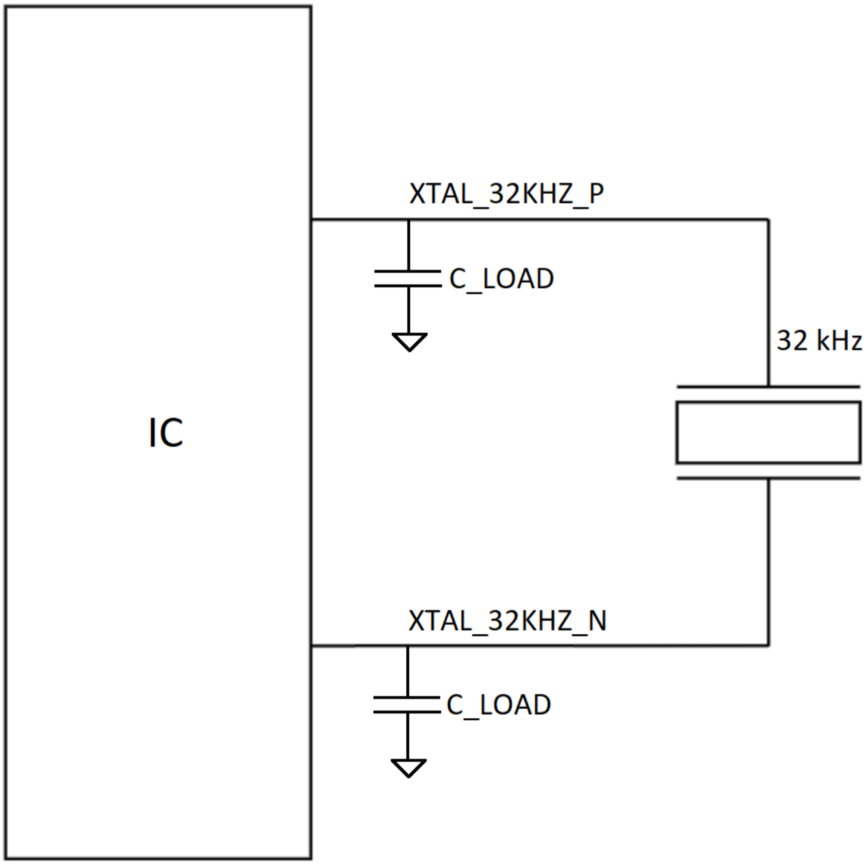
The ICs have a 40 MHz internal oscillator mode that can be used by connecting a 40 MHz crystal between the pins XTAL_IN and XTAL_OUT. They have integrated crystal load capacitors, eliminating the need for external components. Load capacitance must be calibrated and stored in eFuse using calibration software. Refer to AN1336 for the calibration procedure. The figure below shows the connections.



4 SiWx917 32 kHz Clock Wiring

The device has dedicated pins for the external 32 kHz crystal: XTAL_32KHZ_P and XTAL_32KHZ_N. The load capacitors on both pins must be fine-tuned based on layout design.

When an oscillator is used, the UULP_VBAT_GPIO port can be used as an input for the clock signal. Check the SiWx917 data sheet for more information.



5 Crystal Parameters

5.1 Quality Factor

The quality factor Q is a measure of the efficiency or the relative storage of energy to the dissipation of energy in the crystal. The equation below states the relation between R, C, and Q for the electrical-equivalent circuit. In practice, crystals with higher Q-values are more accurate but have a smaller bandwidth for which they oscillate. Therefore, high Q-factor crystals will start slower than crystals with higher frequency tolerance.

$$Q = \frac{X_{LS}}{R_S} = \frac{1}{(X_{CS} \times R_S)} = \frac{1}{(2 \times \pi \times f \times C_S \times R_S)} = \frac{2 \times \pi \times f \times L_S}{R_S}$$

X_{LS} and X_{CS} are the reactance of L_S and C_S, respectively, at the operating frequency of the crystal.

5.2 Load Capacitance

As seen in the equation below, the two capacitors, C_{L1} and C_{L2}, provide a capacitive load for the crystal. The effective load capacitance C_L, as seen from the XTAL_IN and XTAL_OUT pins on the ICs, is the series combination of C_{L1} and C_{L2} through the ground.

$$C_L = \frac{C_{L1} \times C_{L2}}{C_{L1} + C_{L2}} + C_{stray}$$

Where: C_{stray} is the pin capacitance of the microcontroller and any parasitic capacitance and can often be assumed in the range of 2-5 pF.

The right choice of C_L is important for proper operating frequency. Crystals with small load capacitance would typically start faster than crystals requiring a large C_L. Large load capacitors also increase power consumption. Using a crystal with CL is recommended as specified in the Recommended Crystal section.

Note**:** The ICs have internal loading capacitors and do not need external capacitors connected to the crystal. See the device data sheet or reference manual for more information.

5.3 Equivalent Series Resistance

The Equivalent Series Resistance is the resistance in the crystal during oscillation and varies with the resonance frequency. ESR, given by the equation below, will typically decrease with increasing oscillation frequency.

$$ESR = R_S \left(1 + \frac{C_0}{C_L}\right)^2$$

The 40 MHz XO in these ICs cannot guarantee the startup of crystals with ESR larger than a certain limit. Please refer to the device data sheet for further details. The smaller the ESR, compared to this maximum value, the better the gain margin for the crystal startup, which in turn reduces the startup time. Additionally, a small ESR value gives lower power consumption during oscillation.

Note that HF crystals have an ESR of a few tens of Ohms compared to the LF crystals, with ESR values normally measured in kΩ. Therefore, a few Ohms of series resistance have more influence on the startup margin in the MHz range as compared to the kHz range.

5.4 Drive Level

Drive level is a measure of the power dissipated in the crystal. The crystal manufacturer should specify the maximum power dissipation value tolerated by the crystal in the crystal data sheet. Exceeding this value can damage the crystal.

$$DL = ESR \times I^2$$

Here, I is the RMS current flowing through the crystal.

5.5 Minimum Negative Resistance

A critical condition for oscillations to build up requires the energy supplied to exceed the energy dissipated in the circuit. In other words, the negative resistance of the amplifier has to exceed the equivalent series resistance in the crystal. An approximate formula for negative resistance is given in the equation below.

$$R_{neg} = \frac{-g_m}{((2 \times \pi \times f)^2 \times C_{L1} \times C_{L2})}$$

Where: g_m is the transconductance of the oscillator circuitry.

To ensure safe operation of overall voltage and temperature variations, ensure that the ESR does not exceed the device data sheet maximum. This maximum value corresponds to the oscillator circuit's realizable negative resistance.

If the crystal's ESR does not satisfy this criterion, another crystal with a lower ESR should be chosen. The equation above shows an approximate formula for this calculation, excluding shunt capacitance and internal loss.

5.6 Frequency Stability

Frequency stability is the maximum frequency deviation from the specified oscillating frequency over the given operating temperature range.

5.7 Frequency Tolerance

Frequency tolerance is the maximum frequency deviation from the specified oscillating frequency at 25 °C. This parameter gives an indication of variations between individual crystals.

6 40 MHz Recommended Crystals

Below are the 40 MHz crystal specifications required for usage with RS9116 and SiWx917. The product designer must ensure these are followed; otherwise, the crystal oscillator circuitry will not have stable operation and can lead to inoperative crystal oscillator circuitry.

Parameter	Parameter Description	Min	Typ	Max	Units
Fosc	Oscillator Frequency		40		MHz
Mode	Mode of operation	Fundamental			
Resonance	Series or Parallel resonance	Parallel			
Drive	Drive level	100			uW
Fosc_Acc	Frequency Variation with Temp and Voltage	-20		20	ppm*
ESR	Equivalent series resistance			60	Ω
Load cap	Load capacitance range	7		10	pF

* **NOTE**: The Wi-Fi standard requires the transmit frequency to be within 20 ppm of the specified value. The crystal frequency is the reference for this, and the crystal may show a variation due to its manufacturing process, voltage, and temperature. In addition, crystal frequency also changes over time due to aging. To ensure that the transmit frequency would be within +/- 20 ppm over the device's lifetime, the frequency must be trimmed/calibrated during manufacture to provide sufficient margin to account for the drift. For example, if the frequency variation due to the process is 4 ppm, then the variation due to voltage, temperature, and aging must be less than 16 ppm.

The table below lists some of the crystals that have been used along with RS9116 and SiWx917 and tested. The designer must pick a crystal that satisfies their size, tolerance, and temperature range requirements.

Manufacturer	TXC	Epson	Transko
Frequency	40 MHz	40 MHz	40 MHz
Part Number	8Y40070013	FA-20H 40.0000MF10Z-K3	CS22-F1020CQ08-40.000M-TR
CL (pF)	8	10	8
ESR max (Ω)	30	40	60
Frequency Tolerance (PPM)	±8	±10	±10
Frequency Stability (PPM)	±16	±10	±20
Drive Level (µW) Maximum	200	200	300
Operating Temp (deg C)	-40C to +105C	-20C to +75C	-40C to +85C

7 32 kHz Recommended Crystals

Below are the specifications of the 32 kHz crystal or oscillator that can be used with the SiWx917.

Parameter	Parameter Description	Min	Typ	Max	Units
F_{OSC}	Oscillator Frequency		32.768		kHz
Mode	Mode of operation	Fundamental			
Resonance	Series or Parallel resonance	Parallel			
Drive	Drive level	0.5			µW
F_{OSC_ACC}	Frequency Stability*		±250		ppm
ESR	Equivalent series resistance			80	kΩ
Load cap	Load capacitance range	4		12.5	pF
* Combined frequency offset must be below this limit, with temperature induced changes, tolerance, and the variance of load capacitances (load capacitor and parasitic trace impedance).					

32.768 kHz Crystal Specifications

Parameter	Parameter Description	Min	Typ	Max	Units
F_{OSC}	Oscillator Frequency		32.768		kHz
F_{OSC_ACC}	Frequency Variation with Temp and Voltage	-100		100	ppm
Duty cycle	Input duty cycle	30	50	70	%
V_{AC}	Input AC peak-peak voltage swing at the input pin	-0.3	-	VBATT +/- 10%	Vpp

32.768 kHz External Oscillator Specifications

The following tables contain the recommended 32 kHz crystals or oscillators for the SiWx917. These devices were tested and verified. It is recommended to use a crystal rather than an external oscillator.

Manufacturer	EPSON	Micro Crystal
Frequency	32.768 kHz	32.768 kHz
Part Number	MC-146 32.768KA-AC3:ROHS	CM8V-T1A-32.768KHZ-7PF-20PPM-TA-QC
CL (pF)	9	7
ESR max (Ω)	65	70
Frequency Tolerance (PPM)	20	20
Drive Level (µW) Maximum	1	0.5
Frequency vs. Temperature (ppm/degC^2)	-0.04	-0.035
Operating Temp (deg C)	-40 C° to +85 C°	-40 C° to +85 C°

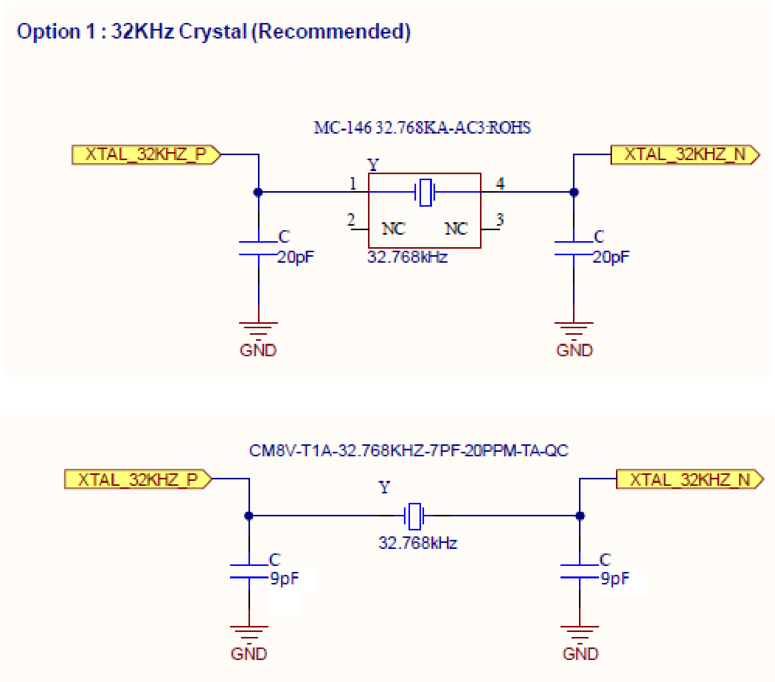
32.768 kHz Crystal Recommendations

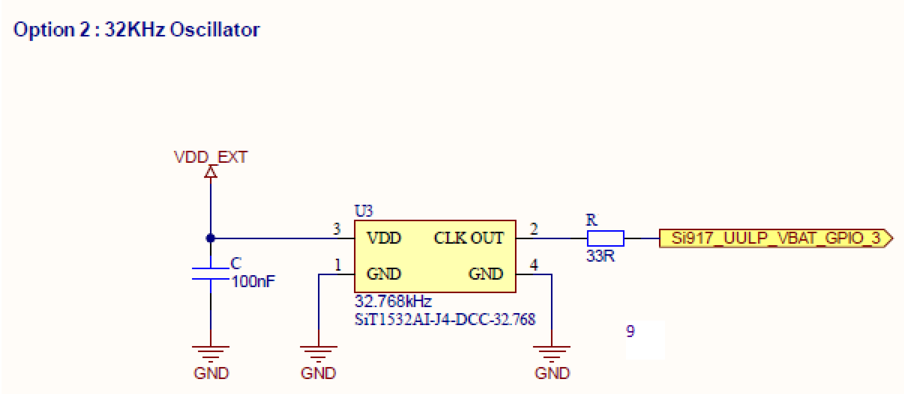
Manufacturer	SiTime			
Part Number	SiT1532AI-J4-DCC-32.768			
	Min	**Typ**	**Max**	**Units**
Frequency Stability (ppm)	-50	-	50	ppm
Input duty cycle(%)	48	-	52	%
Input AC peak-peak voltage swing at the input pin	0.2	-	0.8	Vpp

32.768 kHz External Oscillator Recommendations

The schematic below shows the basic connections for the recommended reference clocks.

Note: One of the three choices on the schematic should be implemented in a design.





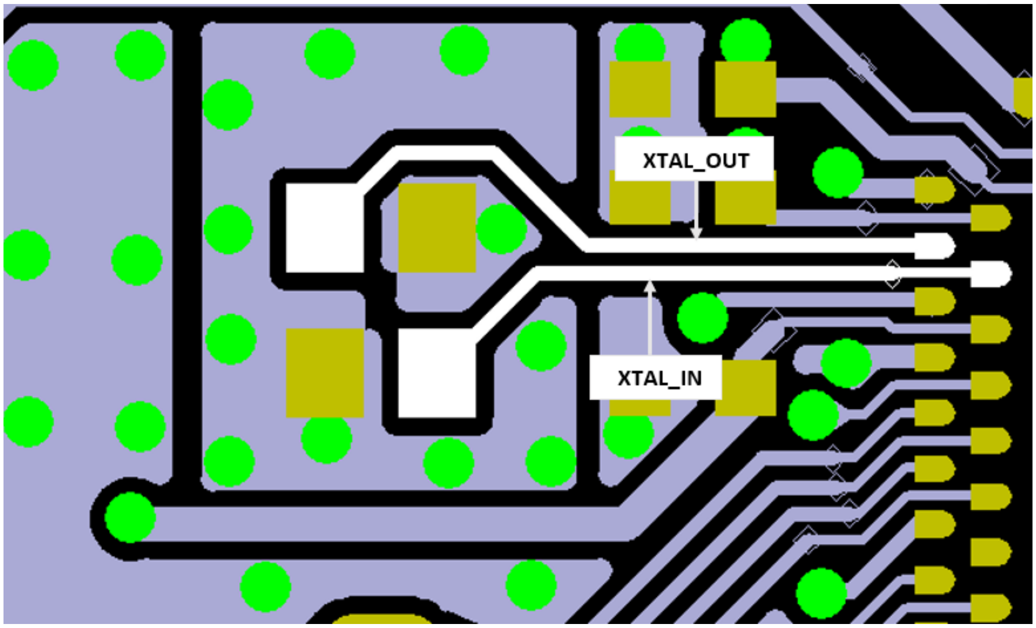
Recommended Connections for 32 kHz Clocks

8 PCB Layout Guidelines

The product designer must follow the guidelines below for the 40 MHz clock during PCB placement and routing:

1. Since the total load capacitance is the summation of PCB trace capacitance and pin capacitance at the XTAL_IN and XTAL_OUT pins, it is recommended that the crystal be placed as close to the SoC as possible to minimize parasitic capacitance.
2. Minimize trace lengths to less than 8 mm.
3. Clocks and frequently switched signals should not be routed close to the crystal.
4. Crystal traces should be protected with ground traces and guard rings.
5. Do not cross the crystal signals with any other signal on any layer.
6. Guard rings should not be connected to other ground connections on the PCB on the Top layer.
7. When two-layer PCBs are used, digital signals should not be routed on the opposite side of the PCB directly under the crystal.
8. It is recommended to fill the opposite side of the PCB under the crystal with a clean ground plane.

The image below provides one of the examples, but the designer must find ways of improving the layout compared to the routed crystal below.

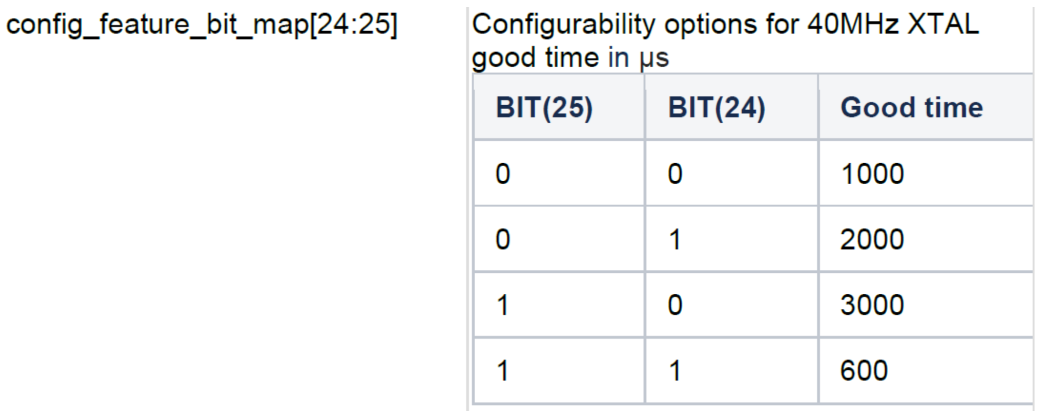


9 Testing

Product testing can begin once the 40 MHz crystal has been identified, and samples are obtained. The product should be tested at applicable temperatures (40C, +25C, +85C) and supply voltage ranges. Also, multiple product samples may need to be tested. Ensure the crystal oscillator circuitry starts and maintains oscillation during the active period of the device. The user must ensure sufficient operating margins before finalizing the circuit.

For measuring the PPM of the crystal circuitry, the designer must essentially measure RF frequency. PPM can be calculated based on the expected and measured RF frequency values. PPM variation must be measured at various RF frequencies - at least min, mid, and max frequency values.

There is an option to configure the Crystal Good time in the software command 'Opermode.' This command is in Config Feature Bitmap[24:25], as shown below. The default is 1000us. The current version of the Programming Reference Manual would have the latest information on configuring the parameters of the internal crystal oscillator. Crystal Good time must be programmed to start up and maintain oscillations within this time. Ensure a sufficient margin of at least 200us between the programmed Crystal Good time value and the measured Startup time. If the margin is much higher, then the power consumption can be higher because the MCU will be idle and wasting power until the programmed Good time is completed. So, consider both the measured Startup time and Power consumption to program a suitable Crystal Good time value.



config_feature_bit_map[24:25]

Configurability options for 40MHz XTAL good time in µs

BIT(25)	BIT(24)	Good time
0	0	1000
0	1	2000
1	0	3000
1	1	600

Below are the guidelines for measuring the Startup time of the Crystal oscillator circuit. Ensure the Startup time is 600us (max) across all testing conditions.

1. Use an active probe with a capacitance of not more than 1 pF.
2. Connect the probe between the XTAL_IN and GND pins.
3. Run one of the applications for starting the RS9116's crystal oscillator circuitry. For example, run the BLE advertising program.
4. Set trigger on XTAL_IN at around 300 mV.
5. Change the time scale of the oscilloscope so that it can capture ~1 ms duration after the trigger.
6. The point at which XTAL_IN voltage amplitude abruptly settles indicates that the fast startup circuit is turned off and the XTAL clock is available (XTAL_VALID point).
7. Measure the time interval between the first rise in XTAL_IN voltage and the point where the oscillations are stable. This point is referred to as XTAL_VALID (Here it is ~300 us).
8. Make sure that the oscillation doesn't collapse after the XTAL_VALID point.
9. Measure the peak-to-peak amplitude of oscillation once it is settled.

Results: Markers

Marker	Horizontal	Vertical	ΔX	1/ΔX	ΔY	ΔY/ΔX	Delta To
M1	-15.5400 µs	---------------		---		---	--
M2	284.160 µs	---------------	299.700000 µs	3.3366700 kHz		---	1

The image above shows the voltage at the XTAL_IN pin while the crystal oscillator is starting up, captured in the oscilloscope. In this case, the time taken for the amplitude to cross the threshold is ~ 300 us from when the oscillator is enabled (time between vertical markers M1 and M2). Once the amplitude threshold is crossed (vertical marker M2), the fast startup circuit is disabled, and the voltage amplitude at XTAL_IN stabilizes.

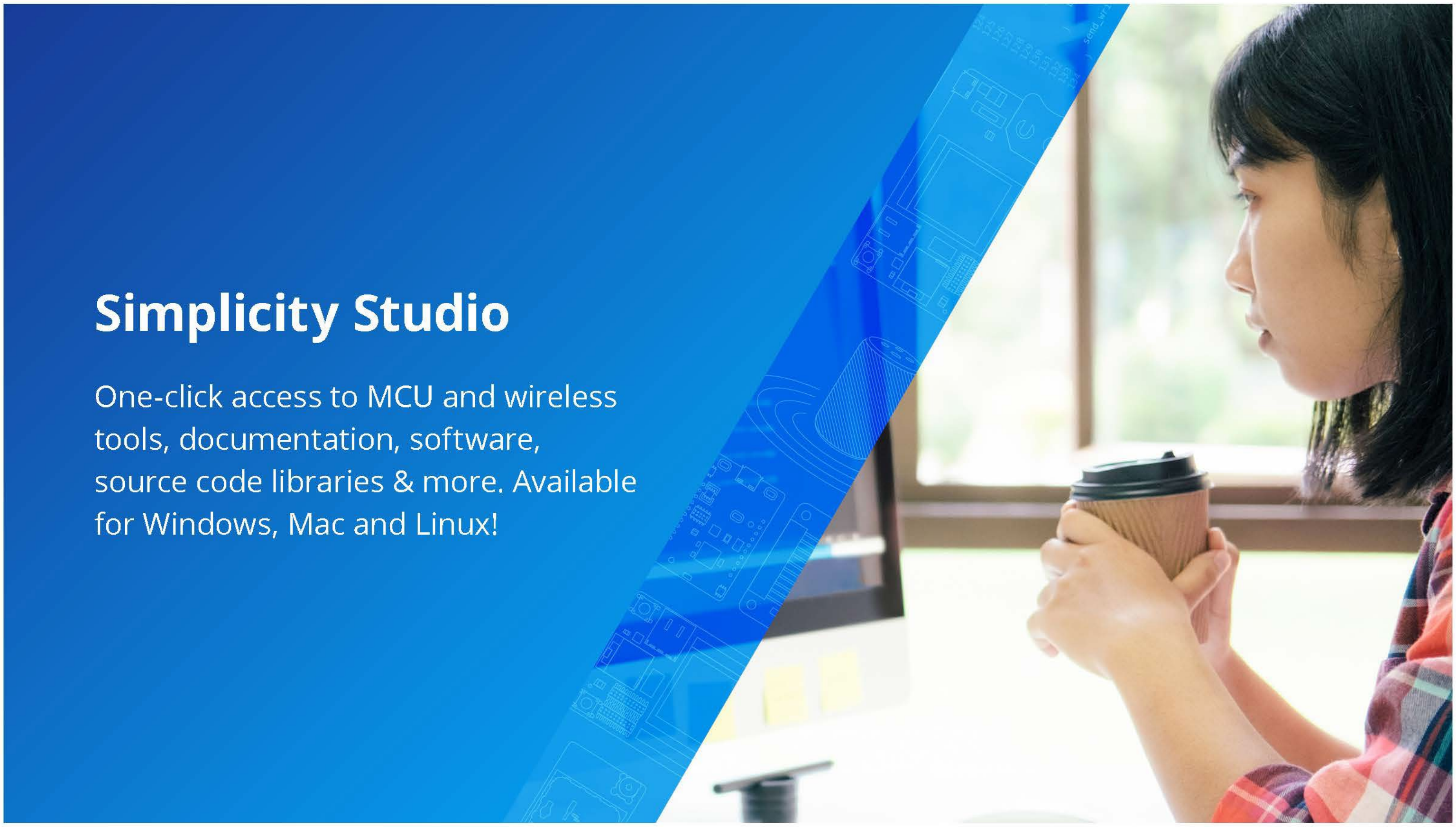
10 Soldering Guidelines

In general, soldering is a sensitive process, especially for low-frequency crystals. To reduce the impact of such a process on the crystal parameters, the user should consider the guidelines below. The user may also check guidelines from the crystal manufacturer and follow the same.

- Exposing crystals to temperatures above their maximum ratings can damage the crystal and affect their ESR value. Refer to the crystal datasheet for the right reflow temperature curve (if not provided, ask the manufacturer).
- PCB cleaning is recommended to obtain maximum performance by removing flux residuals from the board after assembly (even when using "no-clean” products in ultra-low-power applications).

11 Summary

There is much to learn about crystals and crystal oscillators; however, this Application Note can only cover the basics of crystals and crystal oscillators to assist the product design engineer in selecting and using a crystal for the RS9116 or SiWx917 device. The reader is encouraged to study more in-depth about the design and operation of crystal oscillators because they are such an important component in electronic designs today. The product design engineer should also consult with the crystal manufacturer about their product design needs.



Simplicity Studio

One-click access to MCU and wireless tools, documentation, software, source code libraries & more. Available for Windows, Mac and Linux!

IoT Portfolio
www.silabs.com/IoT

SW/HW
www.silabs.com/simplicity

Quality
www.silabs.com/quality

Support & Community
www.silabs.com/community

Disclaimer
Silicon Labs intends to provide customers with the latest, accurate, and in-depth documentation of all peripherals and modules available for system and software implementers using or intending to use the Silicon Labs products. Characterization data, available modules and peripherals, memory sizes and memory addresses refer to each specific device, and "Typical" parameters provided can and do vary in different applications. Application examples described herein are for illustrative purposes only. Silicon Labs reserves the right to make changes without further notice to the product information, specifications, and descriptions herein, and does not give warranties as to the accuracy or completeness of the included information. Without prior notification, Silicon Labs may update product firmware during the manufacturing process for security or reliability reasons. Such changes will not alter the specifications or the performance of the product. Silicon Labs shall have no liability for the consequences of use of the information supplied in this document. This document does not imply or expressly grant any license to design or fabricate any integrated circuits. The products are not designed or authorized to be used within any FDA Class III devices, applications for which FDA premarket approval is required or Life Support Systems without the specific written consent of Silicon Labs. A "Life Support System" is any product or system intended to support or sustain life and/or health, which, if it fails, can be reasonably expected to result in significant personal injury or death. Silicon Labs products are not designed or authorized for military applications. Silicon Labs products shall under no circumstances be used in weapons of mass destruction including (but not limited to) nuclear, biological or chemical weapons, or missiles capable of delivering such weapons. Silicon Labs disclaims all express and implied warranties and shall not be responsible or liable for any injuries or damages related to use of a Silicon Labs product in such unauthorized applications. **Note: This content may contain offensive terminology that is now obsolete. Silicon Labs is replacing these terms with inclusive language wherever possible. For more information, visit www.silabs.com/about-us/inclusive-lexicon-project**

Trademark Information
Silicon Laboratories Inc.®, Silicon Laboratories®, Silicon Labs®, SiLabs® and the Silicon Labs logo®, Bluegiga®, Bluegiga Logo®, Clockbuilder®, CMEMS®, DSPLL®, EFM®, EFM32®, EFR, Ember®, Energy Micro, Energy Micro logo and combinations thereof, "the world's most energy friendly microcontrollers", Ember®, EZLink®, EZRadio®, EZRadioPRO®, Gecko®, Gecko OS, Gecko OS Studio, ISOmodem®, Precision32®, ProSLIC®, Simplicity Studio®, SiPHY®, Telegesis, the Telegesis Logo®, USBXpress®, Zentri, the Zentri logo and Zentri DMS, Z-Wave®, and others are trademarks or registered trademarks of Silicon Labs. ARM, CORTEX, Cortex-M3 and THUMB are trademarks or registered trademarks of ARM Holdings. Keil is a registered trademark of ARM Limited. Wi-Fi is a registered trademark of the Wi-Fi Alliance. All other products or brand names mentioned herein are trademarks of their respective holders.

Silicon Laboratories Inc.
400 West Cesar Chavez
Austin, TX 78701
USA

www.silabs.com