ISL12022 RTC Accuracy Optimization Calibration Procedure

Application Note | May 6, 2008 | AN1400.0

Introduction

Real Time Clock (RTC) devices contain an oscillator and normally require a crystal to operate with the required accuracy. Most commonly used 32.768kHz crystal oscillators have a frequency tolerance of ±20ppm at +25°C, and a nonlinear parabolic temperature drift “Alpha” of -0.034ppm/°C^2. Alpha is parabolic in nature, worsening as the crystal temperature deviates from the turnover temperature, referred to as T0 of the crystal, commonly +25°C.

Following is an example showing the effect of frequency tolerance and Alpha on the accuracy of an RTC.

A crystal oscillator has a frequency error of -15ppm at +25°C and an Alpha of -0.034ppm/°C^2. At +40°C, the crystal will have a total of -22.7ppm drift (-15ppm + [-0.034ppm/°C^2*(40°C - 25°C)^2]). A -22.7ppm drift in one second means 22.7µs slower in a second, which seems very small at the beginning but it accumulates to many minutes in a year. A -22.7ppm drift in a second means losing 2 seconds in a day, 14 seconds in a week, 59 seconds in a month, 716 seconds or 11.9 minutes in a year. It is a problem one would have to live with if using an ordinary RTC on the market but now the problem is solved by using the ISL12022 RTC with embedded temperature compensation function. This application note describes a simple trimming procedure, which optimizes the accuracy of an ISL12022 RTC and presents data for a variety of crystals with calibrated versus uncalibrated.

Architecture of the ISL12022

The ISL12022 block diagram is shown in Figure 1. The “Temperature Sensor” and “Frequency Control” in the block diagram are the essential components for compensating the effect from frequency tolerance and Alpha.

Temperature Sensor

The embedded temperature sensor produces an analog voltage output, which is input to an A/D converter and produces a 10-bit temperature value in degrees Kelvin. The temperature sensor measures the temperature immediately surrounding the ISL12022, including the nearby crystal, and ISL12022 can provide proper compensation for the measured temperature.

Frequency Control

Frequency Control is divided into five different control registers:

- Initial ATR and DTR Register (ITR0, address 0Bh)
- Beta Register (BETA, address 0Dh)
- ALPHA Cold Register (ALPHA, address 0Ch)
- ALPHA Hot Register (ALPHA_H, address 2Dh)
- Turnover Temperature Register (XTO, address 2Ch)

The calibration procedure for trimming the five registers will be discussed in “ISL12022 Calibration Procedure” on page 2.

INITIAL ATR AND DTR REGISTER (ITR0)

These bits are used to trim the initial error (frequency tolerance at +25°C) of the crystal. Both digital (DTR) and analog (ATR) trimming methods are available. The digital trimming uses clock pulse skipping and insertion for frequency adjustment. Analog trimming uses load capacitance adjustment to pull the oscillator frequency. A range of +62.5ppm to -61.5ppm is possible with combined digital and analog trimming, where digital trimming provides ±30.5ppm with 2 bits selection and analog trimming provides +32ppm and -31ppm with 6 bits selection.

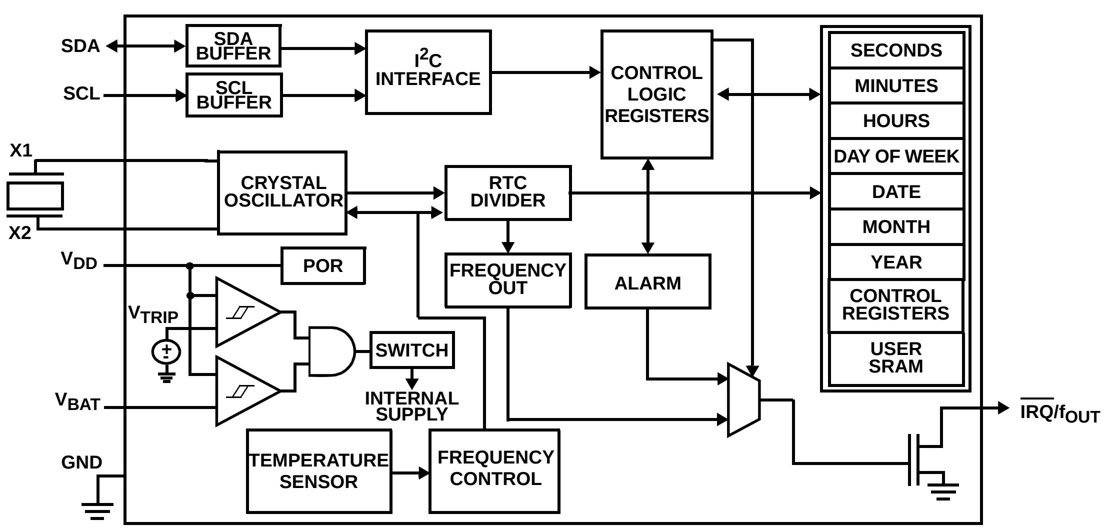

FIGURE 1. ISL12022 BLOCK DIAGRAM

BETA REGISTER (BETA)

Beta is specified to take care of the Cm (motional capacitance) variations of the crystal. Most crystals specify Cm around 2.2fF. For example, if Cm > 2.2fF, the actual ATR steps may reduce from 1ppm/step to approximately 0.80ppm/step. Beta is then used to adjust for this variation and restore the step size to 1ppm/step. BETA values are limited in the range from 01000 to 11111, as shown in Table 1.

ALPHA COLD REGISTER (ALPHA)

The ALPHA Cold Register, ALPHA, is a 7-bit digital representation of the Alpha variable (also known as Temperature coefficient or Parabolic coefficient) from -40°C to +25°C or XT0. ALPHA <7:0> is defined as the (|Actual Alpha Value| x 2048) and converted to binary. For example, a crystal with an Alpha of -0.034ppm/°C^2 is first scaled (|2048*(-0.034)| = 70d) and then converted to a binary number of 01000110b or hexidecimal of 46h.

ALPHA HOT REGISTER (ALPHA_H)

The ALPHA Hot Register, ALPHA_H, is a 7-bit digital representation of the Alpha variable from +25°C or XT0 to 85°C. ALPHA_H has the exact same definition as ALPHA.

The reason to have two Alpha registers for the two temperature ranges is the crystal can have different parabolic behavior at the two temperature ranges, even though the crystal manufacturer only provides one Alpha value for all temperature ranges.

TURNOVER TEMPERATURE REGISTER (XTO)

The apex of the Alpha curve occurs at a point called the turnover temperature, or XT0. Crystals normally have a turnover temperature between +20°C and +30°C, with most occurring near +25°C.

The ISL12022 allows setting the turnover temperature so that temperature compensation can more exactly fit the curve of a crystal. Table 2 shows the values available, with a range from +17.5°C to +32.5°C in +0.5°C increments. The default value is 00000b or +25°C.

ISL12022 Calibration Procedure

ISL12022 ATR, BETA, XTO, ALPHA, and ALPHA_H Trimming Procedure. Please use high resolution frequency counter with at least 7 digits resolution for frequency measurement.

Trimming Instructions

1. SELECT $\overline{IRQ}/f_{OUT}$ OUTPUT FREQUENCY:
Set Register INT(ADDR = 08h) to any desired frequency (f) output on $\overline{IRQ}/f_{OUT}$ pin, where f is the ideal set frequency by FO bits in INT register (address 08h). It is best to select 1Hz for the measurement for higher resolution. Please remember to connect a pull-up resistor from V_{DD} to the $\overline{IRQ}/f_{OUT}$ pin of the ISL12022 since $\overline{IRQ}/f_{OUT}$ is an open-collector output.

2. MEASURE f1 and CALCULATE fppm1:
Set ITR0 register (address 0Bh) to 00h, then measure and record frequency f1 on $\overline{IRQ}/f_{OUT}$ pin. Calculate fppm1 using Equation 1:

$$fppm1 = [(f1/f) - 1] \bullet 10e6 \quad \text{(EQ. 1)}$$

3. MEASURE f2 and CALCULATE fppm2:
Set ITR0 register (address 0Bh) to 3Fh, then measure and record frequency f2 on $\overline{IRQ}/f_{OUT}$ pin. Calculate fppm2 using Equation 2:

$$fppm2 = [(f2/f) - 1] \bullet 10e6 \quad \text{(EQ. 2)}$$

4. MEASURE f3 and CALCULATE fppm3:
Set ITR0 register (address 0Bh) to 20h, then measure and record frequency f3 on $\overline{IRQ}/f_{OUT}$ pin. Calculate fppm3 using Equation 3:

$$fppm3 = [(f3/f) - 1] \bullet 10e6 \quad \text{(EQ. 3)}$$

5. CALCULATE BETA:
Calculate the value of BETA using Equation 4:

$$BETA = |(fppm1 - fppm2)|/63 \quad \text{(EQ. 4)}$$

where fppm1 is the calculated ppm from Instruction 2 and fppm2 is the calculated ppm from Instruction 3.

6. TRIM BETA:
Using the calculated BETA in Instruction 5, find the closest BETA (AT STEP ADJUSTMENT) using the BETA Look-up Table (Table 1) and set the BETA register (address 0Dh) to the corresponding BETA code.
BETA TRIMMED.

7. TRIM ATR:

A. Check if DT is required. If (fppm3 > 32ppm) then set DT to 11b and the new fppm3 = fppm3 – 30.5ppm; else if (fppm3 < -31ppm) then set DT to 01b and the new fppm3 = fppm3 + 30.5ppm. If DT is not required, set DTR to 00b.

B. If DT is required, please use the new fppm3 calculated from line A for the following calculation of the AT code. If DT is not required, please use the original fppm3 from Instruction 4.
Calculate the required step for the AT code (DeltaAT) using Equation 5:

$$DELTA = |fppm3|/BETA \quad \text{(EQ. 5)}$$

where BETA is the calculated value from Instruction 5. DeltaAT must be a positive number from the calculation and rounded to the nearest integer value.

C. Find the AT code (AT) using Equation 6:

$$\begin{aligned} &\text{If } (fppm3 < 0) \\ &AT = 20h(\text{or } 32d) - DeltaAT \\ &\text{else } AT = 20h(\text{or } 32d) + DeltaAT \end{aligned} \quad \text{(EQ. 6)}$$

Set ITR0 register (address 0Bh) to AT and DT.
ATR TRIMMED.

8. TRIM XTO:
Please refer to the crystal's data sheet for XTO or turnover temperature; the typical XTO value will suffice. Use the XTO Look-up Table (Table 2) to find the corresponding XTO code. Set XTO register (address 2Ch) to the XTO code.
XTO TRIMMED.

9. TRIM ALPHA and ALPHA_H:
Please refer to the crystal's data sheet for Alpha (temperature coefficient or parabolic coefficient). Alpha should be given in units of ppm/°C^2; the typical Alpha value will suffice.
Scale Alpha using Equation 7:

$$\text{Scaled Alpha} = (|\text{Actual Alpha Value}| \times 2048) \quad \text{(EQ. 7)}$$

Convert Scaled Alpha to binary by rounding to nearest integer. Set the ALPHA register (address 0Ch) and the ALPHA_H register (address 2Dh) to the Scaled Alpha. ALPHA and ALPHA_H TRIMMED.

TABLE 1. BETA VALUES

BETA<4:0>	AT STEP ADJUSTMENT
01000	0.5000
00111	0.5625
00110	0.6250
00101	0.6875
00100	0.7500
00011	0.8125
00010	0.8750
00001	0.9375
00000	1.0000
10000	1.0625
10001	1.1250
10010	1.1875
10011	1.2500
10100	1.3125
10101	1.3750
10110	1.4375
10111	1.5000
11000	1.5625
11001	1.6250
11010	1.6875
11011	1.7500
11100	1.8125
11101	1.8750
11110	1.9375
11111	2.0000

TABLE 2. XT0 VALUES

XT<4:0>	TURNOVER TEMPERATURE
01111	32.5
01110	32.0
01101	31.5
01100	31
01011	30.5
01010	30
01001	29.5
01000	29.0
00111	28.5
00110	28.0
00101	27.5
00100	27.0
00011	26.5
00010	26.0
00001	25.5
00000	25.0
10000	25.0
10001	24.5
10010	24.0
10011	23.5
10100	23.0
10101	22.5
10110	22.0
10111	21.5
11000	21.0
11001	20.5
11010	20.0
11011	19.5
11100	19.0
11101	18.5
11110	18.0
11111	17.5

Trimming Example

Following is an example of the trimming procedure actually preformed in the lab with the ISL12022 with data collected.

This example uses the Citizen CM200S 32.765kHz 12.5pF crystal. The crystal has a typical frequency tolerance of ±20ppm, a typical turnover temperature of +25°C±5°C, and a typical temperature coefficient of -0.034±0.006ppm/°C^2.

1. SELECT $\overline{IRQ}/f_{OUT}$ OUTPUT FREQUENCY:
$\overline{IRQ}/f_{OUT}$ is connected to a 2kΩ pull-up resistor to V_{DD}. FO bits in INT Register (address = 08h) are set 0011b to select a 1024Hz frequency for trimming measurement.
2. MEASURE f1 and CALCULATE fppm1 using Equation 8:
ITR0 register (address 0Bh) is set to 00h; f1 is 1024.009523Hz from the measurement taken on the $\overline{IRQ}/f_{OUT}$ pin.

$$\text{fppm1} = [(1024.009523/1024) - 1] \bullet 10e6 = 9.3\text{ppm} \quad \text{(EQ. 8)}$$

3. MEASURE f2 and CALCULATE fppm2 using Equation 9:
ITR0 register (address 0Bh) is set to 3Fh; f2 is

1023.935181Hz from the measurement taken on the $\overline{IRQ}/f_{OUT}$ pin.

$$fppm2 = [(1023.935181 / 1024) - 1] \bullet 10e6 = -63.3ppm \quad \text{(EQ. 9)}$$

4. MEASURE f3 and CALCULATE fppm3 using Equation 10: ITR0 register (address 0Bh) is set to 20h; f3 is 1023.971328Hz from the measurement taken on $\overline{IRQ}/f_{OUT}$ pin.

$$fppm3 = [(1023.971328 / 1024) - 1] \bullet 10e6 = -28ppm \quad \text{(EQ. 10)}$$

5. CALCULATE BETA using Equation 11:

$$fppm1 = 9.3ppm, fppm2 = -63.3ppm$$
$$BETA = |(9.3 - (-63.3))| / 63 = 1.152 \quad \text{(EQ. 11)}$$

   TRIM BETA:
   BETA = 1.152; the closest BETA from the BETA Look-up Table (Table 1) is 1.125. The corresponding BETA code for BETA of 1.125 is 10001b or 11h.
   Set the BETA register (address 0Dh) to 10001b.
   BETA TRIMMED.

6. TRIM ATR:

   A. Check if DT is required using Equation 12:

$$fppm3 = -28ppm$$
$$\text{If } (fppm3 < 32) NO$$
$$\text{else If } (fppm3 < -31) NO \quad \text{(EQ. 12)}$$
$$\text{DT is not required; set DTR to 00b}$$

   B. DT is not required; the original fppm3 from Instruction 4 is used.
   Calculate trimmed code for ATR (DeltaAT) using Equation 13:

$$fppm3 = -28ppm, BETA = 1.152$$
$$DeltaAT = |-28| / 1.152 = 24.3 = 24 \quad \text{(EQ. 13)}$$

   C. Find ATR code (ATR) using Equation 14:

$$fppm = -28ppm$$
$$\text{If } (fppm3 < 0)$$
$$ATR = 32 - 34 = 8 \text{ or } 001000b \quad \text{(EQ. 14)}$$
$$\text{DT is not required; set DTR to 00b}$$

   D. ATR = 001000b, DTR = 00b
   Set ITR0 register (address 0Bh) to 00001000b.
   ATR TRIMMED.

7. TRIM XTO:
   From the CM200S data sheet, the typical XTO is +25°C, and from the XTO Look-up Table (Table 2), XTO of +25°C corresponds to 00000b or 10000b. Code 00000b is selected to be the XTO code.
   Set XTO register (address 2Ch) to 00000b.
   XTO TRIMMED.

8. TRIM ALPHA and ALPHA_H:
   From the CM200S data sheet, the typical Alpha is -0.034ppm/°C^2.

$$\text{Scaled Alpha} = (|-0.034| \times 2048) = 69.6 = 70 = 1000110b \quad \text{(EQ. 15)}$$

   Set ALPHA register (address 0Ch) and ALPHA_H register (address 2Dh) to 1000110b.
   ALPHA and ALPHA_H TRIMMED.

Test Results of Calibrated versus Uncalibrated with Different Crystals

Three different 32.768kHz with 12.5pF crystals are selected in order to demonstrate the improvement acheived by performing the calibration. The three crystals are Citizen CM200S, Epson MC-156, and Abracon AB26T. CM200S and MC-156 are surface mount crystals with an operational range of -40°C to +85°C. AB26T is a cylinder type crystal, with an operational range of -20°C to +70°C.

The demonstration is done with V_{CC} = 3.3V, over-temperature, and three compensation settings:

1. No compensation
2. Compensated with default factory data
3. Compensated with calibrated data

No compensation means the temperature compensation function of the ISL12022 is disabled. To disable the temperature compensation function, simply set the TSE bit (Temperature Sensor Enabled Bit, bit 7 address 0Dh) to 0. By doing the demonstration with no compensation, the measurement can show the parabolic behavior of the crystal or typical performance of an ordinary RTC.

Compensated with default typical data means the ISL12022 performed temperature compensation with pre-programmed ITR0, BETA, ALPHA, ALPHA_H, and XTO data. The data is good for a device with 0ppm frequency tolerance, 2.2pF motional capacitance, 0.034ppm/°C^2 Alpha, and +25°C turnover temperature. By compensating with default typical data, the measurement can show the advantage of using ISL12022 embedded temperature compensation function versus an ordinary RTC.

Compensated with calibrated data means the ISL12022 performed temperature compensation with calibrated ITR0, BETA, ALPHA, ALPHA_H, and XTO data from the calibration procedure. By compensating with calibrated data, the measurement can show the advantage of the calibrated ISL12022 versus the uncalibrated ISL12022.

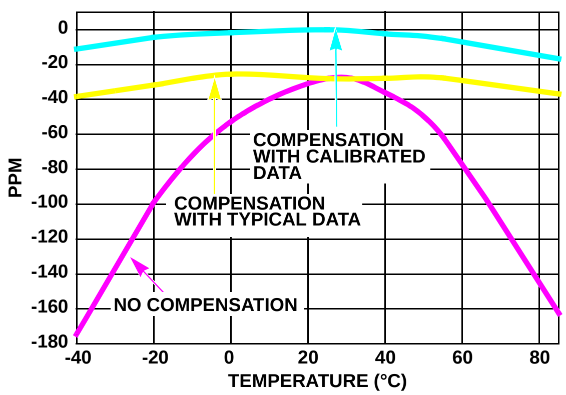

FIGURE 2. CITIZEN CM200S PPM vs TEMPERATURE (-40°C TO +85°C)

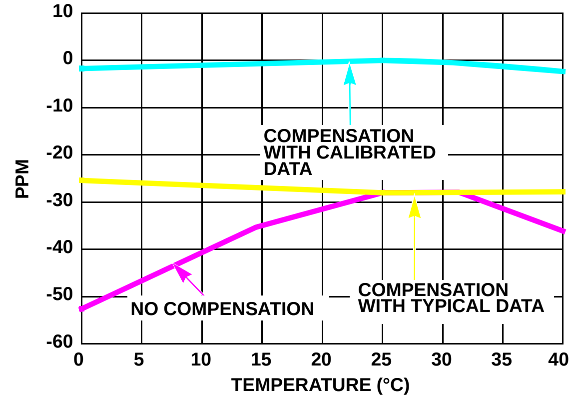

FIGURE 3. CITIZEN CM200S PPM vs TEMPERATURE (0°C TO +40°C)

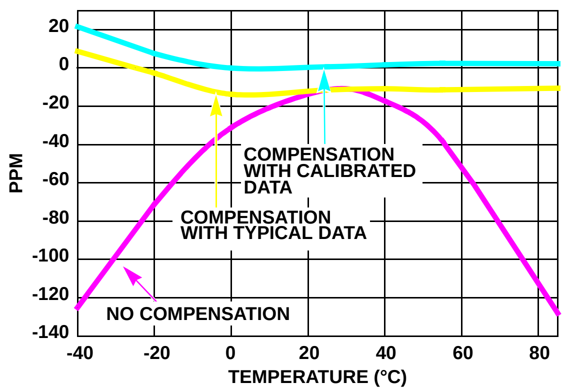

FIGURE 4. EPSON MC-156 PPM vs TEMPERATURE (-40°C TO +85°C)

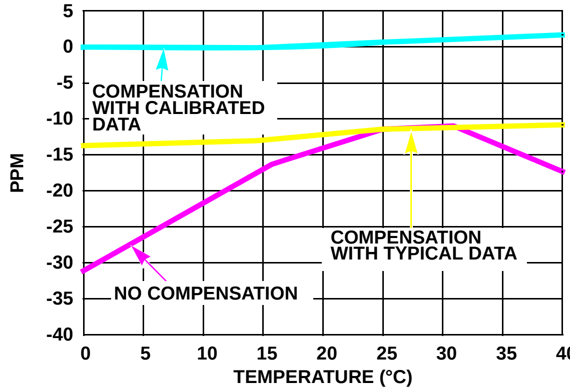

FIGURE 5. EPSON MC-156 PPM vsTEMPERATURE (0°C TO 40°C)

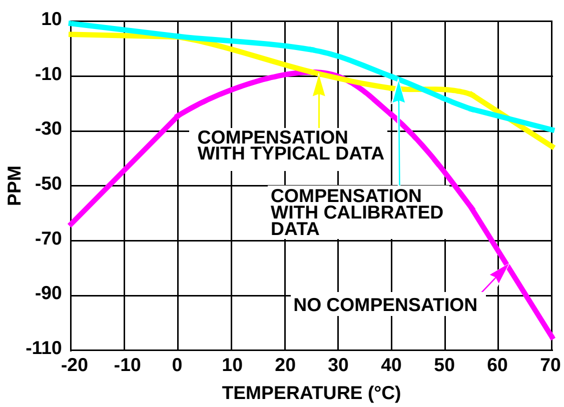

FIGURE 6. ABRACON AB26T PPM vs TEMPERATURE (-20°C TO +70°C)

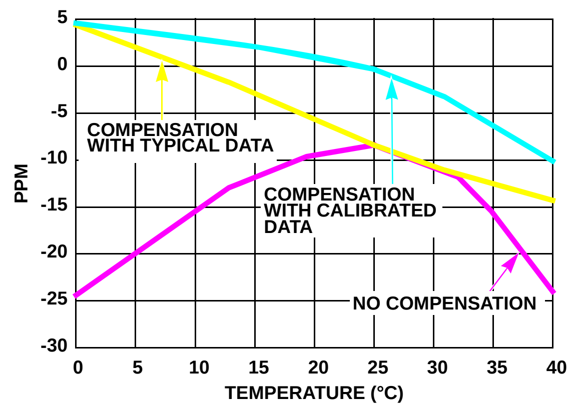

FIGURE 7. ABRACON AB26T PPM vs TEMPERATURE (0°C TO +40°C)

As clearly shown in all the “PPM vs Temperature” plots, a high accuracy of ±10 ppm from 0°C to +40°C or ±20 ppm from -40°C to +85°C RTC system can easily be achieved by using the ISL12022 embedded temperature compensation function with a simple calibration procedure.

Layout Considerations

The crystal input at X1 has a very high impedance, and oscillator circuits operating at low frequencies (such as 32.768kHz) are known to pick up noise very easily if layout precautions are not followed. Most instances of erratic clocking or large accuracy errors can be traced to the susceptibility of the oscillator circuit to interference from adjacent high speed clock or data lines. Careful layout of the RTC circuit will avoid noise pickup and insure accurate clocking.

Figure 8 shows a suggested layout for the ISL12022 device using a surface mount crystal. Two main precautions should be followed:

1. Do not run the serial bus lines or any high speed logic lines in the vicinity of the crystal. These logic level lines can induce noise in the oscillator circuit, causing misclocking.
2. Add a ground trace around the crystal with one end terminated at the chip ground. This will provide termination for emitted noise in the vicinity of the RTC device.

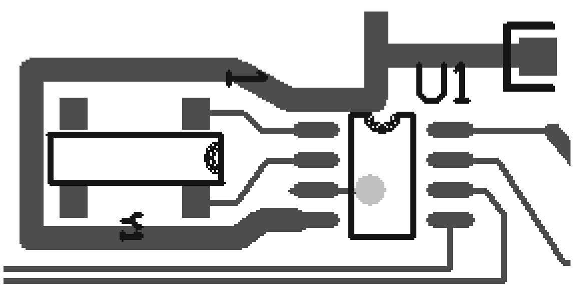

FIGURE 8. SUGGESTED LAYOUT FOR ISL12022 AND CRYSTAL

In addition, it is a good idea to avoid a ground plane under the X1 and X2 pins and the crystal, as this will affect the load capacitance and therefore the oscillator accuracy of the circuit. If the $\overline{IRQ}/f_{OUT}$ pin is used as a clock, it should be routed away from the RTC device as well. The traces for the V_{BAT} and V_{DD} pins can be treated as a ground, and should be routed around the crystal.

Conclusion

ISL12022 can help an RTC system to achieve high accuracy by doing a simple calibration procedure. Once programmed with calibration parameters, however, the calibrated data can be lost once the device is shut down completely, including backup battery supply. In order to restore the calibrated data, the system has to have a way to store the data somewhere such as a EEPROM or flash memory in the system, and have the system set the data back into the ISL12022 when the ISL12022 powers up again along with battery power.

In order for the ISL12022 to achieve extremely high accuracy of ±3.5ppm or better from -40°C to +85°C, the user has to obtain an accurate turnover temperature within ±0.5°C and Alpha within ±0.0003ppm/°C^2 or ±1% of the typical value from the crystal manufacture. This will require testing at least 3 temperature points and doing a set of calculations to determine the XT0 and Alpha parameters. These tests could be time consuming, so the extra accuracy gained may not be worth the additional time.

To circumvent the characterization process, Intersil introduces its new ISL12020M; the M stands for module, where the crystal and the ISL12022 are integrated into one package. The ISL12020M is in a 20 Ld 4mmx5.5mm DFN package, and it is the world’s smallest RTC module package available with ±5ppm or better accuracy from -40°C to +85°C. The ISL12020M has all the features offered by ISL12022 and no calibration is required. The ISL12020M is trimmed at the factory, and all the data is stored in its internal memory so no data gets lost when the power supply is absent. Please contact your local sales representative if better than ±5ppm accuracy is required.

The ISL12020M RTC module with embedded crystal and temperature compensation is the best solution for systems requiring ±5ppm or better accuracy from -40°C to +85°C.

If your system requires accuracy of ±10 ppm from 0°C to +40°C or ±20ppm from -40°C to +85°C, then our ISL12022 RTC device with embedded temperature compensation is a very good solution, considering that one follows the ISL12022 calibration procedure.