Application Report
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VLO Calibration on the MSP430FR4xx and MSP430FR2xx Family

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ABSTRACT

MSP430FR4xx and MSP430FR2xx (FR4xx/FR2xx) family microcontrollers (MCUs) provide various clock sources, including some high-speed high-accuracy clocks and some low-power low-system-cost clocks. Users can select the best balance of performance, power consumption, and system cost. The on-chip very low-frequency oscillator (VLO) is a clock source with 10-kHz typical frequency included in FR4xx/FR2xx family MCUs. The VLO is widely used in a range of applications because of its ultra-low power consumption. Some applications require not only low power but also a higher-accuracy clock. This application report introduces the clock system in FR4xx/FR2xx family MCUs and then discusses how to calibrate VLO against an internal high-accuracy clock. Example code is provided that implements a VLO calibration solution, including test results to show how the solution improves timing accuracy while maintaining the low-power advantages of the VLO. Using a calibrated VLO also saves system cost compared to using an external crystal.

Related software can be downloaded from http://www.ti.com/lit/zip/slaa693.

Contents

List of Figures

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1 Introduction

The very low-frequency oscillator (VLO) provides an internal low-system-cost low-power clock for MSP430™ microcontrollers, especially when used in deep low-power mode. Using VLO, an MSP430 MCU is able to periodically wake up from low-power mode without the need for an external crystal. For many applications in which accuracy is not as critical as power consumption, simply using the VLO as the source for the system real time clock (RTC) counter is a perfect solution. A thermostat is a good example of this, where waking up in approximate time intervals is sufficient for temperature measurement.

However, some applications require not only low power but also a higher-accuracy clock. An air conditioner remote control is a good example of this, where high-accuracy timing is a basic feature needed for sleep timer mode, while low power is needed to extend battery life. For remote controls, system cost is very sensitive so it is preferred to have no external crystal required. Because the VLO is not a high-accuracy clock, using the VLO in this kind of application requires additional calibration. In FR4xx/FR2xx family MCUs, it is possible to calibrate the VLO by using an internal higher-accuracy clock to measure the frequency of the VLO, and then adjust the RTC interval accordingly for more accurate interval timing.

2 FR4xx/FR2xx Clock System

2.1 Clock System Overview

Before discussing the VLO calibration solution, it is important to understand the clock system of the FR4xx/FR2xx family. For more information, see the clock system (CS) chapter in the *MSP430FR4xx and MSP430FR2xx Family User's Guide* (SLAU445). The FR4xx/FR2xx clock system supports four internal and two external clock sources. Users can optimize the clock configuration to select the best balance of performance, power consumption, and system cost.

The four internal clock sources are:

- VLOCLK: Internal very-low-power oscillator with 10-kHz typical frequency
- REFOCLK: Internal trimmed low-frequency oscillator with 32768-Hz typical frequency
- DCOCLK: Internal digitally controlled oscillator (DCO) that can be stabilized by the FLL
- MODCLK: Internal high-frequency oscillator with 5-MHz typical frequency

Of these four clock sources, REFOCLK and DCOCLK are high-accuracy clocks that can be used for VLO calibration. The REFOCLK frequency tolerance is ±3.5% over the full operating temperature and supply voltage range. The DCOCLK can use REFOCLK as reference with the FLL enabled to get high accuracy. The VLOCLK is the lowest-power clock, but it has wider frequency variation than the DCO or REFO. This is why applications that require accuracy may need to calibrate the VLO against these more accurate clock sources. See the device-specific data sheet for more information about clock accuracy specifications of the internal clocks.

The two external clock sources are the low-frequency oscillator LFXT1CLK and high-frequency oscillator HFXT1CLK. These two clocks require an external crystal, and this application report does not discuss them.

Based on the six clock sources, three system clock signals are available for clocking peripherals within the MSP430 microcontroller:

- ACLK: Auxiliary clock. ACLK can be used for low-frequency operation of peripherals. On FR4xx/FR2xx family MCUs, this clock is software selectable as XT1CLK or REFOCLK.
- MCLK: Master clock. MCLK is the main clock source of the CPU and some other digital peripherals directly operated by the CPU or its clock. This clock is software selectable as REFOCLK, DCOCLK, XT1CLK, or VLOCLK.
- SMCLK: Subsystem master clock. SMCLK is the clock for the peripherals that can work independently from CPU operation. This clock always derives from MCLK.

REFOCLK cannot be sourced to peripherals directly, so it should be selected as the clock source of ACLK. ACLK is available for most peripherals from active mode through LPM3. Similarly, the DCOCLK should be selected as the clock source of MCLK and SMCLK and then used by peripherals. DCOCLK is only available in Active mode or LPM0.

For more information, see the clock system (CS) chapter in the *MSP430FR4xx and MSP430FR2xx Family User's Guide* (SLAU445).

2.2 Very Low-Power Oscillator (VLO) Introduction

The internal VLO is a clock source with 10-kHz typical frequency in the FR4xx/FR2xx family MCUs. The VLO is ultra-low power–its typical power consumption is less than 1 µA. With the benefit of its low power consumption, the VLO is widely used in LPM3 and LPM4 to wake up the MSP430 MCU without using an external crystal. The VLO can also be used in LPM3.5 for lower power consumption, but the wake-up time from LPM3.5 is much longer than the wake-up time from LPM3 or LPM4.

In FR4xx/FR2xx family MCUs, the VLO can be selected as the clock source of MCLK and SMCLK. The FR4xx/FR2xx family is a little different from other MSP430 families, because ACLK cannot be sourced from the VLO in FR4xx/FR2xx family MCUs. However, the VLO can be directly selected as clock source of several peripherals (RTC, WDT_A, and LCD_E). The VLO is active when it is the clock source of MCLK, SMCLK, or a peripheral that is in use.

While the VLO is known for its low power, it is a lower-accuracy clock than some of the other clock sources. VLO clock frequency variation can be up to ±50% over different supply voltage, temperature, or process. For applications that do not require a higher-accuracy clock, the VLO can be used directly. For applications that require not only the lowest power consumption but also accurate clock while there is no external crystal, the VLO should be calibrated against an internal high-accuracy clock before using. Because the VLO frequency drifts over temperature and supply voltage, the calibration should be done again if temperature or supply voltage may have changed significantly.

For FR4xx/FR2xx family MCUs, the VLO clock frequency is reduced by 15% (typical) when the device switches from active mode or LPM0 to LPM3 or LPM4. So the VLO should be calibrated in the power mode in which the device is used. Because some clocks are not available in LPM3 or LPM4, which high-accuracy clock sources are available for the calibration can vary. For example, if the VLO will be used in active mode or LPM0, then the high-frequency DCO can be a good choice for the VLO calibration, because it is available in LPM0. REFO could also be used in this case, because it is also available, but the REFO frequency is close to the VLO frequency, so there may be less granularity in the measurement. For VLO use in deeper low-power modes LPM1 through LPM3, the DCO cannot be used for the calibration, because it is not available in these power modes. Therefore, the REFO should be used for VLO calibration in LPM1 through LPM3.

3 VLO Calibration

3.1 Calibration Mechanism

The VLO clock frequency may be different in different devices even with the same supply voltage and temperature, due to normal device-to-device variation. This is the main reason why the VLO needs to be calibrated before using it for accurate timing. The calibration uses an internal high-accuracy clock to measure the VLO clock frequency, and then adjust the period setting of the RTC accordingly to generate the desired interval more accurately. Unlike in other MSP430 MCUs, the VLO in FR4xx/FR2xx MCUs cannot be selected as the clock source of the timer module. The RTC is used in place of one timer for both calibration and timing.

The most important part of calibration is measuring VLO clock frequency. Two methods are available to measure the VLO clock frequency with an internal high-accuracy clock for MSP430 MCUs. As Figure 1 shows, the first method is counting high-accuracy clock cycles within the time of a known number of VLO clock cycles. As Figure 2 shows, the second method is counting VLO clock cycles occurring within a known time period generated by a high-accuracy clock. For the first method, the high-accuracy clock frequency is known, so the actual time period and VLO frequency can be calculated by counting how many of the high-accuracy clock cycles occurred in the fixed number of VLO clock cycles. For the second method, the length of the measurement period is set using the high-accuracy clock, so the number of VLO clock cycles that occur in this fixed measurement period indicates the VLO clock frequency.

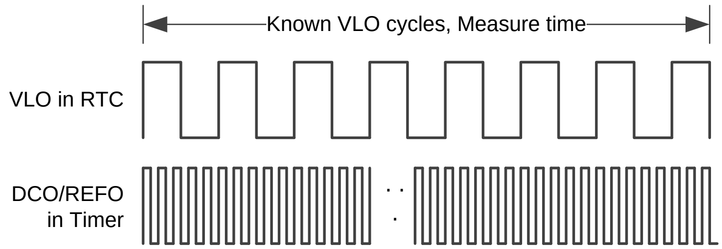

Figure 1. VLO Frequency Measurement Method 1

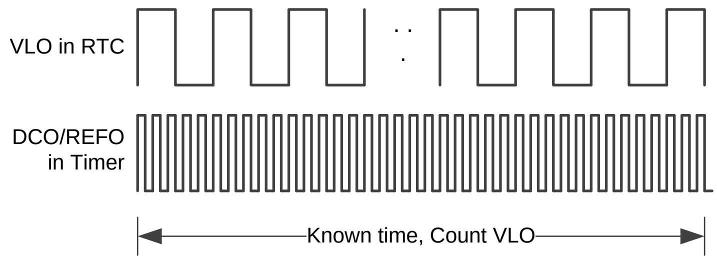

Figure 2. VLO Frequency Measurement Method 2

Usually the high-accuracy clock should also be a high-frequency clock. High frequency means a short period, and a short period can make sure that the error caused by missing one high-frequency clock is quite small. In FR4xx/FR2xx family MCUs, the DCO clock is a high-frequency clock and it can also be quite accurate when stabilized by the FLL. However, the DCO clock is disabled in LPM3, so REFO clock is a good option if calibration needs to be done in LPM3. (Remember that the VLO calibration should be performed in the same operating mode that will be used with the VLO in the main application). The REFO is an internal trimmed low-frequency oscillator with 32768-Hz typical frequency. REFO frequency tolerance is ±3.5% over the full temperature and supply voltage range. Even though the REFO clock frequency is close to the VLO clock frequency, it can be used to measure VLO clock frequency by extending the measurement time or cycles. By using the REFO to measure the time of many VLO clocks, the VLO clock frequency can be calculated by dividing the time by the number of VLO clock cycles. Equation 1 shows how to calculate the VLO clock frequency.

$$f_{VLO} = \frac{f_{REF0} \times Count_{VLO}}{Count_{REF0}} \tag{1}$$

3.2 Peripherals Used for Calibration

The two measurement methods discussed in the previous section use two clocks to generate the same timing. In FR4xx/FR2xx family MCUs, there are three modules (RTC, Timer, and WDT_A) can be used for timing. For WDT_A, only fixed time intervals can be selected. So the RTC and Timer are better options for VLO calibration, because they are more flexible on timing adjustment. Unlike in other MSP430 MCUs, the VLO in FR4xx/FR2xx MCUs cannot be selected as a clock source of a timer module, and it is also not connected to the timer capture input. So for calibration on this device family, the RTC must be used with the VLO as its clock source while the timer module is sourced by a high-accuracy clock. What is more, the RTC outputs a pulse to the timer capture input when an RTC overflow event occurs (see the device-specific data sheet to determine which timer input has this internal RTC connection on the particular device). This internal connection makes it possible for the RTC and timer module to synchronize in hardware without any additional external hardware connections needed. Otherwise, the software needs to handle the synchronization of two timings, which could affect the measurement accuracy because of software time overhead. The first calibration method can take advantage of this peripheral interconnection so that it can achieve higher measurement accuracy (see Figure 3).

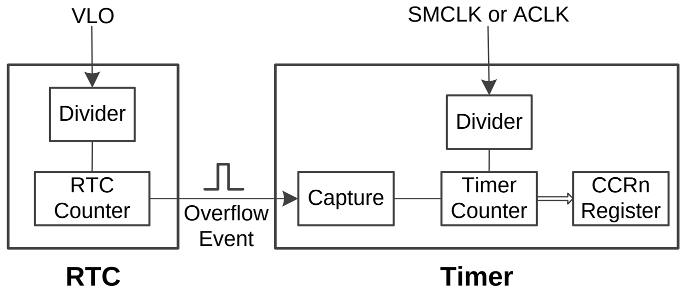

Figure 3. Peripherals Used for VLO Calibration

For different devices in FR4xx/FR2xx family, the related peripherals and interconnection may be different. For example, the timer with the RTC connection in MPS430FR4133 is Timer_A0, but it is Timer_B0 in MSP430FR2311. For details, see the device-specific data sheet.

3.3 Calibration Procedure

For the first calibration method, the procedure is:

1. Configure the RTC. Set the RTCMOD register depending on the calibration time requirement. Select the VLO as the RTC clock source. Start the RTC counter. The RTC interrupt is disabled.
2. Configure the Timer. Set the Timer to capture the RTC output on a positive edge. Select SMCLK/ACLK as the Timer clock source. Start the Timer in continuous mode. The Timer interrupt is enabled.
3. Enter a low-power mode. Enter LPM0 or LPM3, depending on the mode in which the VLO will be working.
4. Wake up by Timer interrupt for the first time. Copy Timer CCRn register value.
5. Enter the same low-power mode again.
6. Wake up by Timer interrupt for the second time. Copy Timer CCRn register value again. Calculate the delta value of two copied CCRn register values.
7. Update RTCMOD register based on the delta value to achieve target timing. Enable the RTC interrupt.

For the second calibration method, the procedure is:

1. Configure the RTC. Set the RTCMOD register with a high value to make sure that the RTC will not overflow during calibration. Select the VLO as the RTC clock source. Start the RTC counter. The RTC interrupt is disabled.
2. Configure the Timer. Set the Timer CCRn register, depending on the calibration time requirement. Select SMCLK/ACLK as the Timer clock source. Start the Timer in up mode. The Timer interrupt is enabled.
3. Enter low-power mode. Enter LPM0 or LPM3, depending on the mode in which the VLO will be working.
4. Wake up by Timer interrupt for the first time. Copy the RTCCNT register value.
5. Enter the same low-power mode again.
6. Wake up by Timer interrupt for the second time. Copy the RTCCNT register value again. Calculate the delta value of two copied RTCCNT register values.
7. Update RTCMOD register based on the delta value to achieve target timing. Enable the RTC interrupt.

During calibration, the low-power mode is entered to save power and to make sure that the VLO is operating under the same conditions that it will operate under in the main application after calibration. If the VLO will be working in active mode or LPM0 in the main application, the MCU should enter LPM0 during calibration. The timer can use SMCLK as a clock source, and SMCLK can be sourced by the DCO with the FLL enabled. If the VLO will be working in LPM3, LPM4, or LPM3.5, then the MCU should enter

LPM3 during calibration. The timer should use ACLK as clock source and ACLK sourced by the REFO. In both calibration methods, the timer will wake the MCU from the low-power mode. For the first method, the timer counter value is copied into the CCRn register by hardware immediately. For the second method, the RTC counter value is copied by software, and software time overhead may impact the measurement accuracy.

In the calibration procedure, the counter value is copied twice to get the delta value, because the first counter value includes the counter setup time, which would impact measurement accuracy. If clock accuracy requirement is not that high, the calibration procedure could potentially be simplified with only one counter value.

When choosing the calibration time period, set the wake-up interval for calibration longer than 1 ms, because the VLO is a low-frequency clock with 0.1-ms typical period. Longer calibration time can help calculate a more accurate average value over several VLO clock cycles. If the VLO is calibrated in LPM3, the wake-up period for calibration should be longer than 40 ms. This is because the VLO frequency may decrease in LPM3 or LPM4 mode and is not as stable as it is in active or LPM0 mode, so a longer averaging period is required for the measurement to get best results.

3.4 Calibration Example Code

There is one example code in the associated source. This example code implements the first VLO calibration method described in the previous section and is based on the MSP430FR2311. With this example code, the MSP430FR2311 wakes up from LPM4 every one second accurately. The GPIO P1.0 is toggled every time after wakeup to indicate the one second timing.

In this example code, VLO calibration is done in LPM3. The RTC is using VLO as clock source and output overflow pulse. Timer_B0 captures the RTC output with ACLK as the timer clock source while ACLK is sourced by REFO. The timing interval is defined by `#define TIMING` at beginning of the code. The calibration time is defined by `#define RTC_CAL`. Figure 4 shows that the RTC can generate 0.998-second timing after VLO calibration. The timing error is within 1% at room temperature with 3-V supply voltage. The MSP430FR2311 average power consumption is approximately 0.8 µA, tested on the target socket board with all unused GPIOs set to output low and no LED connected on the P1.0 pin.

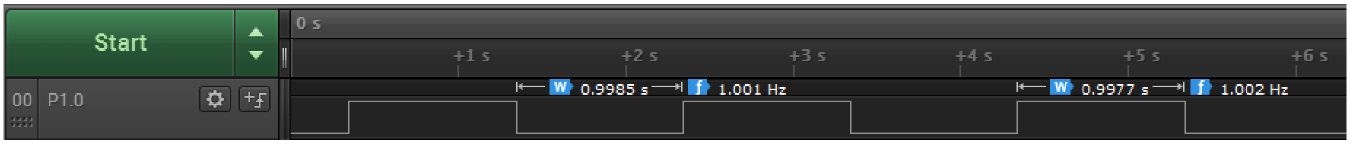

Figure 4. RTC Timing With VLO Calibration

By commenting out the line `#define VLO_CAL` in the code, this example uses the RTC to generate 1-second timing without any VLO calibration for comparison. Figure 5 shows the result, which is that the timing is 0.755 second and has 25% error. The test result shows that VLO calibration greatly improves the RTC timing accuracy.

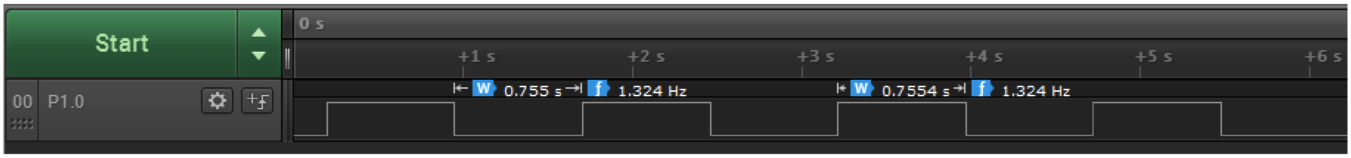

Figure 5. RTC Timing Without VLO Calibration

4 Conclusion

This application report describes how to calibrate the VLO with an internal high-accuracy clock in FR4xx/FR2xx family MCUs. This calibration can be used for applications that require all of the following: high-accuracy clock, ultra-low power, and without external crystal for low cost. With this VLO calibration solution, the ultra-low power VLO can be used to generate high-accuracy timing in LPM4 without an external crystal. A code example is provided, and when this code was used to test the VLO calibration solution, the test result shows that RTC timing accuracy is improved greatly while keeping the ultra-low power consumption of the VLO.

5 References

1. *MSP430FR4xx and MSP430FR2xx Family User's Guide* (SLAU445)
2. *MSP430FR413x Mixed-Signal Microcontrollers* (SLAS865)
3. *MSP430FR231x Mixed-Signal Microcontrollers* (SLASE58)
4. *Using the VLO Library* (SLAA340)
5. *MSP430 Hardware Tools User's Guide* (SLAU278)

Revision History

Changes from January 29, 2016 to February 19, 2016	Page
• Added available clock sources for MCLK	2
• Updated content of Section 4, *Conclusion*	7
• Added items 3 and 5 to Section 5, *References*	7

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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