Application Report

Dramatically Improve Your Lock Time with VCO Instant Calibration

TEXAS INSTRUMENTS

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ABSTRACT

Lock time is the time it takes a PLL to settle to a final frequency (and phase) within a given tolerance when switching from one frequency to another and is critical for fast frequency hopping applications. The lock time consists of the time it takes to write to the device, the VCO calibration time, and the analog settling time of the PLL loop. For very fast switching applications, the VCO calibration time can dominate and this brings the need to ensure that this is fast as possible. This article discusses integrated PLL and VCOs on Si technology, why there is a need for calibration, and some methods to improve for ultra-fast lock time. The LMX2820 synthesizer from Texas instruments is breaking barriers with the ability to do this VCO calibration in under 5 μs.

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Trademarks

1 Overview of Frequency Hopping

The ability to quickly switch between multiple frequencies, also known as frequency hopping, is a critical element in many systems, such as communications, defense radio, and electronic warfare. For these applications, it is imperative that switching between frequencies happens as quickly as possible.

For example, the Link-16 network used by NATO for transferring real-time tactical information requires frequency hopping under 13 µs.[1] [2]

Figure 1-1 illustrates the typical receiver architecture that requires one or more local oscillators (LOs) to generate the different frequency signals and mix them with an incoming receive signal.

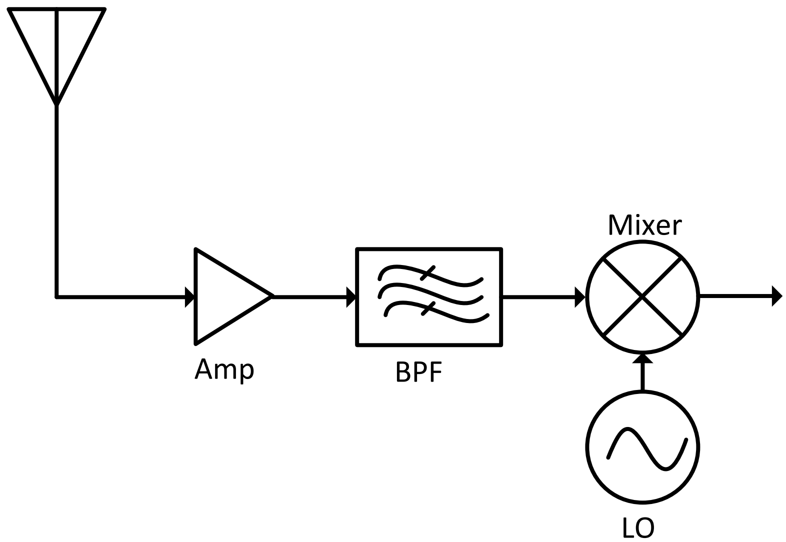

Figure 1-1. Typical Receiver Architecture

In such an architecture, the LMX2820 device can be used as an LO and simplifies the design with two key features: (1) integrating multiple VCO cores into one chip and (2) having ultra-fast VCO calibration. The eight VCO cores in the LMX2820 allow for wideband frequency coverage from 43.75 MHz to 22.4 GHz from a single IC, removing the need for multiple LOs. To switch quickly between these VCO cores, the Instant Calibration function of the LMX2820 device greatly reduces VCO calibration time to less than 5 µs, thus reducing the overall lock time.

This report gives an example of achieving a lock time of under 11 µs with the LMX2820. When compared with other calibration methods available today, it is clear that Instant Calibration provides the fastest solution for designing frequency hopping systems.

2 Integrated VCO Overview

The Voltage Controlled Oscillator (VCO) converts a tuning voltage to an output frequency. It has become increasingly popular to integrate these on integrated circuits along with other functionality. To achieve good phase noise performance and wide tuning range, the VCO frequency range is typically divided into several overlapping bands. This allows the individual bands to have lower VCO gain, which corresponds to better VCO phase noise. By adding all the bands together, they can jointly create a wide tuning range. For this technique to work, a calibration routine has to be used to tell the VCO which is the proper band to use for a given frequency.

2.1 Integrated Silicon VCO Structure

Nowadays, PLLs with integrated VCOs on silicon technologies are very common for the reasons cost, size, wideband frequency coverage, and performance. To achieve good wideband performance while keeping good phase noise performance, it is common practice to use a series of switched capacitors and inductors.

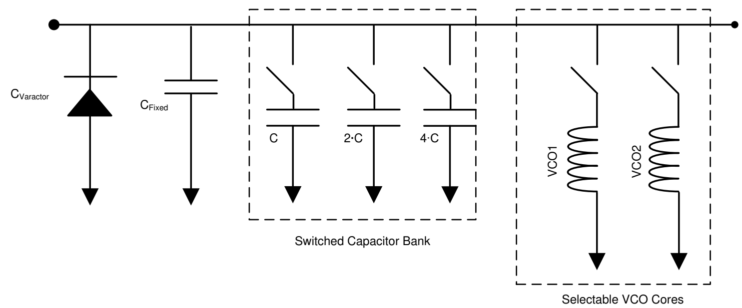

Figure 2-1. Simplified Tank Circuit for Silicon VCO

For this particular example, there are eight capacitor combinations and two inductor combinations, which allow 16 possible frequency bands to be achieved as Figure 2-2 shows.

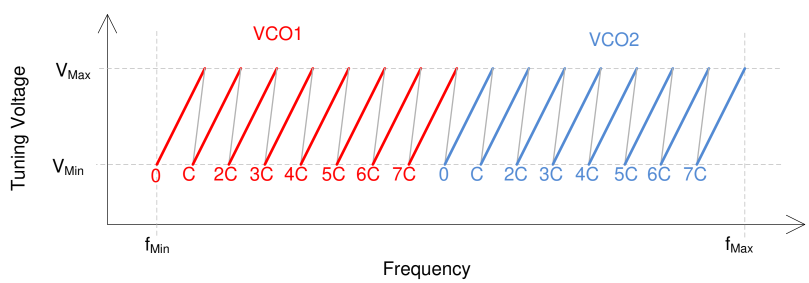

Figure 2-2. Frequency Bands

Modern day synthesizers typically have more capacitors and inductors. For instance, the LMX2820 device has eight VCO cores and 192 different values in the capacitor bank to create 1536 total bands. Between these bands, there is overlap to allow for temperature drift and process variation. In addition to this, there is also an internal amplitude setting that varies as a function of frequency and temperature. So in summary, the three key parameters for the VCO Calibration to determine are:

- VCO_ CORE: This is the inductor choice that greatly impacts the frequency band
- VCO_CAPCODE: This is the capacitor bank setting that changes the frequency band
- VCO_DACISET: This is the amplitude setting that optimizes phase noise

The purpose of the VCO calibration is to find the proper values for these three parameters. This calibration is activated by programmable serial commands when a change in frequency is desired.

2.2 Robustness and Consistency of VCO Calibration

The VCO calibration should be designed to be robust overtemperature. Even if the VCO is calibrated at one extreme temperature and it drifts to the other extreme temperature, the VCO should retain lock and not require reprogramming. For integrated silicon VCOs from Texas Instruments, one can choose to re-calibrate the VCO for some improvement, but this improvement in doing this is less than 1 dB in phase noise. As VCO is designed to tolerate wide temperature drifts, this implies that there is considerable overlap between the frequency bands. This leads to the next aspect of consistency of VCO calibration. As there is considerable overlap of the frequency bands, there are multiple frequency bands that can hit the same frequency. When the VCO does not choose the same calibration settings (VCO_CORE, VCO_CAPCTRL, VCO_DACISET), then there can be differences in spurs, VCO gain, VCO phase noise, and propagation delay. This is especially true if a different VCO core is chosen.

3 Components of Synthesizer Lock Time

The time that it takes a synthesizer to change from one frequency to another is composed of three major components. The first component is the time that it actually takes to tell the synthesizer to change the frequency. This is typically done through a serial programming bus. The second component is the VCO calibration time, which is the time it takes for the VCO to find the correct settings (VCO_CORE, VCO_CAPCODE, VCO_DACISET). After the VCO calibration is finished, there will be some frequency error (Δf). The final component is the analog settle time, which is the time it takes for this final frequency error after the VCO calibration to settle within a given tolerance.

3.1 Write Time

The first thing that needs to be done to get a synthesizer to change frequencies is that this command needs to be sent. Typically several register values need to be changed and the write time is the amount of time it takes to write these registers. For instance, if the SPI programming bus can be run at 75 MHz and one needs to program three 24-bit registers, then this can be done in slightly under 3 µs. The most intuitive way to reduce the write time is to increase the clock speed, which is definitely an effective method.

Another technique is to use shadow registers, also known as double buffering. For this approach, multiple registers can be written before they are needed and then the end of one write can trigger all the register to take place at the same time. This is assuming that one knows the next frequency that is required. In addition to eliminating the write time, shadow registers also can help prevent glitches. For instance, suppose it is required to write the feedback divider (N) in one register and then trigger the VCO calibration by writing to a different register. If the N divider is written first, the VCO will slam into the tuning rail because the frequency is invalid for that band. Then the VCO is programmed to calibrate and it will go to the correct frequency. However, having the VCO tuning voltage at the rail can increase the analog settling time after the VCO calibration is finished. So in summary, shadow registers can eliminate programming time and prevent unnecessarily long analog settling times.

3.2 VCO Calibration Time

Another concern is the time that it takes the VCO to calibrate, which is dependent on the device and setup conditions. The VCO will start at some initial starting point and then the VCO calibration searches for the correct calibration values. The simplest approach is “no assist” calibration in which no effort is used to choose the initial starting point. This is demonstrated with the LMX2594 PLL calibration as Figure 3-1 shows.

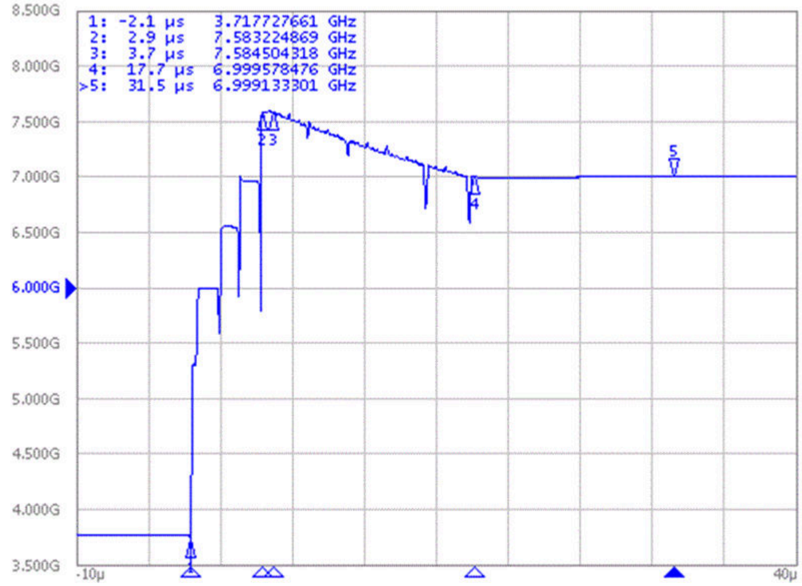

Figure 3-1. LMX2594 VCO Calibration With no Assist

The first step is for the VCO to choose the correct core, that we can see as several step responses that finish at marker 2 at 2.9 µs. After this, it slews through the CAPCODE values to find to the correct one, which is completed at marker 4. The amplitude calibration is where the correct DACISET value is chosen and after this happens, the final analog settling time is finished at marker 5.

A natural question when looking at Figure 3-1 is to wonder if there is a way to assist the VCO calibration with an initial guess to have the VCO start at a closer frequency. Indeed there is a way and this is known as partial assist. By giving an initial guess for VCO_CORE, VCO_CAPCODE, and VCO_DACISET, this improves the VCO calibration, even if the guess is slightly off. Figure 3-2 illustrates this.

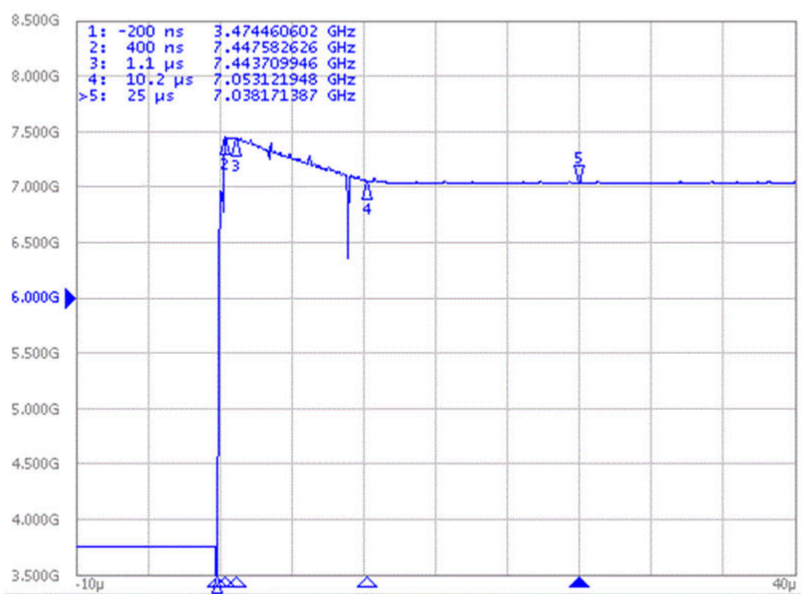

Figure 3-2. LMX2594 VCO Calibration With Partial Assist

Beyond simply giving the VCO an educated starting point, there is also Full Assist Calibration, which involves forcing the exact value. For this method, it requires the device to be locked to the frequency at a previous time and the calibration settings stored in an external memory. Then these values can be read in and forced. Although this does require this to be done for every device, the benefit of eliminating the calibration time is worth it for many. For devices such as the LMX2594 and LMX2820, these same settings can be used over the entire temperature range.

3.3 Analog Settling Time

The VCO calibration will find the correct core (VCO_CORE), band (VCO_CAPCODE), and amplitude setting (VCO_DACISET). During this time, the VCO tuning voltage is forced to a centered voltage which is close to the actual value, but after this, the final frequency error must settle out.

4 Improving VCO Calibration Time With the LMX2820

In Figure 4-1, we can see the raw unassisted calibration time of 153 µs before any enhancements are used. The LMX2820 synthesizer from Texas instruments has several enhancements for fast switching time.

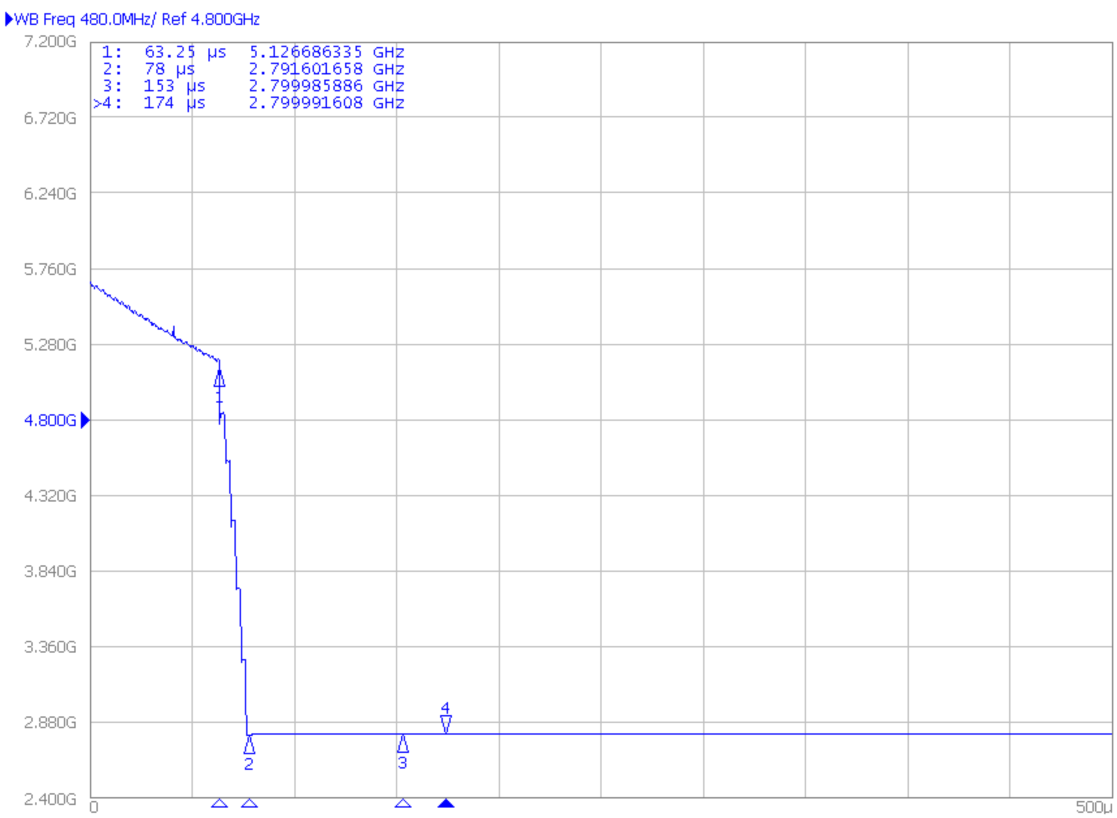

Figure 4-1. LMX2820 Unassisted Lock Time

4.1 Improving LMX2820 VCO Calibration With Partial Assist

The partial assist method can be used to improve the lock time for this example with the LMX2820. To do this, some values were chosen close to, but not equal to, the starting values Table 4-1 shows.

Table 4-1. *VCO Calibration Start Values*

Setting	Actual Value	No Assist Start Value	Partial Assist Start Value
VCO_SEL	1	7	1
VCO_CAPCTRL	186	0	180
VCO_DACISET	336	300	330

Using this partial assist method, the VCO calibration time was reduced from 174 µs to 80 µs. This is a worthy reduction, but instant calibration can do better. For more information and examples on partial assist VCO calibration, see the *Streamline RF Synthesizer VCO Calibration and Optimize PLL Lock Time Application Report*.

4.2 Full Assist Method of Improving VCO Calibration Time

The benefits of partial assist depend on the situation, but typically might be on the order of a 50% reduction in VCO calibration time. This is helpful, but many applications demand more. Full assist addresses this by bypassing the calibration altogether and forcing the correct value. The challenge with this is that these values vary from part to part so one has to lock the device beforehand with the standard calibration and read back the settings. Then one can force them in and bypass the calibration time. Full assist provides the benefit of the fastest calibration time and also consistent values, although it requires a lot of programming overhead. Also, if the write speed is slow, then this will limit how fast the VCO can change frequencies. Full assist VCO calibration can dramatically improve the VCO calibration time, but requires significant setup, so this is why no results are shown for this approach. Another drawback with the full assist mode is that it takes several register writes to change the values of VCO_SEL, VCO_CAPCTRL, VCO_DACISET, PLL N value, and PLL fraction. Between these writes, the PLL will not be at the correct state and will slam the VCO tuning voltage to the rails. To mitigate this, the charge pump can be tri-stated, but this is more programming effort. In summary, full assist calibration is fast and it also has the benefit of always giving the same calibration settings for the same frequency. The drawback is increased programming overhead and also it requires the setup effort of locking the device to all the required frequencies and reading back and storing the calibration values so that later on they can be forced for full assist calibration. For more details and examples with full assist calibration, see the *Streamline RF Synthesizer VCO Calibration and Optimize PLL Lock Time Application Report.*

4.3 Instant Calibration – The Ultimate to Blazing-Fast VCO Calibration

The LMX2820 introduces a new upgrade to full assist calibration called instant calibration. With this instant calibration, the same fast VCO calibration results can be obtained without so much programming and setup overhead. This has several advantages.

1. The calibration values for CAPCODE, CORE, and DACISET are always the same for the same frequency – giving consistent performance. This does assume power is not removed from the device, and there is an initial setup routine for the calibration that is required.
2. The VCO calibration time can be reduced to below 5 μs without compromising performance or reliability.
3. The LMX2820 features double buffering (shadow registers), which not only simplifies switching frequencies, but applies all the register settings for the new frequency at once, so that the VCO tuning voltage does not get slammed to the wrong value

Many different situations were measured using the initial setup condition as shown in Figure 4-2. The VCO frequency, dividers, and INSTCAL_FNUM values were changed, but the other conditions were the same. FCAL_INSTCAL_DLY was set to 250, which makes the VCO calibration time last for 2.5 μs.

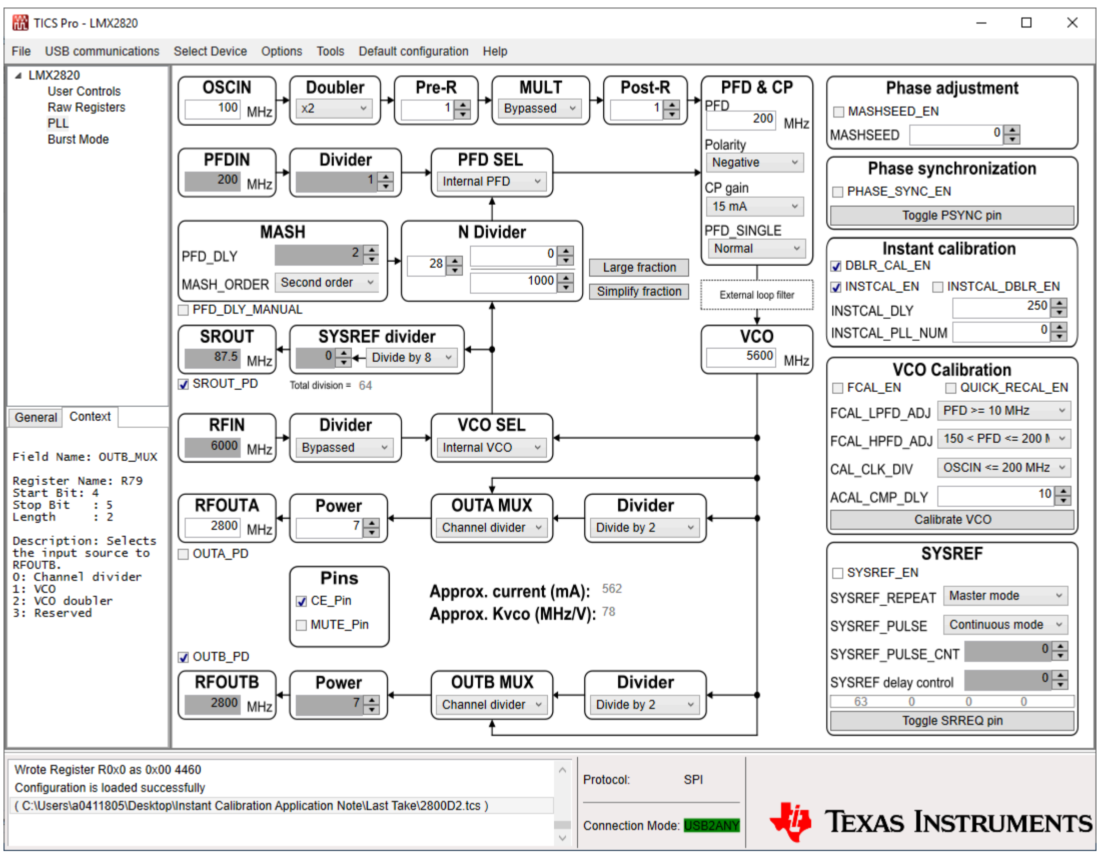

Figure 4-2. TICSPro Setup

The rest of the lock time is due to the analog settling time of the loop. The frequency error at the start of the analog calibration was measured (Δf) and the lock time was measured using the LD pin output and the results are recorded in Table 4-2.

Table 4-2. Lock Time Measurements

Output Frequency (MHz)		VCO Frequency (MHz)		Output Divider		dF (MHz)	Lock Time (µs)
Fstart	Fstop	Fstart	Fstop	DivStart	DivEnd		
5600	6000	5600	6000	1	1	6.7	11.8
6000	5063	6000	10126	1	2	0.5	9.8
5600	6053	5600	6053	1	1	-3.2	9.7
6053	5600	6053	5600	1	1	1.4	10.9
5595	6028	11190	6028	2	1	14.5	12.2
6028	5595	6028	11190	1	2	2.2	9.5
2800	5600	11200	11200	4	2	0.9	11.9
5600	2800	11200	11200	2	4	2.2	10.8

The loop filter impacts the analog settling time of the loop and has some influence.

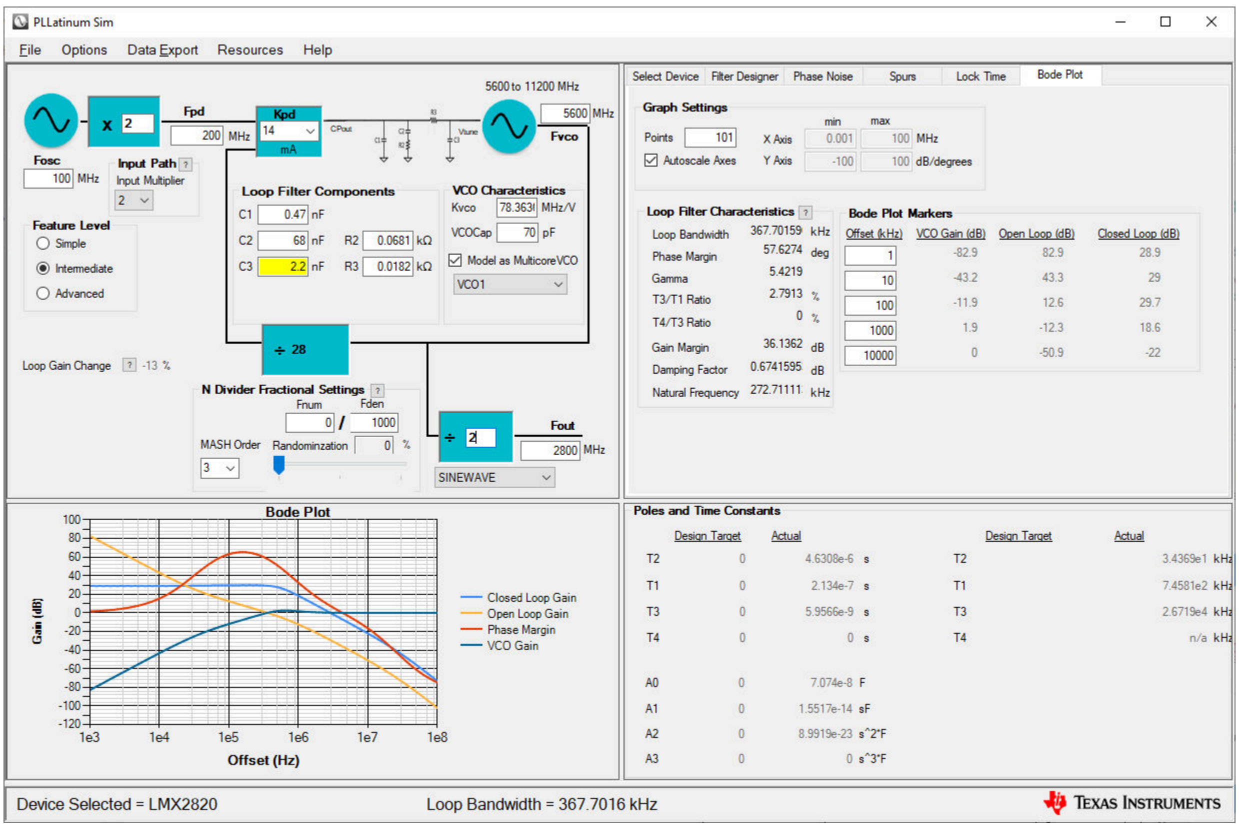

Figure 4-3. Loop Filter Setup

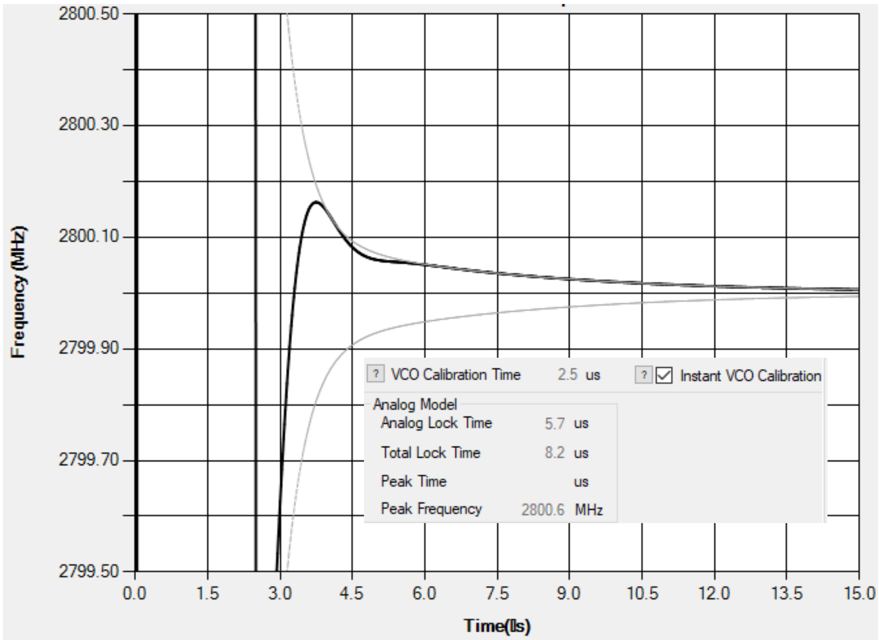

Figure 4-4. Lock Time Simulation

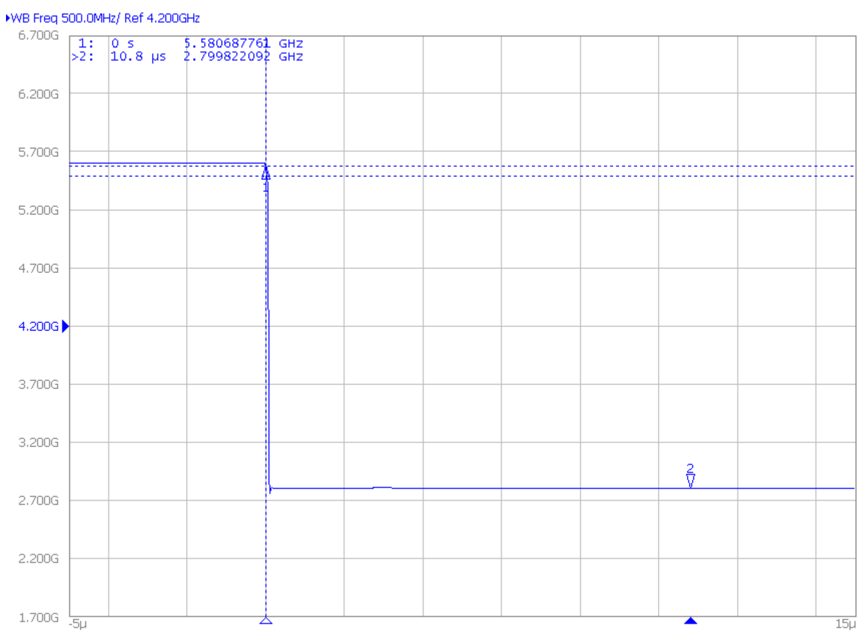

Figure 4-5. Wide Span Instant Calibration With the LMX2820

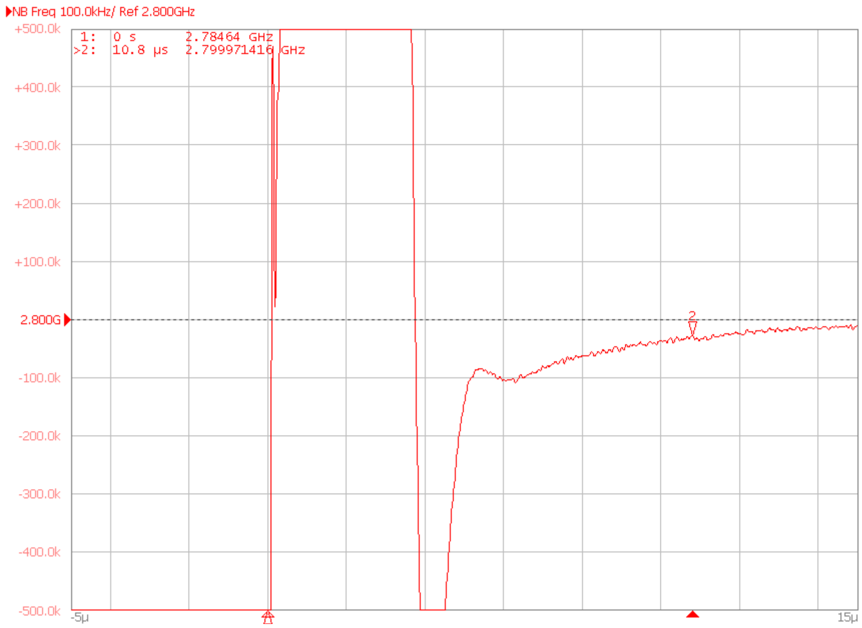

Figure 4-6. Narrow Span Instant Calibration With the LMX2820

Figure 4-6 shows that at 10.8 µs, which is where the lock detect pin indicated lock, the frequency is slightly off on the order of 30 kHz. There is a long tail showing it gradually settling to this point, which sometimes can be improved by changing the capacitor type from X7R to C0G, although this was not attempted. In Figure 4-4 the frequency error after calibration was measured and the settling tolerance of 30 kHz was used and the simulation suggested 8.2 µs, compared to the actual measurement of 10.8 µs. In any case, regardless of measurement technique or capacitor types used, this lock time is blazing fast.

5 Conclusion

For applications requiring fast frequency hopping, the lock time for PLL synthesizers is a critical specification. This time includes the programming time, VCO calibration time, and analog settling time. Silicon based synthesizers with integrated VCOs offer a wide tuning range and some offer advantages to reduce lock time. In particular, the LMX2820 features shadow registers and Instant Calibration allowing for lightning fast calibration without compromising performance.

6 References

1. *Understanding Voice and Data Link Networking*. Northrum Grumman Corporation. December 2014.
2. *LINK 16 ELECTROMAGNETIC COMPATIBILITY (EMC) FEATURES CERTIFICATION PROCESS AND REQUIREMENTS*. US Department of Defense. April 2005.
3. Texas Instruments, *LMX2820 22.4-GHz Wideband PLLatinum™ RF Synthesizer With Phase Synchronization and JESD204B Support Data Sheet*
4. Texas Instruments, *Streamline RF Synthesizer VCO Calibration and Optimize PLL Lock Time Application Report*