Application Note

LMX2820 RF Synthesizer Phase Noise Improvement With Alternative Topologies

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ABSTRACT

The LMX2820 is a low phase noise RF synthesizer. The device offers additional features for cases where improved phase noise performance is needed. This note characterizes the inherent phase noise performance of the LMX2820 with varying PFD frequencies and reference sources. This analysis is used as a baseline to compare against the improvement topologies. The first option uses an external VCO instead of the internal one. This facilitates a higher-Q, lower phase noise VCO at the expense of tuning range. The second option uses an external mixer to bypass the internal N-divider. This eliminates the PLL phase noise degradation that the internal divider introduces. Combining both techniques with a superior reference yields the ultimate realizable phase noise performance.

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1 Introduction

The LMX2820 RF synthesizer inherently provides excellent phase noise performance and operates up to 22 GHz; however, there are cases that need improved phase noise performance. The LMX2820 offers a couple of different topologies to improve synthesizer phase noise. One technique bypasses the internal voltage-controlled oscillator (VCO) and uses an external one. This introduces a superior low phase noise VCO while maintaining the programming features of the PLL device. The second technique uses an external mixer to down-convert the RF frequency to the PFD (Phase Frequency Detector) frequency. This bypasses the internal feedback dividers which are one of the sources for degraded PLL phase noise.

2 Reference Frequency

The foundation of any RF synthesizer is the reference frequency. Achieving the best synthesizer phase noise starts with a high-quality reference source. Not all sources or generators are equivalent. Some show good low offset performance while sacrificing high offset noise floor. Depending on the application, one source can prove more beneficial than another based on the phase noise profile. The following signal generator sources are compared to find the best reference source for the subsequent measurement analysis.

- Rohde & Schwarz (R&S®) SMA100B
- Wenzel oscillator
- Agilent PSG (with UNR enhanced phase noise option)
- R&S SMA100A
- Agilent ESG

Figure 2-1 shows the phase noise comparison between the sources operating at 307.2 MHz. Table 2-1 outlines the RMS jitter integrated from 1 kHz to 40 MHz. The source output power is over 10 dBm and the phase noise measurement were conducted with the Holzworth phase noise analyzer.

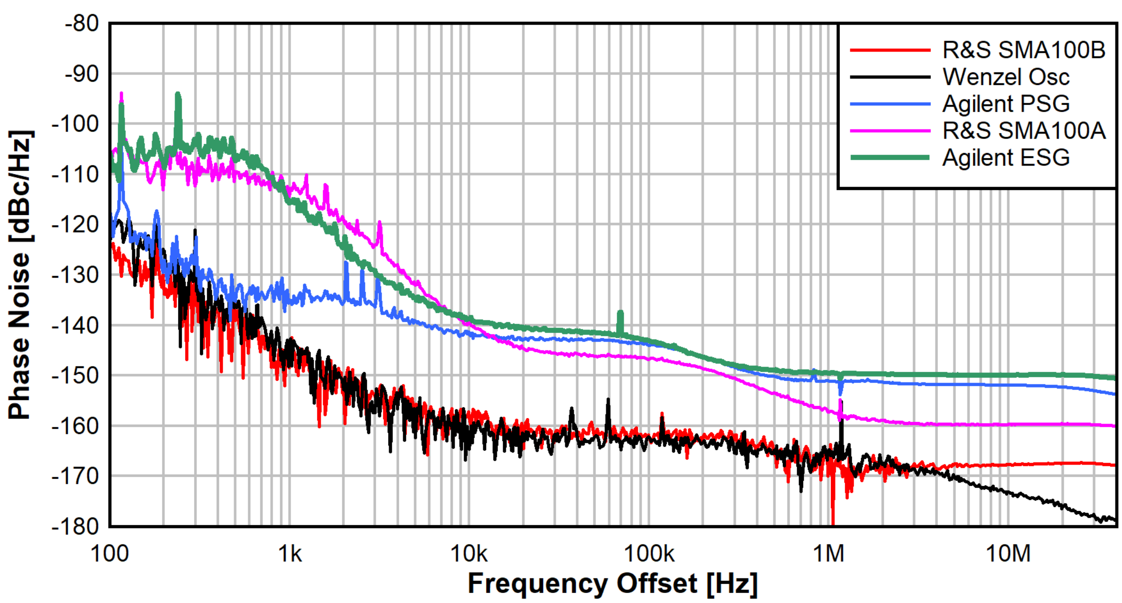

Figure 2-1. Phase Noise Comparison of Reference Sources

Table 2-1. RMS Jitter Comparison of Reference Sources (1 kHz–40 MHz)

Instrument	Jitter
R&S SMA100B	19.5 fs
Wenzel Oscillator	10.4 fs
Agilent PSG	113.4 fs
R&S SMA100A	70.8 fs
Agilent ESG	150.0 fs

The Wenzel oscillator is the premier standard. The oscillator provides excellent close-in and far-out phase noise performance and is ideal for the reference, but it is limited to just one frequency. The Rohde and Schwarz SMA100B rivals the Wenzel. The close-in phase noise is almost as good (or in some offset cases slightly better) than the Wenzel. Only at very high frequency offsets past 3 MHz does the SMA100B significantly deviate from the Wenzel.

The Agilent PSG has good very low frequency offset performance that is close to the Wenzel out to about 300 Hz. After that, there is a significant deviation from the standard. The Rohde SMA100A and the Agilent ESG have noticeable degradation at low-frequency offsets.

Overall, the SMA100B is a good substitute for the Wenzel oscillator for use as a reference to provide flexibility in selecting the reference frequency for the synthesizer.

3 Standard LMX2820 Phase Noise Performance

To understand the performance improvement with alternative topologies, first characterize the inherent LMX2820 performance using the internal VCO. The TIDA-010230 reference design incorporates two LMX2820 synthesizers and includes options for operating in standard or alternative topologies. It is an ideal platform for comparing relative phase noise performance across different settings. Using the TIDA-010230 reference design, the LMX2820 is characterized with different PFD frequencies. Note, the LMX2820 PFD frequency is limited to 400 MHz maximum. It is expected that higher PFD frequencies that translate to lower N-divider values will provide better results.

The phase noise response and integrated jitter is dependent on the reference source. The reference source for the phase noise measurements is the SMA100B which is extremely good; however, it is conceivable that an even better reference source provides slightly improved results. The RMS jitter calculations start at 10 kHz to decouple a bit from the very low frequency offsets that are dominated by the reference performance.

Figure 3-1 shows the phase noise performance of the LMX2820 with various PFD frequencies at 6-GHz output. RMS jitter is integrated from 10 kHz to 40 MHz. Similarly, Figure 3-2 shows the phase noise performance at 9 GHz measured after an RF amplifier to amplify the signal to around 10 dBm. The Agilent E5052 measured performance at frequencies below 7 GHz; the Rohde and Schwarz FSWP measured performance at the higher frequencies.

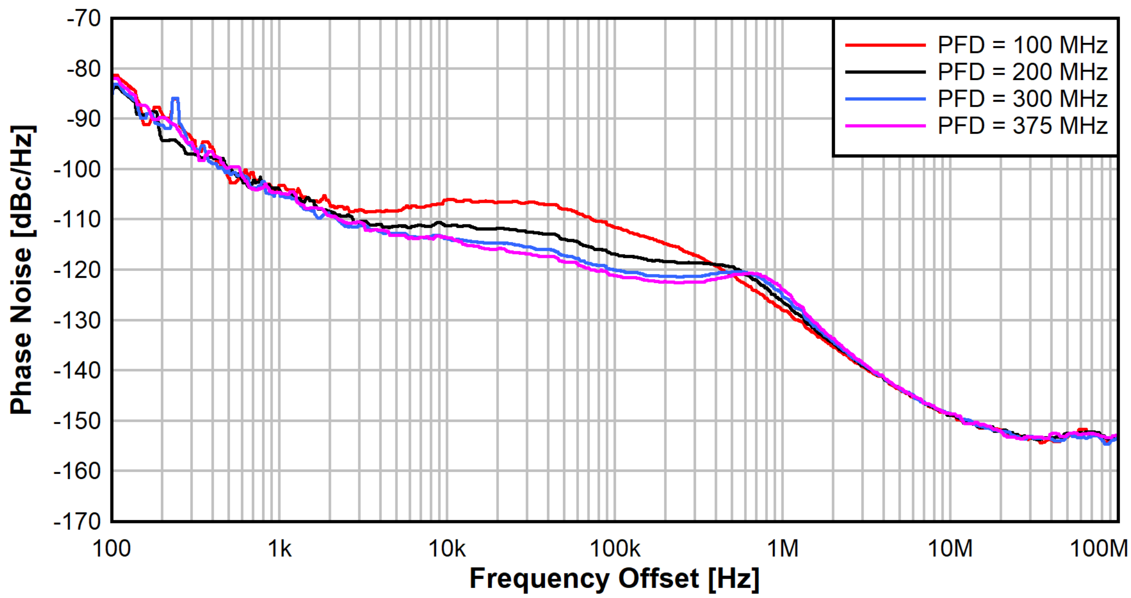

Figure 3-1. LMX2820 Phase Noise Performance Over PFD Frequency at 6-GHz Output

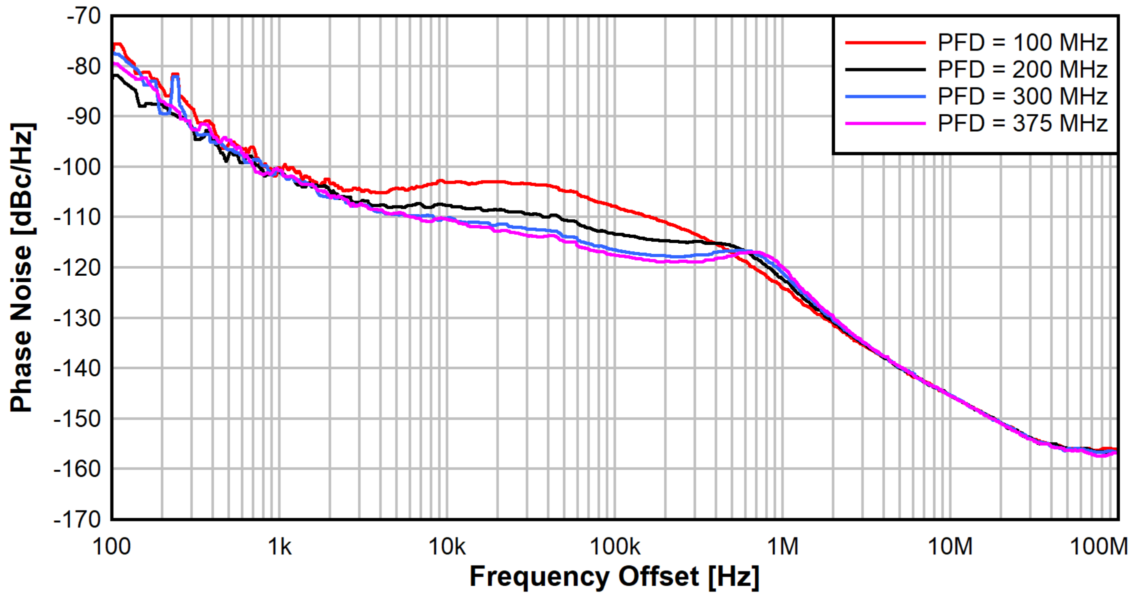

Figure 3-2. LMX2820 Phase Noise Performance Over PFD Frequency at 9-GHz Output

Table 3-1 shows the integrated RMS jitter for 6-GHz output and 9-GHz output. In all cases, the loop filter remains constant; there is some improvement possible with a lower PFD frequency if the loop filter is optimized for the required N-divider setting.

Table 3-1. LMX2820 Integrated RMS Jitter (10 kHz–40 MHz) Over PFD Frequency

	6 GHz		9 GHz	
PFD	N-Divider	Integrated Phase Noise	N-Divider	Integrated Phase Noise
100 MHz	60	62.4 fs	90	61.5 fs
200 MHz	30	43.9 fs	36	46.0 fs
300 MHz	20	38.1 fs	30	40.5 fs
375 MHz	16	36.4 fs	24	37.9 fs

As expected, a higher PFD frequency corresponding to a lower N-divider value yields the best results. The optimum value is at 375 MHz which is convenient for locking to a 6-GHz or a 9-GHz VCO.

The area of the curve that shows the difference is the middle section from around 1k-Hz offset to 1-MHz offset. This area is heavily influenced by the PLL performance and correspondingly the N-divider setting. The reference source dominates the performance at very low-frequency offsets. The VCO performance dominates at high-frequency offsets. These areas do not change significantly with PFD changes.

For the subsequent measurements, the reference will be set at 375 MHz and the synthesizer set to 9-GHz output. A 9-GHz clock is convenient for clocking RF sampling data converters like the AFE7950 operating in S-band or X-band.

4 Pre-multiplier Stage Performance

shows a block diagram of the 3x pre-multiplier stage using the TRF37C75 amplifier. Figure 2-3 compares the phase noise performance of the pre-multiplier stage with that of the signal generator. Table 2-2 reports the integrated jitter performance for each configuration.

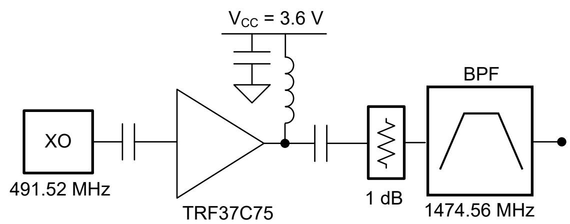

Figure 4-1. 3x Pre-multiplier Stage

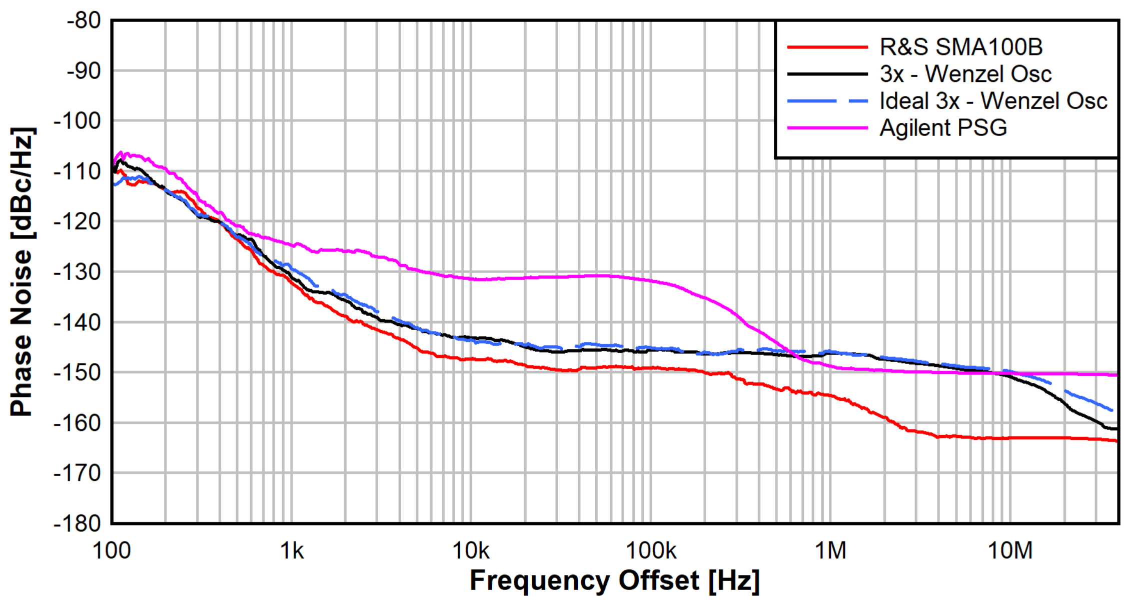

Figure 4-2. Phase Noise Comparison of 1474.56 MHz Signal

As expected, the SMA100B provides the best output at 1474.56 MHz. The 3x multiplied Wenzel oscillator performance is also quite good. Its sweep is nearly identical to the ideal response when the input performance is degraded by 20 * log (n), where n = 3 as the multiplication factor. As before, the multiplied-up Wenzel approach is significantly better than the Agilent PSG.

Table 2-2: Integrated RMS Jitter at 1474.56 MHz

Frequency	Source	RMS Jitter
1474.56 MHz	R&S SMA100B	8.1 fs
	Wenzel Osc - 3x	22.2 fs
	Agilent PSG	35.4 fs

4.1 External VCO Loop Filter Design

The gain (kV) of the external VCO is significantly different than the internal VCO of the LMX2820. As such, the loop filter must be modified to achieve optimum performance. Use TI's PLLatinum™ Simulation Software tool version 1.6.0 or later to optimize the loop filter for the external VCO.

Within the PLLatinum simulation GUI, select the LMX2820 from the *Select Device* menu. This will pre-load the standard configuration for the device. Adjust the following parameters to reflect the set-up configuration and external VCO parameters:

- Fosc, Fpfd: 375 MHz highest PFD frequency yields best phase noise
- Fout, FVCO: 9000 MHz set the VCO frequency to 9 GHz
- KVCO: 0.6 MHz/V VCO gain extracted from its data sheet
- Change *Filter Designer* > 3rd-order filter
- Select Active B topology

Also toggle the *Advanced* radial button under *Feature Level*. Within the *Phase Noise* tab, load a user-specified phase noise file reflecting the reference frequency of the system. This analysis uses a file derived from the measured performance of the SMA100B signal generator operating at 375 MHz. Next, load a file for the open loop phase noise of the external VCO (either from measurement or from the device data sheet). Table 4-1 shows the values used in this analysis.

Table 4-1. Open Loop Phase Noise Parameters for the Z-Comm DRO9000A

Frequency Offset (Hz)	Phase Noise (dBc/Hz)	Notes
1000	-77.8	From data sheet
10000	-106.2	From data sheet
100000	-126.5	From data sheet
10000000	-146	Measured
20000000	-150	Measured
40000000	-154	Measured
100000000	-154	Measured

In the *Integrated Noise* section, change the limits of integration as desired. For this analysis, the limits are 10 kHz to 40 MHz. Pushing the start frequency out to 10 kHz focuses more importance on the PLL and VCO performance and less on the reference frequency performance. For convenience, on the *Filter Design* tab in the *Filter Optimizer* section, select "Jitter (fs)" from the pull-down menu. This displays the simulated integrated jitter performance on the tab without having to switch to the *Phase Noise* tab to see the results.

The active loop filter uses a 3rd-order topology corresponding to the Active B topology. The simulation tool graphs the composite phase noise performance along with the individual contributor components of the VCO and PLL. The default loop filter component values in the simulator will yield a *peaky* phase noise response once the previously-mentioned parameters are changed. This is primarily due to the very low VCO gain of the external VCO. Use the simulator to adjust loop filter values for the optimum response. The general strategy is to decrease the loop bandwidth of the filter to take advantage of the low VCO noise performance.

There are no absolute right values for the loop filter. There are a variety of combinations that will yield good results. The *Calculate Loop Filter* tool in the PLLatinum simulation tool assists with getting close to the goal. Adjust specific components to maintain minimum values or realizable values. From there, additional trial-and-error tweaks achieve optimal jitter performance.

For this analysis, the loop filter bandwidth is around 41 kHz. Figure 4-3 shows the simulation results. Disregard the warning related to the PFD frequency; anything less than 400 MHz is acceptable. Also disregard the warning on the capacitor value C1; keeping the value above 1.5 nF is preferable. Table 4-2 lists the loop filter component values for one optimized solution. The simulated RMS jitter from 10 kHz to 40 MHz is just under 14 fs.

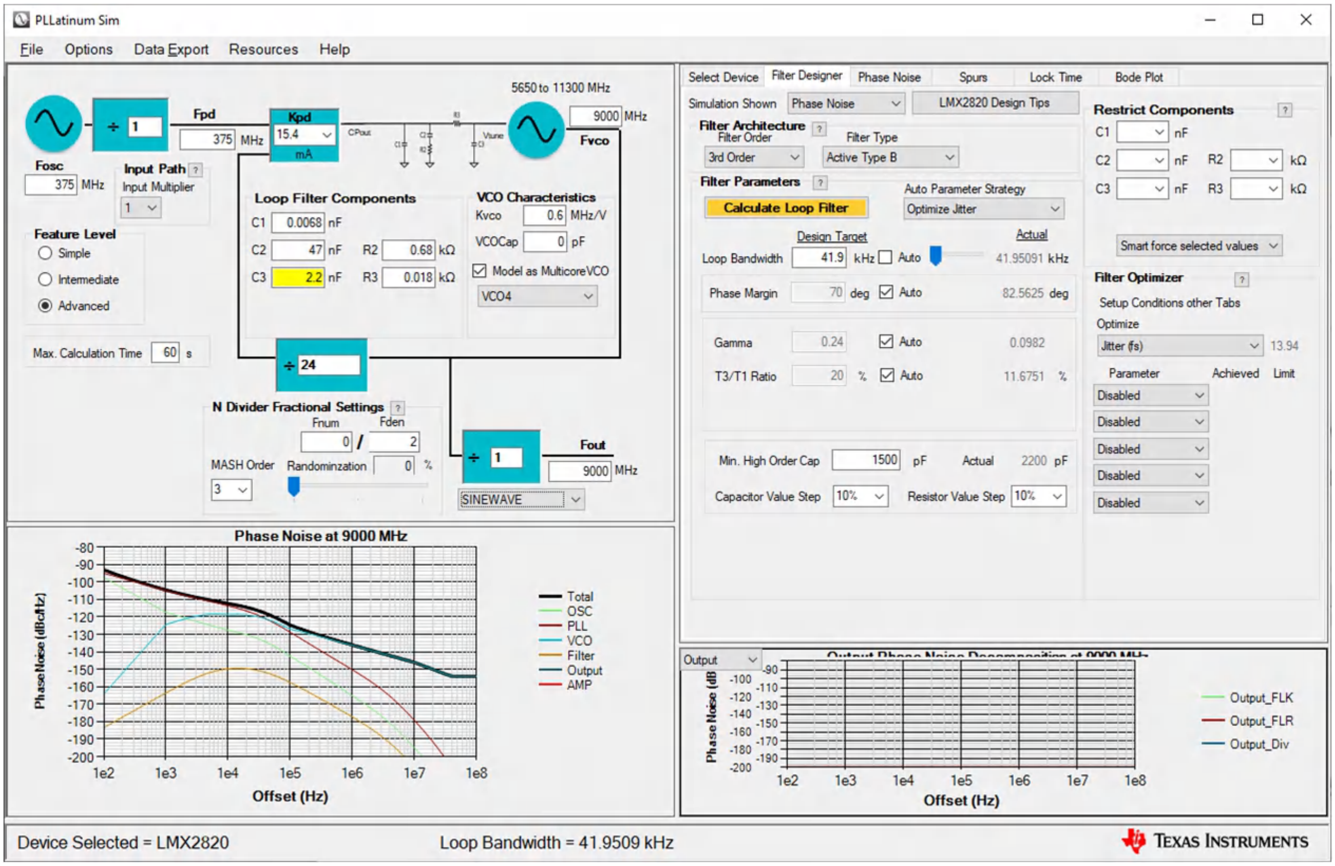

Figure 4-3. External VCO PLLatinum™ Simulation GUI Loop Filter

Table 4-2. Active Loop Filter Component Values

Simulation Reference Designator	Value
C1	6.8 pF
C2	47 nF
R2	680 Ω
C3	2.2 nF
R3	18 Ω

4.2 Active Loop Filter Implementation

Figure 4-4 shows the block diagram for the external VCO and the active loop filter. There are a few key elements to highlight with the topology. When using the external VCO, there is no internal feedback mechanism to feed the PFD circuit. Use an external splitter to split the VCO output to the LMX2820 RF input and to the ultimate synthesizer output. If needed, use an external RF amplifier to boost the synthesizer output and compensate for the splitter loss.

The op amp is a critical component. Select a device that is low noise and supports rail-to-rail outputs. If the output cannot get down to 0 V, then utilizing the entire tuning range is not possible. For a single supply operation, bias the positive terminal at a suitable common-mode voltage. This voltage is roughly half of the maximum charge pump voltage from the device. For this design, a voltage divider operating on a 10-V rail sets the Vcm to 1.2 V.

The op amp is the OPA211. This device has a very low output noise voltage with suitable bandwidth and rail-to-rail output capability. Table 4-3 shows the key specs of the OPA211A.

Table 4-3. Key OPA211 Op-Amp Specifications

Parameter	Specification
Low Voltage Noise (1 kHz)	1.1 nV/√Hz)
Gain BW Product (G = 100)	80 MHz
Slew rate	27 V/µs

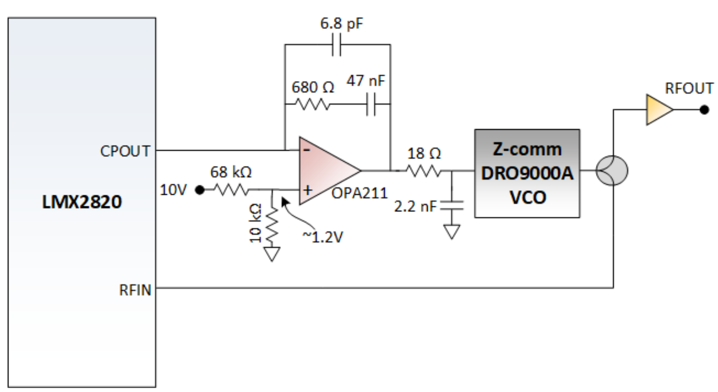

Figure 4-4. Block Diagram of the External VCO Configuration

4.3 External VCO Performance Results

Figure 4-5 shows the external VCO phase noise plot compared to the LMX2820 operating with internal VCO. The SMA100B signal generator provides the reference signal. Reference signal power from the generator is set to 14 dBm to compensate for board trace losses and to ensure a large signal swing (and hence high slew rate) at the reference pin input of the LMX2820. The performance includes active loop filter with the OP211A op amp and the Qorvo NBB-312-T1 output power amplifier. Table 4-4 lists the RMS jitter performance at 9 GHz integrated from 10 kHz to 40 MHz. The phase noise plot shows equivalent performance between the internal VCO and the external VCO out to around a 10-kHz offset. Performance less than 10-kHz offset is still dominated by PLL and reference frequency performance. After which, the superior performance of the external VCO itself dominates. As an example, the spot noise improvement at 1-MHz offset between the external VCO and internal VCO is over 20 dB. Overall, the external VCO with active loop filter yields over a 20-fs improvement in RMS jitter.

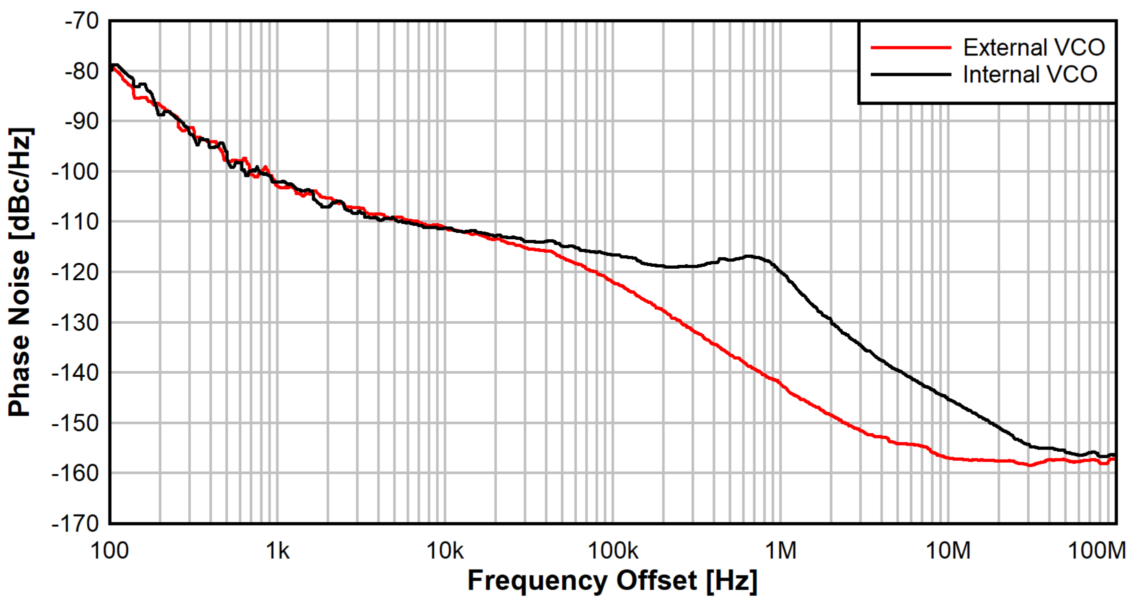

Figure 4-5. External VCO Phase Noise Compared to LMX2820 Internal VCO

Table 4-4. External VCO RMS Jitter Performance Comparison

PFD	N-Divider	RF Out	Internal VCO	External VCO
375 MHz	24	9000 MHz	37.9 fs	13.2 fs

5 External PFD Topology

One of the main noise contributors in the PLL is the N-divider. For high-frequency applications, the N-divider must be fairly large to divide down to a more reasonable low-reference frequency. The external PFD approach uses an external mixer to bypass the internal N-divider. The RF mixer down-converts the VCO frequency to the PFD frequency directly. Of course, for there to be an improvement, the mixing operation must be inherently lower noise compared to the internal dividers. This requires the mixer LO to be low noise in itself. It may seem a bit contradictory to use the LMX2820 for generating a frequency tone that requires another frequency tone for an LO source. This is addressed in the subsequent section.

The TIDA-010230 reference design also provides an option to run with external PFD. Reference the block diagram in Figure 5-1. The output of the internal VCO is amplified and fed into the RF input of the mixer. Properly select the LO frequency to mix the VCO output down to the PFD frequency. The LMX2820 provides an external PFD divider to further reduce the frequency down to the reference if needed. Best performance is when this divider is bypassed (that is, kept at 1).

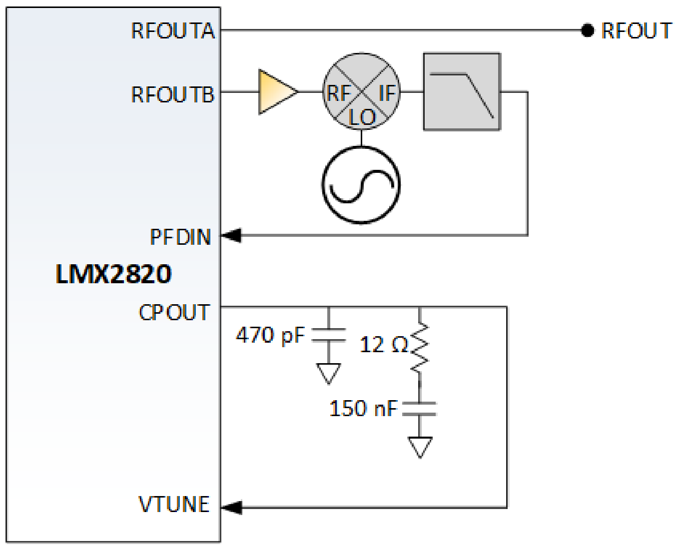

Figure 5-1. Block Diagram of the External Mixer, PFD Topology

Although this topology requires external circuitry and an additional LO source, it still uses the internal VCO. This allows the full range of the VCO to generate frequencies up to 22 GHz.

5.1 External PFD Loop Filter Modification

When using the external PFD feature, the effective N-divider is 1 and the loop filter must be modified to maintain optimum results. The general strategy is to increase the loop bandwidth to take advantage of the low PLL noise as much as possible.

Use the PLLatinum simulation tool to provide a guide to optimize performance. To begin, start with the default values of the LMX2820 setup. As before, load the specific reference phase noise performance file. Keep the default VCO configuration as the internal VCO is still operational. Adjust the limits of integration to 10 kHz to 40 MHz as before. Change the charge pump current to 7 mA; this is the maximum value when operating in external PFD mode. Modify the loop filter to a 2nd-order passive topology; a simplified configuration is sufficient for the minimum divider case.

The tool does not specifically have a mode for external PFD operation. To simulate the external PFD configuration, set the *Fosc* and *Fpd* to the same value as the VCO output. This *tricks* the tool into setting the N-divider to 1. Disregard the red error highlights. With the default loop filter values and the N-divider set to one, the initial phase noise response shows a peaking response around 10 MHz.

Adjust the loop filter values to increase the bandwidth to compensate. Initially target a loop bandwidth around 2000 kHz. The automatic *Calculate Loop Filter* brings the values close to what is needed; afterwards, manually adjust loop filter values to hone in on an optimized and realizable filter. As before, there is no one absolute loop filter solution; Figure 5-2 shows the PLLatinum simulation set-up for the external PFD configuration used in this analysis and Table 5-1 shows the modified loop filter values.

Figure 5-2. PLLatinum™ Simulation for External PFD

Table 5-1. External PFD Loop Filter Values

Simulation Reference Designator	Value
C1	470 pF
C2	150 nF
R2	12 Ω

5.2 External PFD Measurement Results

For the baseline measurements, the Rohde SMA100B supplies the LO signal to the mixer. It is critical that the LO signal be low phase noise with very good low frequency offset performance. Poor phase noise performance in the LO translates directly to the synthesizer output. With the external PFD configuration, the phase noise of the reference is less critical; for these experiments the Agilent PSG signal generator supplies the reference signal.

The LMX2820 output frequency is 9375 MHz. The N-divider is 25. For internal VCO calibration purposes, the internal N-divider must still be set up properly. Switch to the external PFD mode and toggle the frequency calibration bit. The device must first calibrate the internal VCO with the internal dividers before switching to the external PFD input. The LO frequency is 9000 MHz. This sets the PFD frequency to 375 MHz. Figure 5-3 shows the phase noise results with the external PFD compared to the external VCO response. Notice the improved intermediate frequency offset performance due to the effective low N-divider setting and the *normal* internal VCO performance at the high frequency offsets.

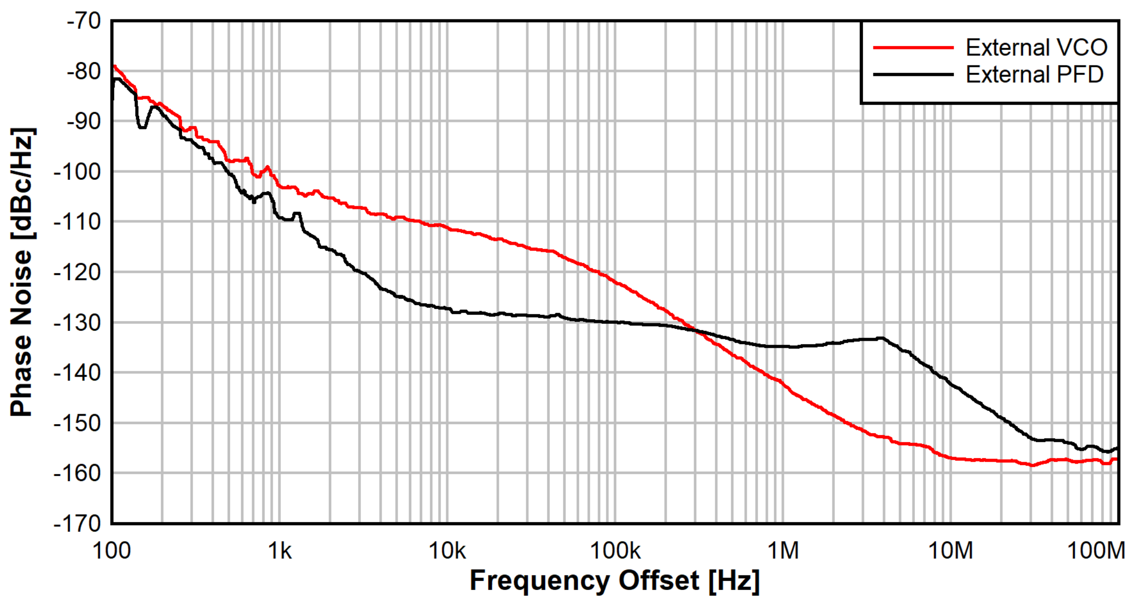

Figure 5-3. LMX2820 External PFD Phase Noise Performance

6 Putting it Together in the Real World

The performance of the LMX2820 with an external PFD using the Rohde SMA100B as the LO source yields excellent phase noise performance. The performance is very attractive, but not practical in a real application. A realistic option is to use an additional LMX2820 as the mixer LO. Using the standard LMX2820 configuration with internal VCO as the LO yields worse performance than just using the device directly. That is expected given the LO source is not improved compared to the source. Alternatively, use a second LMX2820 configured with the external VCO as the LO source. Figure 6-1 shows the block diagram approach for using two LMX2820 devices. The external VCO is followed by cascaded amplifiers to increase the LO drive signal to 16 dBm (or higher). The mixer needs a high LO drive level to ensure best dynamic range and linearity required for best phase noise performance.

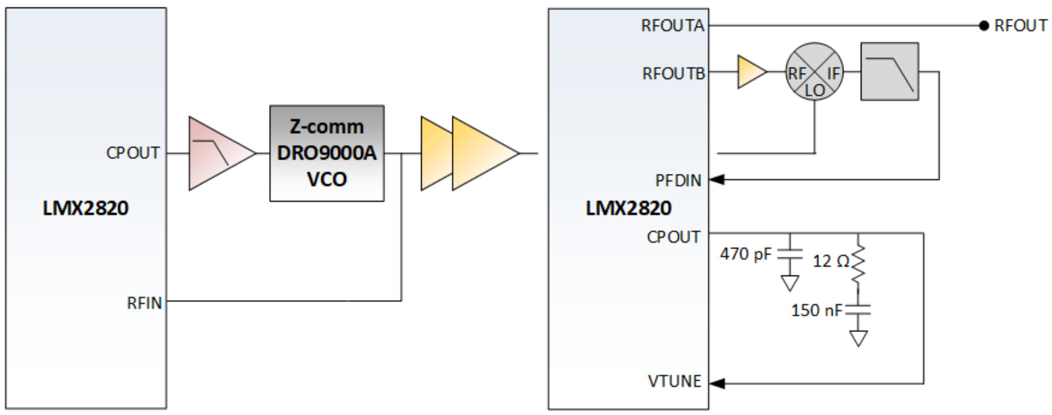

Figure 6-1. Dual LMX2820 Approach for a Real-World Solution

6.1 Real-World Performance Results

Figure 6-2 shows the phase noise performance of the dual LMX2820 approach compared with the stand-alone external PFD (using SMA100B as the LO), the stand-alone external VCO, and the internal VCO. Table 6-1 shows the comparison of integrated jitter between the different configurations.

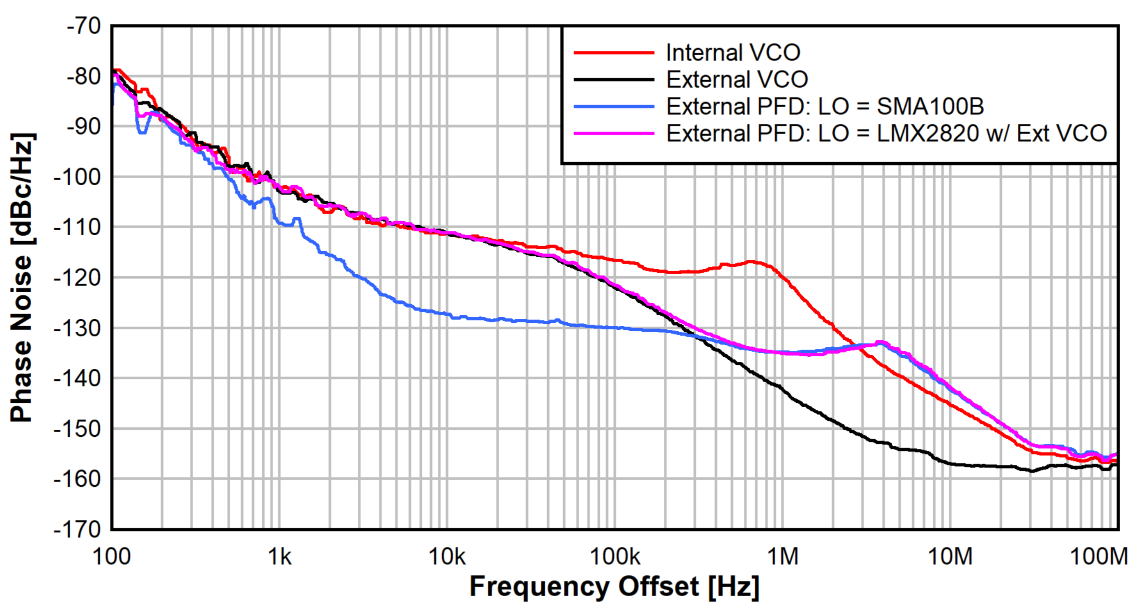

Figure 6-2. Dual LMX2820 Real-World Phase Noise Results

Table 6-1. Integrated RMS Jitter Performance Comparison With External PFD

RF Out Freq	Source	Integrated Phase Noise
9000 MHz	Internal VCO	37.9 fs
9000 MHz	External VCO	13.2 fs
9375 MHz	External PFD (LO = SMA100B)	13.9 fs
9375 MHz	External PFD (LO = LMX2820 with Ext VCO)	18.5 fs

The dual LMX2820 approach yields an integrated phase noise performance under 20 fs. Though not quite as good as the stand-alone external VCO or external PFD with SMA100B as the LO, it is a significant improvement to the internal VCO and provides a response that is comparable to many high-end signal generators. It is a real-world topology that supports the most stringent communication and defense applications.

6.2 Why use the Dual Approach?

Why use the dual LMX2820 approach when something like the external VCO yields better integrated performance? The external PFD topology is still using the internal VCO and thus has the flexibility to tune the frequency over a large range as well as use the internal output dividers. This provides additional flexibility to adjust the synthesizer frequency output that the external VCO approach cannot accomplish.

One option is to use the external PFD divider to adjust the frequency. In essence, this is equivalent to the N-divider adjustment used to change the frequency in the same way. The benefit in the external PFD topology is that the starting point is at the minimum divider value possible (that is, 1). Figure 6-3 shows the external PFD performance response as external PFD divider is adjusted from 1 to 6. This is measured as a relative reference using the SMA100B as the LO source. Of course, the dividers can be further increased to keep moving the output frequency up as desired. Table 6-2 reports the integrated phase noise performance over PFD divider settings.

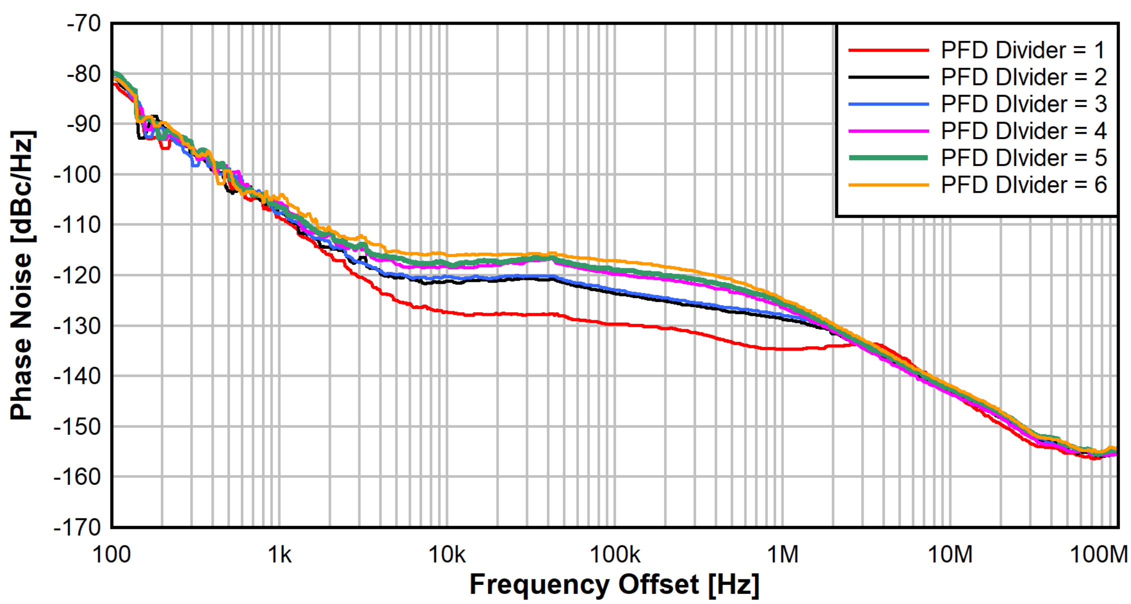

Figure 6-3. External PFD Over PFD Divider

Table 6-2. External PFD Over PFD Divider

PFD Divider	RF Out Freq	Integrated Phase Noise
1	9375 MHz	13.2 fs
2	9750 MHz	13.7 fs
3	10,125 MHz	17.8 fs
4	10,500 MHz	20.3 fs
5	10,875 MHz	21.6 fs
6	11,250 MHz	23.9 fs

The topology also provides the option to use the output dividers to extend the frequency range further. Figure 6-4 shows the phase noise performance across output divider settings from 2 to 16. Table 6-3 reports the integrated phase noise performance across the output divider settings.

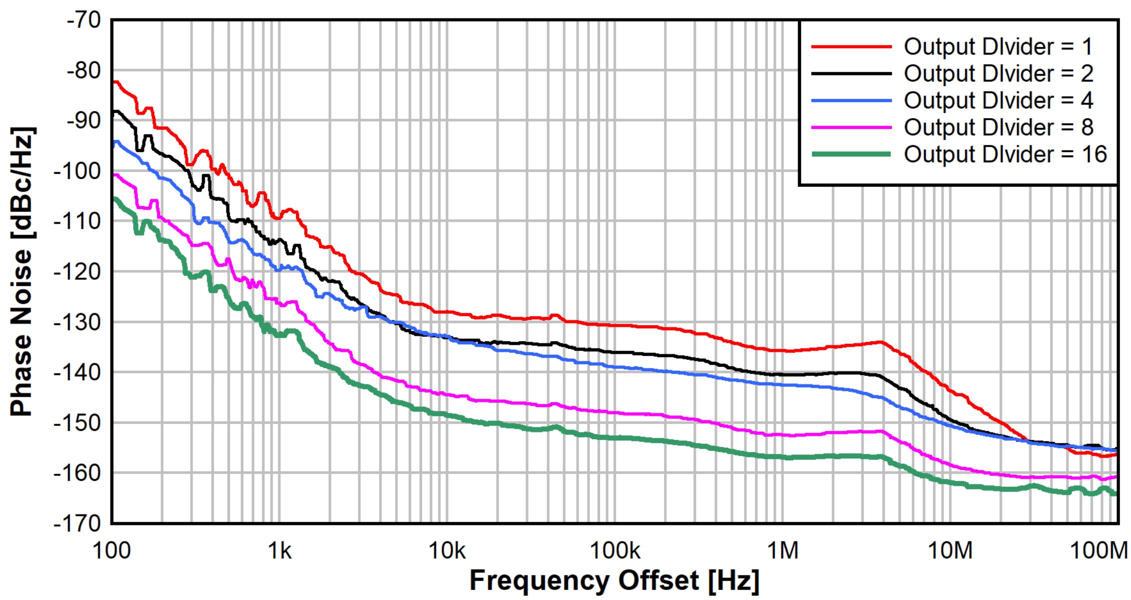

Figure 6-4. Phase Noise Over Output Divider Settings

Table 6-3. Integrated Phase Noise Over Output Divider Settings

Output Divider	RF Out Freq	Integrated Phase Noise
1	9000 MHz	13.0 fs
2	4500 MHz	14.0 fs
4	2250 MHz	20.5 fs
8	1125 MHz	17.3 fs
16	562.5 MHz	22.3 fs

7 Conclusion

The LMX2820 is a good low-noise RF synthesizer device. Two alternative topologies provide improved performance that rival high-end test equipment: external VCO and external PFD. Combining these two approaches yields a real-world topology that provides extremely good phase noise performance while also providing flexibility to adjust the frequency output.

The improved synthesizer performance provides realizable clock and LO solutions for stringent spot noise applications in high-interference systems like wireless infrastructure transceivers and software defined radios. The excellent integrated RMS jitter performance is suitable for clock solutions in high-resolution radar systems and high-QAM rate communication systems.

8 Revision History

Changes from Revision * (April 2022) to Revision A (May 2023)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document	1
• Changed *3 GHz* to *3 MHz*	3
• Changed *300 kHz* to *300 Hz*	3