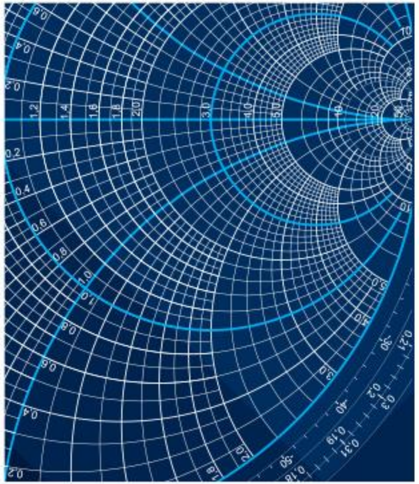
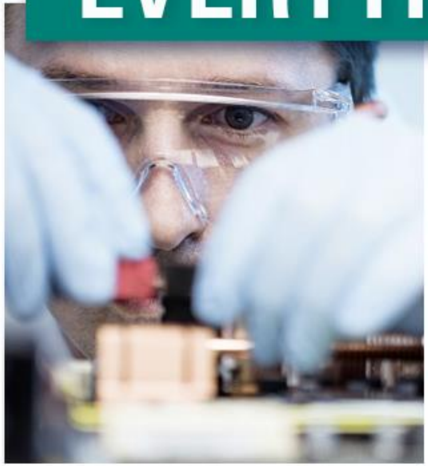


Measurement Techniques

Design Verification & Evaluation

EVERYTHING TEST

Instrument Selection & Optimization



RF TEST: RF Oscillator and VCO Measurements

Rick Daniel
Application Engineer

ROHDE & SCHWARZ
Make ideas real

Agenda

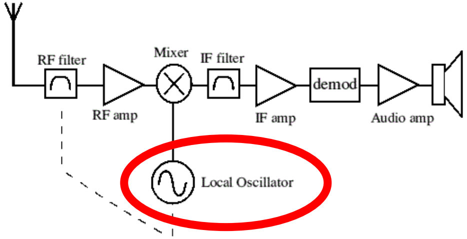
- RF Oscillator Basics
- RF Oscillator Applications
- Common RF Oscillator Measurements
  - Output Power
  - Frequency
  - Phase Noise
  - Harmonics and Spurious
- VCO-Specific Measurements
  - Tuning Sensitivity
  - Tuning Range
  - Settling time
  - Frequency Pushing and Pulling

RF Oscillator Basics

- RF Oscillators generate sinusoidal (CW) signals with output frequencies ranging from kilohertz to tens of gigahertz
- They are generally integrated into higher level assemblies, but are also sometimes used standalone
- Can be fixed frequency or tunable
- Fixed frequency oscillators may have a trim adjustment to allow small frequency changes
- Some RF Oscillator Types
  - Crystal (XO or oven-controlled, OCXO)
  - DRO (Dielectric Resonant Oscillator)
  - VCO (Voltage Controlled Oscillator)
  - MEMS (Microelectomechanical System Oscillator)
  - YIG (yttrium-iron-garnet)
  - Frequency Synthesizer

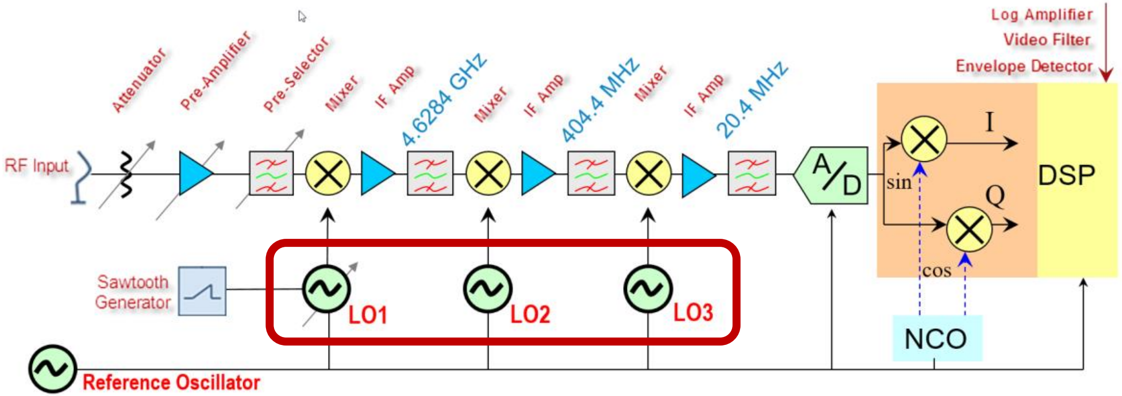
RF Oscillator Applications

- ► Local Oscillators (LO) in Frequency Converters
- ► Clocks for Digital Systems
- ► Reference Oscillators for Frequency Synthesizers
- ► Sweeping Oscillators for Frequency Scanners
- ► Radar Exciters
- ► RF Transmitters
- ► RF Receivers
- ► Many more!



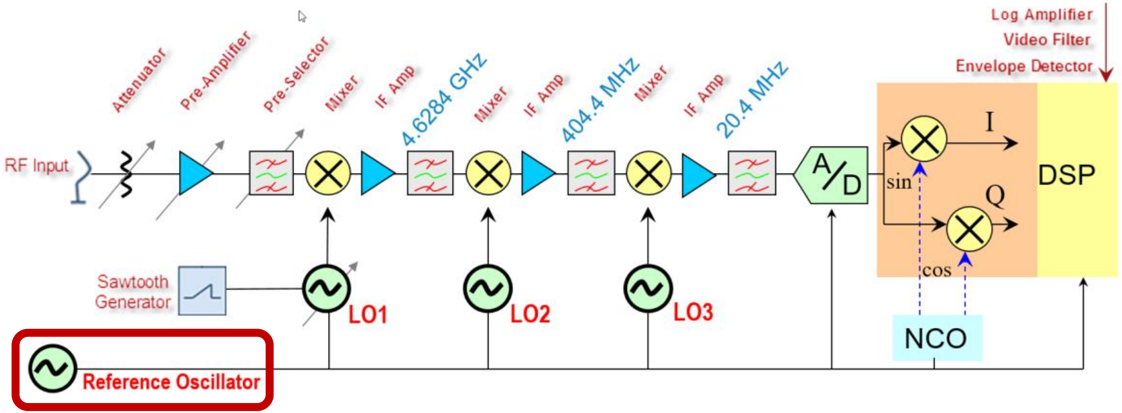
Local Oscillators (LO) in Up/Down Converters

- RF oscillators are commonly used as local oscillators (LO) in up and down converters which are used in transmitters and receivers
- The diagram shows a receiver (as spectrum analyzer) block diagram with three stages of frequency conversion – each stage has an LO
- Power level and phase noise are critical parameters for an LO



Reference Oscillators

► Reference oscillators provide a very stable frequency reference used by the rest of the receiver or transmitter
► 10 MHz reference oscillators are very common, but 100 MHz or higher are also used
► All the LO's in this diagram are synthesized from the reference oscillator so the frequency accuracy and stability of entire receiver is based on the quality of the reference oscillator
► Phase noise and stability are critical parameters for a reference oscillator



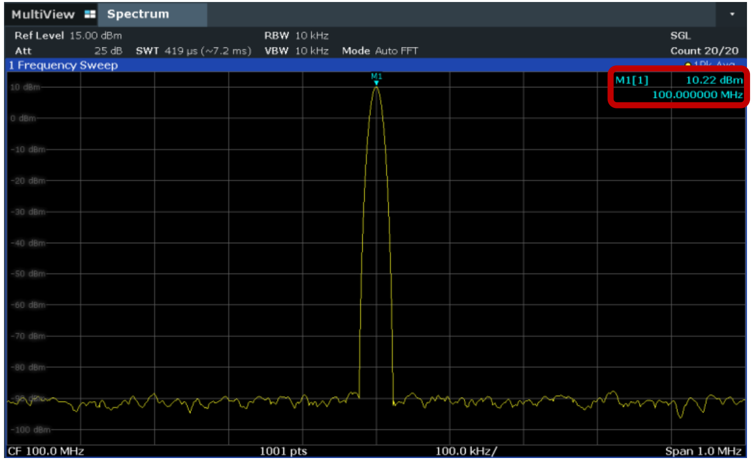
RF Oscillator Measurements

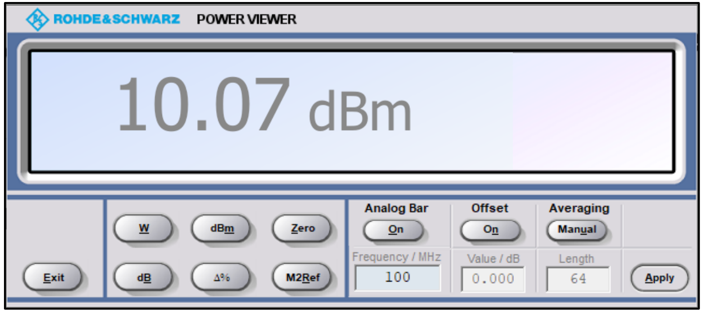
- Common oscillator RF measurements
  - Output Power (over frequency, if tunable)
  - Frequency Accuracy
  - Phase Noise
  - Harmonics
  - Spurious

- Additional measurements for VCOs (Voltage Controlled Oscillators)
  - Tuning Sensitivity (Hz/V)
  - Tuning Range
  - Settling Time
  - Frequency Pushing and Pulling

RF Output Power

- This is a relatively simple measurement that is measured over the frequency range of the oscillator
- The output level is measured using a spectrum analyzer or a power meter
- These are measurements of a 100 MHz OCXO





Frequency Error

- RF frequency used to be measured using a dedicated instrument called a frequency counter
- Frequency counters have been almost entirely replaced with the frequency counter function on modern spectrum analyzers
- Important Points
  - The frequency accuracy of a spectrum analyzer is only as good as its reference, so an external GPS, cesium, or rubidium based reference should be used
  - the standard marker accuracy isn't sufficient – the counter function must be used
- The screenshot shows the frequency of a 10 MHz OCXO to be 10.000000350 MHz → error = 0.35 Hz
- This is expressed in parts per million (ppm) or as a simple ratio in scientific notation
  - 0.35 / 10e6 x 1e6 = 0.035 ppm
  - 0.35 / 10e6 = 3.5 x 10-8

Phase Noise

- Output level and frequency are fairly straightforward concepts and are relatively easy to measure
- Phase noise is more complex, both in concept and in measurement, so we'll spend a little time reviewing the concept of phase noise
- Ideally, the output of an oscillator would be a perfect sine wave, but this is never possible in the real world
- Along with spurious and harmonics, phase noise is a very important measurement of how close an oscillator's output is to the ideal sine wave

What is Phase Noise?

- **Ideal Signal (noiseless)**

  $V(t) = A \sin(2\pi\nu t)$

  where

  A = amplitude

  ν = frequency

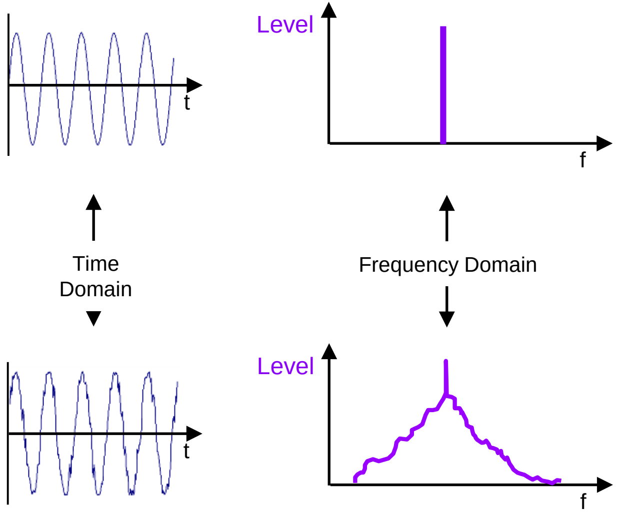
- **Real Signal**

  $V(t) = [A + E(t)] \sin(2\pi\nu t + \phi(t))$

  where

  $E(t)$ = amplitude fluctuations

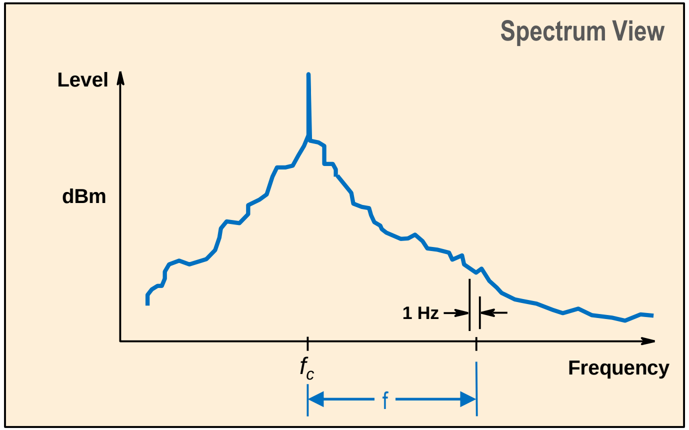
  $\phi(t)$ = phase fluctuations

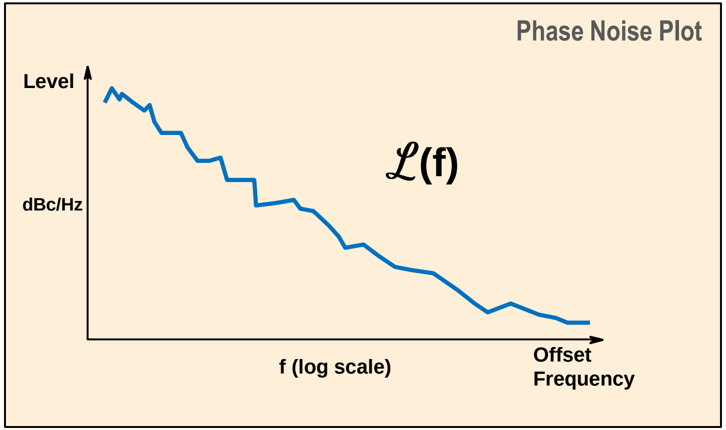


- **Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain**
- **Phase Noise is equivalent to jitter in the time domain**

Phase Noise Concept

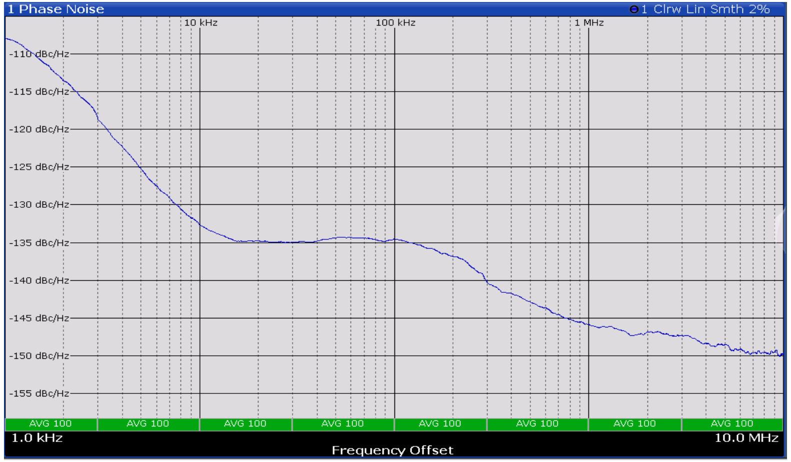
- Phase noise can be thought of as the level of noise in a 1 Hz bandwidth at some offset from the signal frequency, relative to the total signal power (see left graphic)
- $\mathscr{L}$(f) has units of dBc/Hz   ($\mathscr{L}$(f) is pronounced "script L of F")
- A standard phase noise plot displays this with the level (dBc/Hz) on the y-axis and the offset frequency on the x-axis (see right graphic)
- The offset frequency is on a log scale





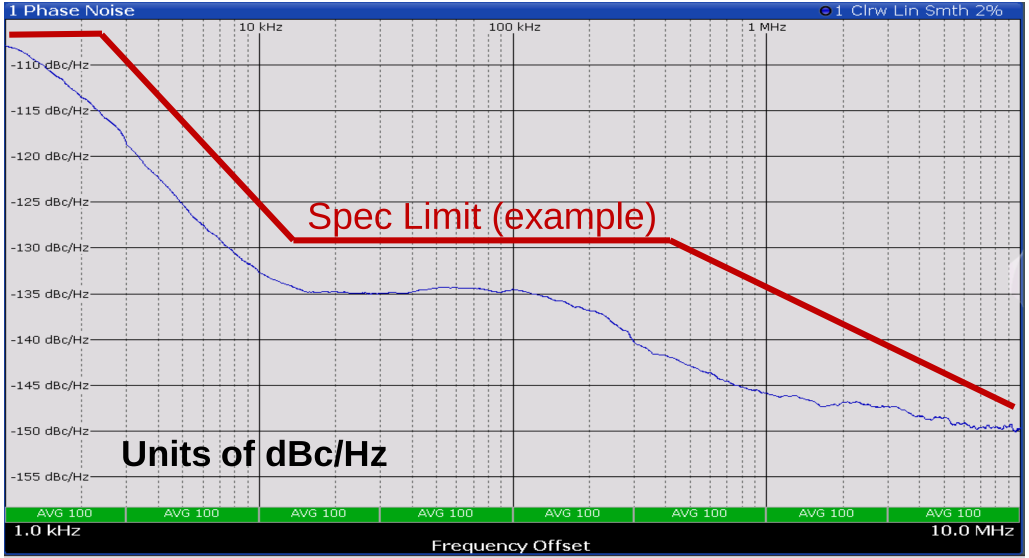
Phase Noise Concept

- Phase noise requirements can be expressed in several different ways
  - The phase noise curve must be below some specified maximum curve
  - Specific points on the curve must be below specified values (spot noise)
  - Integrated phase noise (over a certain range of offset frequencies) must be below a specified value, which can be expressed in units of :
    - dBc (integrated phase noise)
    - Hz (residual FM)
    - Degrees or radians (residual PM)
    - Seconds (jitter)



Quantifying Phase Noise: $\mathcal{L}(f)$

- Plot



- Spot Noise

2 Spot Noise

Type	Offset Frequency [T1]	Phase Noise [T1]
Fixed	1.00 kHz	-107.89 dBc/Hz
Fixed	10.00 kHz	-132.72 dBc/Hz
Fixed	100.00 kHz	-134.53 dBc/Hz
Fixed	1.00 MHz	-145.83 dBc/Hz
Fixed	10.00 MHz	-149.60 dBc/Hz

Spot Noise offsets are user-definable (default to decade offsets)

Integrated Phase Noise

- Values calculated from integration of the phase noise curve

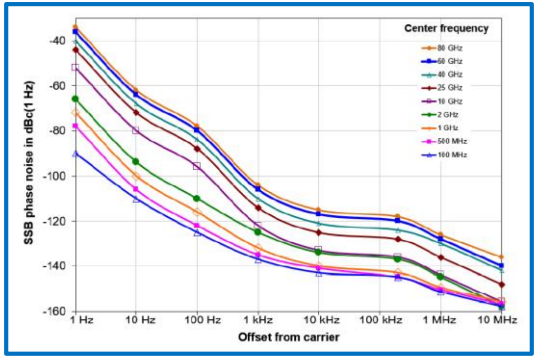
– Integrated Phase Noise	$\int \mathcal{L}(f)df$	(dBc)
– Residual PM	$\frac{180^\circ}{\pi}\sqrt{2\int \mathcal{L}(f)df}$	(deg or rad)
– Residual FM	$\sqrt{2\int f^2 \mathcal{L}(f)df}$	(Hz)
– Jitter	$\frac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)df}$	(sec)

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM	Jitter
1	1	1.000 Hz	1.000 MHz		-71.73 dBc	0.02 °/366.60 µrad	950 mHz	583.460 fs

Measuring Phase Noise

- ► Phase noise can be measured with a Spectrum Analyzer or with a dedicated Phase Noise analyzer (also called a Signal Source Analyzer)
- ► Spectrum analyzers are convenient and fast, but have limited sensitivity due to their own internal phase noise, and their minimum offset frequency is limited to 1 Hz
- ► To determine if a spectrum analyzer is adequate for a particular phase noise measurement, check the spectrum analyzer data sheet for the internal phase noise
- ► The SA's phase noise should be 10 dB or more below the level we want to measure
- ► If spectrum analyzer is not adequate for the measurement, we must use a dedicated phase noise analyzer which can measure 30-40 dB lower phase noise than even the best spectrum analyzer
- ► Phase noise analyzers use very different hardware and measurement techniques than spectrum analyzers

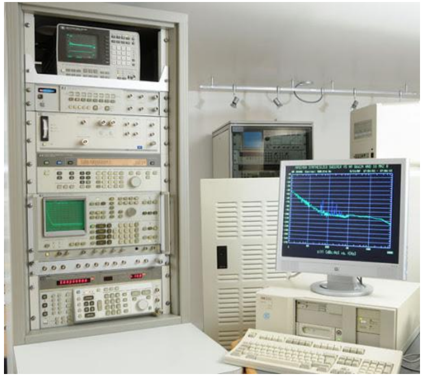


R&S FSW Spectrum Analyzer
Phase Noise (from Data Sheet)

ROHDE&SCHWARZ

Phase Noise Measurement Instruments

- ► Until the early 2000s, a phase noise analyzer was a rack of equipment controlled by a computer and required a two-day training class
- ► Modern phase noise analyzers are single box instruments that look very similar to a spectrum analyzer and can be learned in just a few minutes
- ► Some phase noise analyzers can also function as spectrum analyzers



HP3048 Phase Noise System

FSW Spectrum Analyzer

FSWP Signal Source Analyzer

Phase Noise Measurement

- This screenshot shows a phase noise measurement of a 500 MHz source over an offset range of 100 Hz to 10 MHz

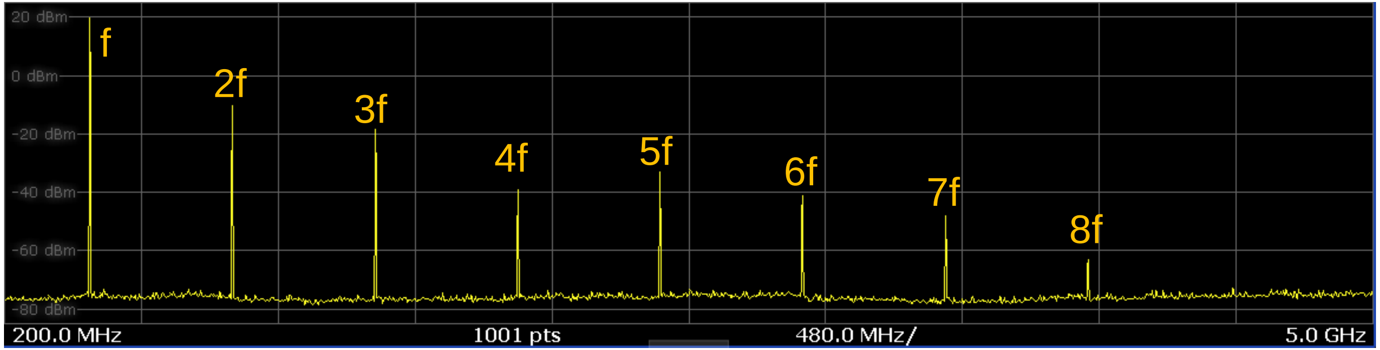
← Phase Noise curve

← Spot Noise values at each offset decade (offset frequencies are user settable)

← Integrated Phase Noise (dBc), Residual PM (deg/rad), Residual FM (Hz), and Jitter (s)

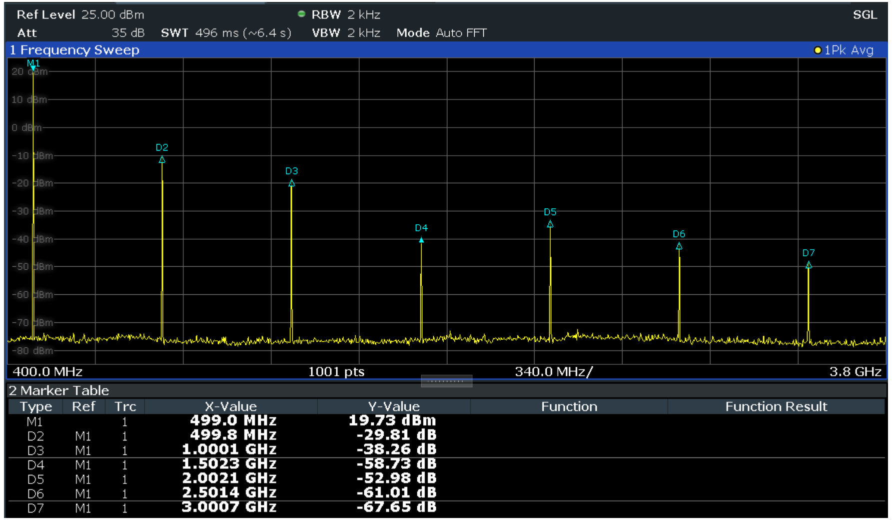
Harmonics

- Harmonics are another measurement of oscillator signal purity
- For a signal at frequency f, harmonic distortion energy falls at 2f, 3f, 4f, …
- Sub-harmonics (f/2 or other fractional ratios) are sometimes present on the output
- Harmonics generally present less of a problem in a design than phase noise, but in some systems the harmonic content must be minimized
- Harmonic levels are expressed as dB relative to the fundamental/carrier, or dBc



Harmonic Measurement

- ► Harmonics are measured using a spectrum analyzer
- ► The traditional test method is to set the spectrum analyzer for a wide sweep that covers the frequency range from the fundamental to the highest harmonic of interest, then use markers and delta markers to measure the various harmonic levels
- ► The resolution bandwidth must be set low enough that the noise floor is well below the measured harmonics, which slows the sweep
- ► This technique works, but the analyzer spends time sweeping between the harmonics (this measurement took ~6.4 seconds)
- ► There is a faster, more efficient method that provides more information

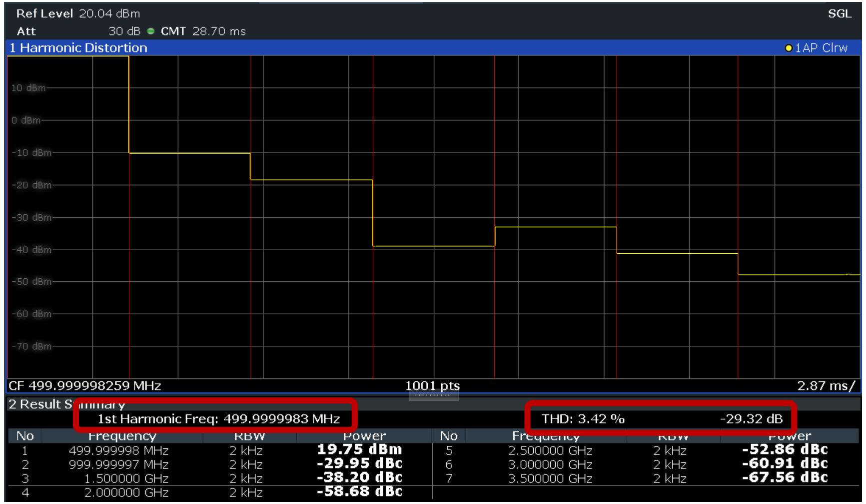


Reference Marker →

Delta Markers →

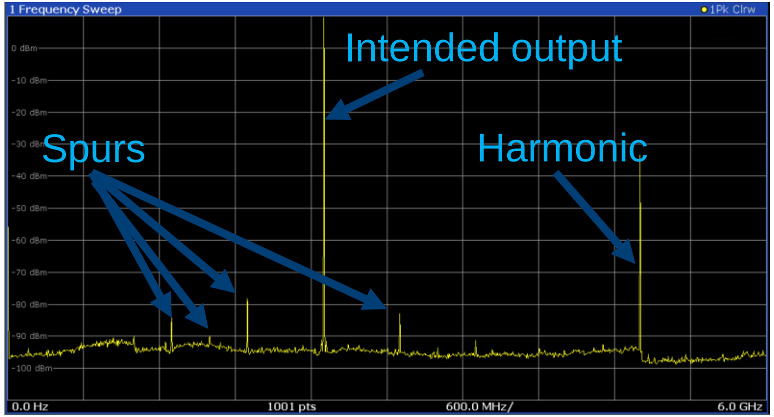
Harmonic Measurement

- Some spectrum analyzers have a harmonic measurement utility
- This utility finds and measures the fundamental frequency very accurately and calculates the harmonic frequencies
- Then the analyzer internally measures only at those frequencies without wasting sweep time between the harmonics
- This technique has advantages:
  - Much faster (29 ms vs. 6.4 s in this example)
  - Measures fundamental frequency with 0.1 Hz accuracy
  - Calculates total harmonic distortion (THD) in units of % and dB



Spurious

- Spurious emissions, or spurs (also called non-harmonic outputs), are unwanted discrete tones produced by the oscillator that are not harmonically related to the output frequency
- Spurious output levels are usually specified lower than harmonic levels (-70 to -100 dBc)
- Spurs are more common in frequency synthesizers than in simple oscillator components like crystals or VCOs
- Common sources of spurs are mixer distortion products, switching power supply clock leakage, leakage from other clocks within a device, etc.
- Spurs are measured using a spectrum analyzer

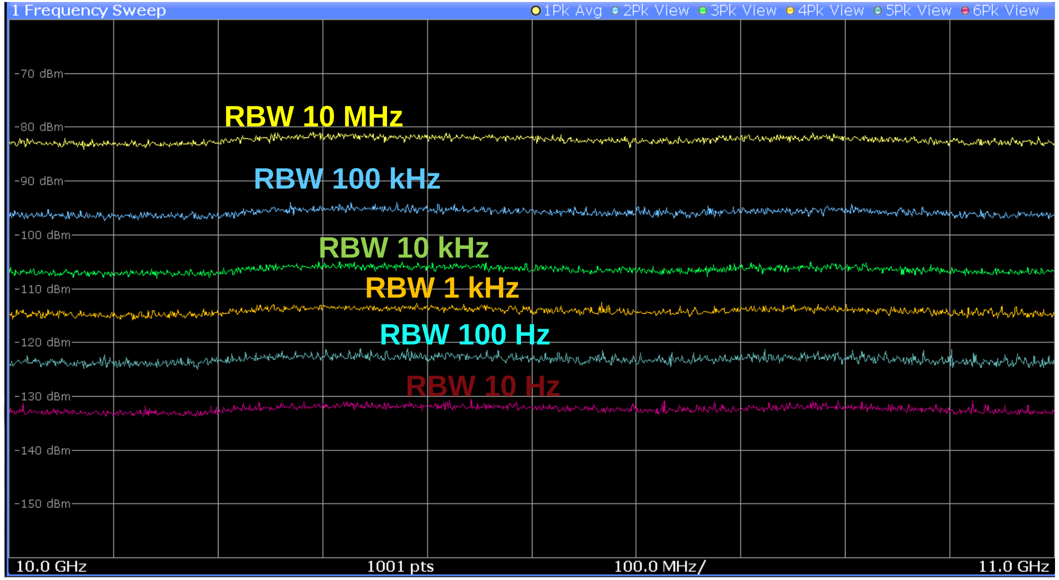


Spurious

- Harmonics are easy to measure because we know exactly where to look
- Spurs are low-level and occur at unknown frequencies so we must search over a wide frequency range (can be many GHz) to look for them
- Spur searching can be a very time-consuming process
  - Spectrum analyzer must sweep over large span
  - Low resolution bandwidth (RBW) necessary to reduce SA noise floor below spur level, which results in slow sweep
  - Many sweep points must be used to accurately measure spur frequency
  - Spurs must be tested to see if they are real or internal to SA

RBW, Noise Floor, and Sweep Time

- We want the SA noise floor to be at least 10 dB below the spurious spec level
- Low noise floor requires low RBW, which results in much longer sweep time
- A low level spur search over a wide frequency range can take hours
- Noise floor varies with frequency – use segmented sweep for optimized RBW



.06 s/GHz

1.2 s/GHz

25 s/GHz

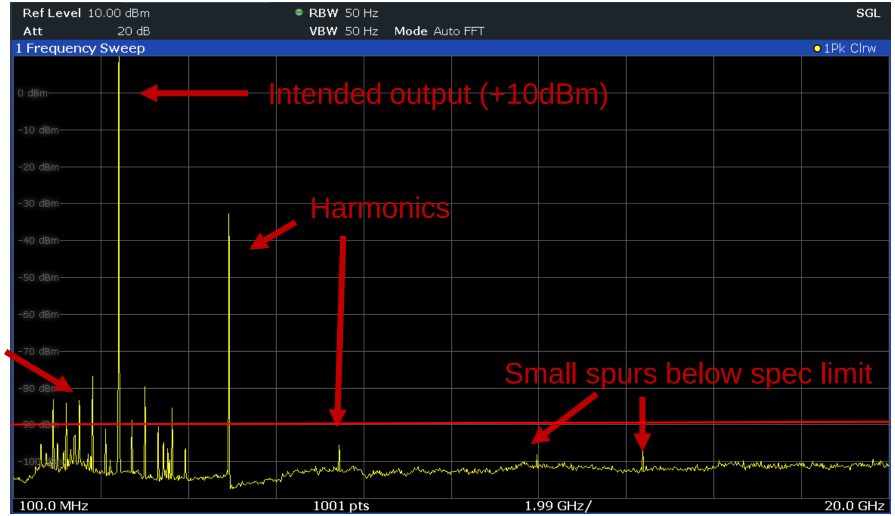
276 s/GHz

456 s/GHz

2428 s/GHz (>40 minutes/GHz)

Spurious Measurement

- Example spurious spec:
  Output at 2.5 GHz, +10 dBm, non-harmonic spurs must be < -90 dBm from 100 MHz – 20 GHz
- Since we're searching for -90 dBm spurs, our noise floor should be < -100 dBm
- We have to set the input attenuator to 20 dB to accommodate the +10 dBm intentional signal which raises the noise floor, so we have to use a low 50 Hz RBW filter to get the required noise floor
- It can be a time consuming iterative process to find the optimum RBW
- The resulting sweep time is 4m 40s

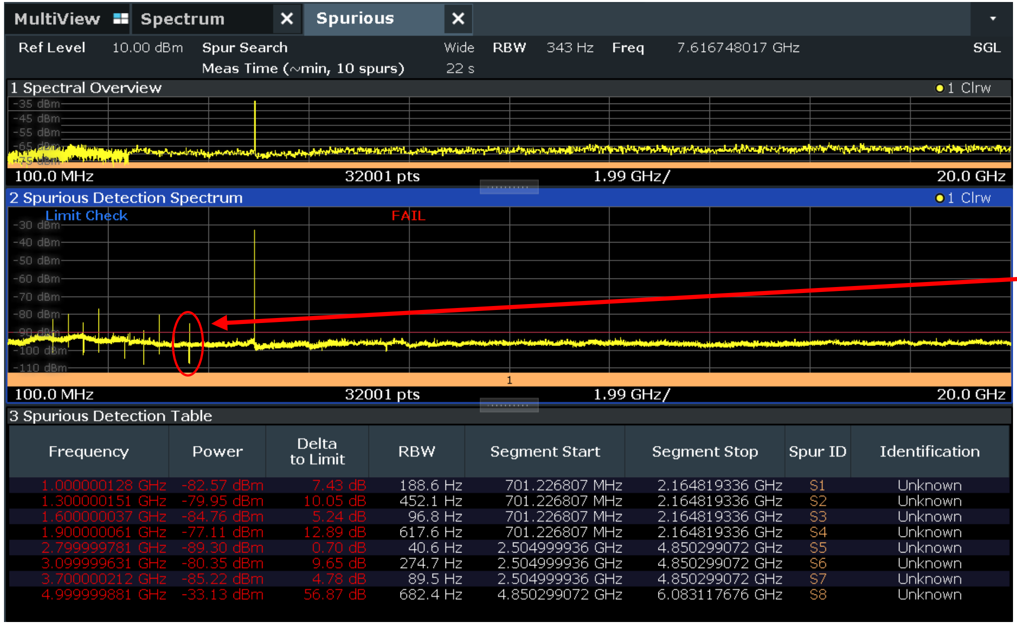


Fast Spurious Measurement

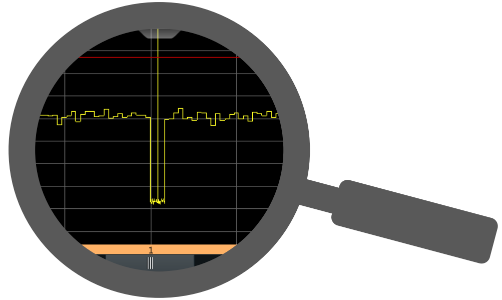
- There is a more modern way to do spur searching that uses a three step process using FFT technology
  - Step 1: SA does a fast sweep to estimate its noise floor. Since the noise floor varies over frequency, the analyzer divides the sweep into segments, each with its own optimum RBW setting
  - Step 2: SA does a sweep with a minimal 2-3 dB noise floor margin and generates a list of candidate spurs (many of these could be SA spurs or false spurs due to the high noise floor)
  - Step 3: SA measures each candidate spur in a small bandwidth with a much smaller RBW (more noise floor margin) to determine if it is a real spur (not an SA spur) and to accurately measure its frequency and level
- This approach saves setup time (no trial and error to manually determine optimum RBW)
- Measurement time is also faster – the lower the required spur measurement level, the bigger the speed advantage – up to 40x faster

Fast Spurious Measurement

- This is the same measurement as before using the fast spur search technique
- This measurement was easier to setup and took about 46 seconds (vs 4m 40s)



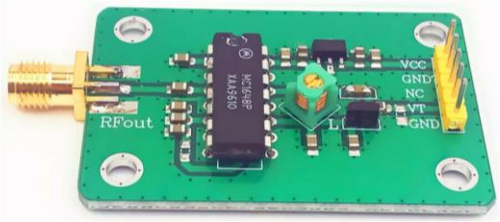
Frequency	Power	Delta to Limit	RBW	Segment Start	Segment Stop	Spur ID	Identification
1.000000128 GHz	-82.57 dBm	7.43 dB	188.6 Hz	701.226807 MHz	2.164819336 GHz	S1	Unknown
1.300000151 GHz	-79.95 dBm	10.05 dB	452.1 Hz	701.226807 MHz	2.164819336 GHz	S2	Unknown
1.600000037 GHz	-84.76 dBm	5.24 dB	96.8 Hz	701.226807 MHz	2.164819336 GHz	S3	Unknown
1.900000061 GHz	-77.11 dBm	12.89 dB	617.6 Hz	701.226807 MHz	2.164819336 GHz	S4	Unknown
2.799999781 GHz	-89.30 dBm	0.70 dB	40.6 Hz	2.504999936 GHz	4.850299072 GHz	S5	Unknown
3.099999631 GHz	-80.35 dBm	9.65 dB	274.7 Hz	2.504999936 GHz	4.850299072 GHz	S6	Unknown
3.700000212 GHz	-85.22 dBm	4.78 dB	89.5 Hz	2.504999936 GHz	4.850299072 GHz	S7	Unknown
4.999999881 GHz	-33.13 dBm	56.87 dB	682.4 Hz	4.850299072 GHz	6.083117676 GHz	S8	Unknown



VCO Measurements

- The measurements discussed to this point apply to all RF oscillator types
- Voltage Controlled Oscillators (VCO's) and other tunable oscillators have some additional parameters that may need to be tested
  - Tuning range
  - Tuning sensitivity
  - Settling time
  - Frequency pushing (output frequency change vs supply voltage)
  - Frequency pulling (output frequency change vs load impedance)

VCO-0964



MC1648 VCO

VCO Measurements

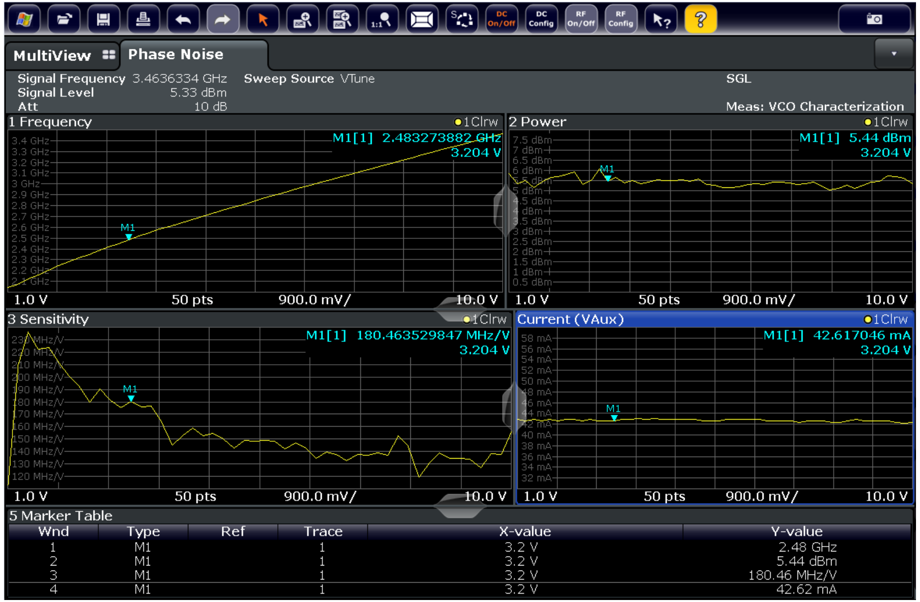
- VCO testing requires a spectrum analyzer, phase noise analyzer, and up to three controllable power supplies for tuning range and sensitivity measurements
- In the past, this required separate instruments and controlling software, but modern Signal Source Analyzers integrate all these functions into a single instrument
- SSA's have many built-in functions geared specifically for VCO testing
  - Two V_{supply} outputs for frequency pushing measurements
  - A low-noise V_{tune} output for tuning range and sensitivity
  - A spectrum analyzer for output power, spurious, and harmonic testing
  - A phase noise analyzer for low-level phase noise and for tracking drifting sources

Controllable V_{supply} and V_{tune} outputs

R&S FSWP Phase Noise Analyzer and VCO Tester

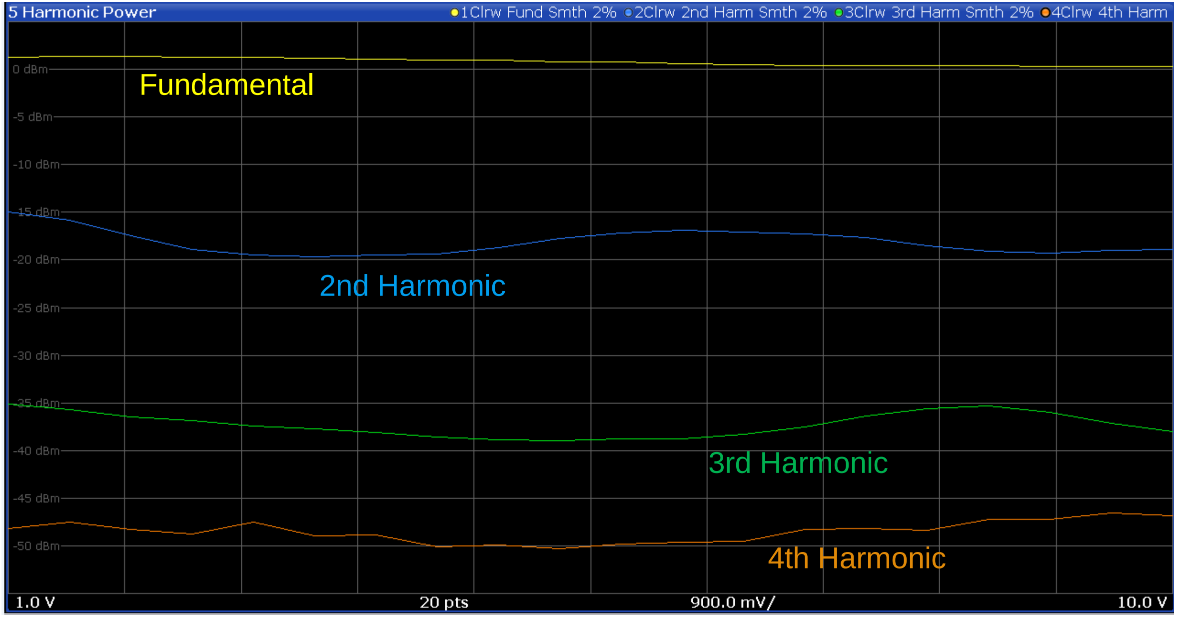
VCO Performance vs Tuning Voltage

- This screenshot shows four measurements, all as a function of Tuning Voltage (V_{tune})
  - Output Frequency, Output Power, Tuning Sensitivity, and Supply Current
- The analyzer measures these four quantities as it sweeps the tuning voltage from 1 to 10 V



Harmonic Levels vs Tuning Voltage

► Measurement of the fundamental, 2nd, 3rd, and 4th harmonic output levels vs tuning voltage



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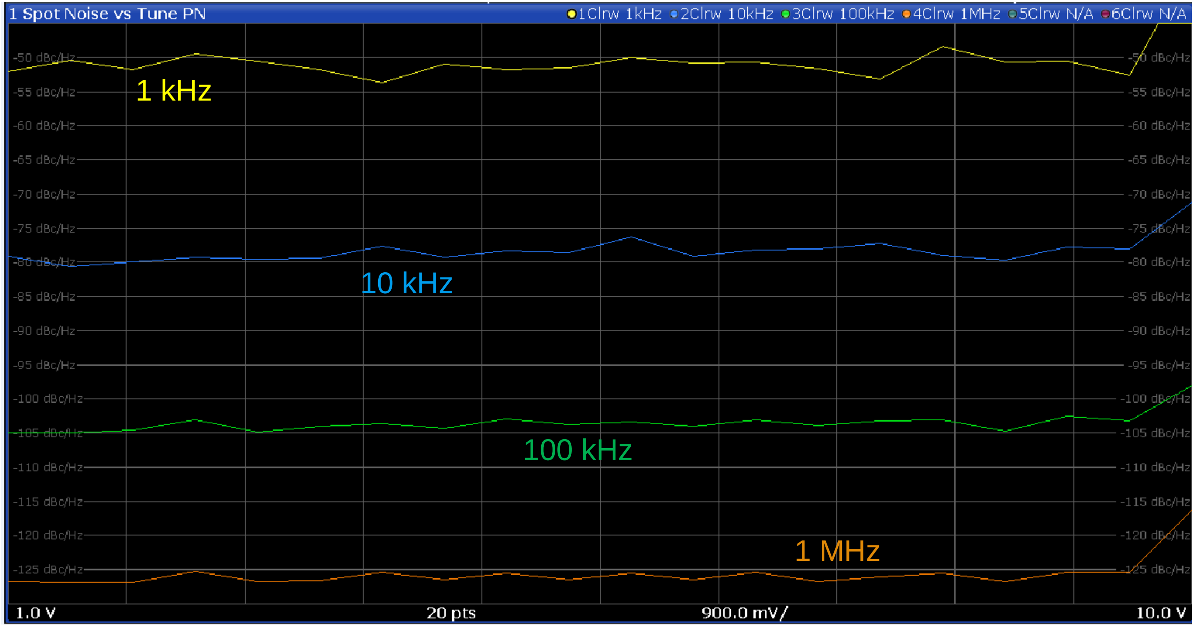
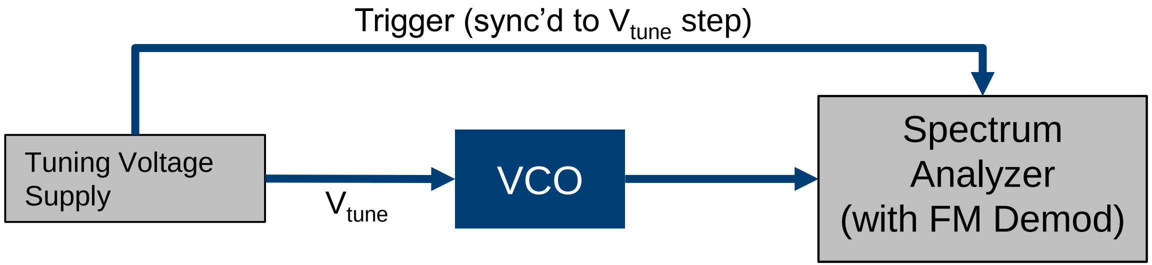
Phase Noise vs Tuning Voltage

▶ Measurement of phase noise (spot noise at four offsets) vs tuning voltage



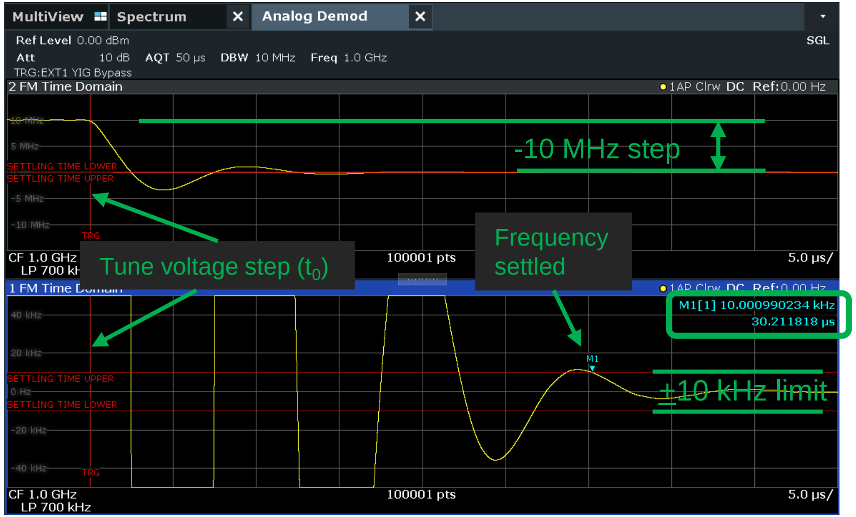
Settling Time

- VCOs are tunable, so the tuning speed, or settling time, is often specified
- The settling time is typically defined as the time between a step change in tuning voltage (t0) and the point when the output frequency is within some tolerance of the final frequency
- Settling time is measured using a spectrum analyzer with an FM demodulation function to measure the instantaneous output frequency of the VCO



Settling Time Measurement

- V_{tune} is stepped down to change the VCO output frequency (-10 MHz in this example)
- The step in V_{tune} establishes t_0 and triggers the 'Frequency vs Time' measurement
- The measurement is shown in two different scales to illustrate the overall step (top) and zoomed in (bottom) to view the final settling to within 10 kHz
- The measured settling time is 30.21 us (10 MHz step settles within +10 kHz in 30.21 us)

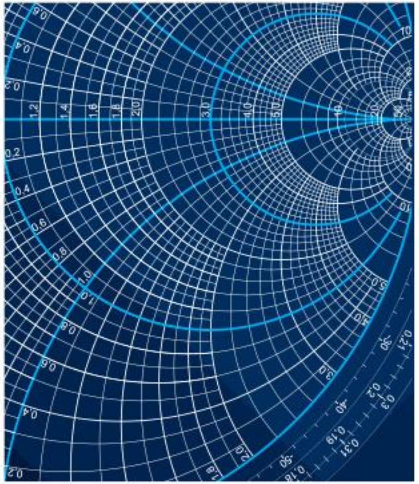


Scale: 5 MHz/div

Scale: 20 kHz/div

SUMMARY / Q&A

- RF oscillators are used to create high-frequency sinusoidal signals and are used in a wide variety of RF equipment
- Several types of RF oscillators are available, from fixed frequency crystal oscillators to tunable voltage controlled oscillators
- Characterizing RF oscillators, especially tunable devices, requires a lot of testing over a wide range of input conditions
- Modern test equipment makes performing these measurements far easier than it was even a few years ago



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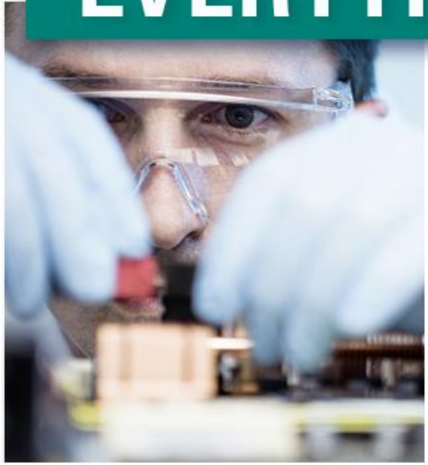
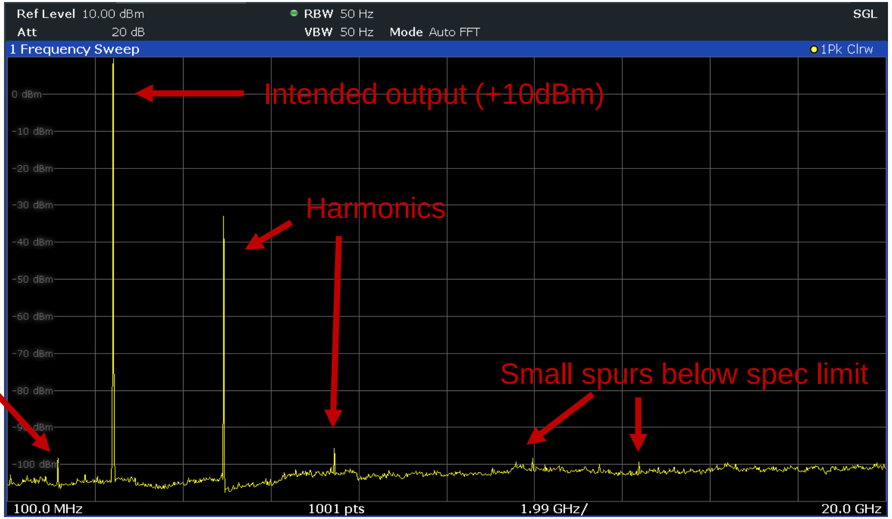


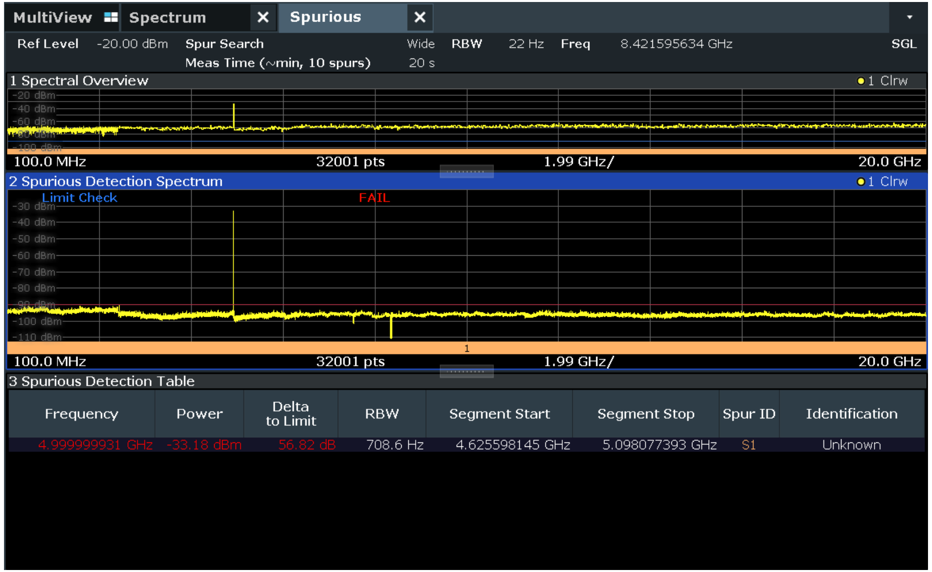
Spurious Measurement

- Example spurious spec:
  Output at 2.5 GHz, +10 dBm, non-harmonic spurs must be < -90 dBm from 100 MHz – 20 GHz
- Since we're searching for -90 dBm spurs, our noise floor should be < -100 dBm
- We have to set the input attenuator to 20 dB to accommodate the +10 dBm intentional signal which raises the noise floor, so we have to use a low 50 Hz RBW filter to get the required noise floor
- It can be a time consuming iterative process to find the optimum RBW
- The resulting sweep time is ~5 minutes



Fast Spurious Measurement

- ► This is the same measurement as before using the fast spur search technique
- ► The only spur found is actually the second harmonic
- ► This measurement was easier to setup and took about 43 seconds (vs 5 minutes)



Frequency	Power	Delta to Limit	RBW	Segment Start	Segment Stop	Spur ID	Identification
4.999999931 GHz	-33.18 dBm	56.82 dB	708.6 Hz	4.625598145 GHz	5.098077393 GHz	S1	Unknown