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Determining the FM Bandwidth of a Wideband Varactor Tuned VCO

General Description

The most basic characteristic of a Voltage Controlled Oscillator (VCO) is the manner in which the oscillator changes frequency as a function of voltage applied to its tuning port. As the state of the art has evolved, the demands placed on VCO's to change frequency in a more agile fashion have increased. VCO's used in phase lock loops are required to acquire phase lock more rapidly. Spread spectrum communications systems are demanding VCO's that can provide direct FSK modulation at faster rates. Frequency hopping radios are changing frequency at ever increasing rates. The common thread in all these applications is a VCO characteristic, Frequency Modulation Bandwidth (FM BW) . Every VCO will have a specified static frequency versus tuning voltage response as well as a tuning sensitivity over the allowed tuning voltage range. The tuning sensitivity curve versus tuning voltage should theoretically be the first derivative of the tuning voltage response versus tuning voltage. A typical room temperature tuning curve for a HMC385LP4 (2.25 – 2.5 GHz) MMIC VCO with buffer amplifier is shown in figure 1 over the specified tuning voltage range.
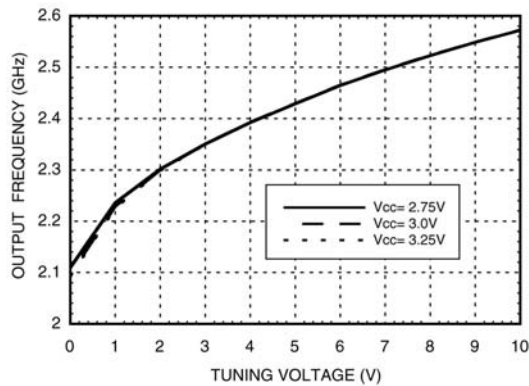

Figure- 1 HMC385LP4 Frequency vs. Tuning Voltage, T=25°C

The corresponding typical tuning sensitivity curve versus tuning voltage for the HMC385LP4 is shown in figure 2. Note that the tuning voltage ranges where the HMC385LP4 tuning curve is the most linear correspond to the tuning voltage ranges where the tuning sensitivity is most constant.
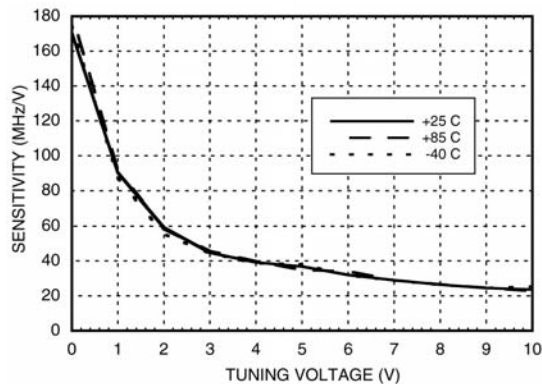

Figure- 2 HMC385LP4 Sensitivity vs. Tuning Voltage, VCC=3V

If a time varying voltage is applied to the tuning port of the VCO, the frequency of the VCO will vary around the frequency determined by the static (DC) voltage applied to the tuning port. The resulting signal from the VCO is a frequency modulated (FM) carrier where the carrier frequency is determined by the DC voltage applied to the VCO tuning port, the FM deviation is determined by the peak to peak voltage of the time varying voltage applied to VCO tuning port and the modulation frequency is determined by the rate of change of the time varying voltage applied to the VCO tuning port. In an ideal VCO, the frequency of the oscillator would faithfully follow the tuning voltage regardless of how fast or how slow that tuning voltage is changed. In a practical VCO, the frequency deviation produced for a constant peak to peak voltage reduces as the frequency of the tuning voltage (modulation frequency) increases. The frequency at which the frequency deviation is reduced to 0.707 (or –3 dB) of the DC or low frequency value is a measure of the frequency response of the tuning port of the VCO. This frequency response will have a low pass characteristic and is commonly referred to as the 3dB FM bandwidth of the VCO. Unfortunately, the VCO FM bandwidth is rarely specified on the data sheet for a VCO.

Application Problem

The FM bandwidth of the VCO is an important piece of design information for applications that require knowledge of how fast a VCO will respond. This bandwidth can be considered the fastest data rate that can be used to FM modulate the VCO. It also corresponds to the fastest rate that can be expected to lock or acquire the VCO in a phase lock loop. Even when FM bandwidth is specified, it is difficult to verify the bandwidth, especially for the desirable VCO's that have FM bandwidths exceeding 10 MHz. Most of the measurement techniques previously described in the literature work for VCO's that have a low to moderate FM bandwidth, but run into practical limitations when high FM bandwidth measurements are attempted.

One of the measurement techniques described in the literature takes advantage of the spectral response of a FM modulated carrier in order to determine the FM bandwidth of the VCO. Since this spectral response follows a Bessel function characteristic, there will be predictable nulls in this response with certain combinations of the ratio of the frequency deviation and modulation frequency. This ratio is known as the modulation index, β. Figure 3 shows the Bessel functions that correspond to the relative amplitude

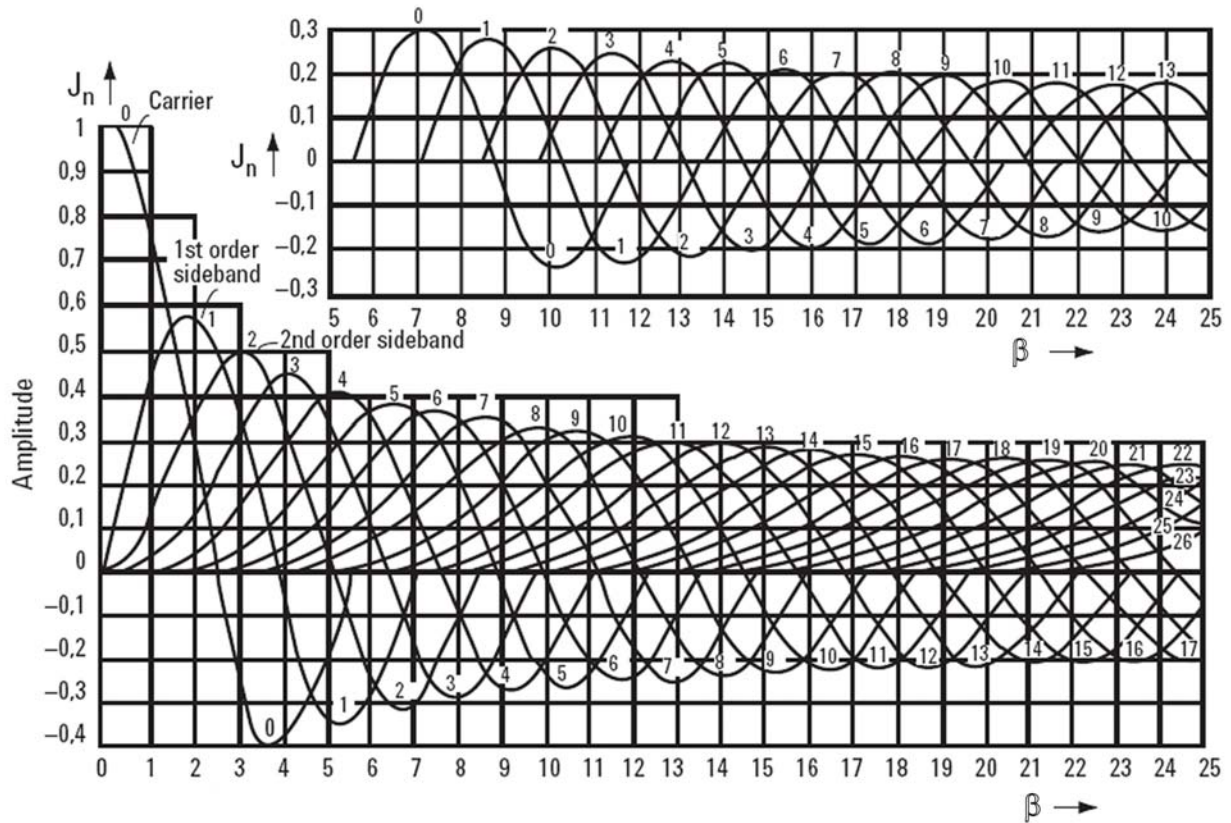of the carrier and the various modulation sidebands as a function of modulation index, β.

Figure- 3 Bessel Functions for FM carrier and sideband amplitude

$\beta = \Delta f_{peak} / f_{modulation} = \Delta f_p / f_m$
where
β**= Modulation Index**
Δf_p**= Peak Frequency Deviation**
f_m**= Frequency of the Modulated Carrier**

Carrier	$J_0 = 0$
First Order Sideband	$J_1 = 0.34$
Second Order Sideband	$J_2 = 0.49$
Third Order Sideband	$J_3 = 0.31$, **etc.**

Values of Modulation Index Where Carrier Amplitude is Zero

Order of Carrier Zero	Modulation Index
1	**2.40**
2	**5.52**
3	**8.65**
4	**11.79**
5	**14.93**
6	**18.07**
n (n >6)	**18.07 + π(n-6)**

The frequency deviation is directly related to the peak to peak tuning voltage applied to the VCO tuning port and the tuning sensitivity (MHz / Volt) of the VCO. Figure 4 shows the relationships between the

carrier frequency, the modulation frequency, the peak frequency deviation and the modulation index, β, as they appear in the frequency domain on a spectrum analyzer.
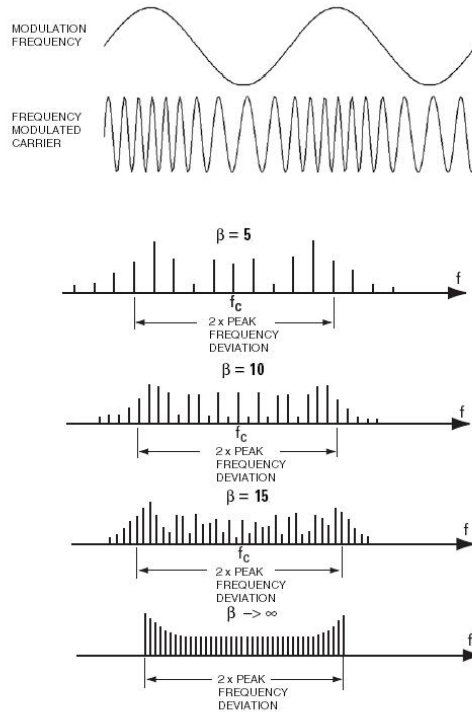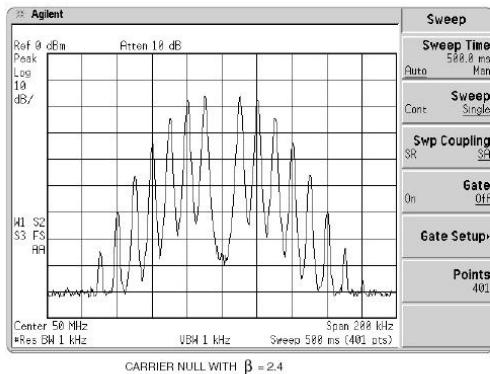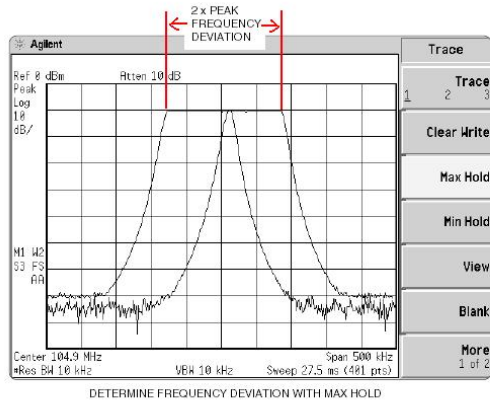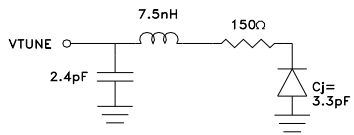

Figure- 4 FM Measured on a Spectrum Analyzer

The easiest way to observe the peak frequency deviation is to put the display of the spectrum analyzer into Max Hold and allow the carrier to trace out the peak to peak frequency excursions as shown in the upper left hand picture in figure 4. This peak to peak excursion will be equal to twice the frequency deviation. The lower right hand picture in figure 4 shows how the carrier and the primary sidebands predicted by the Bessel functions in figure 3 will appear in the frequency domain as a function of modulation index, β.   Note that the Bessel function for the carrier frequency has a null when the modulation index is equal to (2.4). The lower left hand picture in figure 4 shows how this carrier null would appear on a spectrum analyzer.

It has been suggested that this carrier null with β = 2.4 can be used to measure FM bandwidth of a VCO. Assuming that the tuning sensitivity of the VCO is constant, if both the peak to peak voltage and the modulation frequency are increased by the same amount then the modulation index will remain at 2.4 and the carrier will remain at the null. For a practical VCO, however, the carrier will eventually emerge as the modulation frequency is increased. When the carrier level is – 8 dBc below the un-modulated carrier, the modulation index has decreased to 1.697 which corresponds to a 3 dB decrease in modulation index. The corresponding modulation frequency is then declared the 3 dB FM bandwidth. Unfortunately, this technique becomes inapplicable because the tuning sensitivity of a wideband microwave varactor tuned VCO is rarely, if ever, constant and will change in an increasingly nonlinear fashion as the peak to peak voltage applied to the tuning port of the VCO is increased. This is especially true on a VCO with high FM bandwidth. Therefore, it is difficult to separate the changes in the modulation index that are due to the changes in tuning sensitivity from those due to approaching the 3 dB FM bandwidth. This renders this measurement technique impractical for high modulation bandwidth VCO's.

In the Hittite Microwave Designer's Guide, in the VCO data sheets is a simplified description of the Voltage Tuning (VTUNE) Port of the VCO in the section of Pin Descriptions. Figure 5 shows the appropriate portion of this table for the HMC385LP4 2.25 – 2.5 GHz MMIC VCO with Buffer Amplifier.

Pin Number	Function	Description	Interface Schematic
22	VTUNE	Control Voltage Input. Modulation port bandwidth dependant on drive source impedance.	

Figure- 5 HMC385LP4 VTUNE Pin Description

This circuit, if used with the appropriate boundary conditions, will yield reasonable simulation results for VTUNE port match and a conservative simulation of FM bandwidth. The following plots shown in figure 6 are a comparison of simulated versus measured for the VTUNE Port Match for a HMC385LP4 MMIC VCO with Buffer Amplifier (2.25 – 2.5 GHz). The simulation was performed using Eagleware Genesys 2004.03 linear CAE software. The VTUNE port was characterized from 30 KHz to 300 MHz. Unfortunately, not all of the necessary boundary conditions that must be used for the simulation are given on the VCO data sheet. The input impedance of the input port needs to be set to the same value as the series resistor in the VTUNE circuit. In addition, a shunt capacitance needs to be added across the varactor capacitance and the impedance of the output port needs to be set to a higher impedance in order to account for the effects of the VCO resonator and oscillator circuit. These values can be arrived at by making S11 measurements of the VCO VTUNE port and optimizing these two elements in the equivalent circuit in the linear simulator. Simulated data for the FM bandwidth using this equivalent circuit predicted an FM bandwidth of 42 MHz. The FM bandwidth derived in this fashion will usually be lower than the actual measured FM bandwidth of the VCO. A wideband measurement technique must be used to accurately determine the FM bandwidth of a wideband VCO such as the Hittite Microwave series of MMIC VCO's. The corresponding FM bandwidth measured on the HMC385LP4 was 66.6MHz.
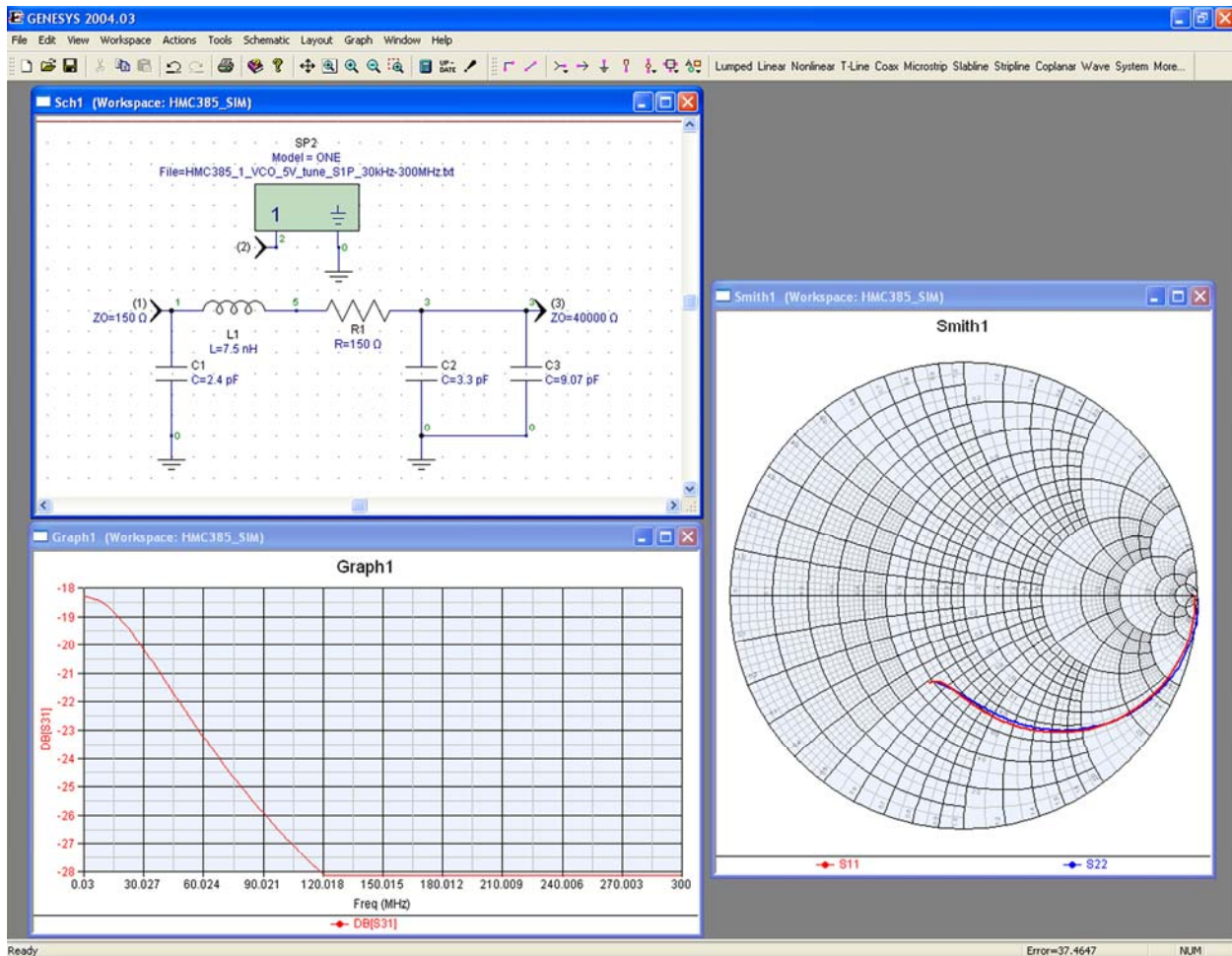
Figure - 6 HMC385LP4 Simulated VTUNE Port

Application Solution and Measurement Approach

Several measurement approaches were evaluated in order to determine the best approach to be used to characterize wide modulation bandwidth VCO's. In addition to the spectrum measurements and modeling approach previously mentioned, the delay line discriminator approach was attempted and ruled out because of the lack of sensitivity at the bandwidths that had to be measured. Ultimately, a direct measurement approach was adopted because of the ease, sensitivity and accuracy of the resulting measurements. The direct VCO FM bandwidth test system used is shown in figure 7. A wideband,(6 GHz BW) Digitized Sampling Oscilloscope (DSO), in conjunction with Vector Signal Analysis (VSA) software was used as the receiver in the test system. A synthesized signal generator was used to apply a step frequency sweep from 100 KHz to 100 MHz at a constant 10 mV rms level to the VTUNE port of the VCO through the RF port of a low frequency bias tee. An additional DC voltage, (6V) was applied through the DC port of the low frequency bias tee and used to adjust the VCO frequency to somewhere in the middle of it's tuning range.

The output of the VCO was continuously sampled by the DSO. The VSA software was first used to perform a Fast Fourier Transform (FFT) on the sampled data to determine the carrier frequency of the VCO. The VSA software was then adjusted to use the carrier frequency as the center frequency and set a frequency span of 200 MHz (Trace A). The VSA software was then set up to perform additional Digital Signal Processing (DSP) on the sampled data. Next, an analog FM demodulation of the data was performed. This processed data then had an additional FFT performed to display the frequency spectrum of the FM demodulated VCO output (Trace B). Both traces were placed in maximum peak hold in order

to trace out the frequency response for both the VCO spectrum as well as the VCO FM demodulated spectrum as the modulation frequency was slowly stepped between 100 KHz and 100 MHz with 401 points. The 3 dB FM bandwidth is simply the frequency at which the VCO FM demodulated spectrum response drops by 3 dB from the low modulation frequency or constant value.
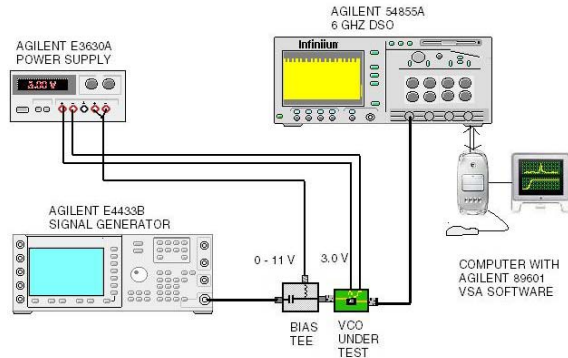
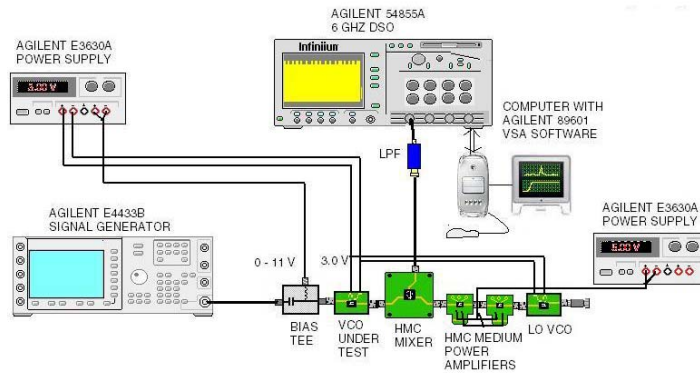**Figure- 7 Direct VCO FM Bandwidth Test System**

A measurement was made using this test system on a HMC385LP4 MMIC VCO with buffer amplifier and the resulting data is shown in figure 8 as a screen capture form the VSA software. The top trace is the frequency spectrum of the VCO integrated using maximum hold as the modulation frequency was changed from 100 kHz to 100 MHz.
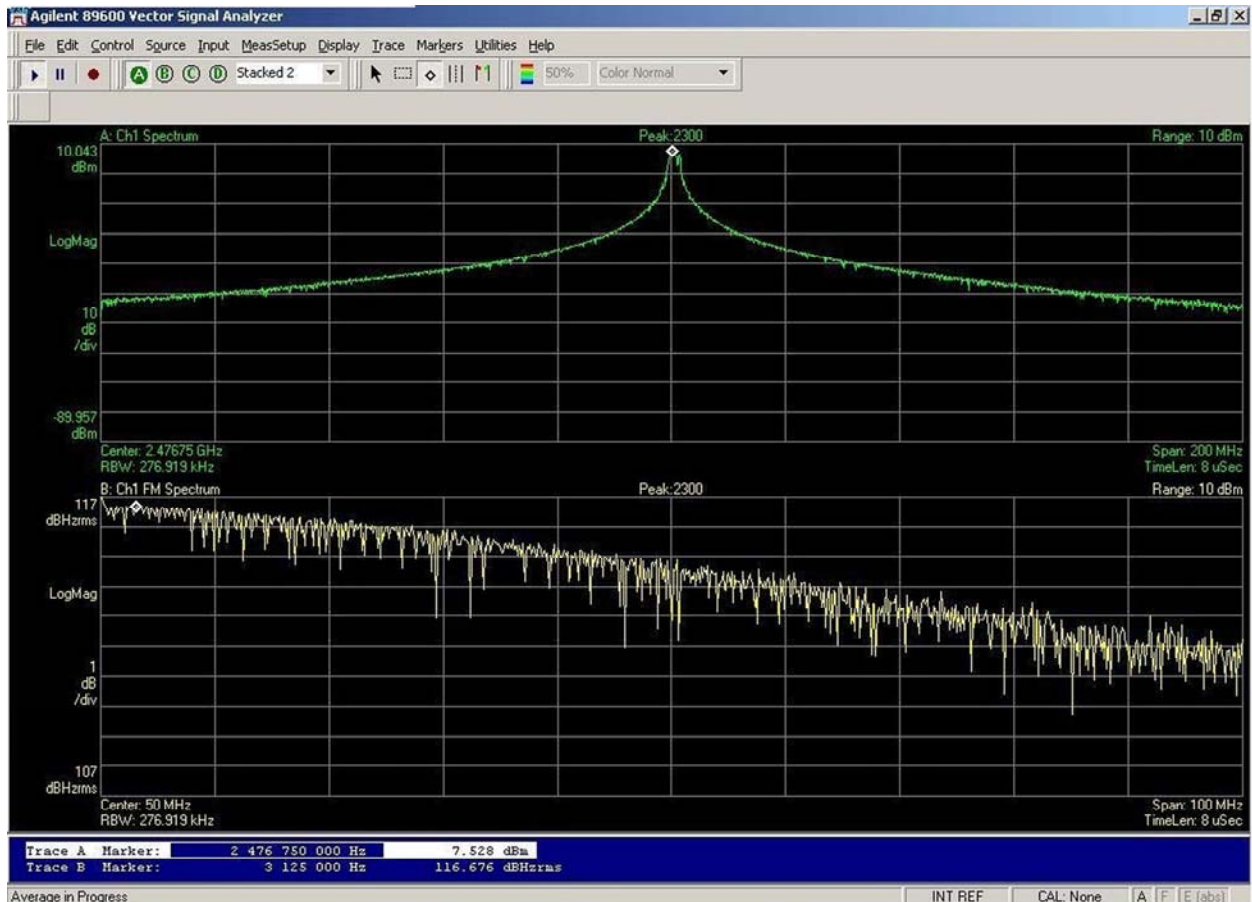
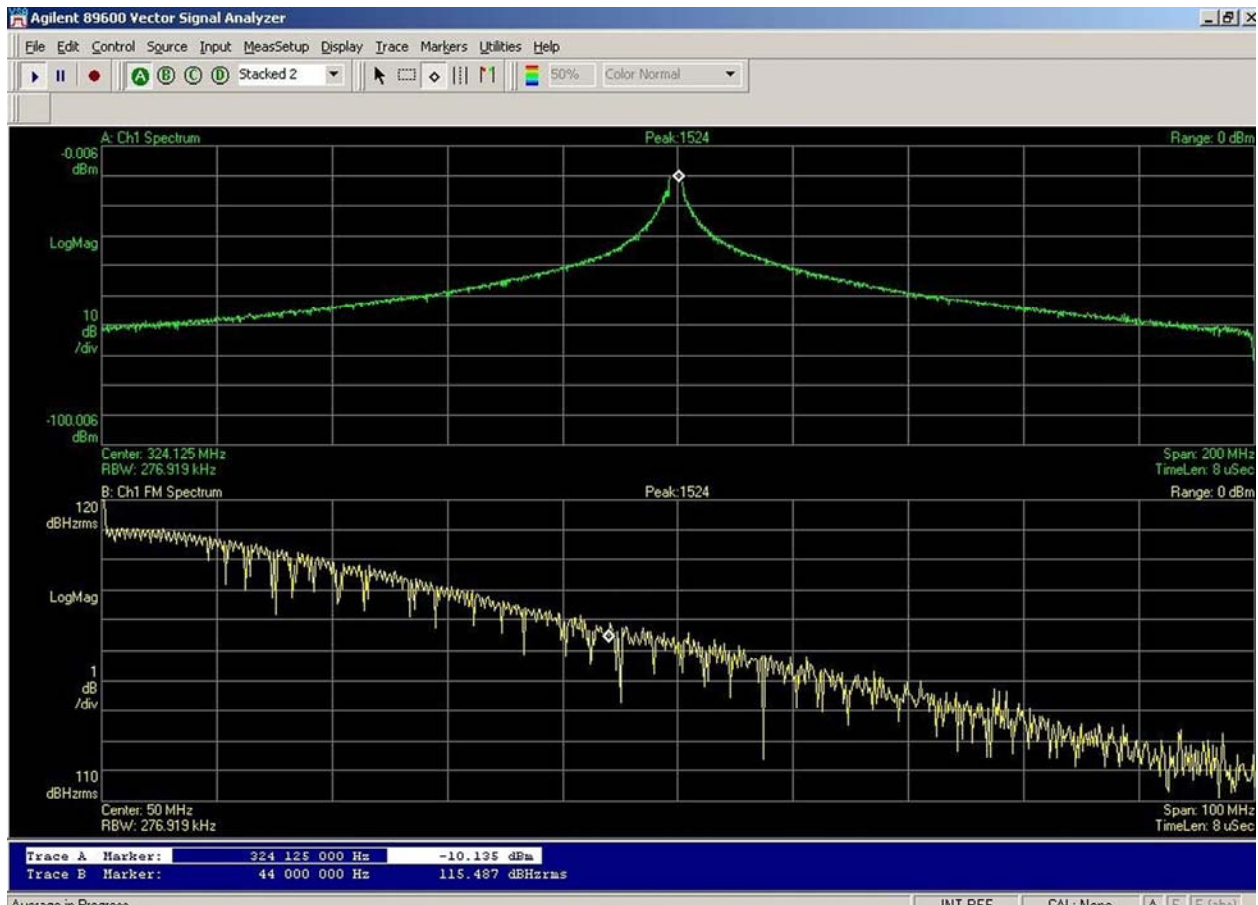**Figure- 8 Measured 3dB FM BW for HMC385LP4 VCO**

The bottom trace is the FM demodulated spectrum of the VCO traced out using maximum hold as the modulation frequency was changed from 100 kHz to 100 MHz. The frequency at which the VCO FM demodulated spectrum response drops by 3 dB from the low modulation frequency for this VCO is 66.6 MHz.

For VCO's that operated above the 6 GHz bandwidth of the DSO, the output of the VCO was down-converted to a frequency range within the instrument's bandwidth. A low pass filter was used on the IF output of the down-converter in order to allow only the desired mixing product into the input of the DSO. A convenient LO is just a second VCO of the type that is to be measured. The modified down-converted direct FM bandwidth test system is shown in figure 9. In most cases, it is unnecessary to provide a tuning voltage to the second VCO used as the LO. The mixer used for the down-converter was a HMC double balanced mixer mounted on an evaluation board that covered the frequency range of the VCO's on its RF and LO ports and had a DC IF output with at least 200 MHz bandwidth.

Figure- 9 Down-converted Direct VCO FM Bandwidth Test System

Measurements made on a HMC401QS16G MMIC VCO with Divide by 8 (13.2 – 13.5 GHz) are shown in figure 10. The LO VCO produced an IF frequency of 324 MHz. A HMC412MS8G double balanced mixer was used as a down-converter. The power level of the fundamental LO VCO (HMC401QS16G) output was boosted to +13 dBm using a cascaded pair of HMC441LP3 medium power amplifiers (6.5 -13.5 GHz). A 500 MHz Low Pass Filter was used on the IF output of the down-converter to prevent the other mixing products from entering the input of the DSO and potentially causing aliasing error. The top trace is the frequency spectrum of the VCO down-converted to 324 MHz and integrated using maximum hold as the modulation frequency was changed from 100 kHz to 100 MHz. The bottom trace is the FM demodulated spectrum of the down-converted VCO traced out using maximum hold as the modulation frequency was changed from 100 kHz to 100 MHz. The frequency at which the VCO FM demodulated spectrum response drops by 3 dB from the low modulation frequency for this VCO is 42 MHz.

Figure - 10 Down-converted measured 3dB FM BW for HMC401QS16G VCO

When using a direct measurement approach with a DSO, care must be taken to prevent out of band signals from aliasing into the measurement frequency range and corrupting the desired measurement. This is due to a phenomena associated with sampling oscilloscopes known as aliasing. When a signal is present that is at a frequency of half of the sampling rate or higher, an aliased version of this signal will falsely appear in the measurement range. When used as a normal DSO, the instrument has a fixed sampling rate of 20 GHz and the input hardware will eliminate any responses above 10 GHz. However, when the DSO is used as a Vector Signal Analyzer, the sampling rate will be adjusted for the selected center frequency and frequency span. The VSA software does have a utility setting to optimize the settings of the time length of the measured sample and the sampling rate in the DSO to avoid exposure to out of measurement band aliases. However, the easiest method to eliminate the out of band alias problem is to not have any out of measurement band signals by using a band limit filter that cuts off above the measurement frequency range of the VCO. A simple low pass filter, selected for the highest VCO frequency, at the output of the VCO is sufficient to eliminate any out of band signals such as harmonics that may come out of the VCO and create an alias response.

Typical results for Hittite VCOs

The majority of the Hittite Microwave MMIC VCO's were characterized using the direct DSO VSA measurement technique for their 3 dB FM bandwidth. The following table summarizes the results.

| VCO	Frequency Range (GHz)	V Tune (Volts)	3dB FM BW (MHz)
HMC384LP4	2.05 -2.25	6	58.6
HMC385LP4	2.25 - 2.5	6	66.6
HMC386LP4	2.6 - 2.8	6	67.5
HMC389LP4	3.35 - 3.55	6	55
HMC390LP4	3.55 - 3.9	6	55.3
HMC391LP4	3.9 - 4.45	6	16.2
HMC416LP4	2.75 - 3.0	6	64.5
HMC429LP4	4.45 - 5.0	6	20
HMC430LP4	5.0 - 5.5	6	19.5
HMC431LP4	5.5 - 6.1	3	23
HMC466LP4	6.1 - 6.72	4	22.3
HMC358MS8G	5.6 - 6.8	4	120
HMC401QS16G	13.2 - 13.5	6	42
HMC398QS16G	14.0 - 15.0	6	47.1

The FM bandwidth decreases slightly if the VCO is operated at a tuning voltage close to 0Vdue to the rapidly changing tuning sensitivity in this region of tuning voltage. VCO's with similar tuning varactors have comparable FM bandwidths.

The lowest FM bandwidth measured is shown in figure 11 and was on the HMC391LP4. The bottom trace shows that this VCO has a FM bandwidth that is still a robust 16.2 MHz.
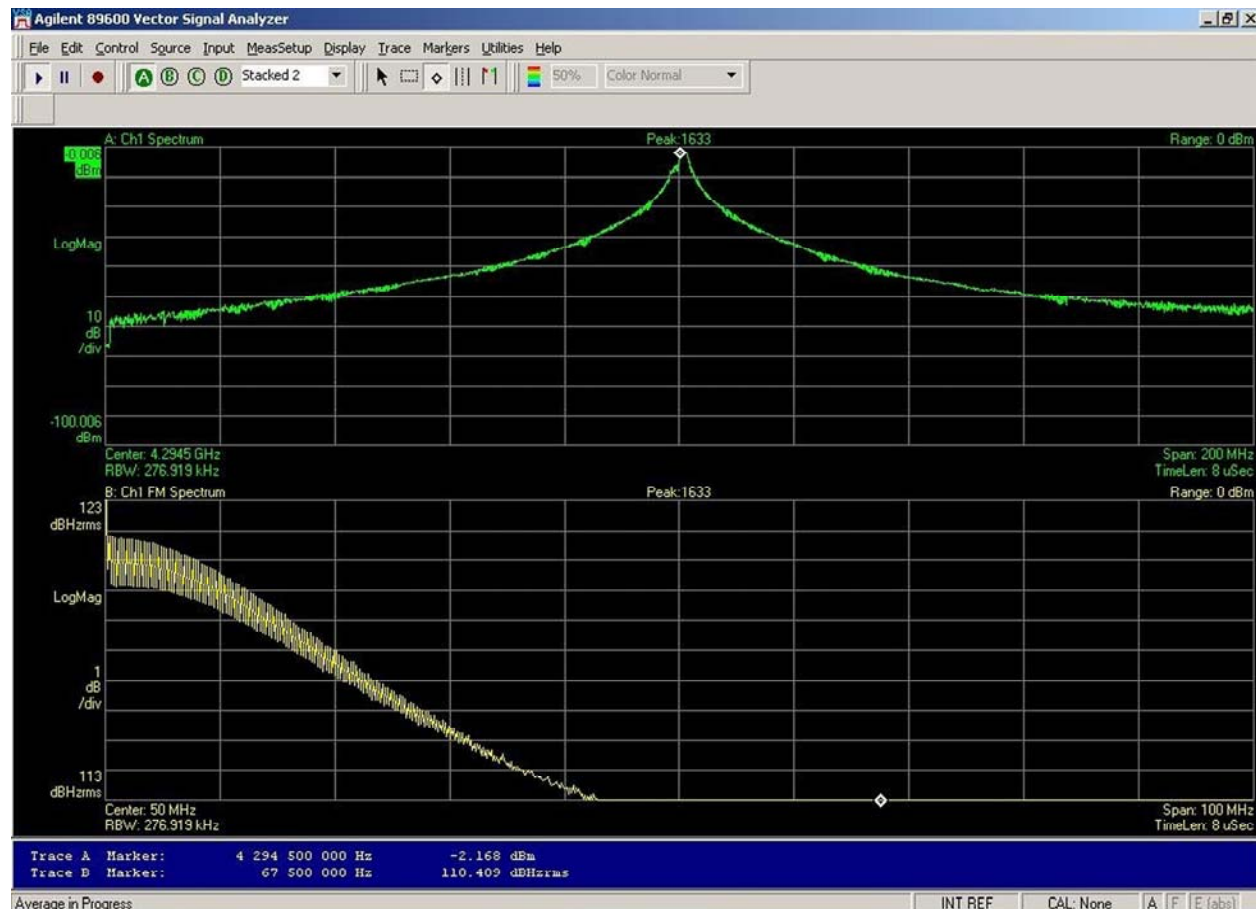
Figure - 11 Measured 3dB FM BW for HMC391LP4 VCO

The highest FM bandwidth measured was on the HMC358MS8G MMIC VCO with Buffer Amplifier (5.8 – 6.8 GHz). The high FM bandwidth on the HMC358MS8G required the measurement frequency span to be increased to 400 MHz and the modulation signal range to be change to 100 KHz to 200 MHz. The HMC358MS8G output frequency was above the bandwidth of the DSO, so the down-converted direct VCO FM bandwidth test system was used . The down-converted test frequency used was 780 MHz and a 1 GHz LPF was used in front of the DSO to prevent alias problems. A HMC168C8 (4.5 – 8.0 GHz) double balanced mixer was used as the down-converter. Since the HMC358MS8G VCO used for the LO had sufficient power output to drive the LO port of the HMC168C8 mixer, a LO amplifier was not needed. The measurements made on the HMC358MS8G are shown in figure 12. The bottom trace shows that the HMC358MS8G has a 3dB FM bandwidth of 120 MHz.
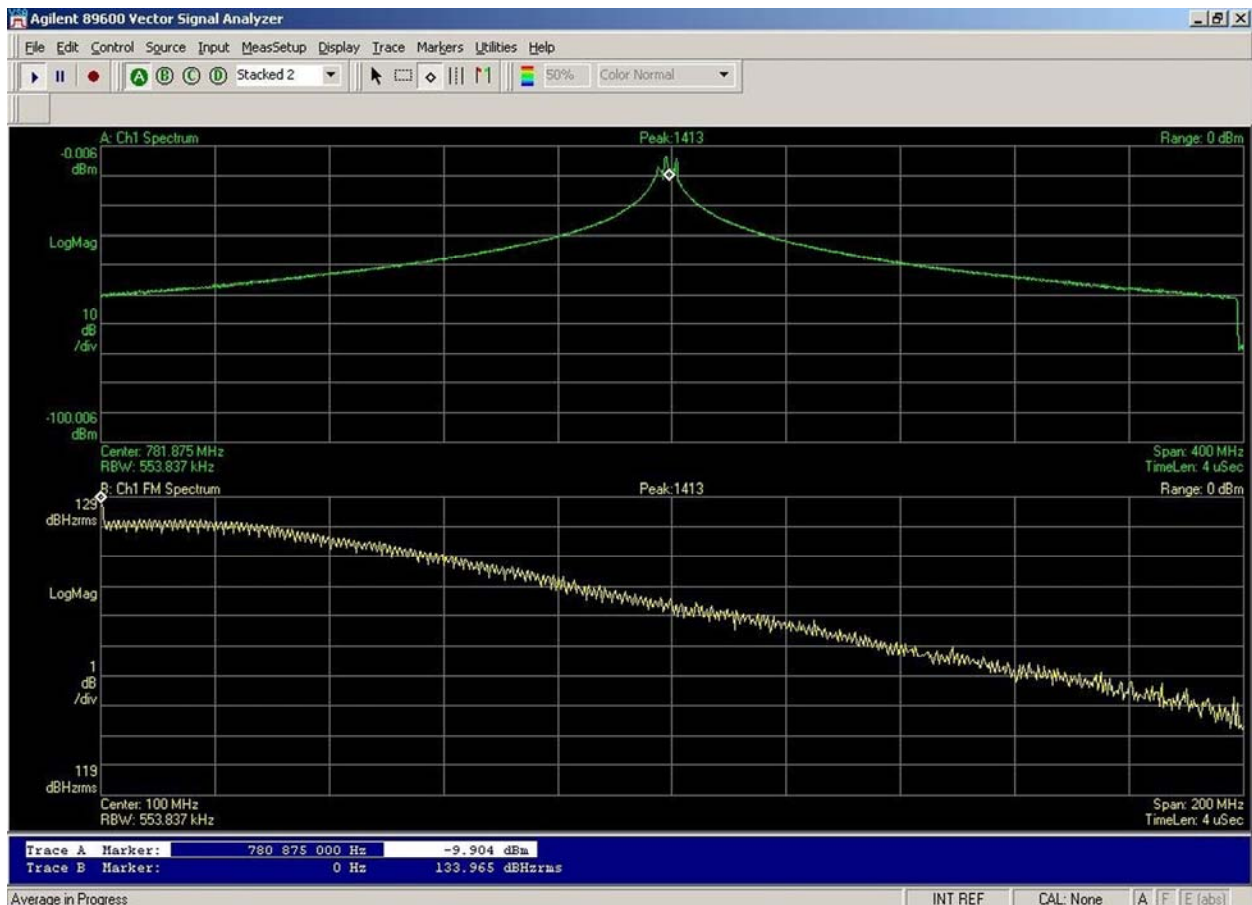
Figure - 12 Down-converted measured 3dB FM BW for HMC358MS8G VCO

Conclusions

A straight forward method has been presented to measure the FM Bandwidth of varactor tuned VCO's. This method is not impacted by the normal varying tuning sensitivity of a practical wide bandwidth VCO and does not suffer from measurement sensitivity problems or measurement bandwidth limitations for VCO's that have FM bandwidths in excess of 10 MHz. A simple downconverter was also presented using a second of the VCO's under test as an LO, in order to measure VCO's that have a frequency range above the measurement bandwidth of the DSO. Measurements were performed on a sample of Hittite Microwave's MMIC VCO's and the data has been presented. All of Hittite Microwave's MMIC VCO's were shown to have wide FM bandwidths and are well suited for the state of the art designs such as fast acquisition PLL's and wideband FSK signal generation that will demand this type of performance.