Mixer Measurement with a Vector Network Analyzer

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Introduction

Mixers are an essential component in many electronic circuits. These devices have the capability of taking in two frequencies and producing the sum and difference. RF signals may be “mixed up” to higher frequencies or “mixed down” to lower frequencies. In a receiver, a particular frequency might be tuned in by mixing it down to a fixed intermediate frequency (IF) where it can be filtered, amplified, and demodulated. Conversely, a signal to be transmitted at some high frequency might be first created by modulating a much lower intermediate frequency followed by a mixer to boost it up to the higher transmit frequency.

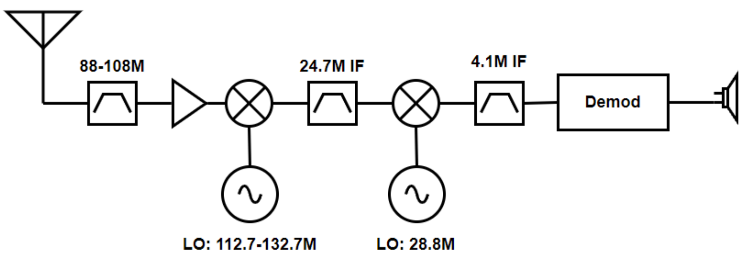

Figure 1 - Double Conversion (Superhet) Receiver

Figure *1* shows a receiver utilizing two mixers to select, amplify and demodulate an RF signal. An RF input signal 24.7 MHz below the Local Oscillator (LO) will create an LO-RF signal, intermediate Frequency or IF at 24.7 MHz which passes through the second bandpass filter. Frequencies 24.7 MHz above the LO (RF-LO), also called *image* frequencies, would also create a 24.7 MHz IF signal, but these are rejected by the 88 to 108 MHz bandpass filter. The first IF frequency of 24.7 MHz was chosen to be high enough to allow for the 88-108 MHz bandpass filter to reject that image. The second mixer stage reduces the signal frequency further so it can be processed by the demodulator section.

We’ve seen here how a mixer might be used in a receiver, but what Vector Network Analyzer (VNA) measurements might we perform on the mixer to characterize it so we can understand how it will perform in a circuit like this?

Mixer Measurement with a Vector Network Analyzer

Conversion Loss (or Gain)

Conversion Loss is the most fundamental measurement. It is the measurement of the amplitude of the IF with respect to the RF input. For instance, if the IF is -10 dBm at a frequency and the RF input is 0 dBm, then the conversion loss would be 10 dB. We can make a scalar measurement of conversion loss using the frequency offset capability of the VNA. Keep in mind that since the RF and IF are at two different frequencies, it is not possible to measure a phase difference between the two. To be able to determine the amplitude ratio from RF to the IF, we'll need to measure the RF input power over the frequency range.

Low-Side LO

Let's set up a mixer measurement with the RF from 4 to 5 GHz, an LO at 3 GHz, and the IF output will be 1 to 2 GHz as in Figure 2. First, set the start and stop frequencies of the VNA to the IF output range which will be measured, 1 to 2 GHz. We'll call this the "Base Range". Set the number of points to whatever is desired, 1000 points in this example and leave the IF Bandwidth at the 10 kHz default setting. In the upper left corner, click on S11 and change it to S21.

It is important that the LO and RF frequency sources are synchronized or share a common 10 MHz time-base reference. If not, the IF could appear outside the IF Bandwidth of the measurement receiver. If it falls just barely within the IF bandwidth, the result will be noisy and lower than expected.

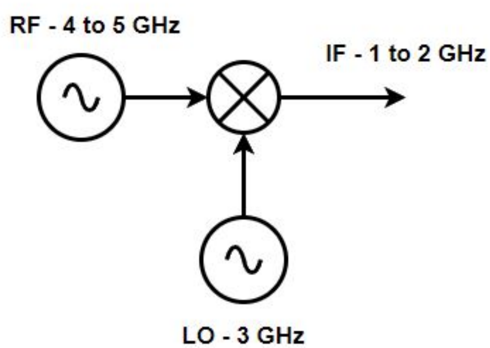

Figure 2 - Low LO

Using a 4-Port VNA, we can set Port-4 as an auxiliary source at 3 GHz to drive the LO of the mixer. The auxiliary source is activated under the Stimulus menu of the VNA. If a

4-Port CMT VNA is unavailable, the LO source must be provided by an external generator. The auxiliary source may be programmed to sweep from a start to a stop frequency, be we will set it to a fixed 3 GHz here.

Next, we can set up the frequency offset.

Mixer Measurement with a Vector Network Analyzer

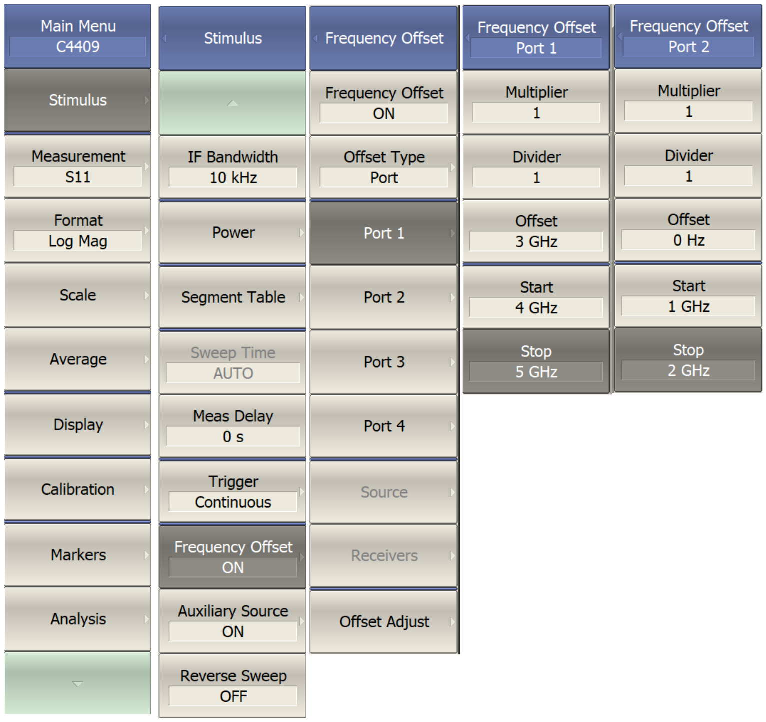

Figure 3 - Frequency Offset Setup

In the Frequency Offset menu, set Port 1 to sweep from 4 to 5 GHz, and Port 2 from 1 to 2 GHz. The Offset, Multiplier and Divider are ways of setting the sweep range based on a linear function of the “Base Range”. Make sure the Frequency Offset mode is turned on and you should see three frequency ranges at the bottom of the screen. The Port 1 sweep range, the Port 2 Receiver range, and the Base Range. Any markers added to traces on the screen will be referenced to the base range, even if making an S11 measurement which should be between 4 and 5 GHz in this case. S11 can still be viewed on the screen and checked visually of course.

Next, choose a calibration kit from the calibration menu and make sure it is selected. A USB power meter will also be needed. From System/Miscellaneous Setup/Power Sensor, choose the power sensor that you will be using. Navigate to Calibrate/Mixer-Converter Calibration/Scalar Mixer Calibration. Ports 1 and 2 will be used to measure from RF to IF so the first setting is fine. The “Forward” setting is also correct for measuring the RF to IF conversion loss from Port 1 to Port 2. If the measurement needs to be made from IF to RF, select “Reverse”. Select “Both” if measurements in both directions are required. In this case, power measurements must be made on the ends of the cables from Ports 1 and 2.

A full 2-Port calibration must be performed on both input and output frequency bands. Use Reflection Port 1 and Port 2 to perform Open, Short and Load calibration on each port. The VNA will automatically switch between bands. Connect Port 1 to Port 2 together with a Thru and perform the Thru calibration. Alternatively, use an Automatic Calibration Module to perform the Reflection and Thru calibrations. This is much simpler.

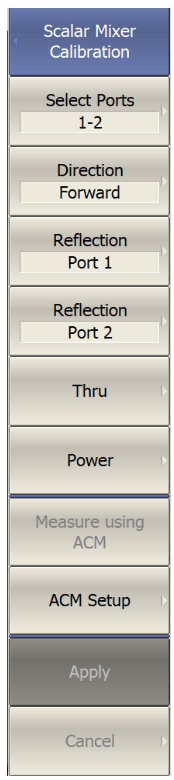

Figure 4 - Vector Mixer Calibration Menu

Finally, attach the power meter to the end of the Port 1 cable and perform the power calibration. After the power measurement, press "Apply" to finish and apply the calibration. The power measurement, along with the full 2-Port calibration is required to bridge the gap between the two frequency bands, RF and IF. Note that this part of the calibration does not correct the output power as the "Power Calibration" does in the Calibration menu. It merely measures the output power and uses the reading for the transmit tracking correction.

Mixer conversion loss will now be measured from Port 1 to Port 2. Scalar Mixer Calibration has been applied, indicated by [SMC] in the trace description.

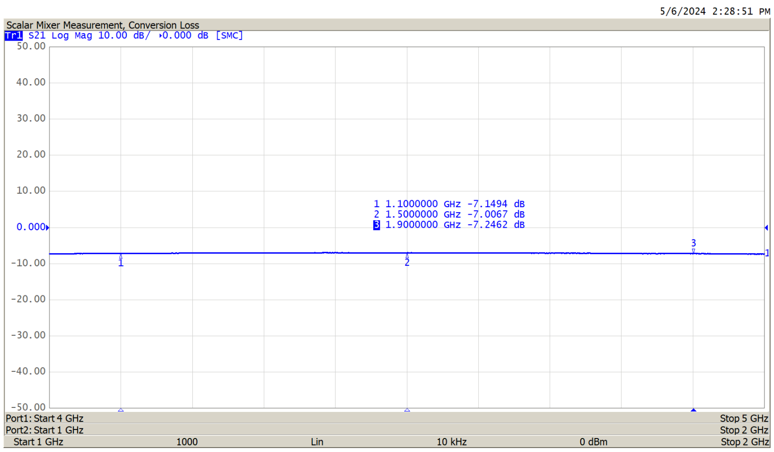

Figure 5 - Conversion Loss Measurement with Low-Side LO

High-Side LO

What if the LO is above the RF as in Figure *6*?

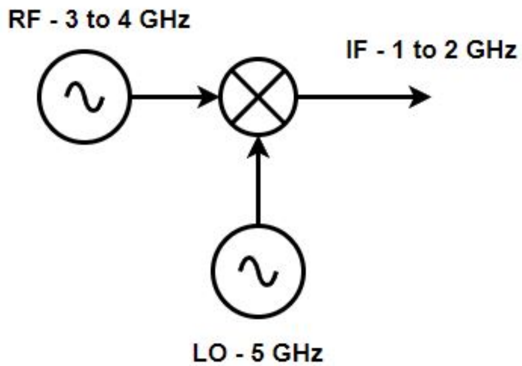

Figure 6 - High-side LO

Here, as the RF sweeps from 3 to 4 GHz, the IF sweeps from 2 to 1 GHz. It looks like we would have to set the base range to start at 2 and end at 1 GHz, but that is not the proper way to make this measurement. Instead, we'll set Port 1 to sweep in the reverse direction from 4 to 3 GHz as in Figure *7*. Then we can set the base range to 1 to 2 GHz and Port 2 to receive from 1 to 2 GHz just as before.

Mixer Measurement with a Vector Network Analyzer

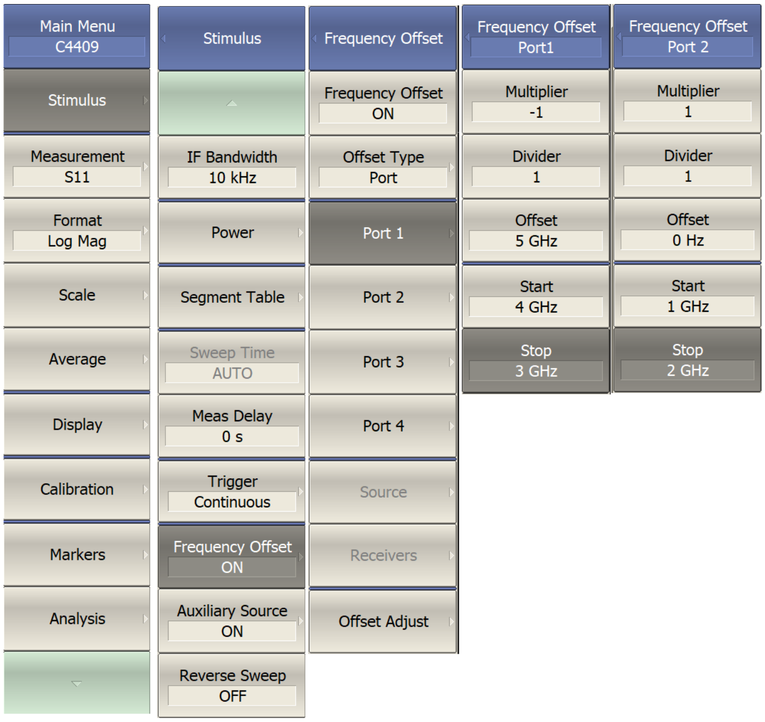

Figure 7 - Setup for High-Side LO

Calibration must be performed as before, using a calibration kit or preferably an Automatic Calibration module, and a power meter.

The IF output is the same, but the conversion loss shown in Figure 8 is a little higher.

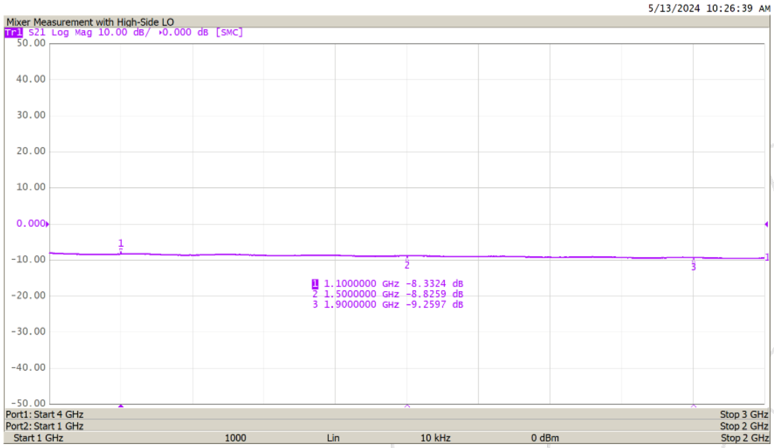

Figure 8 - Mixer Conversion Loss with High-Side LO

Mixer Measurement with a Vector Network Analyzer

See "Scalar Mixer Calibration with a 2-Port VNA" on the Copper Mountain Technologies website.

Compression

Normally, the IF output level will change dB for dB with increases of RF input level up until the point where compression occurs. At that point, increasing the RF level will result in less and less increase in IF level as shown in Figure *9*.

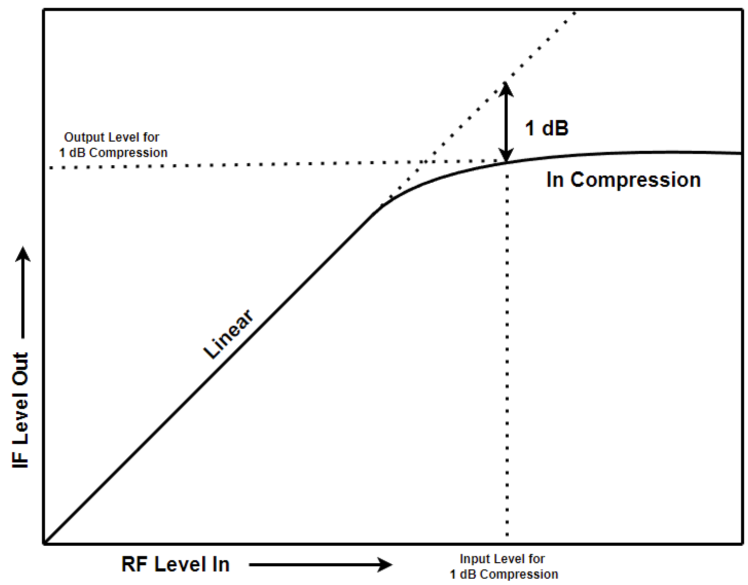

Figure 9 - IF Compression

Compression is easily measured by measuring the conversion loss of the mixer at a chosen frequency and sweeping the RF input power. To make the measurement, click on "Lin" at the bottom of the screen and choose "Pow" to perform a power sweep. Set the frequency for the power sweep at the bottom just to the right of the IF Bandwidth setting, 1.5 GHz in this case as shown in Figure *10*. Set the start and stop power levels by clicking on them at the bottom of the screen, -10 to +15 dBm here. Then adjust a marker until it is 1 dB down from the nominal conversion loss level. (You can turn on a reference marker –Markers/Reference Marker [ON]—and set the reference somewhere on the curve on the left-hand side of the screen and then adjust Marker 1 for a 1 dB delta). Here, 1 dB compression occurs when the RF input level is 11.71 dBm which is better than the published specification of 10 dBm.

See "RF Mixer Characterization" on the Copper Mountain Technologies website.

Mixer Measurement with a Vector Network Analyzer

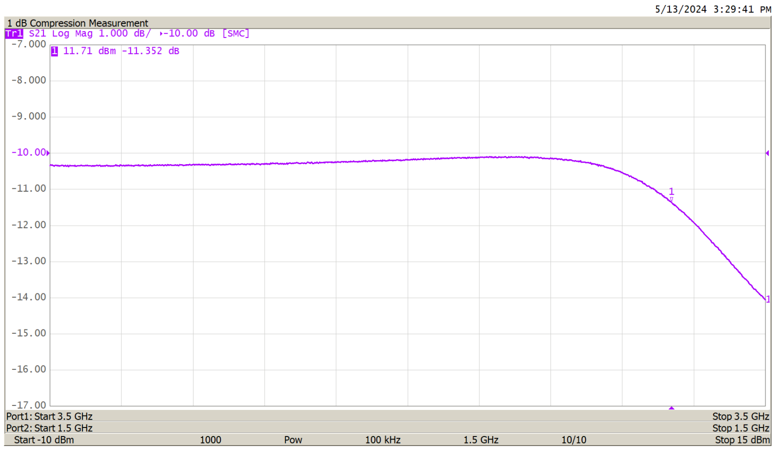

Figure 10 - 1 dB Compression Measurement

Measuring a Block Converter

A Block Converter is an integrated system which translates one frequency range to another. It will certainly make use of one or more mixers with one or more Local Oscillators built into the converter to affect the translation. Frequency offset mode may be used to measure a device such as this, but some care must be taken. The accuracy of the VNA stimulus and receiver center frequency is determined by the internal 10 MHz time-base. If the block converter also has a 10 MHz time-base, the VNA and converter may be synchronized by connecting the 10 MHz references together. The VNA might be set using System/Misc Setup/Ref Source [Internal or External] to generate or receive a time-base standard.

If the block converter does not have a time-base input or output, then it may be necessary to “dial-in” an offset to correct for the difference in frequencies. It isn’t necessary that the two systems be phase-locked, it is only required that the frequency output of the block converter fall within the IF bandwidth of the VNA receiver, hopefully near the center. Start with the VNA IF bandwidth set as high (wide) as possible. If a lower IF Bandwidth is desired, reduce it in steps and observe the result. If the trace becomes noisy, it will be necessary to adjust the frequency offset to center the signal in the VNA receiver. Dial a positive or negative offset into the frequency offset menu or alternatively, “Auto Adjust” may be enabled, and the VNA will automatically move the receiver offset to maximize the IF signal level. The Auto Adjust Period sets how often the VNA will make this correction to account for slow drift. After the offset has been corrected, the VNA IF bandwidth can be reduced if desired.

Mixer Measurement with a Vector Network Analyzer

What is IP2?

IP2 is the theoretical point where the second harmonic of the input signal is equal in amplitude to the input signal as seen on the output of the mixer. Normally, this second harmonic would not be an issue, but it is a component of various troublesome intermodulation products. Of course, if the intended IF frequency range includes the second harmonic of the RF input, this would present a problem.

The IP2 of a mixer might be measured using the frequency offset mode. Set the Start and Stop frequencies of the VNA to include both the input range and the harmonic range. In other words, if the input is 2 to 3 GHz, set the Start and Stop to 2 GHz and 6 GHz respectively. Perform Port 1 power calibration and Port 2 Receiver calibration as shown in Figure *11*. A bandpass or lowpass filter will be required on Port 1 to eliminate the harmonics generated by the VNA itself. Install that filter on the end of the Port 1 cable, change the Stop frequency to 3 GHz and repeat the Port 1 Power Calibration. This could not have been done before because the attenuation of the filter would make power calibration impossible. The Stop frequency can now be reset to 6 GHz.

Mixer Measurement with a Vector Network Analyzer

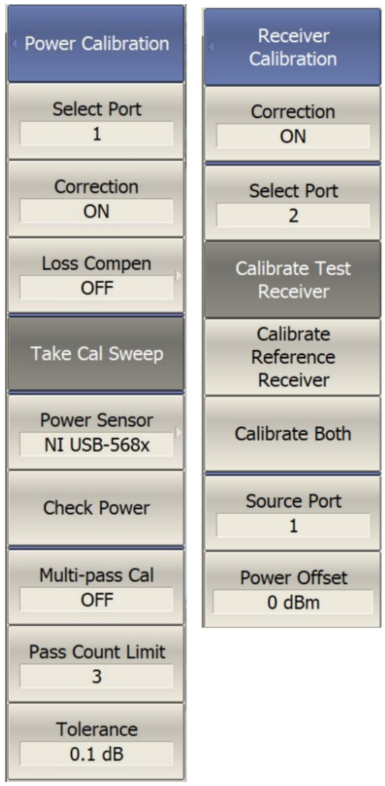

Figure 11 - Power and Receiver Cal

Using the Frequency Offset mode, set Port 1 to sweep from 2 to 3 GHz and the Port 2 from 4 to 6 GHz. A measurement of S21 now depicts an accurate measurement of the dB ratio of the second harmonic to the injected fundamental. The input power level can be adjusted up and down to observe the level change of the second harmonic.

Measuring IP3

The Third Order Intermodulation Intercept or IP3 is a useful measure of the linearity of a device. Typically, two tones are applied to the RF input of a mixer and the third order intermodulation products are evaluated on the IF output. If the two input tones are at F_1 and F_2 then the third order products appear equally spaced on either side of F_1 and F_2. They are created by $2*F_1-F_2$ and $2*F_2-F_1$.

Mixer Measurement with a Vector Network Analyzer

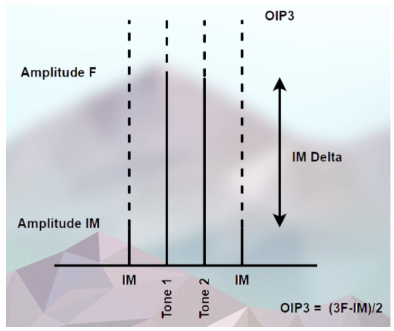

Figure 12 - IP3 products

For a mixer, the IP3 is usually referred to the RF input level, Input IP3 or IIP3. The dB delta between the two tones and the third order products are measured on the IF output and the IP3 is calculated as shown in Figure *12*. Since these measurements are made on the IF output, it can be referred back to the input by adding back the conversion loss of the mixer.

Vector Mixer Calibration

Scalar mixer calibration was described earlier, where the input and output frequencies differed. No fixed phase relationship can exist between disparate frequencies so only magnitude results are possible. Sometimes it is necessary to know the delay or delay flatness from the input to the output of the mixer though. Good delay flatness over frequency is required to prevent distortion of phase-amplitude constellations and degradation of the Error Vector Magnitude (EVM) of signals with broadband complex modulation. Signal delay through a device is given by $-d\Phi/d\omega$, so somehow phase must be determined, or at least the change of phase.

The simplest way to achieve this is to mix the IF output of the Mixer Under Test (MUT) back up or down to the RF frequency so the input and output frequencies are identical. A second mixer or “Reference” mixer is used to accomplish this as shown in Figure *13*.

Mixer Measurement with a Vector Network Analyzer

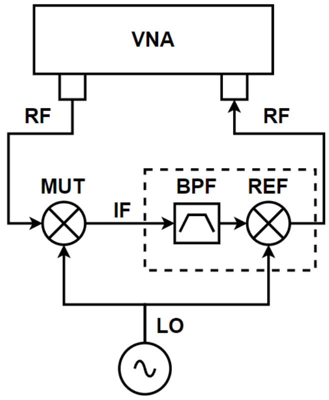

Figure 13 - Vector Mixer Cal setup

The signal labeled "RF" is a common frequency and the VNA can now measure phase. The bandpass filter here is essential. If we take the example where the RF is 12 to 13 GHz and the LO is 14 GHz, the desired IF might range from 1 to 2 GHz, but there will also be an IF signal from 26 to 27 GHz. Both signals applied to the REF mixer will regenerate the same 12 to 13 GHz RF signal but with very different phase and amplitude. The constructive and destructive interference between the two signals creates unacceptable ripples in the response. Hence, the bandpass filter passes only the desired mixing product and eliminates the other. Choose this filter to pass the desired 1 to 2 GHz IF and reject the 26 to 27 GHz IF by at least 40 dB.

Note that a millimeter-wave mixer might be tested with a VNA which does not cover that range. If the RF frequency is 79 to 81 GHz and the IF is 14 to 16 GHz for a given system requirement, the mixer may be driven by the VNA from 14 to 16 GHz with the LO set to 95 GHz. The resulting (filtered) 79 to 81 GHz signal will be mixed back down by the reference mixer to 14 to 16 GHz which is within the range of an 18 GHz or higher VNA. The mixer may be measured in the forward or reverse direction to obtain the RF to IF and IF to RF response. For more information see "mmWave Mixer Measurement with a Low Frequency VNA".

This method looks like it will work well, but how to remove—de-embed—the transfer function of the REF mixer? If the REF mixer were a passive network, we would simply measure it's 2-Port S-Parameters to characterize it and use the built-in de-embedding feature of the VNA to remove its effects. But the mixer is not a passive device, its output frequency is not the same as its input and it can't be directly measured in this way.

We'll make use of some general properties of S-Parameter networks to accomplish this.

Mixer Measurement with a Vector Network Analyzer

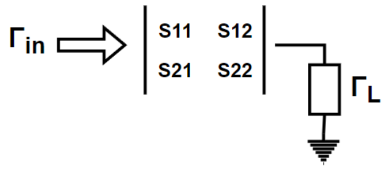

Figure 14 - Looking into S-Param Network

If the S-Parameter network of Figure *14* is known, then Γ_{in} may be calculated from:

Eq1) $\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}$ (Mason's Rule)

If the S-Parameter network is that of the Reference Mixer and is unknown, we can apply three different values of Γ_L to the output of the network and solve three equations to obtain the parameters. Why three instead of four? We can't hope to separate the effects of S_{21} and S_{12} from each other since they appear as a product, so we make the assumption that the response is reciprocal, that is $S_{21} = S_{12}$ and the numerator becomes $S_{21}^2 * \Gamma_L$. We can then apply a Short, Open and Load for the three values of Γ_L and solve the system of equations. In fact, the VNA automatically manages this calibration in the Vector Mixer Calibration menu.

What are the limitations of this method?

If we assume that the output of the REF mixer is well matched, that is, $S_{22} \approx 0$, then the denominator of the second term of Equation 1 is simply 1. The reflection coefficient, Γ_{in} looking into the mixer will be the S_{11} of the mixer plus S_{21}^2 multiplied by Γ_L. When a 50Ω load is applied for Γ_L we'll simply see S_{11}. With a perfect Open applied, we'll see S_{11} + S_{21}^2, where S_{21} is essentially the conversion loss of the mixer. If the conversion loss is high, like 15 dB, then S_{21}^2 is 0.032 in linear terms. With a Short applied, we'll see S_{11} - S_{21}^2. So in this example, when measuring the three standards to determine the effective S-Parameters of the Ref mixer, we'll see the vector S_{11} and $S_{11} \pm 0.032$.

Mixer Measurement with a Vector Network Analyzer

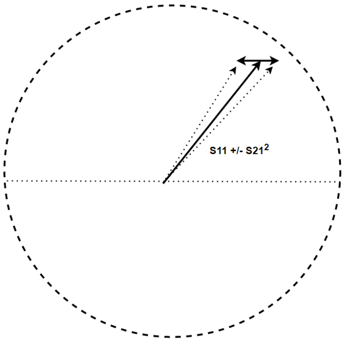

Figure 15 - Vector Calibration

As the conversion loss of the Ref mixer increases, the three vectors which must be measured to solve for the Ref mixer S-Parameters converge and the solution becomes ill-conditioned and noisy. The calculated value of S_{22} is particularly sensitive. The Ref mixer should have a conversion loss of no more than 10 dB for best results.

Performing Vector Mixer Calibration

To perform Vector Mixer Calibration, first perform a full 2-port calibration on the end of the test cables. Then attach the Ref mixer with its IF filter and excite it with the LO.

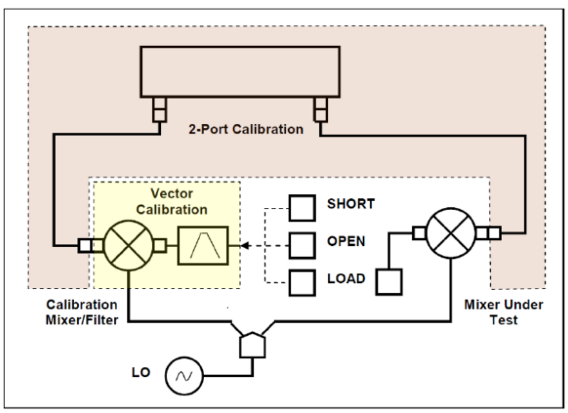

Figure 16 - Ref Mixer De-Embedding

Select the Open, Short and Load calibration kit which will be used in the Calibration/Cal Kit menu. Navigate to Calibration/Mixer/Converter Calibration/Vector Mixer Calibration. With the Reference mixer attached to Port 1 as shown in Figure *16*, select Port 1, Enter the LO frequency and the mixing scheme below that. Attach the Open, Short and Load in turn and press the buttons on the menu. If "Setup Option" is checked, the Ref mixer de-embedding will be automatically applied when the calibration is complete. If an

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Automatic Calibration Module (ACM) is available, it can be used instead of a manual kit. Using that menu choice, a touchstone de-embedding file may be saved for future use.

After calibration is complete, the conversion loss or gain of the Mixer Under Test may be measured and because phase information is available, it is possible to measure the delay and evaluate delay flatness. See "Vector Mixer Calibration" on the Copper Mountain Technologies website.

Conclusion

Copper Mountain Technologies produces many Vector Network analyzers for your mixer testing needs. Our products are all highly accurate, metrology grade instruments as verified by our on-site ISO-17025 certified laboratory. Please visit our website to see these products and to peruse more technical information such as this and view our many informative webinars.