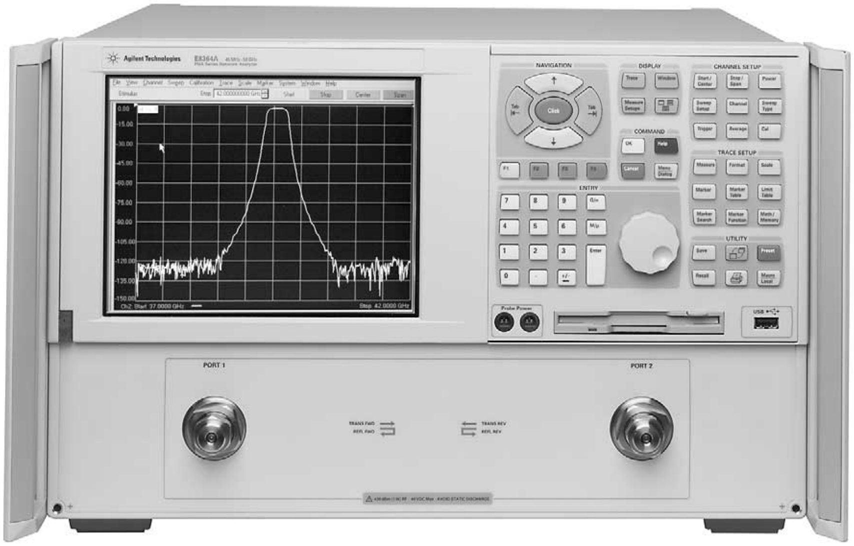
Agilent
PNA Microwave Network Analyzers

Application Note 1408-3

Improving Measurement and Calibration Accuracy using the Frequency Converter Application



Agilent Technologies

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Introduction

Frequency-translating devices such as mixers and converters are fundamental building blocks of most RF and microwave communication systems. Accurately characterizing the performance of these devices is a critical factor in the design process. The microwave (MW) PNA Series vector network analyzers can be used to measure frequency-translating device specifications such as conversion loss magnitude and phase, absolute group delay, port match, and isolation.

This application note discusses the recommended procedure for testing frequency-translating devices using the PNA Series frequency converter application, as well as Agilent's patented scalar- and vector-mixer calibration techniques. The application note outlines the procedures for selecting appropriate calibration and test system components to reduce measurement errors and achieve the best accuracy.

To get the greatest benefit from this application note, you should have an understanding of fundamental network analysis and the vector- and scalar-mixer calibrations. Agilent application notes 1408-1, 1408-2, and two white papers on vector-mixer characterization offer in-depth material regarding mixer measurements and calibration techniques. See the reference section for details on how to obtain these documents. Additionally, MW PNA's online help describes the frequency converter application (FCA) and the mixer calibrations with in-depth explanations, detailed diagrams, and PNA screen images. The online help is available on each MW PNA instrument, and it can be accessed from **http://na.tm.agilent.com/pna/onlinehelp.html**.

Frequency Converter Application: Scalar and Vector-Mixer Calibrations

The MW PNA Series frequency-offset capability is implemented in an integrated hardware and firmware solution. The frequency-offset mode hardware lets you independently set the MW PNA's source and receiver frequencies for measuring mixers. The firmware automates frequency converter measurements. FCA offers an easy-to-use graphical user interface and advanced calibration techniques, including the scalar-mixer calibration (SMC) and vector-mixer calibration (VMC).

SMC can be used to characterize the conversion loss magnitude and reflection parameters of mixers. A conversion loss magnitude measurement is a ratio of the output power (at the output frequency) to the input power (at the input frequency). The calibration is based on a combination of port and device match characterization and power meter measurements. With SMC, the input and output power levels are accurately determined by calibrating the network analyzer with a power meter, thereby transferring the accuracy of a power meter to the network analyzer. By using the network analyzer's one-port calibration ability, the port and device input and output reflection coefficients are measured. Using the known vector reflection coefficients of the test port, the device, and the power sensor, SMC corrects for mismatch loss. Since SMC is referenced to a traceable standard (power sensor/meter measurements), it provides the best specified measurement of conversion loss magnitude.

VMC offers measurements of conversion loss magnitude, phase, and absolute group delay by using a combination of calibration standards (such as short, open, load or ECal), and a "calibration mixer/IF-filter" pair during calibration. Vector-mixer calibration is based on a modified two-port error model, however the steps and standards used to determine the error terms differ from the traditional two-port calibration. In the case of a frequency-translating device, the procedures differ because the input and output frequencies are different and additional calibration steps are required. In VMC, the calibration standards are still used to determine the directivity and match error-terms. A "calibration mixer/IF-filter" pair is used as a new standard to determine the transmission tracking term. A calibration mixer that is assumed to be reciprocal, is characterized for input match, output match, and conversion loss (both magnitude and phase).

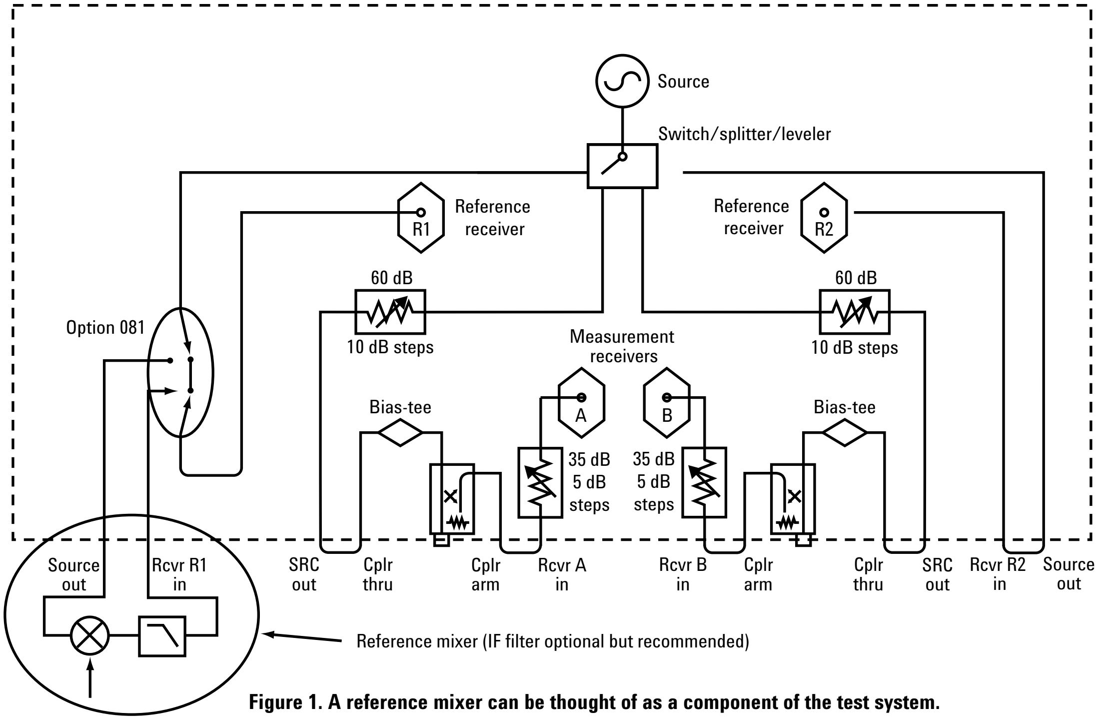
The first section of this application note examines various topics unique to the vector-mixer calibration process. The second section discusses general recommendations for making accurate mixer measurements, both scalar and vector.

Vector-Mixer Calibration Considerations

Reference mixer, calibration mixer, mixer-under-test

A vector-mixer measurement requires three mixers: a reference mixer, a calibration mixer, and a mixer or device-under-test (DUT). In this section, we explain the difference between these three mixers.

Reference mixer: The purpose of the reference mixer is to provide a phase reference for the measurements. The reference mixer is connected in the reference receiver path of the network analyzer, between the "source out" and "receiver R1 in" ports, as shown in Figure 1. The reference mixer can be considered part of the test system setup, like the network analyzer or test cables. The reference mixer does not need to be moved, connected, or disconnected during the calibration or measurement process; it remains in place all the time. The reference mixer is switched in and out of the measurement path, as needed, by the firmware. See the switch labeled Option 081 in Figure 1. As explained in the *Reference Mixer Attributes* section, there are very few requirements on the reference mixer.

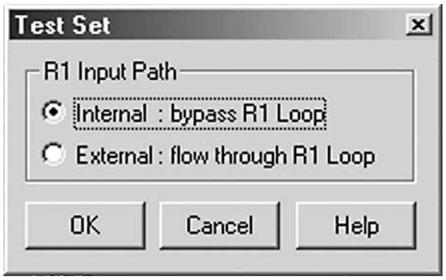


Reference mixer (IF filter optional but recommended)

Figure 1. A reference mixer can be thought of as a component of the test system.

Note

The user can also switch the reference mixer in and out using the menu item **Channel**, **Test Set** control, shown in Figure 2. Although, generally, the user lets the firmware control the position of the reference mixer switch.



Test Set

R1 Input Path

● Internal : bypass R1 Loop

○ External : flow through R1 Loop

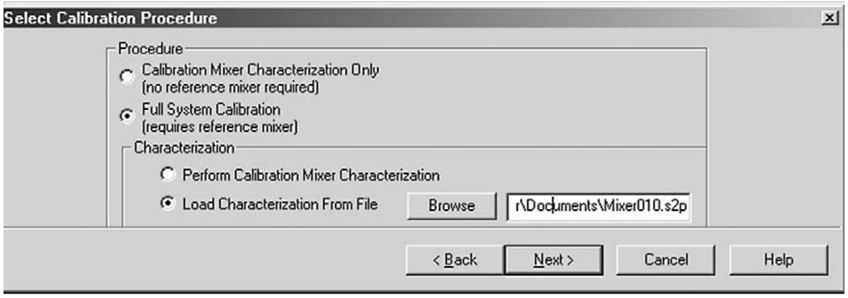
Figure 2. The reference mixer can be switched in and out using the network analyzer firmware.

Calibration mixer: The calibration mixer is both characterized for its response and measured as a calibration standard during the vector-mixer calibration process. It can be thought of as another calibration standard, like the open, short, or load. It actually serves as the "thru" standard in a vector-mixer calibration. It is used during the calibration, and then it is set-aside during the measurement process. You can store it in a box, similar to a calibration kit container, and just think of it as another calibration standard. There are a few requirements for the calibration mixer, just as an open and a short standard have a few requirements. These requirements are explained on page 6.

DUT: The DUT is separate from the reference mixer and the calibration mixer. It is the unknown device you wish to measure. However, if your DUT meets the requirements of a reference or calibration mixer, you can use one of your DUTs as the reference or calibration mixer. You would simply label a DUT as a "reference mixer," another DUT as a "calibration mixer," and then use them as part of your test system and a calibration standard, respectively.

Vector-mixer calibration process

The vector-mixer calibration process requires characterized data of the calibration mixer. The “Select Calibration Procedure” dialog box (see Figure 3) allows you to perform calibration mixer characterization only, or perform a full system calibration. By selecting “Calibration Mixer Characterization Only”, you perform a 2-port calibration, characterize the calibration mixer, and save the data in .S2P format. This process does not require a reference mixer. Make this selection if you want to save the mixer characterization data to a file that will be downloaded later as part of a full system calibration. Alternatively, by selecting “Full System Calibration”, you can download mixer characterization data previously saved, or you can perform the mixer characterization steps as part of the calibration process (requires a reference mixer). The calibration process includes a step where the calibration mixer is measured as a “through” standard.


Select Calibration Procedure

Procedure
○ Calibration Mixer Characterization Only (no reference mixer required)
● Full System Calibration (requires reference mixer)

Characterization
○ Perform Calibration Mixer Characterization
● Load Characterization From File: r\Documents\Mixer010.s2p

Figure 3. Vector-mixer calibration process.

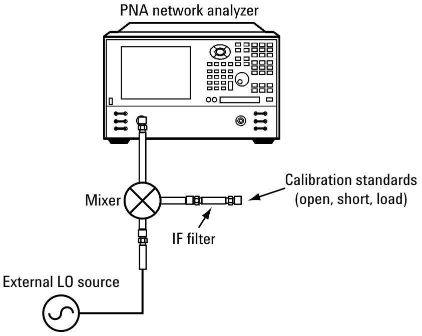


Figure 4. Setup for calibration mixer characterization.

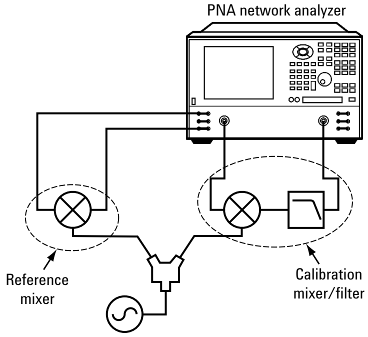


Figure 5. Setup for system calibration.

IF bandwidth

It is recommended that you perform a calibration with narrow IF bandwidths (1 kHz or less), to ensure low noise levels. For the measurement process, you can widen the IF bandwidth to increase measurement speed.

Calibration mixer attributes

Frequency range

The frequency range of a calibration mixer should be the same or wider than the frequency range of the DUT, for both input and output frequencies. If more than one DUT is tested using the same setup, select a calibration mixer with broad frequency coverage, one that covers the frequency range of all devices to be tested.

There is a time advantage to using a broadband mixer as the calibration and reference mixers. This is because most of the VMC calibration time is in connection and disconnection of components. The calibration procedure includes a few network analyzer sweeps; which are very fast on a MW PNA. A broadband calibration with many points takes a short amount of time and, from then on, the user can interpolate the calibration and apply it to various measurements. Be aware though that with VMC, you can use calibration interpolation only if the LO frequency is the same.

Note

With SMC, there is not much time advantage to a broadband calibration, as the most time-consuming task is the power-meter calibration. If you want to attain an accurate power-meter calibration over a wide frequency range, you need to measure many points. So you can perform either a broadband calibration with many points, or a narrowband calibration with fewer points. The calibration time is approximately the same, because it really depends on the number of points.

The advantage of a broadband SMC calibration is that you can use calibration interpolation for different LO frequencies. The LO frequency is not part of an SMC cal; the input and output frequencies are the two frequency variables. So as long as the input and output frequencies of the DUT were part of the calibrated frequency range, then calibration interpolation is valid. Additionally, a broadband scalar-mixer calibration is useful for measuring harmonics or spurs.

Return loss

The return loss of the calibration mixer is not critical to a first degree. During the measurement, VMC corrects for the mismatch errors associated with the main reflected signals (RF reflection off port 1, IF reflection off port 2). However, the harmonic and spurious products can reflect off the mixer and network analyzer test ports and create error terms. So, a device with better return loss will yield lower uncertainty. If RF and IF filtering is used before and after the mixer (respectively), the effects of poor return loss can be reduced. If the conversion loss of the mixer is low enough, attenuators can be used to improve mismatch errors.

The stability of the return loss measurements, or the calibration mixer characterization, is an important factor. It is recommended that you minimize instabilities due to cable movements during the mixer characterization. FCA allows you to characterize the calibration mixer at a different time, compared to when you perform a vector-mixer calibration. So you can characterize the calibration mixer by directly connecting it to the test port of the network analyzer to obtain a stable and very accurate measurement. Then you can connect it to your test system setup and use it as the through standard.

Conversion loss

The one-way conversion loss of the calibration mixer/IF filter combination should be less than 10 dB, to obtain an accurate calibration. If the one-way conversion loss of the calibration mixer exceeds 15 dB, the accuracy of the calibration is highly degraded. Assuming the IF filter has very low loss in the passband region, we will focus on the calibration mixer conversion loss. The reason for the low conversion loss requirement is that the calibration mixer characterization depends on reflection measurements of standards at the output of the mixer. These standards are connected to the output of the calibration mixer/IF filter combination, as shown in Figure 6.

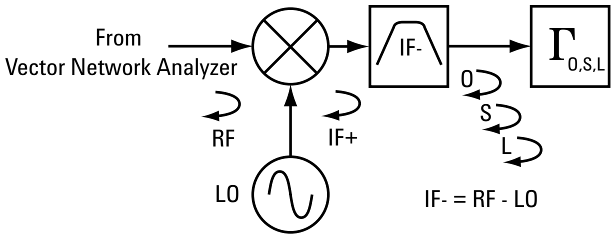


Figure 6. VMC includes steps to measure the reflection of open, short, and load standards.

Conversion loss reciprocity

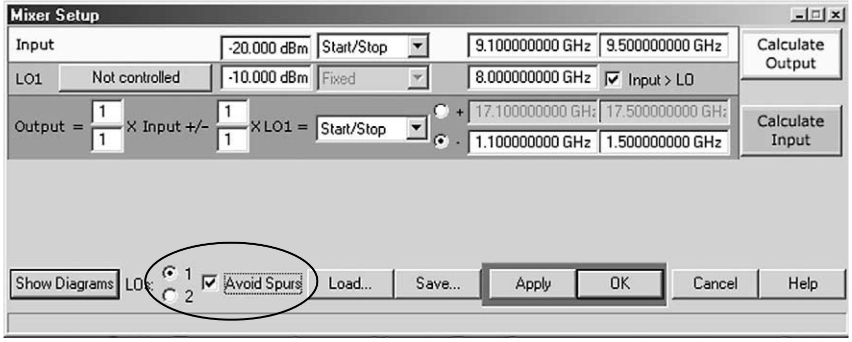
The main requirement of a calibration mixer is that it be reciprocal. Reciprocity means that the forward and reverse conversion loss magnitude and phase are equal. Forward conversion loss or VC_{21} is defined as the loss, when a high-frequency signal is incident upon port 1 and a low frequency or output signal is measured at port 2. Reverse conversion loss or VC_{12} is defined as the loss, when a low-frequency signal is incident upon port 2 and a high-frequency signal is measured at port 1.

The reason for the reciprocity requirement is evident in the theory of the vector-mixer calibration. The calibration process calculates the net response of the forward (VC_{21}) and reverse (VC_{12}) mixer conversion loss by measuring the portion of the signal that travels through the filter and reflects off the calibration standards. In calculating the error terms, the assumption is made that $VC_{21}=VC_{12}$, and from there, the one-way characteristic of the calibration mixer is determined. The assumption that $VC_{21}=VC_{12}$ is based on the conversion loss reciprocity requirement. See Agilent application note 1408-1 for the theory of VMC and a complete error model.

Since reciprocity is a key specification of the calibration mixer, two other sections of this document discuss the topic – *Calibration Mixer Reciprocity Test Algorithm* and *Effects of Calibration Mixer Nonreciprocity on VMC accuracy.*

Higher-order mixing products generation (spurious products)

The spurious generation of a calibration mixer should be low, as spurs can result in measurement errors. Driving the mixer at relatively low power levels will help reduce spurious generation. The network analyzer hardware and firmware help reduce the effects of various spurs by deploying narrowband receivers. The MW PNA receivers are designed such that they will usually not respond to spurious signals. Additionally, the frequency converter application has a built-in "spur avoidance" algorithm that can be applied during the calibration and measurement process. Another practical technique is to slightly change the stimulus or response frequencies or number of points to avoid spurs.



Mixer Setup

Input -20.000 dBm Start/Stop 9.100000000 GHz 9.500000000 GHz

LO1 Not controlled -10.000 dBm Fixed 8.000000000 GHz ☑ Input > LO

Output = 1/1 X Input +/- 1/1 X LO1 = Start/Stop ○ + 17.100000000 GH 17.500000000 GH ● - 1.100000000 GHz 1.500000000 GHz

LOs: ● 1 ○ 2 ☑ Avoid Spurs

Figure 7. FCA's "Avoid Spurs" feature eliminates many measurement spurs.

The problem with higher-order products generated by the mixer is as follows. These products can reflect off the network analyzer ports (which have non-perfect match), re-enter the mixer, re-mix with other products, and generate error signals at the desired output frequencies. The problem can be avoided by using appropriate filtering on both the input and output. See the "Reducing Mismatch Ripple" section for more information on the topic, page 15.

Isolation

There are six mixer isolation terms – RF to IF and LO, LO to RF and IF, IF to LO and RF. The LO leakage term can be a significant error causing a spurious response, due to the high power levels of the LO. Thus, it is critical to reduce the amount of LO leakage, to achieve an accurate vector-mixer calibration. A good calibration mixer has at least 20 dB of LO to RF and LO to IF isolation.

The problem with LO leakage is that the LO signal leaking through the RF or IF port can reflect off the network analyzer port and re-enter the mixer and mix with the other products to create a mismatch error signal. It also can leak to the reference channel path and create additional errors, including “phase unlock” or “power unleveled” errors.

RF power level

The calibration mixer should be operated in its linear region to ensure linear reflections. This generally implies an RF power that is at least 30 dB less than the LO power. The reason for this is that the calibration model assumes linear reflections. If the mixer is operating in its linear region, the IF port reflection coefficient does not change with the RF input power level. However, in the nonlinear region, the reflection term is dependent upon the input power level. Figure 8 shows a graph of the S_{11} of a mixer, over various RF power levels. The LO power of this mixer was set to +14 dBm, the nominal value, so we were not overdriving the mixer with high LO power; we were increasing the RF power level. It is apparent that up to nearly 0 dBm of RF power, S_{11} remains relatively constant; but with +5 dBm RF input power, the S_{11} changes significantly.

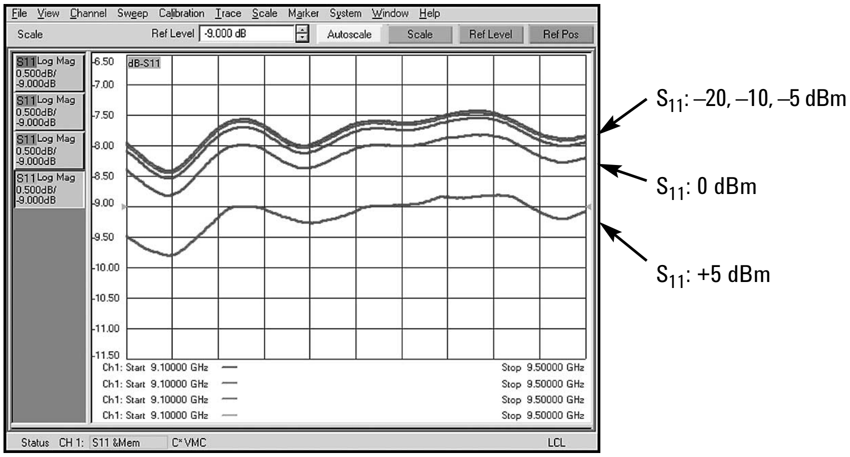


Figure 8. Effects of RF power level variation on S_{11} measurements.

Too much RF power will result in a VMC calibration with significant errors. So, it is recommended that users perform a test similar to the measurement described above to ensure that the calibration mixer is operating in its linear region.

LO power level

The calibration mixer should be driven with the same LO power during the characterization process, as during the “mixer through” measurement portion of the vector-mixer calibration process. This is because the performance of the calibration mixer will depend on the LO power level. The LO power level used to drive the calibration mixer during the calibration process does not have to be the same LO power level used to drive the DUT.

Calibration mixer reciprocity test algorithm

A reciprocal mixer is one where the conversion loss magnitude and phase are the same in both forward and reverse direction. The magnitude reciprocity of a mixer can be determined using FCA's scalar-mixer calibration technique. SMC provides match-corrected conversion loss magnitude measurements. Currently, there is no recommended way to test the phase reciprocity of a mixer.

The procedure below describes the steps necessary to measure the reciprocity of a mixer using SMC. Connect the mixer as shown in the Figure 9, with port 1 connected to the input of the mixer and port 2 connected to the output of the mixer.

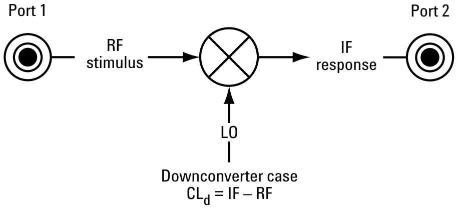
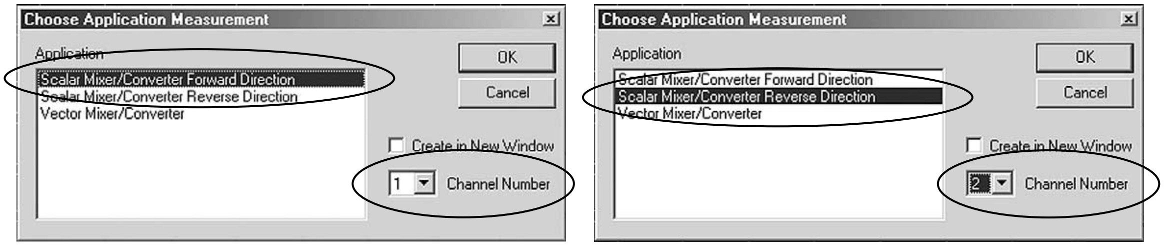


Figure 9. Connect the mixer to measure the forward and reverse conversion loss.

Set up the PNA for both a forward SMC (SC_{21}) and reverse SMC (SC_{12}) measurement. Configure channel 1 to measure SC_{21}, and channel 2 to measure SC_{12}. Both measurements can be made with the same hardware setup. The network analyzer firmware automatically makes both up- and down-conversion measurements.

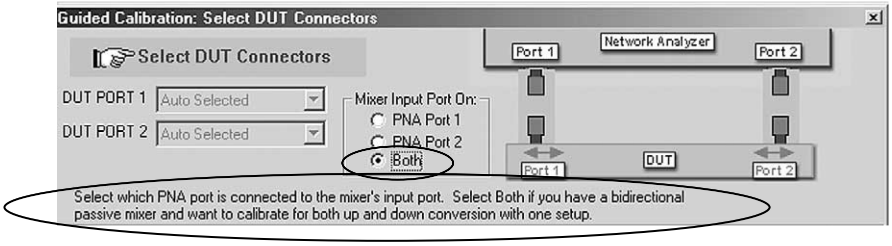


Application
Scalar Mixer/Converter Forward Direction
Scalar Mixer/Converter Reverse Direction
Vector Mixer/Converter
☐ Create in New Window
1 Channel Number

Application
Scalar Mixer/Converter Forward Direction
Scalar Mixer/Converter Reverse Direction
Vector Mixer/Converter
☐ Create in New Window
2 Channel Number

Figure 10. Configure channel 1 to measure SC_{21}, and channel 2 to measure SC_{12}.

SMC has a feature that can be used for calibrating both the forward and reverse measurements at one time (See Figure 11). The calibration wizard will guide you through the calibration.

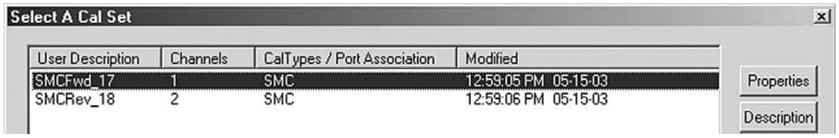


DUT PORT 1 Auto Selected
DUT PORT 2 Auto Selected
Mixer Input Port On:
○ PNA Port 1
○ PNA Port 2
● Both

Select which PNA port is connected to the mixer's input port. Select Both if you have a bidirectional passive mixer and want to calibrate for both up and down conversion with one setup.

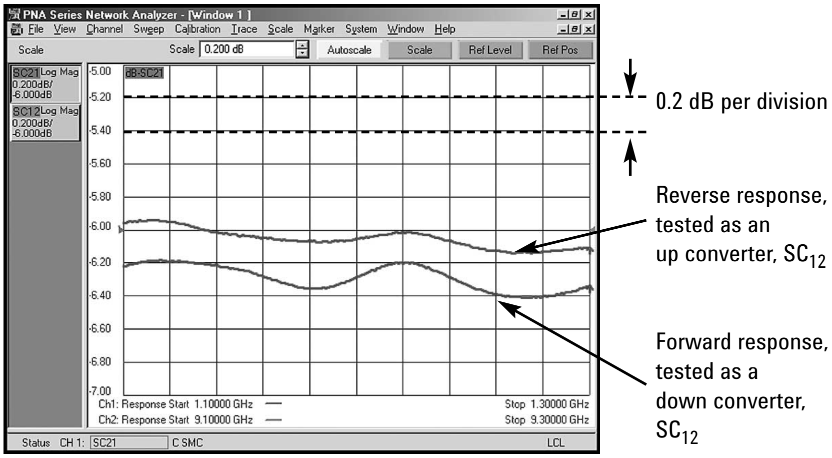
Figure 11. Perform a forward and reverse calibration at the same time, using the SMC Cal Wizard.

Once the calibration is complete, apply the calibration to the two channels (See Figure 12) and compare the results. Figure 13 is an example of the results you can expect. Any difference between the SC_{21} and SC_{12} will lead to an error in the vector-mixer calibration and hence add to the measurement uncertainty.



User Description	Channels	CalTypes / Port Association	Modified
SMCFwd_17	1	SMC	12:59:05 PM 05-15-03
SMCRev_18	2	SMC	12:59:06 PM 05-15-03

Figure 12. Apply SMCFwd_ to the SC_{21} measurement, and SMCRev_** to the SC_{12} measurement.**



Scale 0.200 dB

SC21 Log Mag 0.200dB/ -6.000dB

SC12 Log Mag 0.200dB/ -6.000dB

Ch1: Response Start 1.10000 GHz — Stop 1.30000 GHz

Ch2: Response Start 9.10000 GHz — Stop 9.30000 GHz

Status CH 1: SC21 C SMC LCL

0.2 dB per division

Reverse response, tested as an up converter, SC_{12}

Forward response, tested as a down converter, SC_{12}

Figure 13. Channel 1 is configured to measure SC_{21}, and channel 2 to measure SC_{12}.

Effects of calibration mixer nonreciprocity on VMC accuracy

Note

Keep in mind that the uncertainty due to the nonreciprocity of the calibration mixer is simply one component of the total measurement uncertainty. Traditional elements of measurement uncertainty, such as noise, connector repeatability, system drift, etc. still apply to the conversion loss measurements and should be included in any total system uncertainty calculation.

The nonreciprocity of a calibration mixer translates to an error in the vector-mixer calibration. Figure 14 is an example that shows the effects of nonreciprocity. In this example, we used mixer A as a calibration mixer, and then tested the same mixer A as the DUT. The following three traces are plotted:

- SC_{21}, forward SMC, tested as a down converter
- SC_{12}, reverse SMC, tested as an up converter
- Magnitude of VC_{21}, VMC, tested as a down converter

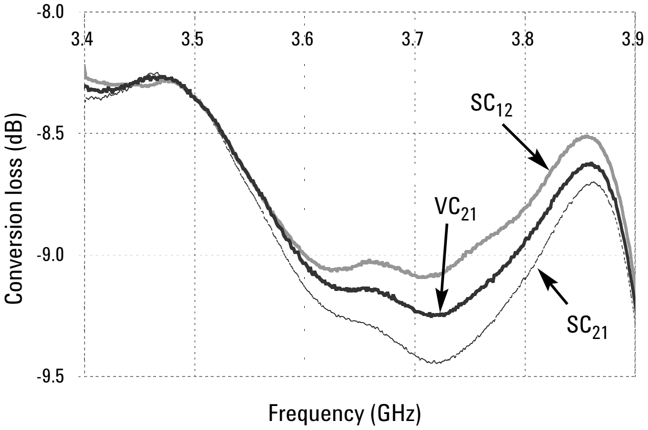


Figure 14. SC_{21}, SC_{12}, and VC_{21} of calibration mixer A.

If a calibration mixer is reciprocal, the SC_{21} and magnitude of VC_{21} should be equal, because they are both measuring the same response. You can observe this behavior in Figure 14 in the low frequency range (3.4 to 3.5 GHz). In the low frequency range, the SC_{21} and SC_{12} traces overlap, meaning the calibration mixer is reciprocal. In this same low frequency range, you can see that the VC_{21} and SC_{21} traces also overlap and the error in the VMC measurement is insignificant.

Now examine the mid-frequency range (3.7 to 3.8 GHz). You can see about 0.4 dB of difference between SC_{21} and SC_{12}. Since VMC averages the SC_{21} and SC_{12} terms (measures the round-trip loss) the VMC error is about half of 0.4 dB or ±0.2 dB. This explains why the VC_{21} trace is about 0.2 dB off from the SC_{21} trace. Essentially, the calibration mixer VC_{21} trace is an average of the cal mixer SC_{21} and SC_{12} traces and any difference in SC_{21} and SC_{12} translates to an error in the VC_{21} measurement.

Figures 15 and 16 demonstrate a similar concept. Figure 15 shows the reciprocity of a calibration mixer (mixer B). Figure 16 shows the SC_{21} and VC_{21} measurement of another mixer (mixer C) when mixer B was used as the calibration mixer in a vector-mixer calibration. From Figure 15, you can conclude that any vector-mixer cal performed with mixer B as the cal mixer will have about 0.5 dB of measurement error. In Figure 16, we can see the VC_{21} trace of mixer C is within 0.5 dB of the SC_{21} trace.

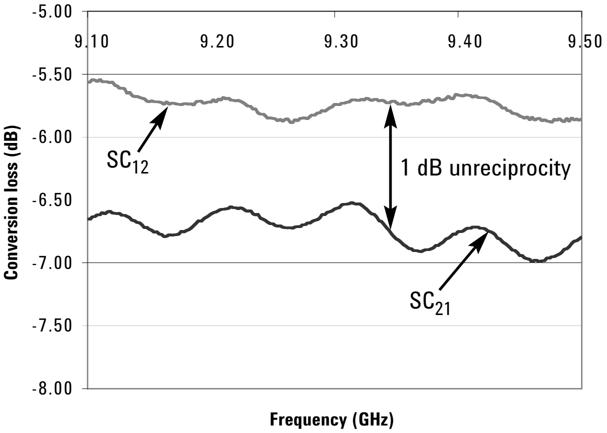


Figure 15. **Calibration mixer (mixer B) SC_{21} and SC_{12} has about 1 dB of nonreciprocity.**

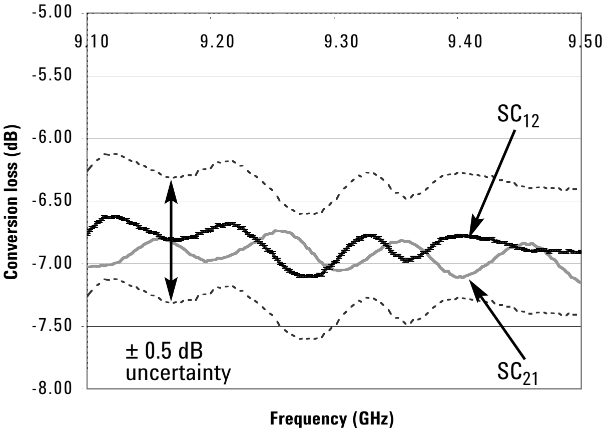


Figure 16. **DUT (mixer C) SC_{21} and VC_{21} with error range. VMC performed using mixer B.**

To obtain an accurate vector measurement, a reciprocal cal mixer is needed.

Note

If you are only interested in magnitude measurements only, SMC is a better technique. It has a simpler setup and provides you with traceable magnitude measurements. If you want phase and group delay information, then you need to use VMC. VMC may be more accurate, but it is not traceable. Since SMC depends upon power meter measurements, it is traceable.

Phase errors

Any error in the vector-mixer calibration applies to both the magnitude and phase. As explained in the Agilent white paper *Comparison of Mixer Characterization using New Vector Characterization Techniques*, the phase uncertainty can be estimated from the magnitude uncertainty. Figure 17 is a graphical representation of the phase uncertainty.

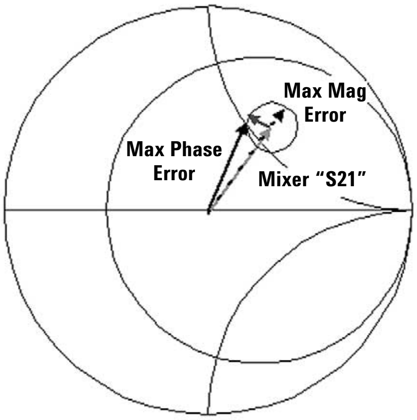


Figure 17. Magnitude error translating into phase error.

Equations to calculate phase uncertainty

Magnitude error in dB = $\pm a$

Maximum phase uncertainty (degrees) = $\text{Arc tan}\,(10^{\frac{a}{20}} - 1)$

Minimum phase uncertainty (degrees) = $\text{Arc tan}\,(1 - 10^{\frac{-a}{20}})$

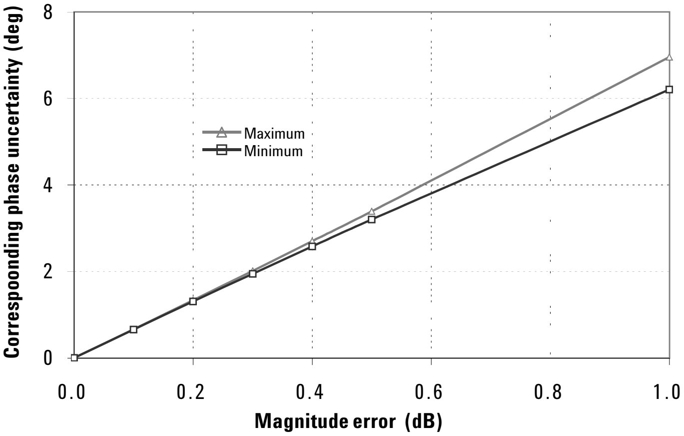


Figure 18. Phase uncertainty, as a result of magnitude nonreciprocity of the calibration mixer.

As an example, the VC_{21} phase data, along with the magnitude data, of mixers A and C are shown in Figures 19 and 20.

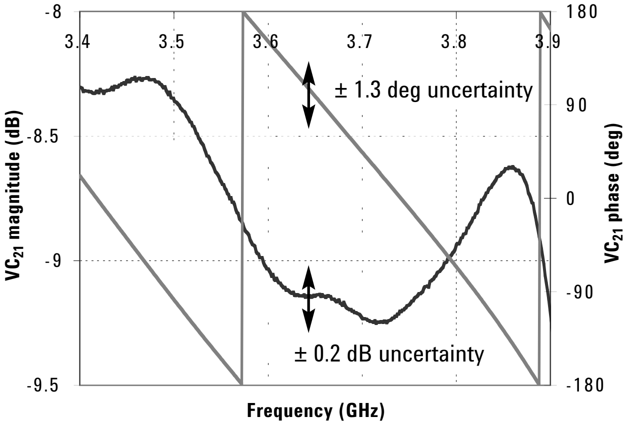


Figure 19. VC_{21} **magnitude and phase data for mixer A.**

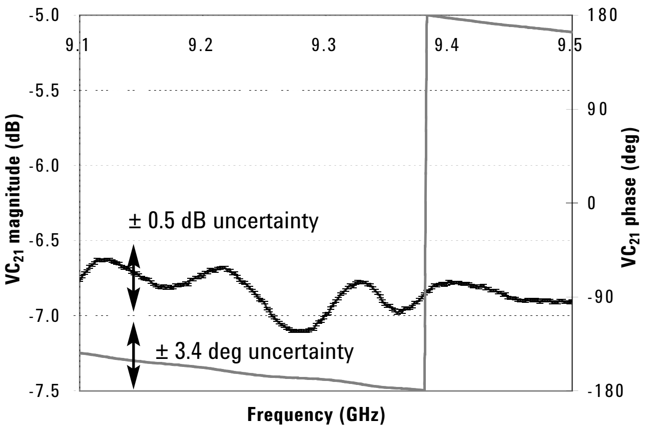


Figure 20. VC_{21} **magnitude and phase data for mixer C.**

Calibration IF filter attributes

The IF filter is used to select the desired mixing product, either the RF+LO or the RF-LO product. The filter should have low loss in the passband region, to minimize measurement uncertainty. Also, the filter should be reflective everywhere that undesired signals exist. Care must be taken to ensure that the stopband of the filter does not come back up where undesirable mixing or leakage products exist. If these undesirable signals are not fully reflected and hence are a function of the open, short, and load terminations, the calibration accuracy is degraded.

Reference mixer attributes

Frequency range

The frequency range of the reference mixer should be the same or wider than the frequency range of the DUT, for both input and output frequencies. If more than one DUT is tested using the same test setup, select a reference mixer with broad frequency coverage, such that it covers the frequency range of all devices that need to be tested.

Conversion loss and conversion loss reciprocity

There are no requirements on the conversion loss of the reference mixer. The reference mixer does not need to be reciprocal.

Return loss

The better the return loss of the reference mixer, the lower the measurement uncertainty. Return loss of 10 dB or better is sufficient.

Isolation

Similar to a calibration mixer, the isolation of a reference mixer should be examined. See the section on isolation of calibration mixers, page 8.

LO power level

The LO power level driving the reference mixer should be the kept the same during calibration and measurement time. This ensures that the performance of the reference mixer does not change from calibration to measurement time.

Scalar- and Vector-Mixer Measurement Considerations

Reducing mismatch ripple

Scalar measurements

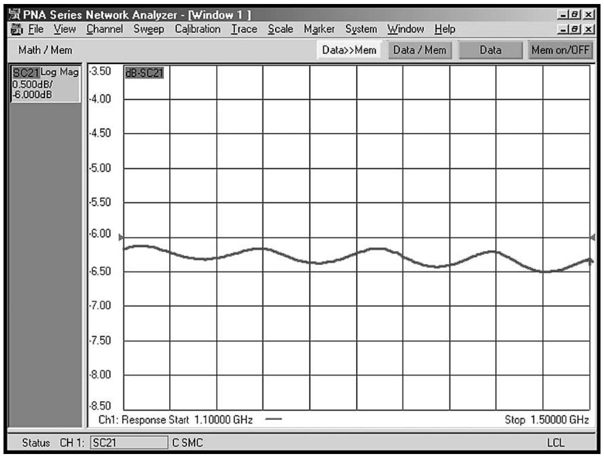
One of the main challenges of mixer measurements is the presence of multiple signals and spurs due to the nonlinear nature of mixers. The effect of unwanted signals is generally measurement ripple. Identification and reduction of these undesirable signals is a critical part of mixer measurements. A spectrum analyzer is a good tool to use to identify the signals. Filters, isolators, and attenuators are common components used to reduce the significance of unwanted signals.

In this section, we use an example to demonstrate the effects of input RF filtering or attenuation in reducing the levels of spurs and leakage signals, and hence, mismatch ripple.

The example frequency settings for our test mixer are:

RF: 9.1-9.5 GHz
LO: 8 GHz
IF: 1.1-1.5 GHz.

The initial calibrated conversion loss (SC_{21}) measurement of this mixer, seen in Figure 21, shows about 0.4 dB of ripple.



0.5 dB/division,
<0.4 dB of ripple

Figure 21. Initial conversion loss (SC_{21}) measurement shows about 0.4 dB of ripple.

Let's investigate the source of this ripple. A starting point is to suspect ripple due to mismatch errors. We know that SMC corrects for the fundamental mismatch terms (RF reflection off port 1, IF reflection off port 2); therefore, we are looking for other sources of mismatch. We can start the troubleshooting by adding an attenuator to the input or output ports to determine if attenuation on either side will reduce the ripple level.

Note

If your MW PNA has the source attenuator option (Option UNL), you can increase the source attenuation instead of adding attenuators. The source attenuators are adjustable in 10 dB steps. If you change the source attenuator setting, you need to perform a new calibration.

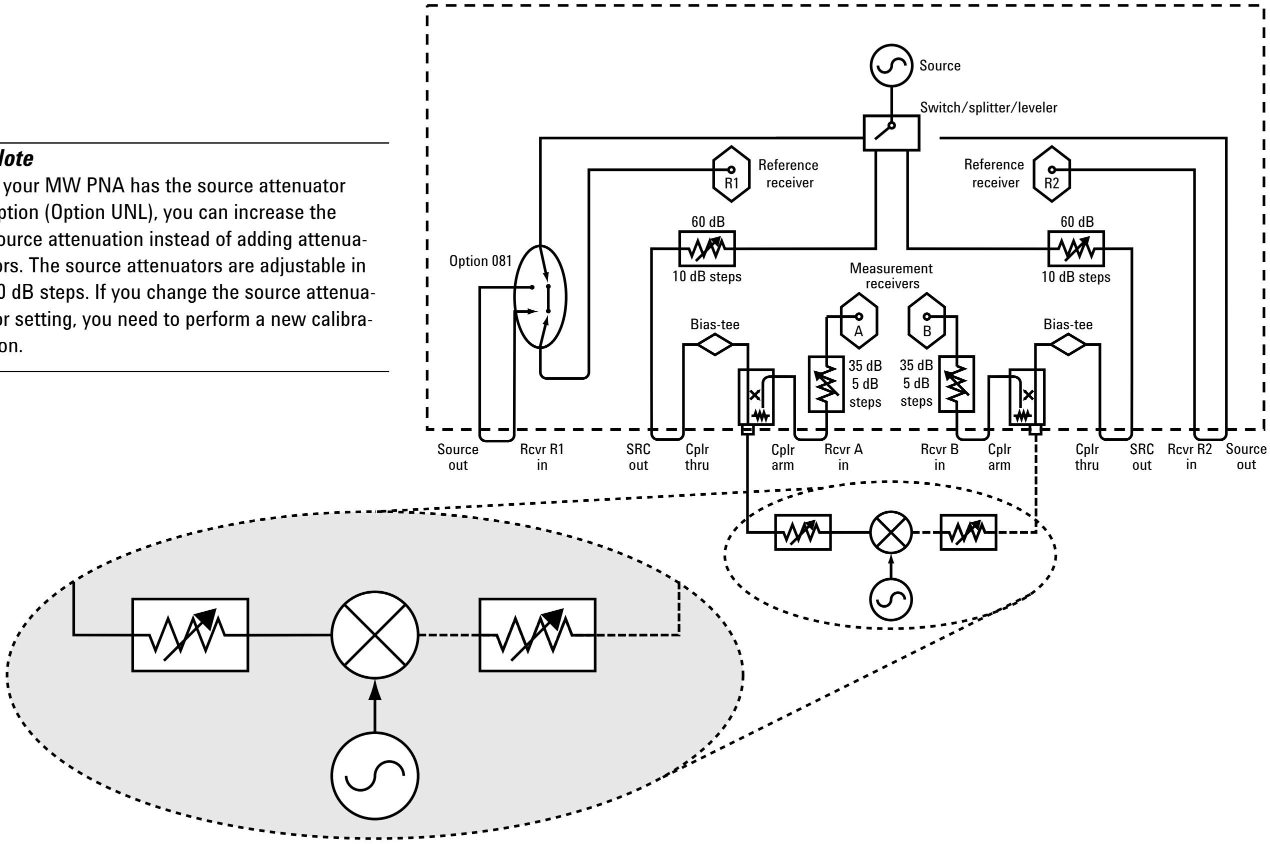


Figure 22. Connect the attenuators to either the input or output port to isolate the source of mismatch.

There is no need to initially perform a calibration with the attenuator, as we are just looking to see if the ripple level changes or not. The absolute level of the conversion loss will change by the amount of attenuation (about 6 dB in this example), but if the mismatch error is not on either port, then the ripple amount will not change. Figure 23 shows the measurement results in three cases: no attenuators, a 6 dB attenuator on the input port, a 6 dB attenuator on the output port.

Note

In this example, the data for the three cases is plotted on a graph. During measurements, you can simply use the network analyzer' "**data→memory**" and "**data/memory**" features to investigate the ripple variations.

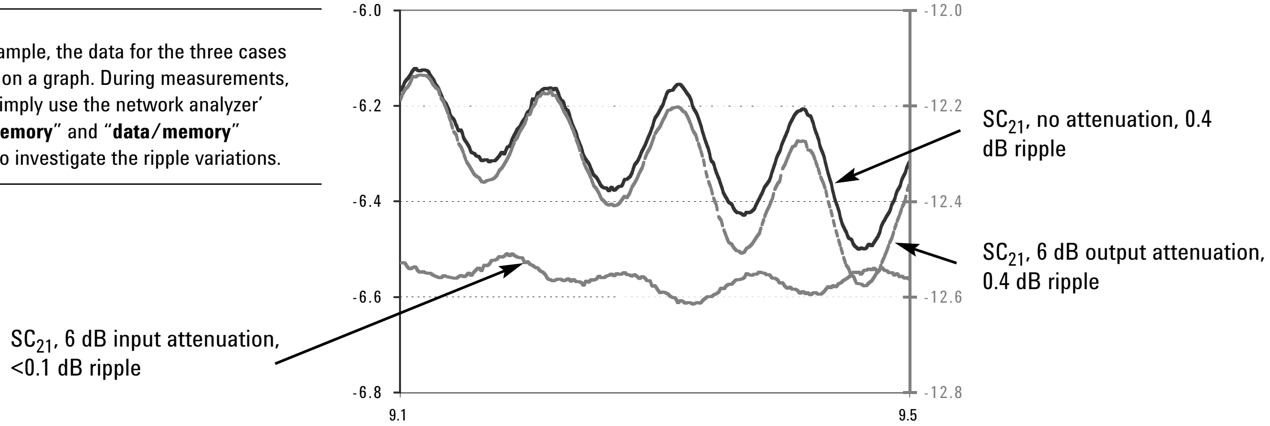


Figure 23. Ripple differences between no attenuation and 6 dB attenuation on the input or output ports.

As you can see in Figure 23, addition of the padding to the input port reduced the amount of ripple, but adding it to the output port did not make any difference. Therefore, it appears that the mismatch is due to interactions on the input port. Let's look into the cause of the input mismatch.

To investigate reflected signals on the input side of the mixer or port 1, connect a spectrum analyzer to the "CPLR ARM" jumper, as shown in Figure 24. The signals you observe on the spectrum analyzer are the signals that would be incident upon port 1 of the network analyzer. These signals would in turn, be reflected back due to the imperfect match of the test set, and appear as an input to the mixer.

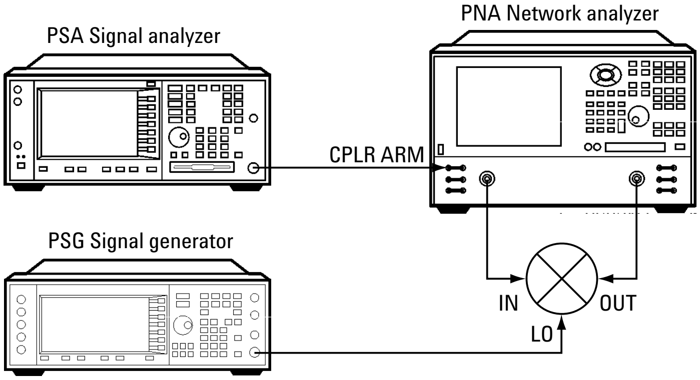
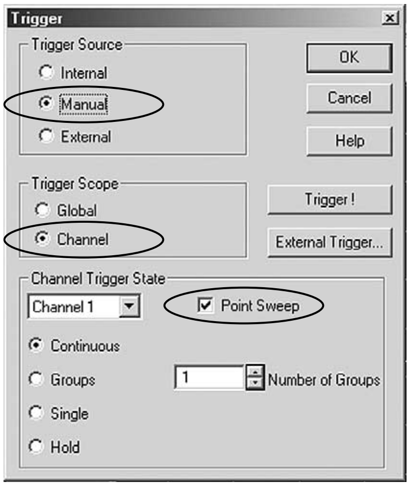


Figure 24. Connect a spectrum analyzer to the "CPLR ARM" to investigate signals incident upon port 1.

You may want to take advantage of either the "Manual Point Trigger" mode of the network analyzer or the "Max Hold" feature of the spectrum analyzer so you can observe the signals.



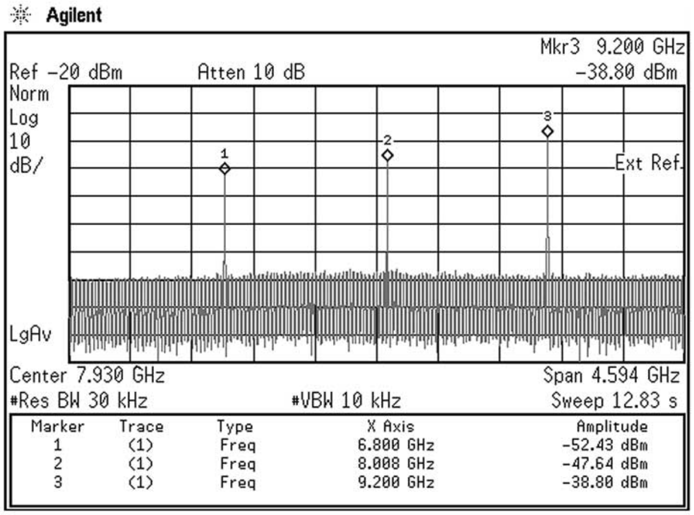
Trigger Source
○ Internal
● Manual
○ External

Trigger Scope
○ Global
● Channel

Channel Trigger State
Channel 1
☑ Point Sweep
● Continuous
○ Groups
1 Number of Groups
○ Single
○ Hold

Figure 25. The "Manual Point Trigger" mode of the VNA is useful for troubleshooting spurs.

In this example, we were sweeping the RF from 9.1-9.5 GHz. Using manual triggering, we stopped the network analyzer source at 9.2 GHz; with the LO at 8 GHz, we expect a low-side IF of 1.2 GHz. Figure 26 shows the response seen on the spectrum analyzer.



Mkr3 9.200 GHz
Ref −20 dBm Atten 10 dB −38.80 dBm
Norm
Log
10
dB/
LgAv
Center 7.930 GHz Span 4.594 GHz
#Res BW 30 kHz #VBW 10 kHz Sweep 12.83 s

Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	6.800 GHz	−52.43 dBm
2	(1)	Freq	8.008 GHz	−47.64 dBm
3	(1)	Freq	9.200 GHz	−38.80 dBm

Figure 26. Signal incident upon port 1 of the network analyzer, viewed on a spectrum analyzer.

Let us identify the tones:

Marker 1 at 6.8 GHz: The main IF signal of 1.2 GHz reflects off of the network analyzer port 2 and mixes with the 8 GHz LO to produce a 6.8 GHz signal incident on port 1; so, we are measuring this signal. This 6.8 GHz signal will then reflect off the network analyzer port 1, re-mix with the 8 GHz LO, and produce a valid IF of 1.2 GHz. This signal is not corrected for and causes mismatch ripple.

Marker 2 at 8.0 GHz: This is the LO leakage. The LO power for the mixer is +13 dBm; the network analyzer coupler loss is about 16 dB; the LO to RF isolation typical performance of this mixer is supposed to be 35 dB. We measure a –47 dBm signal, so this mixer clearly meets its LO to RF isolation specification. This signal will reflect off the network analyzer port 1 and mix with the fundamental RF of 9.2 GHz to produce a valid IF of 1.2 GHz. This signal is not corrected for and causes mismatch ripple.

Marker 3 at 9.2 GHz: This is the RF reflection term. This RF tone will reflect off the mixer and re-enter port 1. The scalar-mixer calibration corrects for this reflected signal, so we do not need to be concerned with this signal.

Let us see how we can reduce the error due to the signals at markers 1 and 2 (6.8 and 8 GHz). An RF band pass filter that only passes the 9.1-9.5 GHz RF range would filter out both the 6.8 and 8 GHz signals and reduce the error; a 9 GHz high-pass filter would also work. An alternative solution is to add attenuators to port 1 of the network analyzer to reduce the level of re-reflected signals. The source power level can be increased to make up for the loss of the attenuators. The advantage of attenuation is that attenuators are easy to find, whereas finding a filter with the desired response may not be as easy.

We recommend that the attenuators be added between the “SRC OUT” and “CPLR THRU” jumper as shown in Figure 27.

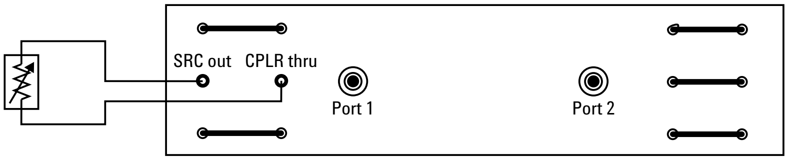
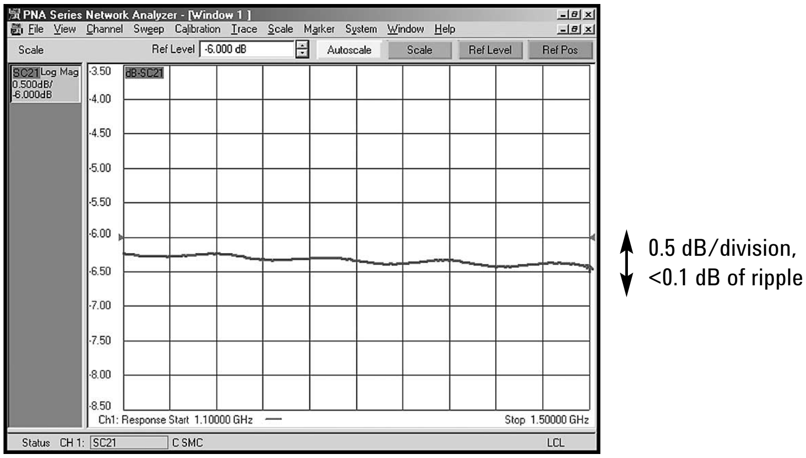


Figure 27. Connect attenuators between the source out and coupler input to reduce measurement ripple.

The reason it is better to add the attenuator between the jumpers instead of directly at the test port is related to directivity. Adding loss at the output of the coupler degrades raw directivity by twice the value of the attenuator. This is why it is usually not a good idea to place attenuators or use lossy cables on any network analyzer test port that will be used for reflection measurements. Even when calibration is used to correct for the effect of the loss, the stability of the calibration will be worse (i.e., more drift will occur) due to the degraded raw directivity. Attenuation added between the source and the coupler, or between the coupled port and the receiver, would not affect raw directivity.

We added 6 dB of attenuation between the “SOURCE OUT” and “COUPLER THRU” jumpers, and performed a new calibration. The results are shown in Figure 28. We were able to reduce the ripple level significantly by adding an attenuator to the input port (compare to Figure 21).



0.5 dB/division,
<0.1 dB of ripple

Figure 28. Conversion loss (SC_{21}) measurement with 6 dB of input attenuation – showing little ripple.

There are other possible sources of mismatch error which were insignificant in this example but can be considerable in other cases. One such case is where the RF signal incident upon the mixer leaks through the mixer, reflects off port 2, re-enters the mixer as another leakage term, reflects off port 1, and re-enters the mixer as an error signal. This signal is not corrected for through the calibration. So to obtain the most accurate measurement, it is important to reduce the level of these unwanted signals.

Vector measurements

The example in this case is based on a scalar measurement. The concepts and concerns apply to a vector-mixer measurement as well, and the recommended solutions can be applied to vector measurements.

Effects of leakage

Scalar measurements

A scalar measurements setup is quite simple, so the main isolation terms of concern are the LO to RF and LO to IF isolation. The LO leakage terms can be filtered out using RF or IF filters.

Vector measurements

The vector-mixer calibration and vector-mixer measurement setups are similar, and any leakage concerns apply to both the calibration and measurement. In Figure 29, you can see a few of the possible leakage paths that would result in calibration and measurement errors. The dotted lines represent the RF leakage paths. The worse the RF to LO isolation of the mixers, the more significant this error term. The solid lines represent the LO leakage paths, which are critical if the reference, calibration, or DUT mixers have poor LO to RF or LO to IF isolation.

In Figure 30, you can see how the addition of isolators in key positions can reduce the significance of these leakage terms. The isolators shown in Figure 30 would need to pass the LO signal while preventing the RF signals from leaking through.

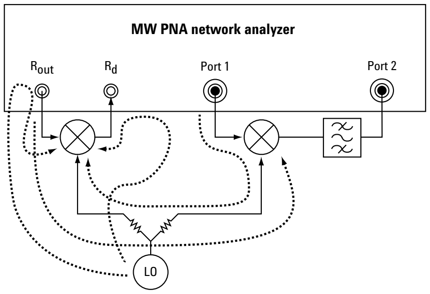


Figure 29. Possible leakage paths that would result in measurement errors.

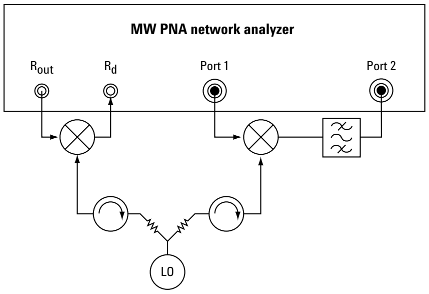


Figure 30. Increase the measurement accuracy by using isolators in key positions.

Effects of LO power variation

Most mixers are sensitive to variations in the LO power level. The conversion loss and reflection coefficient of mixers varies considerably with changes in LO power. So, it is important to test and operate mixers with a known and specified LO power. Maintaining a constant and known LO power level is simpler with a scalar measurement versus a vector measurement. The reason is that the setup for a scalar measurement is simpler.

With a vector-mixer calibration, the calibration mixer should be driven with the same LO power during the characterization process as during the through portion of the vector-mixer calibration process. If the calibration mixer characterization and system calibration processes are completed at one-time, it is easy to maintain a constant power level.

The LO power level driving the reference mixer should be the kept the same during calibration and measurement. This ensures that the performance of the reference mixer does not change between calibration and measurement. If you are using isolators or filters during the calibration process, be sure to use them also during the measurement process, as they will effect the LO power incident upon the reference mixer.

Pay attention to the method you use to alter the power level, if:

- You are using a single LO source to drive both the reference and calibration (or DUT) mixers, and
- The DUT and the calibration mixer have different LO power level requirements.

An example is used to demonstrate the point.

Cal mixer requirement: +14 dBm LO power
DUT requirement: +11 dBm LO power

During the vector-mixer calibration process, the reference mixer is driven with +14 dBm of LO power (See Figure 31). During the measurement process, the LO power level is reduced to +11 dBm because a single LO source is used to drive the reference mixer and the DUT, and the DUT required a lower LO power level (See Figure 32). This results in measurement errors because the conversion loss of the reference mixer differs, when driven with +14 versus +11 dBm of LO power.

The recommended method is to continue to drive the reference mixer with +14 dBm but drive the DUT with +11 dBm. Insert a 3 dB pad in the DUT path to decrease the LO power driving the DUT (See Figure 33). As a result, the LO power driving the reference mixer is kept the same, while the DUT is driven with the desired power. You can use amplifiers or attenuators to vary the power levels. Amplifiers, while more difficult to locate than attenuators, often have the added benefit of providing isolation.

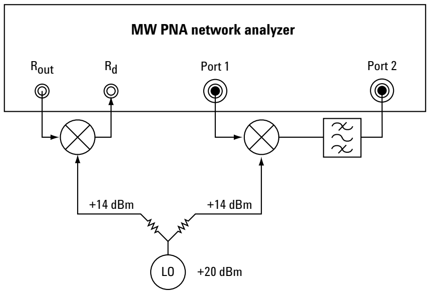


Figure 31. Correct calibration setup.

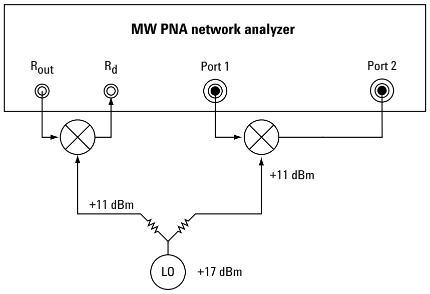


Figure 32. Incorrect test setup. The LO power driving the reference mixer is different from the power during calibration.

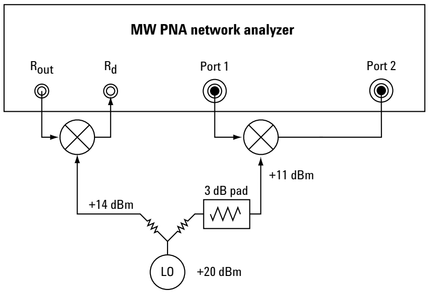
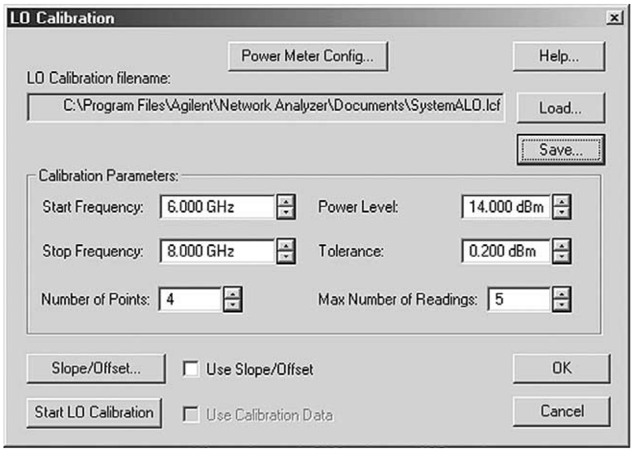


Figure 33. Correct test setup. The LO power driving the reference mixer kept the same during calibration and measurement.

Note
When measuring dual converters, keeping track of the various LO power levels and maintaining power level consistency are critical issues that must be recognized and dealt with appropriately.

LO power calibration

The frequency converter application offers a feature for calibration and leveling of the LO power level. It is available from the mixer configuration menu. Using this feature, you can use a power meter to calibrate the LO power driving the DUT or the calibration mixer.



LO Calibration filename: C:\Program Files\Agilent\Network Analyzer\Documents\SystemALO.lcf

Calibration Parameters:
Start Frequency: 6.000 GHz
Stop Frequency: 8.000 GHz
Number of Points: 4
Power Level: 14.000 dBm
Tolerance: 0.200 dBm
Max Number of Readings: 5

☐ Use Slope/Offset
☐ Use Calibration Data

Figure 34. Use the LO Calibration feature of FCA to accurately control the LO power levels.

A quick check of the mixer calibrations

When troubleshooting a calibrated measurement, it is often useful to briefly check the validity of the calibration. With a standard two-port calibration, users would often check the S_{21} of a through connection, expecting approximately 0 dB, or measure the S_{11} of a load, expecting better than 35 dB.

With SMC and VMC, a quick way to check your calibration is to have a golden mixer; and after a calibration, test the golden mixer and look for the expected results. A golden mixer is a device that has been tested before, is stable, and the performance is known. Other methods of checking the scalar-and vector-mixer calibrations are explained below.

An easy way to check a scalar-mixer calibration is to examine the incident power and output power measured by the receivers.

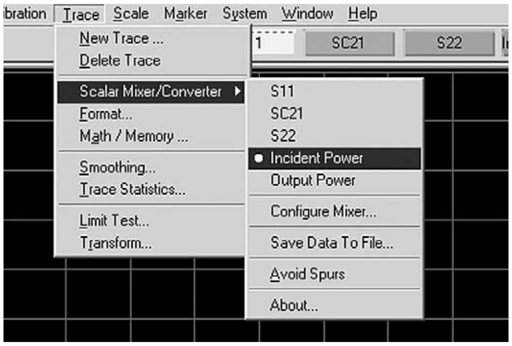
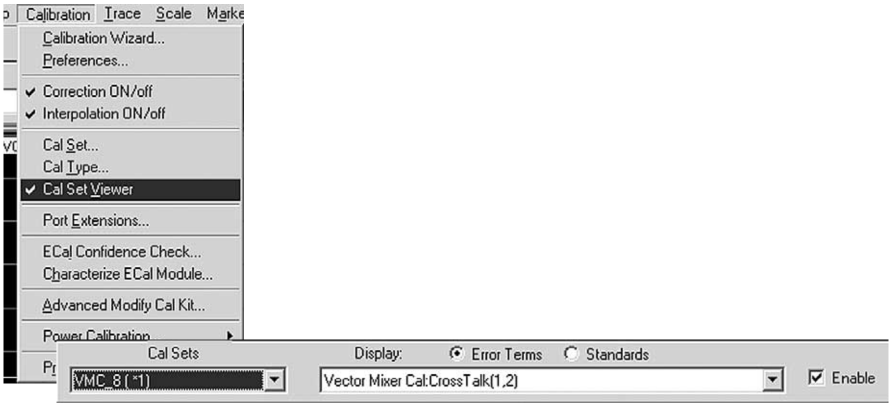


Figure 35. You can measure the incident power and output power with the scalar-mixer measurement setup.

To test the calibration of the receivers in measuring incident power, first connect a power sensor to port 1 of the network analyzer (or the input point of your mixer). For a given frequency, compare the incident power measured by the network analyzer to the power meter reading. The difference should be minimal.

To test the calibration of the receivers in measuring output power, connect a source first to a power meter and record the value. Then connect the source to port 2 of the network analyzer and read the displayed output power. The power meter reading should be very close to the one on the network analyzer.

For VMC, a quick check method is to view the calibration set. You can view the calibration set using the menu item "Cal Set Viewer".



Cal Sets: VMC_8 (*1)
Display: ● Error Terms ○ Standards
Vector Mixer Cal:CrossTalk(1,2)
☑ Enable

Figure 36. Use the "Cal Set Viewer" to examine the calibration parameters.

The data in the calibration set can provide you with information on the plausibility of your calibration. For example, if the source match terms appear incorrect, you can suspect a bad two-port calibration. In a VC_{21} measurement, often large measurement ripples seen in the calibrated measurements can also be seen in the calibration data set; generally in the transmission tracking term. Table 1 contains a list of plausible values for the various VMC error terms.

Table 1. VMC error terms.

Error terms	Plausible value[1]	Description	Method of determining error term
Directivity (1,1)	> 20 dB	Port 1 directivity at input frequency	Standard error term. Based on the two one-port calibrations and a through measurement or the full two-port cal part of or VMC.
Source match (1,1)	> 16 dB	Port 1 source match at input frequency	
Reflection tracking (1,1)	± 1.5 dB	Port 1 reflection tracking at input frequency	
Directivity (2,2)	> 20 dB	Port 2 directivity at output frequency	
Source match (2,2)	> 16 dB	Port 2 source match at output frequency	
Reflection tracking (2,2)	± 1.5 dB	Port 2 reflection tracking at output frequency	
Load match (2,1)	> 20 dB	Port 2 load match at output frequency	
Transmission tracking (2,1)	5 to 10 dB	Forward transmission tracking or S_{21} magnitude. It represents the approximate **conversion loss of the calibration mixer**.	Based on the cal mixer characterization and measurement.
Load match (1,2)	-200 dB	Port 1 load match. The source will not be at port 2 for a VMC measurement.	Term not needed in VMC, so it is zeroed out.
Transmission tracking (1,2)	0 dB	Reverse transmission tracking or S_{12}. The mixer transmission is measured in one direction.	
Crosstalk (1,2)	-200 dB	Port 1 to 2 crosstalk	
Crosstalk (2,1)	-200 dB	Port 2 to 1 crosstalk	

You can view the SMC cal set also, though SMC is based on a custom error model. So the SMC error terms differ from the standard two-port model. Table 2 has a list of these error terms.

Table 2. SMC error terms.

Error terms	Plausible value[1]	Description	Method of determining error term
Directivity (1,1)	> 20 dB	Port 1 directivity at input frequency	Standard error term. Based on the two one-port calibrations and a through measurement or the full two-port cal part of SMC.
Source match (1,1)	> 16 dB	Port 1 source match at input frequency	
Reflection tracking (1,1)	± 1.5 dB	Port 1 reflection tracking at input frequency	
Directivity (2,2)	> 20 dB	Port 2 directivity at output frequency	
Source match (2,2)	> 16 dB	Port 2 source match at output frequency	
Reflection tracking (2,2)	± 1.5 dB	Port 2 reflection tracking at output frequency	
Load match (2,1)	> 20 dB	Port 2 load match at output frequency	
Transmission tracking (2,1)	± 1.5 dB	Forward transmission tracking or S_{21} magnitude	
ETF (2,1)	These terms are unique to the SMC error model. They are based on the source, power meter, and receiver measurements, and are used to calibrate the MW PNA receivers for accurate match-corrected absolute power measurements. The range of values these terms can take on is variable and is dependent on the whole test system setup.		
Power Offset Input (1,1)			
Power Offset Output (1,1)			
T1_input (1,1)			
T1_output (1,1)			

---

[1] < 10 GHz. Range depends on instrument and calibration kit used.

Summary

The frequency converter application and its associated scalar- and vector-mixer calibrations provide you with the tools necessary to determine the characteristics of frequency-translating devices with good accuracy. You can make the measurements easily and be confident in the results.

If you want to achieve the highest degree of accuracy, that is, you want a conversion loss with the least mismatch error or the cleanest group delay with the least noise and ripple, then you need to pay more attention to your test setup. The nature of nonlinear device test setups leads to numerous signals and signal paths. You need to configure the hardware for clean and known signal paths, and perform a high-quality calibration. Reduce the level of unwanted signals, using filters, isolators, or attenuators. Additionally, select appropriate calibration standards to obtain the best calibration.

In the end, accurately characterizing the performance of your frequency-translating device will allow you to create a better and more efficient design, which will in turn lead to a lower cost and more competitive product.

Recommendations for Accurate Measurements

- Select a calibration mixer with conversion loss less than 10 dB and isolation more than 20 dB. (VMC specific)
- Select a calibration mixer that is reciprocal. (VMC specific)
- Characterize the calibration mixer directly at the test port for maximum stability. (VMC specific)
- Set the RF and LO power levels incident upon your calibration mixer such that the mixer operates in its linear region.
- Use RF and IF filters on the input and output of the mixers respectively, to reduce the effects of harmonics and spurs.
- Reduce the IF bandwidth setting during the calibration process to less than 1 kHz, to reduce the noise level. You can increase it during the measurement process.
- Use isolators in the LO path appropriately to reduce LO leakage.

References

These documents can be found under the library information on the Agilent MW PNA website **www.agilent.com/find/pna**.

[1] *Mixer Transmission Measurements Using the Frequency Converter Application*, Agilent Application Note 1408-1, literature number 5988-8642EN

[2] *Mixer Conversion Loss and Group Delay Measurement Techniques and Comparisons*, Agilent Application Note 1408-2, literature number 5988-9619EN

[3] *Novel Method for Vector-mixer Characterization and Mixer Test Systems Vector Error Correction*, White Paper, literature Number 5988-7826EN

[4] *Comparison of Mixer Characterization using New Vector Characterization Techniques*, White Paper, literature Number 5988-7827EN

Web Resources

For additional literature and product information about the Agilent PNA Series visit:
www.agilent.com/find/pna

For additional information about Agilent electronic calibration (ECal) modules visit:
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(fax) (81) 426 56 7840
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