Accurate Vector Mixer Measurements with a Vector Network Analyzer

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⎍ 1 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 frequency offset function provided by Siglent SNA series allows the source to work at the mixer's input frequency while the receiver alternates operation between the mixer's input and output frequencies. Since phase comparison of different frequencies is meaningless, the phase characteristics of frequency conversion device cannot be obtained. This technique is called scalar mixer measurement. To obtain the phase characteristics of a mixer, we need to use vector mixer measurement techniques.

⎍ 2 Small Signal Model of Mixers

Since phase is a relative value, its measurement requires a reference baseline. Co-frequency devices can be directly characterized by the phase difference between the input and output signals to insert the phase shift. While mixers have different input and output frequencies, they cannot be directly compared in phase, and its phase characteristics are very much related to the operating mode, so a clear definition of the phase characteristic model of a mixer is needed before exploring its test method.

The output signal of a mixer contains multiple spectrum components. Take fundamental frequency mixing as an example, the input signal of mixer be denoted as IN and the local oscillator as LO. The mathematical expression for multiplying the two signals can be described as follows:

$$\cos(\omega_{IN}t) \times \sin(\omega_{LO}t) = \frac{1}{2}[\sin(\omega_{IN} + \omega_{LO})t - \sin(\omega_{IN} - \omega_{LO})t]$$

Thus the output will have frequency elements at the sum and difference of the two input signals. LO signal has many harmonics (all odd if it is symmetrical signal) and so there will also be outputs at the sum and difference of each of the harmonics of the signals with the input signal as well, sometimes referred to as intermodulation spurs, or higher-order products. Designers extracts the required frequency components at the output through filtering according to actual needs. To simplify the analysis, the mixers mentioned below are all in fundamental mixing mode. If the frequency of the filtered output signal is higher than that of the input signal, it is defined as an upconverter, and if the frequency of the output signal is lower than that of the input signal, it is a downconverter.

Even though the very nature of mixers is non-linear, for the most part the transfer of signal from the RF port to the IF port is linear in its behavior, and can be modeled much like S-parameters in an amplifier. If the change in frequency is set aside, if the amplitude of the input signal changes by a factor of two, the amplitude of the output signal also changes by a factor of two. And if one applies a small modulated signal to the RF input, the same modulated signal will appear at IF output, without distortion. Then the relationship between the individual output components and the input signal can be approximated as linear, except that the phase

and frequency of different output components will show different trends as the phase/frequency of the input signal changes.

If the frequency of the filtered output signal is $\omega_{IN} + \omega_{LO}$, the phase and frequency change of the signal is in the same direction as that of the input signal. If the frequency of the filtered output signal is $\omega_{IN} - \omega_{LO}$ and $\omega_{IN} > \omega_{LO}$, the phase and frequency changes of the signal and the direction of change of the input signal are also the same, these two cases are called standard or normal mode. When $\omega_{IN} < \omega_{LO}$, the frequency of the output signal should be $\omega_{LO} - \omega_{IN}$, and its phase and frequency change is opposite to the direction of the input signal, which is called mirror mode. Assuming that the power variation of the local oscillator does not affect the frequency conversion characteristics of mixer (the normal operating condition of mixer is generally driven by a sufficiently high power of the local oscillator, and this assumption is valid), both modes can be obtained based on the small signal model of incident and scattered waveforms, and the schematic diagrams of the incident and scattered waveforms for the ideal normal mixer and the mirror mixer are as follows:

Schematic of a normal (a) and image (b) mixers showing incident and scattered waves

When the input signal of an ideal mixer is converted from port 1 to port 2, the amplitude and phase are constant and there are no reflections at the port, at which time the output signal at port 2 can be expressed as:

$$\text{normal mixer: } b_{RF} = a_{LO} * a_{IF}$$
$$\text{mirror mixer: } b_{IM} = a_{LO} * a_{IF}^*$$

The a_{IF}^* in the mirror mixer in the above equation refers to the conjugate of the input signal. When the IF frequency/phase is increased, the IM shows an inverse change, so the conjugate representation is used, and the output signal of port 2 can also be written in the following form:

$$b_{IM}^* = a_{LO}^* * a_{IF}$$

The signal added to port 2 of the ideal mixer will also be converted to the input frequency with the same unchanged amplitude and phase and no reflection at the port, at which point the signal at port 1 can be represented as:

$$\text{normal mixer: } w_{IF} = w_{RF} - a_{LO}; \ b_{IF} = a_{LO}^* * a_{RF}$$
$$\text{mirror mixer: } w_{IF} = w_{LO} - a_{IM}; \ b_{IF} = a_{LO} * a_{IM}^*$$

Writing the above expression in matrix fashion yields the following scattering matrix for an ideal mixer:

$$\text{normal mixer:} \begin{bmatrix} b_{IF} \\ b_{RF} \end{bmatrix} = \begin{bmatrix} 0 & a_{LO}^* \\ a_{LO} & 0 \end{bmatrix} \cdot \begin{bmatrix} a_{IF} \\ a_{RF} \end{bmatrix}$$

$$\text{mirror mixer:} \begin{bmatrix} b_{IF} \\ b_{IM}^* \end{bmatrix} = \begin{bmatrix} 0 & a_{LO} \\ a_{LO}^* & 0 \end{bmatrix} \cdot \begin{bmatrix} a_{IF} \\ a_{IM}^* \end{bmatrix}$$

Where the amplitude of LO does not affect the frequency conversion characteristics, $|a_{LO}| = 1$

Compared with ideal mixer, the real mixer has reflections on the input and output ports, and the amplitude and phase of signal will be affected by the frequency response of the device and change during transmission. By placing all these influences on the IF or RF side, or splitting to both the IF and RF sides, the schematic diagram of a real mixer can be obtained as follows:
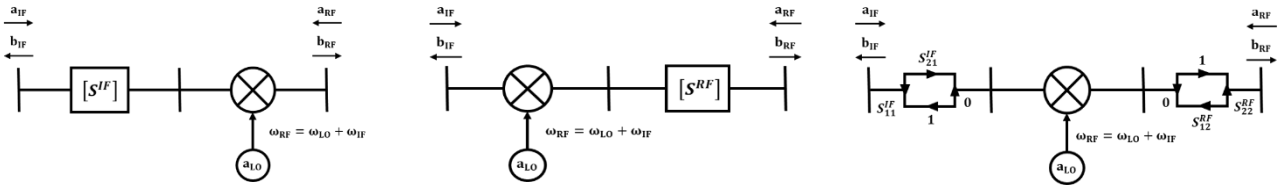
Schematic representations of mixers with non-ideal responses

The non-ideal normal mixer scattering matrix can be obtained from the above figure:

$$\begin{bmatrix} b_{IF} \\ b_{RF} \end{bmatrix} = \begin{bmatrix} S_{11}^{IF} & a_{LO}^* * S_{21}^{IF} \\ a_{LO} * S_{21}^{IF} & S_{22}^{IF} \end{bmatrix} \cdot \begin{bmatrix} a_{IF} \\ a_{RF} \end{bmatrix} = [S^{IF}] \cdot \begin{bmatrix} a_{IF} \\ a_{RF} \end{bmatrix}$$

$$\text{or} \begin{bmatrix} b_{IF} \\ b_{RF} \end{bmatrix} = \begin{bmatrix} S_{11}^{RF} & a_{LO}^* * S_{21}^{RF} \\ a_{LO} * S_{21}^{RF} & S_{22}^{RF} \end{bmatrix} \cdot \begin{bmatrix} a_{IF} \\ a_{RF} \end{bmatrix} = [S^{RF}] \cdot \begin{bmatrix} a_{IF} \\ a_{RF} \end{bmatrix}$$

Even though the S-matrix for $[S^{IF}]$ and $[S^{RF}]$ refers to different frequencies, the elements have identical values and one can say that $[S^{IF}] = [S^{RF}]$, remembering that they are indexed by different frequencies. By analogy, a non-ideal mirror mixer scattering matrix can be obtained:

$$\begin{bmatrix} b_{IF} \\ b_{IM}^* \end{bmatrix} = \begin{bmatrix} S_{11}^{IF} & a_{LO} * S_{21}^{IF} \\ a_{LO}^* * S_{21}^{IF} & S_{22}^{IF} \end{bmatrix} \cdot \begin{bmatrix} a_{IF} \\ a_{IM}^* \end{bmatrix} = [S^{IF}] \cdot \begin{bmatrix} a_{IF} \\ a_{IM}^* \end{bmatrix}$$

$$\text{or} \begin{bmatrix} b_{IF} \\ b_{IM}^* \end{bmatrix} = \begin{bmatrix} S_{11}^{IM*} & a_{LO} * S_{21}^{IM*} \\ a_{LO}^* * S_{21}^{IM*} & S_{22}^{IM*} \end{bmatrix} \cdot \begin{bmatrix} a_{IF} \\ a_{IM}^* \end{bmatrix} = [S^{IM}]^* \cdot \begin{bmatrix} a_{IF} \\ a_{IM}^* \end{bmatrix}$$

〰 3 Measurement Principle

The common mixer phase test is to obtain the delay or phase nonlinearity from the input to the output. From the matrix model in the previous section, it can be seen that even though the effect of LO power on the mixer frequency response has been ignored, the phase change in the LO signal will still be reflected at the mixer's output. Therefore, it is necessary to consider the impact of LO phase on frequency conversion characteristics based on the specific conditions. The existing mixer delay or phase nonlinearity test methods mainly include up/down conversion method, vector mixer characterization (parallel path using a reference mixer), modulated signal method and phase-coherent receiver method.

Test Method	Calibration Mixer	Accuracy	Frequency Resolution	Dynamic Range	Embedded LO	Phase Consistency
Up/Down Conversion	required	medium	high	high	not support	support
Modulation	not required	low	low	low	support	not support
Vector Mixer Characterization	required	high	high	high	support	support
Phase-Coherent Receiver	not required	high	high	high	support	not support

Since SNA5000A series does not have the reference channel, it is impossible to phase-lock the reference receiver frequency to the MUT frequency. So the up/down conversion method is used to measure the vector S parameters of the MUT. The method uses an additional inverse/reciprocal mixer (it can be either up-converted or down-converted, and the transmission characteristics of the two frequency conversion directions are the same, i.e., S21=S12) with the same frequency range as the MUT and opposite frequency conversion direction so that the input and output frequencies are the same. Amplitude and phase tests can be performed directly with a network analyzer to get the overall response of a mixer pair, while the MUT response is inferred by compensating for the effect of the reconverting mixer in some way. It can be seen that the frequency change process during measurement is as follows: output from the excitation port of the vector network -> down-conversion of the calibration mixer -> up-conversion of the MUT -> reception at the receiver port of the vector network. After down-conversion and then up-conversion, the signal frequency of the two ports of vector network is the same.
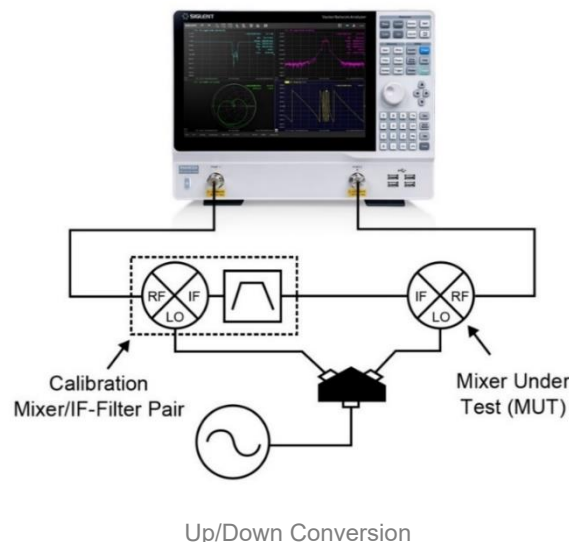

Up/Down Conversion

Using up/down conversion method, VNA can measure a mixer without operating in frequency offset mode. Since both ports work at the same frequency, it is possible to obtain the phase characteristics of the entire system. If the phase characteristics of the VNA itself, cable and calibration mixer/filter pair can be removed, the final phase characteristics reflect only those of the Mixer Under Test (MUT), thus achieving vector mixer measurement. While very straightforward in concept, this approach has some limitations:

[1] It requires a reconverting mixer that matches the frequency range of the DUT mixer but operates in the opposite conversion mode, that is, if one's MUT is a down-converter, the reconverting mixer must be an up-converter.

[2] It requires that the LO be shared between the up and down converting mixers; if either mixer has an embedded LO, or the MUT is a dual-stage mixer, the method is not practical.

[3] For proper results, a band-pass filter must be used between the mixers to remove the image signal, or else the reconverting mixer will reconvert both the RF and the IM signal, resulting in an erroneous response. The effects of the filter response must be compensated for in the overall response, and mismatch between the filter and the mixers can lead to errors in the overall result.

[4] Higher-order products that fall within the bandwidth of the image filter may reconvert in the second mixer and create an error in the overall response, which cannot be filtered out.

[5] The calibration and accuracy depend upon the characterization of the reconverting mixer.

In addition to the distinction between normal and mirror frequency conversion modes, the mixer operates in a variety of states, including fixed LO with synchronously sweeping the input and output signals or fixed OUT/IN with synchronously sweeping the LO and input/output signals.

– Fixed LO, Swept IN and OUT (support): This measurement eliminates the need to control an external signal source through the network analyzer. It is sufficient to manually configure the external signal source to the desired LO frequency. It is also possible to use Port3 or Port4 of the network analyzer as the LO. The mixer operates in sweep mode and can measure the loss, phase and group delay of MUT.

Fixed LO
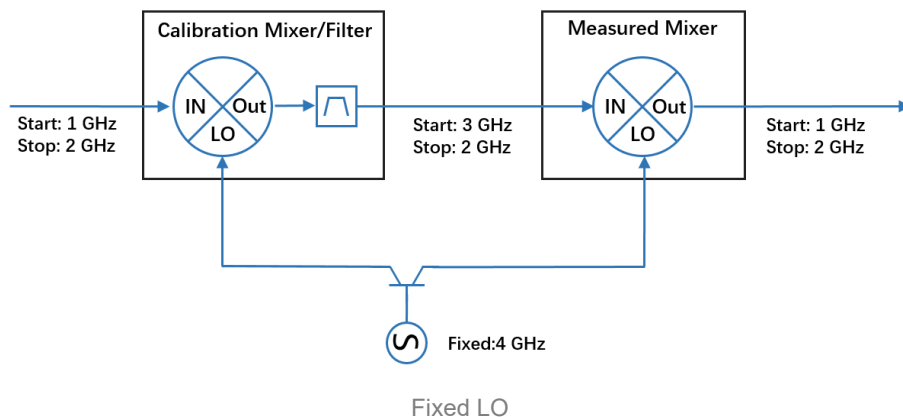
– Fixed IN, Swept OUT and LO (support): This measurement requires control of an external signal source to maintain frequency synchronization between the mixer input port and the local oscillator port. The network analyzer controls the external signal source to output LO of corresponding frequency through the SCPI command during frequency sweep. Since fixed IN, the MUT group delay cannot be calculated.

Fixed IN
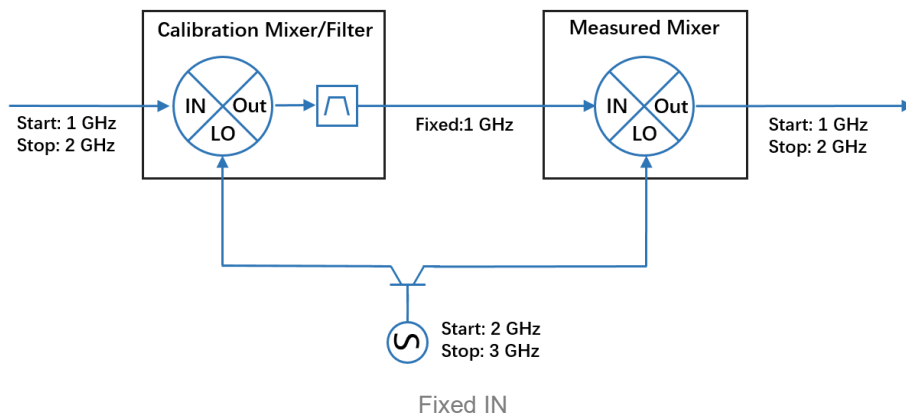
- Fixed OUT, Swept IN and LO (not support): This measurement is due to the fact that the calibration mixer has a frequency response at only one frequency point and the LO signal frequency is not fixed at that frequency point, where the frequency response of the calibration mixer changes due to a change in the LO frequency. Therefore, it is not possible to de-embed a single-port network by using the S-parameters of a single frequency point, i.e., vector mixer calibration is not possible, so this mode is not supported.


Fixed OUT
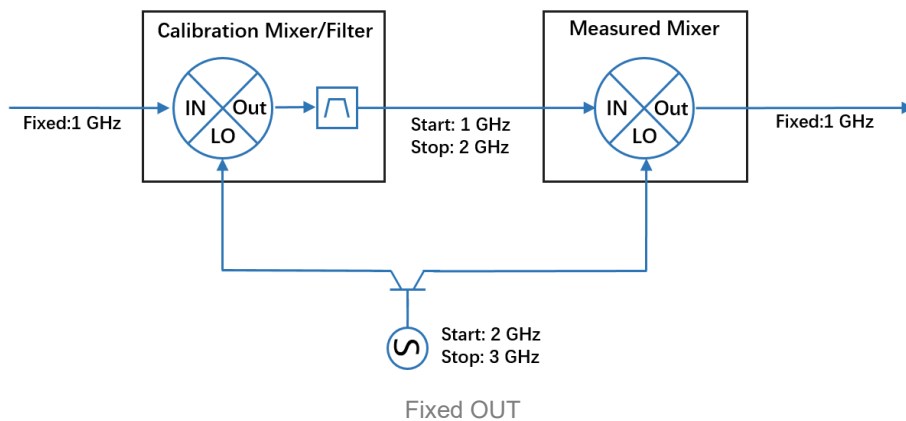
4 Vector Mixer Calibration

Errors in vector mixer measurements using up/down conversion method are primarily divided into two types: errors of the VNA and cables, and errors introduced by calibration mixer/filter pair. Performing a full two-port calibration removes the VNA and cable errors. If the S-parameters of the calibration mixer/filter pair are available, then the errors introduced by the calibration mixer/filter pair can be removed by de-embedding. The remaining errors such as mismatch between mixer and filter, reconversion of mixer output harmonics etc. cannot be removed.
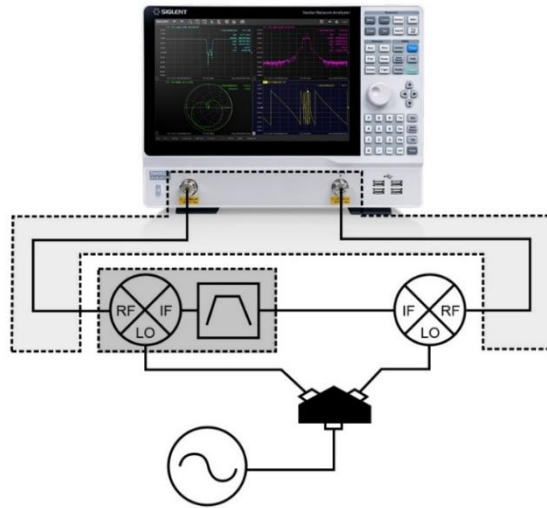
Vector Mixer Error Elimination Diagram

The forward error model of the whole system under test is shown in the figure below, in which E_D (directional error), E_S (source mismatch error), E_{RT} (reflection tracking error), E_{TT} (transmission tracking error), E_L (load mismatch error), E_X (crosstalk error) are the classical twelve error models, which can be derived through full two-port calibration. The following is an example of a downconverter, where the input is RF and the output is IF. E_D, E_S, and E_{RT} are embodied in RF, and E_L is embodied in IF, and can be corrected by standard S-parameter calibration. Port2 and port1 of the VNA operate at different frequencies, and therefore the E_X can be ignored. The reference path in the transmission test contains the responses of cables, adapters, and mixer/filter combinations, and the difference between the two can be obtained by plugging a mixer/filter combination with known parameters into the measurement path, i.e., the E_{TT}. FA_{11}, FA_{21}, FA_{12} and FA_{22} are the S-parameters of the calibrated mixer/filter combinations, and the error model of the de-embedding is shown below. It can be seen that the error model after de-embedding agrees with the error model of the measured DUT after performing full two-port calibration.
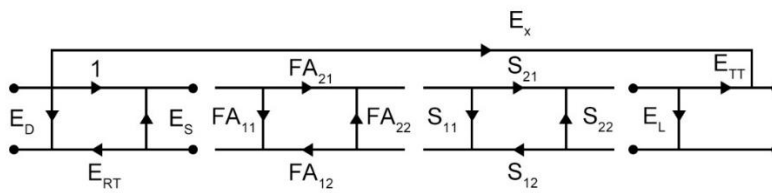

Forward Measurement Error Model
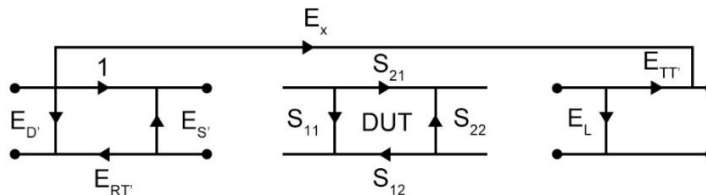
Forward measurement error model after de-embedding of calibration mixer/filter Pair

Therefore, the whole vector mixer calibration flow is: VNA performs full two-port calibration -> characterizes the S-parameters of the calibration mixer/filter pair -> performs de-embedding to eliminate the error of calibration mixer/filter pair. How to obtain the S-parameters of calibration mixer/filter pair is the focus of

vector mixer calibration.
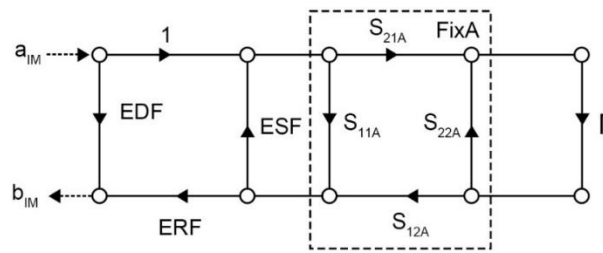

Characterizes Calibration Mixer/Filter Pair
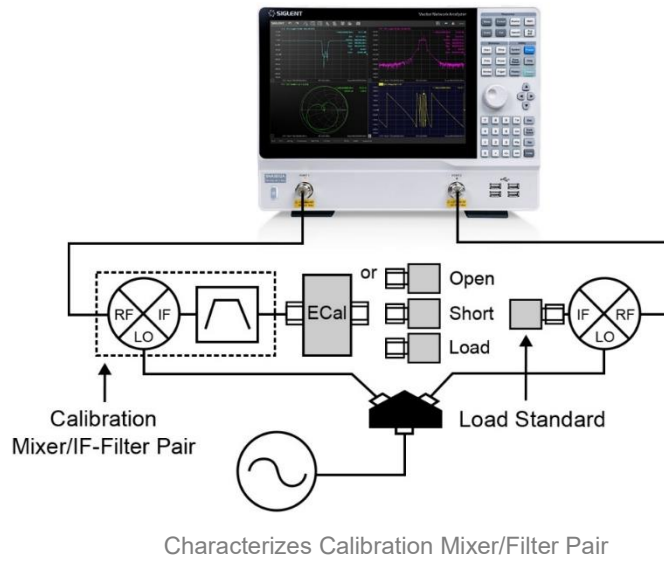
The schematic for characterizing the S-parameters of the calibration mixer/filter pair via a VNA is shown in Fig. The process is equivalent to single-port calibration at output port of the mixer/filter pair: standards (open, short and load) are connected to the output of the calibration mixer/filter pair, and the reflected IF signal is passed through the calibration mixer again for the second frequency conversion, the S-parameters of the calibration mixer/filter pair are calculated based on the single-port network error model. The power has a great influence on the characterization of the calibration mixer/filter pair, so in order to get accurate characterization results, the environment during the single-port calibration should be the same as that of the actual measurement after calibration, so as to make sure that the MUT is at the same power during the characterization and the actual measurement. The OSL calibration is performed by connecting the LO ports of the calibration mixer and the MUT through a one-part-two power divider, and connecting a standard load to the input port of the MUT, and connecting the output port to the receive port of the VNA.
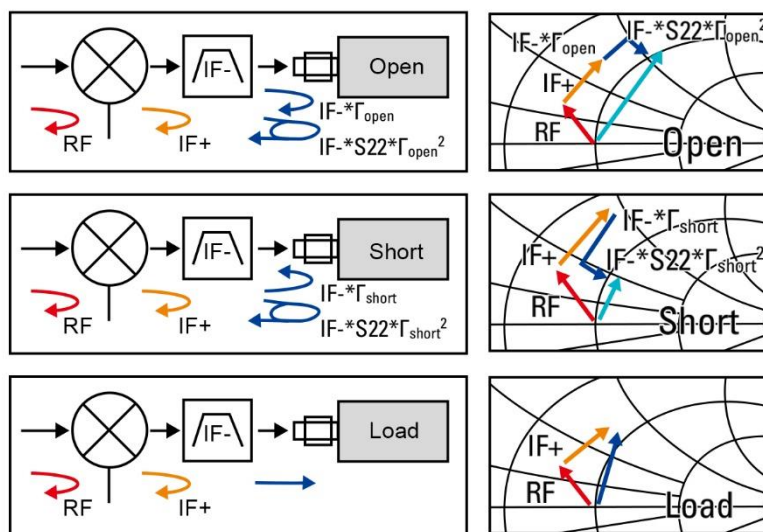
Principle of Parameter Extraction for Mixer/Filter Pair

In this case the IF- signal is the conversion that is desired; the IF+ signal (from the sum of RF and LO) will reflect off the IF filter rather than passing through, and so will not appear at the mixer output. For up-converting mixers, the filter should pass the IF+ signal and reject the IF- signal.

From this one can see that, for each standard, there are up to four major contributors to the overall reflection response: reflection from the mixer S11 of the RF signal (marked as RF), reconverted reflection from the IF+ signal (which reflects off the stopband of filter, marked IF+), reconverted reflection off the cal standard (marked IF-*Γ) and reconverted re-reflected signal off the cal standard and S22 of the cal mixer/filter pair (marked IF-*Γ*S22*Γ). These are illustrated as vectors in the right half of the figure. If a one-port calibration is performed using each of the standards, the resulting error terms can be mapped to the mixer response. For each standard, the S11 and IF+ reflections are unchanged, and in the construction of a one-port cal, they represent the directivity error term; this is S11 of the mixer. The two-way transmission through the mixer is essentially the average of the open and short response, and so represents the reflection tracking term, or S21·S12. And the difference between the open and short is the source match term of the one-port cal, or S22 of the mixer.

Characterization of Cal Mixer/Filter Pair S-parameters

The error model characterizing the cal mixer/filter pair is shown in Fig. There are four unknown S-parameters and a single-port calibration can only provide three equations for the error terms. In order to obtain the S-parameters for the calibration mixer/filter pair, it is required that the calibrated mixers be reciprocal to reduce the number of unknowns, i.e., S21 = S12. For passive mixers, they theoretically satisfy this condition of reciprocity. At this point we have three equations and three unknowns. Assuming that the error coefficients of the port connecting the mixer/filter pair after full two-port calibration are EDF, ESF and ERF, and that the error coefficients of the port are measured to be EDF_{MUT}, ESF_{MUT} and ERF_{MUT} after single-port calibration of the calibration mixer/filter pair, the following equations are available for the calibration mixer/filter pair S-parameters.

$$S_{11\_\text{MUT}} = \frac{\text{EDF}_{\text{MUT}} - \text{EDF}}{[\text{ERF} + \text{ESF} \cdot (\text{EDF}_{\text{MUT}} - \text{EDF})]}$$

$$S_{21\_\text{MUT}} = S_{12\_\text{MUT}} = \frac{\sqrt{\text{ERF} \cdot \text{ERF}_{\text{MUT}}}}{[\text{ERF} + \text{ESF} \cdot (\text{EDF}_{\text{MUT}} - \text{EDF})]}$$

$$S_{22\_\text{MUT}} = \text{ESF}_{\text{MUT}} - \frac{\text{ESF} \cdot \text{ERF}_{\text{MUT}}}{[\text{ERF} + \text{ESF} \cdot (\text{EDF}_{\text{MUT}} - \text{EDF})]}$$

〰 5 Using the Vector Mixer Measurement Application

5.1 Test Conditions

The MUT, calibration mixer model are MCA1-80MH +, for passive mixer (reciprocal), the basic indicators are as follows:

LO/RF	IF	LO Power	Conversion Loss
2.8 GHz - 8 GHz	DC - 1250 MHz	+13 dBm	5.6 dB

The filter is a low-pass filter with a filter cutoff frequency of 170 MHz and strong rejection from 200 MHz to 3 GHz, so the output frequency of the calibrated mixer is allowed to fall within the passband of the low-pass filter, and the input frequency falls outside the passband. Set the mixer to operate as follows during test: The operating state of the calibration mixer:

LO (Fixed) Input	RF (Swept) Input	IF = LO - RF Output
3 GHz	2.83 GHz - 2.99 GHz	170 MHz - 10 MHz

The operating state of the mixer under test:

LO (Fixed) Input	RF (Swept) Input	IF = LO - RF Output
3 GHz	170 MHz - 10 MHz	2.83 GHz - 2.99 GHz

The power splitter model SHX-0.5-6-2N has an insertion loss of 1.6 dB. In order to meet the operating power of the mixer LO, the output power of the RF signal source is at least 13+3+1.6=17.6 dBm. 3 dB is the distribution loss of the power splitter, which indicates that when the signal is split into two paths, the power of each path is halved compared to the original signal. The four-port vector network analyzer is equipped with dual sources for local excitation, while the two-port vector network analyzer requires an external RF source to provide the local oscillation signal. The Vector Network Analyzer model number is SNA5084X and the RF signal source model number is SSG3032X with the following operating modes:

RF	Power
3 GHz	20 dBm

The number of sweep points is 1001, the IF bandwidth is 10 kHz, the input port of the calibration mixer is connected to the network analyzer Port1, the output port of the mixer under test is connected to the network analyzer Port2, the calibration device used is an electronic calibration kit, and the full two-port calibration method is SOLR.

5.2 Perform Measurements

5.2.1 Prepare Measurement Environment

The measurement environment is prepared according to the test conditions, the RF signal source is set at 3 GHz, the RF power is 20 dBm, the output port of RF signal source is connected to the input port of a one-part-two power divider, one of the output ports of the one-part-two power divider is connected to the LO port of the calibrated mixer, and the other port is connected to the LO port of the mixer under test.

Measurement Environment Map
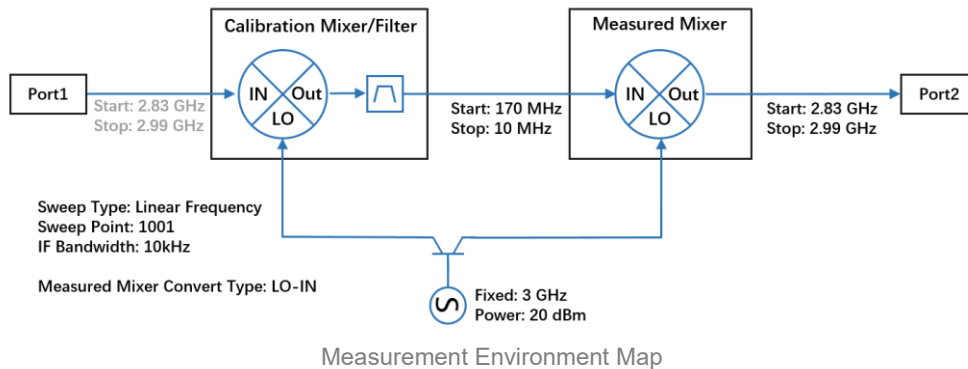
5.2.2 Enter Vector Mixer Measurement Mode

Press *Meas* -> *Mode...* -> *Vector Mixer Measurement (VMM)*. Enter vector mixer measurement mode. Check "Show Setup Dialog" to open the mixer measurement configuration dialog. Uncheck "New Channel" to apply vector mixer measurement mode to the current channel.

5.2.3 Configure Mixer Measurement Parameters

Configure the mixer measurement parameters according to the measurement environment map.

[1] Set the sweep type to linear sweep, the number of sweep points to 1001 and the IFBW to 10 kHz.

[2] Keep the default configuration of Power module.

[3] Select "-" for DUT Output, and leave "Input > LO" unchecked so that the operating mode of the MUT is LO-IN. Set the start frequency of MUT Output to 2.83 GHz and the stop frequency to 2.99 GHz. Set the LO frequency to 3 GHz in Fixed mode, and click "Calc DUT Input" to calculate the start frequency and stop frequency of MUT Input automatically.

[4] Set the VNA Port1 to be connected to the input port of the calibration mixer and Port2 to be connected to the output port of the MUT, and select "Not Controlled" for "Local", so as not to control the external signal source.

[5] Click "Save..." to save the configuration so that it can be recalled by "Load" next time. Click "OK" to apply the configuration and close the mixer measurement configuration dialog box.

5.2.4 Perform Vector Mixer Calibration

[1] Select *Cal* -> *Mixer Calibration...* to open the vector mixer calibration dialog box.

[2] Complete the full 2-port calibration using the electronic calibration kit to obtain the VNA and cable error.
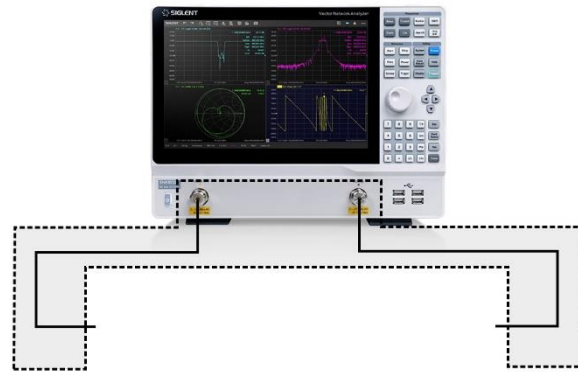
Full 2-Port Calibration Diagram

[3] After completing the full 2-port calibration, click *Next>* to enter the characterization cal mixer/filter pair calibration configuration box. Select ECal. Determine the port connection relationship according to the setting of Mixer Setup module and connect the cable to the mixer. Connect standard load to the input port of the mixer under test and the ECal to the output port of the filter as shown in the figure below. And then click the corresponding calibration task to complete characterization calibration mixer/filter pair calibration.
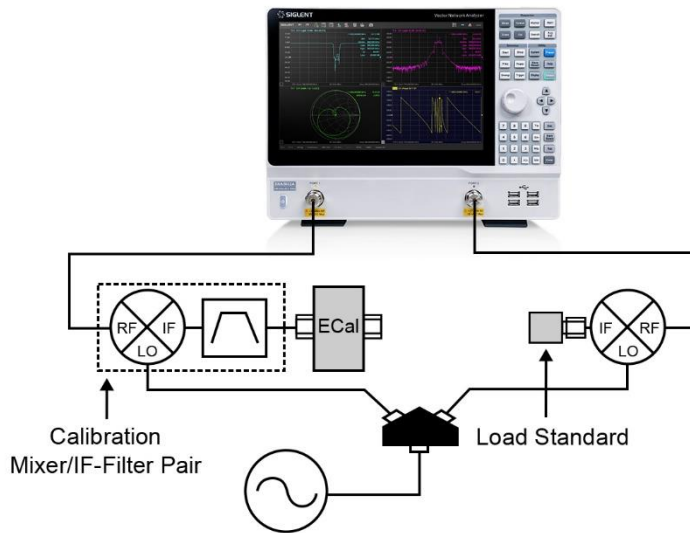
Characterization Calibration Mixer/Filter Pair Calibration Schematic

[4] Check *Save Calibration Mixer/Filter S2P File* after completing the calibration of the characterization calibration mixer/filter pair. *Click Select S2P File Path* to save the s2p file of the calibration mixer/filter pair for next vector mixer calibration. Click *Finish* to embed the calibration mixer/filter pair and complete the vector mixer calibration.

5.3 Measurement Results

The loss of the MUT is within the specification.

⎍ 6 Summary

Traditional performance evaluations generally focus on the mixer's port SWR, isolation and conversion loss/gain characteristics, while vector mixer measurement can simultaneously capture phase and amplitude information. By fixed LO with synchronously sweeping the input and output signals or fixed IN with synchronously sweeping the LO and output signals, calibrated conversion loss/gain, match, group delay and phase shift between devices can be obtained.

The vector mixer measurement function supports various sweep modes such as linear frequency sweep, power sweep and segment sweep, and allows flexible setting of parameters such as source port power, local oscillator port power, and attenuation. The four-port model has built-in dual signal sources, and the second source can be used as the LO or provide the LO signal by controlling an external signal generator. The intuitive user interface can easily complete the measurement configuration, and the calibration wizard guides the user through calibration process to provide comprehensive and accurate mixer/converter characteristic measurements.

About SIGLENT

SIGLENT is an international high-tech company, concentrating on R&D, sales, production and services of electronic test & measurement instruments.

SIGLENT first began developing digital oscilloscopes independently in 2002. After more than a decade of continuous development, SIGLENT has extended its product line to include digital oscilloscopes, isolated handheld oscilloscopes, function/arbitrary waveform generators, RF/MW signal generators, spectrum analyzers, vector network analyzers, digital multimeters, DC power supplies, electronic loads and other general purpose test instrumentation. Since its first oscilloscope was launched in 2005, SIGLENT has become the fastest growing manufacturer of digital oscilloscopes. We firmly believe that today SIGLENT is the best value in electronic test & measurement.

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