Application Note

MILLIMETER WAVE MEASUREMENTS

with Vector Network Analyzer ZNA/ZNB3000 and Option K8

Products:

- R&S®ZNA<xx>
- R&S®ZNB30<xx>
- R&S®ZC<xxx>

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Contents

1 Overview

RF engineers are increasingly confronted with the task of characterizing devices operating in the mmwave range. The vector network analyzers (VNAs) R&S ZNA and R&S ZNB3000, along with R&S or RPG ZC<xxx> mmwave converters, provide a broad range of measurement solutions fulfilling this task. This application note is intended to provide help for choosing the right measuring instruments and accessories, interconnecting them correctly, setting up the instruments, calibrating them and finally obtaining measurement results.

Both linear and nonlinear measurement quantities are covered. In both categories, one further distinguishes between devices that do not change the frequency of the input signal (e.g. transmission lines, attenuators, amplifiers) and those that do (e.g. mixers, frequency multipliers). Generally, the complexity of setup and calibration is higher in the latter case.

The mmwave converter user interface is designed to assist the user with defining the wanted measurement quantities and their associated parameters like source power, LO frequency, and tone distance for two-tone measurements. It shows the needed setup schematically and proposes how to calibrate this setup including all necessary steps. Many common pitfalls lurking when calibration is completely done manually are avoided by automatic compilation of the calibration.

Following this concept, the chapters of this application note first give a brief description of the characterization quantities treated in the chapter, then outline the measurement setup, take a look at calibration and provide examples of measurement results as they appear on the VNA display.

2 System Setup and Calibration of mmwave Converters

This chapter refers to the setup of mmwave measurements in general. In the context of the application note at hand, mmwave applications are understood as measurements that require one or more banded mmwave frequency converters in addition to the basic VNA. For the sake of simplicity, only converters of the ZC family are considered here. In principle, older ZVA-Zxxx or converters from other suppliers are operated in the same way as ZCxxx, except for the features enabled by the USB interface of the ZCxxx. Neither can they be automatically recognized by VNA software nor do they autonomously monitor their vital functions.

2.1 Fundamentals of converter operation

We begin with the fundamentals of mmwave converter operation. This can usually be skipped by readers who are familiar with mmwave converter operation.

mmwave converters are frequency extenders for vector network analyzers (VNAs). Similar to the VNA itself, they incorporate three sub-units: A frequency multiplier, which converts the VNA source signal to the mmwave range, a test set for the separation of outgoing and incoming waves, and a receiver unit with one or two downconverters, which translate one or both of the separated wave quantities to a frequency range receivable by the VNA. Fig. 1 shows a schematic of the mmwave converter R&S ZC110 for the band 75 GHz – 110 GHz (WM-2540[1], also known as WR10[2]).

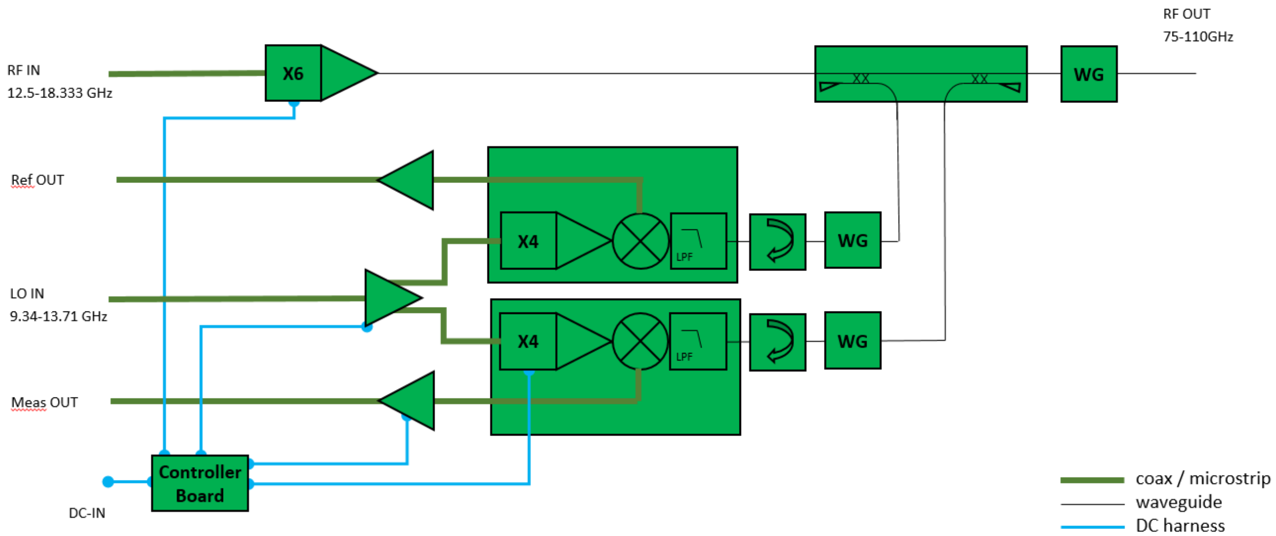

Fig. 1: ZC110 Schematic

The frequency of the stimulus signal fed into the converter via connector RF In is multiplied by a factor of 6. Then the signal enters the main branch of a dual directional coupler. Outgoing and incoming waves (from the converter's perspective) are coupled out and routed to the reference and the measurement receiver, respectively. Isolators and filters in front of the receiver inputs prevent higher-order mixing products from leaving the mixers and subsequently the test port, thereby causing unwanted measurement artifacts. The LO signal entering the converter via LO In is split and amplified, in some cases also multiplied, before being

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[1] Band designation according to IEEE 1785
[2] Band designation according to EIA

applied to the mixers. The IF signal, typically at some 100 MHz, is amplified and conveyed to the IF outputs Ref Out and Meas Out.

With RF In, LO In and the two receiver outputs, a ZC110 features four RF connectors on its rear panel. There are two ways to connect the corresponding signal lines to the base ZNA. Fig. 2 shows the recommended one using inputs IF Reference <i> and IF Meas <i> of the ZNA, where i is the port number. These rear panel connectors come along with option ZNA-B26. Furthermore, as shown in Fig. 3, the converter IF can also be fed into the front panel inputs of option ZNA-B16 (direct source and receiver access). This corresponds to the connection scheme used for the R&S ZVA, which was the predecessor of the ZNA.

With both connection methods, the source signal is provided by the ZNA test port to which the converter has been assigned. Basically, it would also be possible to use the associated source output on the front panel, if option ZNA-B16 (direct source and receiver access) is installed, but usually this does not offer an advantage. The power available at the test port is normally sufficient for converter operation, and one must take care not to overload a converter input (10 dBm max).

The LO can be provided either by rear panel output Conv LO (if option ZNA-B8 is installed) or by any ZNA source yet unused in the current converter configuration. When a source has been selected as LO for a particular port, it becomes unavailable for other purposes in the setup. For example, test ports 1 and 2 have a common signal source, unless option R&S ZNA-B3 is installed. If a converter has been assigned to port 1, this source provides the RF signal for the converter and cannot simultaneously supply the LO. In this case, use e.g. port 3 or 4, if the R&S ZNA has 4 ports. Or install option R&S ZNA<xx>-B3 (3rd and 4th internal source). The converter setup dialog (see Fig. 5) tracks the usage of the available sources and does not allow for using a source twice within the converter configuration. However, source assignment conflicts arising from the operation of the device under test (DUT) itself are not detected.

Operation with the R&S ZNB3000 is similar to operation with the R&S ZNA. Fig. 4 shows the 2-port converter configuration using the R&S ZNB3000. In this setup, the R&S ZNB3-B8 option is required for mmwave converter measurements with the R&S ZNB3000. It provides the LO signal to both converter LO IN connectors via a splitter, as well as the direct IF inputs for IF Meas and IF Ref for both ports. The user interface is the same as that of the R&S ZNA and is available after installing the R&S ZNB3-K8 option. Supported mmwave applications with R&S ZNB3000 are S-parameter and mixer measurements up to 330 GHz.

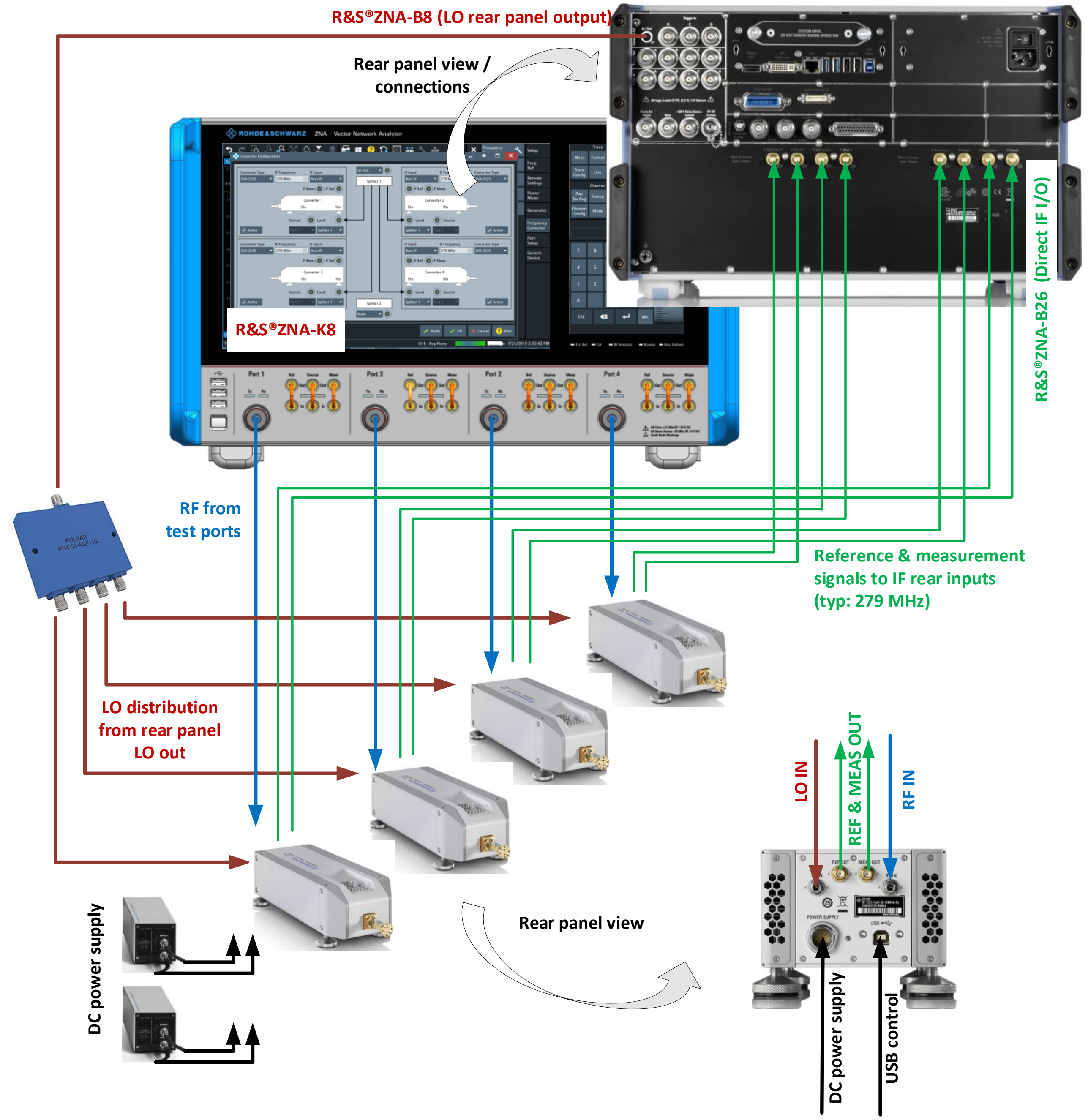


Fig. 2: Converter configuration with rear panel IF inputs

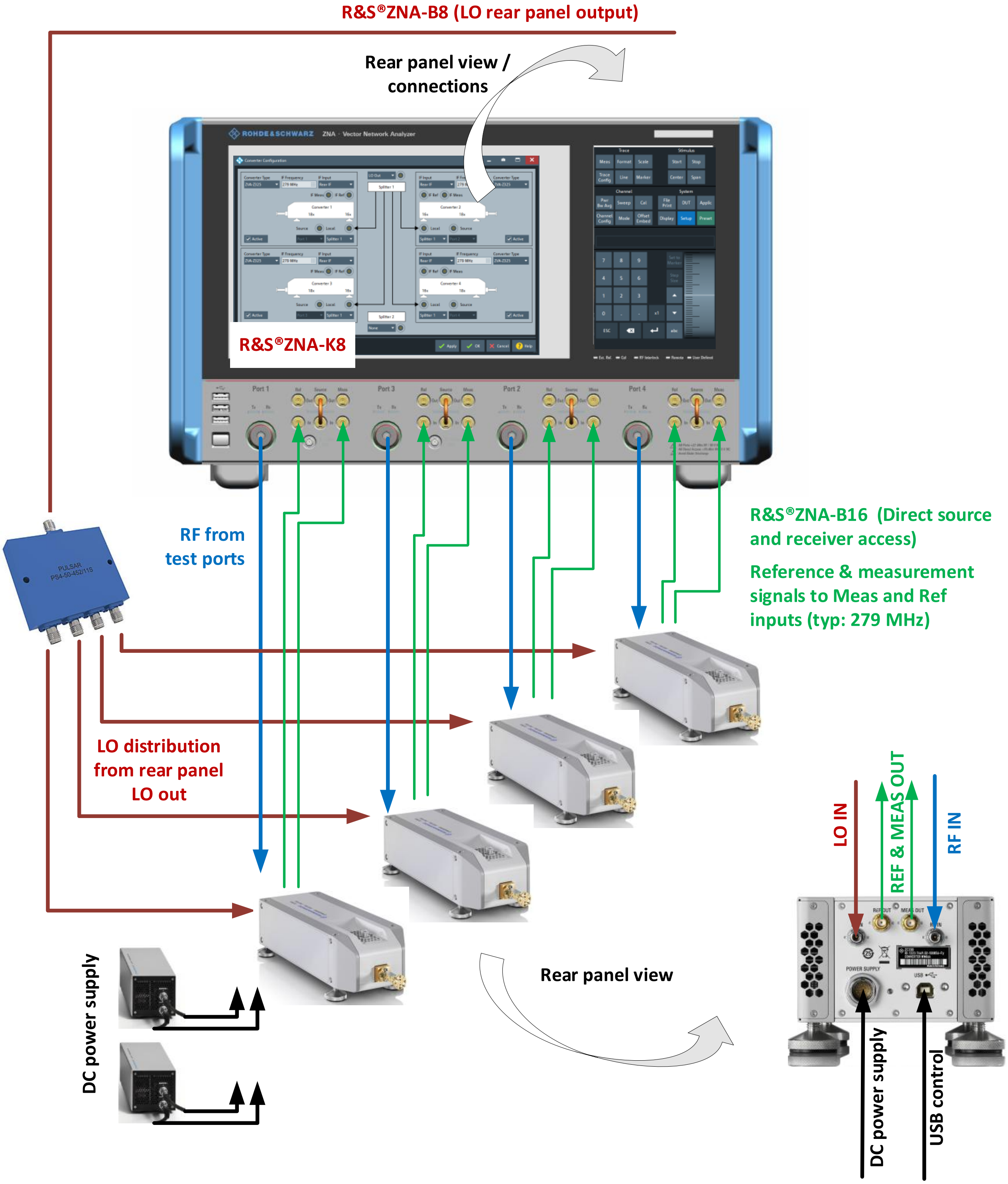


Fig. 3: Converter configuration with front panel direct source and receiver access inputs

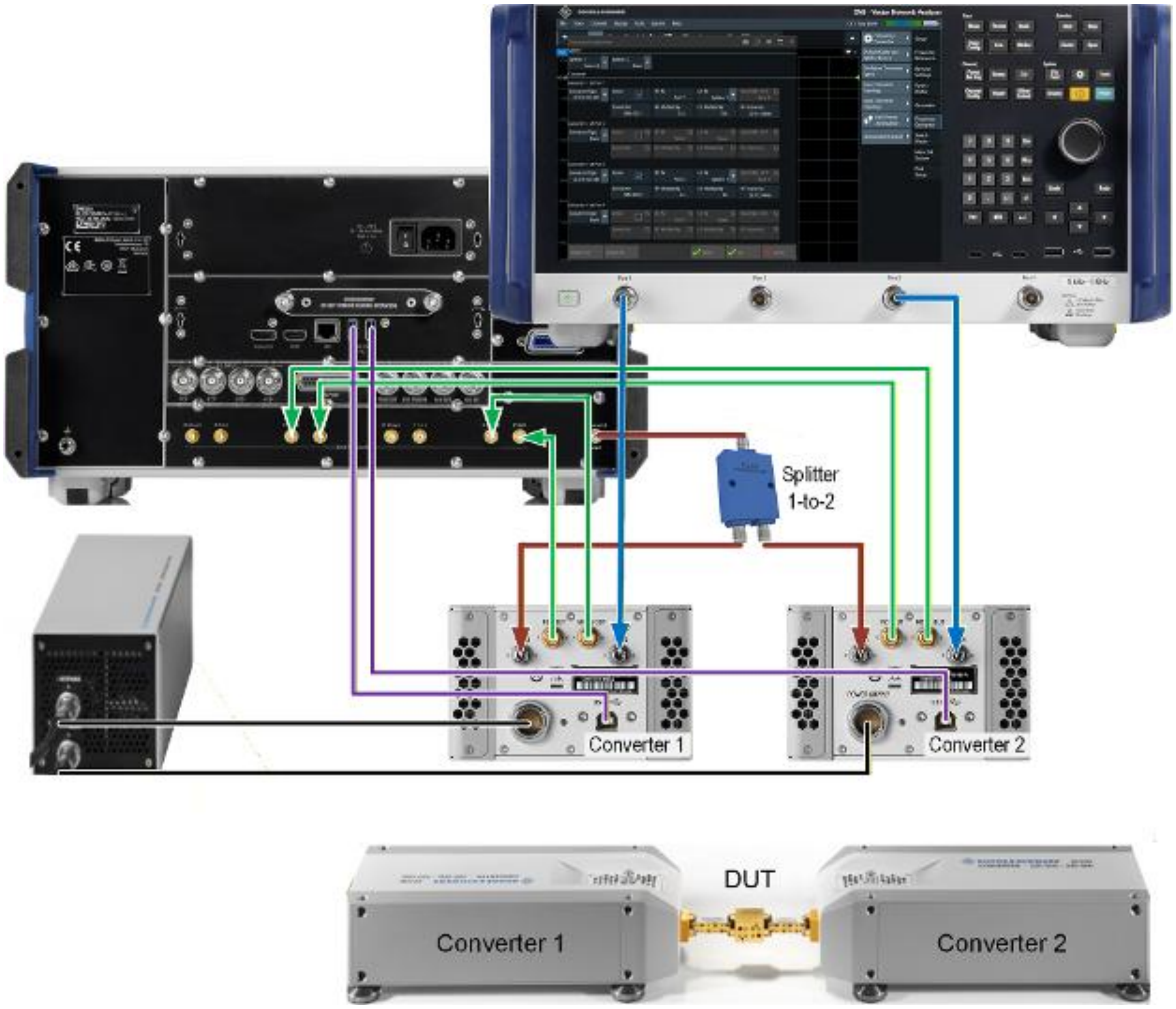


Fig. 4: Converter configuration with R&S ZNB3000

2.2 Converter configuration via VNA user interface

While the USB interface of ZCxxx converters allows the VNA software to load the characteristic data of a converter, like source and LO multiplication factors, it cannot detect whether this converter is actually used in the current setup. Consequently, it cannot determine to which VNA test port a particular converter has been connected. Therefore, the assignment of converters to VNA test ports must be done manually via **Setup → Frequency Converter → Frequency Converter.**


Converter Configuration

Splitter
Splitter 1: Conv. LO
Splitter 2: None

Converter
Converter 1 at Port 1
Converter Type: ZC170-101427
Active: ☑
RF IN: Port 1
LO IN: Splitter 1
MEAS/REF OUT: Rear IF
Connector: WM-1651
RF Multiplicity: 12x
LO Multiplicity: 10x
IF Frequency: 279 MHz

Converter 2 at Port 2
Converter Type: ZC170-102538
Active: ☑
RF IN: Port 2
LO IN: Splitter 1
MEAS/REF OUT: Rear IF
Connector: WM-1651
RF Multiplicity: 4x
LO Multiplicity: 10x
IF Frequency: 279 MHz

Converter 3 at Port 3
Converter Type: None
Active: ☐
RF IN: Port 3
LO IN: None
MEAS/REF OUT: Rear IF
Connector
RF Multiplicity
LO Multiplicity
IF Frequency

Converter 4 at Port 4
Converter Type: None
Active: ☐
RF IN: Port 4
LO IN: None
MEAS/REF OUT: Rear IF
Connector
RF Multiplicity
LO Multiplicity
IF Frequency

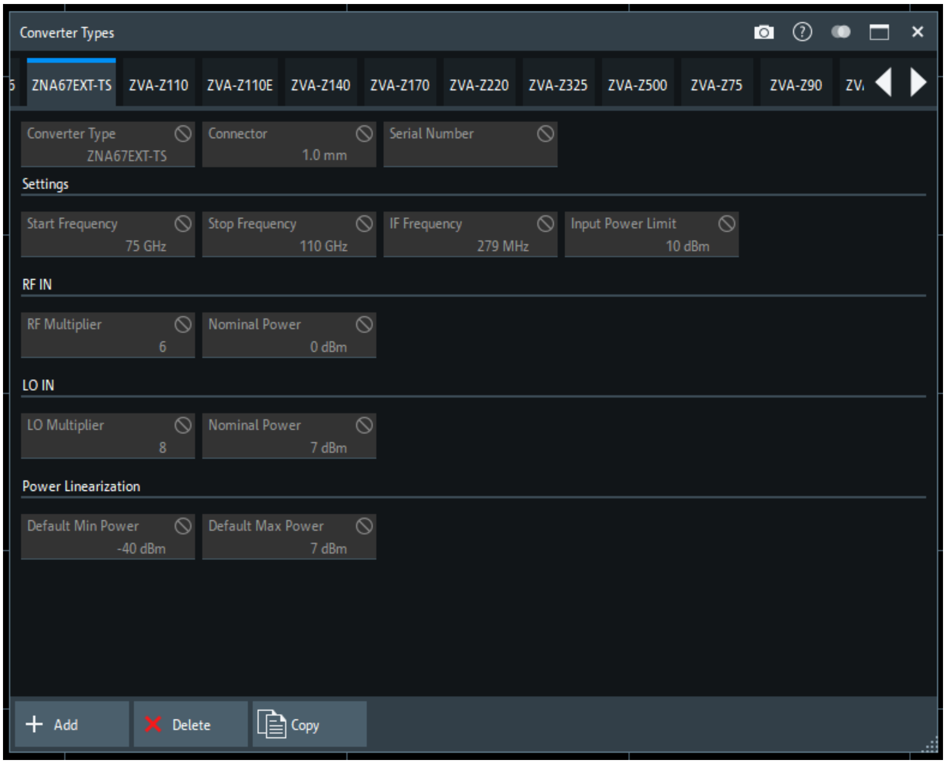
Fig. 5: Converter configuration dialog

1. For each port, dropdown list **Converter Type** offers all individual ZCxxx converters that have been connected via USB to the VNA after the last factory preset. Note that resetting the VNA to factory state also resets this list. Converters of the same type can be distinguished by their serial numbers. Furthermore, ZVA-Zxxx (1st converter generation from R&S) and types defined via **Configurate Converter Types** can be selected.
2. The source signal for the converter must be provided by the source of the port to which the converter has been assigned. Therefore, field **RF IN** cannot be edited.
3. Dropdown field **LO IN,** however**,** offers all LO source options that are available.
4. If option ZNA-B8 is installed, output **Conv LO** in the **Splitter field** on the rear panel will be the preferred choice in many cases, since a) this does not “sacrifice” a complete port with all the valuable components not needed for a LO source (like coupler and receivers) and b) frequency (up to 26.5 GHz) and power (up to 20 dBm) ranges of this output optimally match the requirements of a R&S mmwave converter. In addition to the frequency sources of the ZNA that have not yet been assigned to an active converter port, all configured external generators are selectable. Furthermore, if the LO source feeds more than one converter, a n-way splitter (2 ≤ n ≤ 4) can be inserted between source and converter. Dialog **Converter Configuration** offers two splitters, named **Splitter 1** and **Splitter 2**, which are associated with different LO sources. For the operation with the R&S ZNB3000 the option ZNB3-B8 includes the **Conv LO** and is required for the use if the R&S ZNB3-K8 user interface.
5. Dropdown field **MEAS/REF OUT** allows the user to determine how the IF output signals of the respective converter are fed into the ZNA. If option ZNA-B26 is installed, one can feed them into the

rear panel IF inputs of the ZNA (option **Rear IF**) or, if option ZNA-B16 is installed, into the front panel connectors **Ref In** and **Meas In** (option ZNA<xxx>-B16 Direct Access). For the operation with the R&S ZNB3000 the option ZNB3-B8 includes the **rear panel IF inputs** and is required for the use if the R&S ZNB3-K8 user interface.

6. If checkmark **Active** is set for a particular port, the respective converter will be activated when pressing **OK** or **Apply** (see below). Activating a converter means that the associated RF and LO sources are set to the frequency and power needed for proper operation of this converter. In this context, losses of cables and LO splitters can be taken into consideration, see chapter 2.3.1.1.
7. After having completed converter configuration, it can be activated by pressing either **OK**, which closes the dialog, or converters **Apply**, which leaves it open. This will only have a visible effect if at least one port has a converter assigned to it and if checkmark **Active** of this port has been set. Then the existing channels are replaced by a single one covering the highest frequency band among the active converters with default settings. This frequency range may not fit for all activated converter types, which possibly causes error messages.

VNA firmware needs information about some basic characteristics of converters in order to be able to handle them correctly. Information e.g. about source multiplication factor and order of the harmonic of the mixers is obtained from data that is either individually assigned to and shipped with each converter (ZCxxx family) or integrated into the VNA firmware (ZVA-Zxxx family). Subdialog **Converter** Types shown in Fig. 6 opens via **Setup → Frequency Converter → Configurate Converter Types**.



Converter Type: ZNA67EXT-TS
Connector: 1.0 mm
Serial Number:

Settings
Start Frequency: 75 GHz
Stop Frequency: 110 GHz
IF Frequency: 279 MHz
Input Power Limit: 10 dBm

RF IN
RF Multiplier: 6
Nominal Power: 0 dBm

LO IN
LO Multiplier: 8
Nominal Power: 7 dBm

Power Linearization
Default Min Power: -40 dBm
Default Max Power: 7 dBm

Fig. 6: Converter type configuration

Here, all converter types known to the VNA are listed as tabs. For each type, frequency range, test port connector type, RF and LO multiplication factors and required input powers are displayed. The settings of converters that have been read from their built-in memory (e.g. ZCxxx) or those of predefined types (e.g. ZVA-Zxxx) cannot be edited. To change parameters for experimental purposes, create a copy of this converter first, edit the parameters, and select the copy. Or create a new type via **+ Add**.

Note that converter configuration and – if existing – related power linearization data are not only valid for the currently active channel or preset. This global setting is valid for all channels and will not be deleted by

System → Preset, except in case that option **Normal, GUI, Ext. Setup** has been selected in the **Preset** menu.

2.3 Calibration

Since the hardware components of mmwave converters, as well as those of VNAs, cannot be assumed as ideal, their deviation from ideality must be mathematically corrected for to obtain accurate measurement results. For the fundamentals of system error and power calibration / correction, refer to the documentation of the VNA. Nonlinear DUT behavior can be described by quantities like compression or intercept point. In this case, exact knowledge of the absolute powers of the waves incident on or coming from the DUT is required. For this purpose, one must perform a power calibration. The combination of system error and power calibration is called smarter calibration.

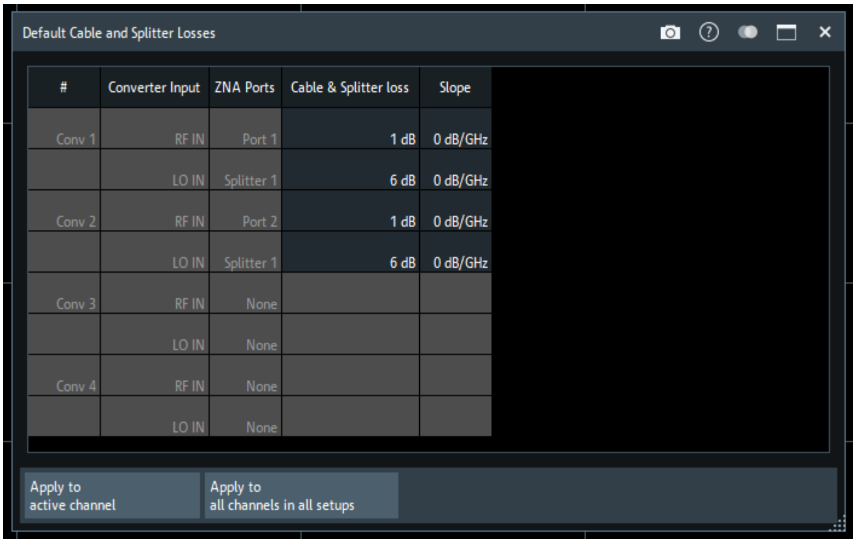
2.3.1 Ensuring proper power levels on the cables between VNA and converter

Before looking at the various ways offered by VNA firmware to calibrate the converter test ports, it will be discussed how the user can establish proper power levels in the signal lines connecting converter and base VNA.

R&S mmwave converters are remote front ends of a complete VNA system, connected to the base VNA via cables. Providing sufficient RF and LO input power to the converter is mandatory to obtain the specified output power and transmission dynamic range at the waveguide test port. R&S converters are designed for +7 dBm input power at both RF In and LO In, with a small tolerance region of few dBs below and above that value. Cable losses may compromise system operation severely if they exceed a certain amount. The following two chapters explain how to make sure that the required input power is available at the RF In and LO In connectors of the converter.

2.3.1.1 Specifying cabling losses

Often VNA and converters are set up on a table with minimum distances between the components. In a typical setup, source signal is fed to the converters via R&S ZV-Z19<x> cables with a maximum length of 1 m. To provide the LO signal, two cables of this type are connected in series with the power splitter in between. In such a scenario, it is sufficient to use the predefined cable loss model. The losses assumed by this model can be set via **Setup → Frequency Converter → Default Cable and Splitter Losses**. This opens the table shown in Fig. 7, here shown with default entries for the frequency-independent losses of cables and LO splitter. Regardless of the number of converters fed by a splitter, its default loss is set to 6 dB. This is a pretty good estimate for a configuration with two converters, in case a two-way splitter is used. For other numbers of converters, the value should be adapted to the actual number of splitter outputs. For longer LO cables, frequency-dependent loss can be modeled by a simple linear slope.



#	Converter Input	ZNA Ports	Cable & Splitter loss	Slope
Conv 1	RF IN	Port 1	1 dB	0 dB/GHz
	LO IN	Splitter 1	6 dB	0 dB/GHz
Conv 2	RF IN	Port 2	1 dB	0 dB/GHz
	LO IN	Splitter 1	6 dB	0 dB/GHz
Conv 3	RF IN	None		
	LO IN	None		
Conv 4	RF IN	None		
	LO IN	None		

Fig. 7: Dialog Default Cable and Splitter Losses

Note that the losses set in dialog **Default Cable and Splitter Losses** become effective in the port configuration (**Channel Config→ Port Config → Port Settings**) as soon as a converter configuration is activated via **Apply** or **OK** in the **Converter Configuration** dialog. Hence, the default losses should be set before activating a converter configuration. If converters have already been activated, however, losses can be belatedly corrected by changing the default loss values and pressing **Apply to active channel** or **Apply to all channels in all setups**.

2.3.1.2 LO input power calibration

In case transmission loss between LO source(s) and converter input(s) is not well known or does not increase linearly with frequency, it may be advisable to perform a power flatness calibration for the respective source(s). This flatness cal can be initiated via **Cal → Scalar Power Cal**, which makes the dialog appear that is shown in Fig. 8.

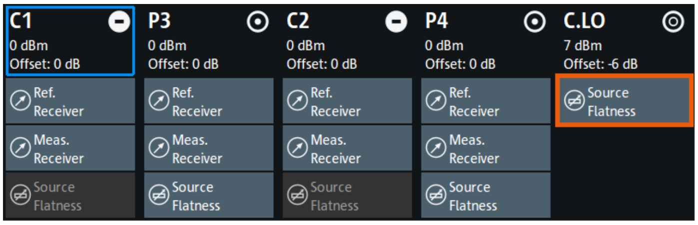


Fig. 8: Power flatness cal for LO source

Here, pressing **Source Flatness** in the rightmost column **C.LO** initiates a power flatness calibration of VNA rear panel output Converter LO Out. Power flatness calibration is an iterative process, which loops through the two steps of measuring actual power and adjusting it by the difference wanted power - actual power, until this difference is within a user-defined tolerance window. For details of power flatness calibration, in particular with respect to its user-definable parameters, refer to VNA documentation.

2.3.1.3 IF power considerations

In contrast to RF and LO power, IF power is usually of minor concern. By default, converters are operated at an IF frequency of 279 MHz (R&S ZNA) and 52.123 MHz (R&S ZNB3000), where cable losses are pretty low. Unless the IF signal path exhibits significant attenuation and / or IF frequency is considerably increased, IF losses will not lead to noticeable degradation of system characteristics, for example of dynamic range.

On the other hand, note that excessive IF power may drive the VNA receivers in compression, which can lead to unexpected error-corrected measurement results. R&S converters are individually adjusted to provide -10 dBm at most. This is well below the 0.1 dB compression point of the IF inputs on the VNA rear panel (option ZNA-B26 or ZNB3-B8), which amounts to -4 dBm. When feeding the IF into the front panel inputs of option ZNA-B16, it might be necessary to add external pads, since the 0.1 dB compression point is already reached around -8 dBm.

2.3.2 Test port scalar power calibration

This subchapter covers the simplest form of calibration, which is scalar power calibration. Only a power meter and through connections are required, except for measurement receiver self-calibration of a port. In the latter case an additional short circuit is needed.

Cal → Scalar Power Cal invokes the dialog already known from Fig. 8, here shown again in Fig. 9. Here, button **C1 Ref. Receiver** is marked, since this is the usual starting point for all power calibrations.

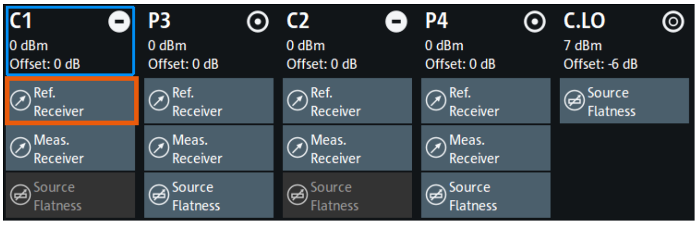
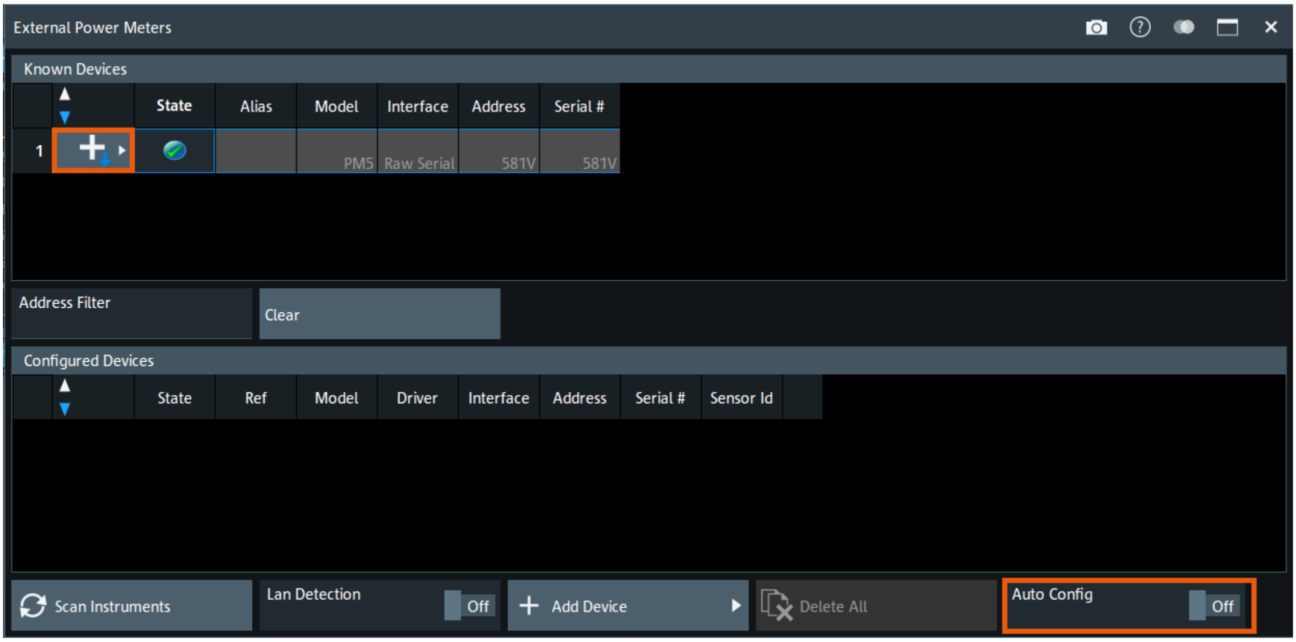


Fig. 9: Start dialog for power calibration

All VNA ports are listed as columns of a table. Those to which a converter has been assigned are designated C<n>, where n is the port number, and marked with a waveguide flange symbol. Various calibration options are described in the following. The dialogs appearing during converter power calibration are the same as in VNA baseband operation.

2.3.2.1 Power meter configuration

Before being able to perform a power calibration at a converter test port, a suitable mmwave power meter must be configured. R&S NRP<xxx>TWG are thermocouple-based power meters with waveguide test port. They are available for frequencies up to 170 GHz. These power sensors just need to be connected to the USB bus, which is sufficient to have them configured automatically. For the widespread power meters PM4 and PM5 from VDI-Erickson, VNA firmware includes pre-installed USB drivers. These instruments require one further step before being ready for use: Open the power meter configuration dialog via **Setup → Power Meter → Power Meters...** After having switched **Auto Config** off, The PM5 will appear in table **Known Devices** in the upper half of dialog **External Power Meters**, see Fig. 10. Then press the **+** button on the left side of this table entry.



Known Devices

	State	Alias	Model	Interface	Address	Serial #
1	✓		PM5	Raw Serial	581V	581V

Configured Devices

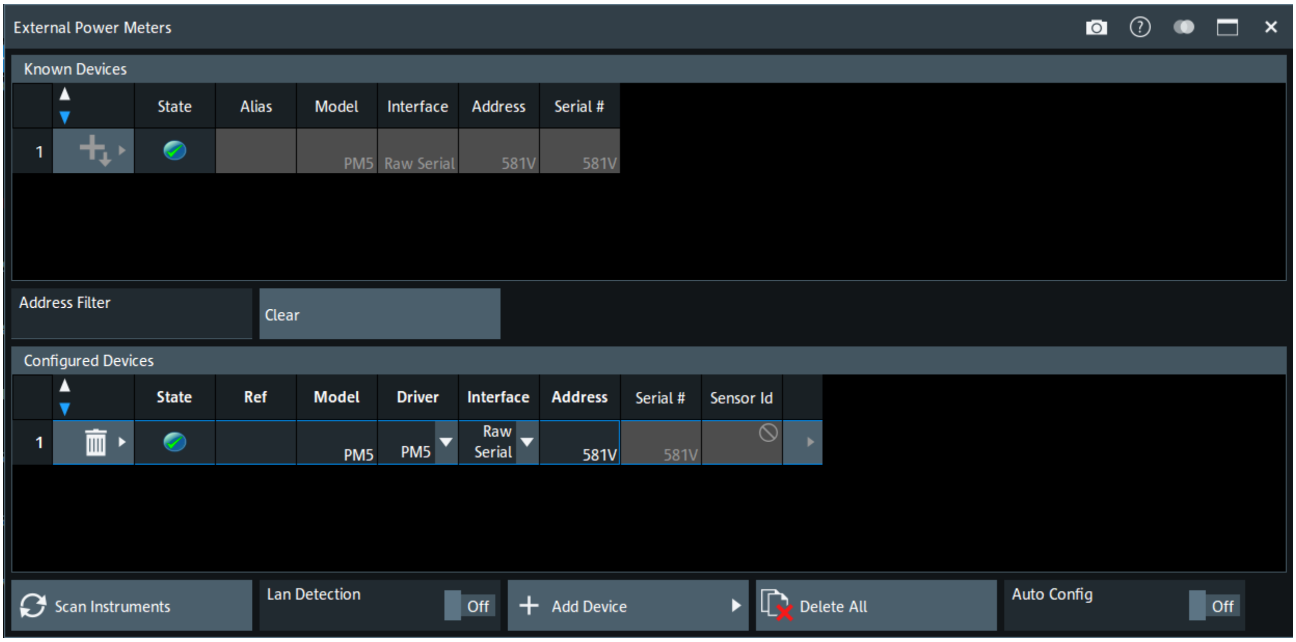
	State	Ref	Model	Driver	Interface	Address	Serial #	Sensor Id

Lan Detection Off

Auto Config Off

Fig. 10: Configuration of PM5: Step 1

This moves the PM5 to table **Configured Devices** in the lower half of the dialog, see Fig. 11:



Known Devices

	State	Alias	Model	Interface	Address	Serial #
1	✓		PM5	Raw Serial	581V	581V

Configured Devices

	State	Ref	Model	Driver	Interface	Address	Serial #	Sensor Id
1	✓		PM5	PM5	Raw Serial	581V	581V	

Lan Detection Off

Auto Config Off

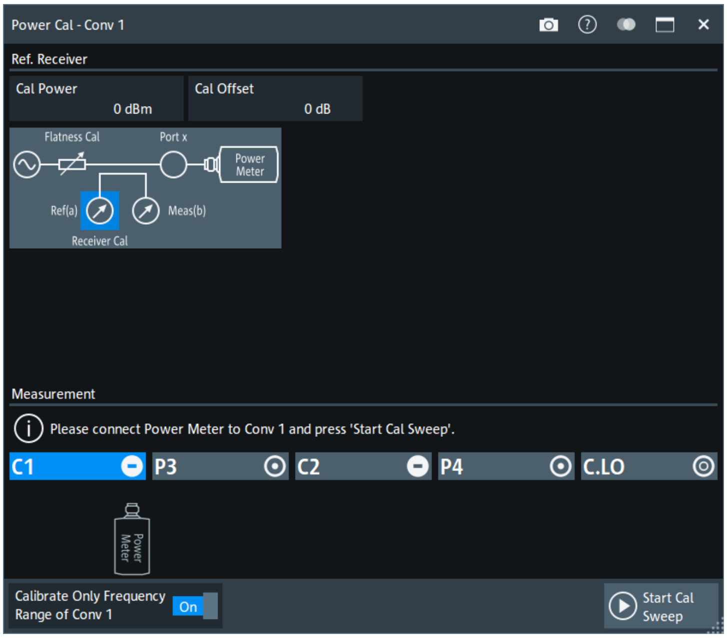
Fig. 11: Configuration of PM5: Step 2

Now the PM5 is available as Pmtr n, where n is the number in the first column of table **Configured Devices**.

2.3.2.2 Reference receiver calibration

Although it is possible to perform a pure source power flatness calibration by using only a power meter, it is recommended to start with a reference receiver calibration (button **Ref. Receiver** in Fig. 9). While power meters are able to measure the absolute power of a signal with high accuracy, they are inherently slow. This applies especially to those containing a thermocouple sensor or -even slower- that are based on the calorimeter principle, like the ones from VDI Erickson. In addition, power meters offer only limited dynamic range. In order to take advantage of the speed and measurement range of the heterodyne receivers of a modern VNA, a transfer calibration from a power meter to one of the VNA receivers, typically the reference channel (a wave) receiver, can be performed. This transfer process, however, is afflicted with the drawback that most power meters are broadband and thus receive all spectral components of the signal, like harmonics, spurious and broadband noise. Total measured power is assigned to the signal amplitude detected by the narrowband reference receiver of the VNA. Since the latter signal carries only a part of the total spectral power, the calibrated reference receiver generally overestimates signal power. For converters, a discrepancy between broadband and narrowband power is mostly caused by subharmonics close to the stimulus frequency. For a ZC110 with a source multiplication factor of 6, for example, the 5th and 7th harmonic of the VNA source frequency may appear within the waveguide band (here WM-2540) and can make the power measured by the meter differ by 2-3 dB from the a wave result. An obvious deviation, however, occurs only when power is changed after reference receiver cal, causing a change of the subharmonic content of the signal.

Clicking on button **Ref. Receiver** opens the dialog shown in Fig. 12:



Cal Power 0 dBm

Cal Offset 0 dB

Please connect Power Meter to Conv 1 and press 'Start Cal Sweep'.

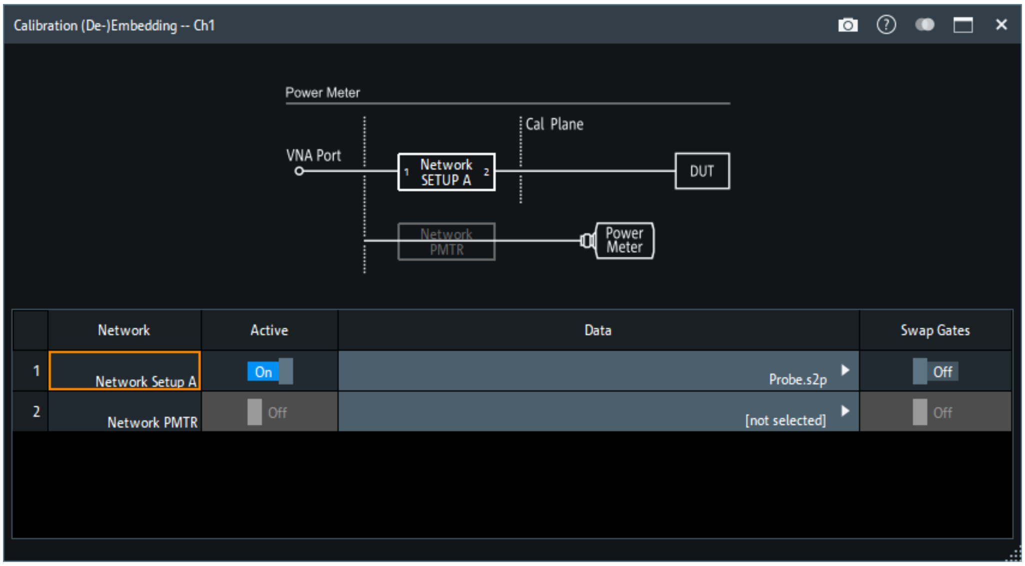
Calibrate Only Frequency Range of Conv 1 On

Fig. 12: Reference receiver calibration for converter power linearization

The calibration sweep can be started via **Start Cal Sweep**. Note that two traces are displayed: Power measured by the power meter and the a trace of the converter port to be calibrated. During the first sweep, these traces will differ, but from the second one on they will be congruent - if both measurements are stable. The congruence of the traces proves that the transfer calibration was successful, with the abovementioned accuracy restrictions caused by broadband reception of the power meter

2.3.2.3 Reference plane shift of power meter

For mmwave frequencies, only power meters with waveguide or coaxial connectors are available. Converters, however, are often used for on-wafer measurements. In this case, the wanted reference plane of the power calibration is probably located on wafer. Since a power meter can only be connected directly to the waveguide test port flange of the converter, the reference plane must be shifted to the wanted location. VNA firmware provides this feature, if the two-port between waveguide flange of the probe tip and ref plane on wafer is known. **Cal → Power Cal Settings → Calibration (De-)Embedding** open the dialog shown in Fig. 13:



	Network	Active	Data	Swap Gates
1	Network Setup A	On	Probe.s2p	Off
2	Network PMTR	Off	[not selected]	Off

Fig. 13: Shifting the reference plane of a power calibration

The schematic shown in the dialog includes two scenarios that commonly require a shift of the reference plane:

1. The upper part of the schematic depicts the situation mentioned above: The power meter can only be connected to the waveguide port of the converter. After power meter measurement, the reference plane must be shifted. In this case, the two-port will comprise the probe itself, adapters between converter and probe, if applicable, and usually a piece of planar line between probe tips and on-wafer reference plane.
2. The lower part of the schematic addresses the case that a two port is placed between converter and power meter during power meter measurement. The power meter may, for example, be connected to the coupled arm of a coupler, thus enabling permanent converter output power measurement. In this case, measured power must be corrected by coupling loss. Another motivation for placing a coupler between converter and power meter could arise from the fact that the converter provides more output power than the meter can tolerate. Similarly, an attenuator could be placed in between. In these cases, the meter readings must be corrected accordingly.

Please note that both scenarios may apply in conjunction.

There are two approaches for obtaining the S-parameters of the two-port mentioned above:

1. Direct measurement: Since the connector types of the two-port are generally unequal (e.g. rectangular waveguide on one side and planar transmission line like microstrip or coplanar waveguide on the other), a calibration method allowing for this will be needed. This could be UOSM or adapter removal.
2. Indirect measurement: A so-called Delta Cal, which is invoked via **Cal: Cal Utilities: Delta Cal**, allows to determine the S-Parameters of Network Setup A or Network PMTR in Fig. 13 as difference between an "outer" and an "inner" calibration. For details, refer to the documentation of the VNA.

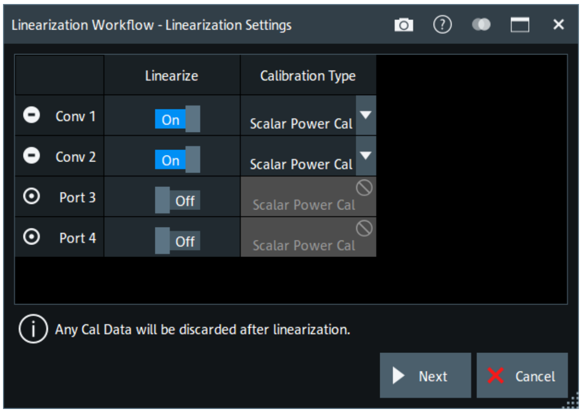
2.3.2.4 Measurement receiver calibration

After having performed a reference receiver calibration at one of the VNA ports, the measurement receiver of any test port can be power calibrated, too. Press button **Meas Receiver** (see Fig. 9) of the port to be calibrated. If the ports of reference and measurement receiver calibrations are different, simply establish a through connection between the ports. In case the measurement receiver of the same port is to be calibrated, connect a flush short to the test port. VNA firmware prompts the user to perform the correct action.

2.3.3 Source power linearization

Source power linearization (formerly called "leveling") designates the recording of a correction table that allows the user to set the wanted source power at the converter test port directly via the user interface of the VNA. Due to the multiplier chain in the converter source path, P_{TPout} as a function of P_{RFin} is nonlinear. The correction table represents the inverse of this nonlinear function, which means that it is used to determine the power P_{RFin} the VNA must provide to input RFIn to obtain a wanted P_{TPout}. P_{TPout} vs P_{RFin} may be nonlinear but should be monotonically increasing to avoid ambiguities. This is the case for almost all ZC converters. Some converters exhibit a maximum of P_{TPout}, beyond which the output power decreases. But such behavior is recognized upon recording the table and P_{RFin} will be limited.

After connecting a power meter to the converter test port (see 2.3.2.1), launch the linearization workflow via **Set-Up → Frequency Converter → Start Power Linearization,** which opens the dialog **Linearization Settings** shown in Fig. 14.


Linearization Workflow - Linearization Settings

	Linearize	Calibration Type
Conv 1	On	Scalar Power Cal
Conv 2	On	Scalar Power Cal
Port 3	Off	Scalar Power Cal
Port 4	Off	Scalar Power Cal

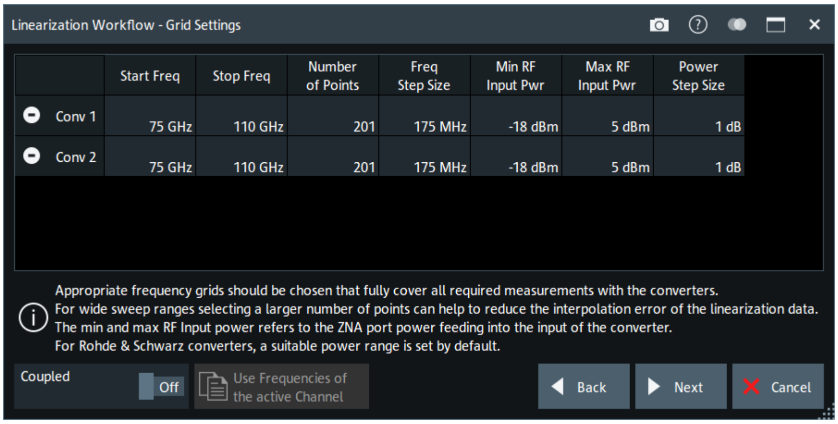
Any Cal Data will be discarded after linearization.

Fig. 14: Linearization Settings

Frequency converters that were configured as described in chapter 2.2 are automatically listed and enabled for linearization (field **Linearize** is **On**).

Drop-down **Calibration Type** influences the accuracy with which the absolute power is measured during initial reference receiver calibration. With default setting **Scalar Power Cal,** the unmodified reading of the power meter is assumed to represent the true power value. **Vector Power Cal**, on the other hand, applies a so-called smarter correction to the power meter reading. This removes power measurement uncertainties caused by mismatch between waveguide test port and power meter. For details, see chapter 2.3.5.2. However, since mmwave power meters, like all power meters, are generally well-matched, these uncertainties in most practical situations are small compared to the uncertainty due to harmonics and subharmonics, as explained in chapter 2.3.2.2. Thus, letting **Calibration Type** = **Scalar Power Cal** will provide satisfactory results in most cases.

Click **Next** to proceed to the **Grid Settings** (see Fig. 15).



Linearization Workflow - Grid Settings

	Start Freq	Stop Freq	Number of Points	Freq Step Size	Min RF Input Pwr	Max RF Input Pwr	Power Step Size
Conv 1	75 GHz	110 GHz	201	175 MHz	-18 dBm	5 dBm	1 dB
Conv 2	75 GHz	110 GHz	201	175 MHz	-18 dBm	5 dBm	1 dB

Appropriate frequency grids should be chosen that fully cover all required measurements with the converters.
For wide sweep ranges selecting a larger number of points can help to reduce the interpolation error of the linearization data.
The min and max RF Input power refers to the ZNA port power feeding into the input of the converter.
For Rohde & Schwarz converters, a suitable power range is set by default.

Coupled: Off

Fig. 15: Grid Settings

Entry fields **Start Freq**, **Stop Freq**, **Number of Points** and **Freq Step Size** allow the user to specify the frequency grid over which linearization data is to be recorded. If all configured converters operate in the same mmwave band, and if the measurement application does not imply frequency conversion, it is generally sufficient to define a common frequency grid for all converters. The default setting for this grid corresponds to the nominal full waveguide band, with 201 frequency points. In case converters for different bands have been configured, the default grid for each converter equals its respective band. For higher linearization accuracy and if the converter exhibits significant frequency response of the function P_{TPout} vs. P_{RFin}, increasing the number of points will reduce interpolation error.

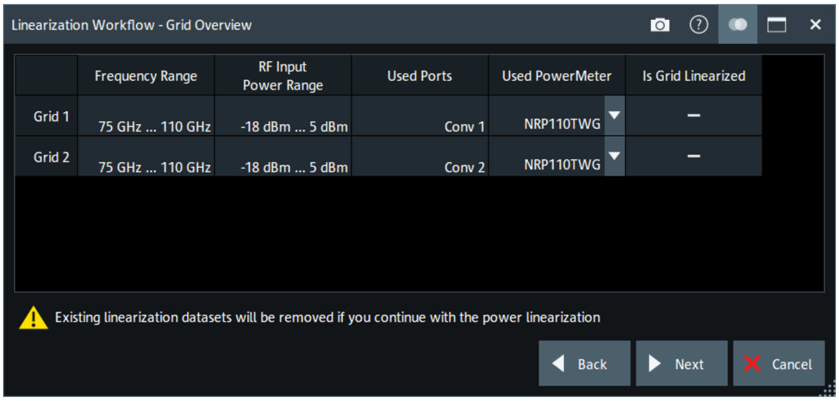
If measurements that require two-tone stimulus are to be performed, linearization frequency range should be chosen somewhat larger than the actual frequency range in order to accommodate for some margin. Calibration of intermodulation measurements, for example, is performed from **Start Freq** - 4 Δf to **Stop Freq** + 5 Δf, where Δf equals the **Delta Frequency** defined in **Meas → Intermodulation → Measurement Setup**. The asymmetry is caused by the fact that for intermodulation measurement, the lower tone equals the nominal frequency of a point, whereas for two-tone group delay measurements (option ZNA-K9) the two actual measurement frequencies are located symmetrically around the nominal frequency: **Delta Frequency**/2 below and above.

For applications implying frequency conversion, e.g. with converters for different mmwave bands, it may be necessary to define individual linearization frequency ranges for each converter.

Note that entry fields **Number of Points** and **Freq Step Size**, like in the **Sweep** menu, represent a single internal parameter and thus mutually align to each other.

Min and **Max RF Input Power**, together with **Power Step Size**, determine the grid of power values applied to input RF In. For ZVA-Zxxx and older ZCxxx converters, the default ranges are provided by VNA firmware, whereas newer ZCxxx come with their individual range stored in their internal flash memories. The default value of 1 dB for **Power Step Size** is appropriate for most converter types, if the slope of P_{TPout} vs P_{RFin} is not too large. In former firmware versions (before 3.1) automatic level control (ALC) could only be activated if linearization had been performed with **Power Step Size** set to 1 dB, but this restriction is not valid any longer.

Clicking **Next** opens the **Grid Overview** (see Fig. 16), where one can finally check the frequency and power grids that will be used for power linearization:



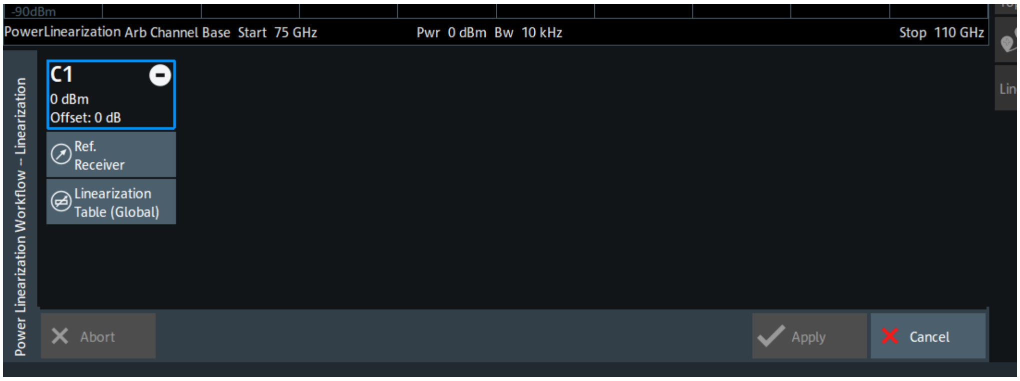
	Frequency Range	RF Input Power Range	Used Ports	Used PowerMeter	Is Grid Linearized
Grid 1	75 GHz ... 110 GHz	-18 dBm ... 5 dBm	Conv 1	NRP110TWG	–
Grid 2	75 GHz ... 110 GHz	-18 dBm ... 5 dBm	Conv 2	NRP110TWG	–

Existing linearization datasets will be removed if you continue with the power linearization

Fig. 16: Grid Overview

Note that proceeding to the next wizard dialog will delete any existing linearization data sets. If you want to keep this data, cancel now or save/export before continuing.

Next proceeds to the dialog shown in Fig. 17, from where the linearization can actually be initiated.



PowerLinearization Arb Channel Base Start 75 GHz Pwr 0 dBm Bw 10 kHz Stop 110 GHz

Fig. 17: Action buttons for performing the linearization

Since converter power linearization comprises a two-dimensional sweep over frequency and input power, a means is required for measuring the actual output power of the test port with high speed and over a large dynamic range. This is provided by a reference receiver calibration described previously in chapter 2.3.2.2. For linearization, the advantages mentioned there count for even more. Clicking button **Ref. Receiver** opens the same dialog as shown in Fig. 12, and the calibration process is identical to the one described there.

Linearization Table (Global) starts the two-dimensional sweep over frequency and power fed into RFIn. The measured converter output power at the test port is displayed as a family of traces with RFIn power as parameter (see Fig. 18.)

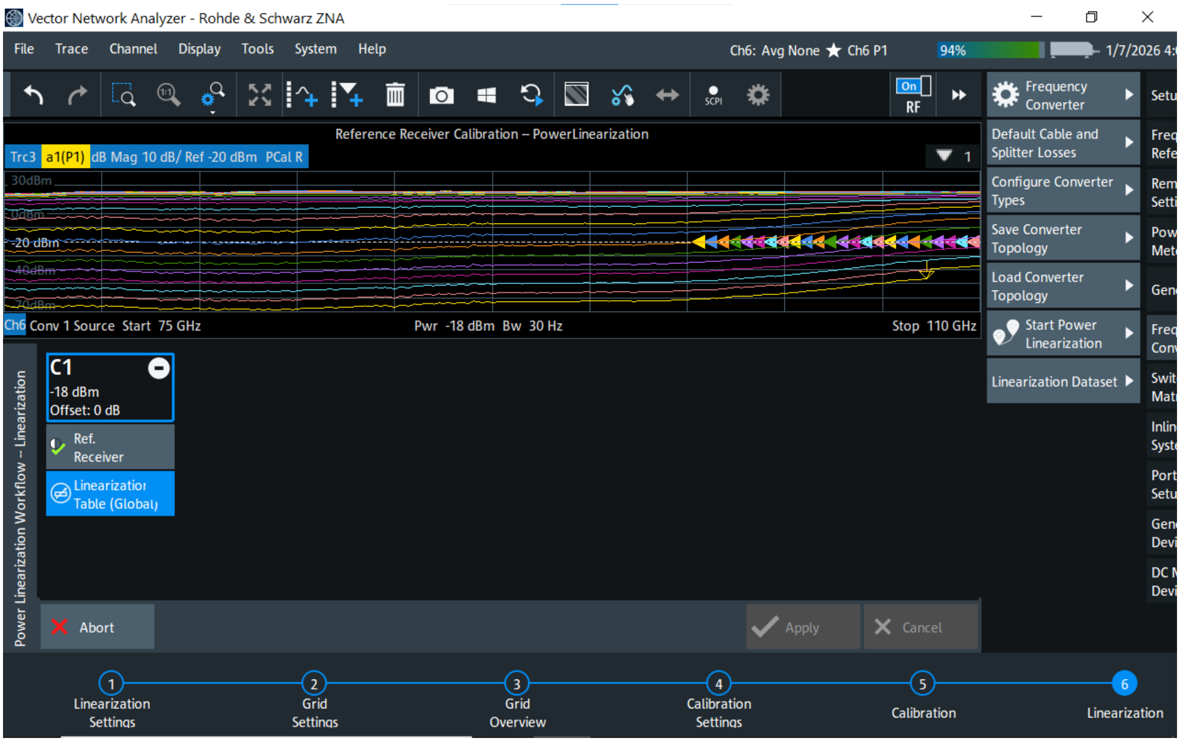
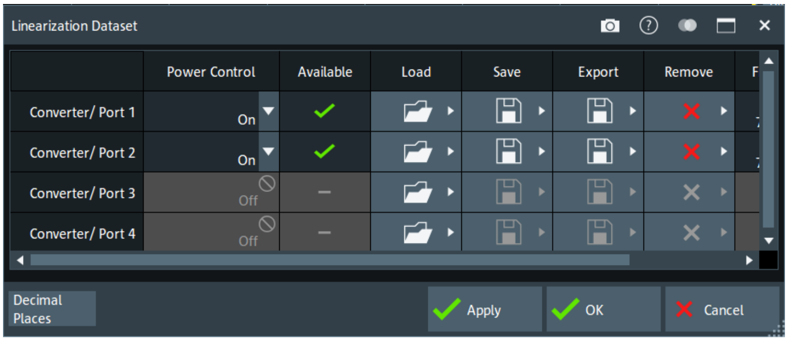


Fig. 18: Family of test port output power traces with RFIn power as parameter

Setup: Frequency Converter: Linearization Dataset opens the table shown in Fig. 19. A checkmark in column **Available** indicates that power linearization data is available. In this case, column **Power Control** allows activating or deactivating the use of the linearization data. If activated, the desired output power can directly be set via **Power Bw Avg: Power**. **Decimal Places** specifies the number of valid digits of frequency and power values in case that linearization data is exported as an ASCII file. When viewing the a wave of a linearized converter, one may note that the power may not be as flat over frequency as expected. These deviations are caused by interpolation errors. In order to obtain flatter converter output power, an additional power flatness calibration can be performed.



	Power Control	Available	Load	Save	Export	Remove	F
Converter/ Port 1	On	✓				✗	
Converter/ Port 2	On	✓				✗	
Converter/ Port 3	Off	–				✗	
Converter/ Port 4	Off	–				✗	

Fig. 19: Overview of available linearization datasets

2.3.4 Source power flatness calibration

Like for coaxial ports, a source power flatness calibration can be performed for converters, too. For details of this iterative calibration process, especially for the meaning of the parameters available in **Cal: Power Cal Settings**, refer to VNA documentation. While for flatness calibration of a coaxial port, entry **Convergence** should be kept at its default value 1, a significantly smaller value (e.g. 0.1 to 0.3) will be appropriate for converters that have not been linearized previously. Keeping **Convergence** = 1 for an unlinearized converter will cause the iteration process to oscillate.

2.3.5 System error and smarter calibration

As mentioned previously, the fundamental concepts of system error calibration and correction are assumed to be known to the reader. Therefore, this chapter will focus on the peculiarities related to converters.

2.3.5.1 Preferred calibration method

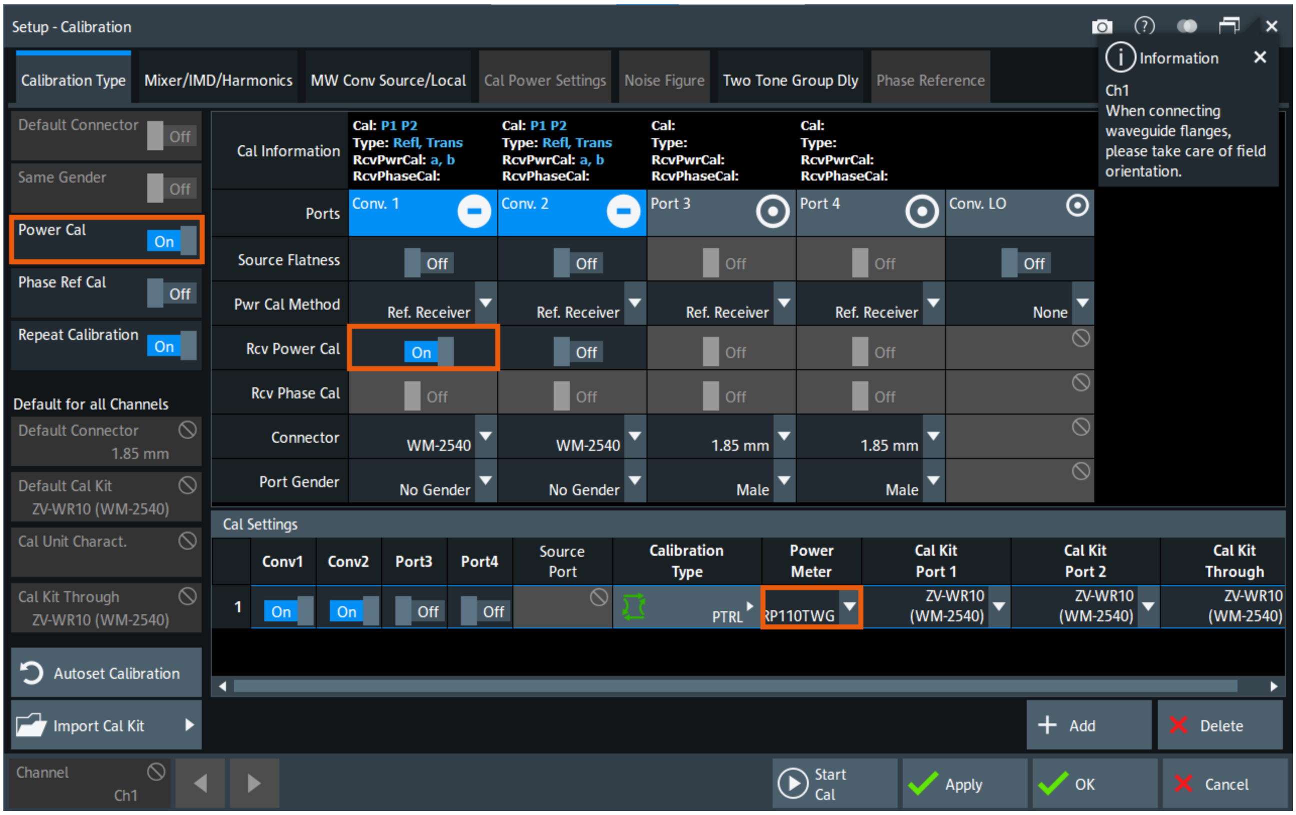
One of these specifics is the availability of calibration standards and the resulting preference for particular calibration procedures. When working with converters, the transmission line type at the reference plane to be calibrated will in most cases be either a rectangular waveguide or a planar line type like coplanar waveguide (in case of on-wafer measurements). The open circuit is one of the standards frequently used in the coaxial world - and thus to be found in each commercial calibration kit. In waveguide, an Open cannot be built, since an open waveguide acts as a badly matched antenna with a return loss is about -13 dB. Such a device is unusable as calibration standard, especially since the exact value of its reflection coefficient depends on the free-space environment around the test port. Therefore, the open is replaced by an offset short, physically consisting of a zero-length Short ("flush" Short) offset by a λ/4 offset line ("shim"). While the phase of the reflection coefficient is ideal (-180°) only close to the center of the respective waveguide band, this does not matter since deviations from ideality at the band edges are smaller than ±180° and therefore do not cause singularities due to phase zeros. In terms of calibration method terminology, all methods containing an O for open keep their name (e.g. OSM or TOSM) with a shift in the meaning of letter "O": When referring to waveguide calibration, O stands for an "Offset Short" instead of an "Open".

When working with waveguides, OSM is mostly chosen for precise one-port calibrations like in the coaxial world, TOSM is not that widely used. The main reason for this is the fact that there is a better alternative: TRL: In coaxial, TRL is used almost exclusively in metrology, due to two reasons: 1. it is band-limited and 2. manipulation of a coaxial airline is tedious, especially at higher frequencies. These disadvantages do not apply to waveguide: A waveguide band is band-limited as well (less than an octave and thus more limiting than the 1:8 band usually assumed for TRL) and the line standard is very simple: In fact, it is just the aforementioned λ/4 shim, which is part of every waveguide calibration kit. The flush Short is an easy-to-use reflect standard, and a Through in waveguide is the simplest standard of all: just connect the two waveguide ports. In addition, TRL is far less stringent than TOSM in terms of standard characterization. While TOSM requires all standards to be fully characterized a priori, attenuation of the TRL line needs not to be known, its length only approximately. One must know the phase of the reflection coefficient of the Reflect standard only with an uncertainty of ±90°. To sum up, ease of use and non-requirements in terms of standard characterization make TRL the preferred calibration method in waveguide, even in case that just a one-port calibration is needed – if a second converter is available.

The same advantages also hold for on-wafer calibration. Planar lines are generally not band-limited, thus the disadvantage of covering only a 1:8 frequency range may carry more weight. But this can be overcome by using NIST multiline TRL instead of simple TRL. At mmwave frequencies, lines can exhibit some attenuation. For the multiline TRL procedure, this is even advantageous, since it increases accuracy.

2.3.5.2 Smarter calibration

A full system error calibration establishes the error coefficients of all calibrated ports with the exception of a common scalar factor. This factor can be determined by a reference receiver calibration at an arbitrary port. Such a combined system error and power calibration is referred to as smarter calibration in the context of VNA firmware. The dialog shown in Fig. 20 is invoked by **Cal: Start Cal: Configure/Start Calibration**. Two steps are required to start a smarter cal. Switch **Power Cal** on, this enables the switches in the previously greyed table lines **Source Flatness** and **Rcv Power Cal**. Then switch on **Rcv Power Cal** in the column of the port where the power meter is to be connected. If a power meter has been configured, button **Start Cal** is enabled, and the calibration wizard can be started. For fundamentals of system error calibration and for details of the calibration workflow, refer to VNA documentation.



Information

Ch1
When connecting waveguide flanges, please take care of field orientation.

Default Connector Off
Same Gender Off
Power Cal On
Phase Ref Cal Off
Repeat Calibration On

Default for all Channels
Default Connector 1.85 mm
Default Cal Kit ZV-WR10 (WM-2540)
Cal Unit Charact.
Cal Kit Through ZV-WR10 (WM-2540)
Channel Ch1

Ports	Conv. 1	Conv. 2	Port 3	Port 4	Conv. LO
Cal Information	Cal: P1 P2 Type: Refl, Trans RcvPwrCal: a, b RcvPhaseCal:	Cal: P1 P2 Type: Refl, Trans RcvPwrCal: a, b RcvPhaseCal:	Cal: Type: RcvPwrCal: RcvPhaseCal:	Cal: Type: RcvPwrCal: RcvPhaseCal:	
Source Flatness	Off	Off	Off	Off	Off
Pwr Cal Method	Ref. Receiver	Ref. Receiver	Ref. Receiver	Ref. Receiver	None
Rcv Power Cal	On	Off	Off	Off	
Rcv Phase Cal	Off	Off	Off	Off	
Connector	WM-2540	WM-2540	1.85 mm	1.85 mm	
Port Gender	No Gender	No Gender	Male	Male	

Cal Settings

	Conv1	Conv2	Port3	Port4	Source Port	Calibration Type	Power Meter	Cal Kit Port 1	Cal Kit Port 2	Cal Kit Through
1	On	On	Off	Off		PTRL	RP110TWG	ZV-WR10 (WM-2540)	ZV-WR10 (WM-2540)	ZV-WR10 (WM-2540)

Fig. 20: Starting a smarter calibration

3 Linear Device Characteristics

A VNA system including converters, set up and calibrated according to chapter 2, is ready to measure the S-parameters of a non-frequency-converting DUT. After some initialization settings, which are described in chapter 3.2, a VNA with converter can also measure match and conversion loss of a mixer. The fundamentals of these parameters, which describe the behavior of a linear circuit, will not be considered in the following. This chapter will focus on the specific features related to converter operation.

3.1 Non-converting DUT (amplifier)

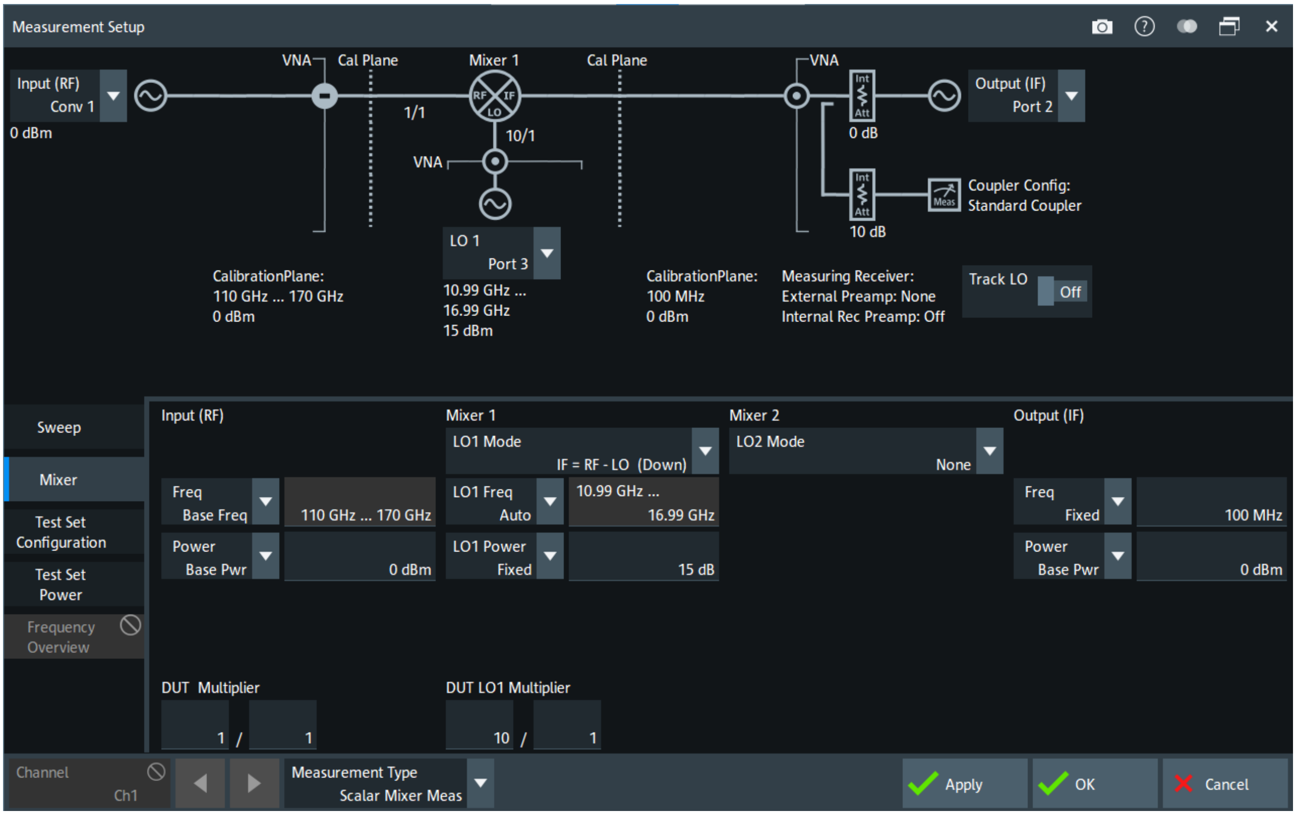
When measuring an amplifier, care must be taken in order not to overload the measurement receiver of the VNA port connected to the output of the DUT. If a receiver overload is detected, a corresponding message appears on the VNA display. Since there are no receiver step attenuators available for converters, either reduce DUT input power or place a waveguide attenuator between DUT output and associated converter test port. Attenuators with fixed attenuation as well as tunable ones are available e.g. from Radiometer Physics (WFA and WTA series). This method, however, is tainted with the disadvantage of decreased directivity of the converter connected to the output of the DUT. Lack of directivity may compromise the ability of this converter to measure the output reflection coefficient, which may induce ripple on the measured gain trace.

Some high-gain amplifiers (e.g. LNAs) require rather low source signal power when being measured. In addition to setting the source power electronically as described in chapter 2.3.3, source power can also be reduced with the help of the built-in waveguide tunable attenuator of the converter. ZC140 and all waveguide bands above are fitted with this feature, as well as the ZC75.

3.2 Frequency-converting DUT (mixer)

3.2.1 Mixer measurement setup

In principle, mmwave mixer measurements are set up in the same way as in the base VNA. As an example, Fig. 21 shows how the measurement of a D-band harmonic mixer (n=10) is set up via **Meas: Mixer Params: Setup Frequency Converting DUT....**



Input (RF): Conv 1
0 dBm

CalibrationPlane:
110 GHz ... 170 GHz
0 dBm

LO 1: Port 3
10.99 GHz ...
16.99 GHz
15 dBm

CalibrationPlane:
100 MHz
0 dBm

Measuring Receiver:
External Preamp: None
Internal Rec Preamp: Off

Output (IF): Port 2
0 dB
10 dB
Coupler Config:
Standard Coupler
Track LO: Off

Input (RF)
Freq: Base Freq — 110 GHz ... 170 GHz
Power: Base Pwr — 0 dBm

Mixer 1
LO1 Mode: IF = RF - LO (Down)
LO1 Freq: Auto — 10.99 GHz ... 16.99 GHz
LO1 Power: Fixed — 15 dB

Mixer 2
LO2 Mode: None

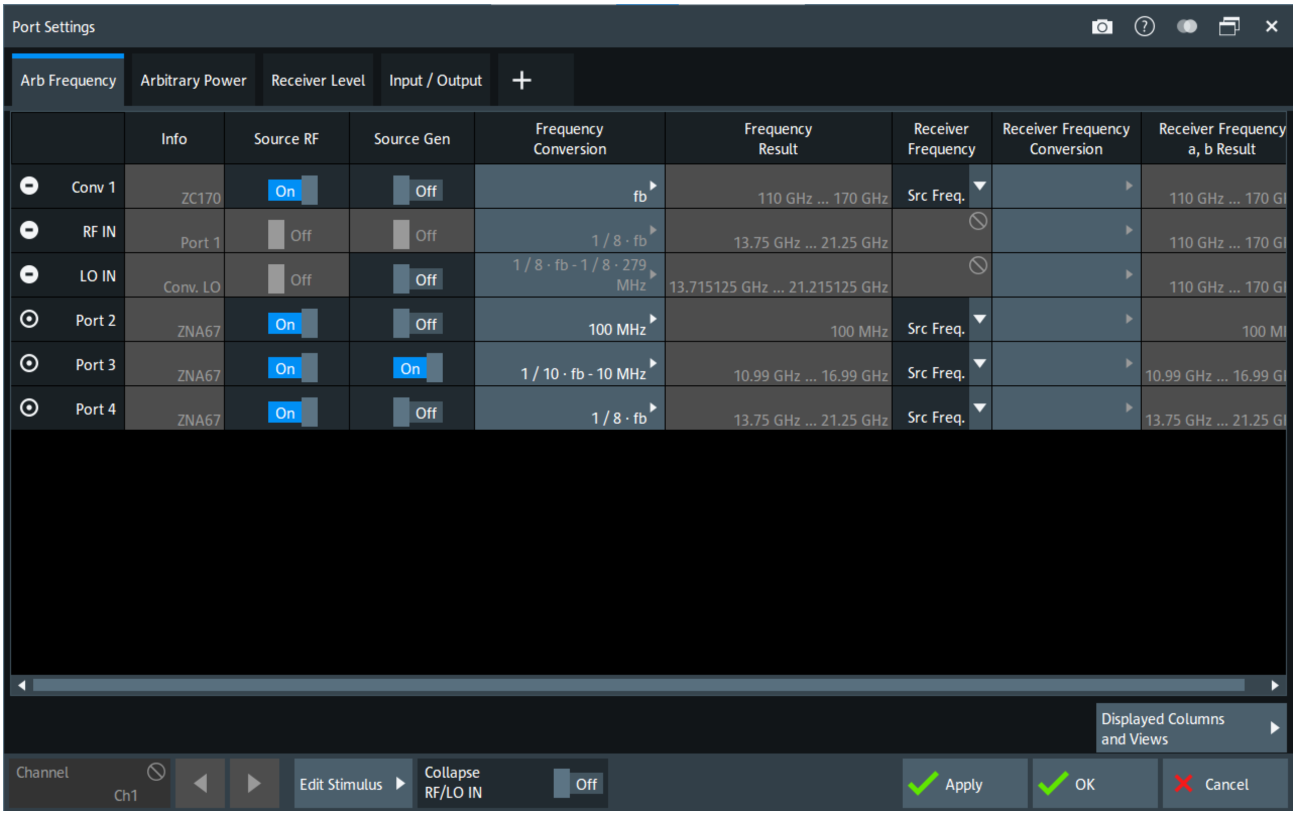
Output (IF)
Freq: Fixed — 100 MHz
Power: Base Pwr — 0 dBm

DUT Multiplier: 1 / 1
DUT LO1 Multiplier: 10 / 1

Measurement Type: Scalar Mixer Meas

Fig. 21: mmwave mixer measurement setup

This setup is based on a converter configuration with just a single converter assigned to port 1 (configuration not explicitly shown). All other ports remain with their coaxial base configuration. Port 2 receives the IF signal of the mixer, port 3 provides the LO, which is swept in parallel to the RF to provide a constant 100 MHz IF. The setup shown is only possible if option ZNA<xx>-B3 (third and fourth internal source) has been installed in the ZNA, since Port 1, 2 and 3 are all operated at different frequencies. Please note that Fig. 21 shows only the frequency conversion due to the DUT, whereas the port configuration depicted in Fig. 22 (**Channel Config: Port Config: Port Settings...**) also includes the RF and LO input frequencies of the converter. This provides a complete overview of the internal ZNA source and receiver frequencies.

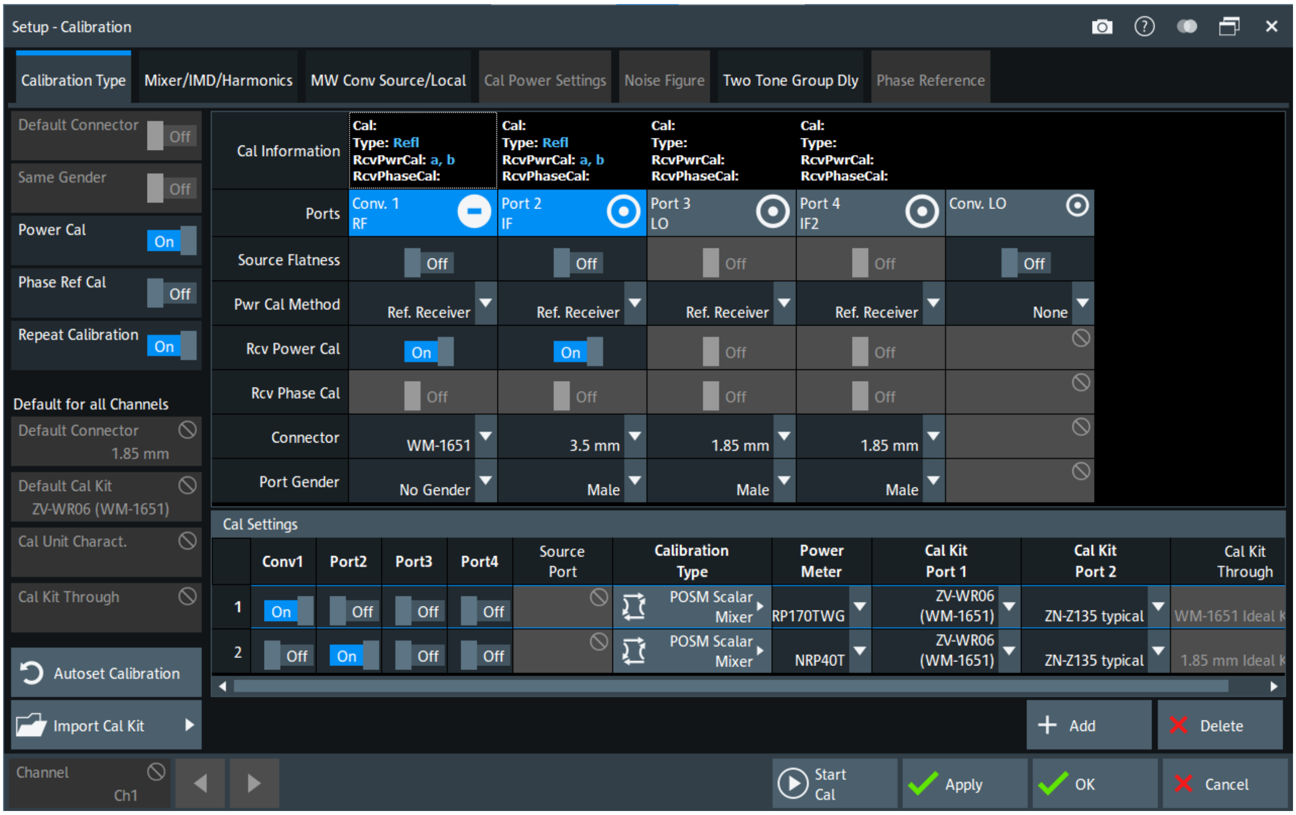


	Info	Source RF	Source Gen	Frequency Conversion	Frequency Result	Receiver Frequency	Receiver Frequency Conversion	Receiver Frequency a, b Result
Conv 1	ZC170	On	Off	fb	110 GHz ... 170 GHz	Src Freq.		110 GHz ... 170 G
RF IN	Port 1	Off	Off	1 / 8 · fb	13.75 GHz ... 21.25 GHz			110 GHz ... 170 G
LO IN	Conv. LO	Off	Off	1 / 8 · fb - 1 / 8 · 279 MHz	13.715125 GHz ... 21.215125 GHz			110 GHz ... 170 G
Port 2	ZNA67	On	Off	100 MHz	100 MHz	Src Freq.		100 M
Port 3	ZNA67	On	On	1 / 10 · fb - 10 MHz	10.99 GHz ... 16.99 GHz	Src Freq.		10.99 GHz ... 16.99 G
Port 4	ZNA67	On	Off	1 / 8 · fb	13.75 GHz ... 21.25 GHz	Src Freq.		13.75 GHz ... 21.25 G

Fig. 22: Port configuration resulting from DUT frequency conversion settings of Fig. 21

3.2.2 Mixer measurement calibration

In case of a frequency converting measurement, conversion must be set up before starting calibration. By default, the setup from Fig. 21 results in the default calibration suggestion of Fig. 23.



Default Connector: Off
Same Gender: Off
Power Cal: On
Phase Ref Cal: Off
Repeat Calibration: On

Default for all Channels
Default Connector: 1.85 mm
Default Cal Kit: ZV-WR06 (WM-1651)
Cal Unit Charact.
Cal Kit Through
Channel: Ch1

Cal Information	Cal: Type: Refl RcvPwrCal: a, b RcvPhaseCal:	Cal: Type: Refl RcvPwrCal: a, b RcvPhaseCal:	Cal: Type: RcvPwrCal: RcvPhaseCal:	Cal: Type: RcvPwrCal: RcvPhaseCal:	
Ports	Conv. 1 RF	Port 2 IF	Port 3 LO	Port 4 IF2	Conv. LO
Source Flatness	Off	Off	Off	Off	Off
Pwr Cal Method	Ref. Receiver	Ref. Receiver	Ref. Receiver	Ref. Receiver	None
Rcv Power Cal	On	On	Off	Off	
Rcv Phase Cal	Off	Off	Off	Off	
Connector	WM-1651	3.5 mm	1.85 mm	1.85 mm	
Port Gender	No Gender	Male	Male	Male	

Cal Settings

	Conv1	Port2	Port3	Port4	Source Port	Calibration Type	Power Meter	Cal Kit Port 1	Cal Kit Port 2	Cal Kit Through
1	On	Off	Off	Off		POSM Scalar Mixer	RP170TWG	ZV-WR06 (WM-1651)	ZN-Z135 typical	WM-1651 Ideal K
2	Off	On	Off	Off		POSM Scalar Mixer	NRP40T	ZV-WR06 (WM-1651)	ZN-Z135 typical	1.85 mm Ideal K

Fig. 23: Default suggestion for the calibration of mixer measurement of Fig. 21

Note that for both input and output ports of the mixer, a full one-port calibration is proposed. These will be performed at the frequencies associated with the RF and IF port frequency ranges of the mixer, respectively. The “P” in POSM, which stands for power, makes the VNA conduct smarter calibrations in both frequency ranges. These smarter calibrations include absolute power calibrations for a_1 and b_2, enabling the VNA to measure the correct scalar value of conversion loss b_2/a_1. Although 2xPOSM is the most accurate calibration method for scalar mixer calibration, simple scalar power calibrations could do as well. Since the latter ones do not correct for multiple reflections between converter (test port 1) and RF port of DUT, the measured conversion loss might exhibit larger ripple. The IF is fixed at 100 MHz in this example, therefore multiple reflections between IF port of the DUT and VNA test port 2 will not contribute to ripple. For typical measurement results with a scalar calibration, refer to Fig. 25 below.

3.2.3 Mixer group delay measurement

Group delay, which - in the case of a mixer - is the derivative of conversion loss phase vs frequency and a linear property of the mixer as well, cannot be measured with a simple scalar calibration as described in 0, because this does not provide any information about the conversion loss phase. Instead, a vector mixer calibration must be performed. For this type of calibration, basically the same requirements must be fulfilled as when operating the ZNA in its base frequency range. These are:

1. Option ZNA-K5 (Vector Mixer Measurement) is installed on the ZNA
2. The DUT mixer has an LO input that is accessible from outside (no embedded LO)
3. The LO signal for the DUT mixer is provided by an internal source of the ZNA, and the ZNA is operated in **Phase Mode** = **Coherence On** (preferably **Low Phase Noise**)
4. Either the DUT mixer itself must be reciprocal, or a reciprocal calibration mixer is available. Most passive mixers without amplifiers or isolators are sufficiently reciprocal by design. For group delay

measurement, even a constant phase offset between up- and down-conversion losses would be allowed

The process of vector mixer calibration, which is basically the same as in the base frequency range of the ZNA, is not exemplified here. For details, refer to ZNA documentation. Fig. 24 shows some linear characteristics – magnitude of conversion loss, RF and IF port match, conversion loss phase and group delay – obtained with vector mixer calibration. Besides the mixing diodes, this DUT does not contain potentially dispersive elements like filters or amplifiers. Therefore, group delay is rather flat, since it is mainly given by the lengths of the transmission lines inside the mixer. For comparison, the S-parameter magnitudes of the same mixer after a scalar mixer calibration are pictured in Fig. 25. Besides some minor ripple, the result is similar to the one obtained with vector mixer calibration. The latter screenshot also contains measurement results of the a-waves incident onto the RF and IF port, respectively. Not that a_2 is a straight line since the IF frequency is constant in this example.

In case the mixer LO is not accessible from outside, a two-tone signal must be applied to the DUT. This requires a dual-source converter ZCDSxxx or two converters combined via a magic T. Furthermore, option ZNA-K9 (Group delay measurements on frequency converters without LO access) and a reference mixer with known group delay is needed. This reference mixer can be characterized e.g. via ZNA-K5 as sketched above. For details of option ZNA-K9, please refer to application note 1EZ81 from Rohde & Schwarz.

Fig. 24: D-band mixer measured with vector mixer calibration: Upper: Conversion loss, lower left: RF and IF port match, lower right: conversion phase and group delay

Fig. 25: Magnitudes of mixer S-parameters after scalar mixer calibration + incident waves of RF and IF port

4 Nonlinear Device Characteristics

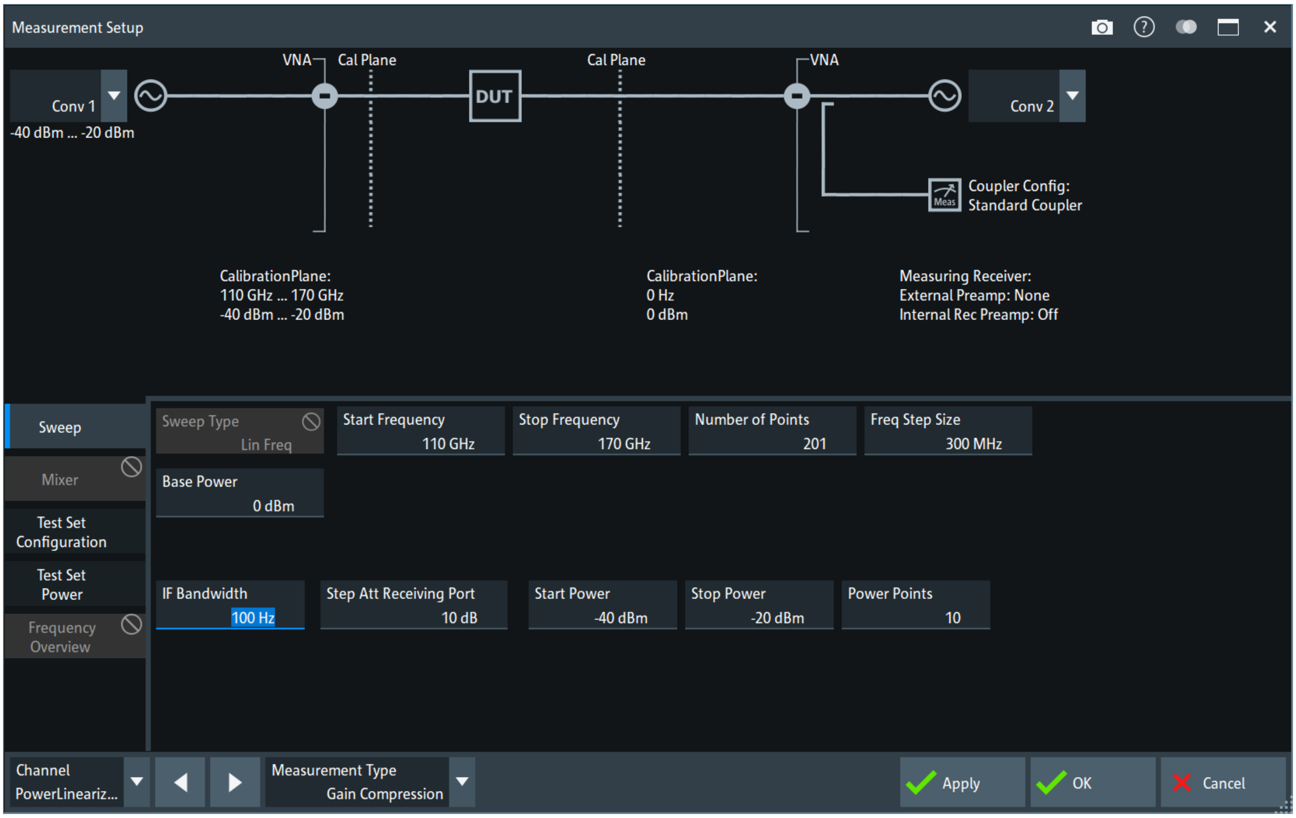
Like the ZNA in its native frequency range, a ZNA with converter can also be used to determine quantities describing the nonlinear behavior of components. The most important figures to be mentioned in this context are compression point and intermodulation products.

4.1 Non-converting DUT (amplifier)

4.1.1 Compression point

To determine the compression point of an amplifier – with reference to the input or output of the DUT – a smarter calibration, as detailed in chapter 2.3.5, is sufficient. Here again, take care not to overload the measurement receiver of the converter connected to the DUT output. **Meas: Measurement Menu = S-Parameters: Gain Compression: Measurement Setup** calls the dialog shown in Fig. 26. The algorithm implemented in ZNA firmware performs a two-dimensional search for the wanted compression level of a transmission factor. The transmission factor can be selected via dropdown fields for source and receiver ports. In Fig. 26 Conv1 serves as source port is and Conv2 as receiver. Hence the compression of S_{21} is to be measured. At each frequency point of the grid given by **Start Frequency**, **Stop Frequency** and **Number of Points / Freq. Step Size**, source power is increased, beginning at **Start Power** with an increment defined by (**Stop Power** - **Start Power**) / (**Power Points** - 1). As soon as S_{21} decreases by more than **Compression Value**, the power sweep stops. Depending on the quantity selected in the **Meas** menu (**Compression Point Power In** or **Compression Point Power Out**), the ZNA source or DUT output power at which the specified **Compression Value** is expected to be reached is determined by linear interpolation. If the wanted compression cannot be reached, e.g. because the source power of the converter is limited, a message appears. In this case, the measurement quantity **Compression Point Delta S-Param** indicates the degree of compression that can be reached at maximum source power.

Note that entry field **Step Att Receiving Port** has no effect if the DUT output signal is received by a mmwave converter.


Measurement Setup

Conv 1
-40 dBm ... -20 dBm

Conv 2

Coupler Config:
Standard Coupler

CalibrationPlane:
110 GHz ... 170 GHz
-40 dBm ... -20 dBm

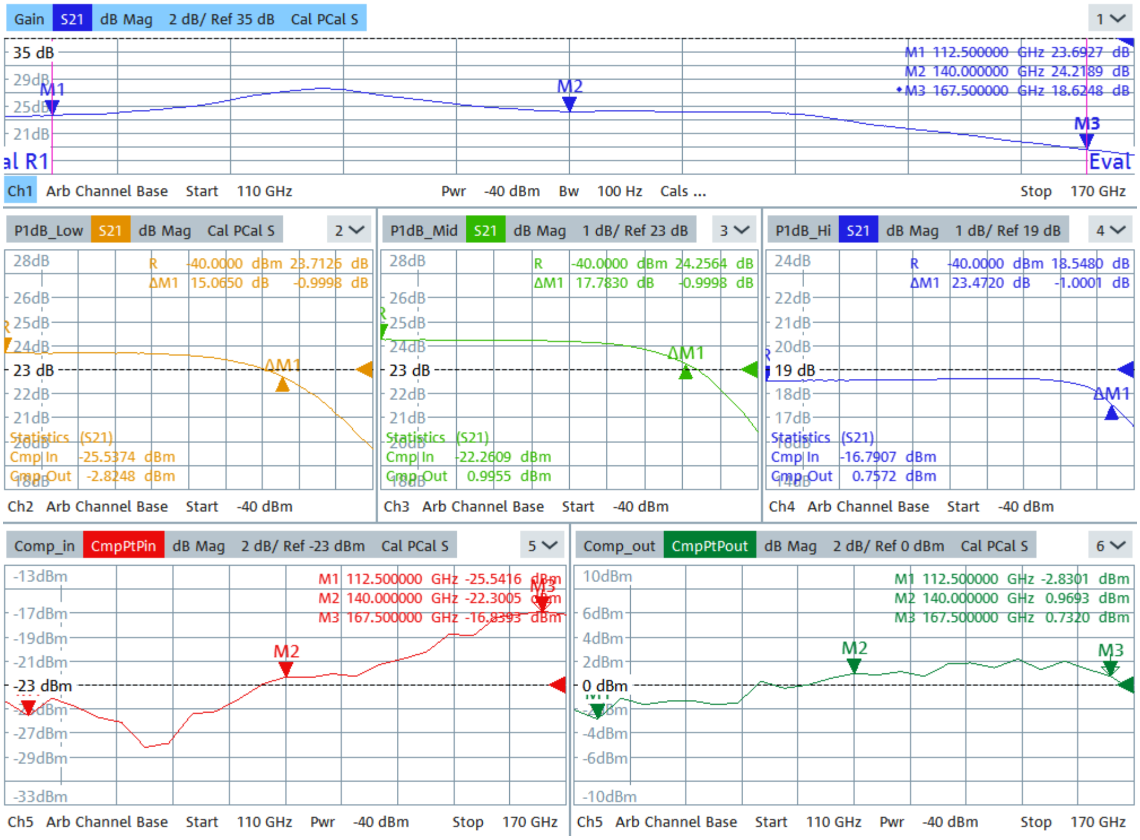
CalibrationPlane:
0 Hz
0 dBm

Measuring Receiver:
External Preamp: None
Internal Rec Preamp: Off

Sweep Type: Lin Freq
Start Frequency: 110 GHz
Stop Frequency: 170 GHz
Number of Points: 201
Freq Step Size: 300 MHz
Base Power: 0 dBm
IF Bandwidth: 100 Hz
Step Att Receiving Port: 10 dB
Start Power: -40 dBm
Stop Power: -20 dBm
Power Points: 10

Channel: PowerLineariz...
Measurement Type: Gain Compression

Fig. 26: Setup of compression point measurement of a D-band low noise amplifier


Gain S21 dB Mag 2 dB/ Ref 35 dB Cal PCal S

M1 112.500000 GHz 23.6927 dB
M2 140.000000 GHz 24.2189 dB
M3 167.500000 GHz 18.6248 dB

Ch1 Arb Channel Base Start 110 GHz Pwr -40 dBm Bw 100 Hz Cals ... Stop 170 GHz

P1dB_Low S21 dB Mag Cal PCal S
R -40.0000 dBm 23.7126 dB
ΔM1 15.0650 dB -0.9998 dB
Statistics (S21)
Cmp In -25.5374 dBm
Cmp Out -2.8248 dBm
Ch2 Arb Channel Base Start -40 dBm

P1dB_Mid S21 dB Mag 1 dB/ Ref 23 dB
R -40.0000 dBm 24.2564 dB
ΔM1 17.7830 dB -0.9998 dB
Statistics (S21)
Cmp In -22.2609 dBm
Cmp Out 0.9955 dBm
Ch3 Arb Channel Base Start -40 dBm

P1dB_Hi S21 dB Mag 1 dB/ Ref 19 dB
R -40.0000 dBm 18.5480 dB
ΔM1 23.4720 dB -1.0001 dB
Statistics (S21)
Cmp In -16.7907 dBm
Cmp Out 0.7572 dBm
Ch4 Arb Channel Base Start -40 dBm

Comp_in CmpPtPin dB Mag 2 dB/ Ref -23 dBm Cal PCal S
M1 112.500000 GHz -25.5416 dBm
M2 140.000000 GHz -22.3005 dBm
M3 167.500000 GHz -16.8393 dBm
Ch5 Arb Channel Base Start 110 GHz Pwr -40 dBm Stop 170 GHz

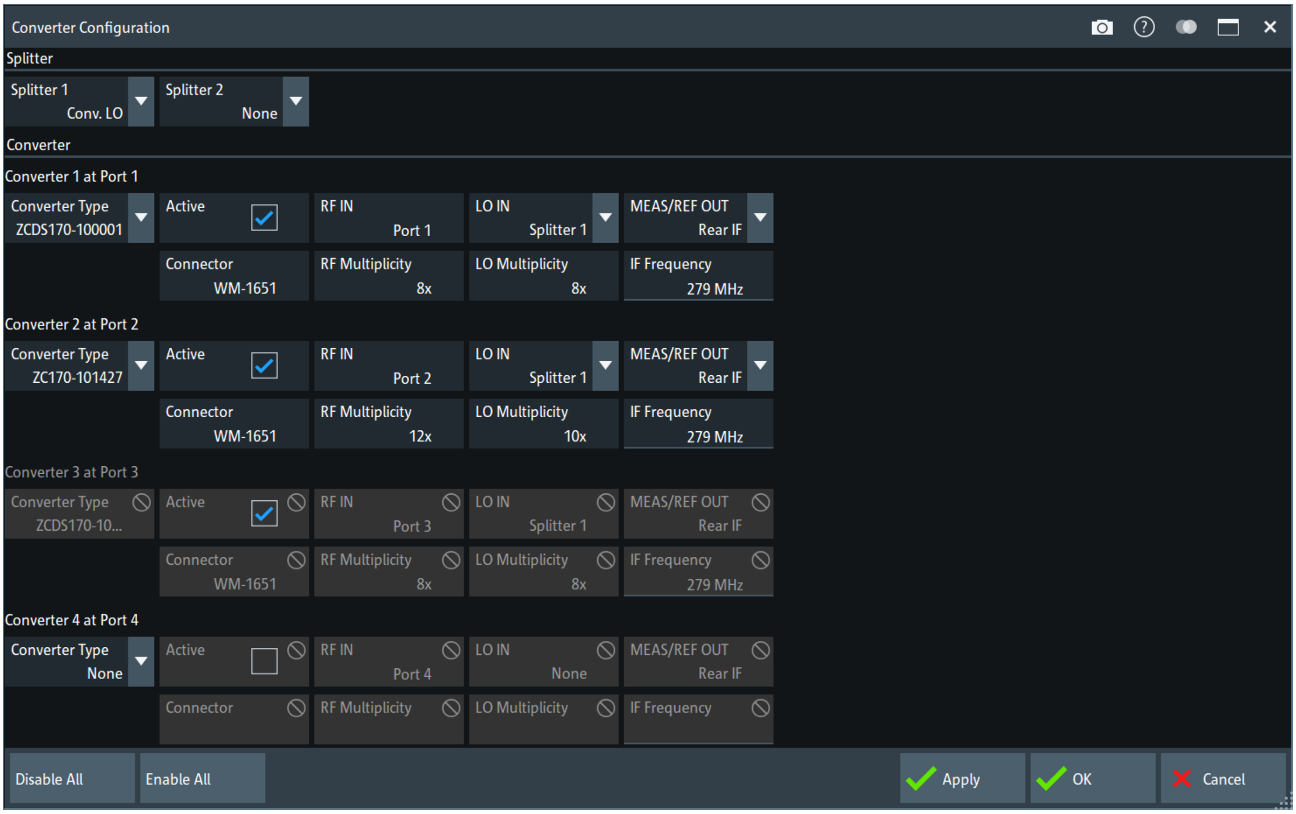
Comp_out CmpPtPout dB Mag 2 dB/ Ref 0 dBm Cal PCal S
M1 112.500000 GHz -2.8301 dBm
M2 140.000000 GHz 0.9693 dBm
M3 167.500000 GHz 0.7320 dBm
Ch5 Arb Channel Base Start 110 GHz Pwr -40 dBm Stop 170 GHz

Fig. 27: D-band low noise amplifier: Upper: Gain vs frequency, middle: Gain vs power, lower: gain compression point vs frequency at input/output

The upper trace in Fig. 27 shows the small-signal gain of a D-band LNA when driven with a source power far below compression (-40 dBm). In the lower diagrams, one can see input (left) and output (right) 1 dB compression point vs frequency, measured in a 2D sweep as described above. To check the validity of the results, a power sweep was performed for each of the three frequencies labeled with marker M1 to M3 (middle row of diagrams). The corresponding 1 dB compression points at input and output of the DUT were determined with the help of **Trace Config: Trace Statistics: Compression Point**, showing good agreement with the 2D sweep.

4.1.2 Intermodulation

Intermodulation measurements require a two-tone stimulus signal. While it is possible to combine two normal ZC converters, for example with the help of a magic T, using a dual-source converter like e.g. the ZCDS170 is much easier and more convenient. In this case, the combined a-waves can be measured with a single reference receiver, which is not possible when an external combiner is used. Fig. 28: Dual-source converter configuration for non-frequency-converting DUT. Fig. 28 illustrates a typical converter configuration with port 1 and 3 as dual sources. This is the only port assignment allowed for dual-source converters. In case one selects a dual-source converter for port 1, port 3 automatically adopts the second source of the same converter, and its dropdown field becomes disabled.



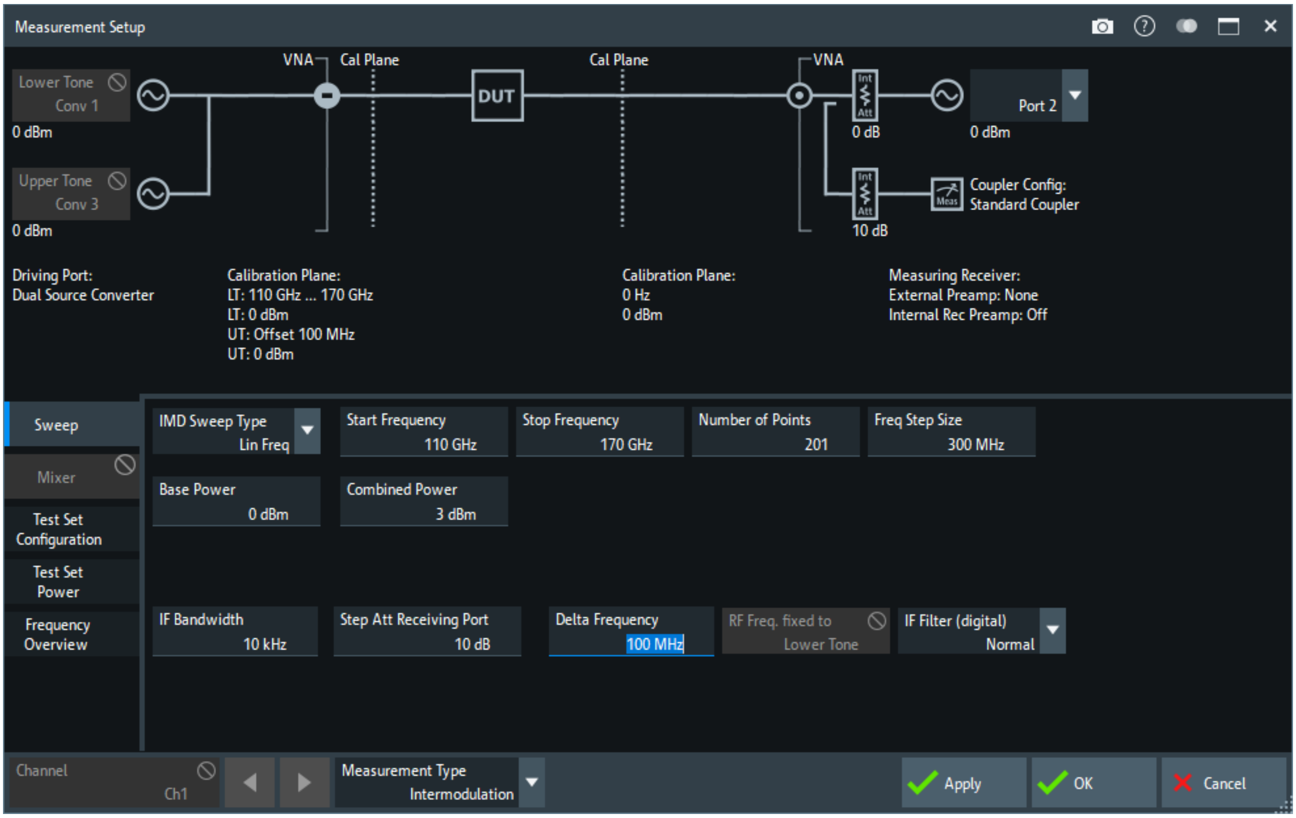
Splitter 1: Conv. LO
Splitter 2: None

	Converter Type	Active	RF IN	LO IN	MEAS/REF OUT	Connector	RF Multiplicity	LO Multiplicity	IF Frequency
Converter 1 at Port 1	ZCDS170-100001	☑	Port 1	Splitter 1	Rear IF	WM-1651	8x	8x	279 MHz
Converter 2 at Port 2	ZC170-101427	☑	Port 2	Splitter 1	Rear IF	WM-1651	12x	10x	279 MHz
Converter 3 at Port 3	ZCDS170-10...	☑	Port 3	Splitter 1	Rear IF	WM-1651	8x	8x	279 MHz
Converter 4 at Port 4	None	☐	Port 4	None	Rear IF				

Fig. 28: Dual-source converter configuration for non-frequency-converting DUT

Currently (FW version 3.2) it is necessary to split the converter IF output signals Meas Out and Ref Out to ZNA rear panel inputs IF Meas and IF Reference, e.g. with the help of a SMA T junction and two additional IF cables.

Before starting calibration, the intermodulation measurement must be set up via **Meas: Intermodulation: Measurement Setup.** With the converter configuration of Fig. 28, the setup of Fig. 29 and the default calibrations offered for this setup (Fig. 30), one obtains the result shown in Fig. 31. Previously, a source power linearization has been performed. For details of intermodulation calibration, refer to ZNA documentation.



Lower Tone: Conv 1, 0 dBm

Upper Tone: Conv 3, 0 dBm

Port 2: 0 dBm

0 dB

10 dB

Coupler Config: Standard Coupler

Driving Port:
Dual Source Converter

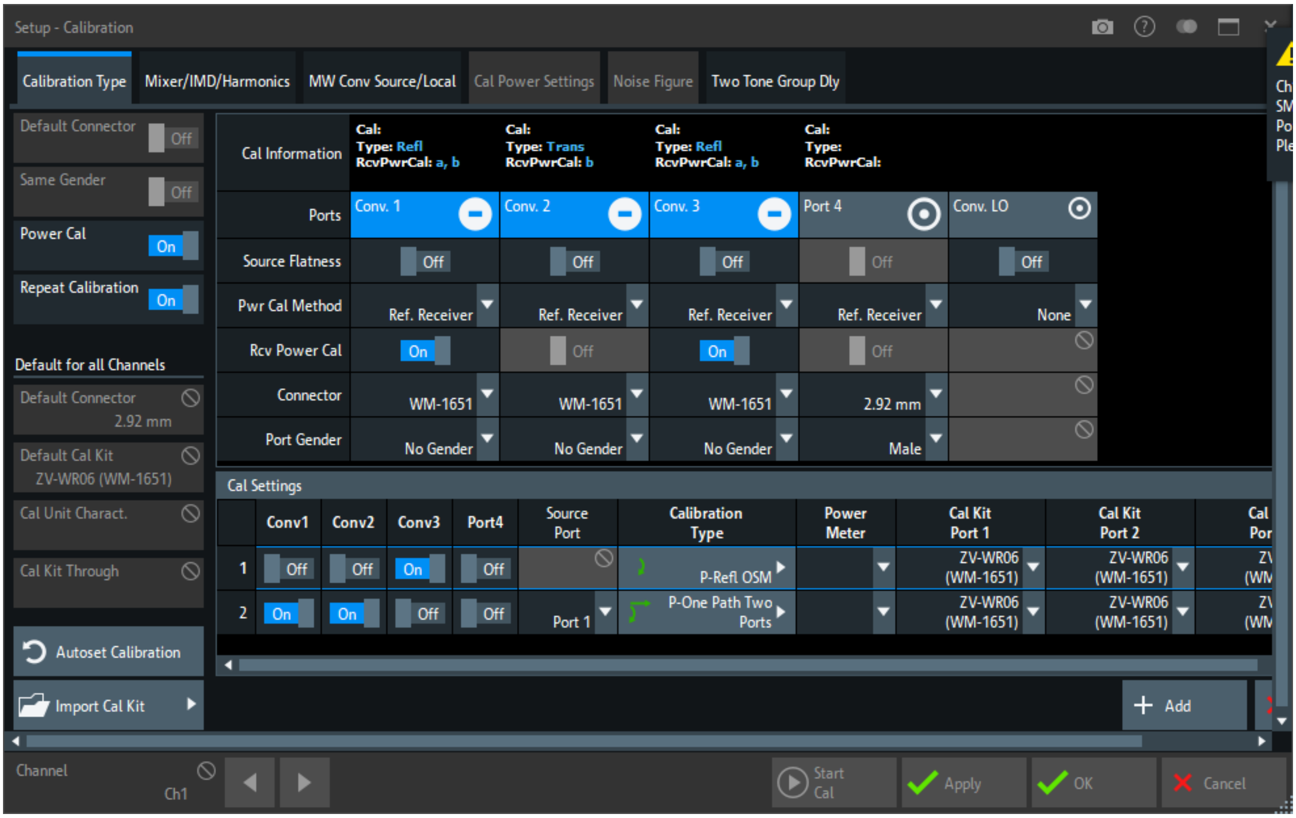
Calibration Plane:
LT: 110 GHz ... 170 GHz
LT: 0 dBm
UT: Offset 100 MHz
UT: 0 dBm

Calibration Plane:
0 Hz
0 dBm

Measuring Receiver:
External Preamp: None
Internal Rec Preamp: Off

Setting	Value
IMD Sweep Type	Lin Freq
Start Frequency	110 GHz
Stop Frequency	170 GHz
Number of Points	201
Freq Step Size	300 MHz
Base Power	0 dBm
Combined Power	3 dBm
IF Bandwidth	10 kHz
Step Att Receiving Port	10 dB
Delta Frequency	100 MHz
RF Freq. fixed to	Lower Tone
IF Filter (digital)	Normal
Channel	Ch1
Measurement Type	Intermodulation

Fig. 29: Amplifier intermodulation measurement setup



Default Connector: Off

Same Gender: Off

Power Cal: On

Repeat Calibration: On

Default for all Channels

Default Connector: 2.92 mm

Default Cal Kit: ZV-WR06 (WM-1651)

Cal Unit Charact.

Cal Kit Through

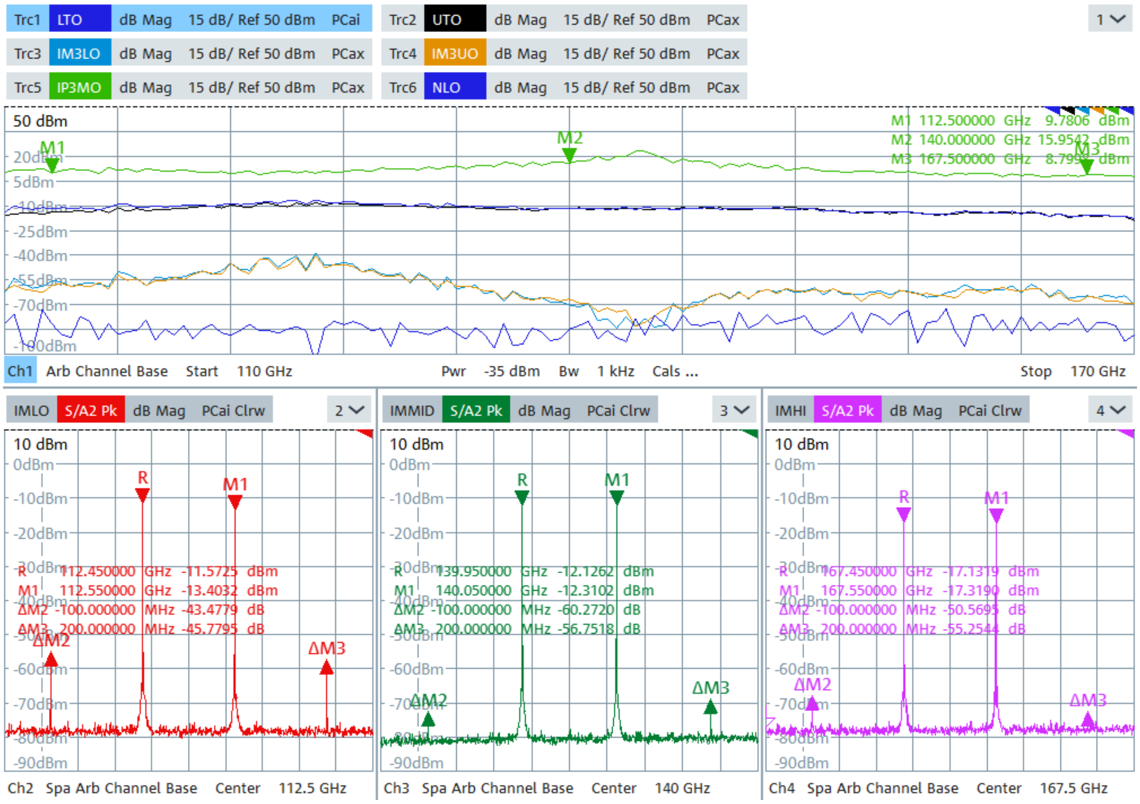
Ports	Conv. 1	Conv. 2	Conv. 3	Port 4	Conv. LO
Cal Information	Cal: Type: Refl RcvPwrCal: a, b	Cal: Type: Trans RcvPwrCal: b	Cal: Type: Refl RcvPwrCal: a, b	Cal: Type: RcvPwrCal:	
Source Flatness	Off	Off	Off	Off	Off
Pwr Cal Method	Ref. Receiver	Ref. Receiver	Ref. Receiver	Ref. Receiver	None
Rcv Power Cal	On	Off	On	Off	
Connector	WM-1651	WM-1651	WM-1651	2.92 mm	
Port Gender	No Gender	No Gender	No Gender	Male	

Cal Settings

	Conv1	Conv2	Conv3	Port4	Source Port	Calibration Type	Power Meter	Cal Kit Port 1	Cal Kit Port 2	Cal Por
1	Off	Off	On	Off		P-Refl OSM		ZV-WR06 (WM-1651)	ZV-WR06 (WM-1651)	Z (WM
2	On	On	Off	Off	Port 1	P-One Path Two Ports		ZV-WR06 (WM-1651)	ZV-WR06 (WM-1651)	Z (WM

Channel: Ch1

Fig. 30: Default calibration for intermodulation measurement



M1 112.500000 GHz 9.7806 dBm
M2 140.000000 GHz 15.9542 dBm
M3 167.500000 GHz 8.799 dBm

R 112.450000 GHz -11.5725 dBm
M1 112.550000 GHz -13.4032 dBm
ΔM2 -100.000000 MHz -43.4779 dB
ΔM3 200.000000 MHz -45.7795 dB

R 139.950000 GHz -12.1262 dBm
M1 140.050000 GHz -12.3102 dBm
ΔM2 -100.000000 MHz -60.2720 dB
ΔM3 200.000000 MHz -56.7518 dB

R 167.450000 GHz -17.1319 dBm
M1 167.550000 GHz -17.3190 dBm
ΔM2 -100.000000 MHz -50.5695 dB
ΔM3 200.000000 MHz -55.2544 dB

Fig. 31: Intermodulation measurement of a D-band LNA

The upper diagram shows the fundamental tones LTU and UTO, the upper and lower 3rd order intermodulation products IM3LO and IM3UO as well as the resulting 3rd order intercept point IP3MO. To make sure that the intermodulation products are real signals above noise floor, the noise floor NO is included, too. All measured quantities are related to the output of the DUT, indicated by an O in the name of the quantity.

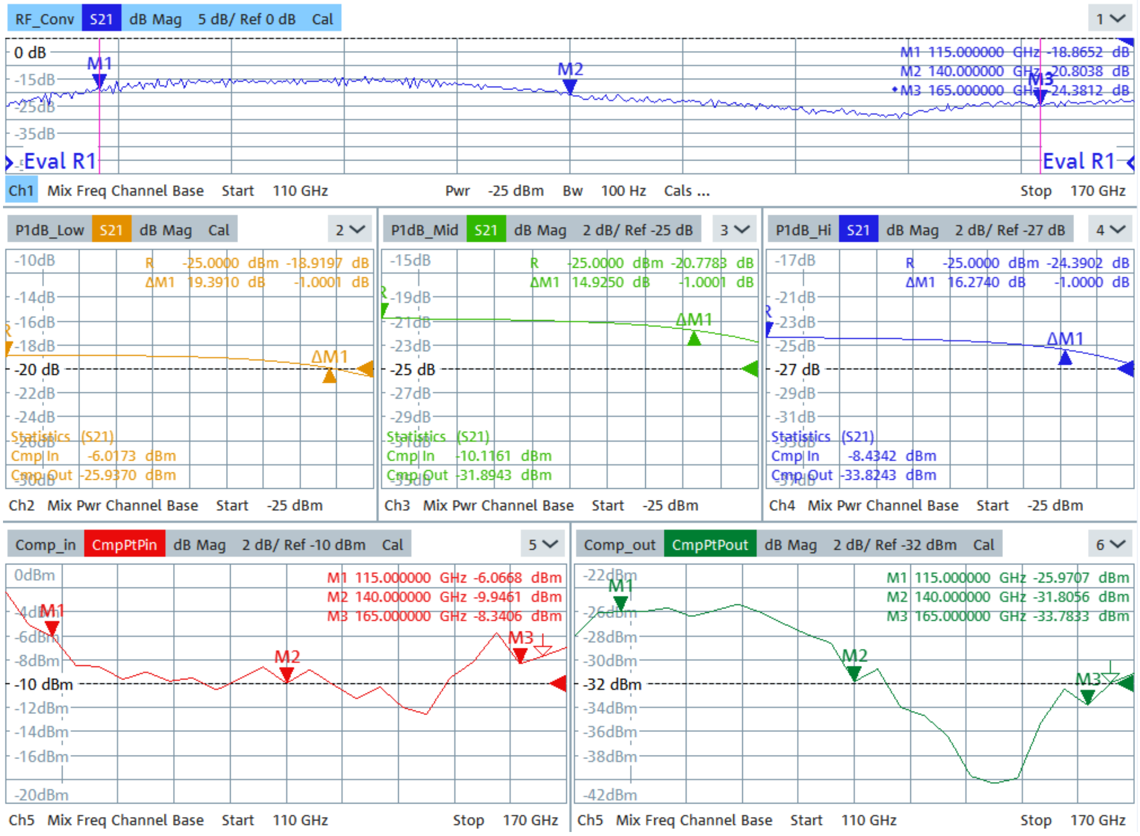
The lower row of diagrams depicts spectrum views of fundamental tones and 3rd order intermodulation products, obtained with the help of **Spectrum = Marker**. This creates a new channel in which the two stimulus signals (fundamental tones) are kept constant, such that the frequency of the lower tone corresponds to the position of the active marker, and the receiver is swept in spectrum analysis mode as with option ZNA-K1.

Note that to obtain these graphs, the frequency grids of converter source linearization, calibration and IMD measurement were chosen in a way that all frequencies of interest (fundamental tones and intermodulation products) were placed on grid points, hence no interpolation was required. If interpolation is allowed, increased ripple on the measured traces may result.

4.2 Frequency-converting DUT (mixer)

4.2.1 Compression point

With the same harmonic mixer as used for chapter 3.2 in the same frequency conversion configuration and with the same smarter calibration, the compression behavior depicted in Fig. 32 was measured. As for the amplifier measurement (Fig. 27), the powers for 1 dB compression at the mixer's input and output were verified by explicit power sweeps at three frequency points. Again, the results agree well.



```
M1 115.000000 GHz -18.8652 dB
M2 140.000000 GHz -20.8038 dB
M3 165.000000 GHz -24.3812 dB
```

```
R    -25.0000 dBm -18.9197 dB
ΔM1   19.3910 dB   -1.0001 dB
Statistics (S21)
Cmp In   -6.0173 dBm
Cmp Out -25.9370 dBm
```

```
R    -25.0000 dBm -20.7783 dB
ΔM1   14.9250 dB   -1.0001 dB
Statistics (S21)
Cmp In  -10.1161 dBm
Cmp Out -31.8943 dBm
```

```
R    -25.0000 dBm -24.3902 dB
ΔM1   16.2740 dB   -1.0000 dB
Statistics (S21)
Cmp In   -8.4342 dBm
Cmp Out -33.8243 dBm
```

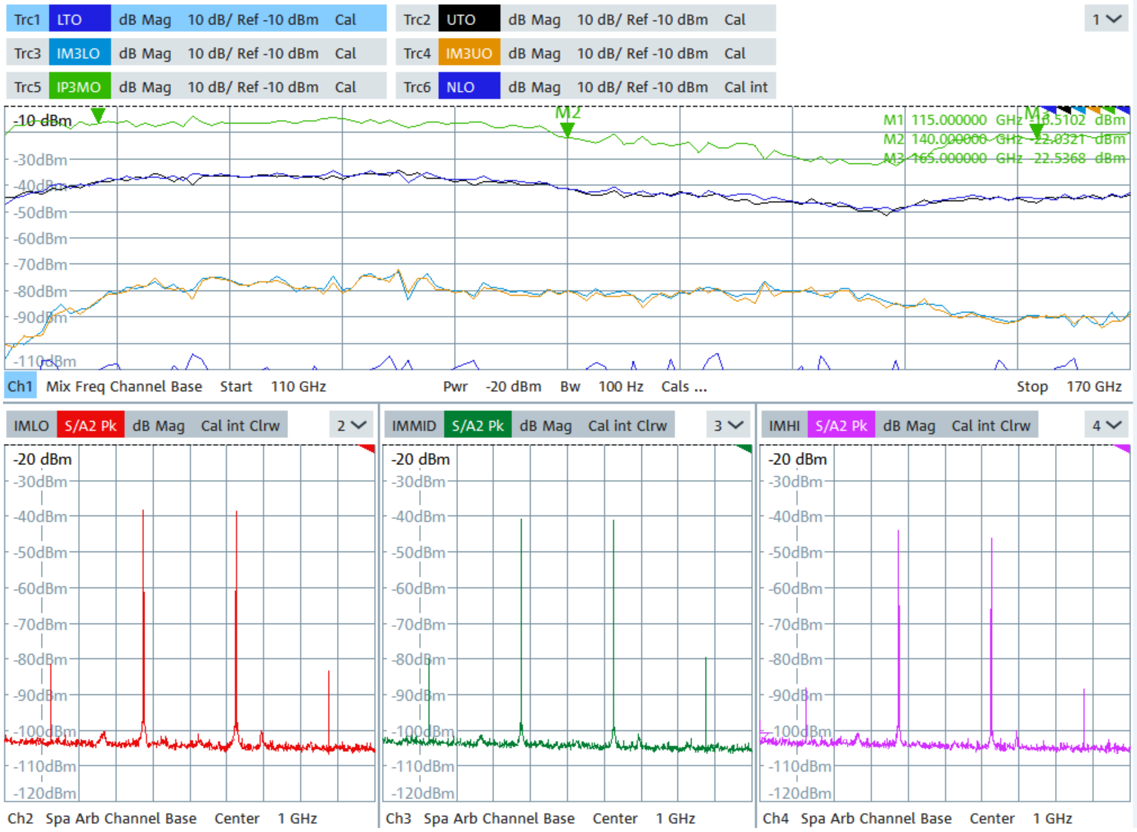
```
M1 115.000000 GHz -6.0668 dBm
M2 140.000000 GHz -9.9461 dBm
M3 165.000000 GHz -8.3406 dBm
```

```
M1 115.000000 GHz -25.9707 dBm
M2 140.000000 GHz -31.8056 dBm
M3 165.000000 GHz -33.7833 dBm
```

Fig. 32: D-band mixer compression measurement

4.2.2 Intermodulation

For the mixer, Fig. 33 shows the same intermodulation measurement quantities as Fig. 31 for the amplifier. And, as in this case, the spectral views confirm the swept-frequency results for selected frequency points. Again, source power linearization and smarter calibration were performed with frequency grids avoiding the need for interpolation.



Trc1 LTO dB Mag 10 dB/ Ref -10 dBm Cal
Trc2 UTO dB Mag 10 dB/ Ref -10 dBm Cal
Trc3 IM3LO dB Mag 10 dB/ Ref -10 dBm Cal
Trc4 IM3UO dB Mag 10 dB/ Ref -10 dBm Cal
Trc5 IP3MO dB Mag 10 dB/ Ref -10 dBm Cal
Trc6 NLO dB Mag 10 dB/ Ref -10 dBm Cal int

M1 115.000000 GHz -13.5102 dBm
M2 140.000000 GHz -22.0321 dBm
M3 165.000000 GHz -22.5368 dBm

Ch1 Mix Freq Channel Base Start 110 GHz Pwr -20 dBm Bw 100 Hz Cals ... Stop 170 GHz

IMLO S/A2 Pk dB Mag Cal int Clrw
IMMID S/A2 Pk dB Mag Cal int Clrw
IMHI S/A2 Pk dB Mag Cal int Clrw

Ch2 Spa Arb Channel Base Center 1 GHz
Ch3 Spa Arb Channel Base Center 1 GHz
Ch4 Spa Arb Channel Base Center 1 GHz

Fig. 33: Intermodulation measurement on D-band mixer

5 Ordering information

Designation	Type	Order No.
Vector Network Analyzer	R&S®ZNA<xx>	Refer to data sheet ZNA
Vector Network Analyzer	R&S®ZNB30<xx>	Refer to data sheet ZNB3000
mmwave Converters	R&S®ZC<xxx>	Refer to data sheet ZCxxx

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