RF Measurements Demystified: an Introduction to VNAs & Microwave Lock-in Amplifiers

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Application Engineer Vector Network Analyzer

ROHDE&SCHWARZ

Make ideas real

Agenda

- ► Vector Network Analyzers
  - – Architecture and S-Parameter Basics
  - – Portfolio
  - – Advanced Testset
  - – VNA Live Demo
- ► Lock-in Amplifiers
  - – Introduction to lock-ins
  - – SHFLI Introduction
  - – Focus Applications
  - – SHFLI Live demo
- ► Conclusion

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Typical VNA Applications
Component characterization

Component test at all design stages…
- R&D
- Device characterization
- High-Volume Manufacture/Test

Passive devices

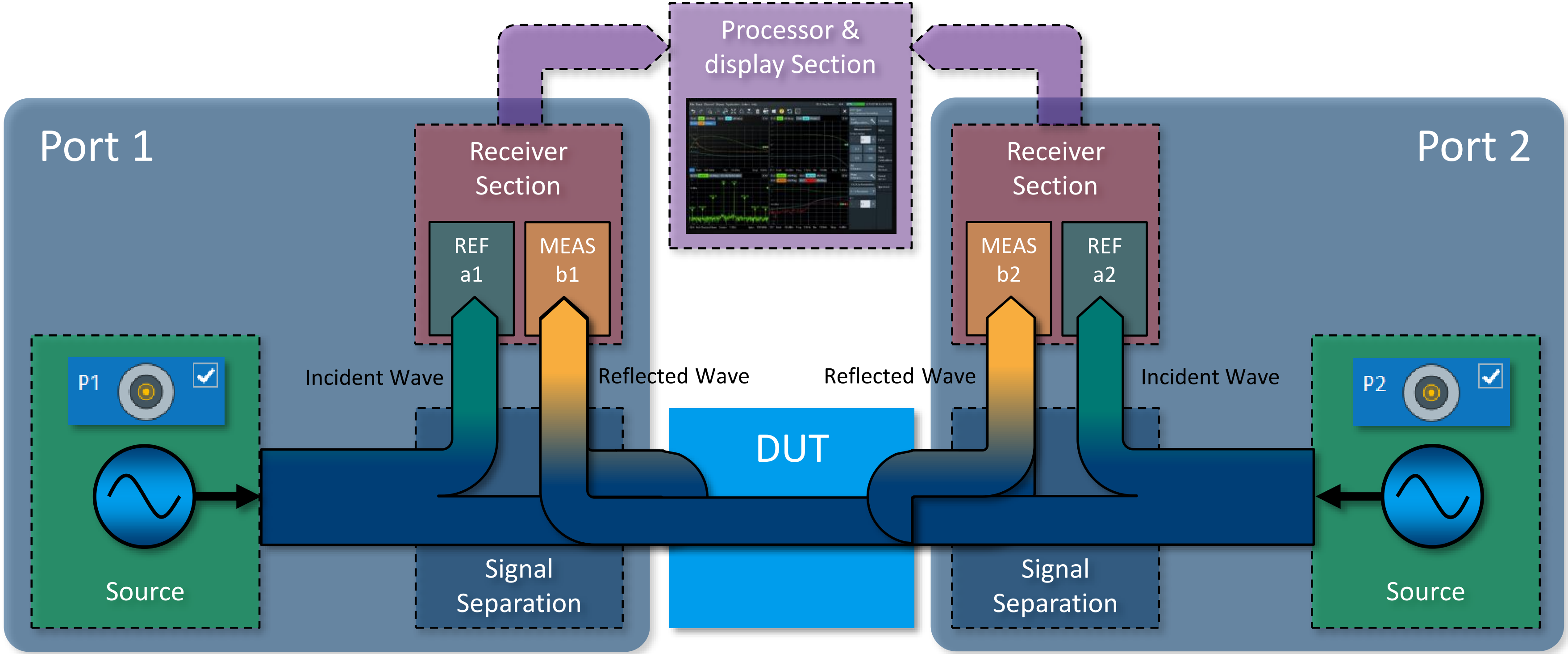
Antennas
Filters
Power combiners, splitters, backplanes, cables, adapters, mixers

Active devices

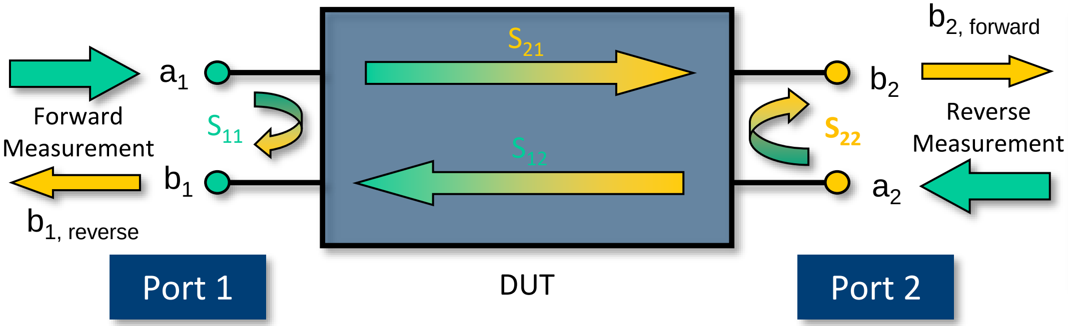
Amplifiers (LNA, PA)
Active Planar Antenna Arrays
Front End Modules (FEM)
Up/Downconverters
Subassemblies

S-Parameter Basics

Realisation of network analyser test set (bi-directional test set)



S-Parameter Basics
Definition of S-parameter matrix



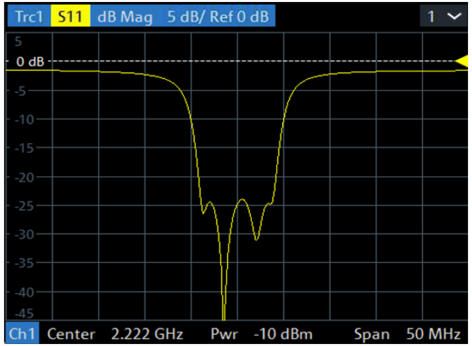
$S_{11} = b_1/a_1 \,|_{a2=0}$ Forward reflection coefficient (input match)

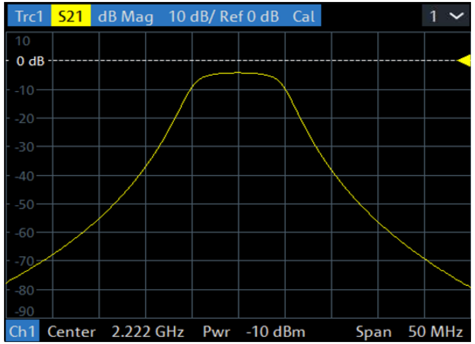
$S_{22} = b_2/a_2 \,|_{a1=0}$ Reverse reflection coefficient (output match)

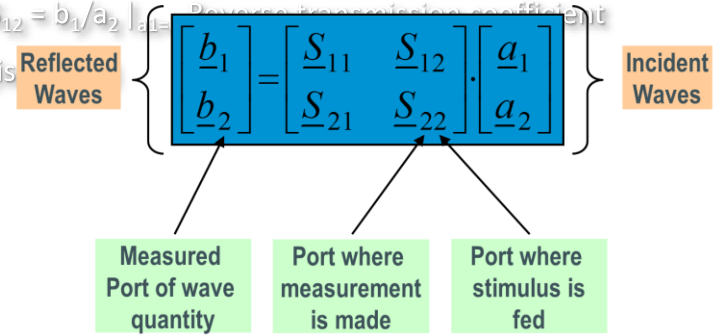
$S_{21} = b_2/a_1 \,|_{a2=0}$ Forward transmission coefficient (gain or loss)

$S_{12} = b_1/a_2 \,|_{a1=}$ Reverse transmission coefficient (is

Example: Filter S-Parameters



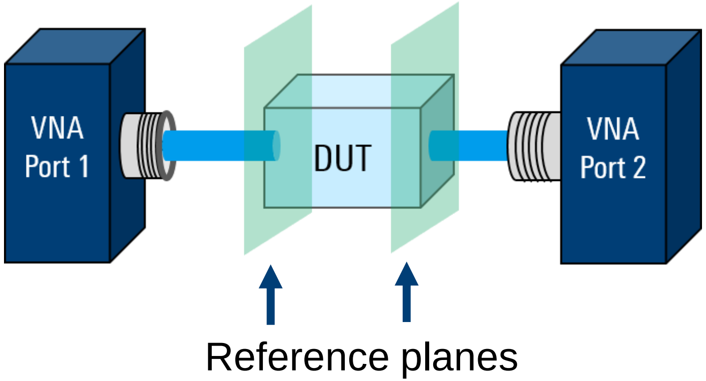




$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

VNA System Error Correction (Calibration)

- ► Correction of systematic errors of the instrument and cables (test set)
- ► Reference plane: the point where the **known** calibration standards are presented, typically coaxial connector
- ► Typically used calibration kits consists of Through, Open, Short and Match standards (TOSM)
- ► Also automatic calibration units available
- ► To further shift the reference plane use fixture modelling and Deembedding



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R&S VNA Evolution Since 1950…

1950s
Z-g-Diagraph (ZDU/ZDD)

1970s
ZPV

1980s
SWOB/ZAS/ZAM/ZWOB

2000s
R/ZVT/ZVL/ZVH

75 years of
Innovation

2010s
ZNA/ZNB/ZND/ZN
ZNL

2025
ZNB3000

R&S VNA Portfolio and General Features

ZNL (entry level)
- 2 Port
- Up to 20 GHz
- S-Parameter
- Power sweep @CW

ZNB (Midrange)
- 2 and 4 Port
- Up to 54 GHz
- S-Parameter
- Power sweep @CW
- Frequency conversion meas.

ZNA (High End)
- 2 and 4 Port
- Up to 67 GHz (1.2 THz)
- S-Parameter
- Power sweep @CW
- Frequency conversion meas.
- Advanced Testset

Multiport Measurements

- Switch matrix solutions
  - Frequency range up to 26.5 GHz
  - Supports full crossbar measurements up to 48 Ports
  - Easy setup with ZNB and ZNA
  - Alternatively RF relay based solutions up to 67 GHz

- ZNBT true Multiport VNA
  - Frequency range up to 40 GHz
  - Up to 24 ports (parallel measurements possible)
  - Faster and higher accuracy measurements

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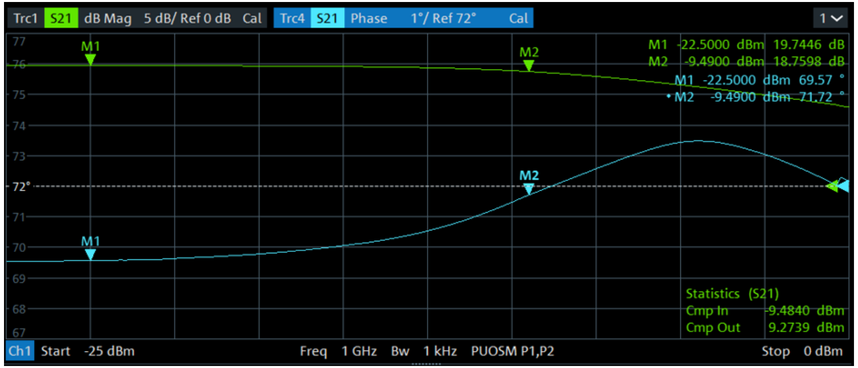
Advanced VNA Measurements

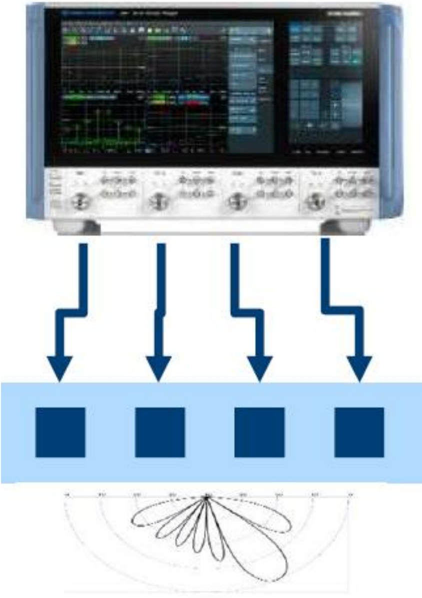


- ▶ Power sweep
  - – Use CW frequency signal and ramp up / down power
  - – Power Sensor used for calibration of absolute power level
  - – show components characteristics depending on applied power level, e.g. compression of amplifiers

- ▶ Frequency conversion measurements
  - – Measure characteristics of device under test with different input and output frequencies
  - – Example: RF mixer conversion loss test

- ▶ Measure simultanuously at different frequencies
  - – Utilize optional second two internal LO

Advanced VNA measurements

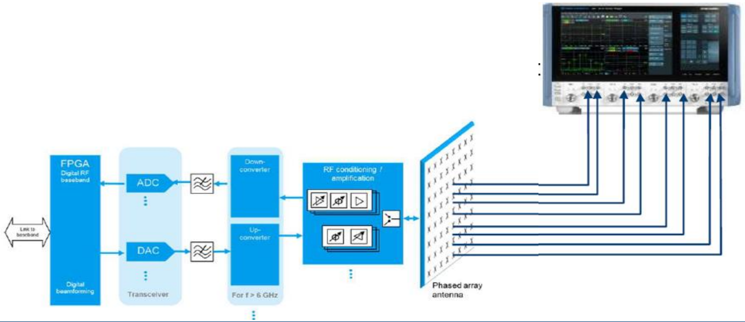


- ► Four independant phase coherent sources
  - – Example: phased array antenna measurements

☑ Source Coherence On ☑ Use Port Match and Calibration

	#	Def'd Phase Coherence	Phase Start	Phase Span	Gen	Channel Base Power	Port Power Offset	Power Result
1	Port 1	☑	0°	0°	☐	Pb(-80 d...	0 dB	-100 dBm
2	Port 2	☐	180°	0°	☐	Pb(-80 d...	10 dB	-70 dBm
3	Port 3	☐	0°	0°	☐	Pb(-80 d...	20 dB	-60 dBm
4	Port 4	☐	90°	0°	☐	Pb(-80 d...	0 dB	-80 dBm

- ► Using eight parallel receivers
  - – Direct receiver Access



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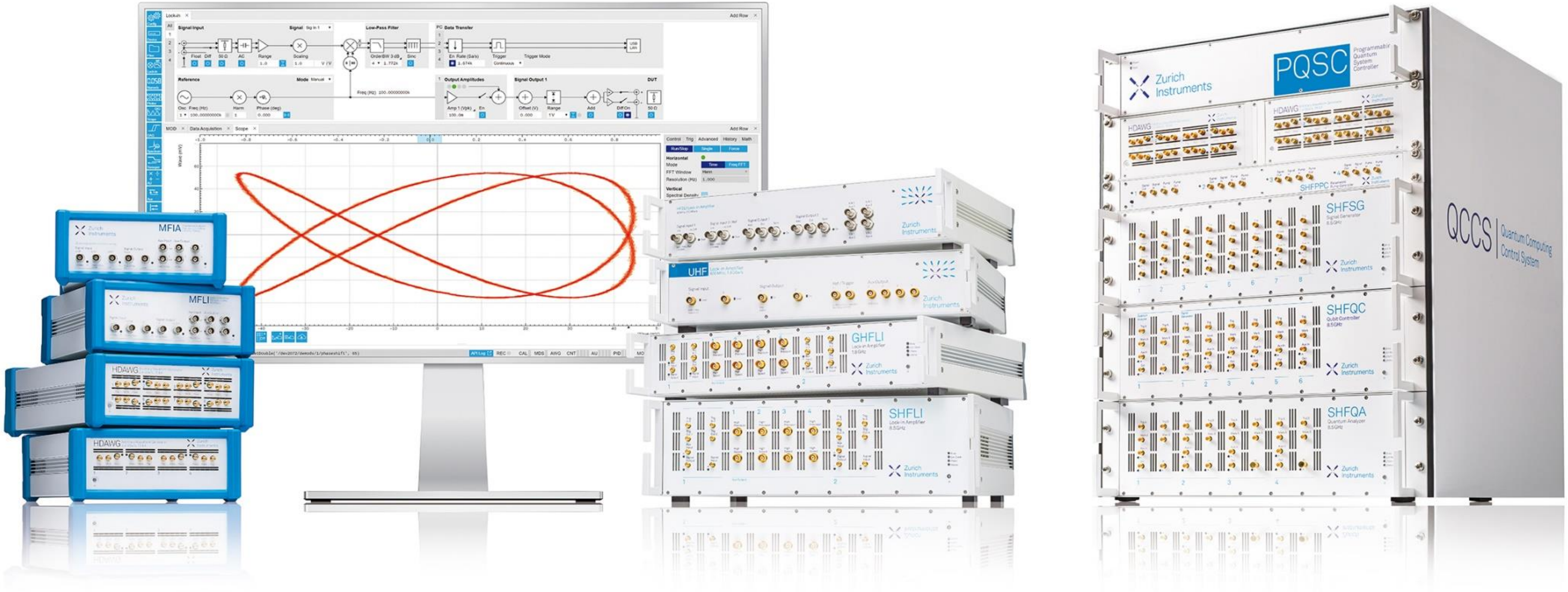
Zurich Instruments AG

An R&S Subsidiary since 2021



Lock-in Amplifiers Fundamentals

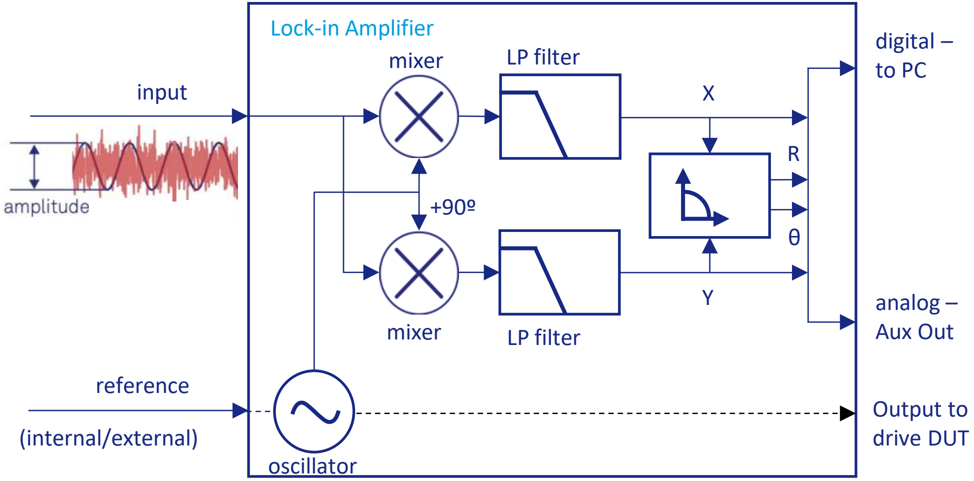
Benefits of using lock-in amplifiers

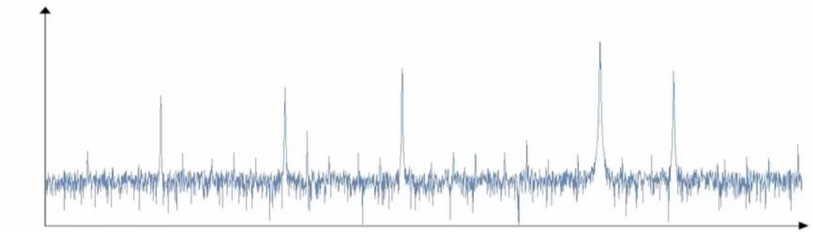
- Recover small periodic signals in noisy backgrounds
- Fast & precise measurements, select bandwidth to optimise precision
- Multiple frequencies can be measured simultaneously and continuously
- Sync measurement to internal or external reference for phase coherence
- Measured signal can be used to create on-instrument feedback loops
- Sideband analysis and FM/AM Modulation
- Arbitrary waveform generators for pulsed measurements

Lock-in Amplifiers Fundamentals

Precisely Measure Amplitude and Phase of your Periodic Signal Buried in Noise

- Input signal is mixed with reference signal and a 90° phase-shifted copy
- Can use external or internal reference
- Mixing result undergoes low-pass filter stage to isolate signal from noise
- Amplitude and Phase (R & θ) or In-phase and Quadrature component (I & Q, or X & Y)
- Can be streamed to PC, output as analog voltage or used on the instrument for control
- Transfer function similiar to band-pass filter
- Lock-in amplifiers provide fast, precise and multi-frequency measurements



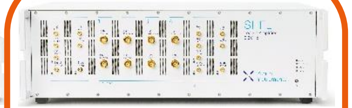


Zurich Instruments Lock-in Amplifier Portfolio

From DC to 8.5 GHz







	MFLI	HF2LI	UHFLI	GHFLI	SHFLI
Frequency range	500 kHz/ 5 MHz	50 MHz	600 MHz	1.8 GHz	8.5 GHz
# Osc, Demods	4	6	8	8	8
Input noise	2.5 nV/√Hz	5 nV/√Hz	4 nV/√Hz	<3.5 nV/√Hz	<3.5 nV/√Hz
Min time const.	337 ns	1 µs	30 ns	14 ns	14 ns

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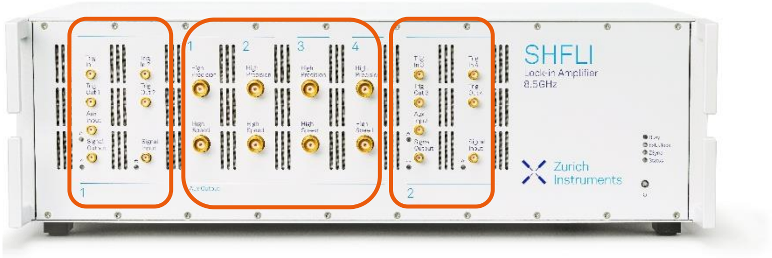
SHFLI Lock-in Amplifier - DC to 8.5 GHz

- Highlights
  - 8 demodulators and up to 8 oscillators
  - 2 Independent input/output channels
  - 4 high-speed & 4 high-precision aux outputs
  - 3.5 nV/√Hz input noise, 14 ns time constant
  - LabOne® control software and toolset

- Key applications
  - Sensors: MEMS, NEMS, SAW devices, BAW devices, quantum sensing
  - Cavity optomechanics, optical PLLs
  - RF-reflectometry, qubit readout
  - Microwave microscopy



Upgrade options:

MultiFreq — Multifrequency

PID/PLL — PID Controllers

MOD — Sideband analysis

AWG — Arbitrary waveform generator

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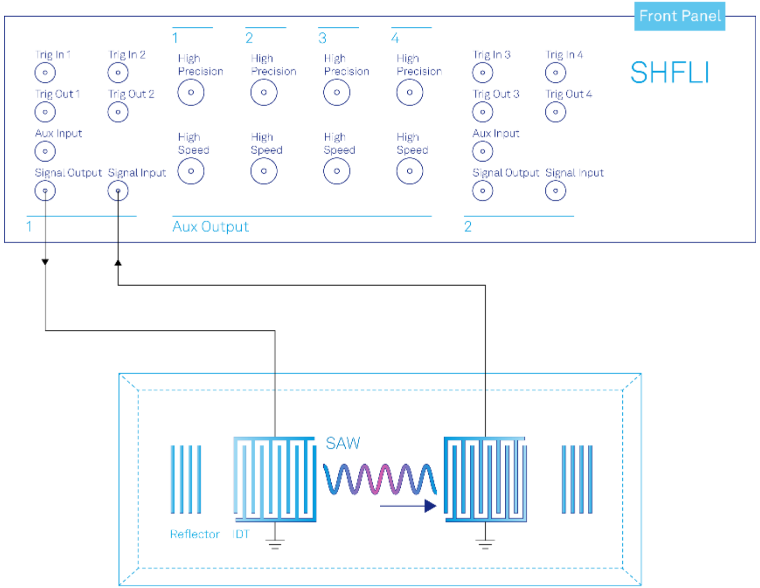
SHFLI Applications – Surface Acoustic Wave Resonators

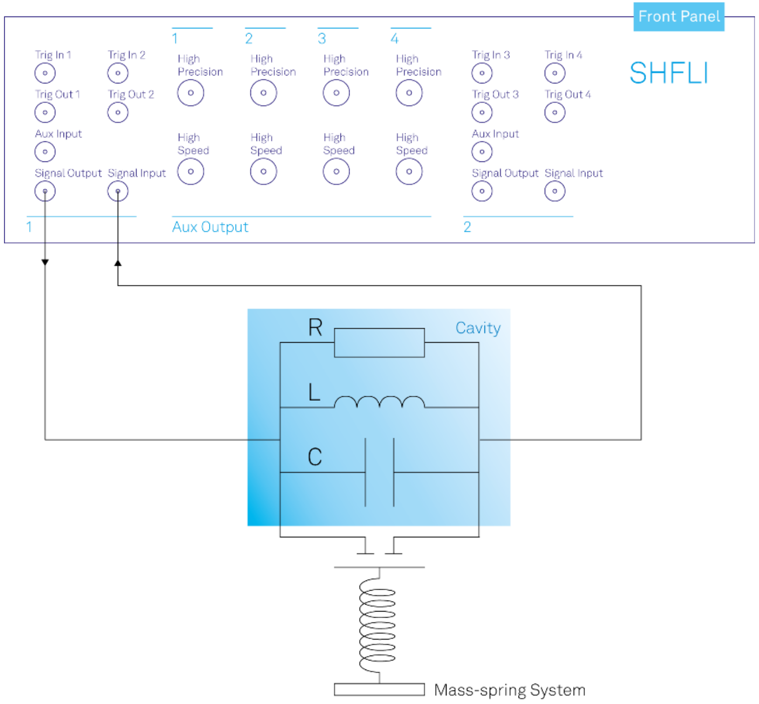
- SAW Resonators overview
  - Resonators used in sensing
  - Stable & compact; portable devices, sensing
  - Surface wave on piezoelectric substrate
  - Resonant cavity formed between reflectors

- Characterization with the SHFLI
  - Measure resonant peak precisely
  - Multiple-frequency (up to 8) schemes are easy
  - 4 PID controllers for stabilization
    - DFRT, Pound-Drever-Hall schemes
  - Measure sidebands in FM/AM mode
  - AWG for pulsed measurements



SHFLI Applications – Cavity Optomechanics

- Cavity Optomechanics overview
  - Explores interaction between phonons & photons
  - Field confined in cavity interacts with mechanical oscillator at quantum level
  - Creates sidebands encoding info about system
  - Application includes quantum science & quantum sensing



- Characterization with the SHFLI
  - Detect faint variations in mechanical system
  - Measure sidebands to reveal info on displacement, quantum states, thermal state
  - Set up feedback loops to stabilize, improve SNR
  - Time-trace measurements for ringdown

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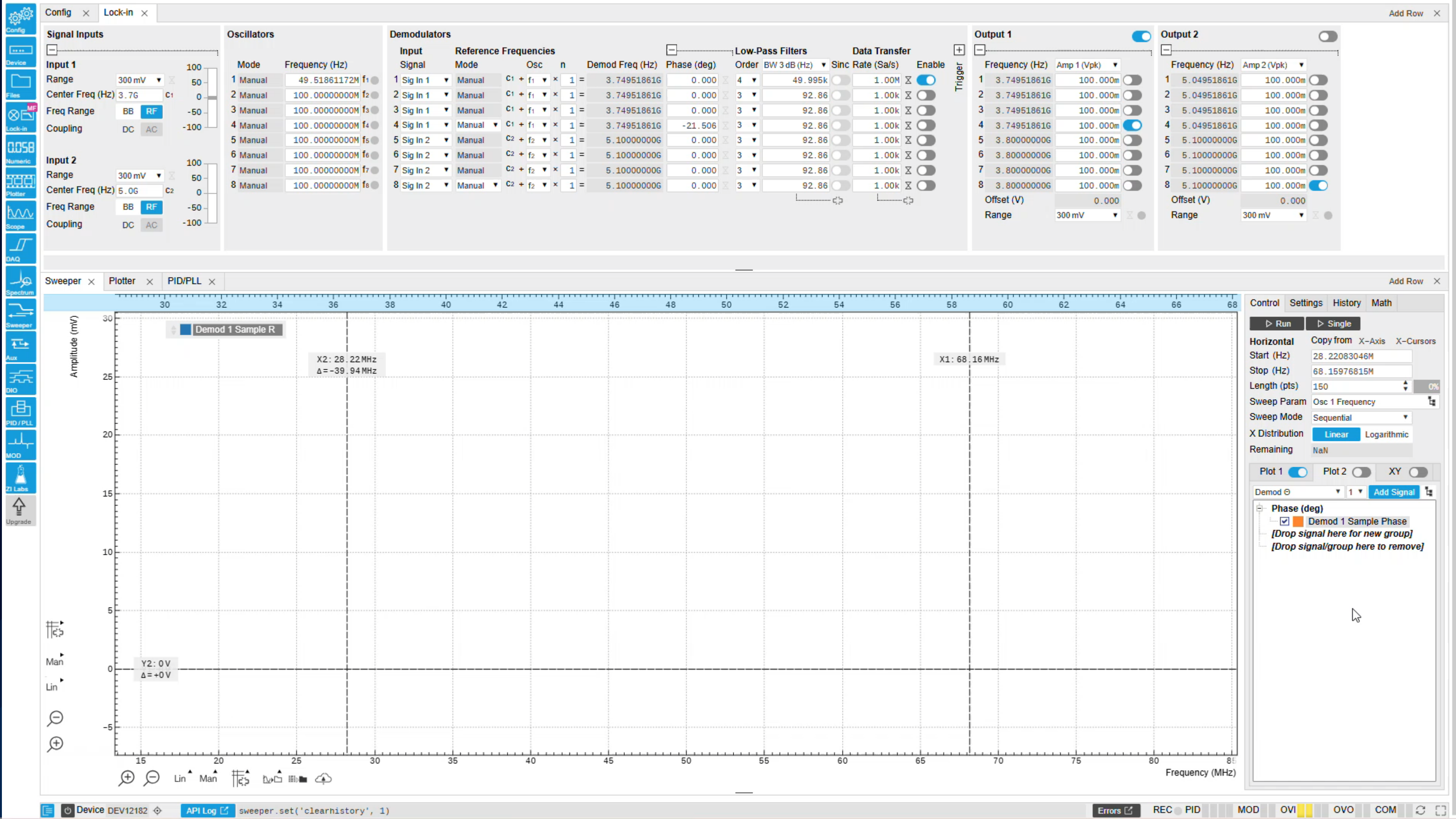
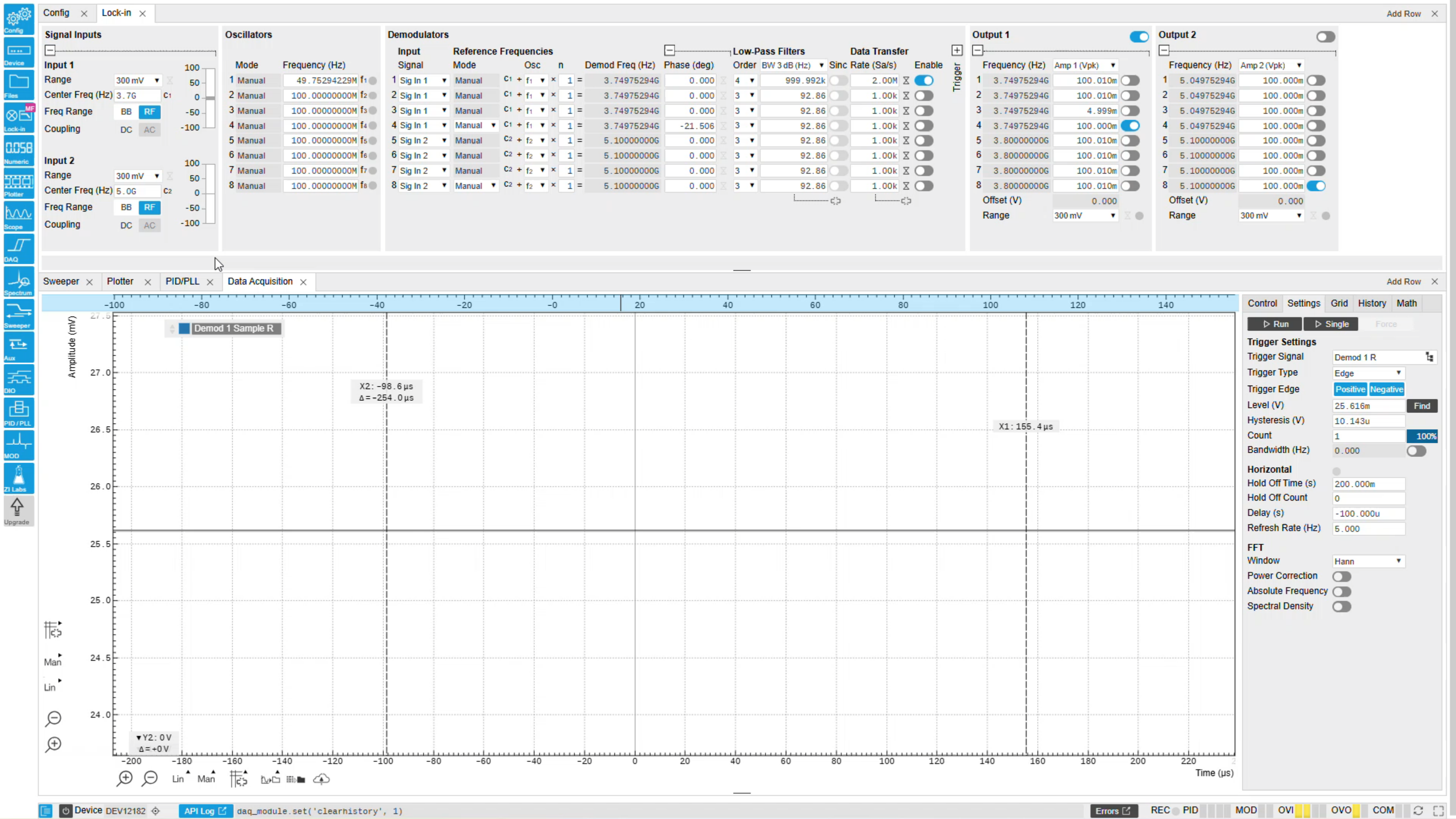


Config
Lock-in
Add Row
Signal Inputs
Input 1
Range 300 mV
Center Freq (Hz) 3.7G
Freq Range BB RF
Coupling DC AC
Input 2
Range 300 mV
Center Freq (Hz) 5.0G
Freq Range BB RF
Coupling DC AC
Oscillators
Mode Frequency (Hz)
1 Manual 49.51861172M
2 Manual 100.00000000M
3 Manual 100.00000000M
4 Manual 100.00000000M
5 Manual 100.00000000M
6 Manual 100.00000000M
7 Manual 100.00000000M
8 Manual 100.00000000M
Demodulators
Input Signal
Reference Frequencies
Mode Osc n Demod Freq (Hz) Phase (deg)
Low-Pass Filters
Order BW 3 dB (Hz)
Data Transfer
Sinc Rate (Sa/s) Enable
Trigger
1 Sig In 1 Manual 3.749518616G 0.000 4 49.995k 1.00M
2 Sig In 1 Manual 3.749518616G 0.000 3 92.86 1.00k
3 Sig In 1 Manual 3.749518616G 0.000 3 92.86 1.00k
4 Sig In 1 Manual 3.749518616G -21.506 3 92.86 1.00k
5 Sig In 2 Manual 5.100000000G 0.000 3 92.86 1.00k
6 Sig In 2 Manual 5.100000000G 0.000 3 92.86 1.00k
7 Sig In 2 Manual 5.100000000G 0.000 3 92.86 1.00k
8 Sig In 2 Manual 5.100000000G 0.000 3 92.86 1.00k
Output 1
Frequency (Hz) Amp 1 (Vpk)
1 3.749518616G 100.000m
2 3.749518616G 100.000m
3 3.749518616G 100.000m
4 3.749518616G 100.000m
5 3.800000000G 100.000m
6 3.800000000G 100.000m
7 3.800000000G 100.000m
8 3.800000000G 100.000m
Offset (V) 0.000
Range 300 mV
Output 2
Frequency (Hz) Amp 2 (Vpk)
1 5.049518616G 100.000m
2 5.049518616G 100.000m
3 5.049518616G 100.000m
4 5.049518616G 100.000m
5 5.100000000G 100.000m
6 5.100000000G 100.000m
7 5.100000000G 100.000m
8 5.100000000G 100.000m
Offset (V) 0.000
Range 300 mV
Sweeper
Plotter
PID/PLL
Demod 1 Sample R
X2: 28.22 MHz
Δ=-39.94 MHz
X1: 68.16 MHz
Y2: 0 V
Δ=+0 V
Amplitude (mV)
Frequency (MHz)
Control Settings History Math
Run Single
Horizontal Copy from X-Axis X-Cursors
Start (Hz) 28.22083046M
Stop (Hz) 68.15976815M
Length (pts) 150
Sweep Param Osc 1 Frequency
Sweep Mode Sequential
X Distribution Linear Logarithmic
Remaining NaN
Plot 1 Plot 2 XY
Add Signal
Phase (deg)
Demod 1 Sample Phase
[Drop signal here for new group]
[Drop signal/group here to remove]
Device DEV12182
API Log
sweeper.set('clearhistory', 1)
Errors REC PID MOD OVI OVO COM


Config
Lock-in
Add Row
Signal Inputs
Input 1
Range
Center Freq (Hz)
Freq Range
Coupling
Input 2
Oscillators
Mode
Frequency (Hz)
Demodulators
Input Signal
Reference Frequencies
Low-Pass Filters
Data Transfer
Order
BW 3 dB (Hz)
Sinc
Rate (Sa/s)
Enable
Trigger
Demod Freq (Hz)
Phase (deg)
Output 1
Output 2
Amp 1 (Vpk)
Amp 2 (Vpk)
Offset (V)
Range
Sweeper
Plotter
PID/PLL
Data Acquisition
Demod 1 Sample R
Amplitude (mV)
X2: -98.6 µs
Δ = -254.0 µs
X1: 155.4 µs
Y2: 0 V
Δ = +0 V
Time (µs)
Control
Settings
Grid
History
Math
Run
Single
Force
Trigger Settings
Trigger Signal
Demod 1 R
Trigger Type
Edge
Trigger Edge
Positive
Negative
Level (V)
25.616m
Find
Hysteresis (V)
10.143u
Count
1
100%
Bandwidth (Hz)
0.000
Horizontal
Hold Off Time (s)
200.000m
Hold Off Count
0
Delay (s)
-100.000u
Refresh Rate (Hz)
5.000
FFT
Window
Hann
Power Correction
Absolute Frequency
Spectral Density
Device DEV12182
API Log
daq_module.set('clearhistory', 1)
Errors
REC
PID
MOD
OVI
OVO
COM

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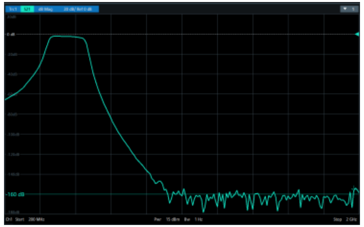
Summary Microwave Lock-in Amplifiers

- Fast measurements of small signals with high noise rejection
- Multiple-frequency operation at 8 frequencies, each with independent parameters
- On-instrument feedback loops provide stability and allow for detuning measurements
- sideband modulation allow for advanced feedback mechanisms

- Applications
  - MEMS, NEMS, SAW devices, BAW devices, quantum sensing
  - Cavity optomechanics, optical PLLs
  - RF-reflectometry, qubit readout
  - Microwave microscopy

Summary Vector Network Analyzers

- Main Task: reflection and transmission characterisation of RF components
  - Passive, like antennas, filters, cables
  - Or active like amplifiers and frequency converting components like mixers
- Calibration in terms of S-parameter and absolute power



- Key specs of VNAs are:
  - Output power of up to 20 dBm
  - Dynamic range of around 150 dB, with special settings up to 170 dB
- Special software and hardware features
  - Individual control over up to five phase coherent sources
  - Direct access to all eight receivers to measure simultaneously at same frequency
  - Measure several signals simultaneously at different frequencies

Summary Comparative Benefits

- ► Microwave Lock-in amplifiers
  - – Fast measurements of small signals with high noise rejection
  - – Measure detuning on resonances of sensors, cavities, resonators
  - – On-instrument feedback loops

- ► Vector Network Analyzers
  - – Calibrated S-parameter reflection and transmission measurements of active and passive devices, including absolute power levels
  - – Flexible and versatile testset with direct access to multiple sources and receivers

Find out more

www.rohde-schwarz.com
[R&S Vector Network Analyzer Website]()

Zurich Instruments AG
www.zhinst.com/products/shfli-lock-in-amplifier

Thank you!

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