Presenter:
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Load Pull Fundamentals

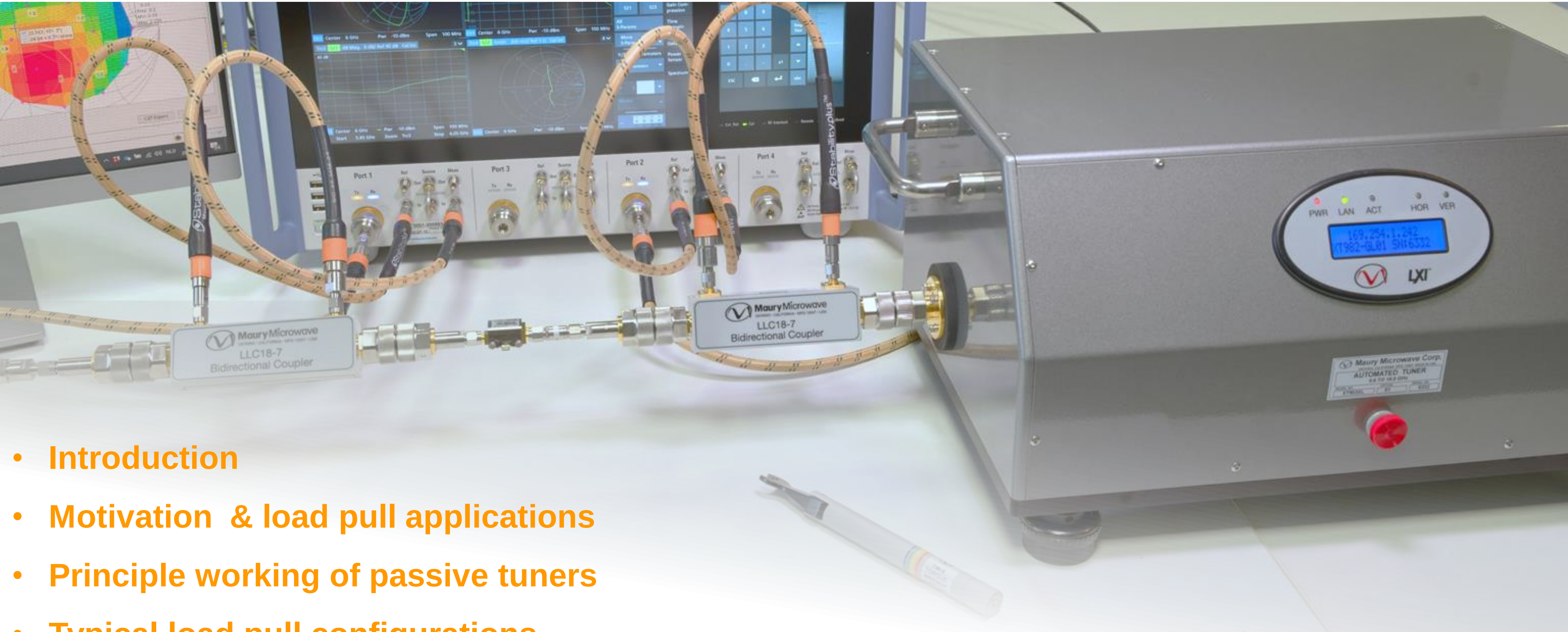
HITECH
RF & Microwave solutions

Maury Microwave
Your Calibration, Measurement & Modeling Solutions Partner!

AMCAD Engineering
Advanced Modeling for Computer-Aided Design

https://hitechbv.nl/
https://www.maurymw.com/
https://www.amcad-engineering.com/

Agenda



- Introduction
- Motivation & load pull applications
- Principle working of passive tuners
- Typical load pull configurations.

HITECH

European Premier partner of:

Maury Microwave

Your Calibration, Measurement & Modeling Solutions Partner!

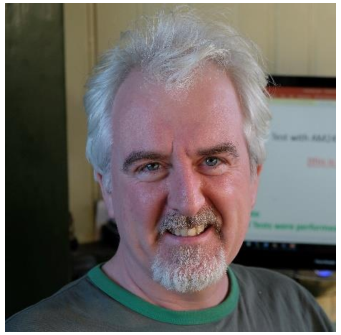
Based in Ontario, California USA Maury offers turnkey characterization solutions including measurement and modeling software, impedance tuners, load pull, T&M amplifiers and noise parameter systems.

AMCAD Engineering

Advanced Modeling for Computer-Aided Design

Based in Limoges, France Amcad engineering is an innovative company , specialized in the development of software and hardware solutions for testing, modeling and simulating radiofrequency electronic circuits.

Your Device Characterisation Team



JIM CREED
Application Engineer

KAMAL MUSTAFA
Application Engineer

RANNY HASSOON
Application Engineer

CHRIS CAENEN
Account Manager

DIRK FABER
Business Development

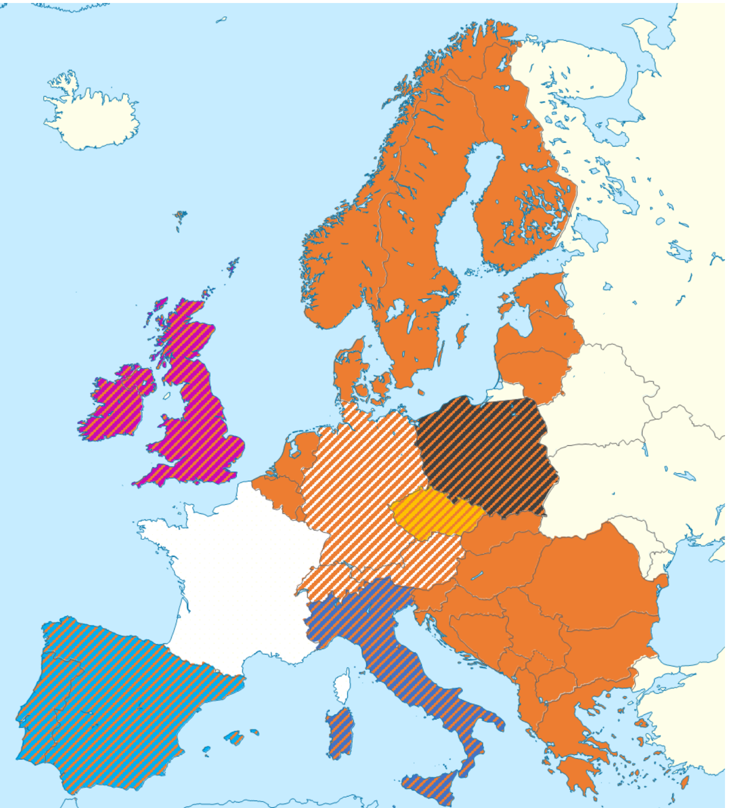
OLIVER KANZLER
Technical Sales

- Quality matters: we are ISO9001:2015 certified.
- Together with out customers and partners we provide the best “Device Characterization” solutions for the job.
- We believe in innovation and technology; we are looking for partnerships to ensure customers success. Not only now, but also in the long term.
- Hitech’s team delivers consultancy and training for RF design, measurements and simulations.

HITECH
RF & Microwave solutions

Territory coverage and responsibillity

We are responsible for sales, support, installation and training activities for Maury Microwave through whole Europe, <u>except France</u>. Together with our partners in major regions we provide best solutions in terms of *<u>Precision Calibration and Device Characterization.</u>*



Sales responsibillity and first contact:

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MRC GIGACOMP – specialists in RF
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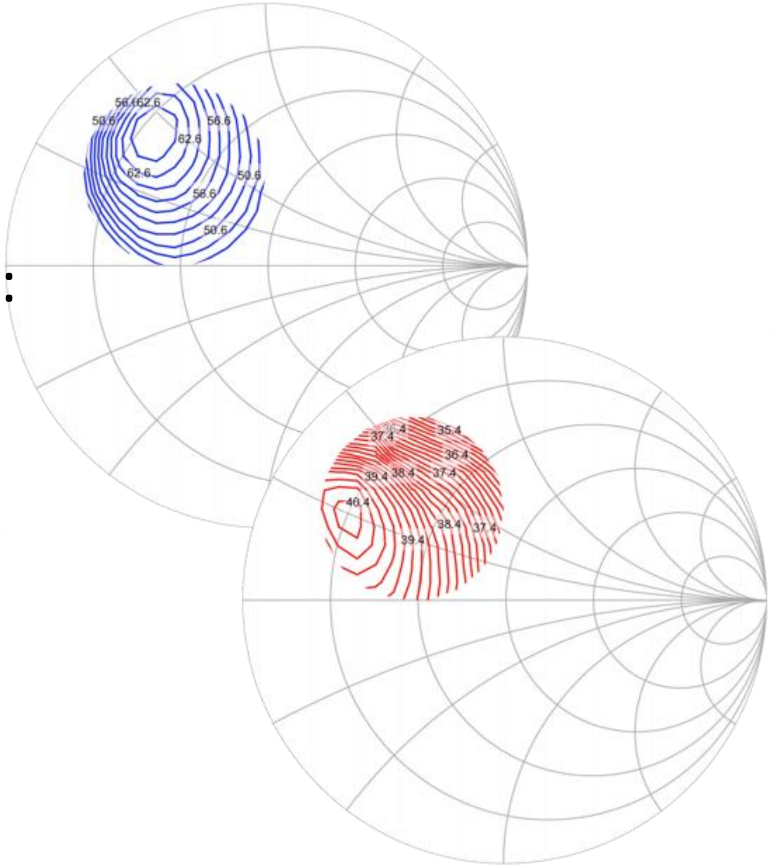
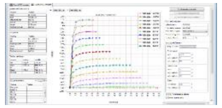
Motivation for load pull measurements

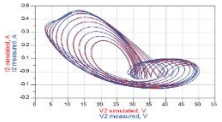
- S-parameters provide information about linear response of the device under test (DUT)
- RF/Microwave transistors exhibit non-linear behavior:
  - harmonic generation
  - frequency mixing, etc.
- Transistor performance is highly dependent on its load impedance
- Load-pull enables characterisation of the non-linear DUT behaviour under large-signal excitations and non-50 Ω load impedances



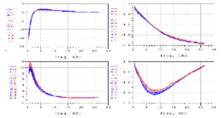
Loadpull applications



- **Transistor characterization**
  - Unmatched devices in 99% of all cases measured on wafer

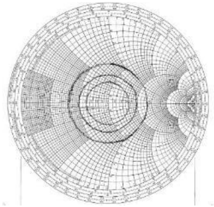


- **Model validation / extraction**
  - Extract compact or behavior models for simulation software



- **Matching network design**
  - Circuit design to optimize power transfer to reduce energy loss

- **Performance test**
  - E.g. Power amplifiers to test with different loads



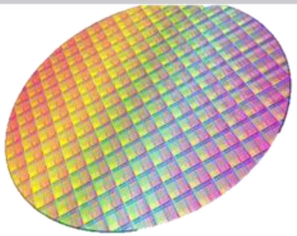
- **Reliability test**
  - E.g. Radio transceivers for basestations, Power amplifiers, rf-circuitry

Component level

Circuit level

System level

Component level

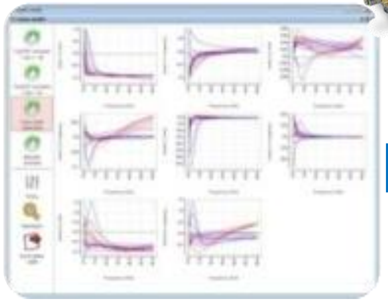


5 Steps for characterizing components

Step1

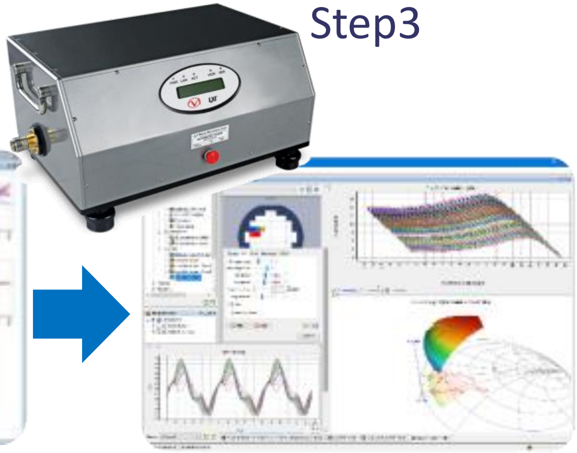
Pulsed IV & S-parameter test, bench control

Step2



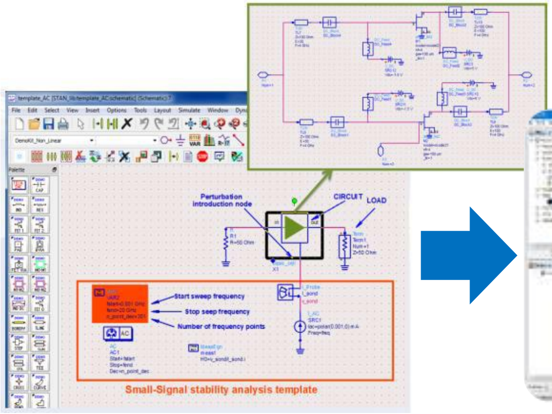
Transistor model extraction based on pulsed IV data

Step3



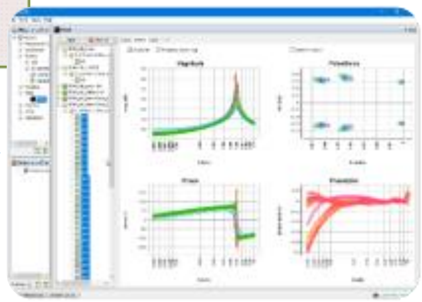
Load pull bench control - transistor model validation

Step4



Circuit Design using AMCAD models in 3rd party circuit simulator

Step5



IC Stability analysis

- **AM3200 PIV (up to 1500V pulsed drain voltage)**
- **IVCAD Software**
- **Accessories & Interconnect**

- **Tuners**
- **IVCAD Software**
- **Amplifiers**
- **Accessories & Interconnect**

- **IVCAD Software**

https://www.maurymw.com/MW_RF/IVCAD_Advanced_Measurement_Modeling_Software.php

Circuit level and systems

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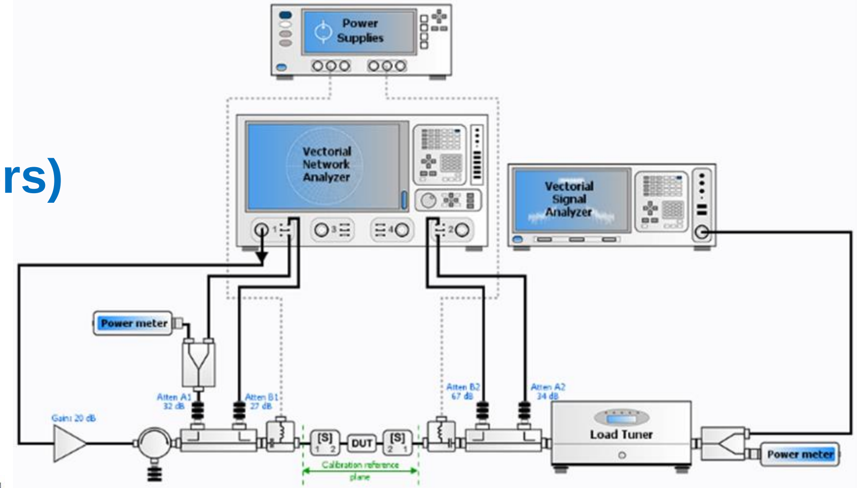
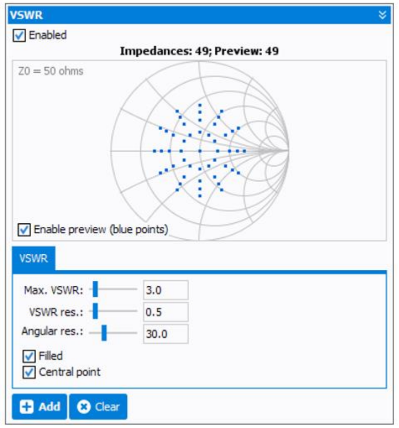
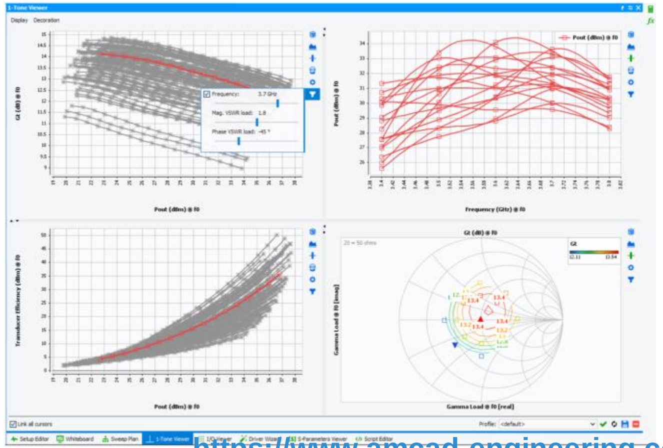
- Constant VSWR testing **(Tuners)**
- S-Parameters (Pulsed and CW)
- 1-Tone (Pulsed and CW) **(Tuners)**
- 2-tone signals (Pulsed and CW) **(Tuners)**
- Fast Spurious Detection **(Tuners)**
- Modulated signal
- DPD evaluation







https://www.amcad-engineering.com/software/iqstar/

System level

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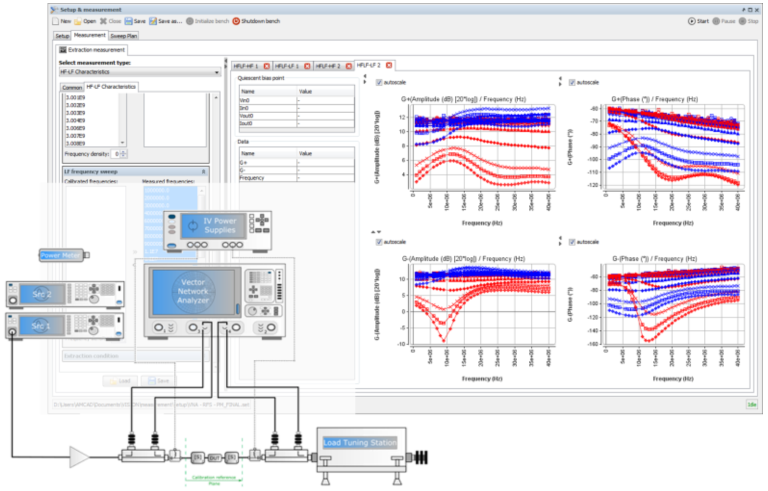
For extracting different types of behavioral models for system simulation , we need:

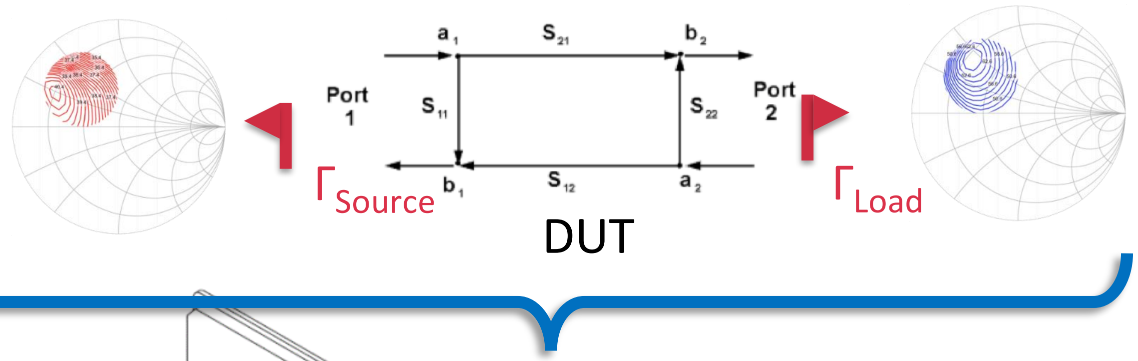
- 1-Tone measurements for in-band frequency memory effect
- 3-Tone measurements for High & Low frequency effects
- **Load Pull tuner** control for bilateral models
- Circuit and system validation measurement using standard hardware
- Validation on multiple signals: 2-Tones; Pulsed; LTE; 256 QAM; File based
- Feedback to circuit and system modeler for model tuning
- Possibility to optimize circuit models based on system measurement results



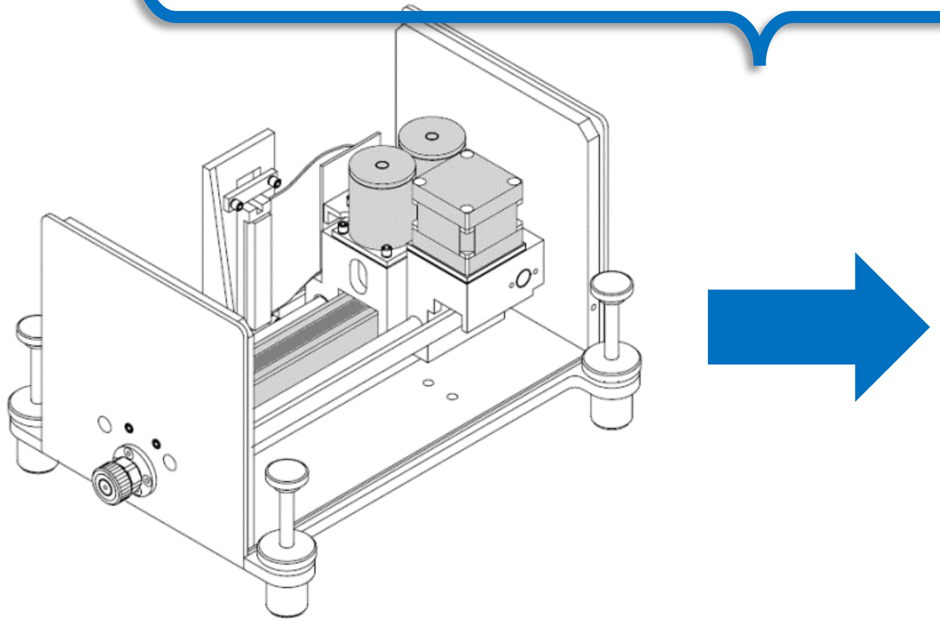
https://www.amcad-engineering.com/software/vision/

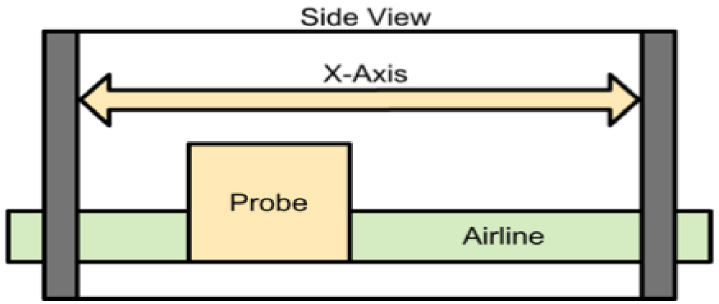
Passive Impedance Tuners

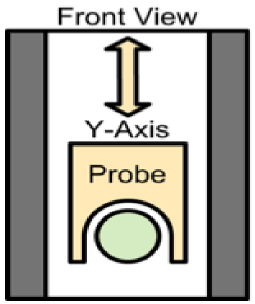
A passive tuner consists of a precision 50Ohm slabline consisting of two parallel plates and a center conductor, and a metallic probe. Depending on the probe's position in relation to the DUT, part of the signal is reflected back towards the DUT, and the magnitude of reflection (or gamma, or VSWR) increases.



$$\Gamma_{Load,n}(f_n) = \frac{a_{2,n}(f_n)}{b_{2,n}(f_n)}$$



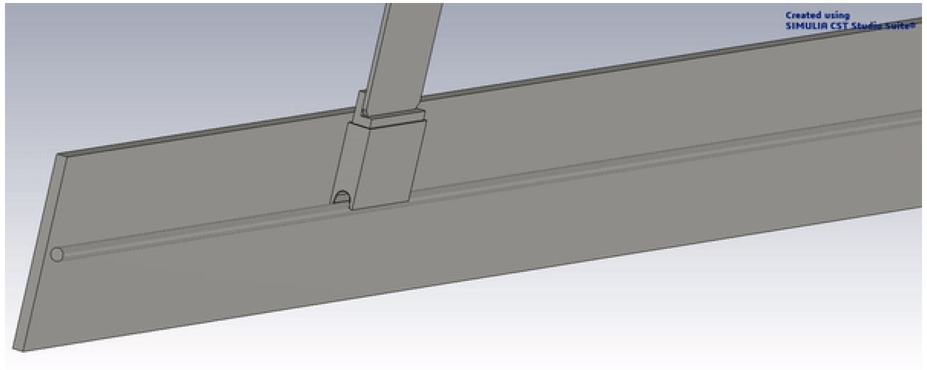


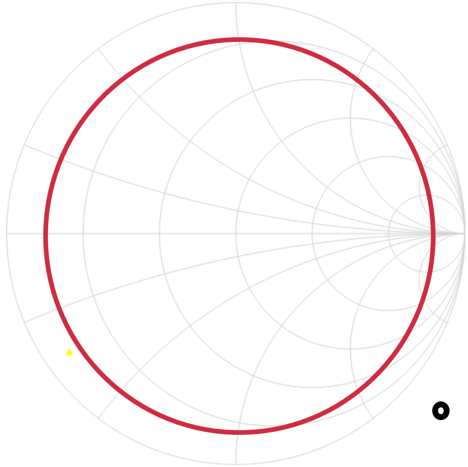


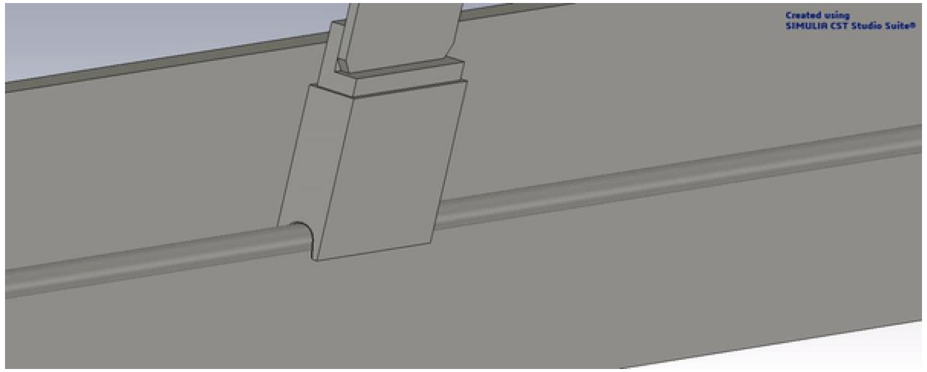
Passive Impedance Tuners

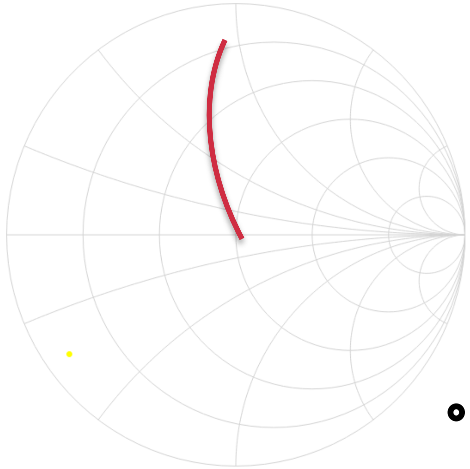
- Probe movement above airline controls the reflection coefficient (Γ)
- Movement on X-axis controls phase of Γ
- Movement on Y-axis controls magnitude of Γ

$$\Gamma_{Load,n}(f_n) = \frac{a_{2,n}(f_n)}{b_{2,n}(f_n)}$$





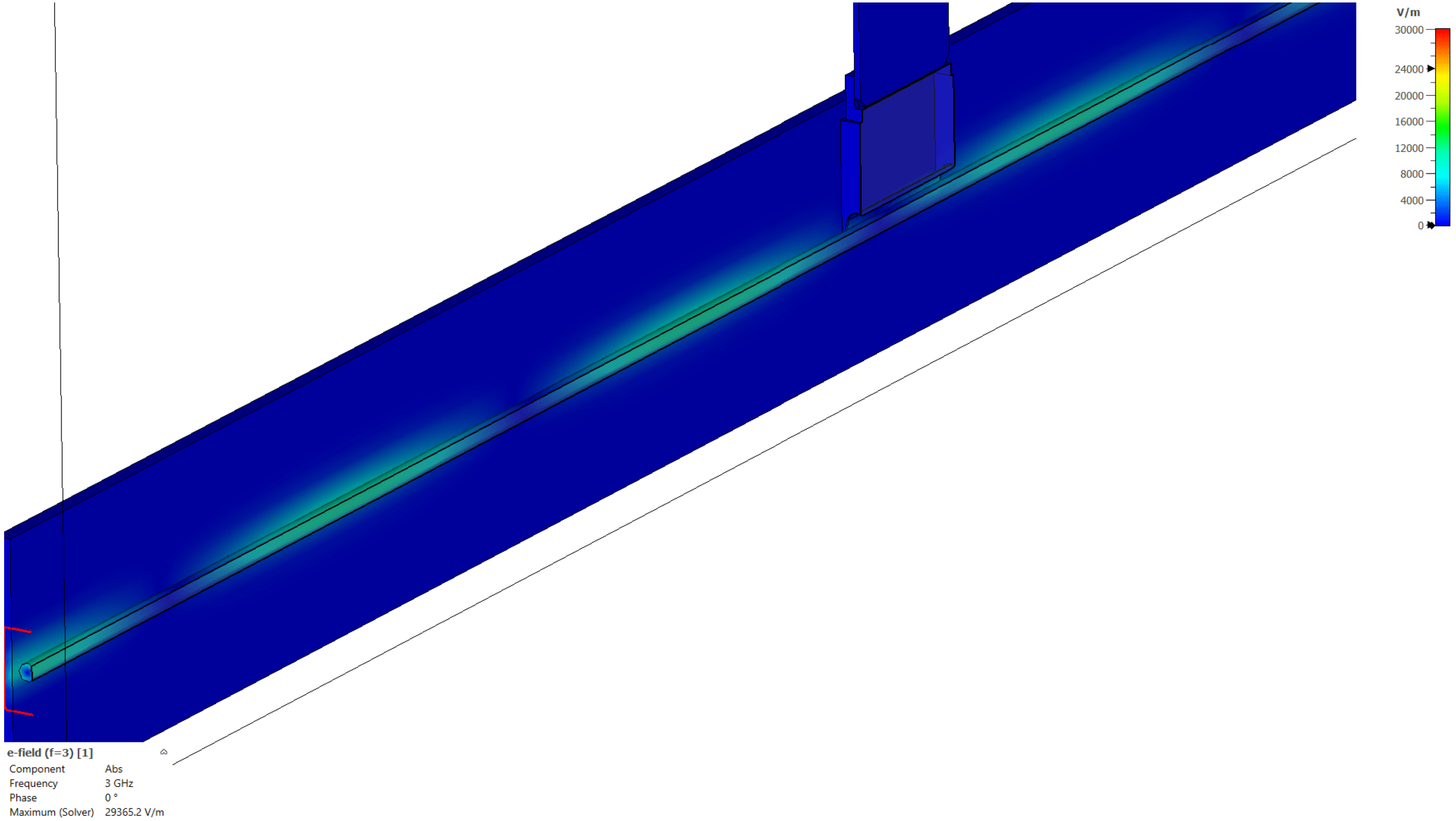




Passive Impedance Tuners

Probes full retracted:

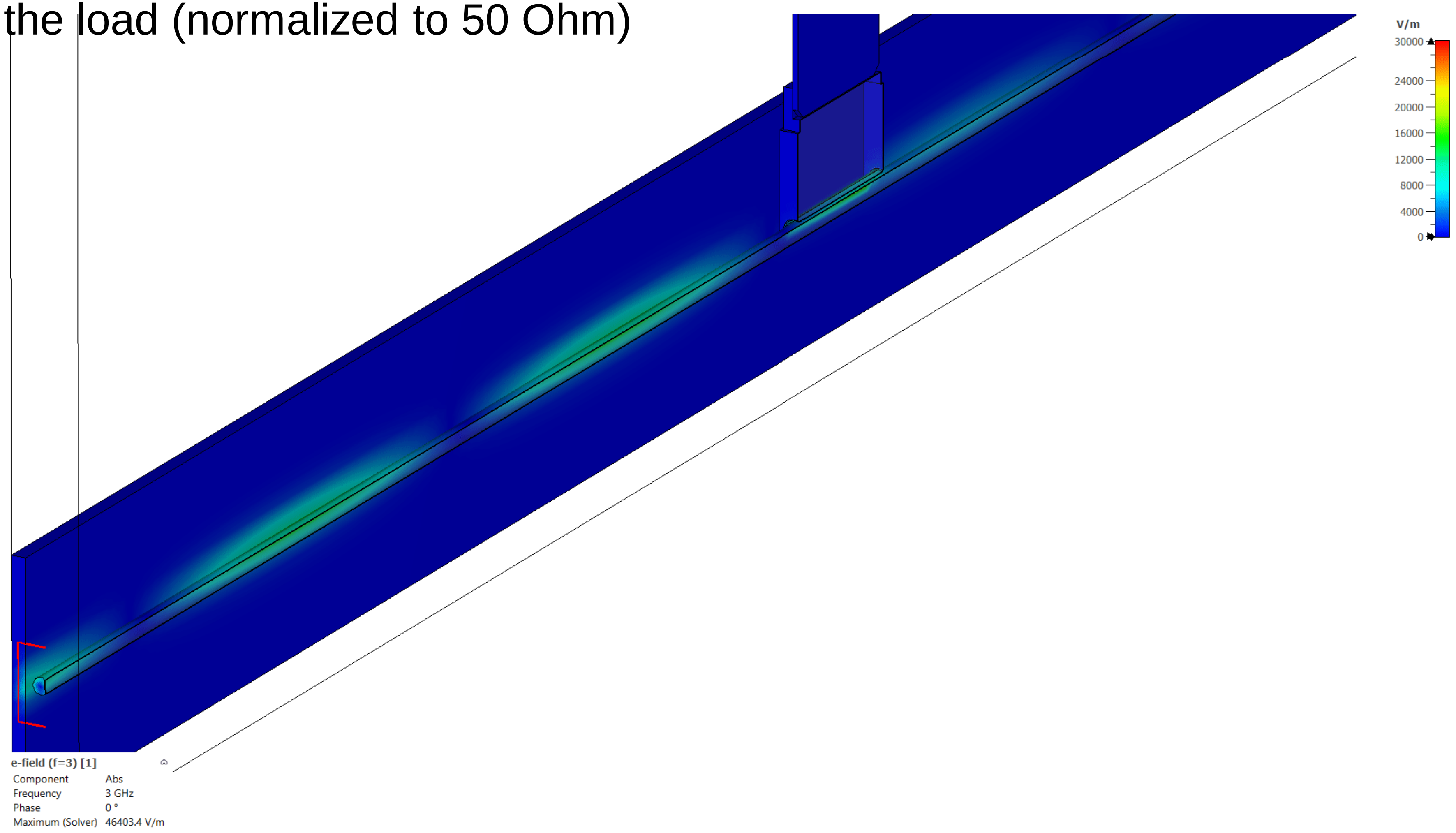
Tuner acts like a transmission line, probe has no influence on electromagnetic field



Passive Impedance Tuners

Probes moving towards airline:

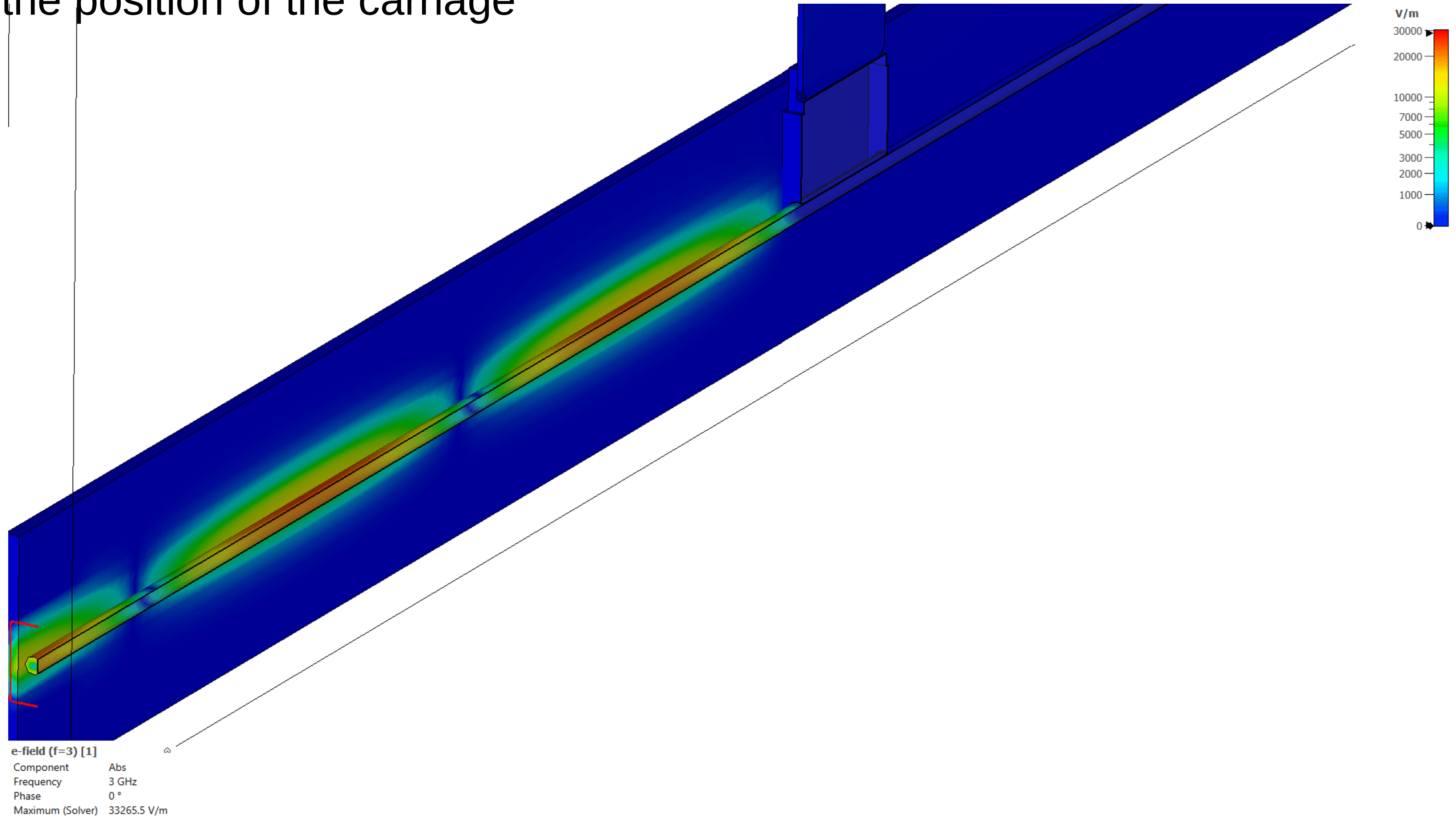
Electromagnetic energy is being reflected causing a mismatch presented to the load (normalized to 50 Ohm)



Passive Impedance Tuners

Probes down to airline:

All electromagnetic energy is reflected, tuner acts like a open / short depending on the position of the carriage



Types of passive Impedance Tuners

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Stub tuners

basic laboratory tools used for matching load impedances to provide for maximum power transfer between a generator and a load. Typical applications include:

- power and attenuation measurements,
- tuned reflectometer systems
- providing a DC return for single-ended mixers and detectors.

Manual Impedance Tuners

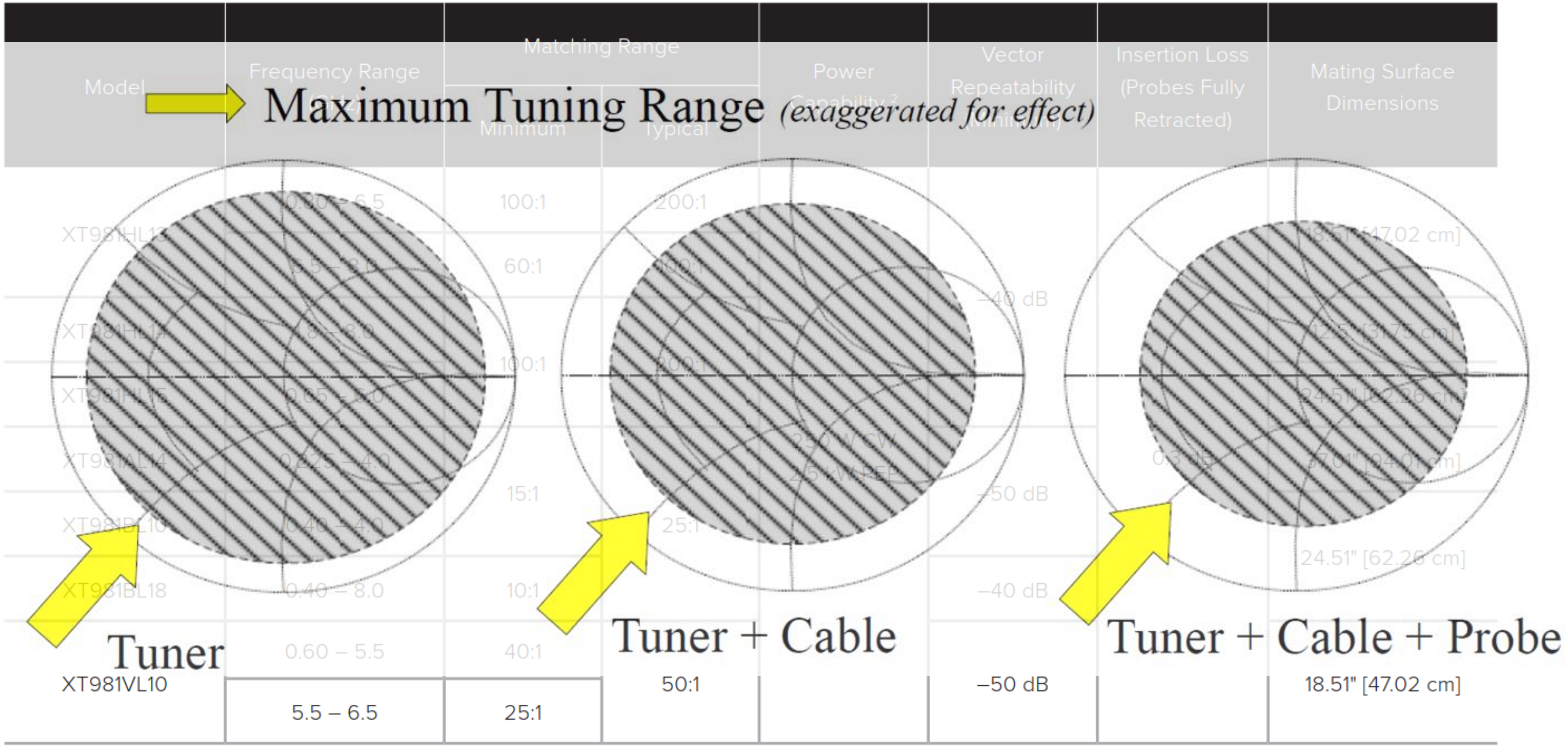
- Used to change the load presented to a DUT (manual)
    - can be considered a continuously-variable mismatch load/termination
- Generally used for manually matching a non-50Ω DUT for characterization
  Models available between 400 MHz and 50 GHz

Automated Impedance Tuners

- Used to change the load presented to a DUT (automated, programmable)
    - can be considered a continuously-variable mismatch load/termination
- Can be used standalone or part of an integrated solution
- Models available between 225 MHz and 110 GHz (coaxial and waveguide)

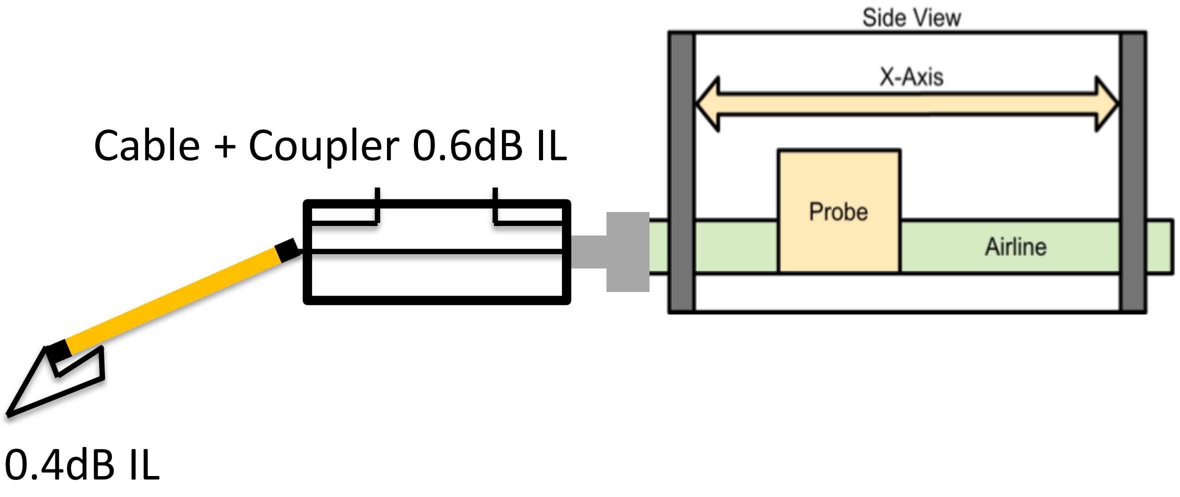
Tuning range

Tuning range is impacted due to losses between tuner and DUT



Tuning Range

Frequency	28 GHz



- $VSWR_{tuner} = 15{:}1 \rightarrow |\Gamma_{tuner}| = \mathbf{0.87}$
- $IL_{coupler + cable + probe} = 1\ dB$
- $VSWR_{Load} = 5.6{:}1 \rightarrow |\Gamma_{load}| = \mathbf{0.69}$

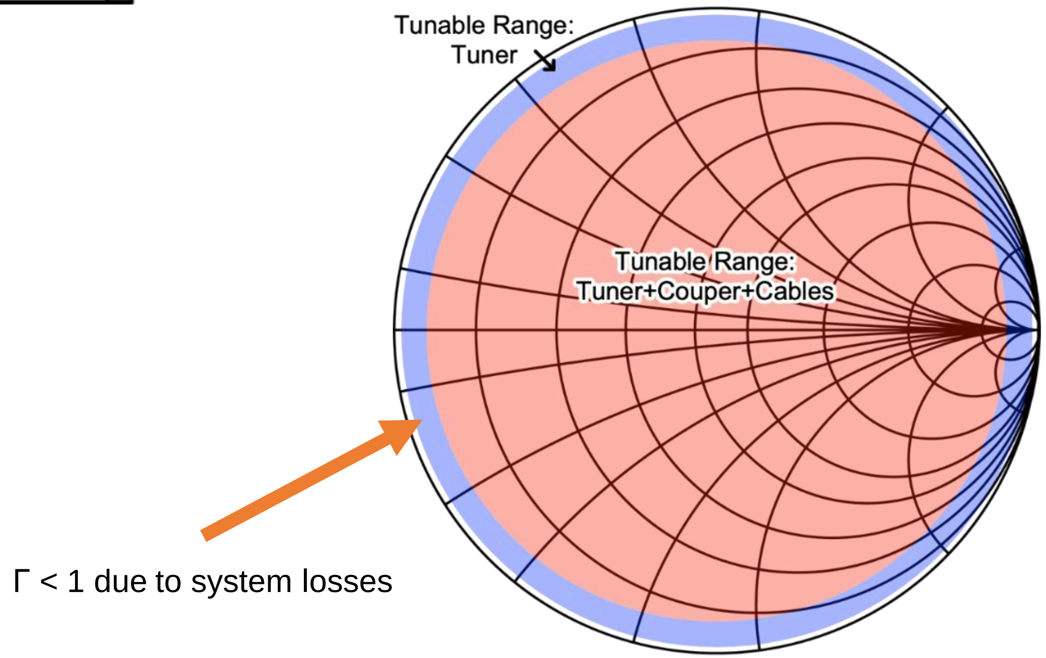
Reference formulas:

$$RL_{tuner} + RL_{coupler+cable+probe} = RL_{dut}$$

$$RL_{tuner} = -20Log\left(\frac{VSWR_{tuner} - 1}{VSWR_{tuner} + 1}\right)$$

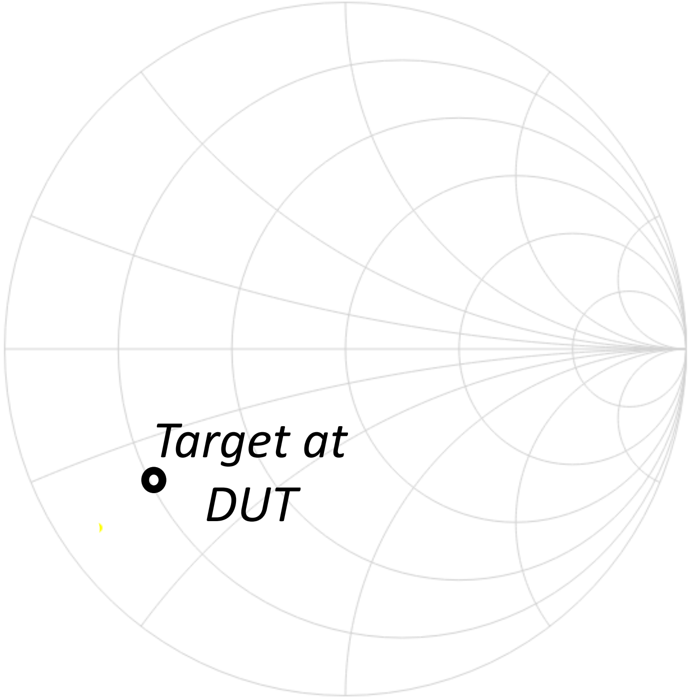
$$RL_{coupler+cable+probe} = 2(IL_{coupler+cable+probe})$$

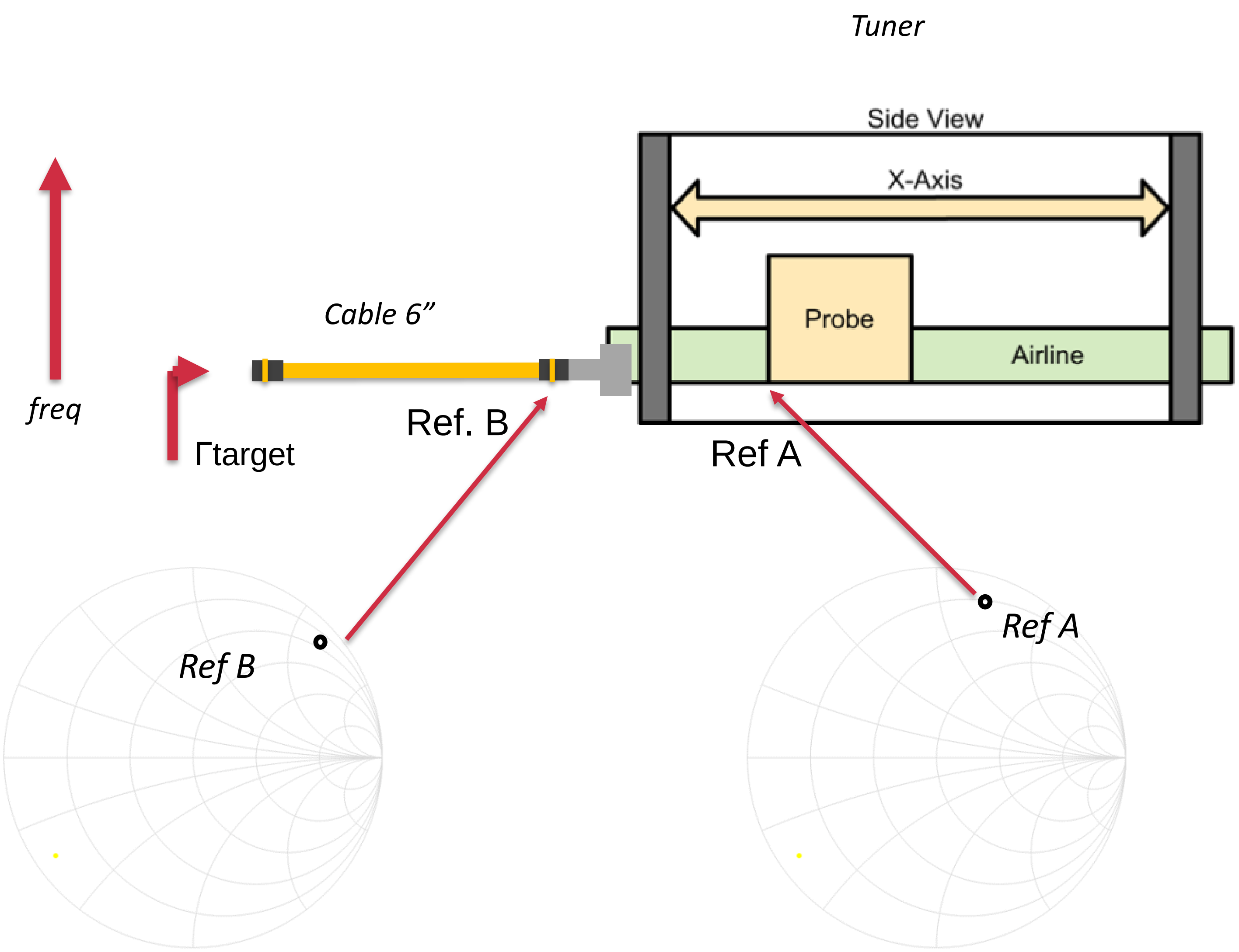
$$\Gamma_{dut} = 10^{\left(\frac{-RL_{dut}}{20}\right)}$$



Phase skew

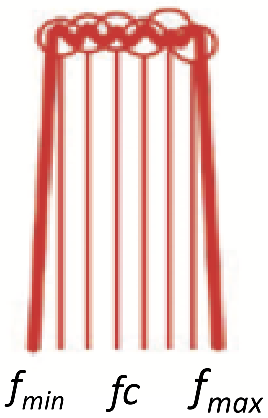
CW signal

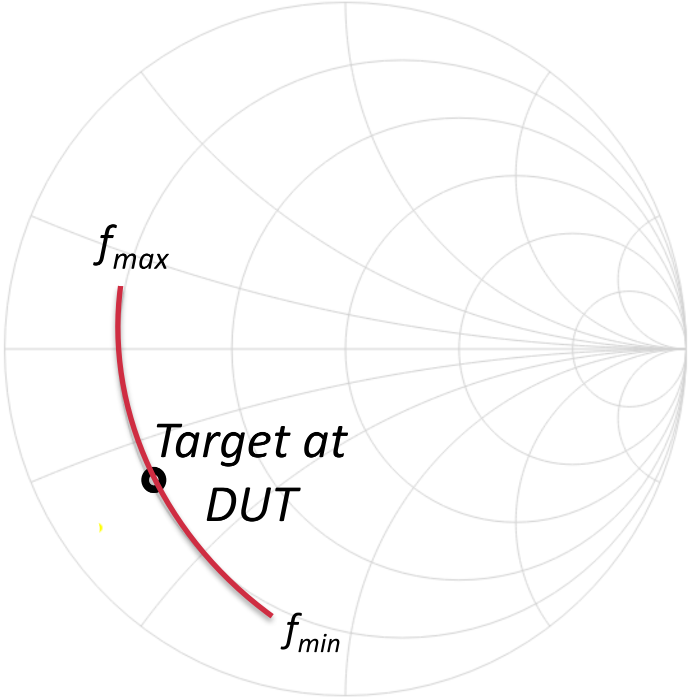


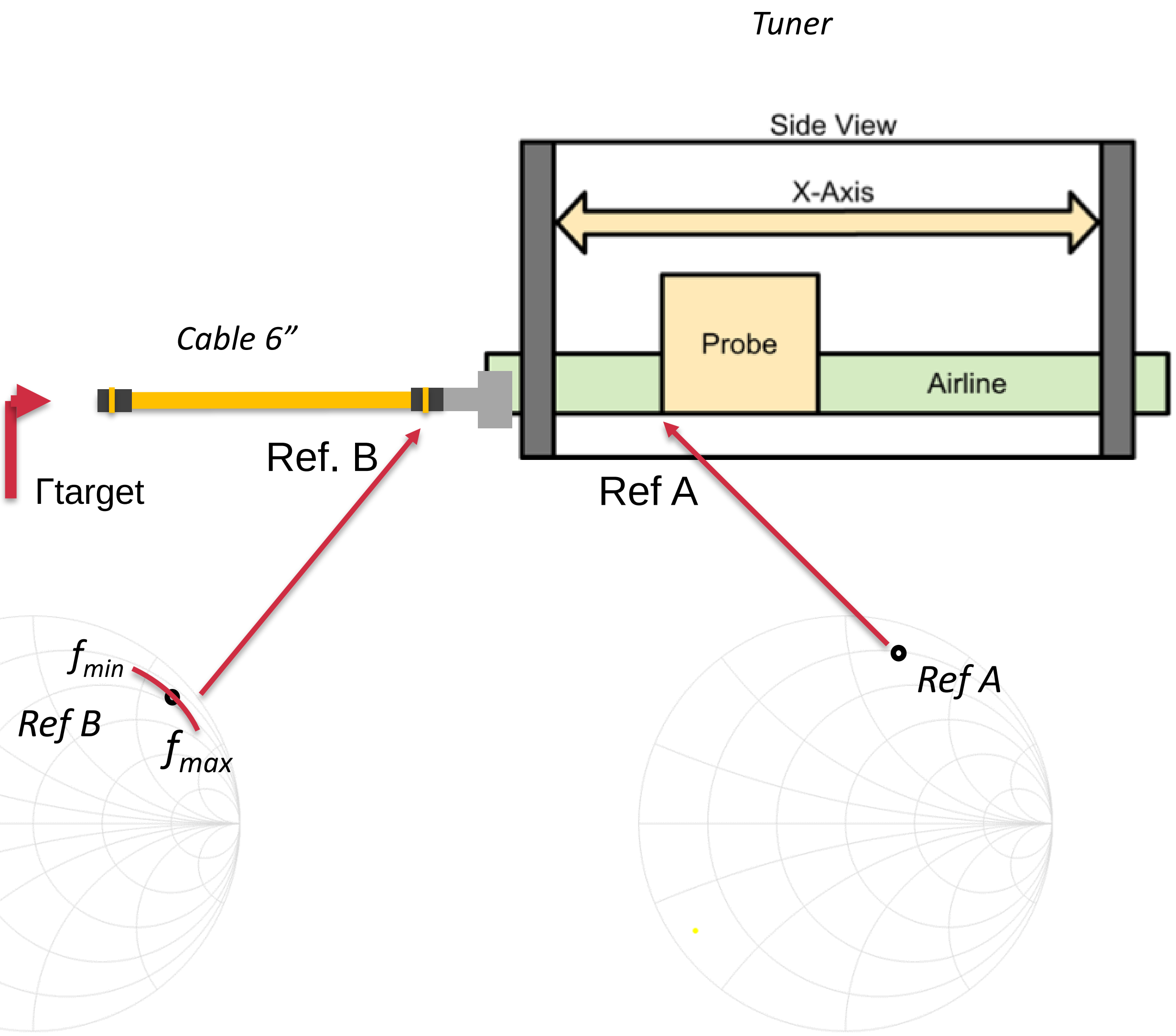


Phase skew

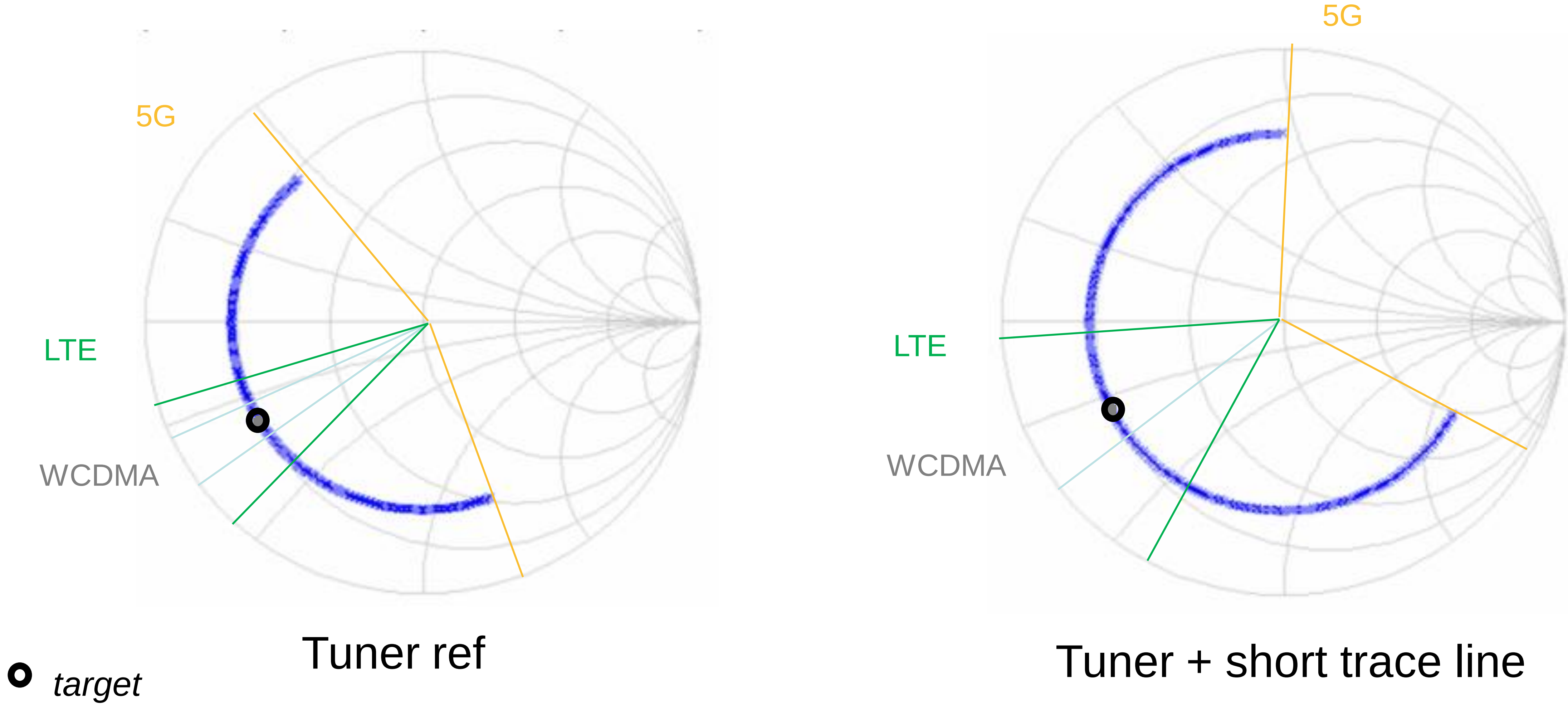
Modulated Signal







Phase skew



Tuner ref

Tuner + short trace line

Introduction Nano5G Tuner

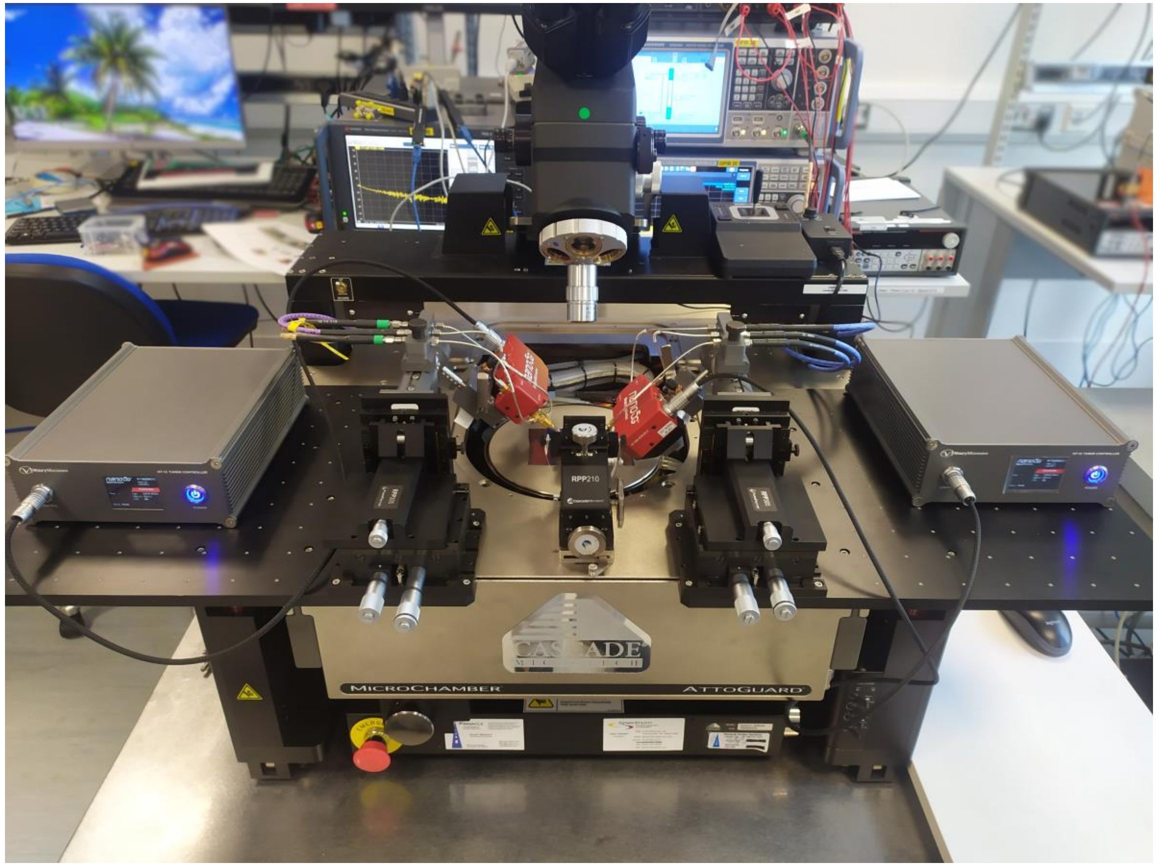
Nano5G, 18 GHz-50 GHz tuner directly mounted to probe

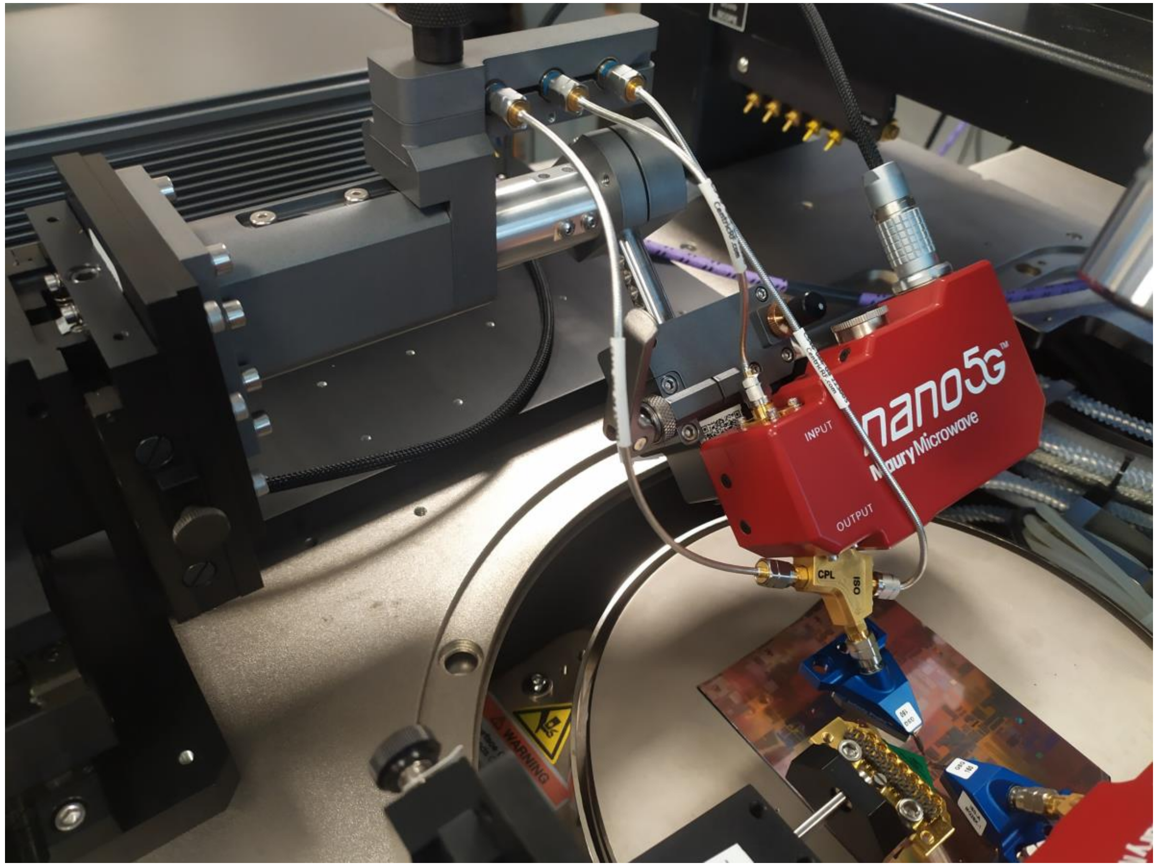
Challenges:
- Tuning range
- Phase skew

Nano5G:
- 1/10 of the volume and weight of other solutions:
  - Weight: **317.5 Gram**
  - Dimensions: **6cm x 4cm x 11.4cm**
- No cable needed between probe and tuner
- Integrated coupler (optional, IL)

Integration of Nano5G

Nano5G, 18 GHz-50 GHz tuner directly mounted to probe





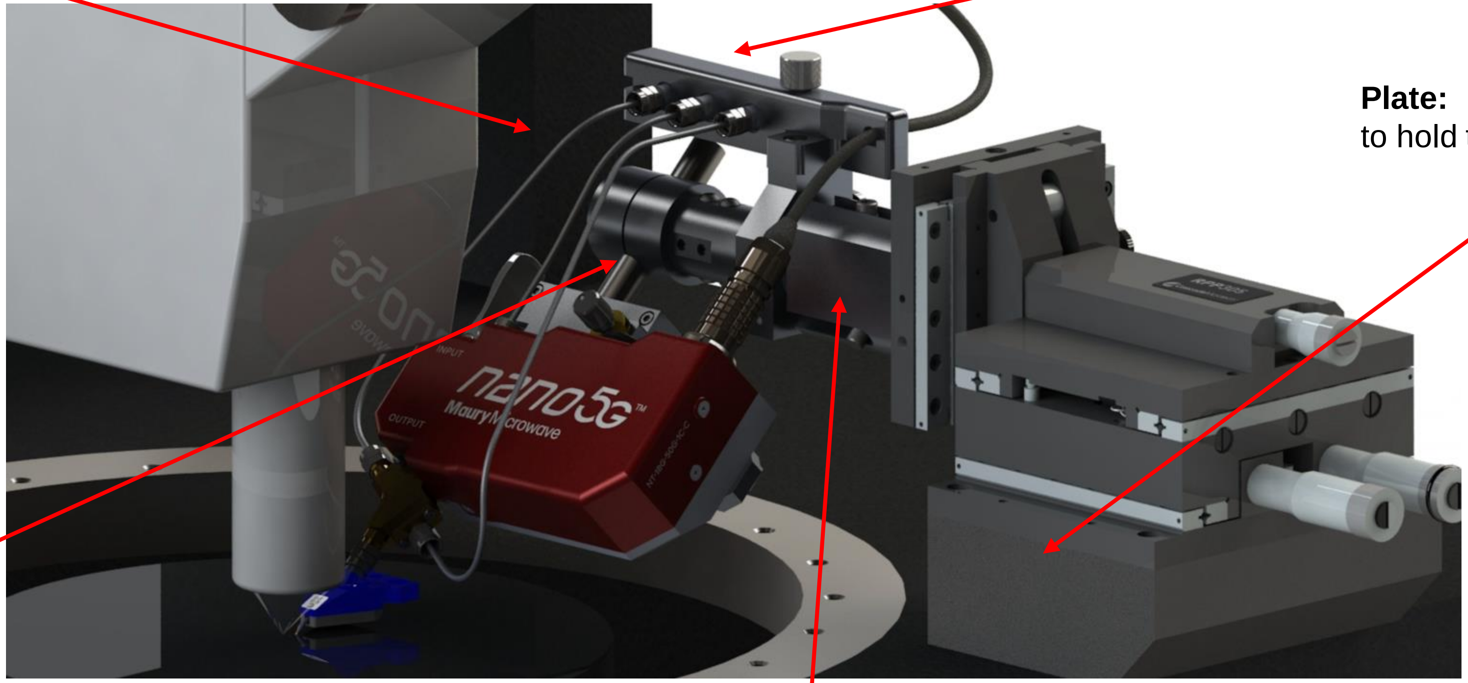
Integration of Nano5G

Nano5G, 18 GHz-50 GHz tuner directly mounted to probe

Short RF 1.85 mm cables:
Qty 3(only for NT-18G-50G-1C-C)

Cable management bracket:
to simplify VNA connections(only for NT-18G-50G-1C-C)

Plate:
to hold the304/305 positioner

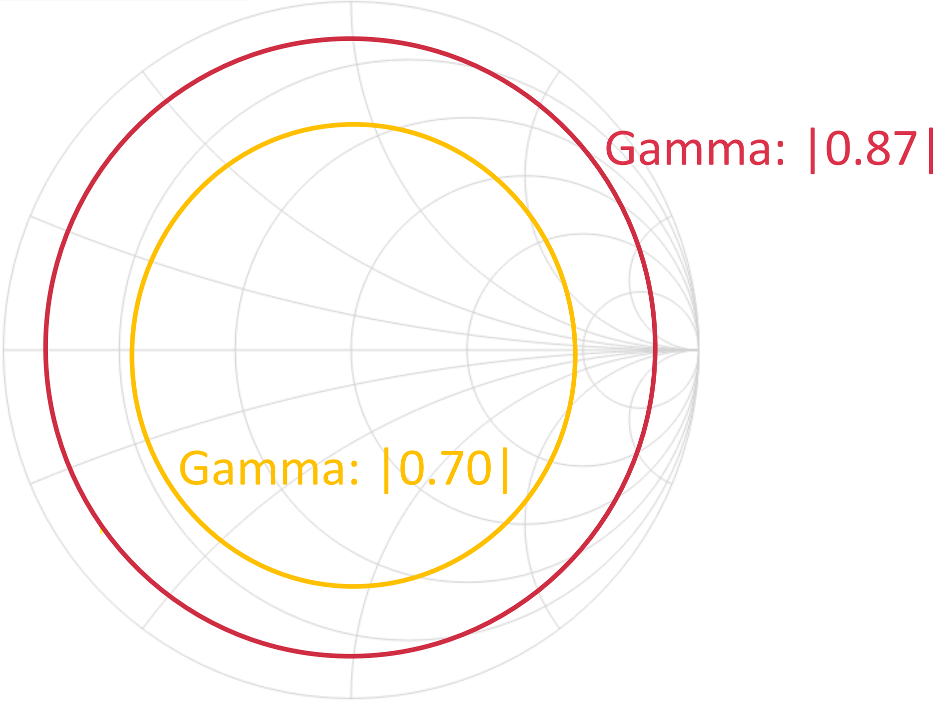


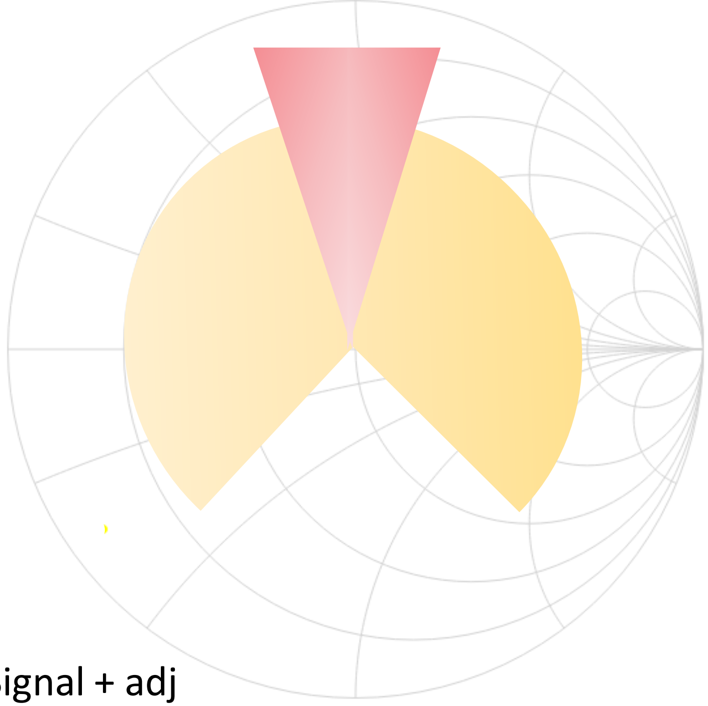
Angled bracket:
to hold the nano5G at 45 degrees
Note:the bracket includes planarity adjustment

Positioner arm:
To connect RPP304/305 positioner with the dedicated angled bracket

Features and benefits Nano5G

Frequency	28 GHz





100MHz Signal + adj
channels (left and right)

Tuning range

(MT984AL01 + coupler with integration cable + probe vs Nano5G + probe)

Phase skew

(MT984AL01 + coupler with integration cable + probe vs Nano5G + probe)

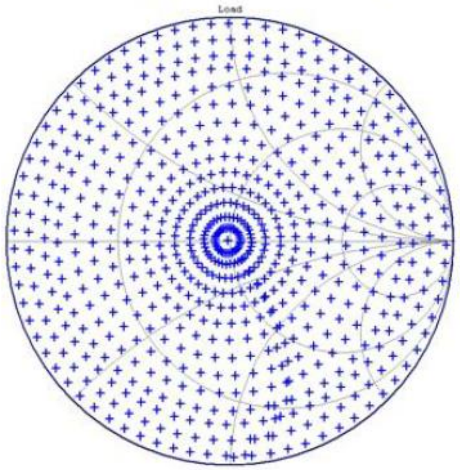
Important considerations

- **Speed:**
  - DVT applications require hundreds of measurements to cover different signal bands and modulation types. Tuning speed is essential
- **Accuracy:**
  - Check and balance to gain confidence in your data
- **On wafer measurements:**
  - Adding components in front of the tuner element will:
    - Reduce the tuning range at the DUT reference
    - Increase the phase skew of the selected impedance against the signal BW

Characterizing Automated Tuners

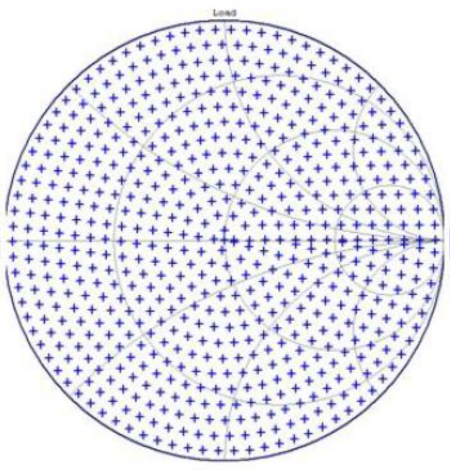
To automate tuners, software must know the positions corresponding with its impedances. There are four methods to characterize a tuner:

Adaptive Modeling



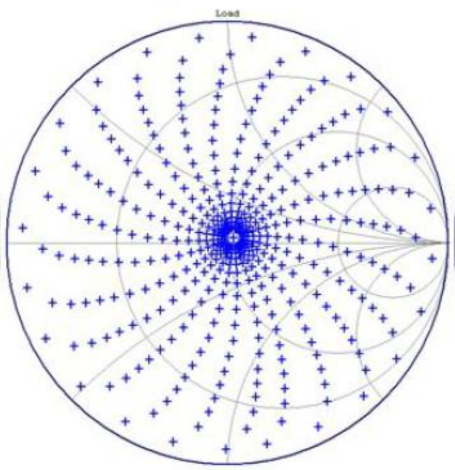
- Fast calibration
- Support interpolation
- Most commonly used method for power measurements

Step Reflection



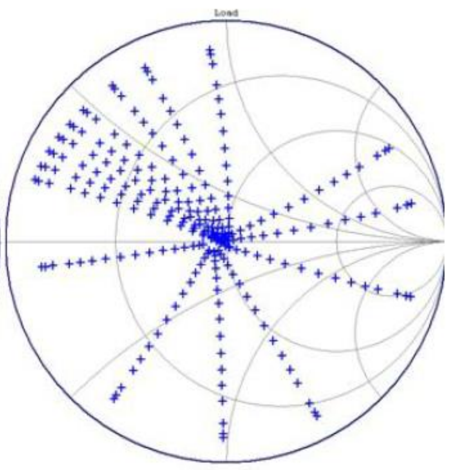
- Evenly spaced
- Slow calibration
- Interpolation not supported

Step Position



- Uneven spaced pattern
- Faster calibration
- Mainly used for traditional Noise measurement

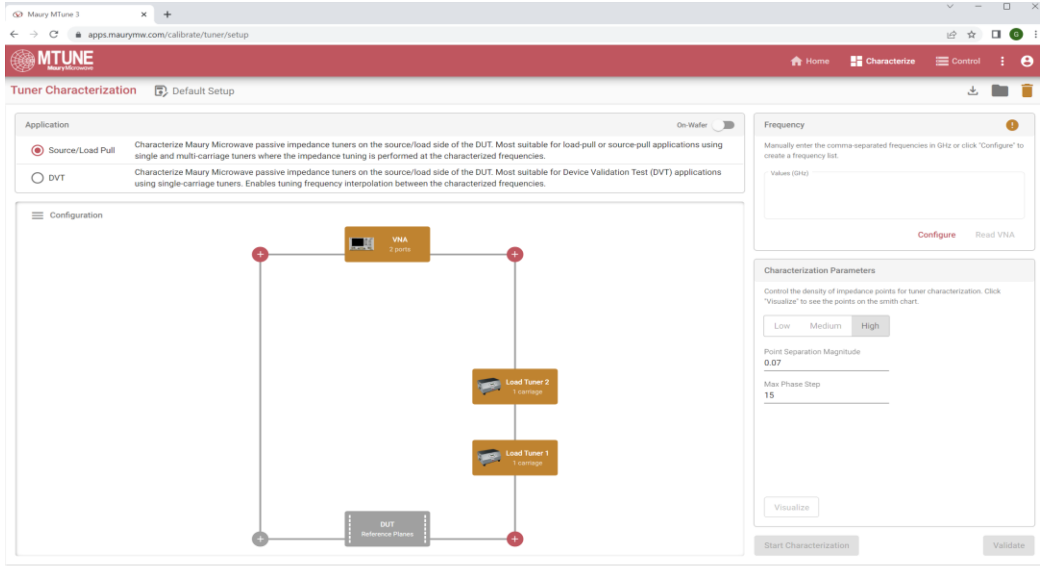
Fix Position



- Uneven spaced pattern
- Fastest calibration
- Limited gamma coverage
- Mainly used for Fast noise Measurement

Characterizing Automated Tuners

MTune3 is a software package that allows device characterization and control of multiple tuner configurations for automated impedance tuning.



Compared with previous versions, with MTune3 you will experience:

- Desktop and cloud-based interface
- Automated SW updates
- Improved Wizard

And features:

- Uses a single software platform with most commercial VNAs for tuner characterization
- Creates characterization files (.tunx) for use with compatible tuner systems
- Minimizes common errors with a simplified process empowered by an intuitive GUI
- Validates tuner characterization using VNA measurements for multiple impedance points
- Presents measurement results with advanced visualization tools
- Provides reusable configurations for tuner characterization and control
- Allows controlling multiple tuner positions with frequency interpolation

Controlling Automated Tuners

RF & Microwave solutions

Direct commands

Socket

Mtune 3.0

Direct commands:
- Tuning on board
- Files stored in the tuner SD card
- Easy SW integration

Socket:
- More robust SW integration
- Files stored in the PC

Typical load pull configurations

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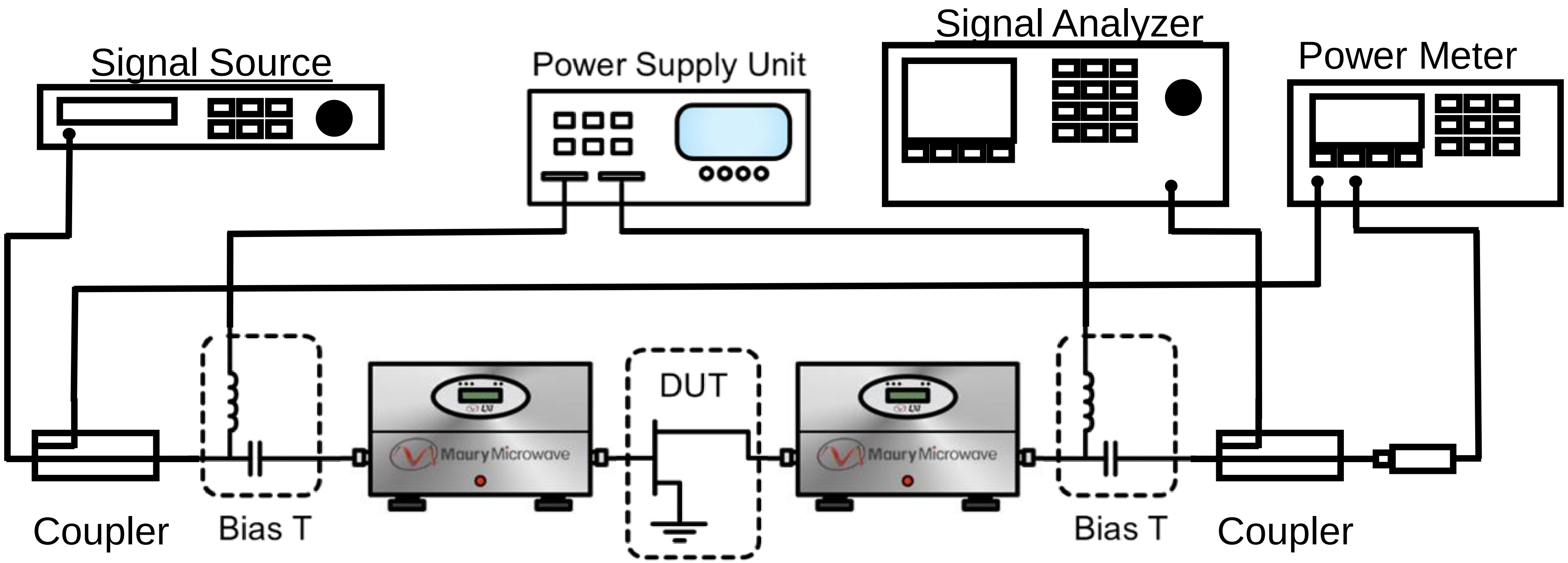
- Traditional loadpull: Power based loadpull measurements
- Vector receiver load pull: VNA based loadpull measurements
- Active loadpull: VNA based loadpull without passive tuner
- Hybrid active vector receiver loadpull: VNA based loadpull with signal injection on load side

Traditional load pull

traditional load pull architectures are mainly based on power meter use, both for input and output power measurements.

power based load pull system are well suited for the determination of optimal load impedances for Pout, Efficiency, Gain, etc.

The input impedance is not known which varies with input power! Therefore, delivered power to the device is unknown and parameters like PAE, transducer gain, and compression can't be measured accurately.



Passive vector-receiver load pull

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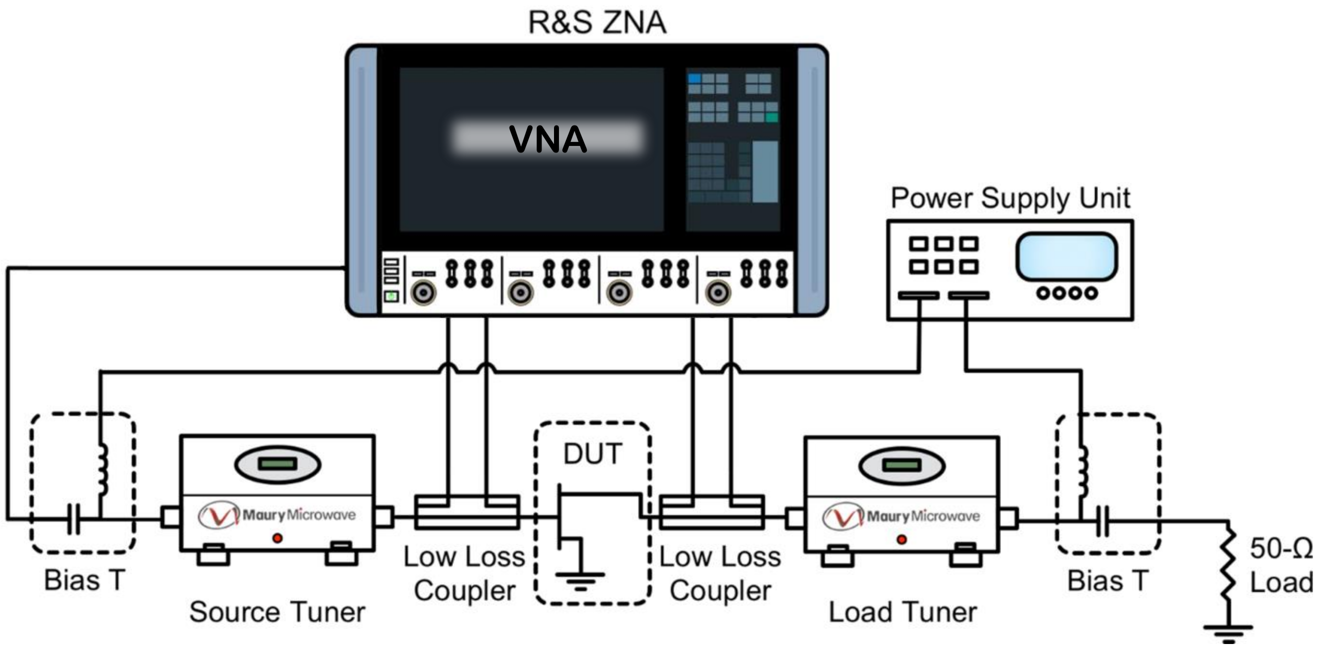
- Uses passive impedance tuners
- Measures vector incident and reflected (*a_x* and *b_x*) waves constant at the calibration reference plane
- Enables calculation of $P_{in.\,del.}$, Power Gain (G_p) and Power Added Efficiency (PAE)
- Measurements performed at calibrated DUT reference plane

$$P_{in,del} = \frac{1}{2}\left(|a_1|^2 - |b_1|^2\right) = \frac{1}{2}|a_1|^2\left(1 - |\Gamma_{in}|^2\right)$$

$$P_{out} = \frac{1}{2}\left(|b_2|^2 - |a_2|^2\right) = \frac{1}{2}|b_2|^2\left(1 - |\Gamma_{load}|^2\right)$$

$$G_p = \frac{P_{out}}{P_{in,del}} = \frac{|b_2|^2\left(1 - |\Gamma_{load}|^2\right)}{|a_1|^2\left(1 - |\Gamma_{in}|^2\right)}$$

$$PAE = \frac{P_{out} - P_{in,del}}{P_{DC}}$$



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Active vector-receiver load pull

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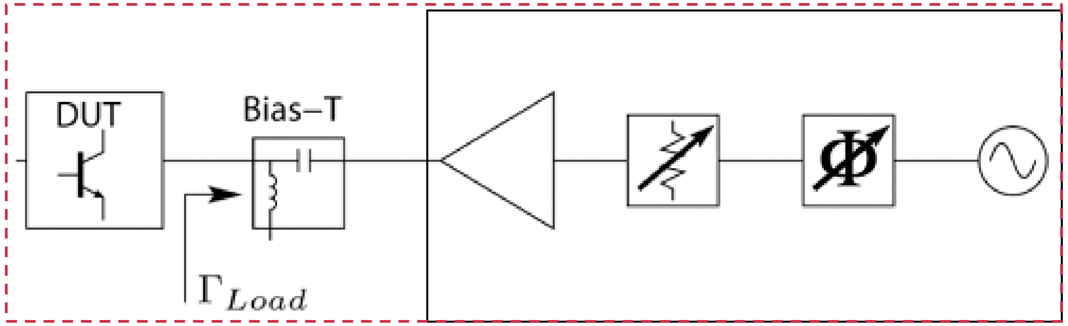
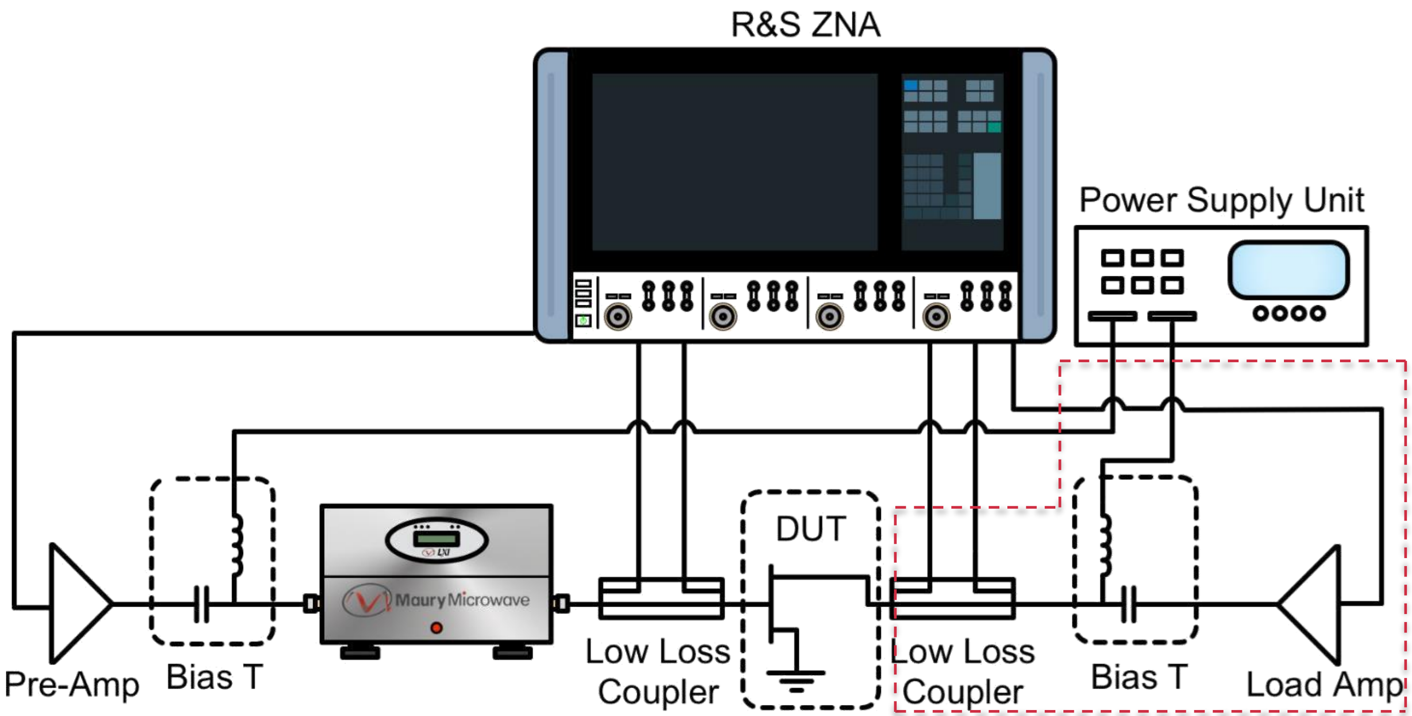
- Active signal injection used for impedance control
- Measures vector incident and reflected (a_x and b_x) waves
- Measurements performed at calibrated DUT reference plane
- Enables $|\Gamma|_{Load} = 1$ and even $|\Gamma|_{Load} > 1$



Gamma controlled by active signal injection



$$\Gamma_{Load,n}(f_n) = \frac{a_{2,n}(f_n)}{b_{2,n}(f_n)}$$

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Hybrid-active vector-receiver load pull

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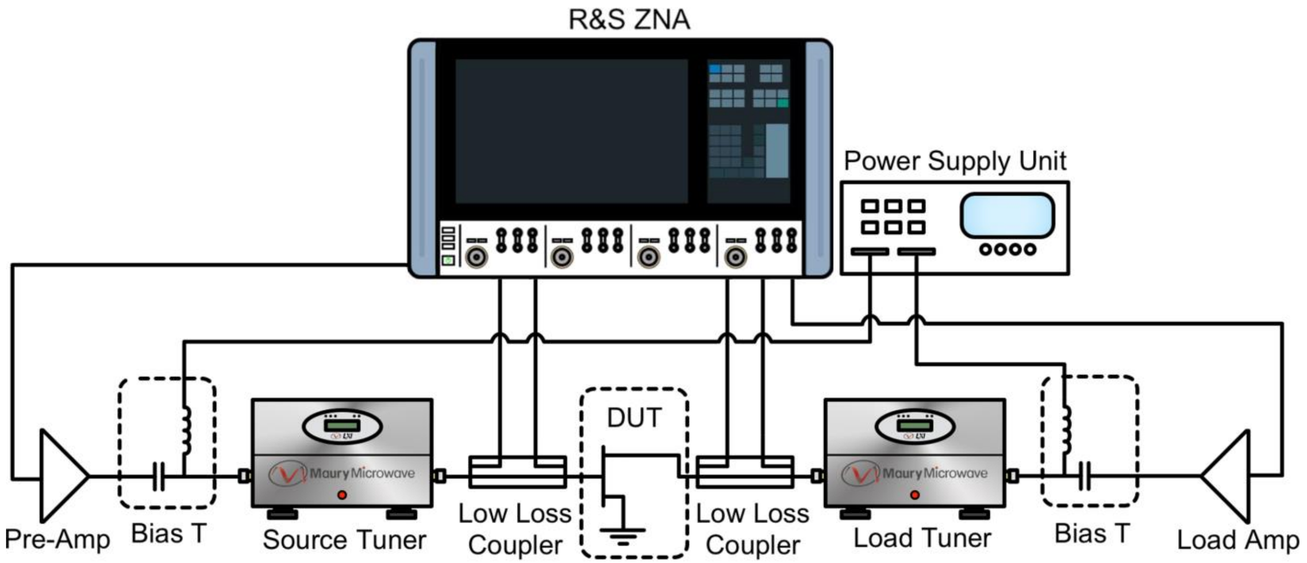
- **Combines passive and active impedance tuning techniques where a signal is being used to overcome losses between tuner and DUT**
- **Often used for:**
  - $|\Gamma|_{Load} > 0.9$ is required for high-power devices – both active and passive tuning at fundamental
  - $|\Gamma|_{Load} > 0.9$ is required at very high frequencies, but load amplifier is low-power
  - Harmonic tuning – fundamental using passive tuner, harmonics using active injection
- **Measurements performed at calibrated DUT reference plane**
- **Enables $|\Gamma|_{Load}$ of 1 and even $|\Gamma|_{Load}$ greater than 1**



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Summary or parameters in function of ΓL

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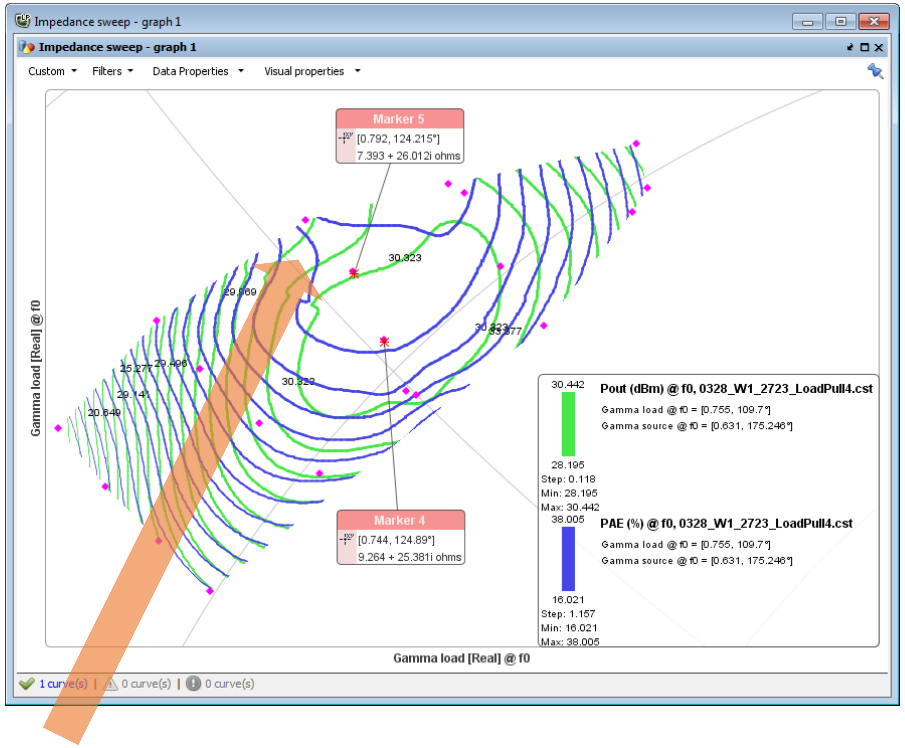
Measurement Parameter	Traditional Load Pull	Vector Receiver Load Pull
Input Reflection Coefficient (Z_{in})	✗	✓
Available Input power ($P_{in, avail}$)	✓	✓
Delivered Input power ($P_{in,del}$)	✗ *	✓
Output power (P_{out})	✓	✓
Power Gain (G_p)	✗	✓
Transducer Gain (G_t)	✓	✓
Power Added Efficiency (PAE)	✗	✓
Efficiency (Eff)	✓	✓
AM/PM	✗	✓
Calibrated Harmonic Power	Spectrum analyzer required	✓
Multi-tone Measurements	Spectrum analyzer required	✓
Modulated Measurements	Spectrum analyzer required	✗
Power Sweep Speed (for 25 power levels)	≈ 20sec	≈ 1sec

* A reflect power meter can be used to calculate delivered input power by measuring the reflected power through a reverse coupler, however the accuracy decreases as the mismatch between source impedance and device input impedance increases.

Hybrid active load pull example

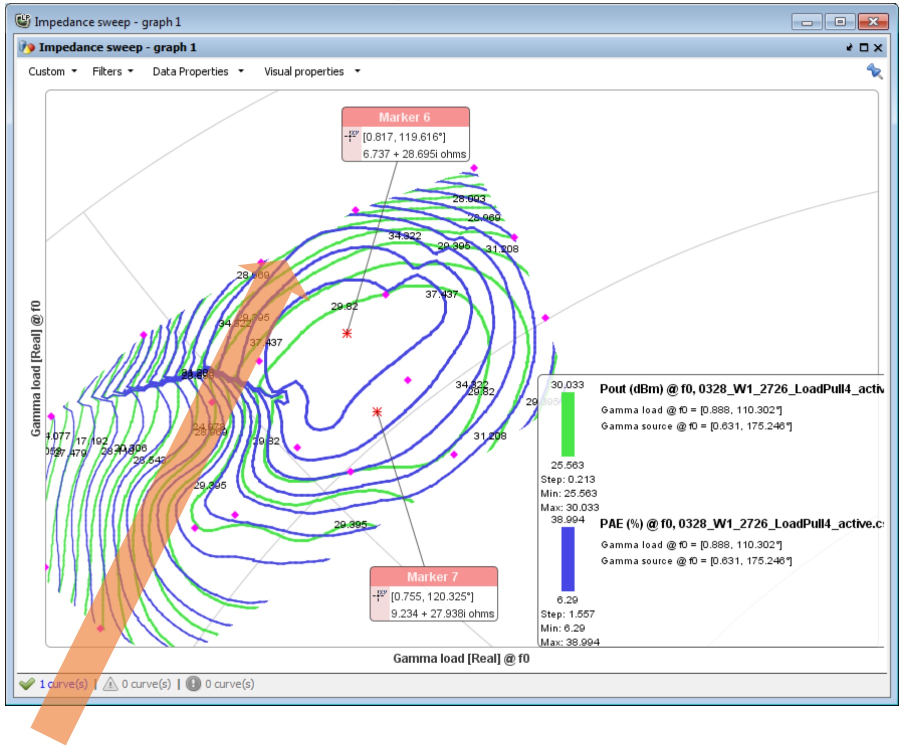
GaN transistor at 38 GHz with P_{out} = 30 dBm

Passive load pull



No closed contours due to system losses

Hybrid active load pull



Closed contours and enough gamma for accurate measurements

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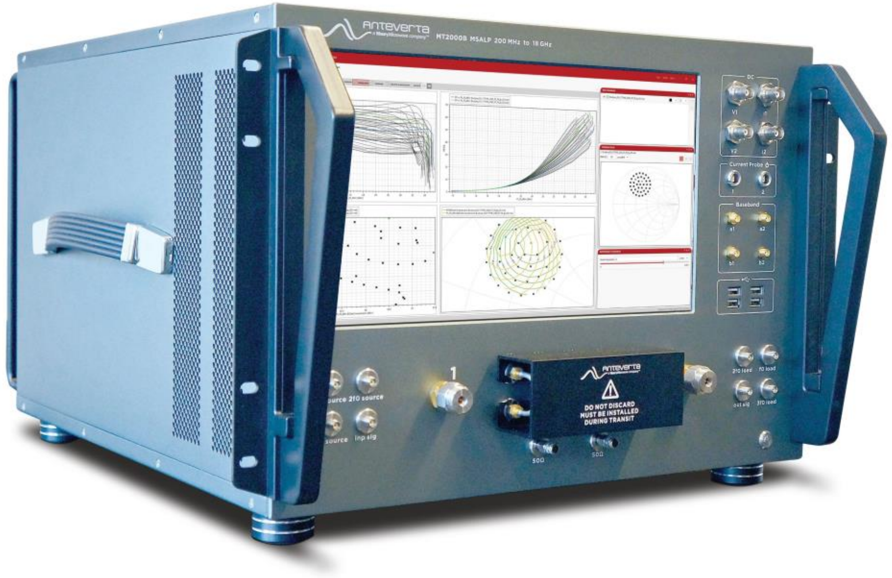
MT1000 and 2000 Mixed signal active loadpull system

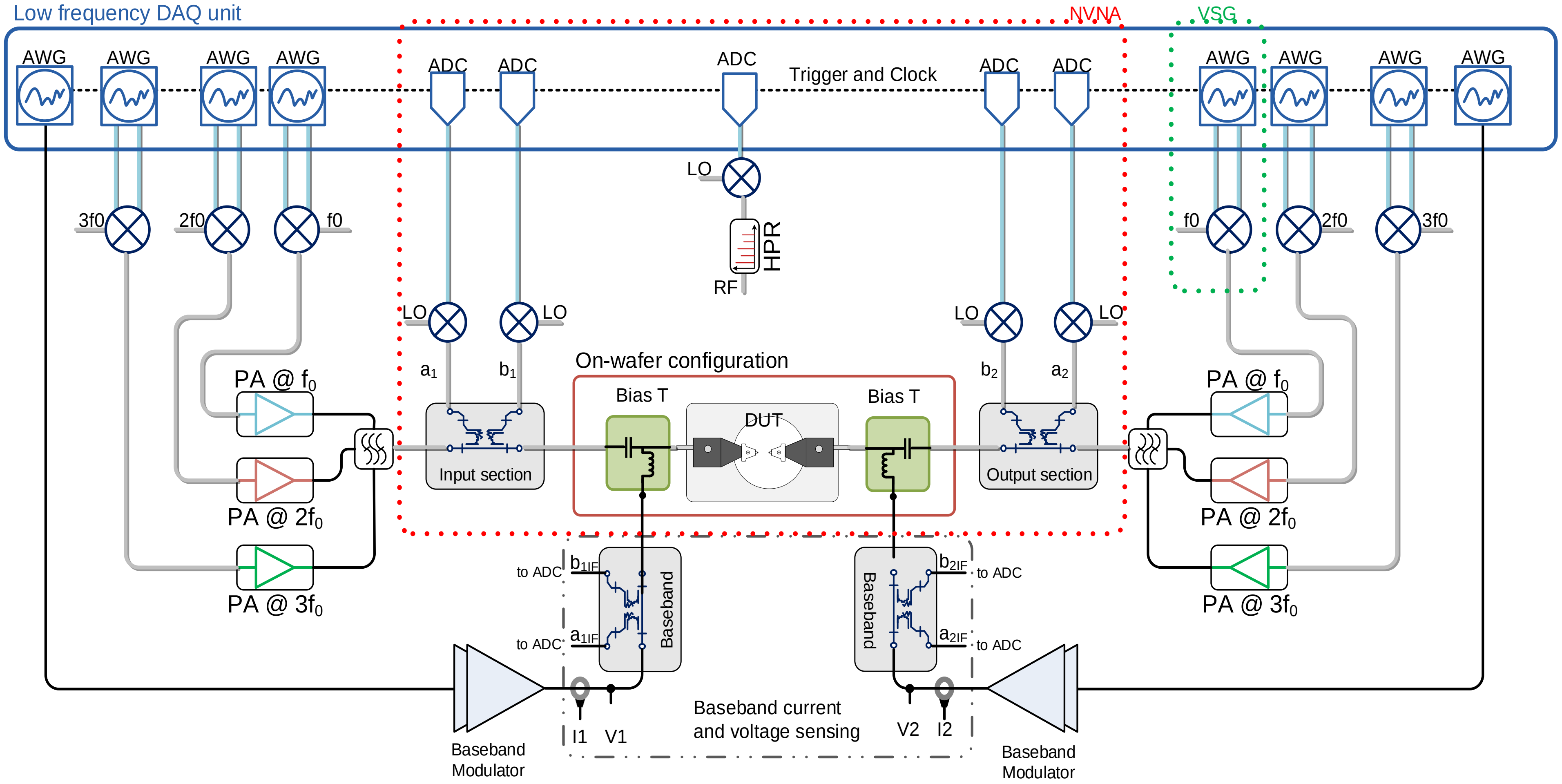


The MT1000 and MT2000 are turnkey one-box load pull solutions that replace the functions typically performed by passive fundamental and/or harmonic impedance tuners, VNAs and/or NVNAs, analog signal generators, vector signal generators, vector signal analyzers and oscilloscopes, and add the capabilities of high-speed load pull measurements and wideband impedance control for (**up to 1000MHz**) modulated signals.

- Single-tone CW and pulsed-CW RF signal
- DC and pulsed-DC bias
- Time-domain NVNA voltage and current waveforms and load lines
- Frequencies between 1 MHz and 67 GHz
- Using ACPR and EVM measurement data in the design of wideband PA circuits **(MT2000)**
- Improving PA linearity based on controlled baseband terminations **(MT2000)**
- Evaluating the performance of a DUT under realistic antenna load conditions **(MT2000)**
- Evaluating the performance of DUT under different matching network topologies **(MT2000)**

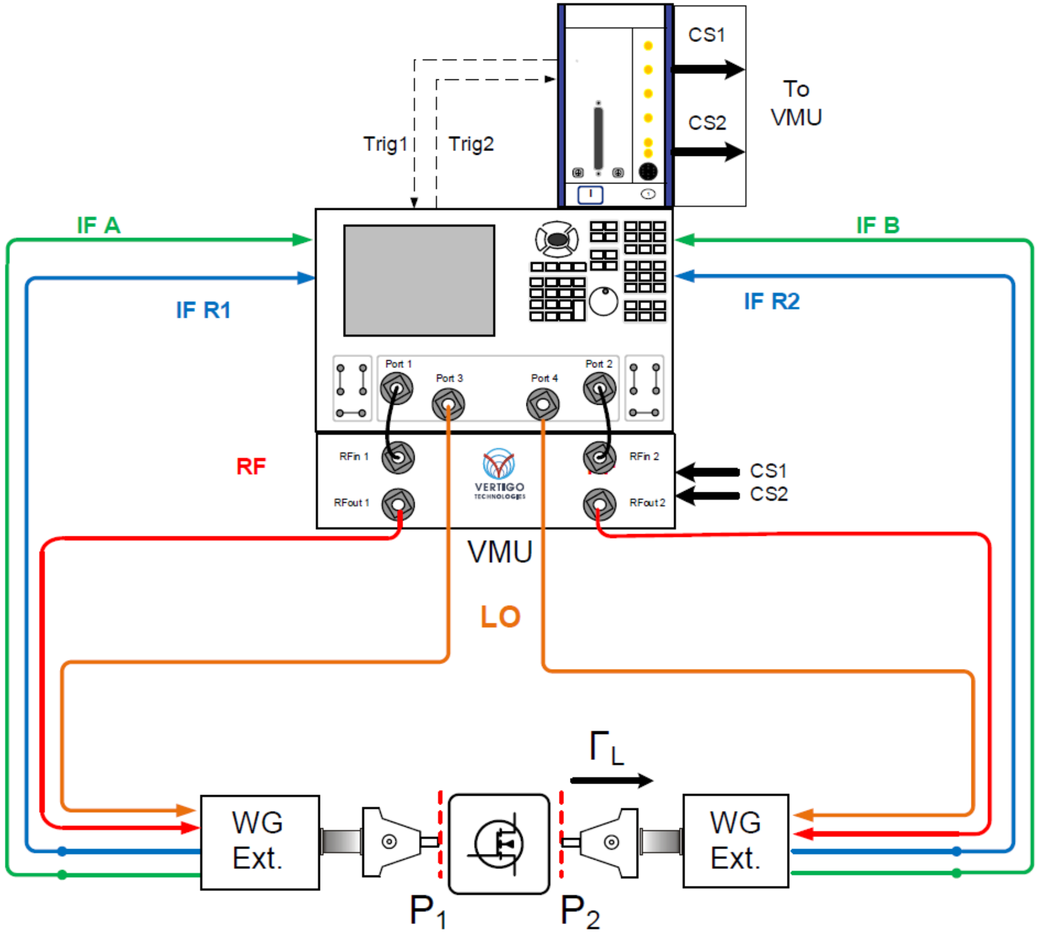
https://www.maurymw.com/MW_RF/Mixed-Signal_Active_Load_Pull_System.php

MT1000 and 2000 Mixed signal active loadpull system



https://www.maurymw.com/MW_RF/Mixed-Signal_Active_Load_Pull_System.php

MMWave Studio: sub-THz active load pull



Works with every available WG mm-wave extender for VNA

Maximum frequency determined by mm-wave extender BW.

Maximum power determined by hardware (ext. and probe loss)

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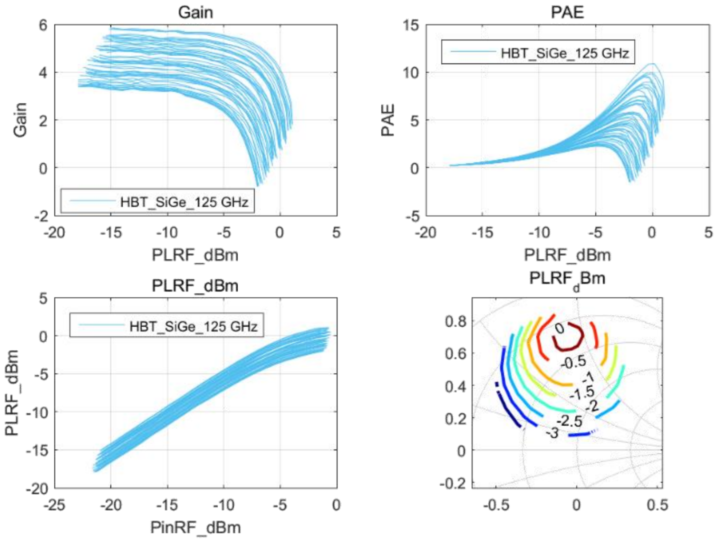
https://www.maurymw.com/MW_RF/MM-STUDIO.php

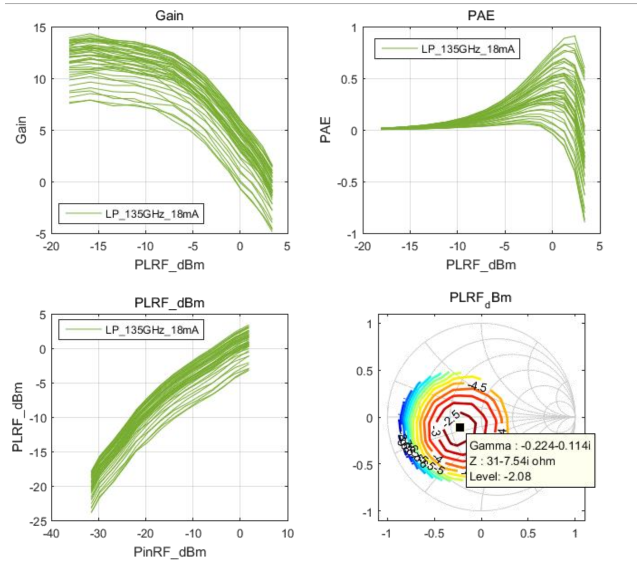
mmW and sub-THz active load pull measurements

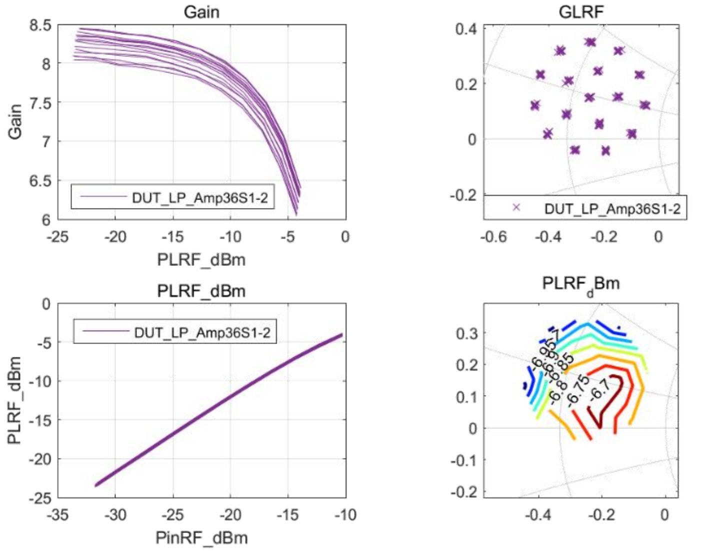
Characterization of **small-cells**: SiGe 130 nm double finger HBT at 125 GHz

Characterization of on-wafer **multi-stage** PA: SiGe BiCMOS at 135 GHz

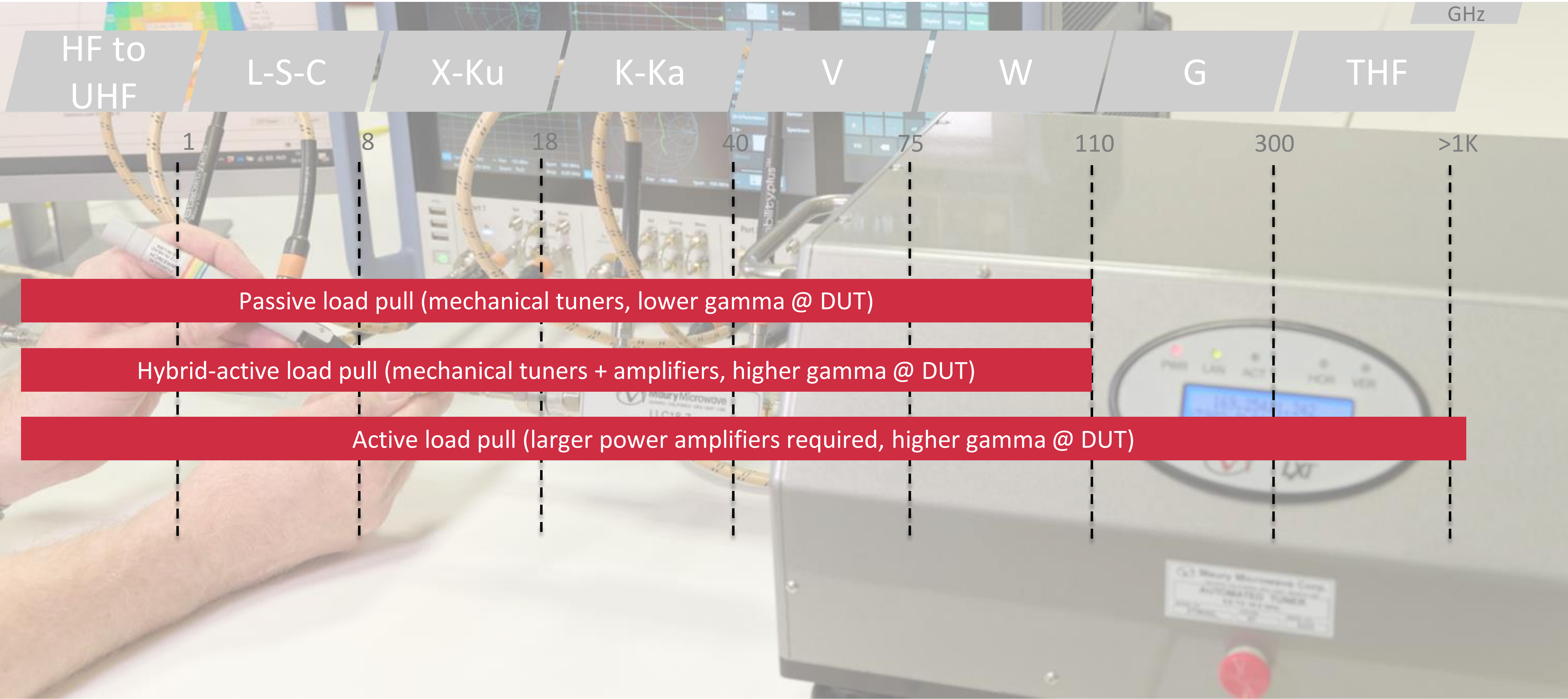
Characterization of on-wafer **multi-stage** PA at 250 GHz







Summary



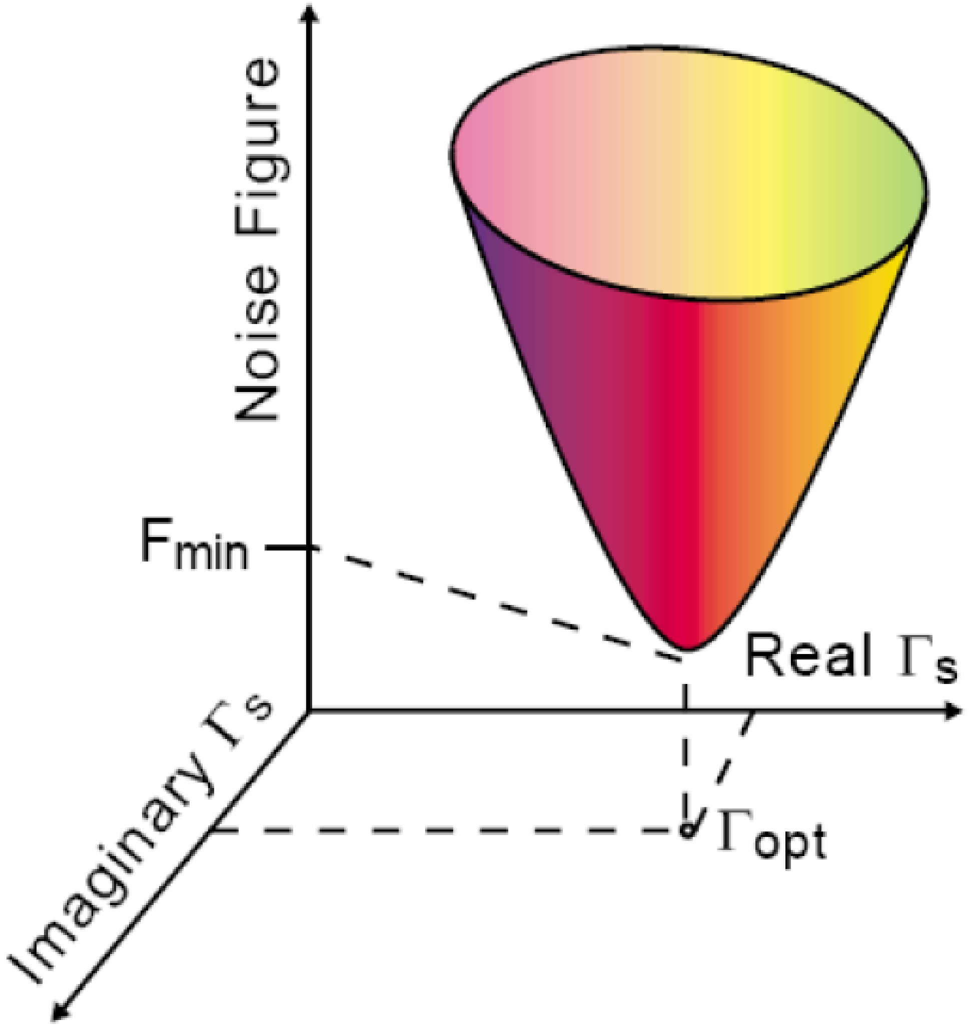
GHz
HF to UHF
L-S-C
X-Ku
K-Ka
V
W
G
THF
1
8
18
40
75
110
300
>1K
Passive load pull (mechanical tuners, lower gamma @ DUT)
Hybrid-active load pull (mechanical tuners + amplifiers, higher gamma @ DUT)
Active load pull (larger power amplifiers required, higher gamma @ DUT)

Overview of noise parameters

- Noise parameter equation is a mathematical construct enabling the computation of the noise factor (or noise figure*) of a DUT for any given source reflection coefficient

$$F = F_{min} + 4r_n \frac{|\Gamma_S - \Gamma_{Opt}|^2}{|1+\Gamma_{Opt}|^2(1-|\Gamma_S|^2)}$$

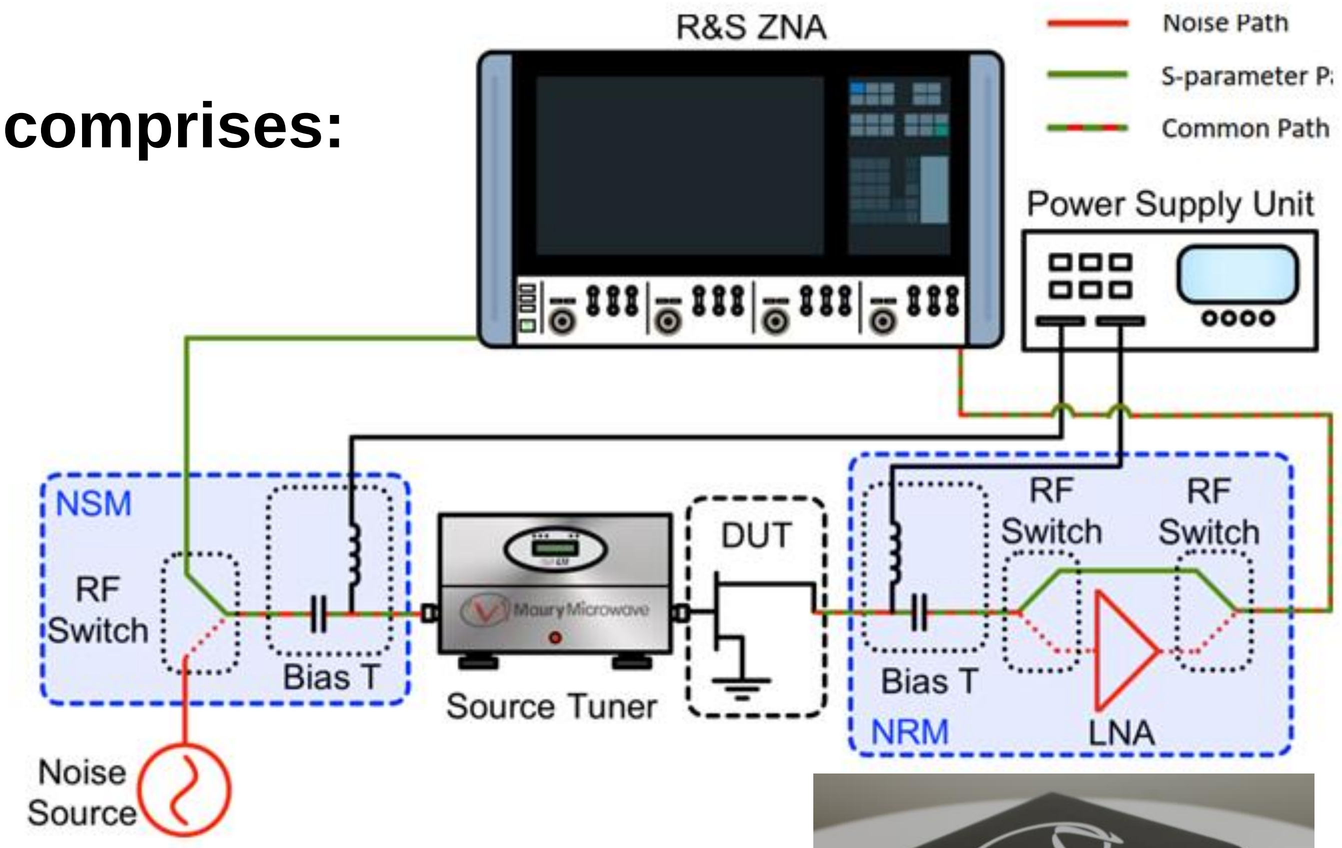
- There are 4 noise parameters
  - F_{min} – the minimum noise factor of the DUT
  - r_n – normalized noise resistance (normalized to the characteristic impedance)
  - X_{Opt} – Real part of the optimum source reflection coefficient (Γ_{Opt})
  - Y_{Opt} – Imaginary part of the optimum source reflection coefficient(Γ_{Opt})
- Noise parameters are computed quantities and are not measured directly
- Computation requires at least 4 independent Γ_S states for each frequency
- Since noise parameters are computed, it is not necessary to reach the actual Γ_{Opt} with the impedance tuner



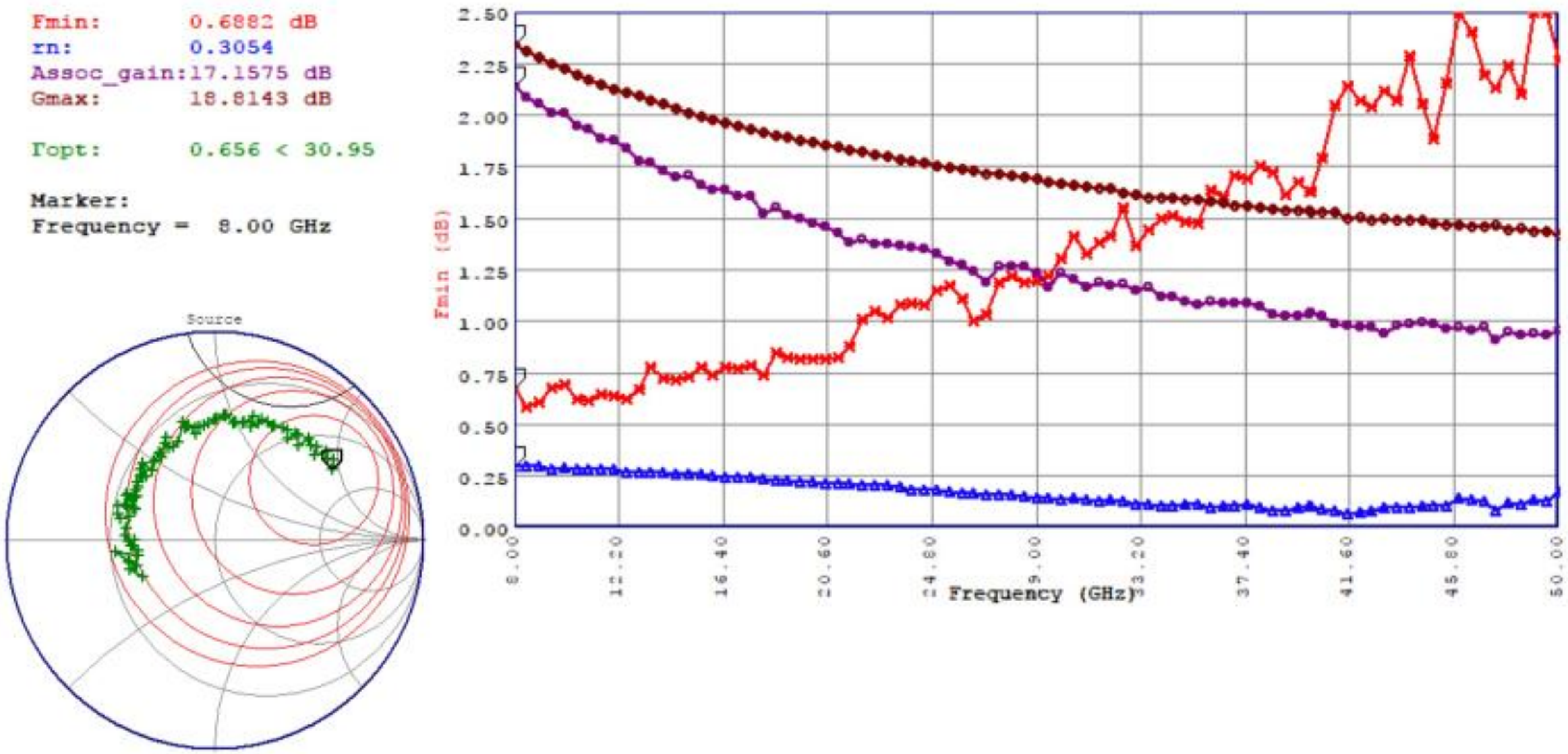
ATS Noise Parameter System Overview

The ATS noise parameter system comprises:

- Vector Network Analyzer
- Noise receiver (integrated or external)
- Impedance tuner
- Noise source
- Noise switching module (NSM)
- Noise receiver module (NRM)
- ATS software
- Bias system (DC power supply)



Measurement of a GaN Transistor



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