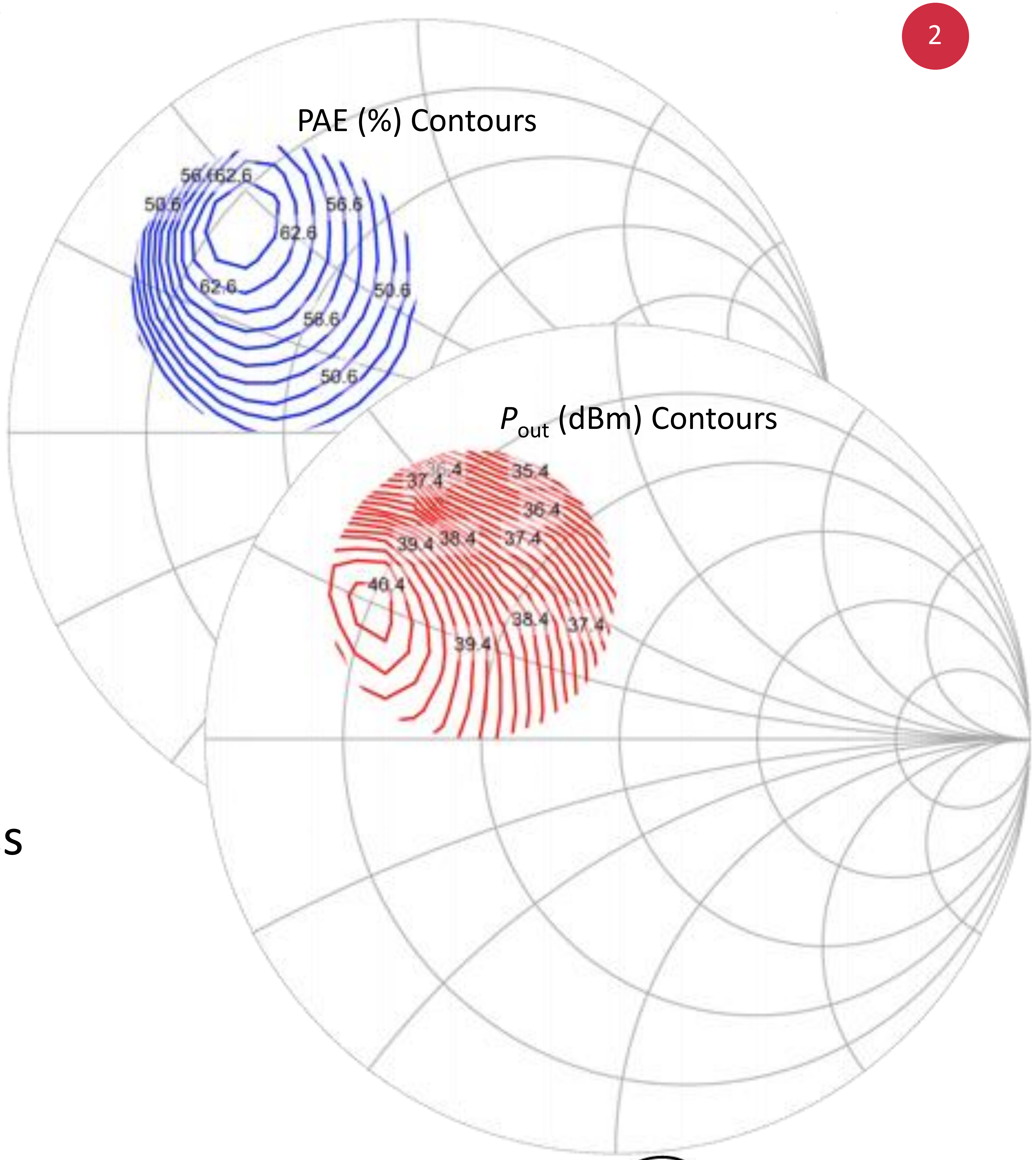
Load-pull techniques for 5G and 6G applications – state of the art and future

Mauro Marchetti

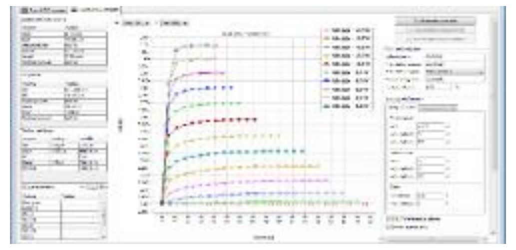
Maury Microwave
Your Calibration, Measurement & Modeling Solutions Partner!

Motivation for Load pull

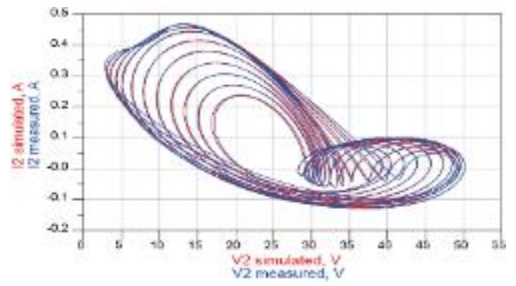
- S-parameters provide information about linear response of the device under test (DUT)
- Transistor performance is highly dependent on its load impedance
- RF/Microwave transistors exhibit non-linear behavior:
    - harmonic generation
    - frequency mixing, etc.
- Load-pull enables characterisation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



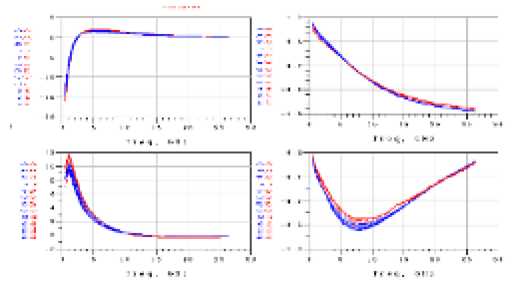
Load pull and source pull applications



Transistor characterization

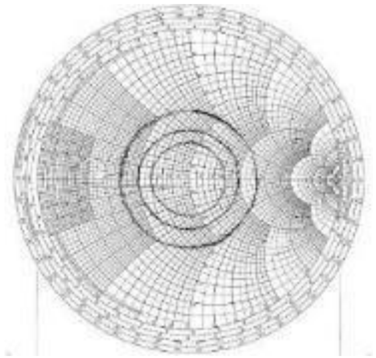


Compact transistor model validation



Behavioral model extraction

Matching network design (PA, LNA…)



Performance test / reliability test

Bandwidth Requirements by Application

Application	Frequency Range	Single Channel Bandwidth	Total Bandwidth (1 Channel + ACLR)	Optimum Channels For Test	Total Bandwidth (n Channels + ACLR)
W-CDMA	800 MHz – 3.5 GHz	5 MHz	15 MHz	5	25 MHz
Multi-carrier W-CDMA	800 MHz – 3.5 GHz	15 MHz	25 MHz	7	35 MHz
LTE	600 MHz – 6 GHz	20 MHz	60 MHz	5	100 MHz
802.11a/b/g	2.4 GHz	20 MHz	60 MHz	5	100 MHz
802.11n	2.4 GHz, 5 GHz	40 MHz	160 MHz	5	200 MHz
LTE-A	800 MHz – 3.5 GHz	100 MHz	300 MHz	5	500 MHz
802.11ac	5 GHz	160 MHz	480 MHz	3	480 MHz
802.11ax	2.4 / 5 GHz	160 MHz	480 MHz	3	480 MHz
5G	600 MHz – 6 GHz	100 MHz	300 MHz	4	600 MHz
5G	28 GHz	400 MHz			
5G	38 GHz	~1 GHz			
6G	95 GHz – 3 THz ???				

5G (and 6G) Challenges for load pull

Higher frequencies → higher losses

Higher bandwidth → modulated signals characterization, phase skew

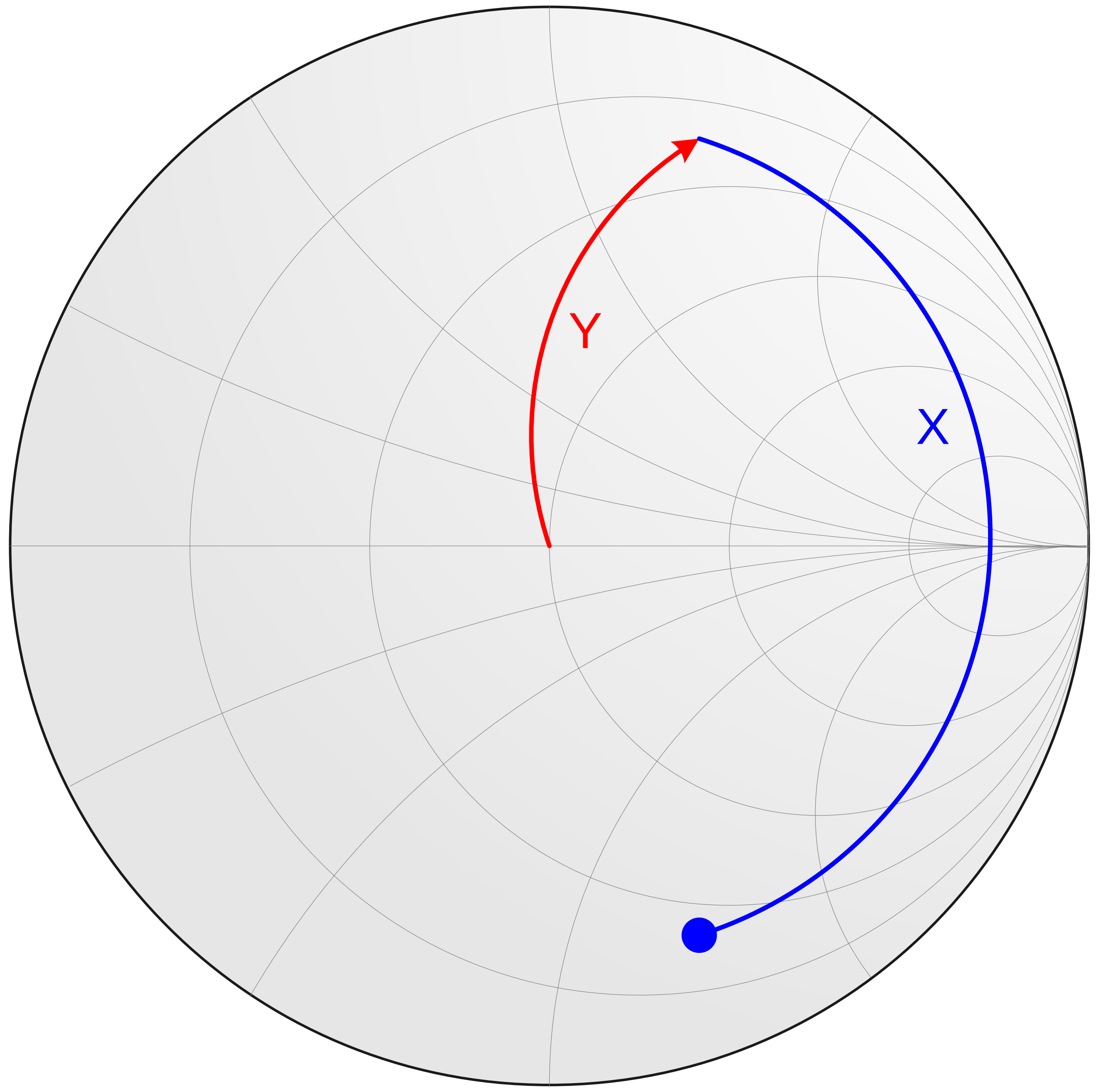
Higher PAR → higher dynamic range

Higher level of integration → new test requirements

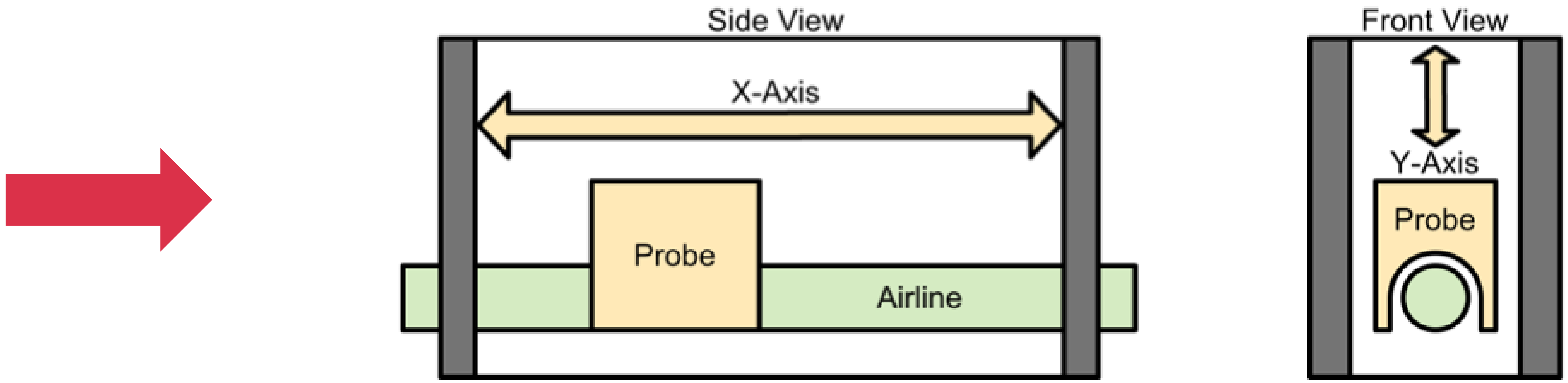
Passive tuning

Slide-screw impedance tuners

- Probe movement above airline controls the reflection coefficient ($\varGamma$)
- Movement on X-axis controls phase of $\varGamma$
- Movement on Y-axis controls magnitude of $\varGamma$
- $|\varGamma|$ is always less than 1 as tuner introduces dissipative loss
- Loss increases with frequency thus $\varGamma$ tunable range shrinks



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



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

Tuning range

Frequency	28 GHz

Ref. formulas:

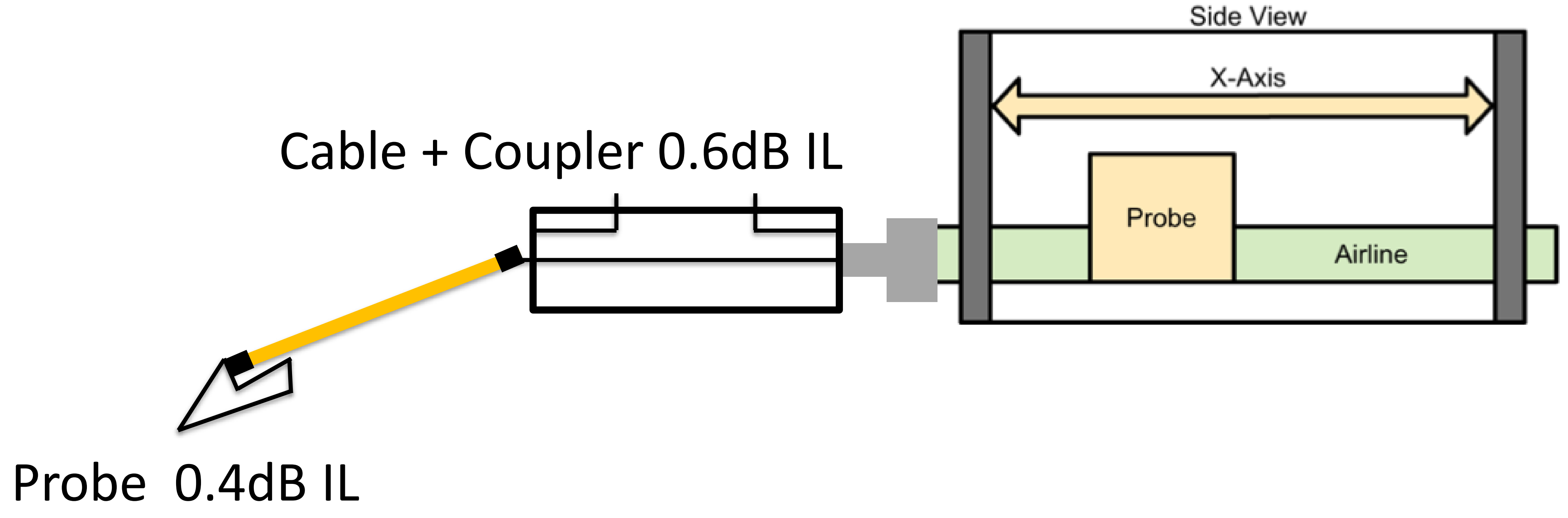
$$RL_{tuner} + RL_{coupler+cable+probe} = RL_{dut}$$

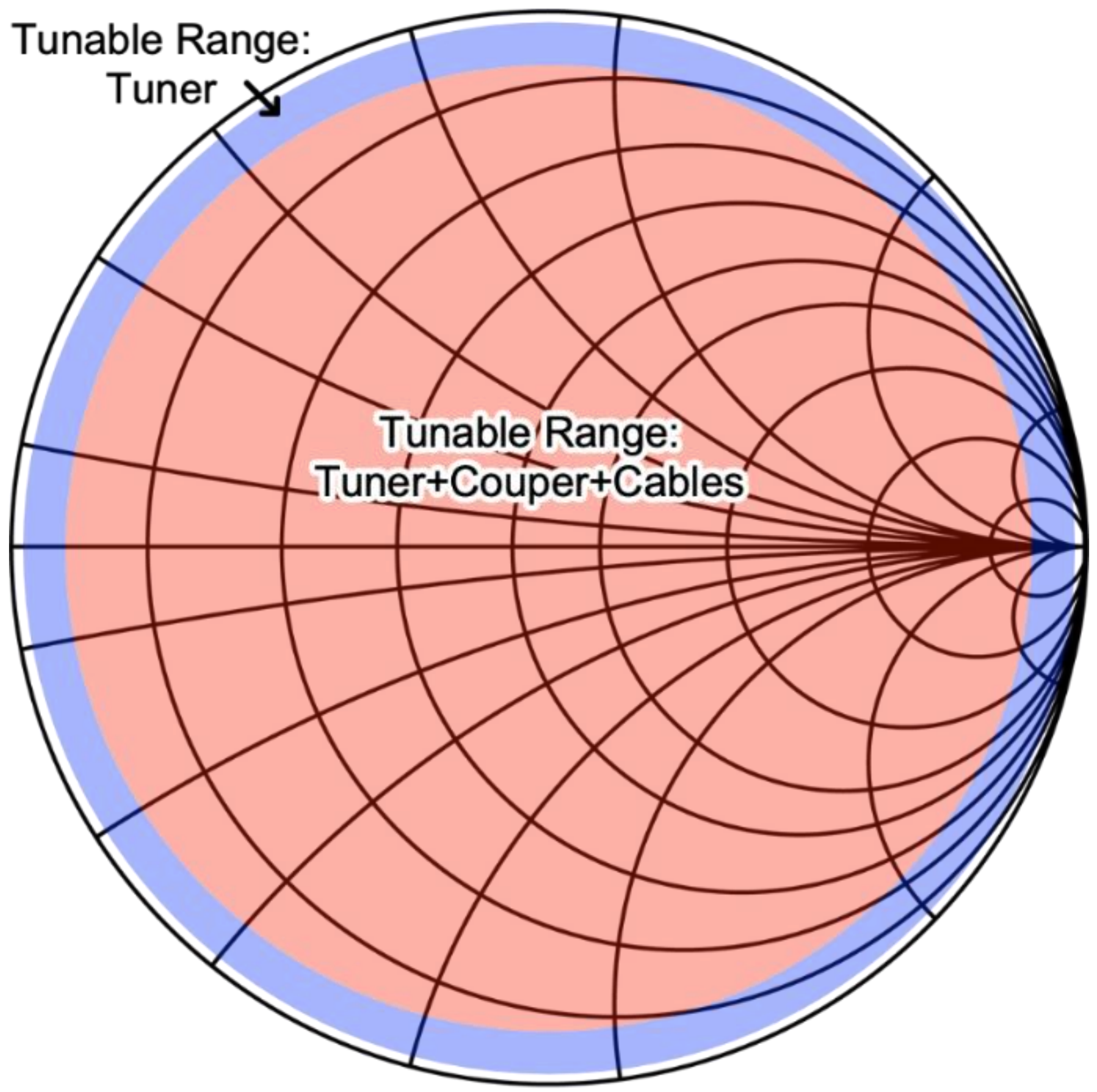
$$RL_{tuner} = -20Log(\frac{VSWR_{tuner} - 1}{VSWR_{tuner} + 1})$$

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

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

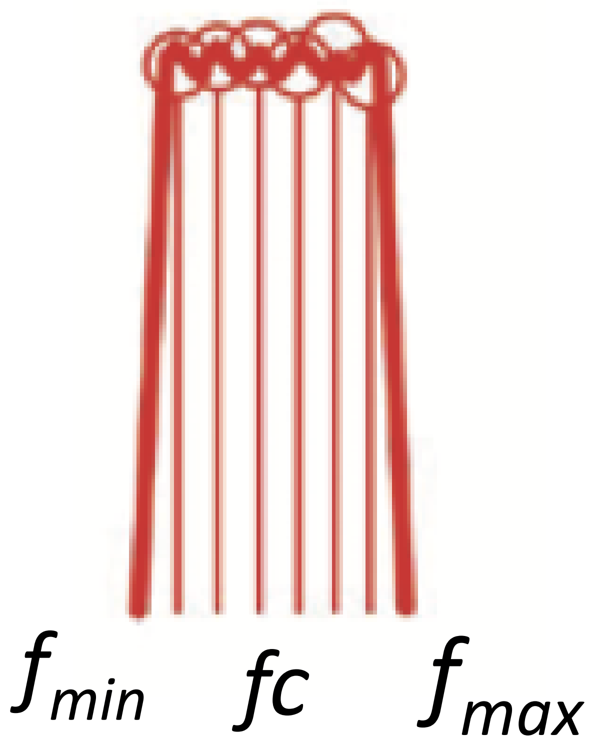
- $VSWR_{tuner}$= 15:1 → $|\Gamma_{tuner}|$= 0.87
- $IL_{coupler + cable + probe}$ = 1 dB
- $VSWR_{Load}$ = 5.6:1 → $|\Gamma_{load}|$ = 0.69

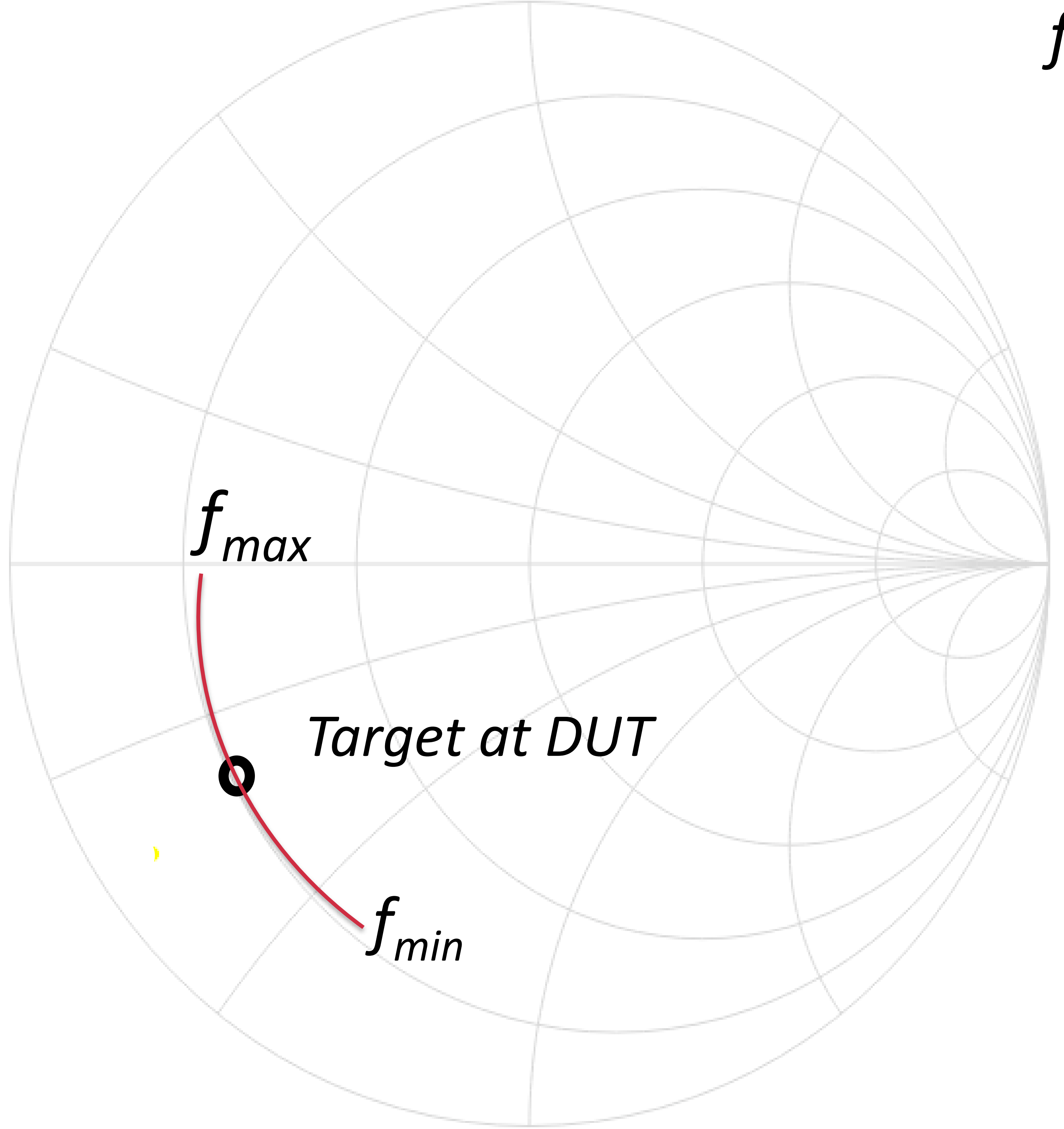


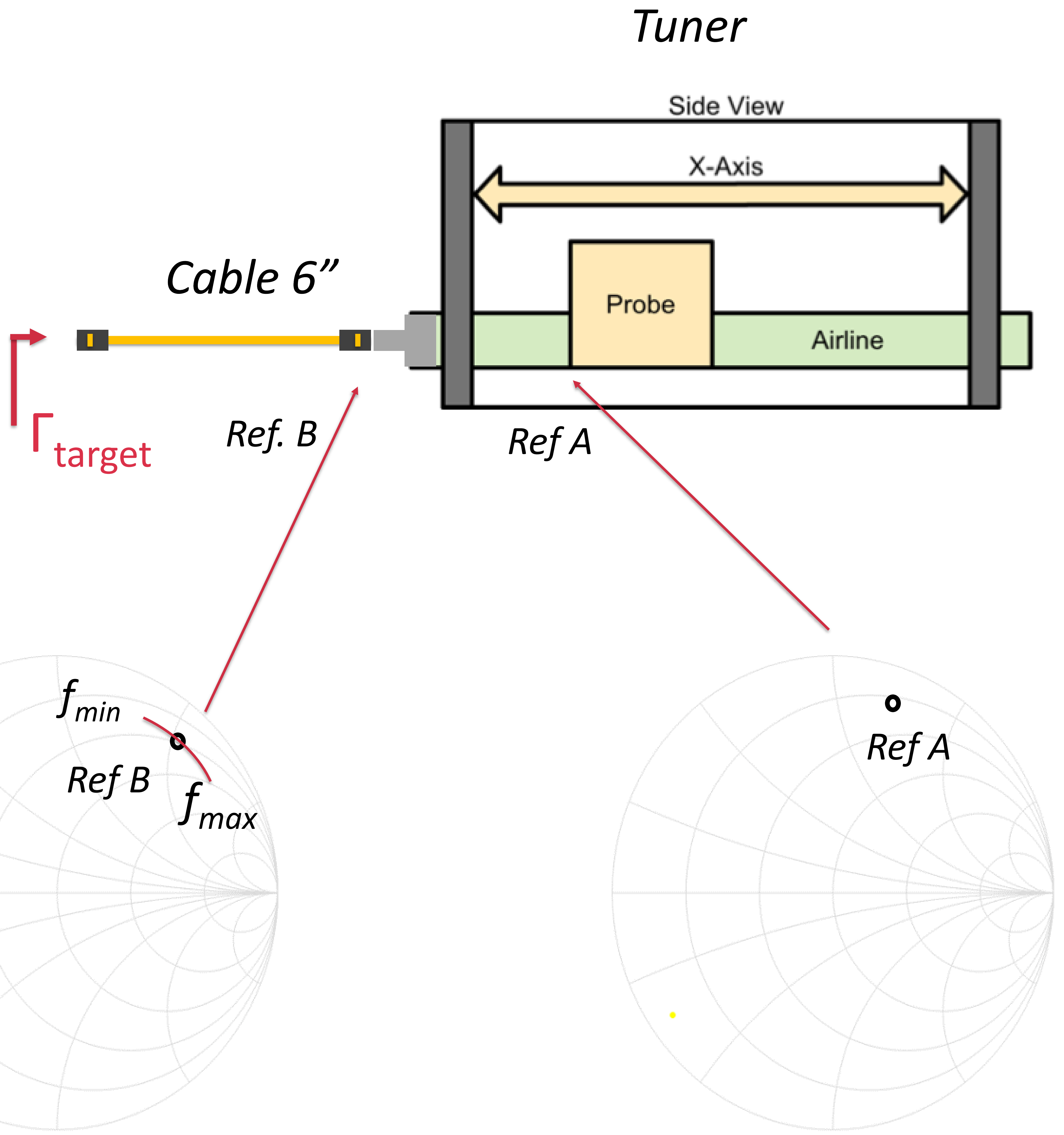


Phase skew

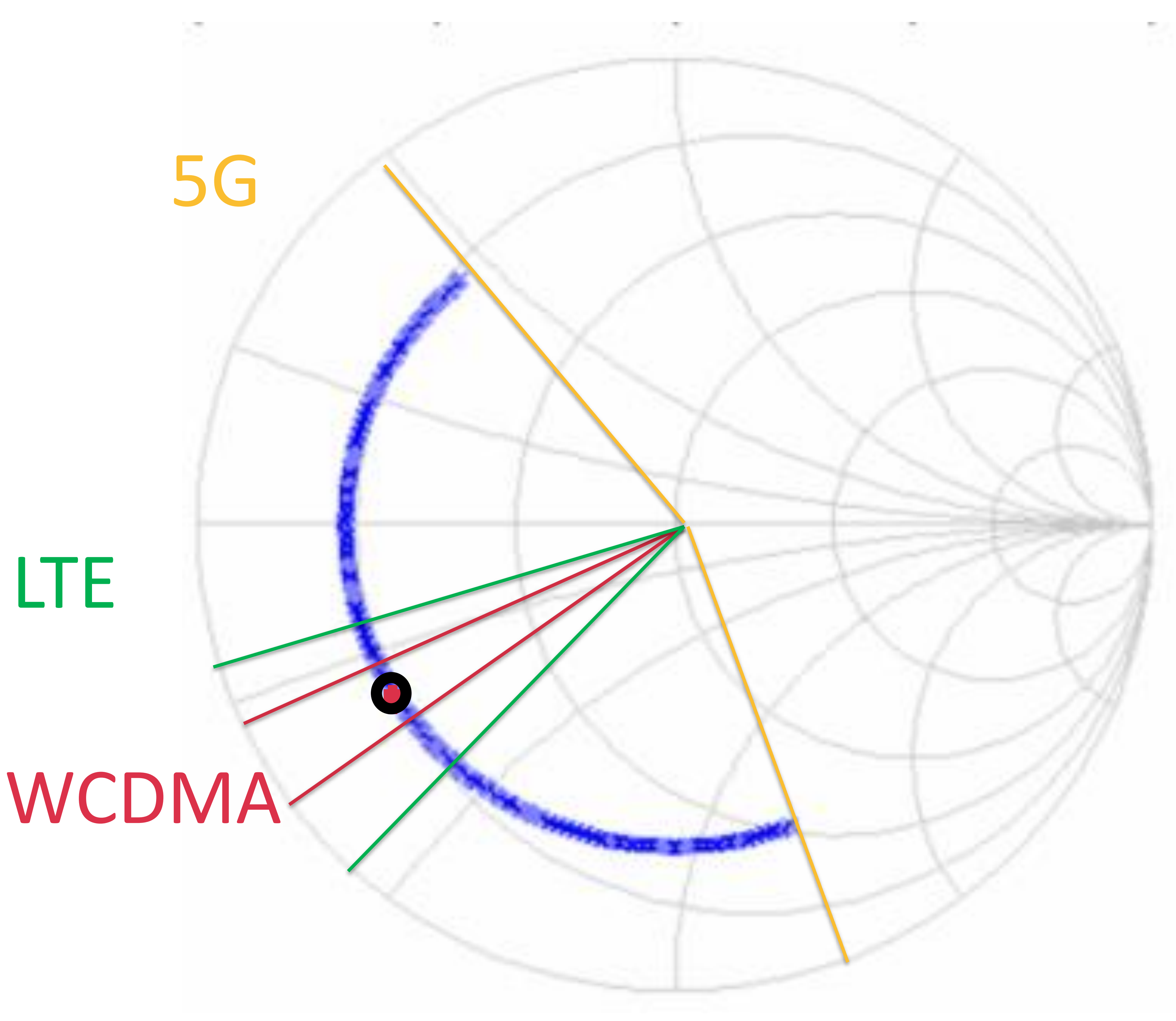
Modulated signal



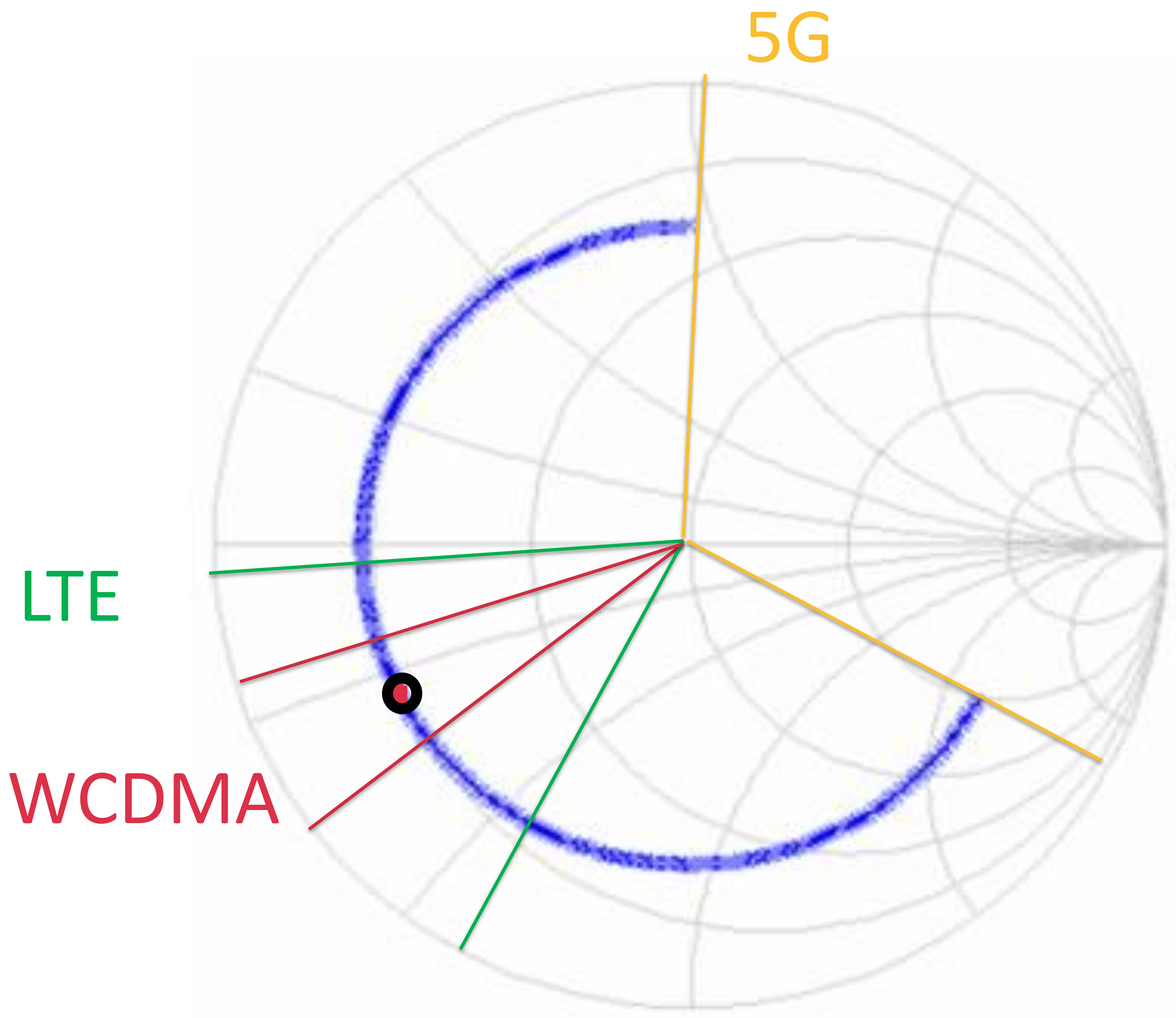




Phase skew



Tuner ref



Tuner + short trace line

target

FR2 and Nano5G

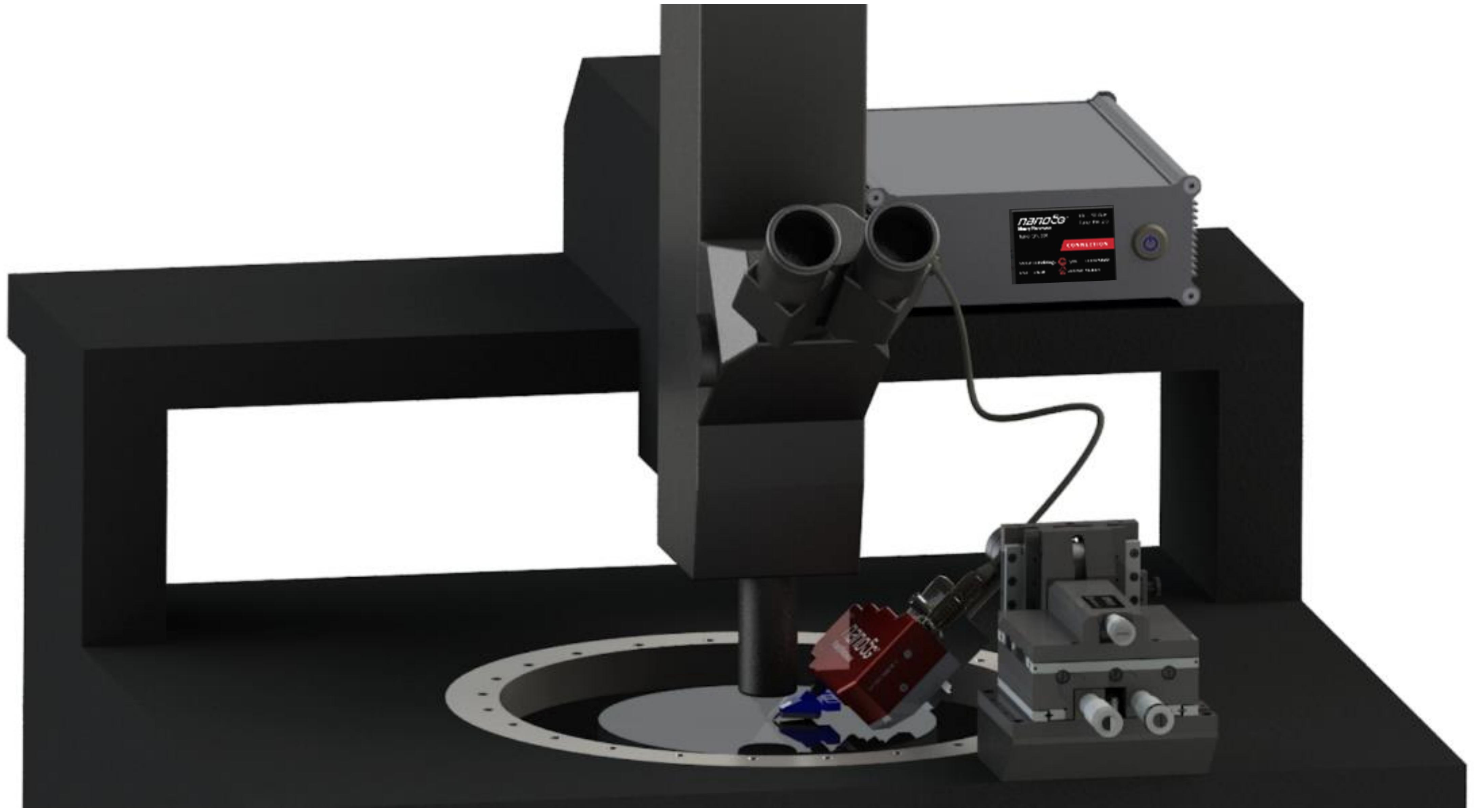
Challenges:

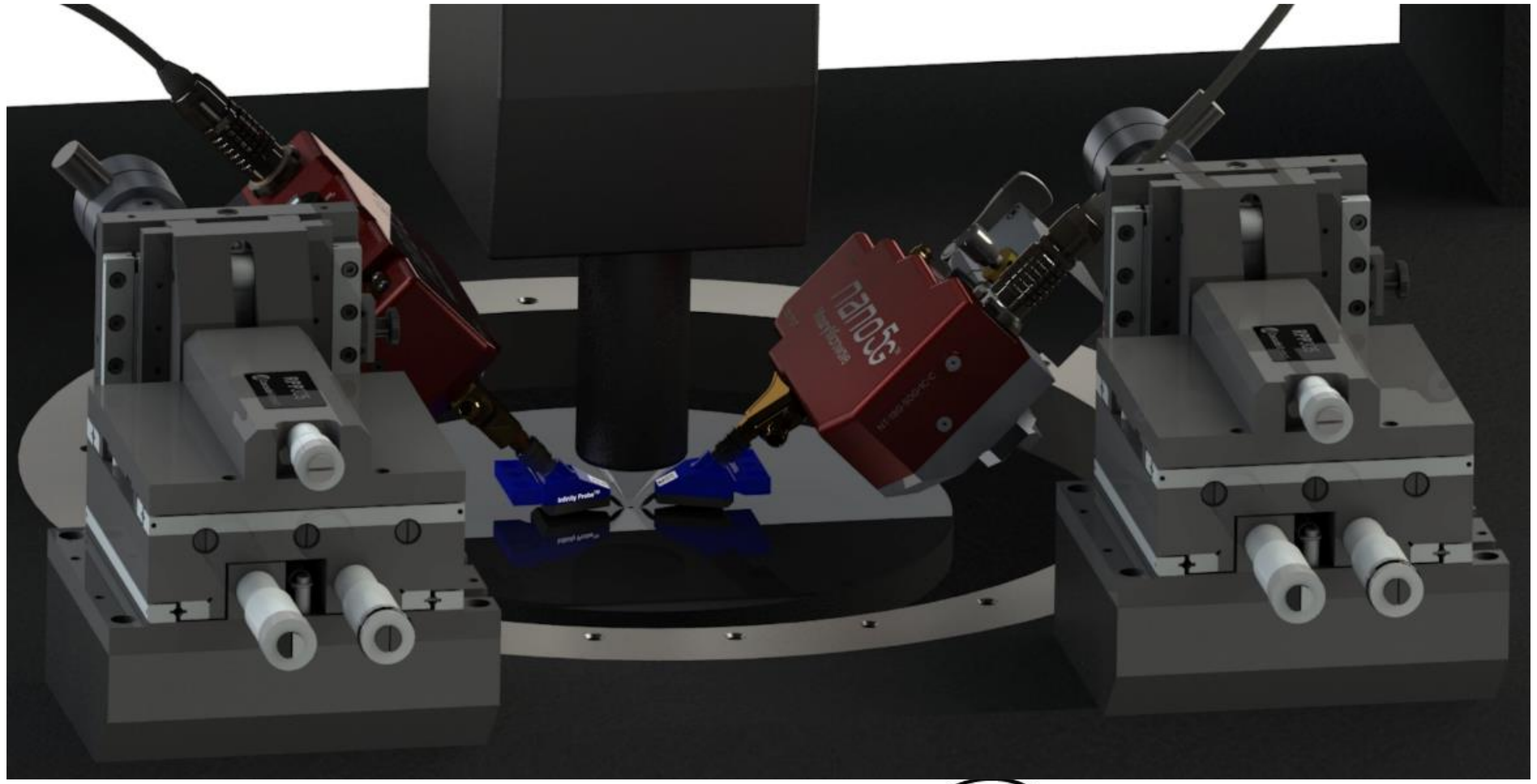
- Tuning range
- Phase skew
- Speed and accuracy
- Easy SW integration

Maury is introducing at IMS2021 **Nano5G**,
18 GHz-50 GHz tuner directly mounted to probe:

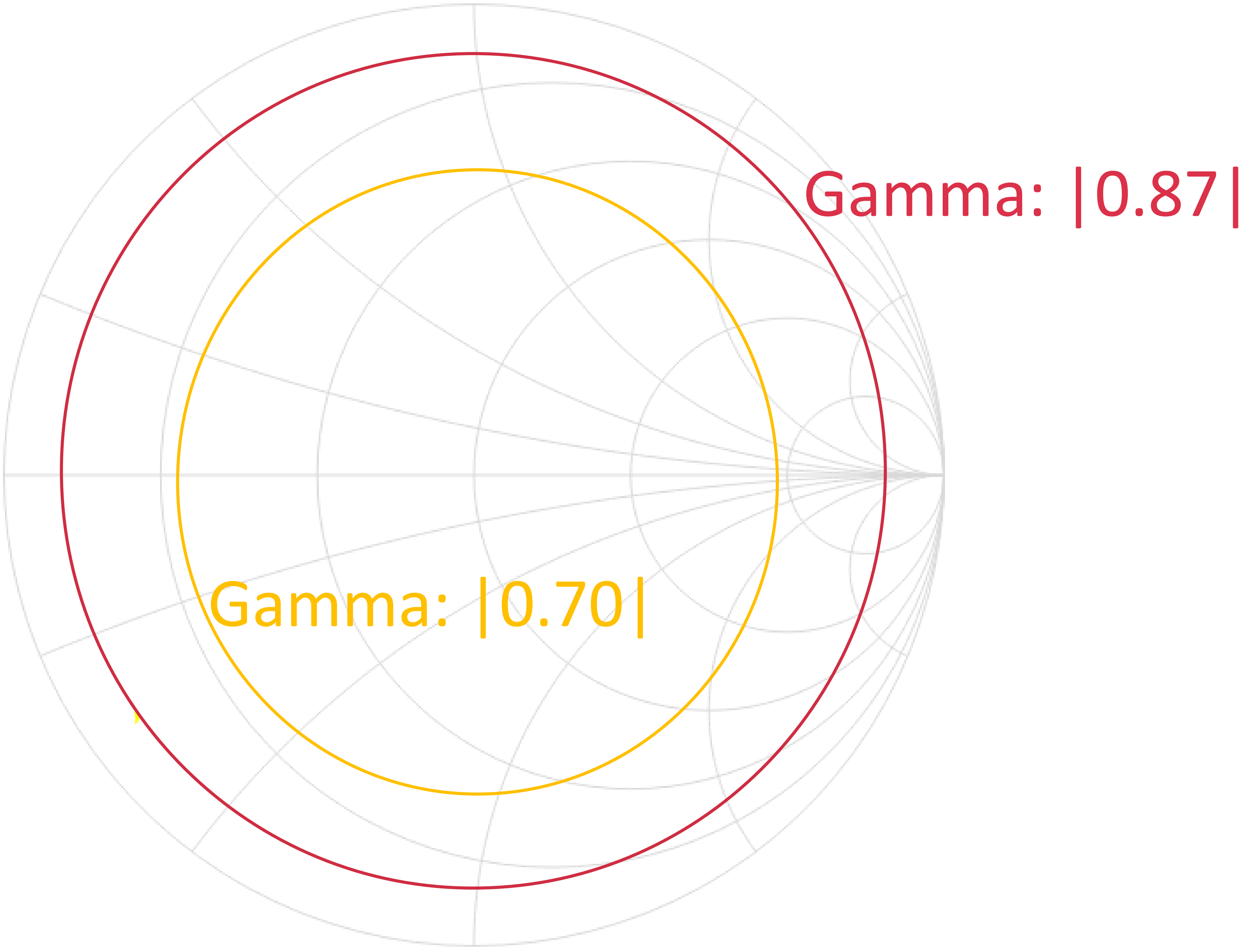
Nano5G:

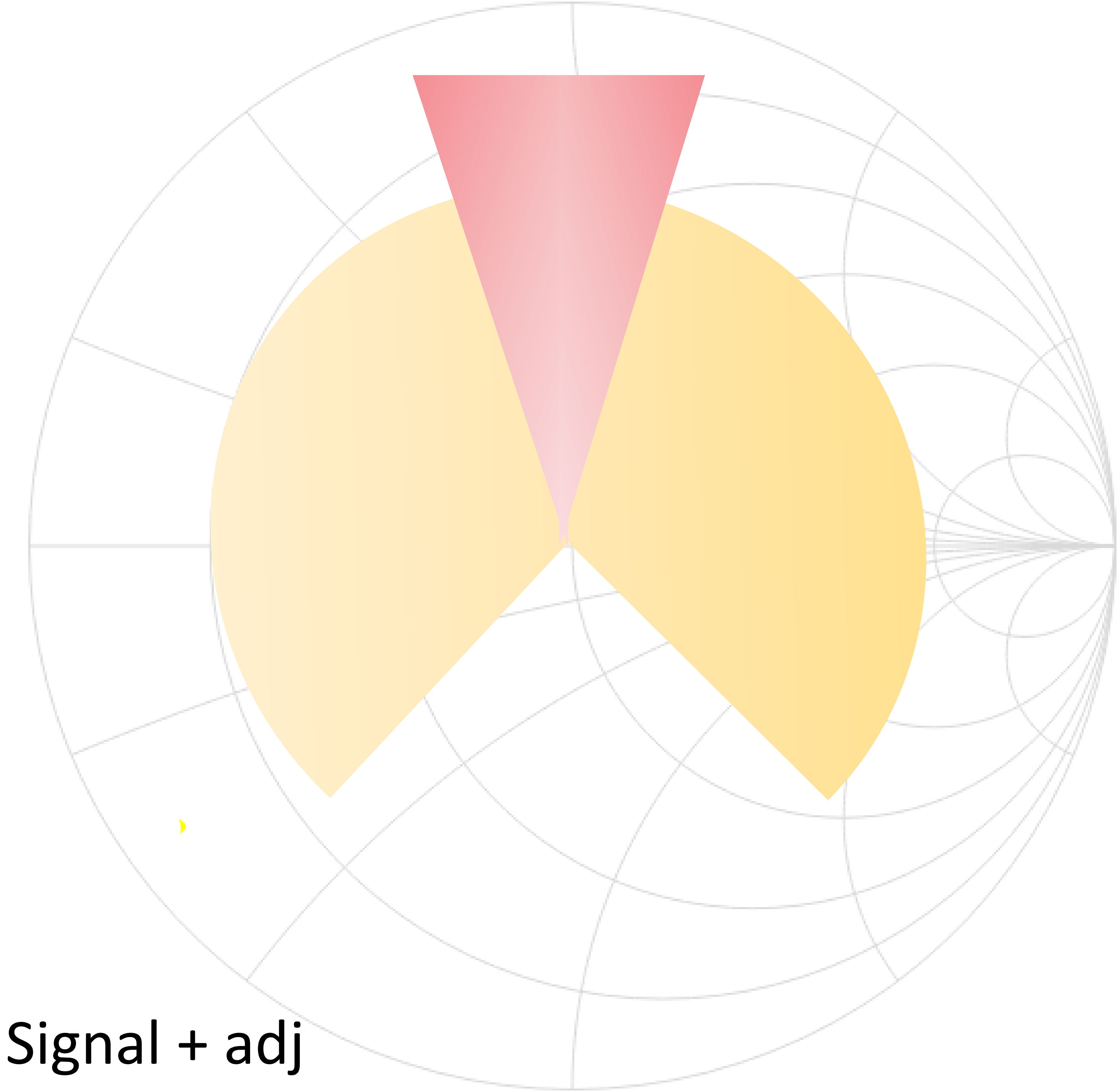
- 1/10 of the volume and weight of other solutions:
  - Weight: 0.7 lbs
  - Dimensions: 2.35”x 1.57” x 4.5”
- No cable needed between probe and tuner
- Integrated coupler (optional)





Features and benefits





100MHz Signal + adj channels (left and right)

Tuning range

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

Phase skew

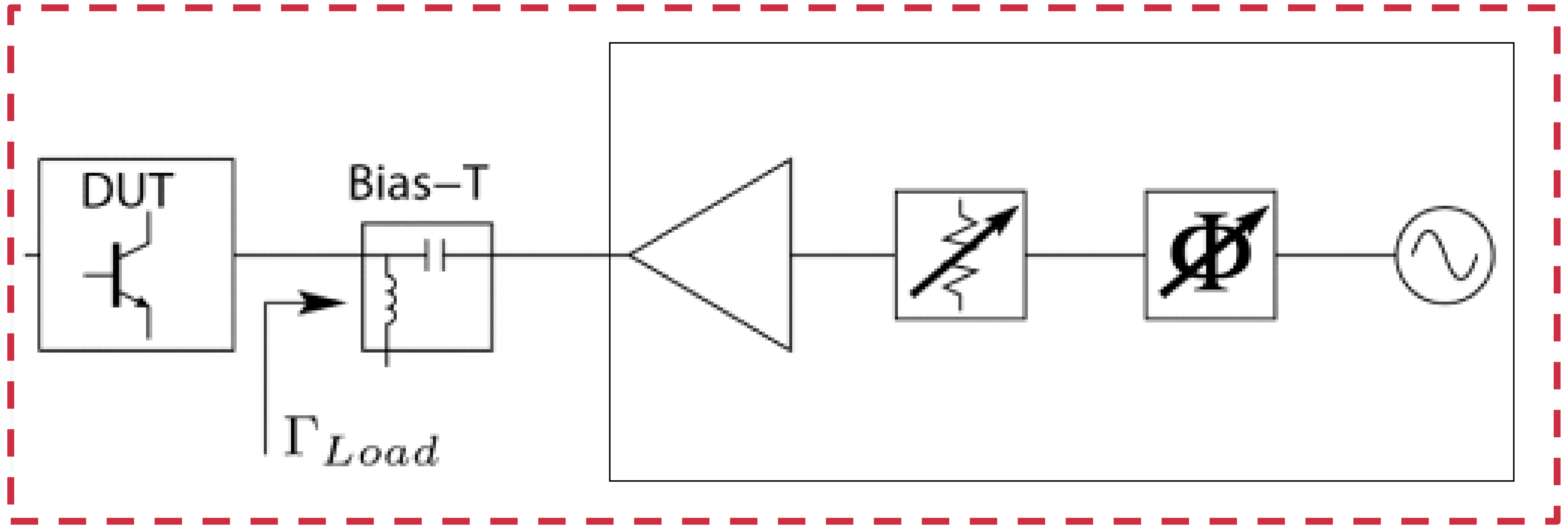
(MT984AL01 + coupler with integration cable + probe vs Nano5G + probe)

Active tuning

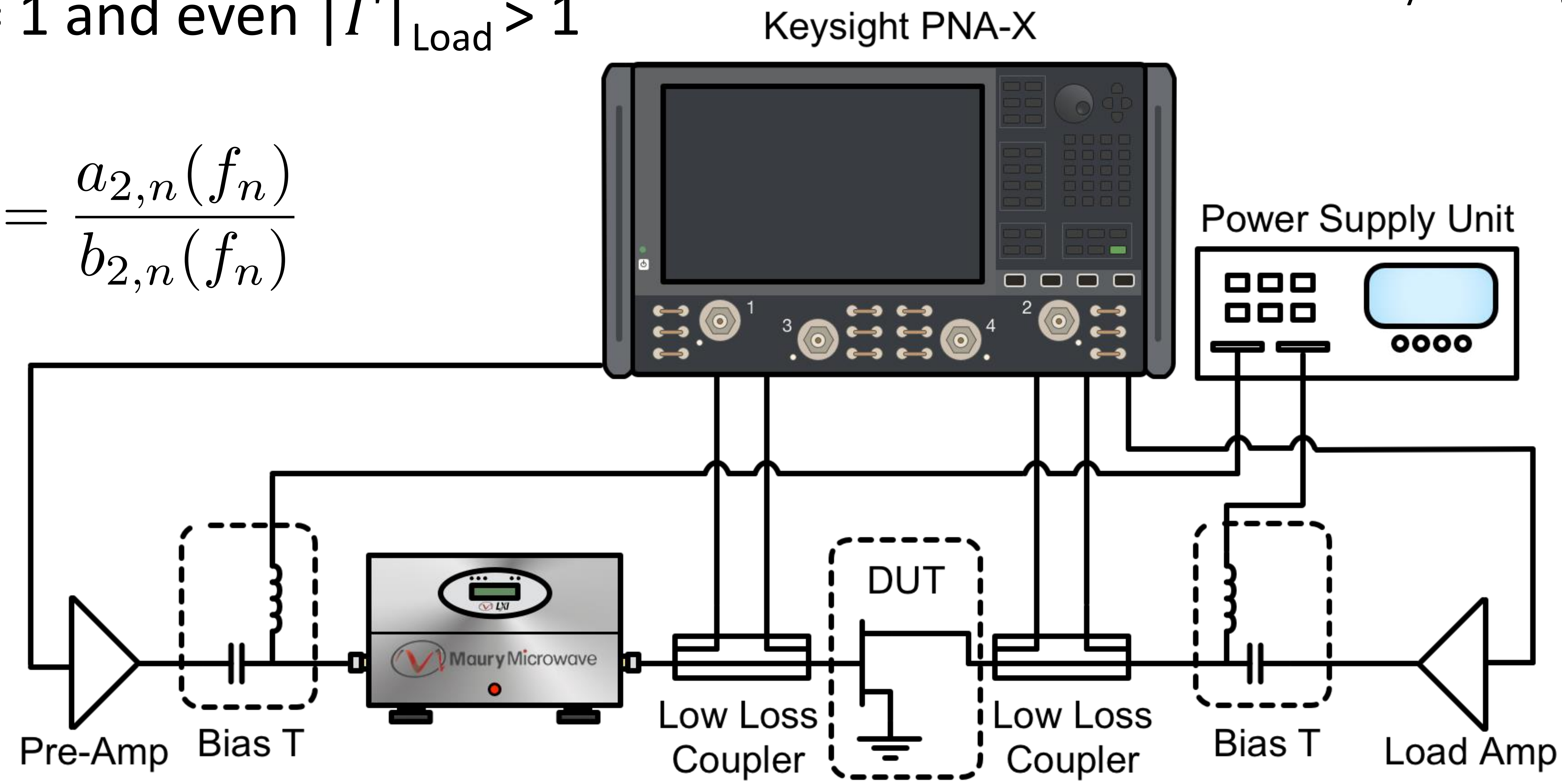
Active load pull

- 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 $|\Gamma|_{Load} > 1$

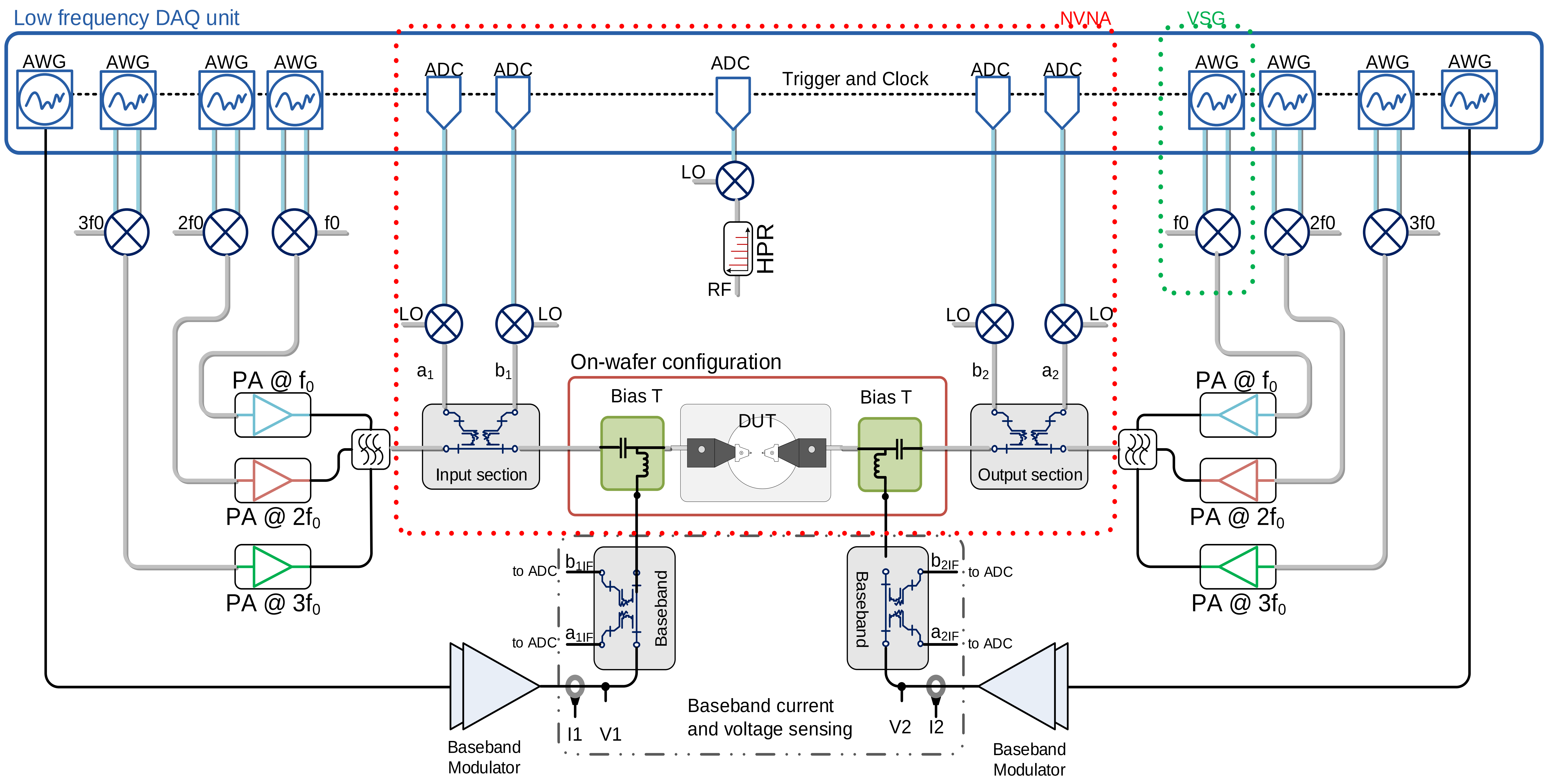
$$\Gamma_{Load,n}(f_n) = \frac{a_{2,n}(f_n)}{b_{2,n}(f_n)}$$



Gamma controlled by active signal injection

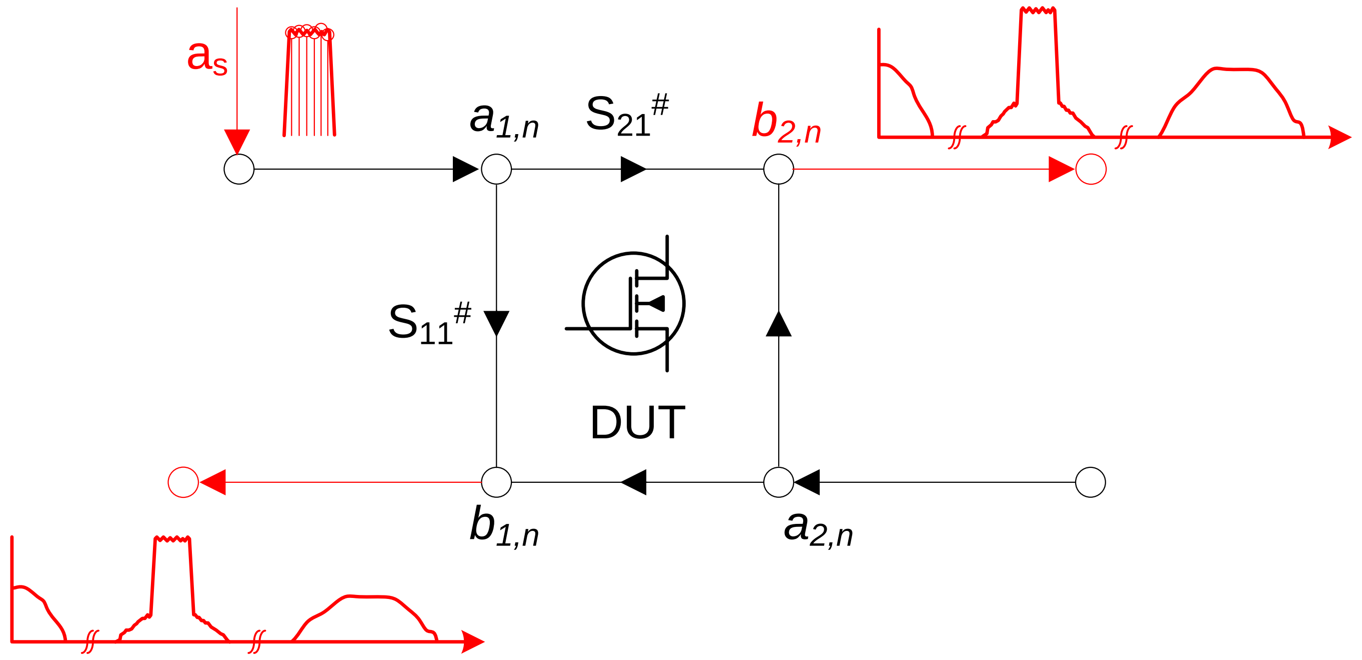


MT2000 mixed-signal vector load-pull for modulated signal characterization

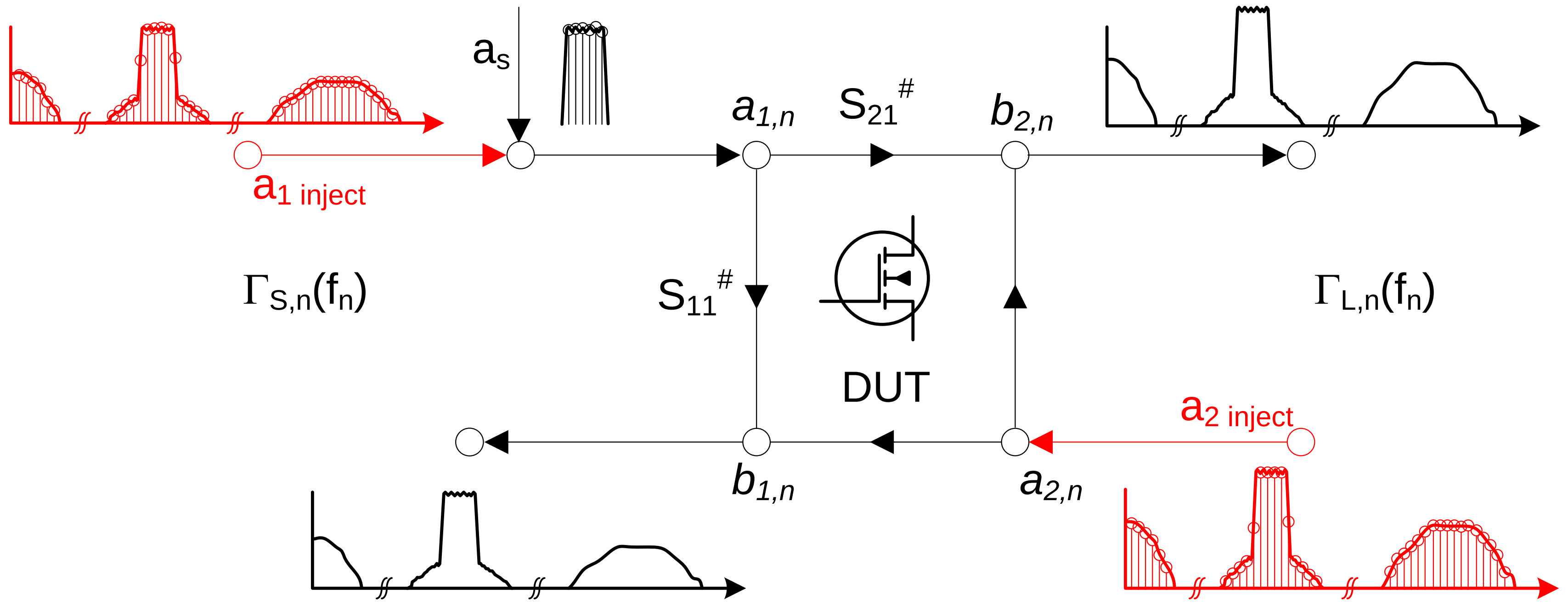


- (N)VNA-like receiver architecture without narrowband filtering in order to allow wideband modulation acquisition
- Multiple vector signal generators (AWGs) are used as active tuners

Wideband Load Pull Algorithm



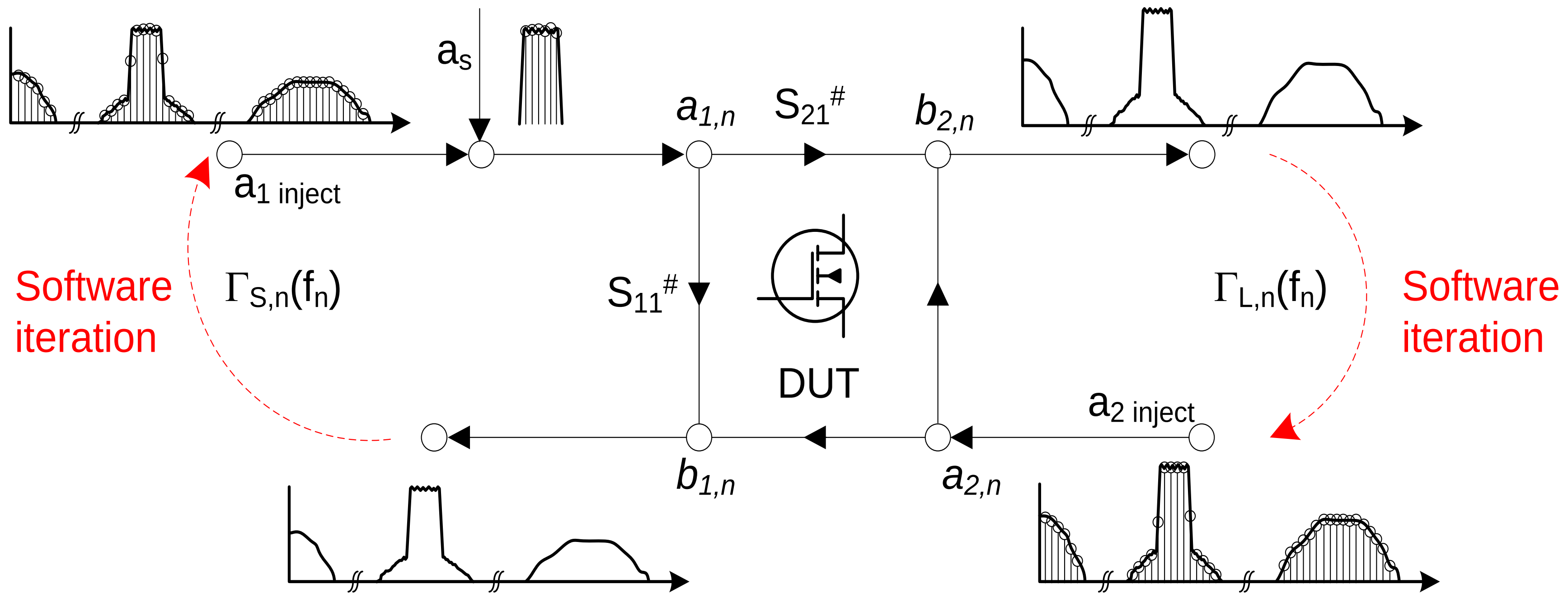
Step 1: A non-linear device excited with a modulated signal will emanate waves (b-waves) at the harmonic and baseband frequencies



Step 2: By measuring the Γ at the DUT, the a-waves to be injected to obtain a user-specified reflection coefficient can be estimated.

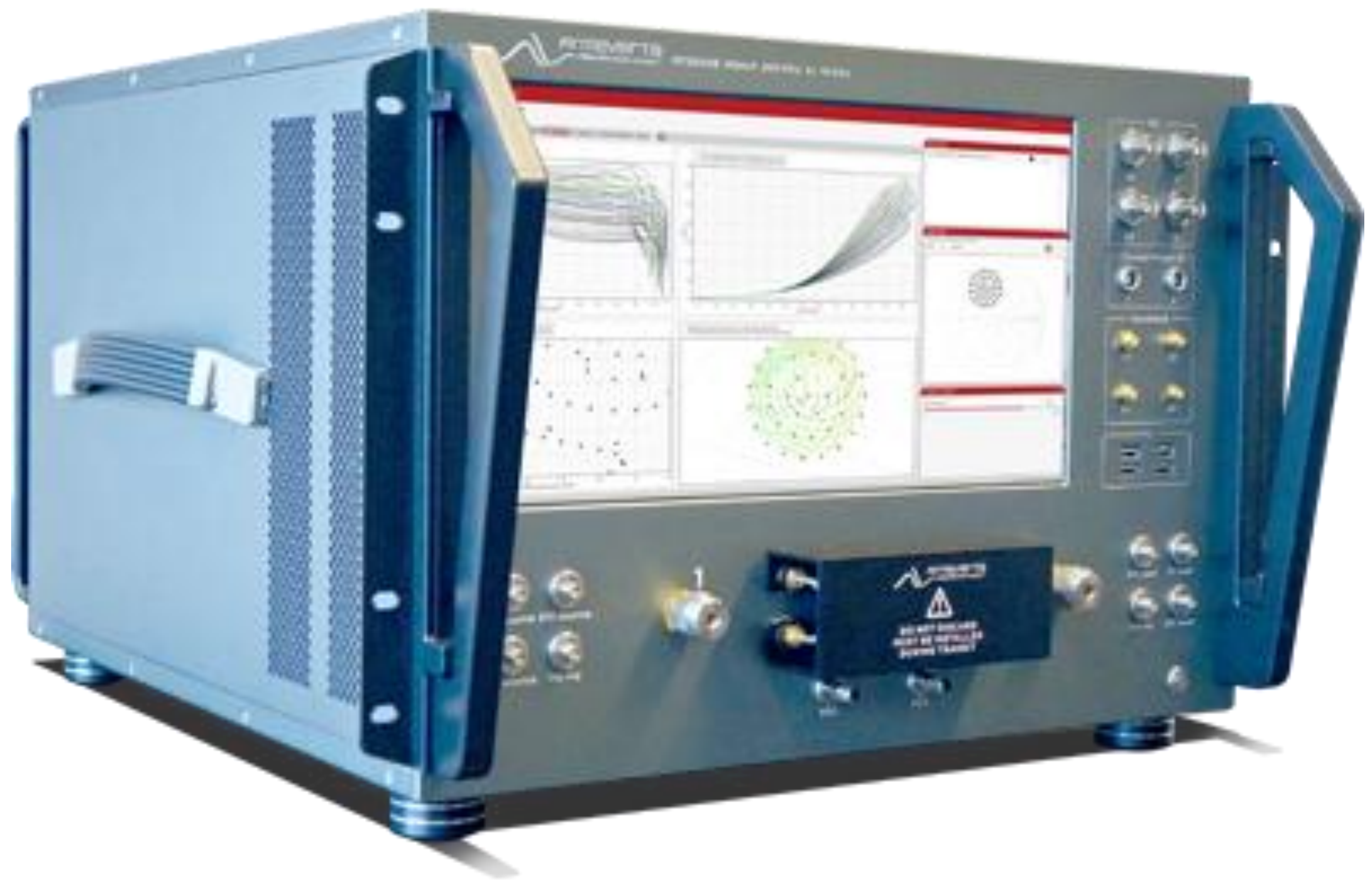
$$\Gamma_{x,n}(f_n) = \frac{a_{x,n}(f_n)}{b_{x,n}(f_n)}$$

x = source (s) or load (l)
n = frequency band, e.g. baseband (0), fundamental (1) and harmonic (2 and up)
$\Gamma_{x,n}(f_n)$ = user defined reflection coefficient vs. frequency



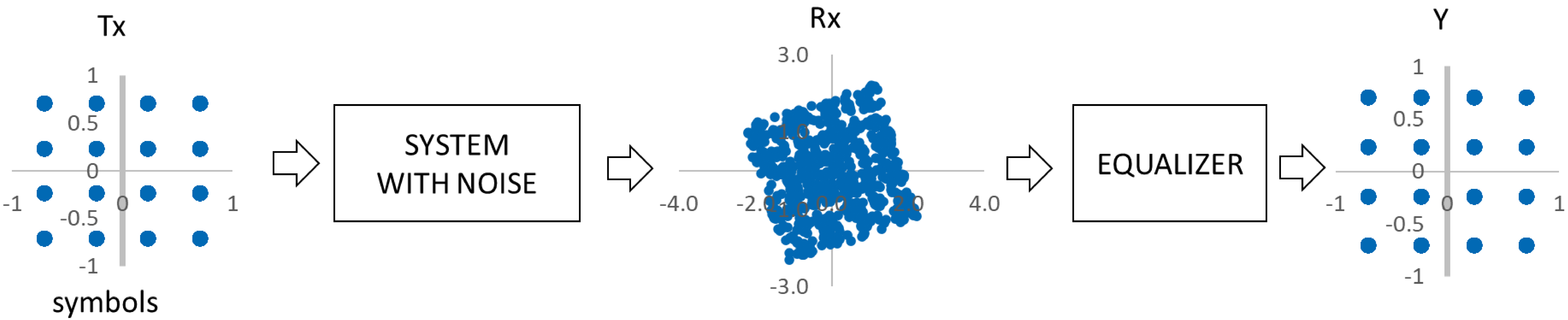
Step 3: Software iteration based on the reflection coefficient measurements at the DUT reference planes

Key features



- Traditional analog and microwave techniques with low-frequency signal acquisition (A/D converters) and generation (Wideband AWG);
- Ultra fast CW and pulsed CW load pull
- Wideband ADCs allow measurement of wideband signals (power, ACPR, EVM)
- Frequency scalable: currently up to **67 GHz**
- System includes **6 VSGs** to generate custom modulations up to **1000 MHz** bandwidth
- Each VSG can be used as an active tuner
- VNA + NVNA + Oscilloscope + Signal Analyzer + Behavioral Model extraction in one solution

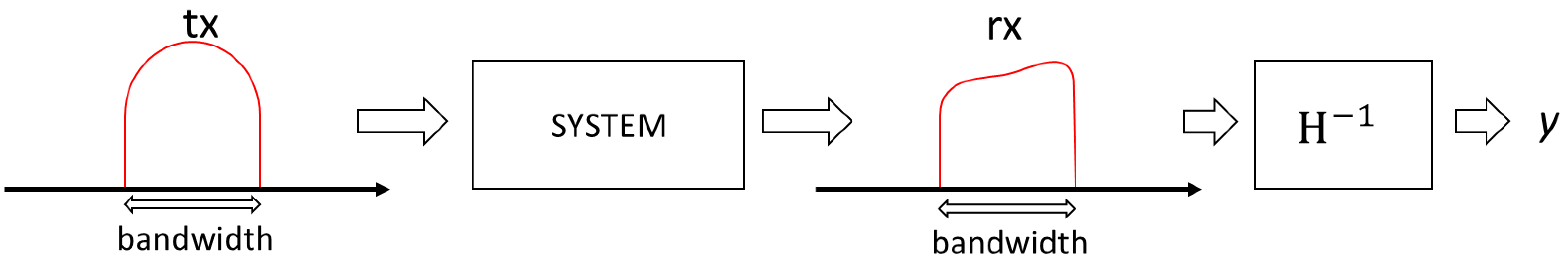
EVM measurements - background



- linear and nonlinear distortion;
- thermal noise;
- ISI;

$$\mathrm{EVM} = \sqrt{\frac{\sum |Y - T_x|^2}{\sum |T_x|^2}}$$

Generalized EVM measurement method



$$\mathrm{Rx(f)} = \mathrm{H(f)Tx(f)} + \mathrm{D(f)}$$

$$\mathrm{rx} = \mathrm{h} \otimes \mathrm{tx} + \mathrm{d}$$

d is the uncorrelated distortion

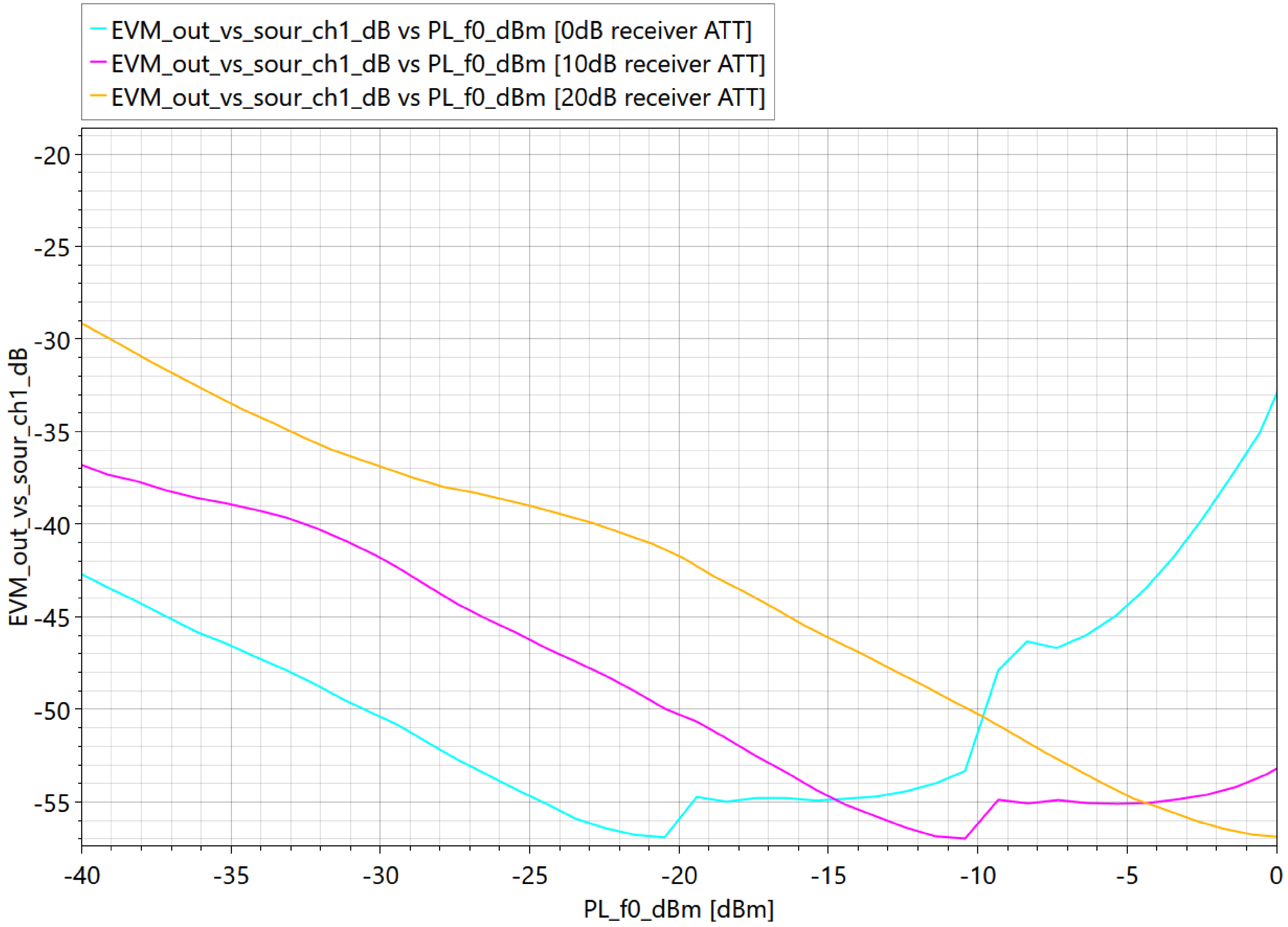
$$\mathrm{EVM} = \sqrt{\frac{\sum|y-\mathrm{tx}|^2}{\sum|\mathrm{tx}|^2}} = \sqrt{\frac{\sum|h^{-1} \otimes rx - \mathrm{tx}|^2}{\sum|\mathrm{tx}|^2}}$$

Estimation of filter[1,2] h

[1] Linear Approximations of Nonlinear FIR Systems for Separable Input Processes, *Martin Enqvist, Lennart Ljung, 2005*

[2] Measurement Methods for Estimating the Error Vector Magnitude in OFDM Transceivers, *Karl Freiberger, 2017*

EVM measurements: noise floor

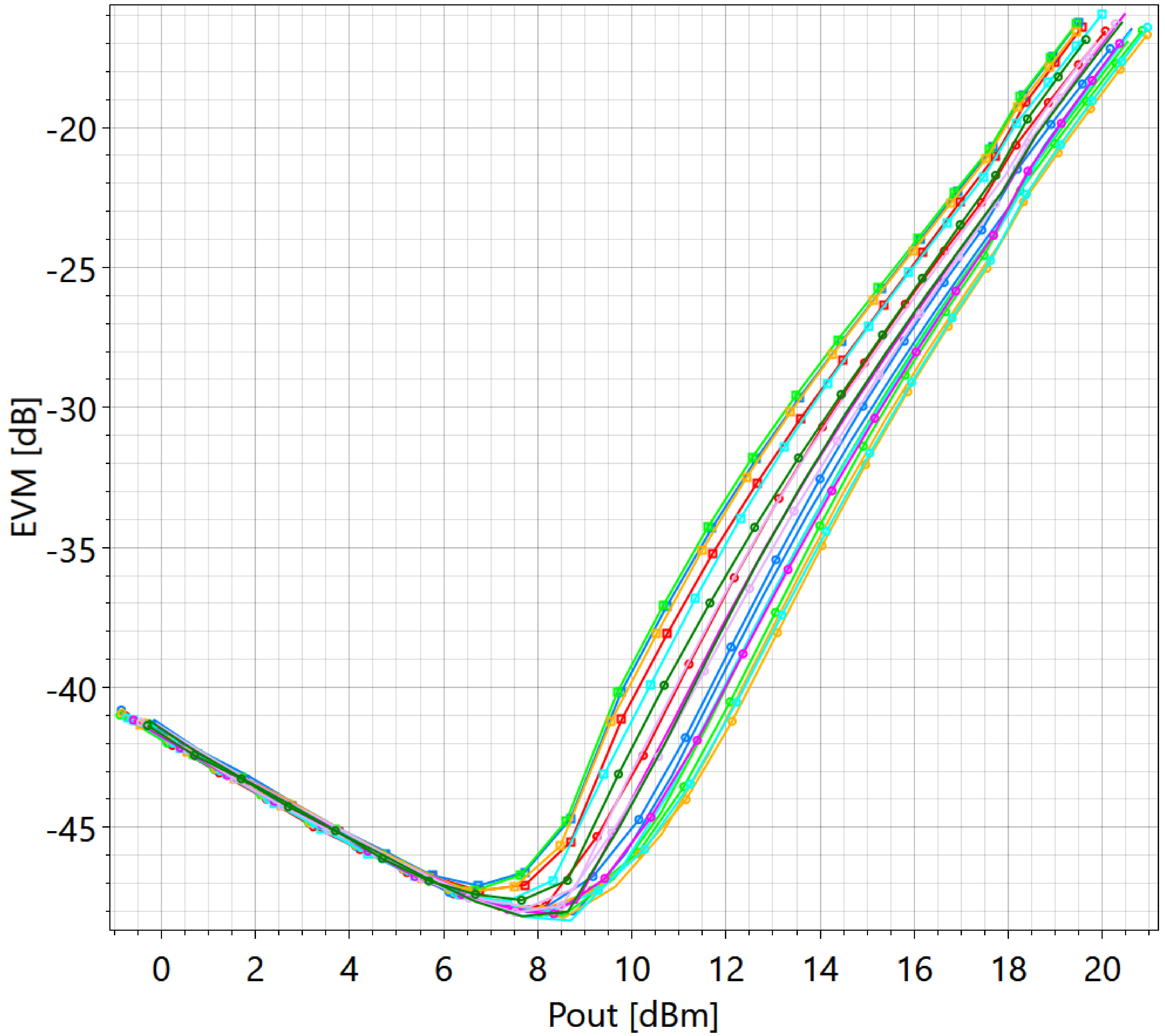


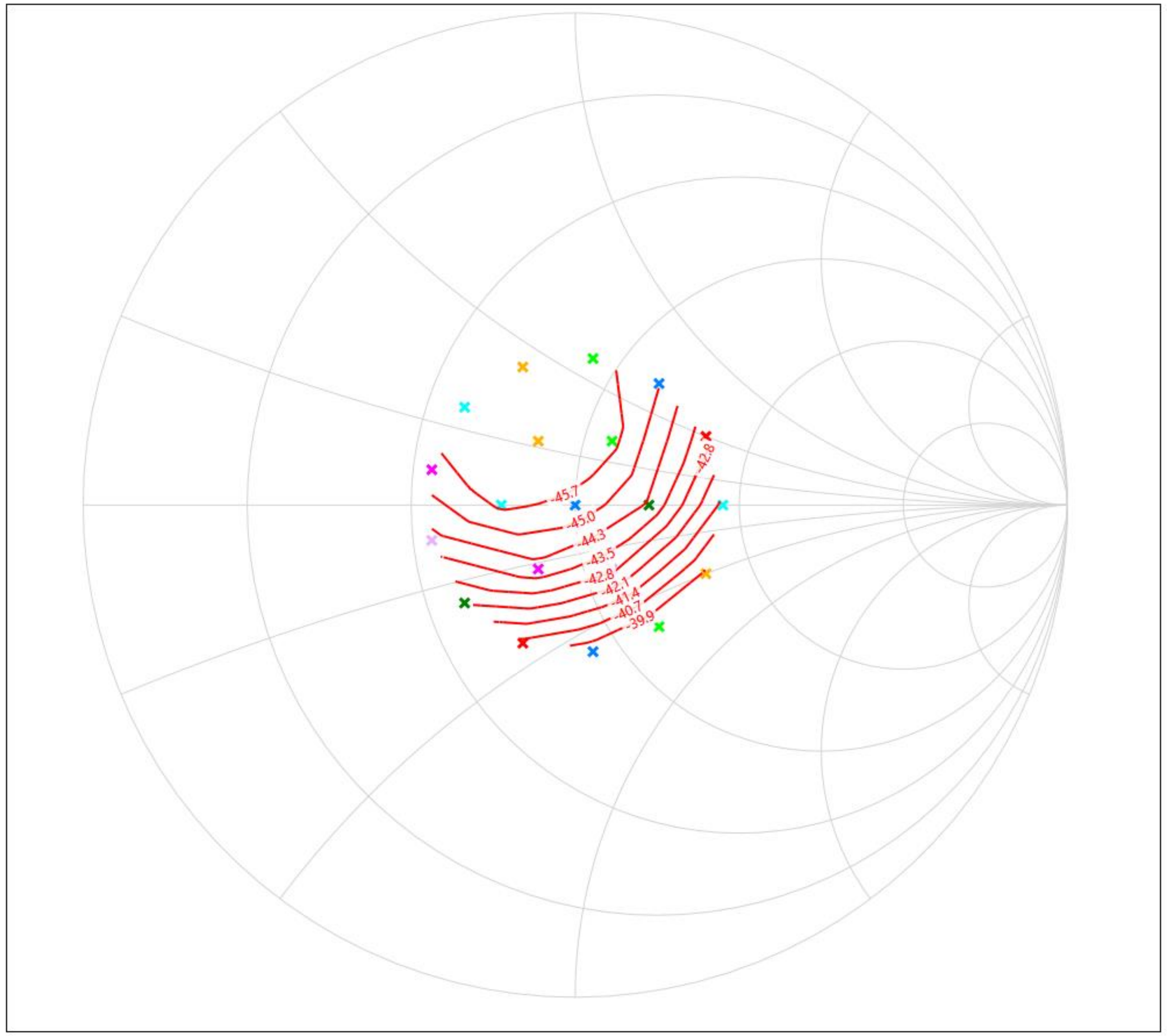
- Signal: fr2_64qam_100M_120khz_cpofdm
- Carrier frequency = 9 GHz

Comments:

- Receiver stepping automated to optimize noise floor across power sweep

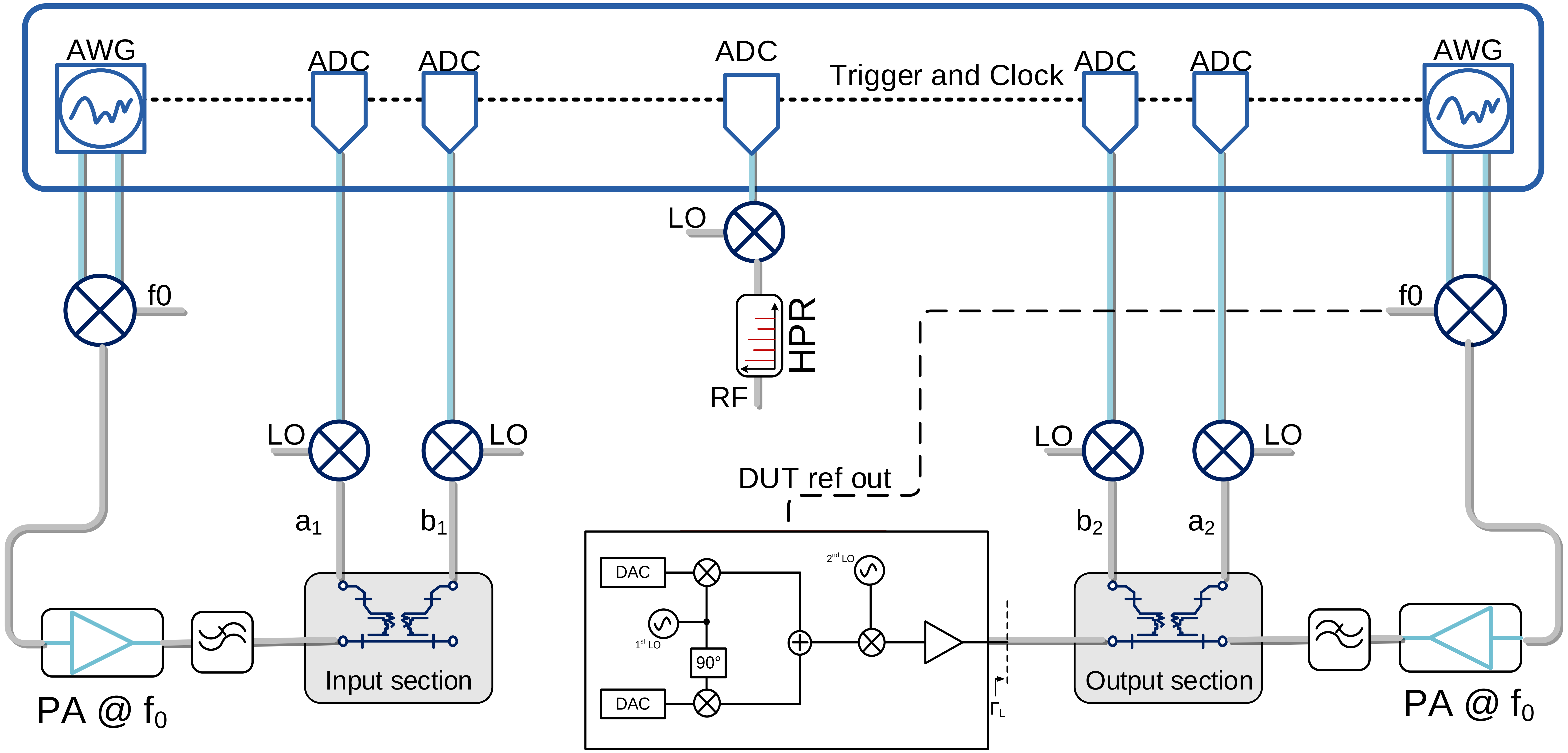
EVM measurements w/ active load pull





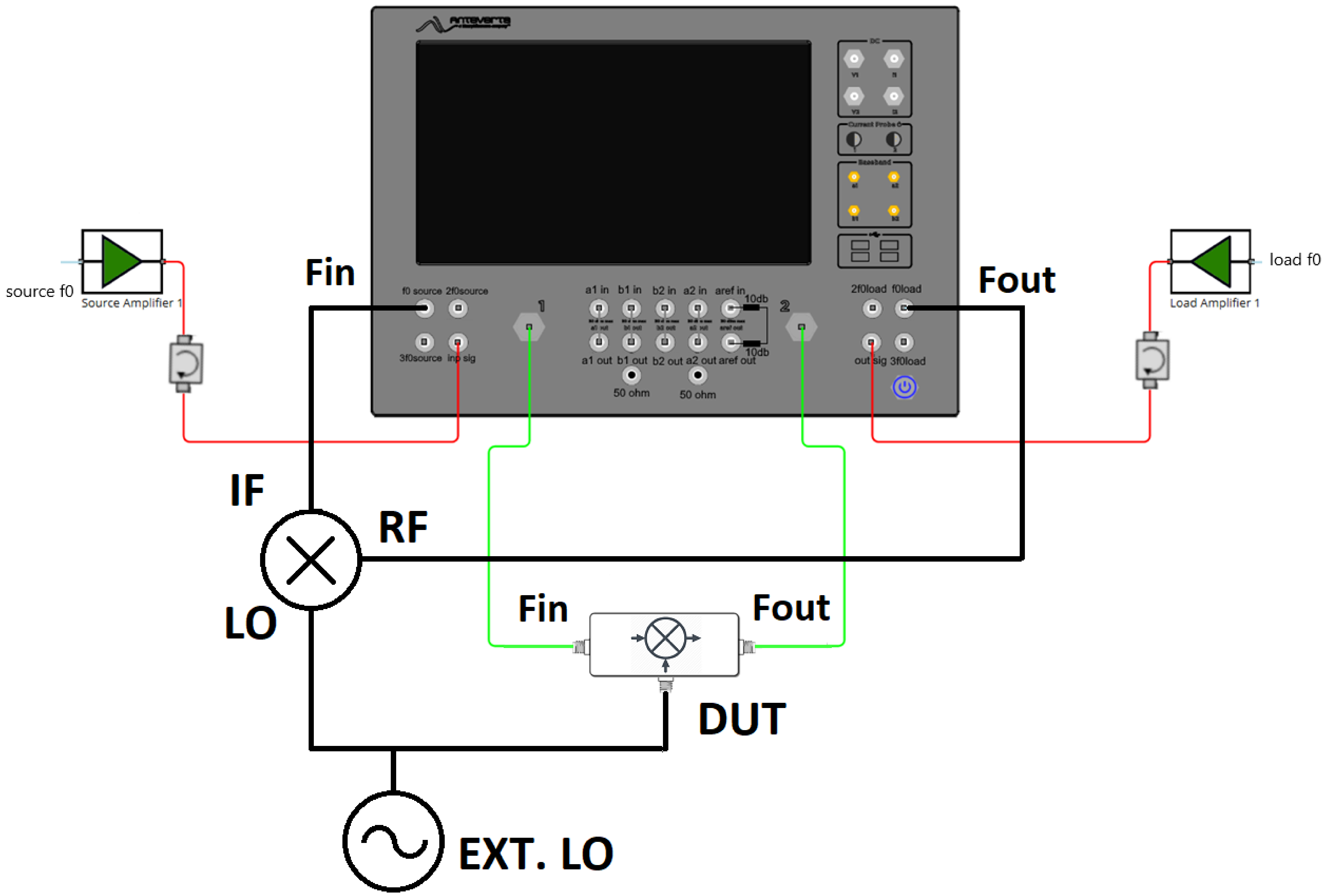
- WLAN 80211ax MCS9 3.5 GHZ, BW = 320 MHz
- Measurements on a matched amplifier module

One-port load pull



- IQ modulator can be driven by an external LO (CW) signal at f0 to achieve phase lock.
- CW, pulse CW and modulated testing are possible in this configuration

Load-pull on upconverters

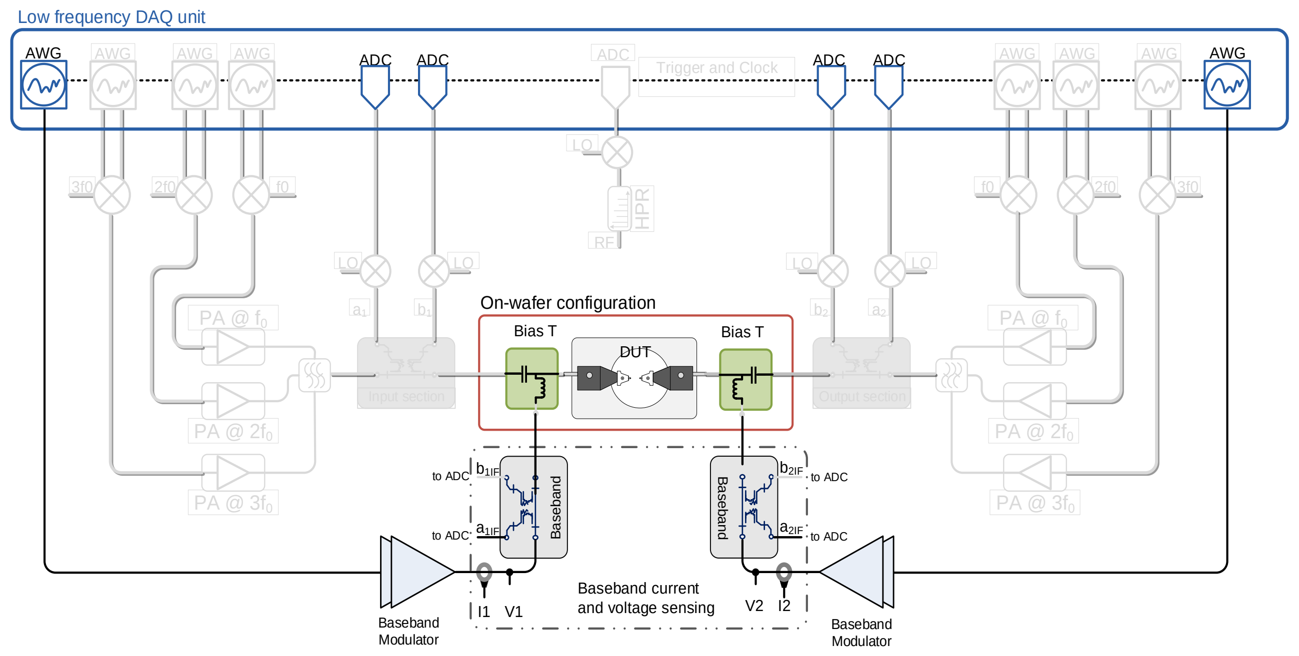


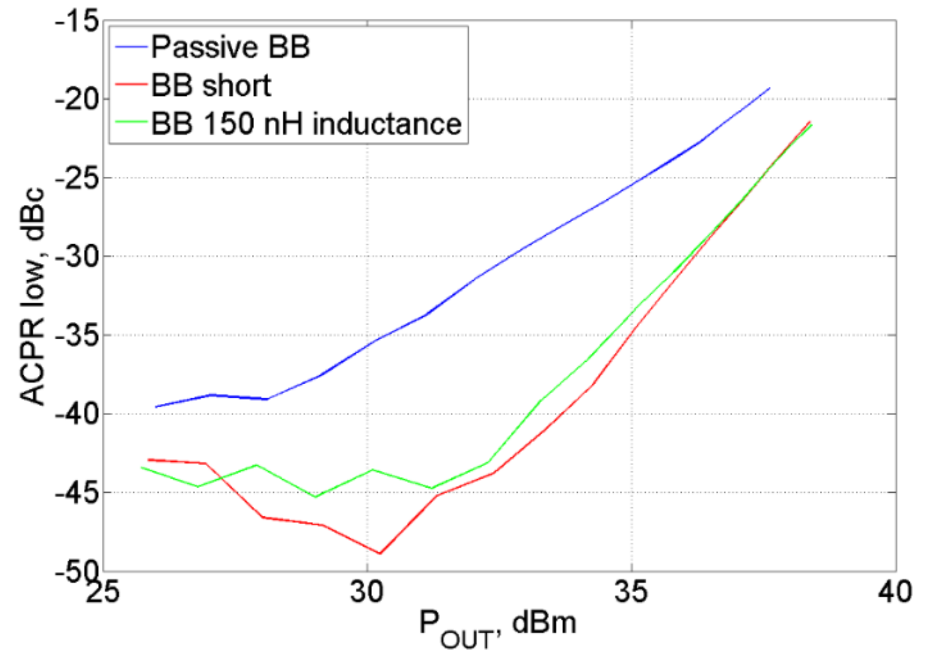
- An external LO is used by the DUT for the up-conversion from Fin to Fout

- The same LO is used with an auxiliary mixer to up-convert the system source signal (Fin) and generate the signal used for the load impedance control (Fout)

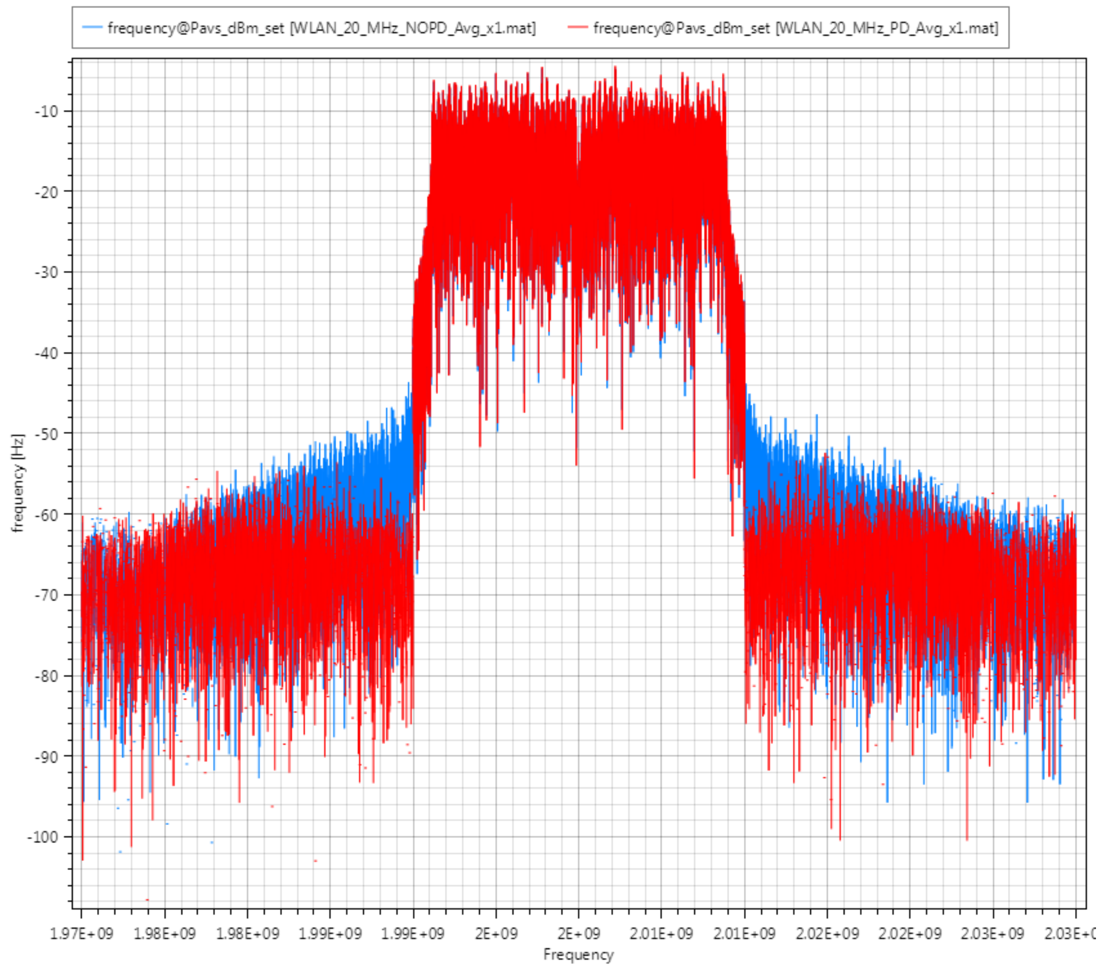
Additional requirements

- Baseband impedance control
  - Active load-pull applied to tune baseband impedance to enhance linearity (up to 200 MHz)





- DPD under load-pull conditions (spectral DPD, time-domain DPD)



...

mmW and sub-THz waveguide passive, active and hybrid-active vector-receiver load pull

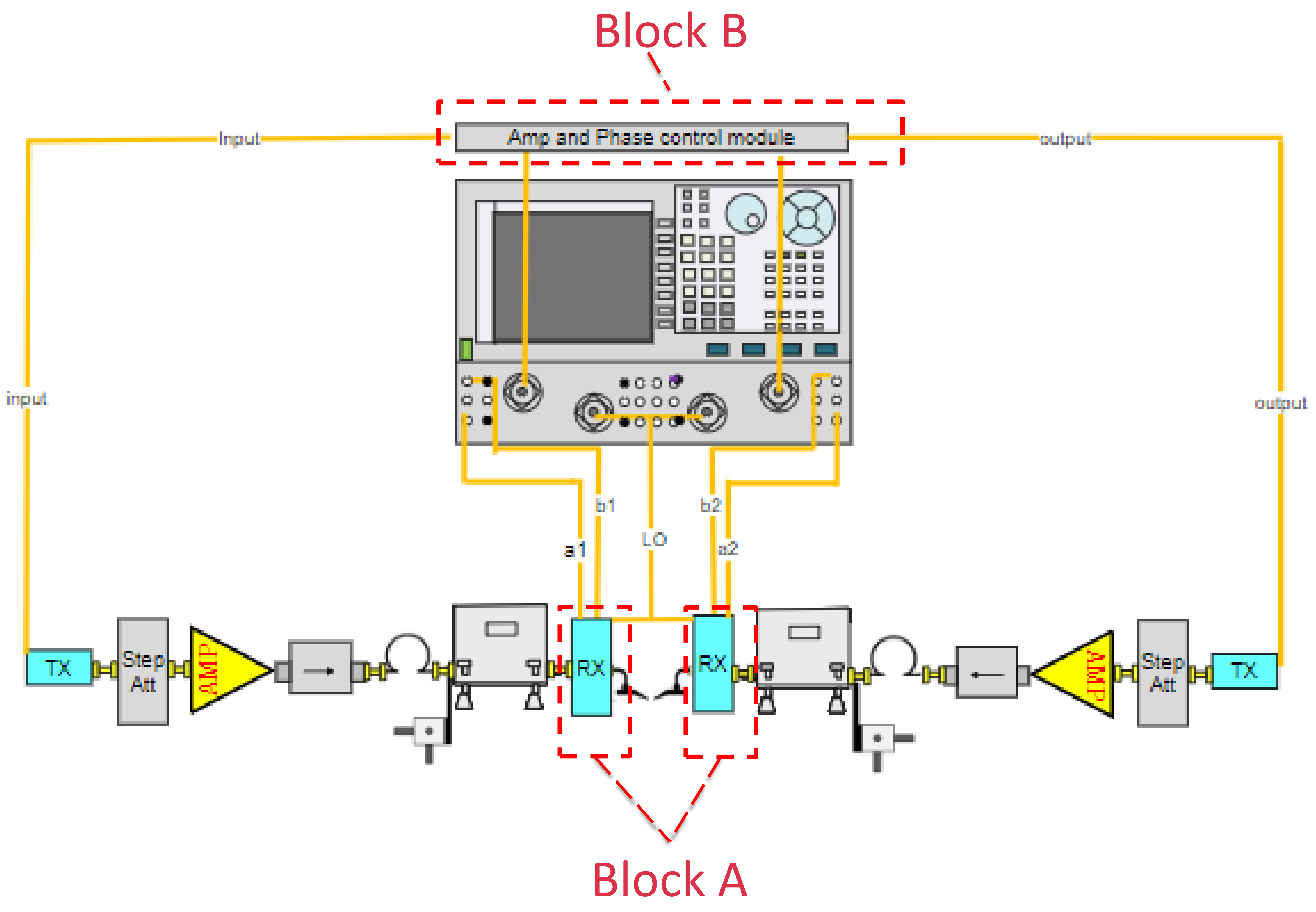
Maury Microwave
Your Calibration, Measurement & Modeling Solutions Partner!

Waveguide load pull

Hardware to empower waveguide passive and hybrid-active load pull

- Low-loss couplers with integrated down-conversion (block A) allows for direct measurement of a- and b-waves

- Input and output amplitude and phase control module before up-conversion (block B) allows for high-resolution control of injected active tuning signal

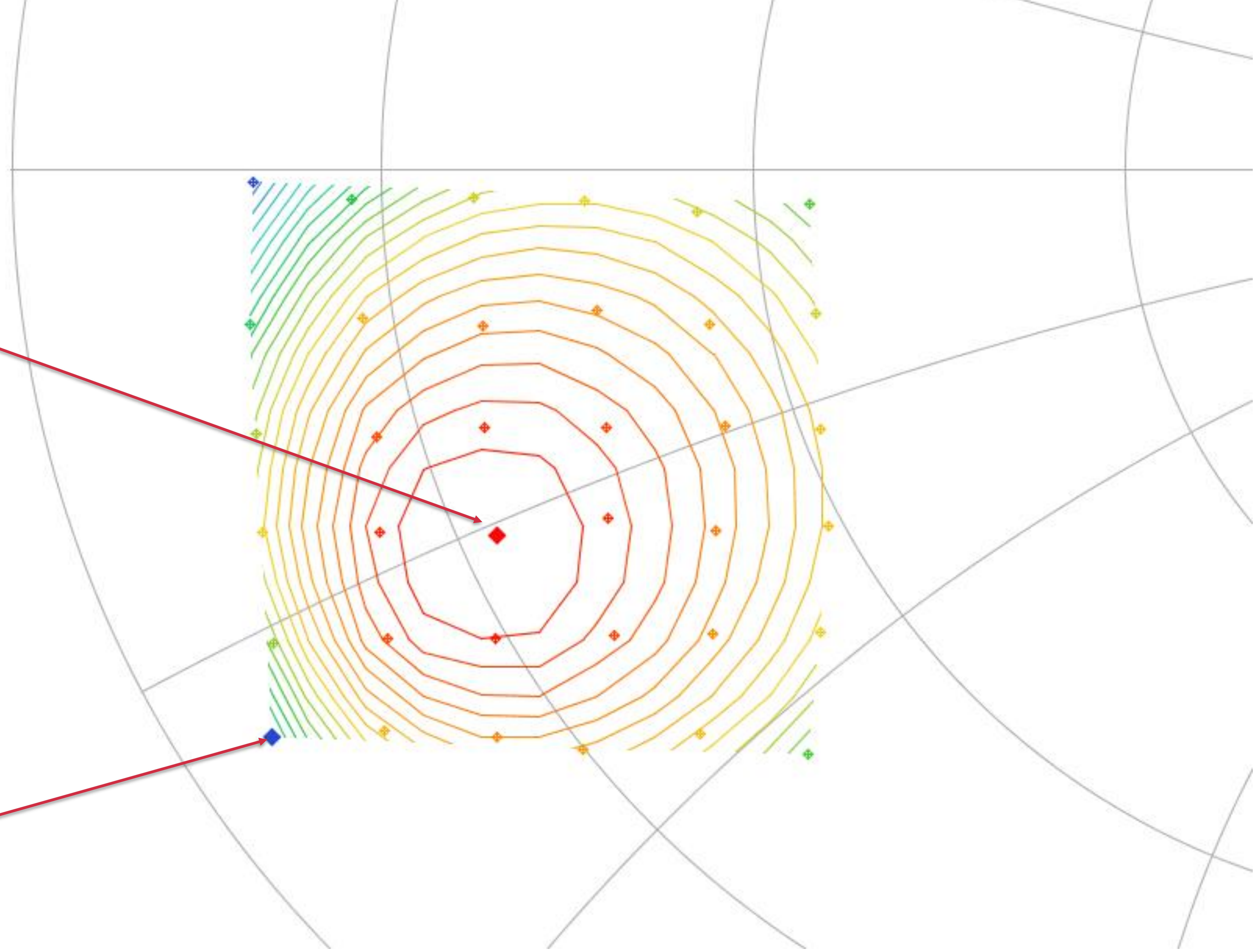


Waveguide passive and hybrid-active LP system

Waveguide passive and hybrid-active LP measurements

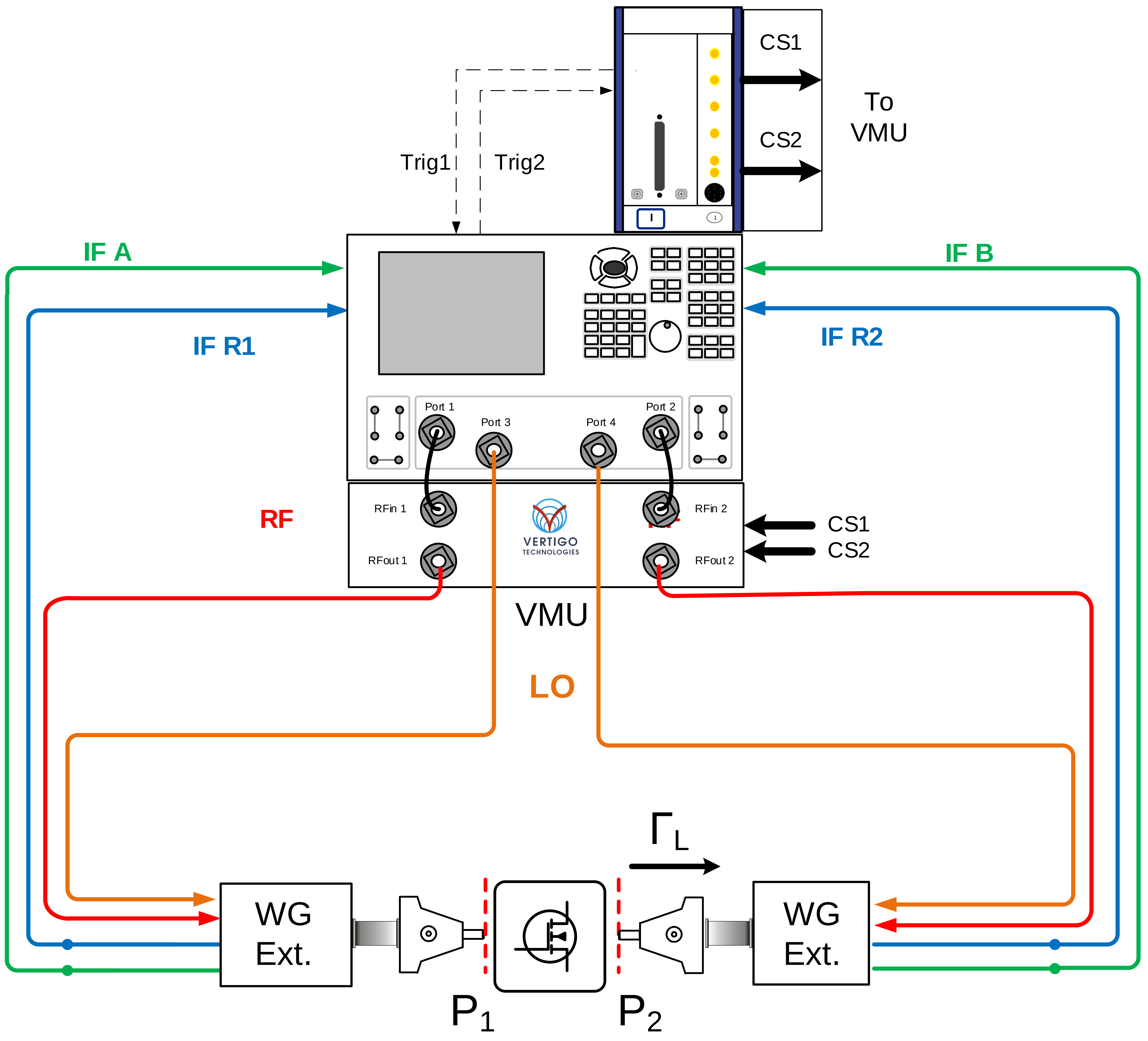
Example: HBT transistor at 80 GHz with P_{out} = 15 dBm

Optimum Eff
|Gamma| → 0.68



Closed contours
|Gamma| → 0.92

mmW and sub-THz active load pull



What:

- Scalable active load-pull
- Based on VNA systems
- Up to 1 THz with WG-based extenders

How:

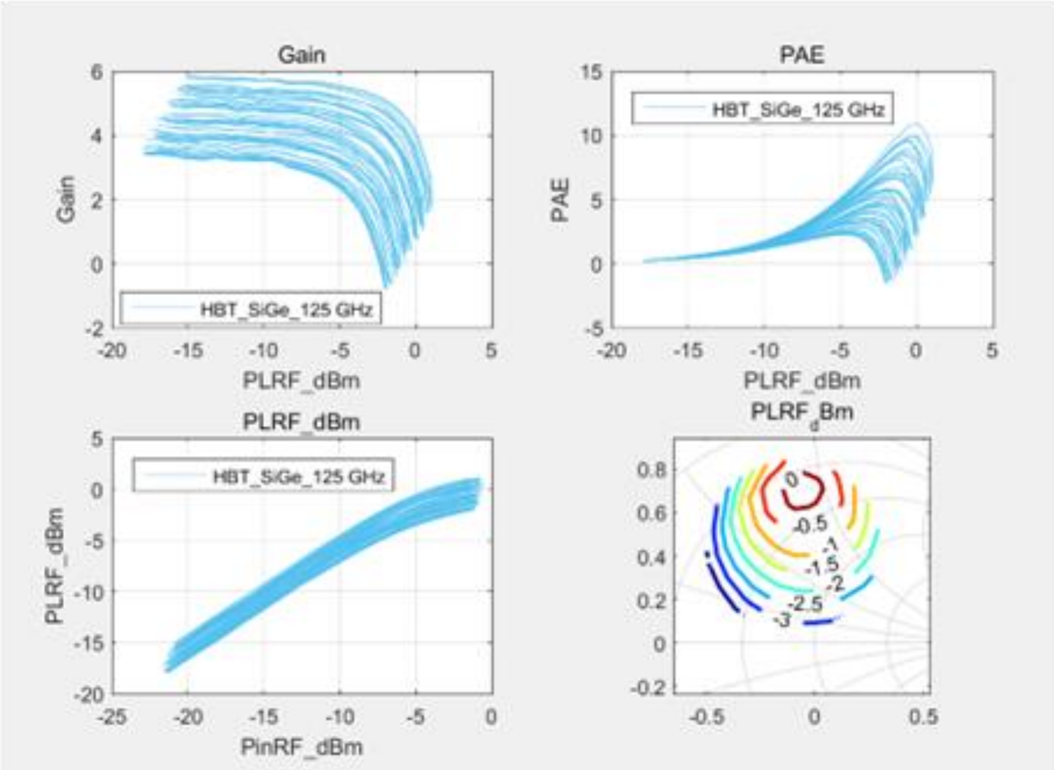
- Additional Vector Modulator Unit
- High accuracy DACs
- External control software

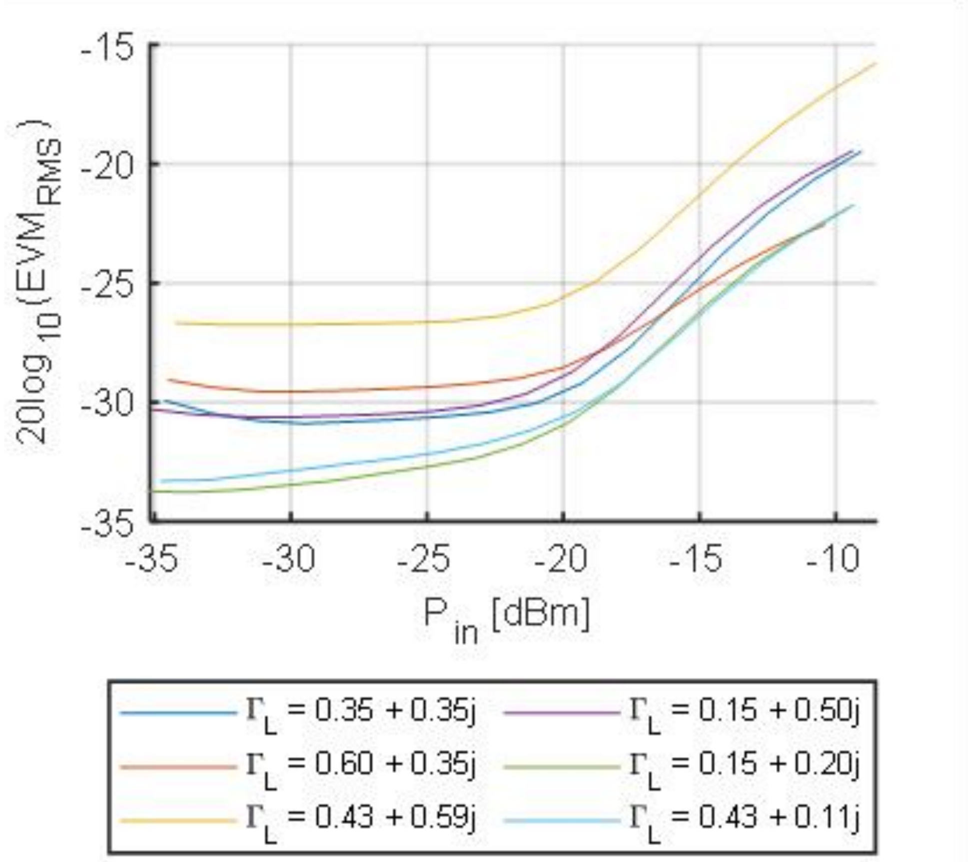
Why:

- Power controlled S-parameters
- Fundamental active load-pull

mmW and sub-THz active load pull system

Fundamental active Load-Pull

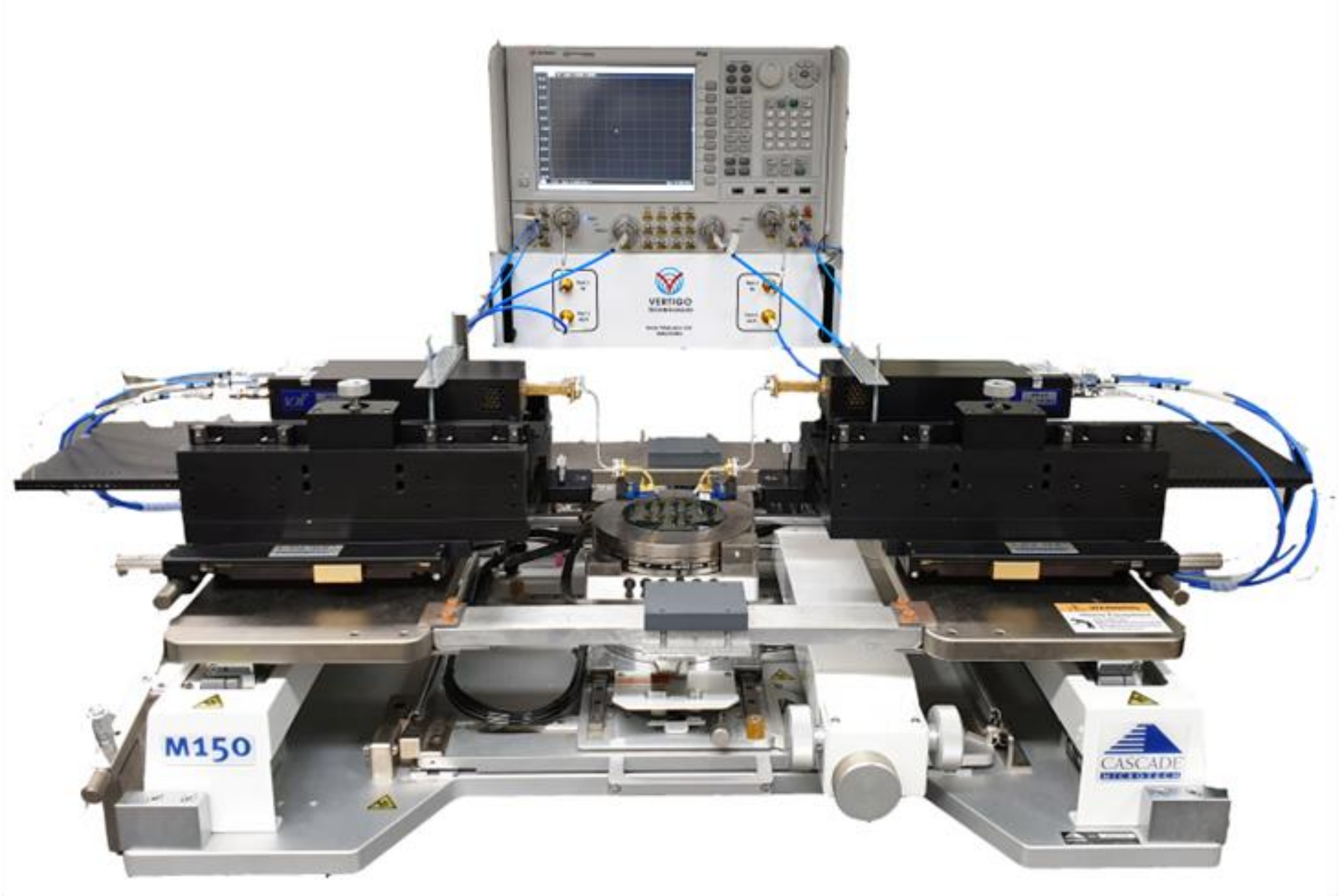




EVM estimation

MMW-STUDIO

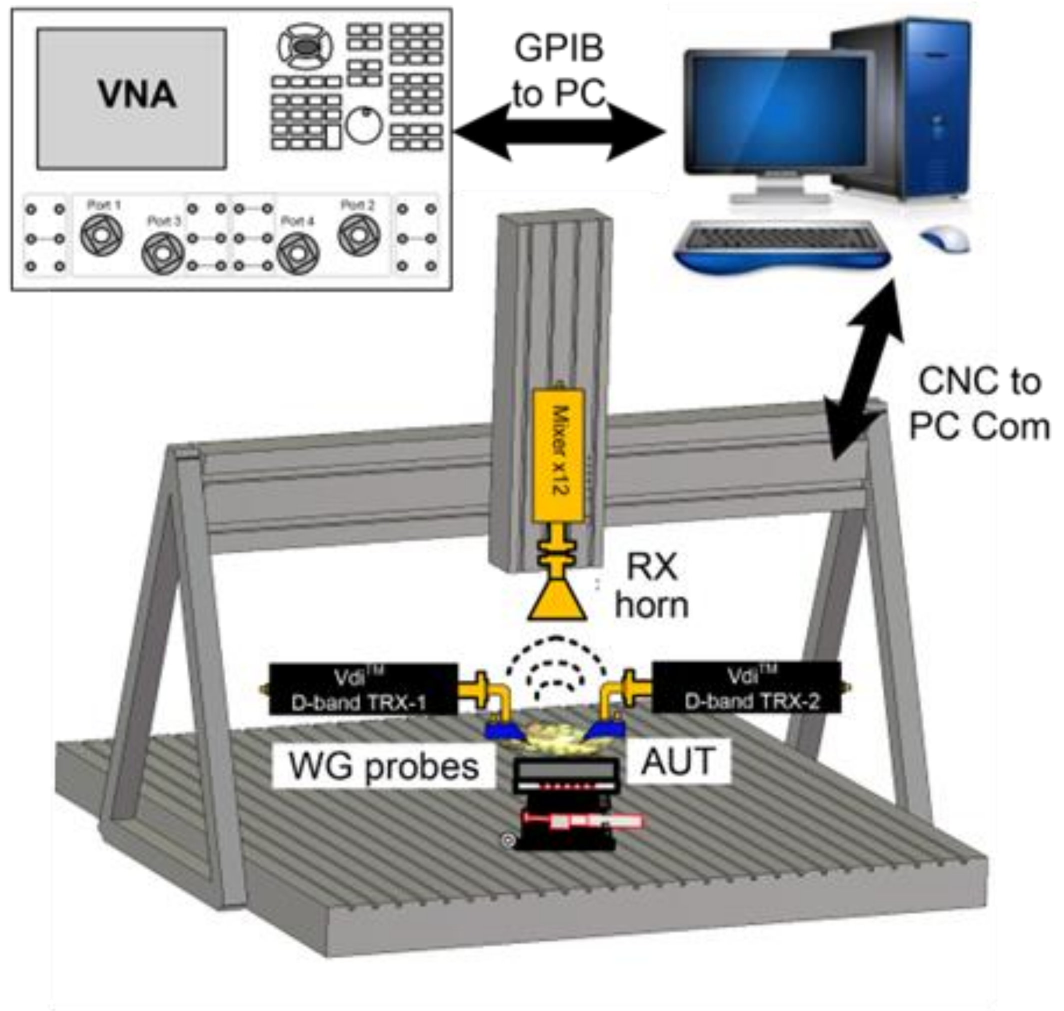
MT920 Series

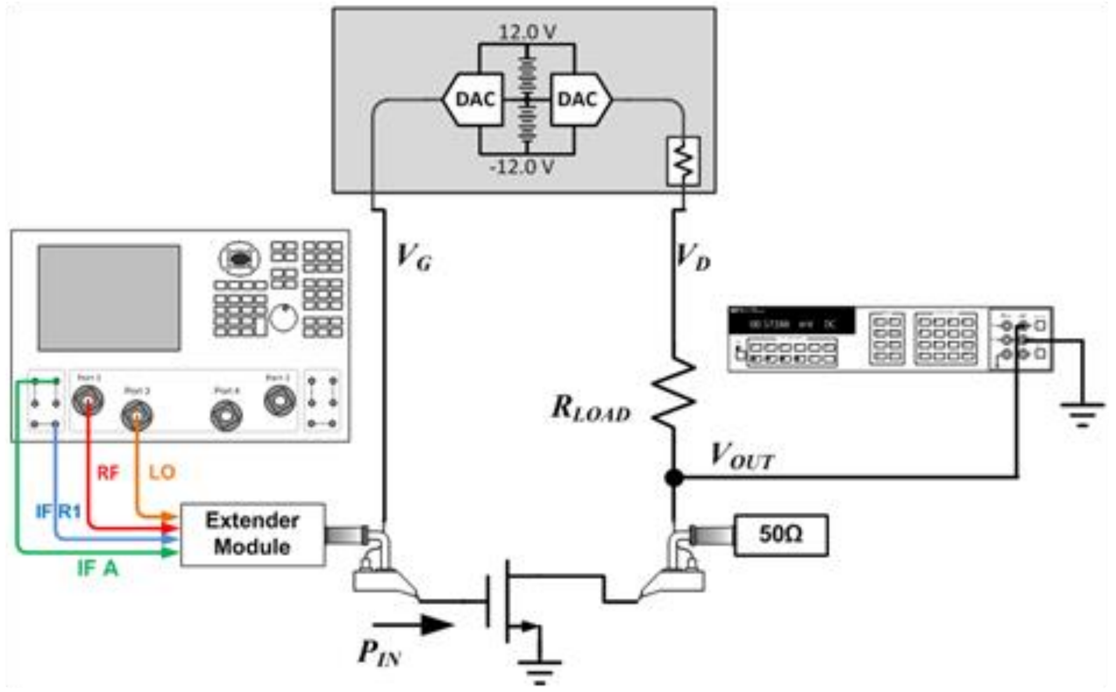


For all waveguide bandwidths up to 1THz
One unique software/hardware add-on
Many applications for 6G testing

Maury Microwave
Your Calibration, Measurement & Modeling Solutions Partner

Over-the-air measurements

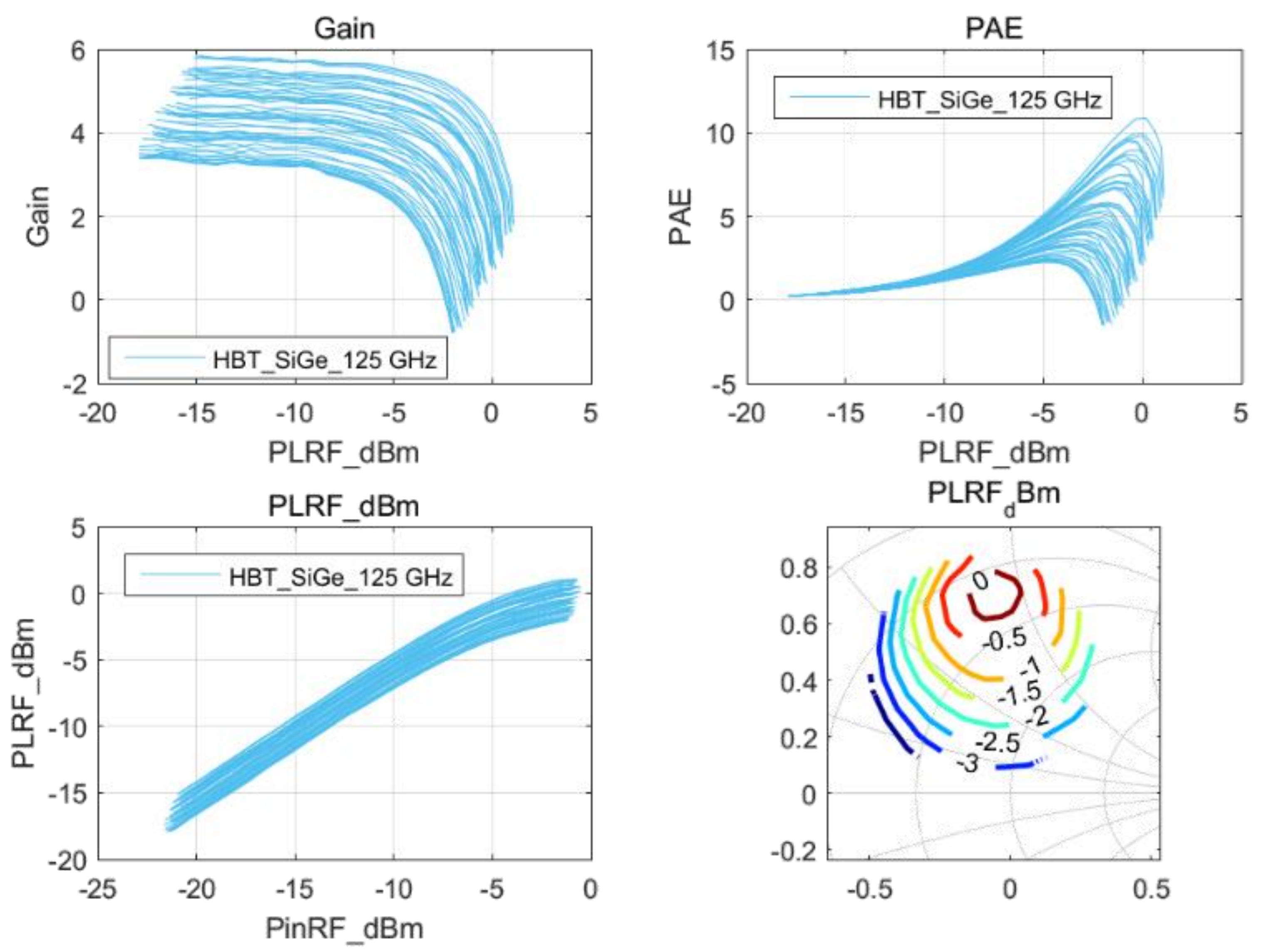




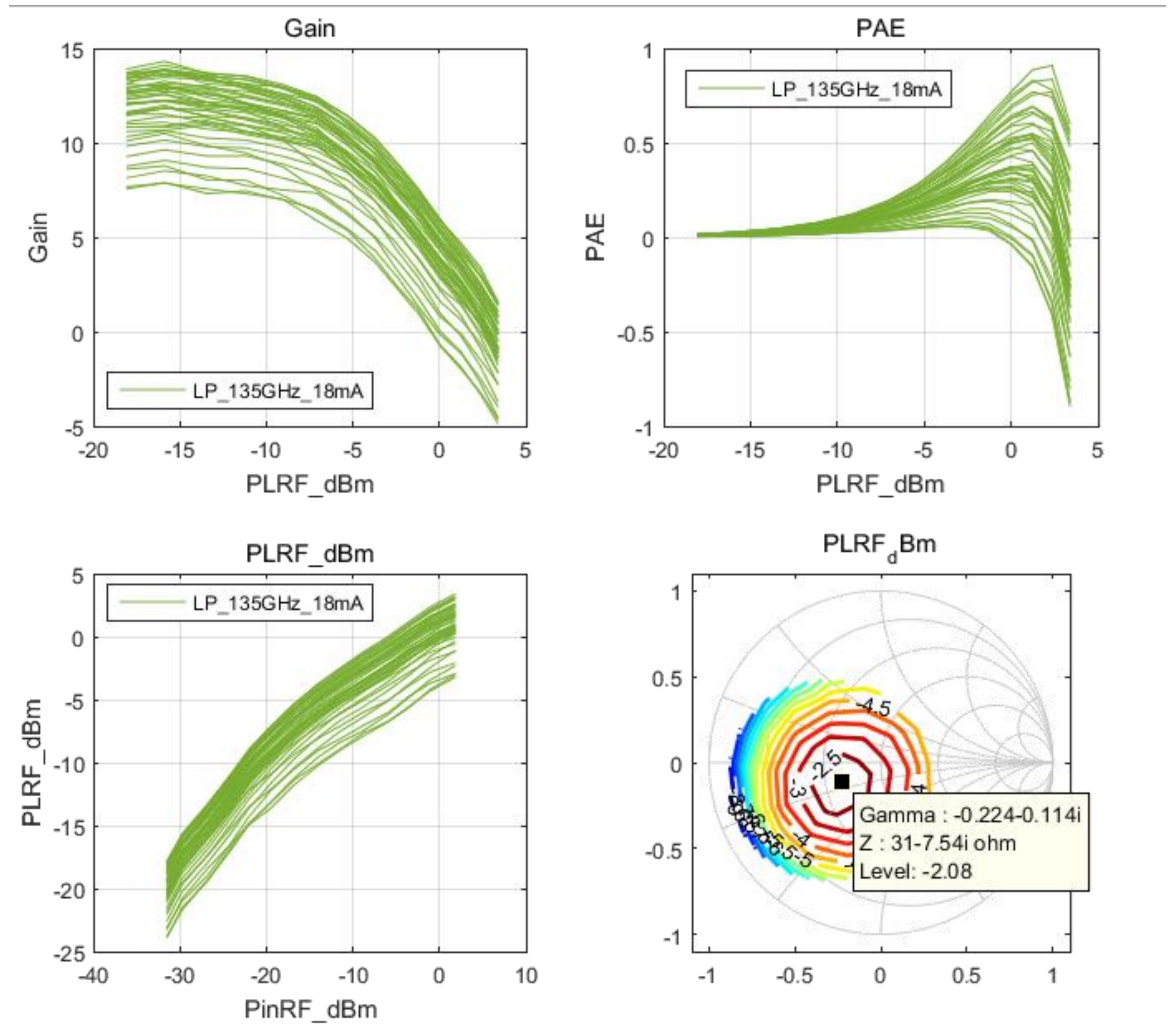
Responsivity measurements

mmW and sub-THz active load pull measurements

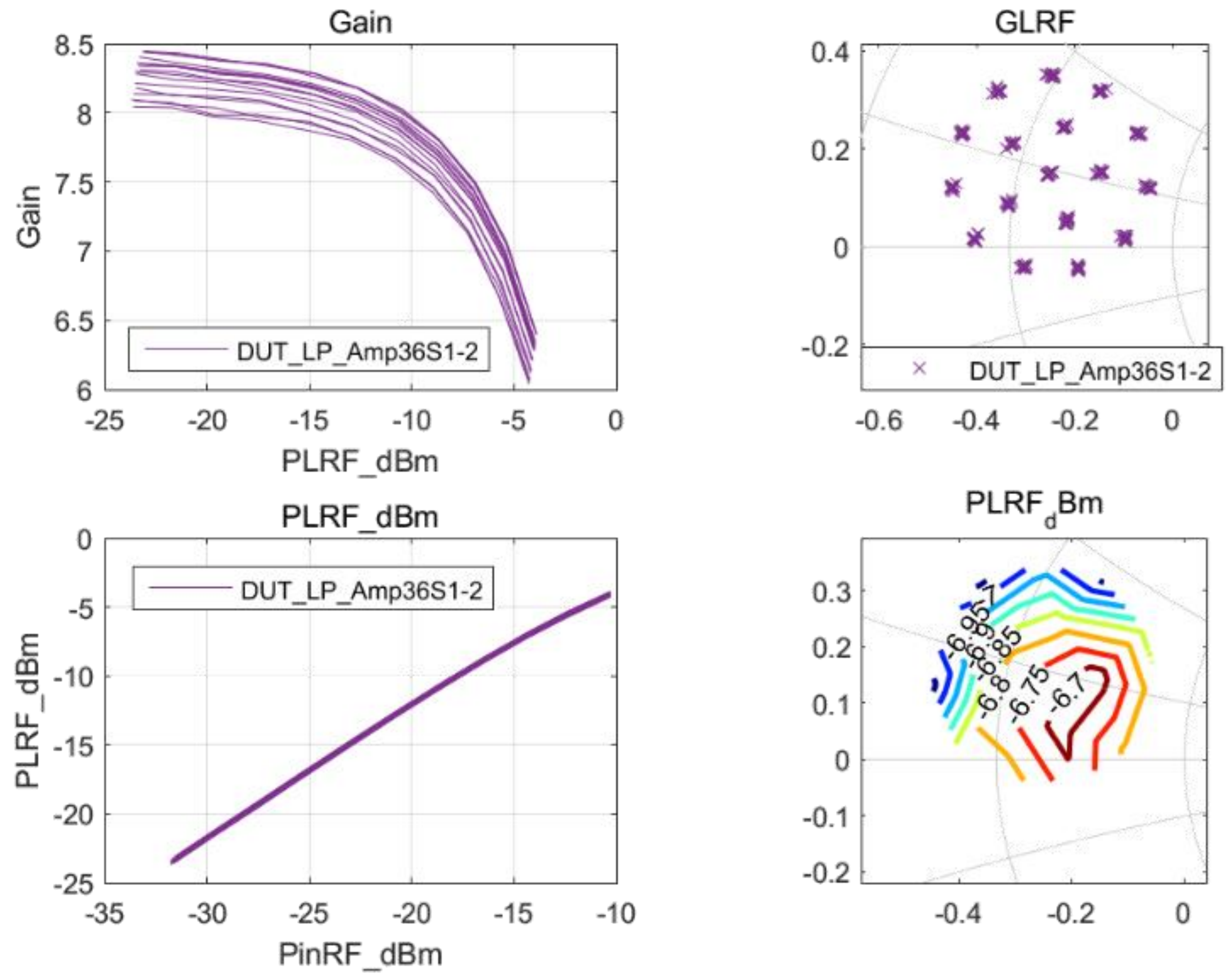
Characterization of **small-cells**: SiGe 130 nm double finger HBT at 125 GHz



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



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



Thank You!

Maury Microwave
Your Calibration, Measurement & Modeling Solutions Partner!