Presenter:
Dirk Faber: dirk.faber@hitechbv.nl

Amplifier Characterization by doing harmonic load pull and large signal measurements

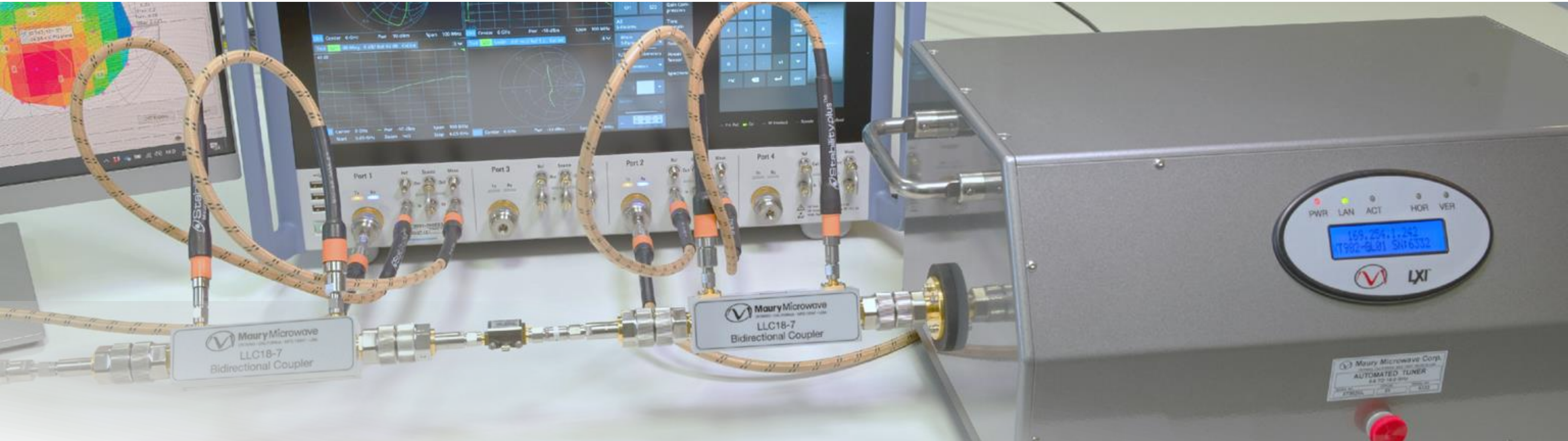
HITECH
RF & Microwave solutions

European master distributor of:

Maury Microwave
Your Calibration, Measurement & Modeling Solutions Partner!

AMCAD Engineering
Advanced Modeling for Computer-Aided Design

Agenda



- Considerations
- Setup and calibration of Vector receiver load pull configuration
- Harmonic vector receiver loadpull
- Large signal and time domain

Passive & hybrid active vector-receiver load pull

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

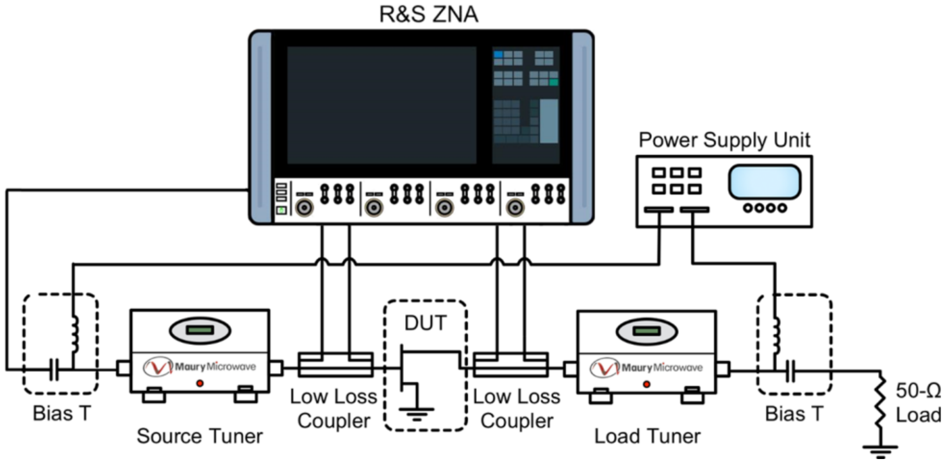
$$P_{in,del} = \frac{1}{2}\left(|a_1|^2 - |b_1|^2\right) = \frac{1}{2}|a_1|^2\left(1 - |\Gamma_{in}|^2\right)$$

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

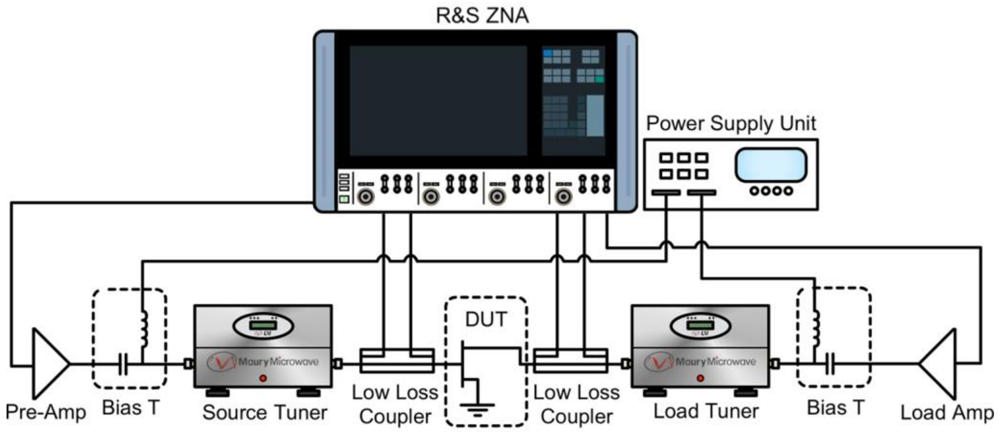
$$G_p = \frac{P_{out}}{P_{in,del}} = \frac{|b_2|^2\left(1 - |\Gamma_{load}|^2\right)}{|a_1|^2\left(1 - |\Gamma_{in}|^2\right)}$$

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

Passive VRLP Configuration



Hybrid active VRLP Configuration (high power, high gamma applications)



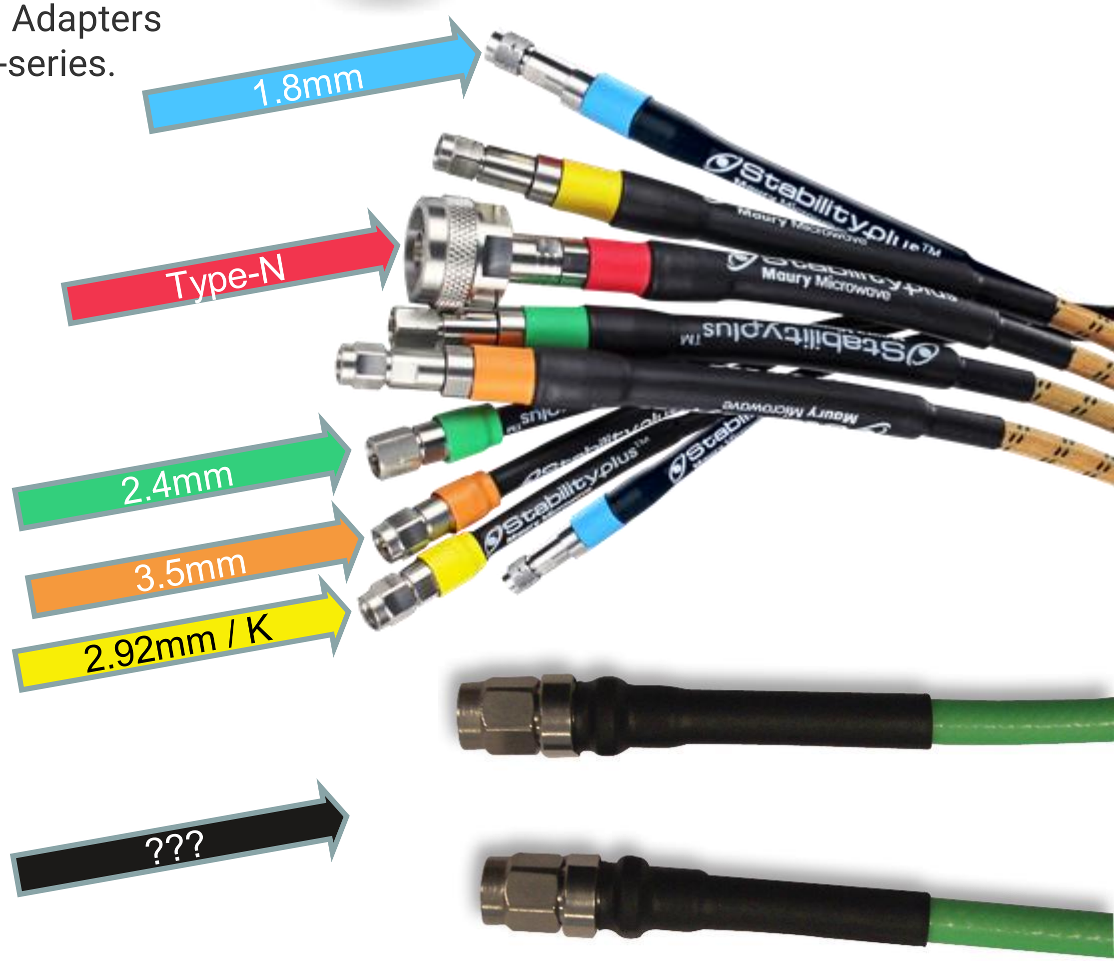
Maury Interconnect

ColorConnect™

ColorConnect™ makes it a simple matter to avoid and eliminate damaged equipment, degraded equipment reliability, degraded performance and lengthy maintenance times due to improper mating (and attempted mating) of incompatible adapters. ColorConnect™ Precision Adapters are available in N Type, 3.5mm, 2.92mm, 2.4mm and 1.85mm in-series and between-series.

COLOR GUIDE	FMAX	CONNECTOR	TORQUE
BROWN	18 GHz	SMA	5 in-lb
VIOLET	18 GHz	7mm	12 in-lb
RED	18 GHz	Precision Type N	12 in-lb
ORANGE	26.5 GHz	3.5mm	8 in-lb
YELLOW	40 GHz	2.92mm (K)	8 in-lb
GREEN	50 GHz	2.4mm	8 in-lb
BLUE	67 GHz	1.85mm (V)	8 in-lb

IEEE P287 color code



https://www.maurymw.com/pdf/1G-009%20ColorConnect.pdf

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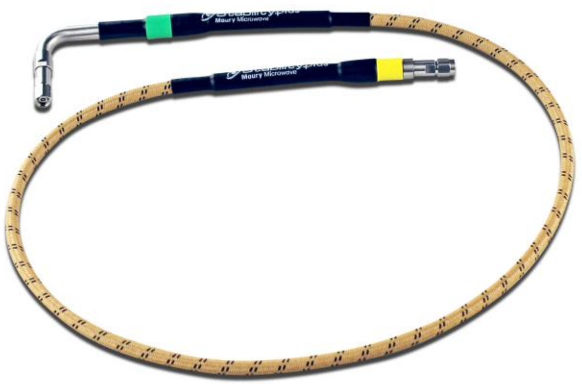
Maury Interconnect

StabilityPlus cable assemblies

Achieve the best measurement uncertainty with the industry’s best phase-stable cable assemblies!

- **Mechanical characteristics which lead to improved uncertainty**
  - Best phase stability with flexure
  - Best insertion loss stability with flexure
  - Superior flexibility
  - Durable, ruggedized and crush resistant
  - Longer flex-life
  - Color-coded connectors



- **Availability**
  - Up to 67 GHz
  - 1.85mm, 2.4mm, 2.92mm, 3.5mm and Type N connectors
  - Low-profile option for high-density applications
  - Right-angle connectors
  - Phase-matched sets
  - 400+ standard assemblies in stock for next-day shipping

StabilityPlus™
Maury Microwave

https://www.maurymw.com/Interconnect_Solutions/Stability_Plus.php

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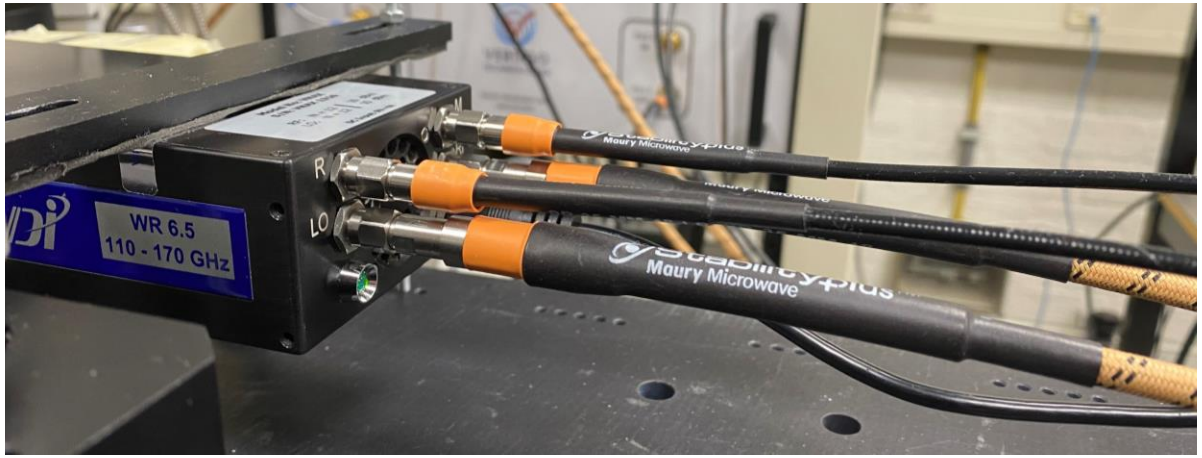
NEW!!!

StabilityPlus “Low Profile” cable assemblies

Feature the same excellent electrical performance as Maury’s ruggedized StabilityPlus™ cables, but with a more compact and flexible design.



30% **lower in cost** compared with StabilityPlus cable assemblies

Stabilityplus™
Maury Microwave

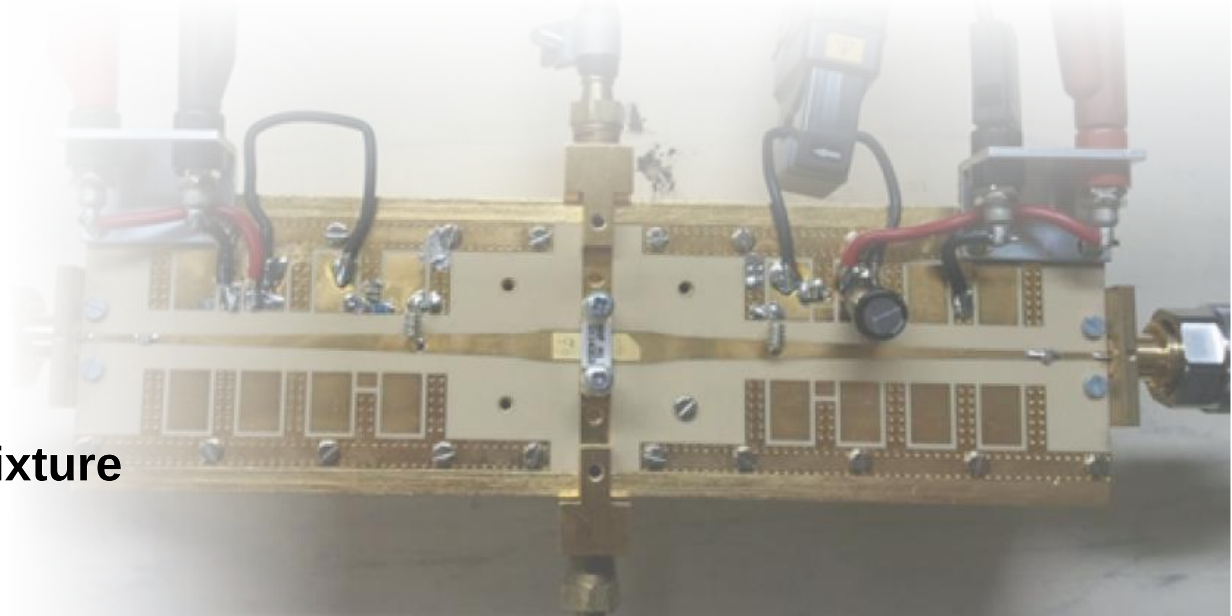
https://www.maurymw.com/Interconnect_Solutions/Stability_Plus_LP.php

Fixturing

As important as the rest of a load pull! It can make and break measurement results.

Consideration to take:

- Water cooling avoids thermal effects
- Integrated biasing on fixture avoids instabilities
- 50Ω to 10Ω impedance transformation increases power transfer
- High quality connectors for low insertion loss
- Include TRL Calibration Kit
- Etc.



Almost every loadpull configuration requires a custom fixture

VRLP setup considerations

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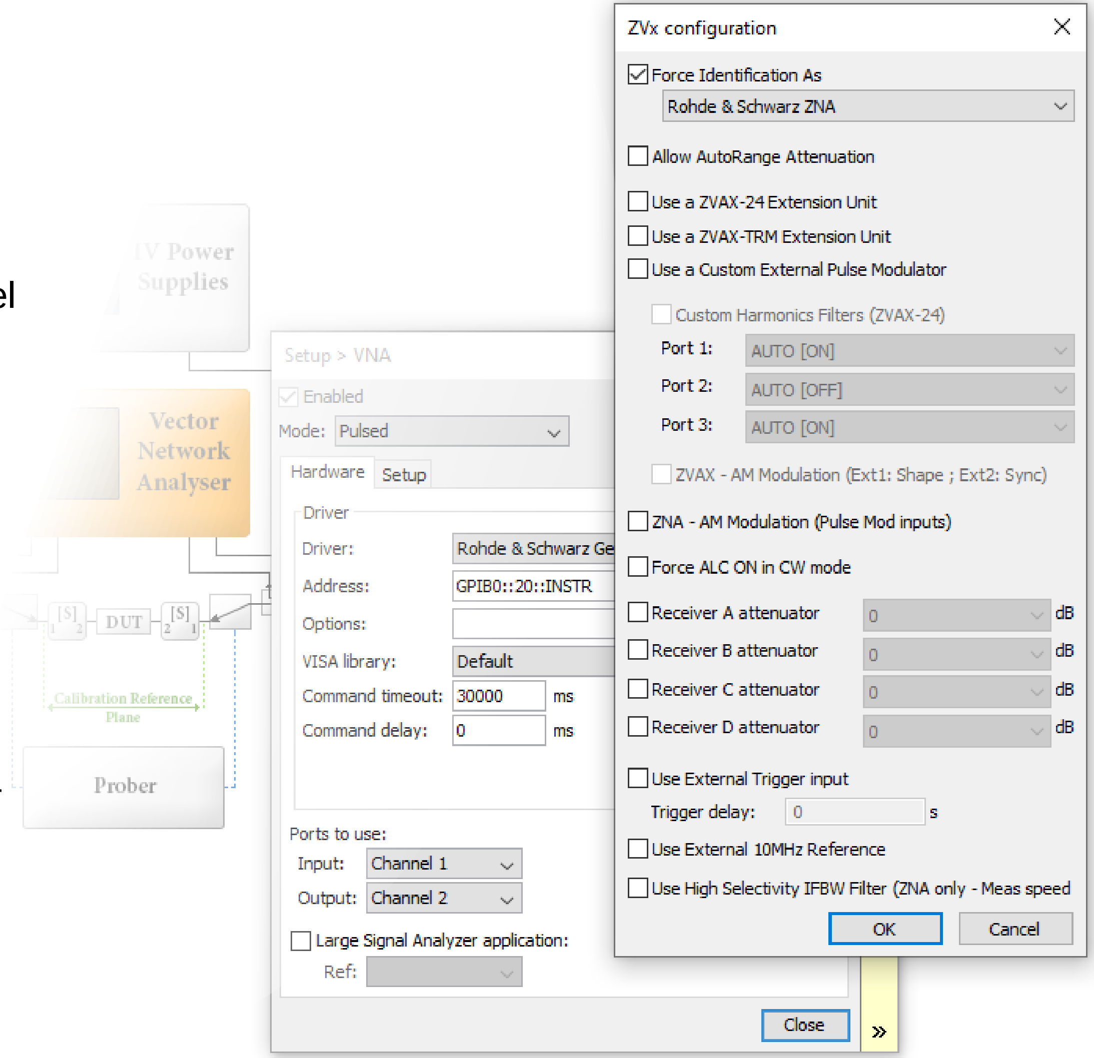
Choice of the measurement mode (CW or Pulsed)

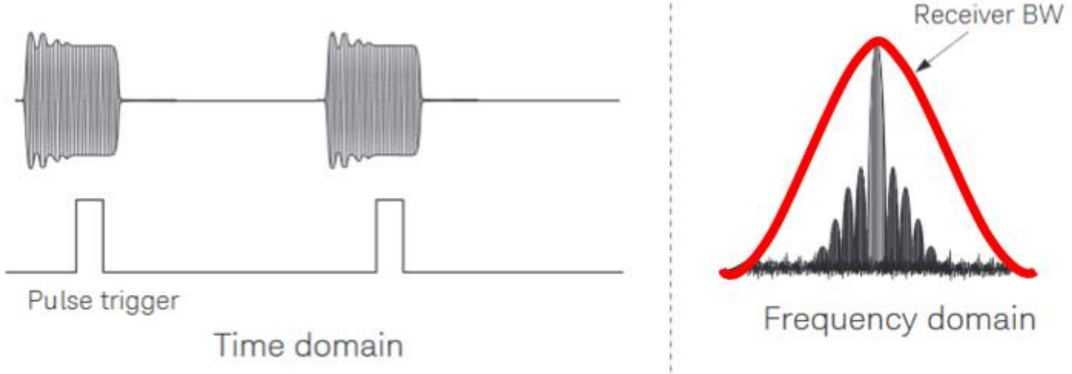
- CW means power is always on during measurement
- CW is easy to setup since no timing / triggering is required
  - Relatively simple instruments can be used
- CW is mainly used for amplifier characterization /validation on circuit level

- Pulsed means sort RF-Pulses; ~100µs with a duty cycle of 10%
- Pulsed is more difficult to setup due to:
  - Timing and triggering
  - Bandwidth filter (NBF or WBF)
  - Choice of equipment
    - VNA with internal pulse modulators or not
    - Source with pulse RF-option or use CW source with external modulator
    - Power meter with pulsed measurement capability
    - DC Power supply or SMU with pulse capability



Wideband vs Narrowband detection

Wideband detection (WBF) is a synchronous detection; A pulse acquisition trigger is required.



Advantages:

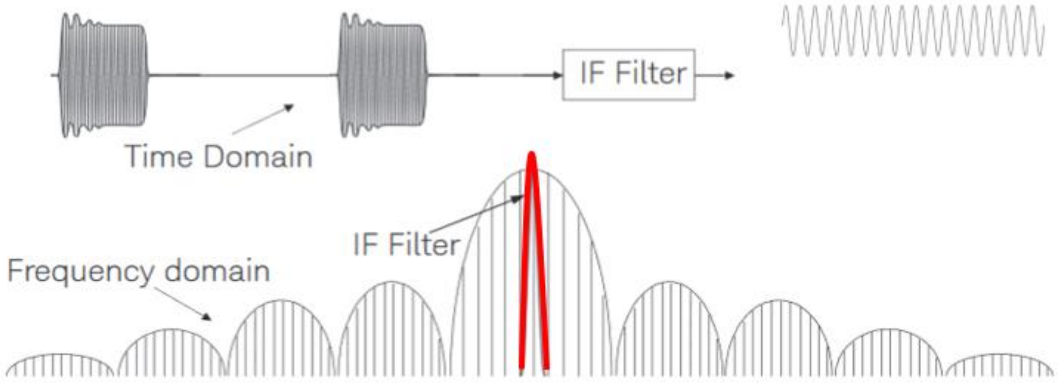
- Fast Measurement Speed
- No loss of dynamic range in function of the duty cycle
- Acquisition window within the pulse is defined. No transient effects take into account (overshoot, rise time, fall time, ringing, ...)

Disadvantages:

- Higher Noise Floor due to the wider IFBW (Dynamic Range = f(IFBW, Averaging) = f(Ton))
- Pulse Width limitations. As pulse width gets smaller, the spectral energy spreads out.
  - IF bandwidth (=1/Ton) has to be high compared to the Pulse Width (e.g. : Ton=100 usec => IFBW=1/(Ton) > 10KHz)

Wideband vs Narrowband detection

Narrowband detection (NBF) is an asynchronous detection.; A pulse acquisition trigger is not required.



Advantages:

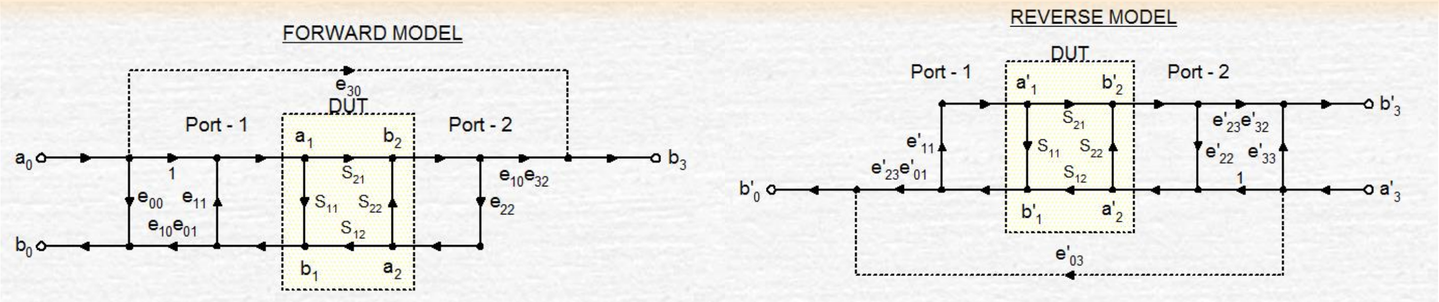
- No lower pulse-width limitations
- Measurement dynamic range is sufficiently high for 1% to 100% of duty cycles

Disadvantages:

- Measurement dynamic range decreases as duty cycle decreases. Average power of the pulses gets smaller, resulting in less SNR (Dynamic range degradation = 20*log(duty cycle)')
- Higher PRF is, slower measurement speed will be but has to be high compared to the IF bandwidth
  (e.g. : T=1msec => IFBW=1/(20*T)= 50Hz; T=10msec =>IFBW=5Hz)
- No acquisition windows within the pulse is defined. Possibility to measure wrong results in function of the transient effects (overshoot, rise time, fall time, ringing, ...) => Average Pulse measurement

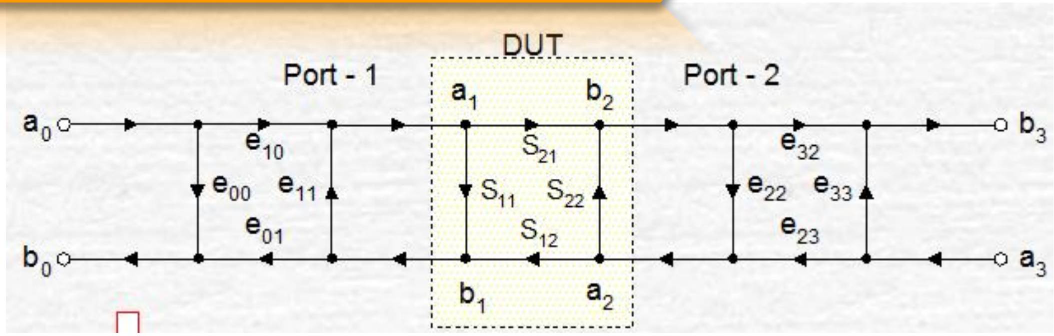
Bench Calibration process

12 Terms error model with classic VNA Calibration



- 10 terms error + 2 terms error for isolation (optional)

8 terms error model



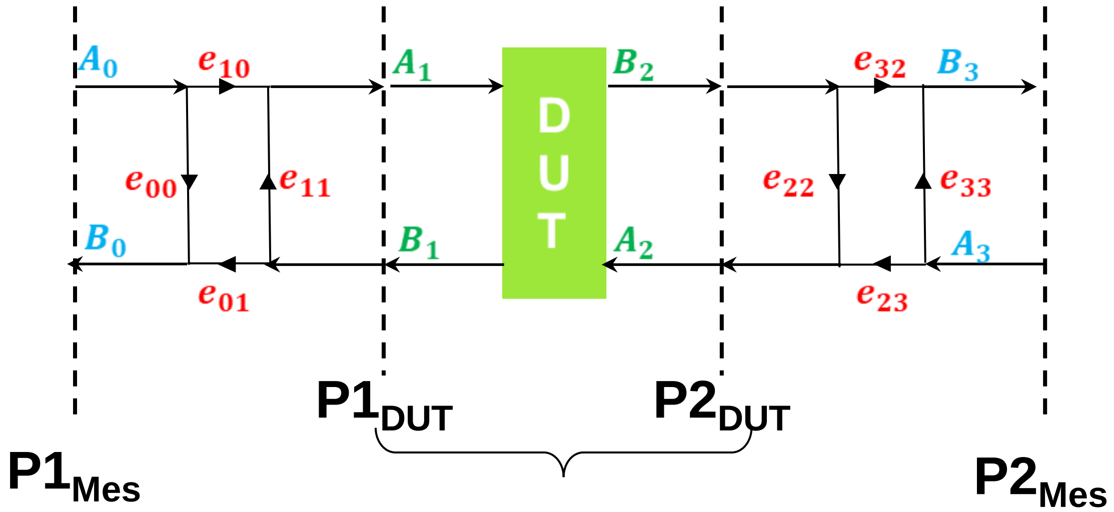
- 8 terms error model applicable only in forward

Bench Calibration process

8 Terms error model

1st step :
UOSM Calibration between P_{1DUT} & P_{2DUT}

- Vectorial correction allow to correct only wave ratio
- A1/B1, A2/B2… real/imaginary corrected
  - Mag(A1), Mag(B2)… ?



UOSM / TOSM / TRL

Coefficient : e00,e11,e10e01,e22,e33,e32e23

$$\begin{pmatrix} A_1 \\ B_1 \end{pmatrix} = \begin{pmatrix} -\Delta ein & e_{11} \\ -e_{00} & 1 \end{pmatrix} . \begin{pmatrix} A_0 \\ B_0 \end{pmatrix}$$

$$\begin{pmatrix} A_2 \\ B_2 \end{pmatrix} = \begin{pmatrix} -\Delta eout & e_{22} \\ -e_{33} & 1 \end{pmatrix} . \begin{pmatrix} A_3 \\ B_3 \end{pmatrix}$$

Bench Calibration process

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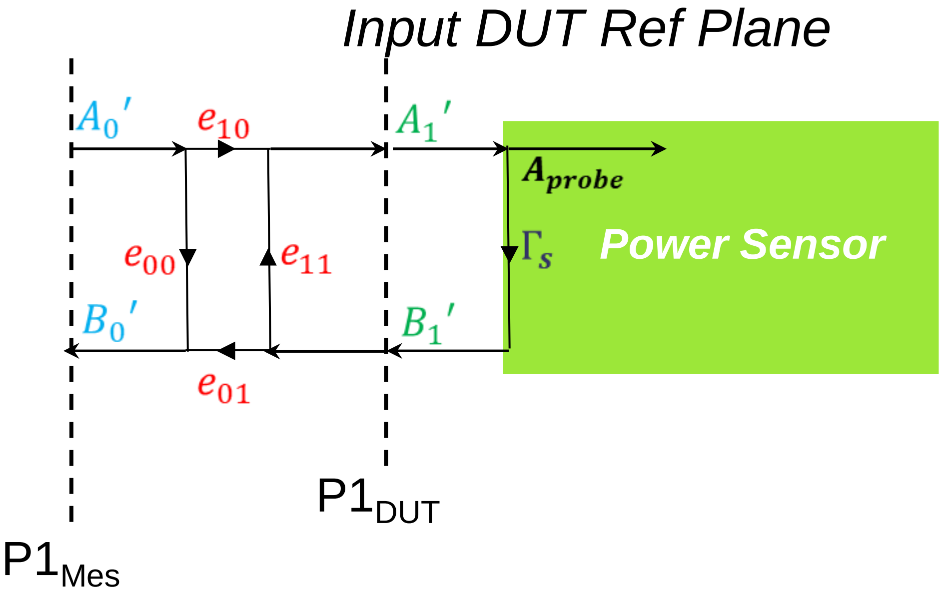
Power Calibration

<u>1^{st} step :</u>
UOSM Calibration between P_{1DUT} & P_{2DUT}

<u>2^{nd} step :</u>
Power Calibration between P_{1DUT} ou P_{2DUT}

Mag(A1), Mag(B2)…
Arg(A1), Arg(B2)… ?



<u>Coefficient $|e10|$</u>

Bench Calibration process

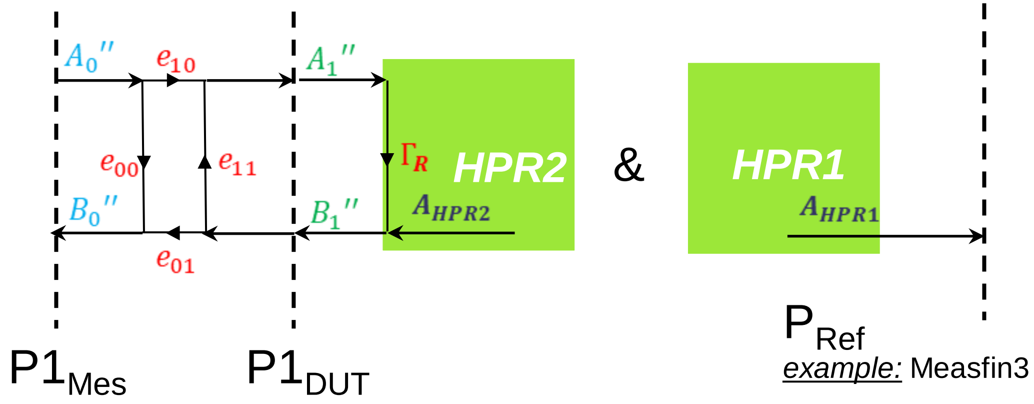
Phase Calibration

<u>1st step :</u>
UOSM Calibration between P_{1DUT} & P_{2DUT}

<u>2nd step :</u>
Power Calibration between P_{1DUT} ou P_{2DUT}

<u>3rd step :</u>
Phase Calibration between P_{1DUT} ou P_{2DUT}

Input DUT Ref Plane, Source 1 OFF



<u>*Coefficient Arg(e_{10})*</u>

Measin3 □ A_{HPR1}

Refin1 □ A_1

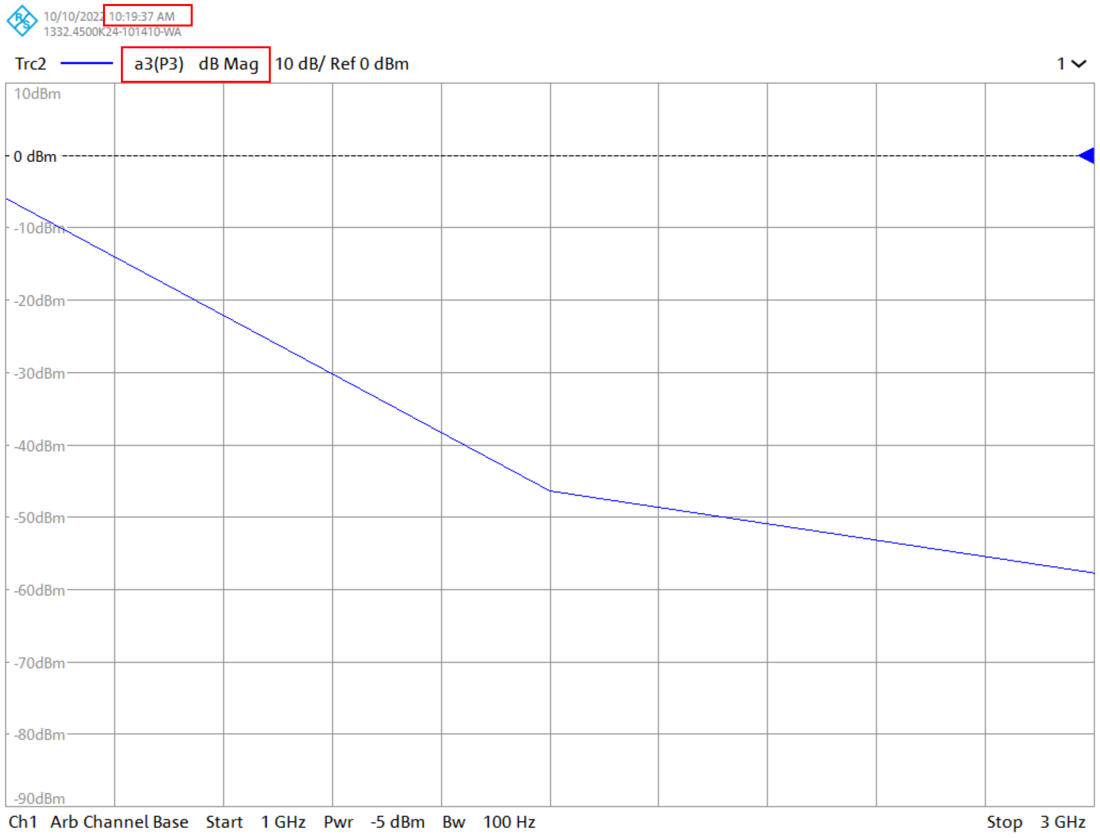
Refin4 □ A_4

Measin1 □ B_1

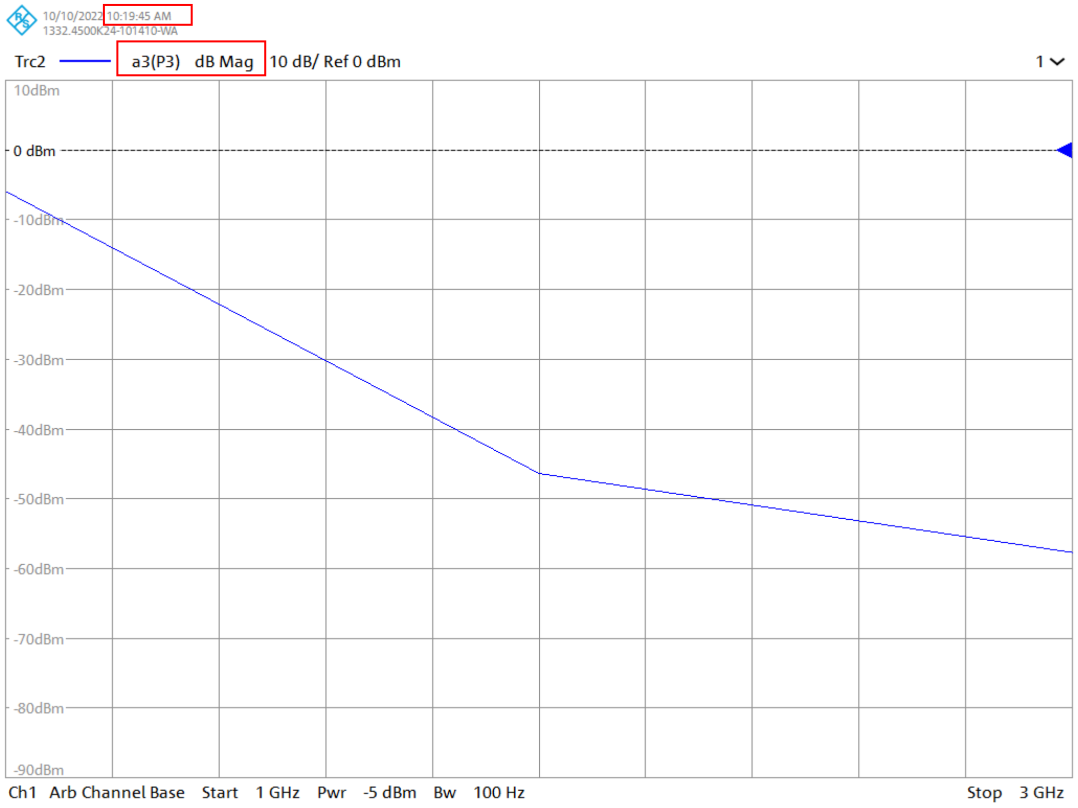
Measin4 □ B_4

Context – Phase Coherence

- With standard VNA, Magnitude measurements of travelling waves don’t present difference between two consecutive sweeps



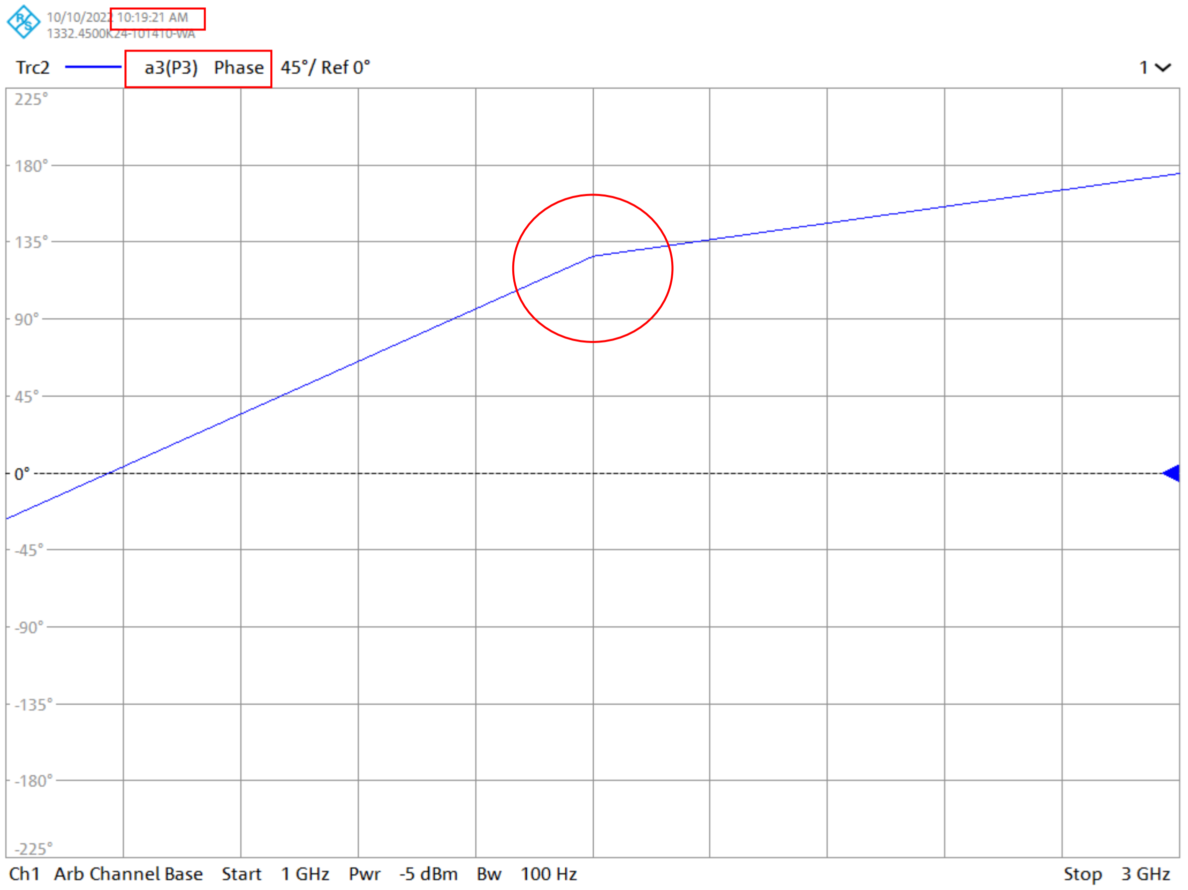
Sweep 1



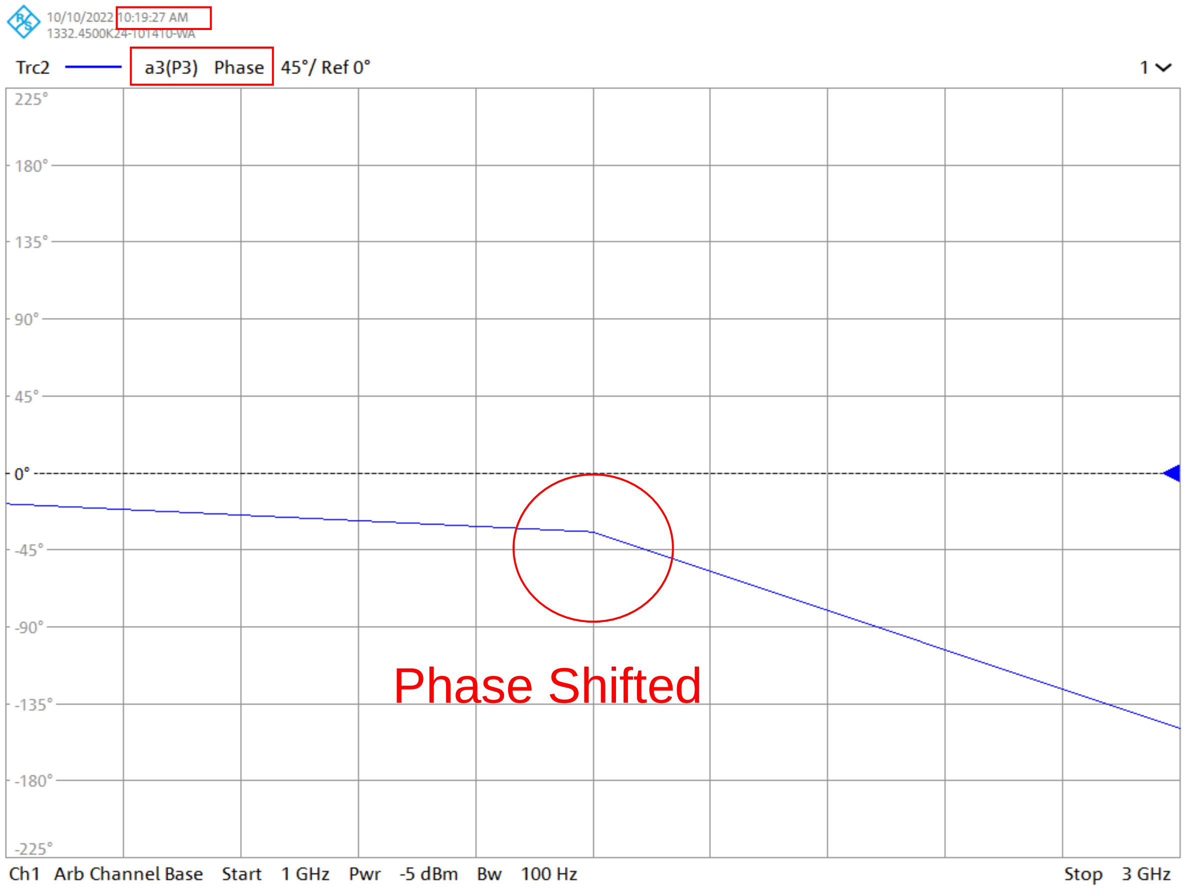
Sweep 2

Context – Phase Coherence

- Phase response changes from one sweep to another.
- Change of the phase of the LO signal from one sweep to another.
- Measurements of the phase will not be the same at a given frequency between two sweeps at the same frequency

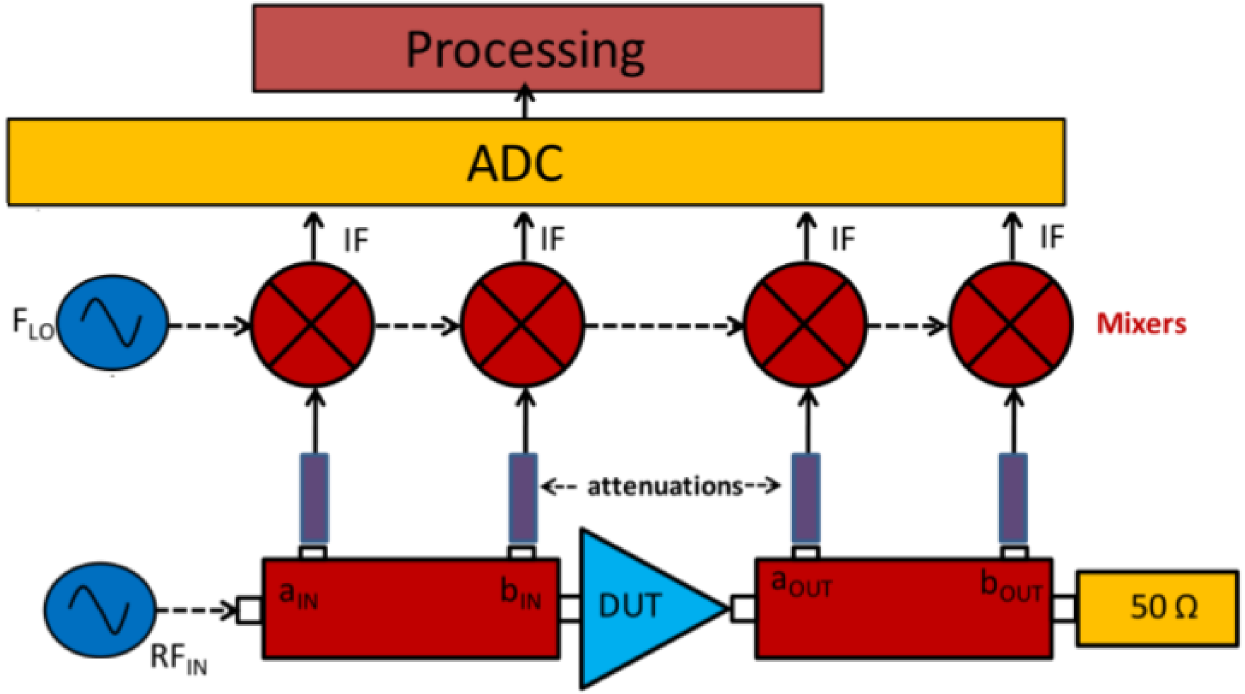


Sweep 1

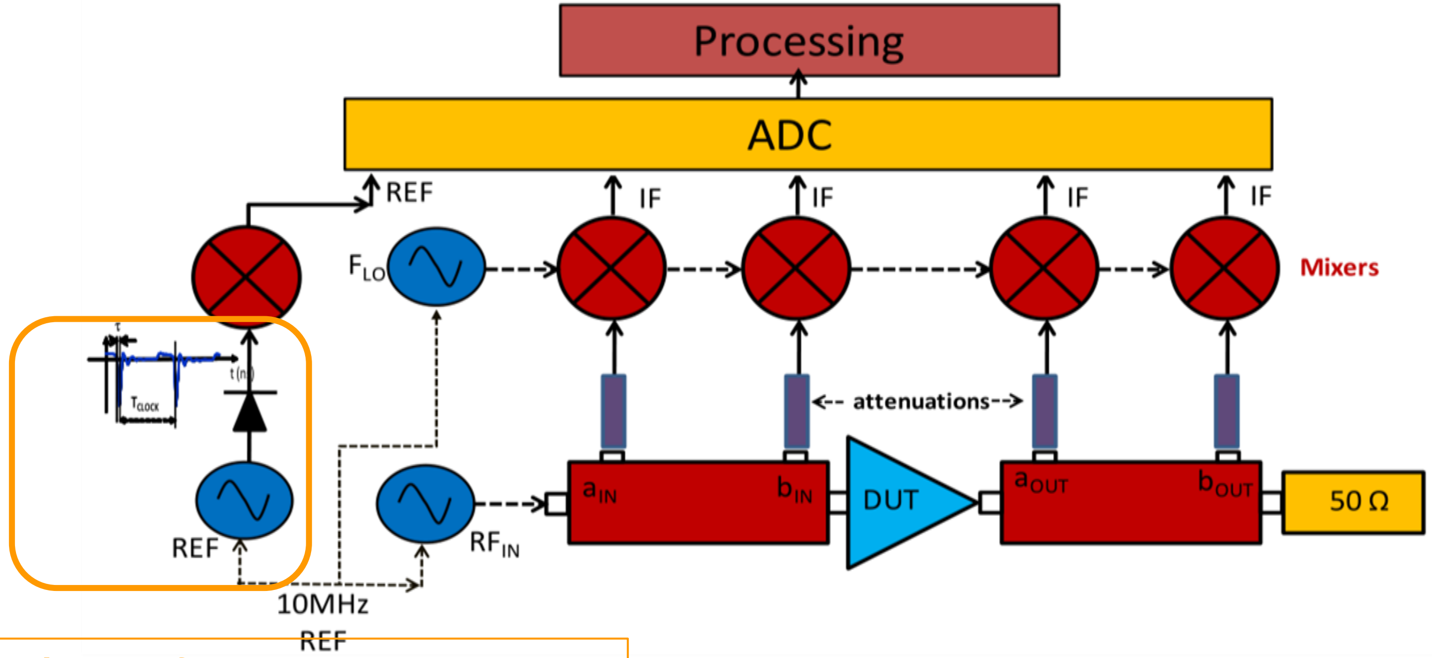


Sweep 2

VNA architecture for incident and reflected wave acquisition



Large signal analysis with ZNA



Phase reference

- VNA’s are mixer-based systems. The LO-phase will change during frequency sweep.
- This means that we cannot directly measure the phase across frequency using unrationed (a1, b1) measurements.

Context – Phase Coherence

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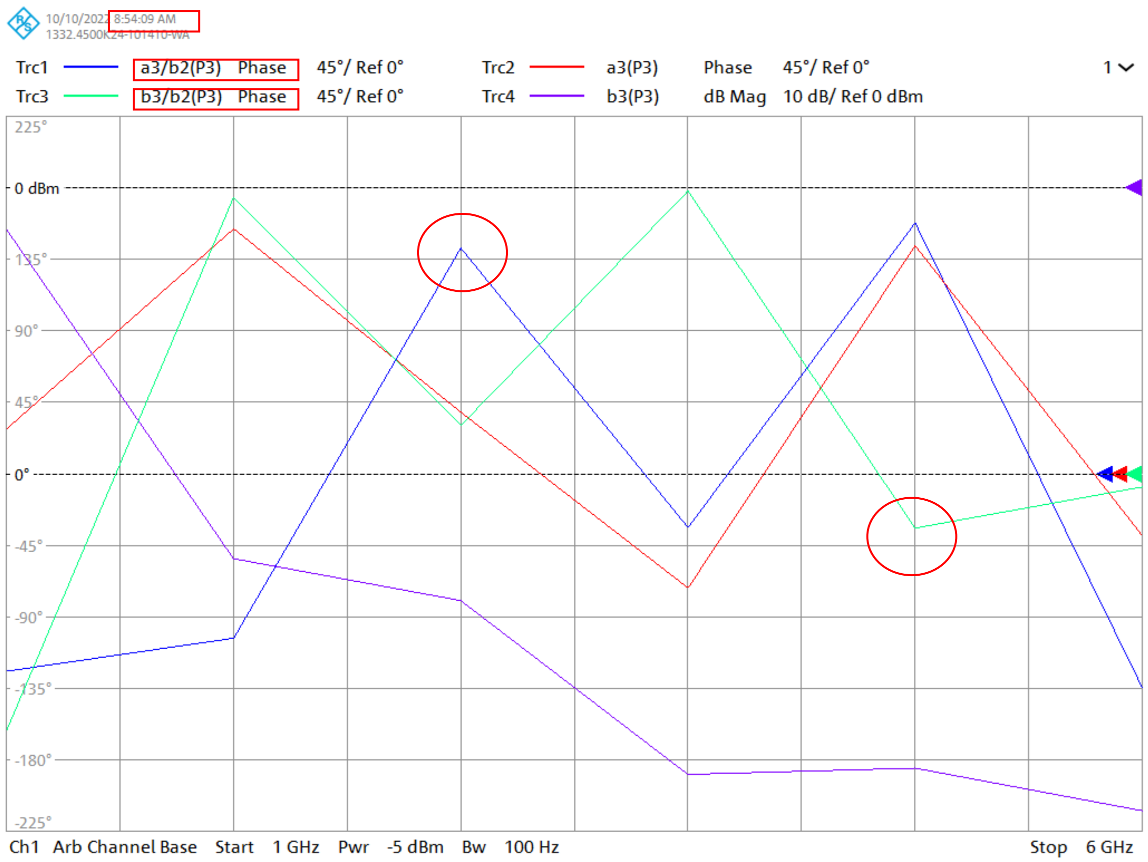
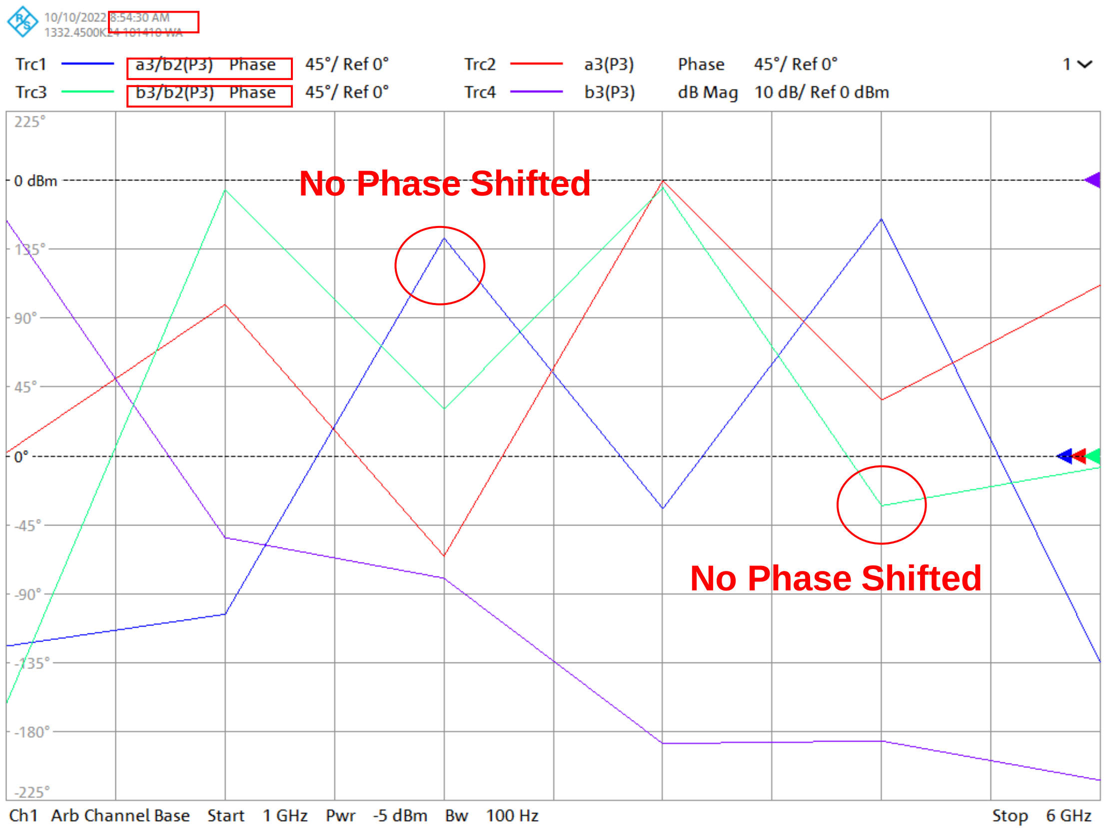
Incident and reflected a and b waves are ratioed against the harmonic phase reference with constant phase relationship versus frequency and from sweep to sweep => Phase coherence



Sweep 1



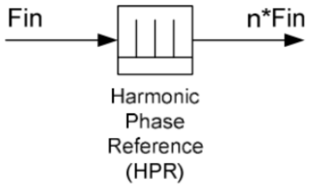
Sweep 2

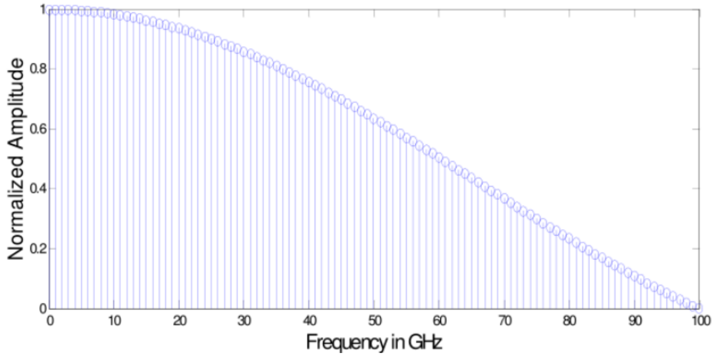
Harmonic Phase Reference

The LSA requires two phase reference modules:

- One phase reference module is used to maintain a static cross-frequency phase relationship.
- A second phase reference standard is used to calibrate the cross-frequency phase at the device reference plane.

AMCAD HPR727A
can generate signals up to 26.5GHz at frequency intervals as small as 10MHz.





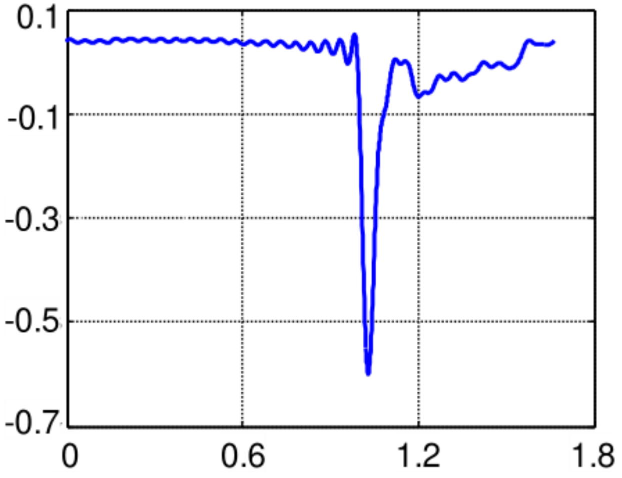
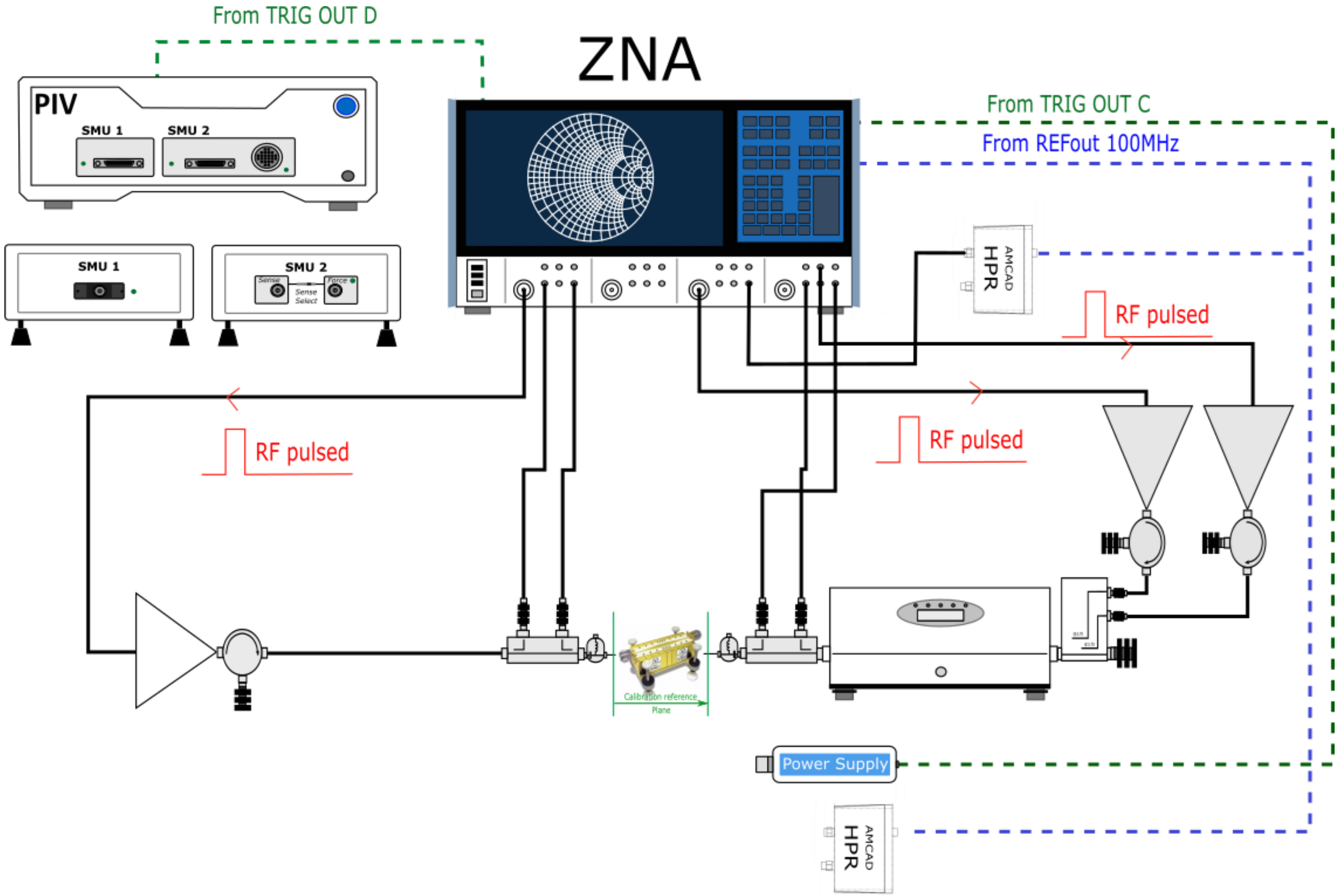


Figure 1:6 Time domain HPR signal

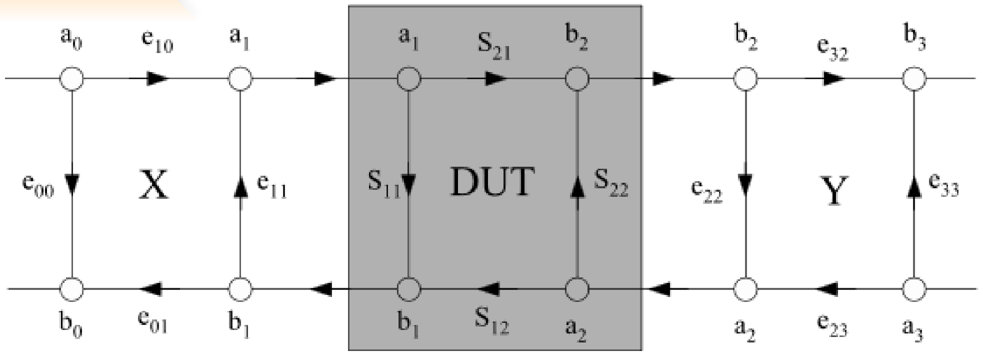
When the phase reference is driven with Fin frequency, it generates $* Fin$ at the output.

AMCAD & R&S ZNA Large Signal Application



Bench Calibration process

Summary



The transmission term $\frac{e_{01}}{e_{32}}$ is calculated from the thru measurement. Using the assumption that the thru is reciprocal ($S_{12} = S_{21}$) it can be shown that [5]:

$$\frac{e_{01}}{e_{32}} = \pm\sqrt{\frac{S_{12M}(e_{00}e_{11} - \Delta_X)}{S_{21M}(e_{22}e_{33} - \Delta_Y)}} \qquad (1)$$

$$\begin{bmatrix} b_1 \\ b_2 \\ a_1 \\ a_2 \end{bmatrix} = \frac{1}{e_{01}} \begin{bmatrix} 1 & 0 & -e_{00} & 0 \\ 0 & k & 0 & -ke_{33} \\ e_{11} & 0 & -\Delta_X & 0 \\ 0 & ke_{22} & 0 & -k\Delta_Y \end{bmatrix} \begin{bmatrix} b_0 \\ b_3 \\ a_0 \\ a_3 \end{bmatrix}$$

$$|e_{01}|^2 = \frac{|b_0 e_{11} - a_0 \Delta_X|^2 - |b_0 - a_0 e_{00}|^2}{P_{meter}}$$

$$\varphi(e_{01}) = \varphi\left(\frac{b_0 - b_0\Gamma_R e_{11} - a_0 e_{00} + a_0 \Delta_X \Gamma_R}{a_R}\right)$$

where P_{meter} is the power measured by the power meter, a_R the incident wave and Γ_R the reflection coefficient of the phase reference.

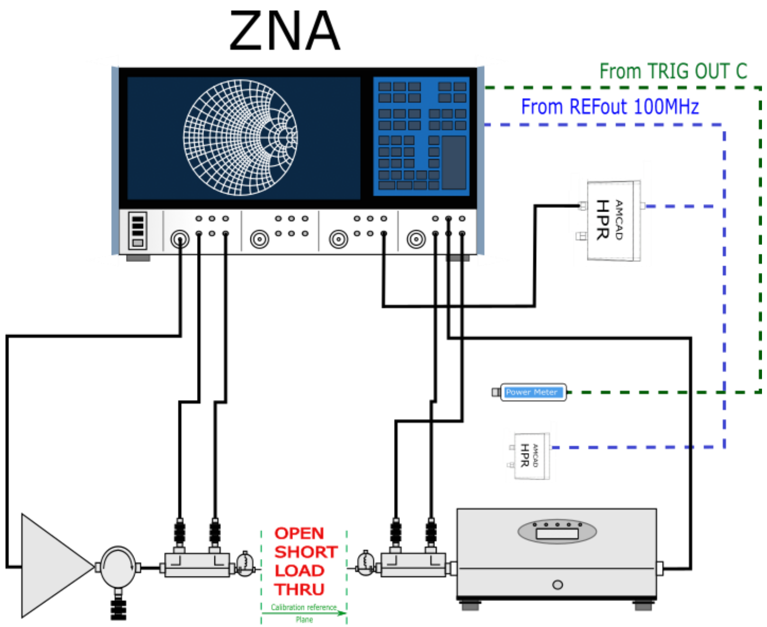
Bench Calibration process

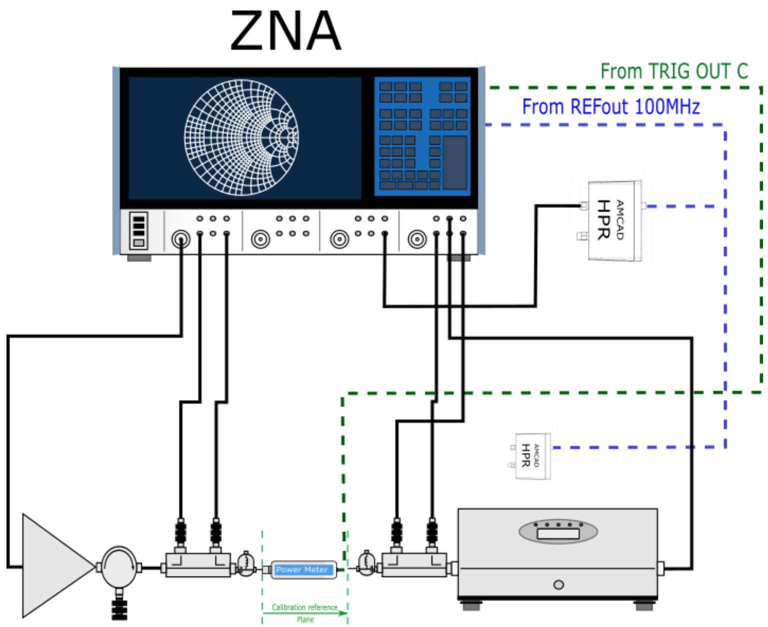
RF & Microwave solutions

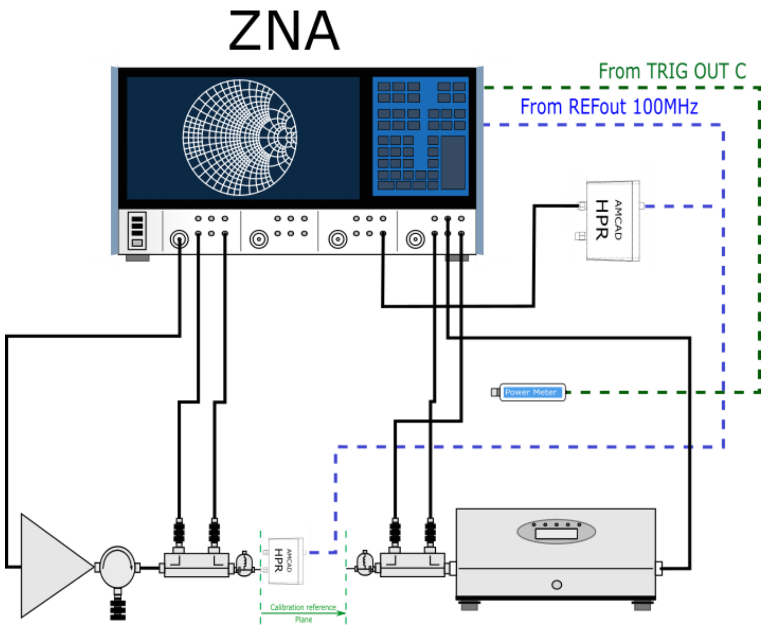
Coaxial Calibration

- **3 steps Calibration :**

  - Full 2 Port Calibration







Bench Calibration process

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Coaxial Calibration

- **3 steps Calibration :**
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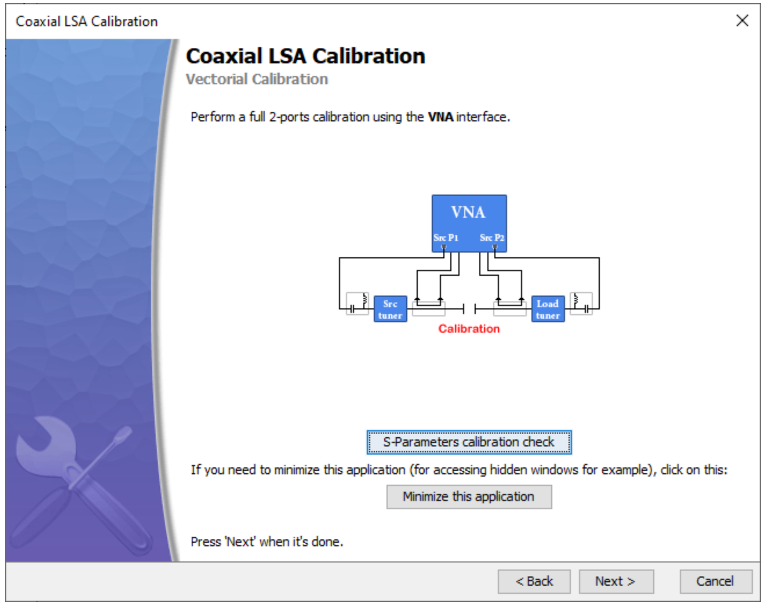
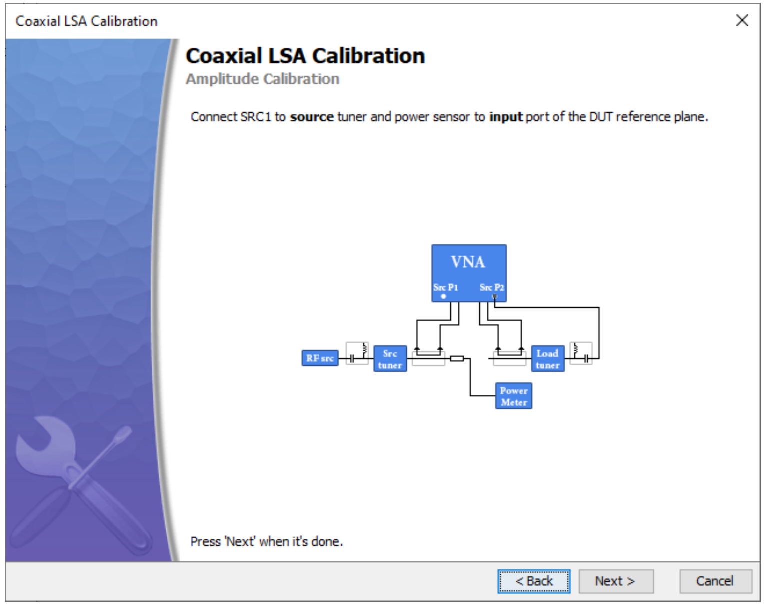
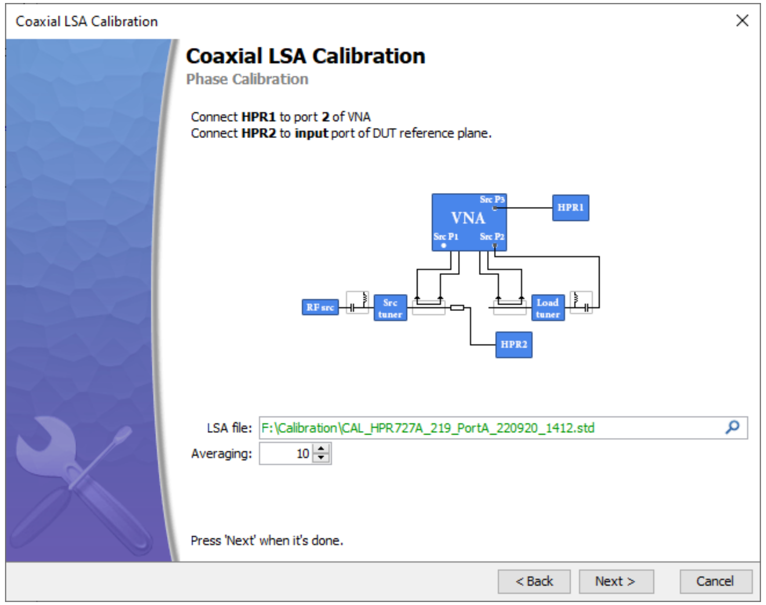




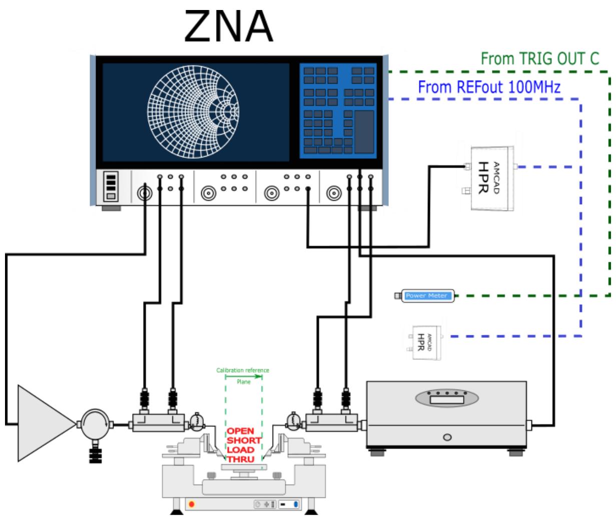


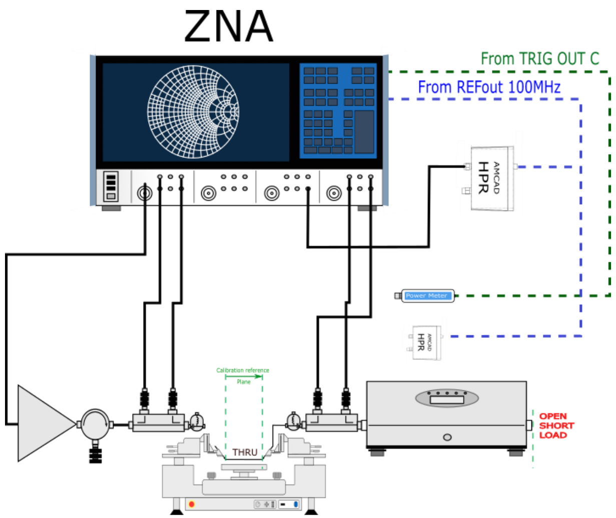
Bench Calibration process

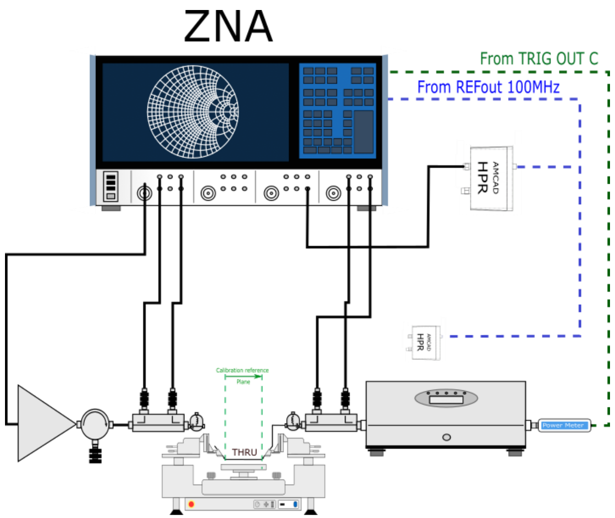
On Wafer Calibration

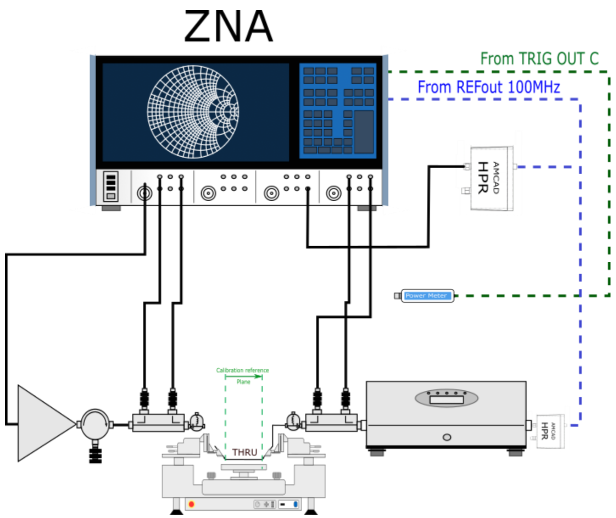
- **4 steps Calibration :**

- Full 2 Port Calibration







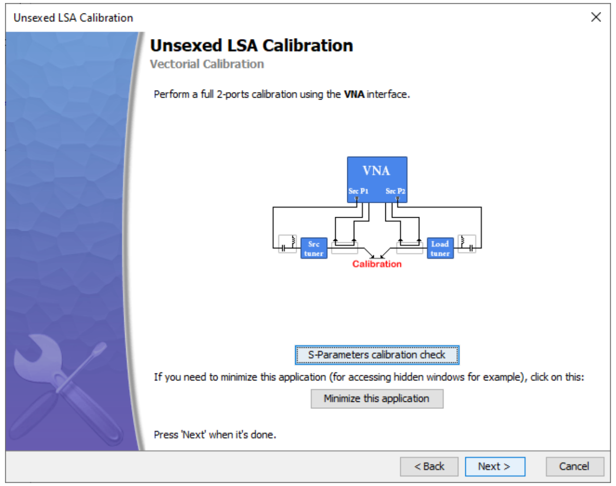


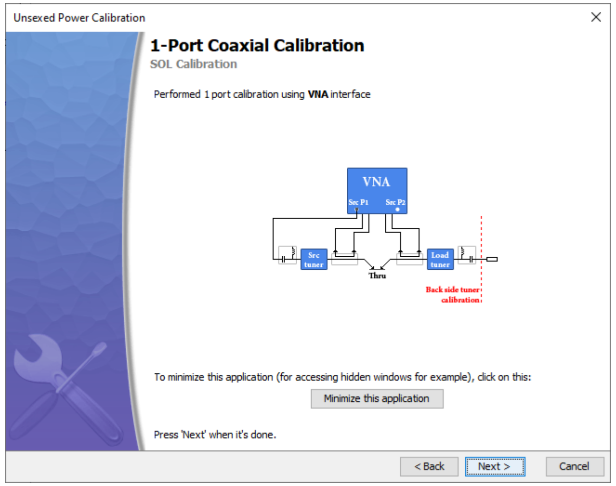
Bench Calibration process

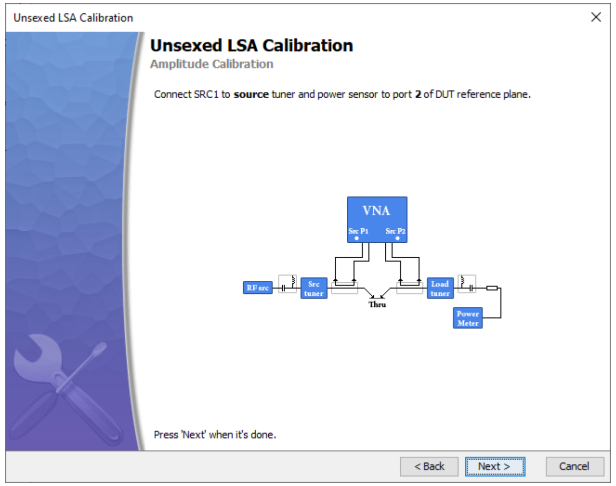
On Wafer Calibration

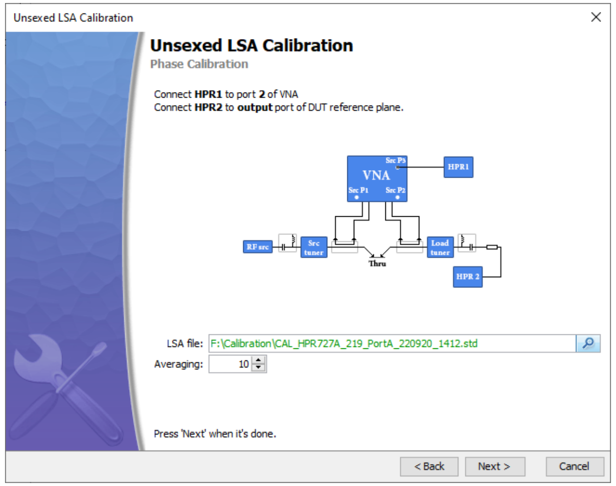
- **4 steps Calibration :**

- Full 2 Port Calibration



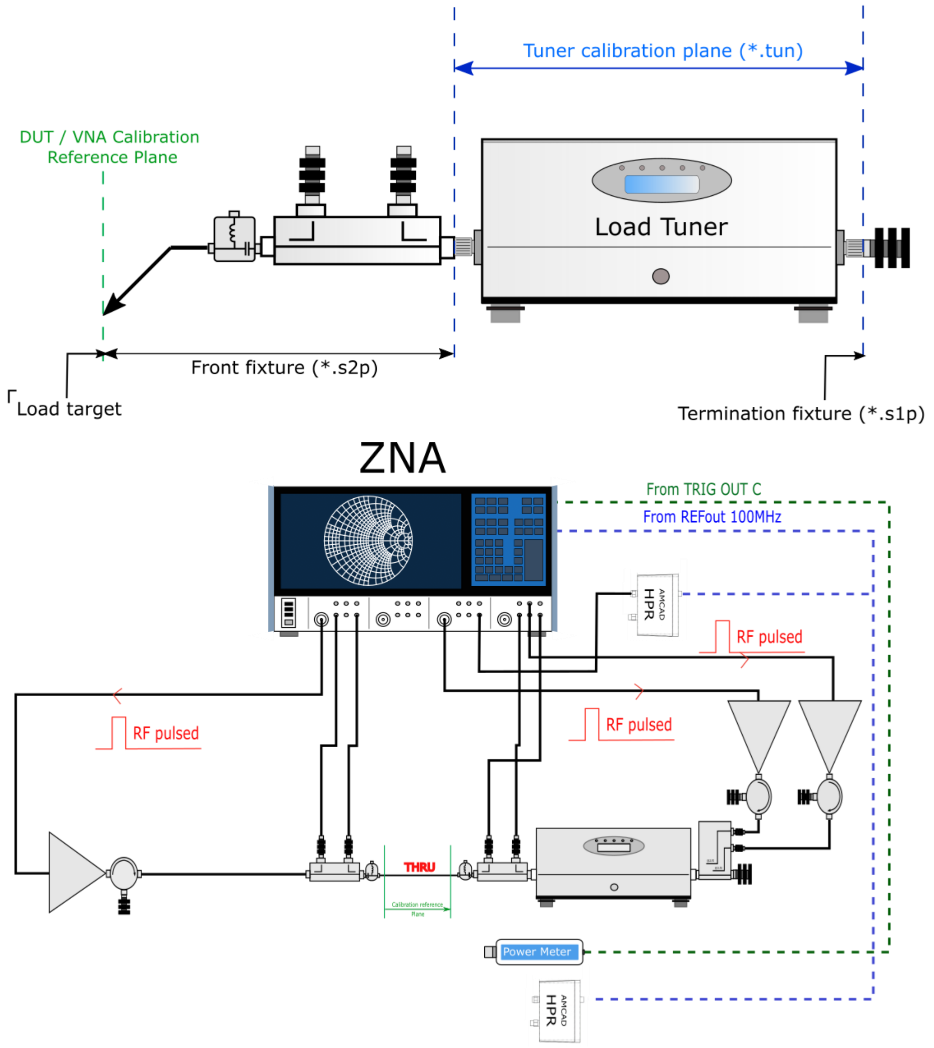


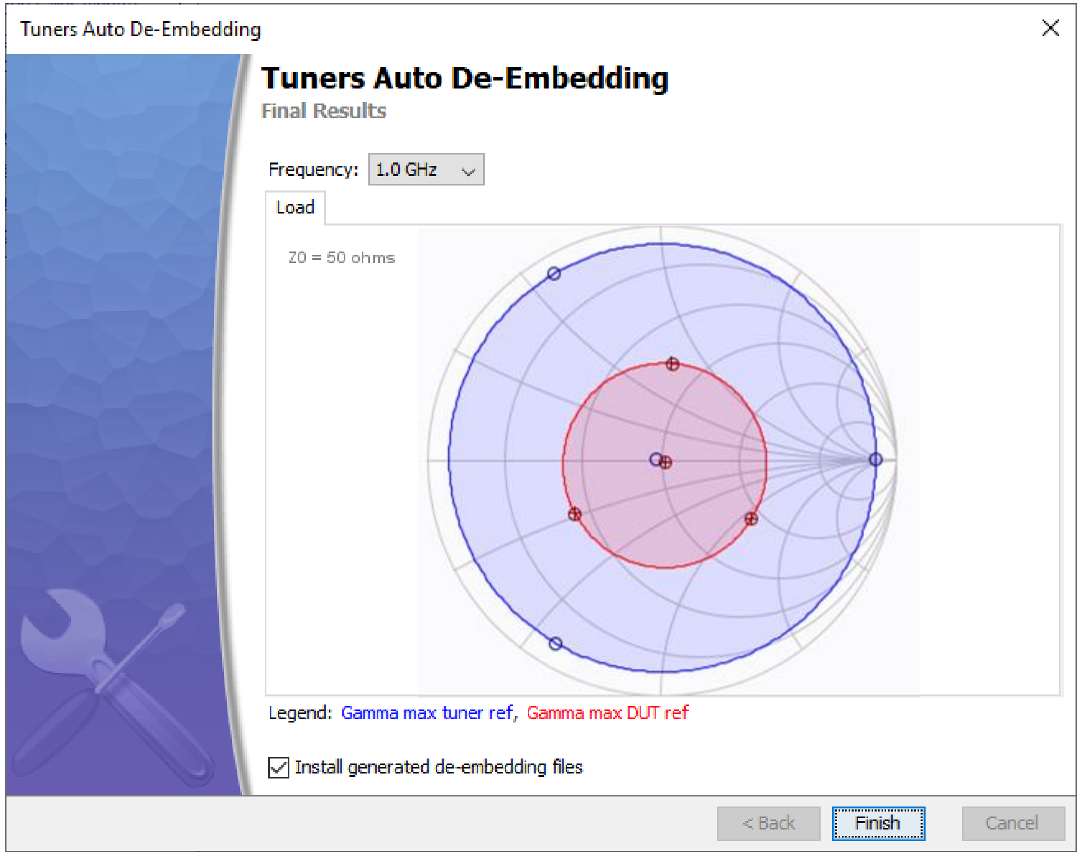




- SOL Calibration

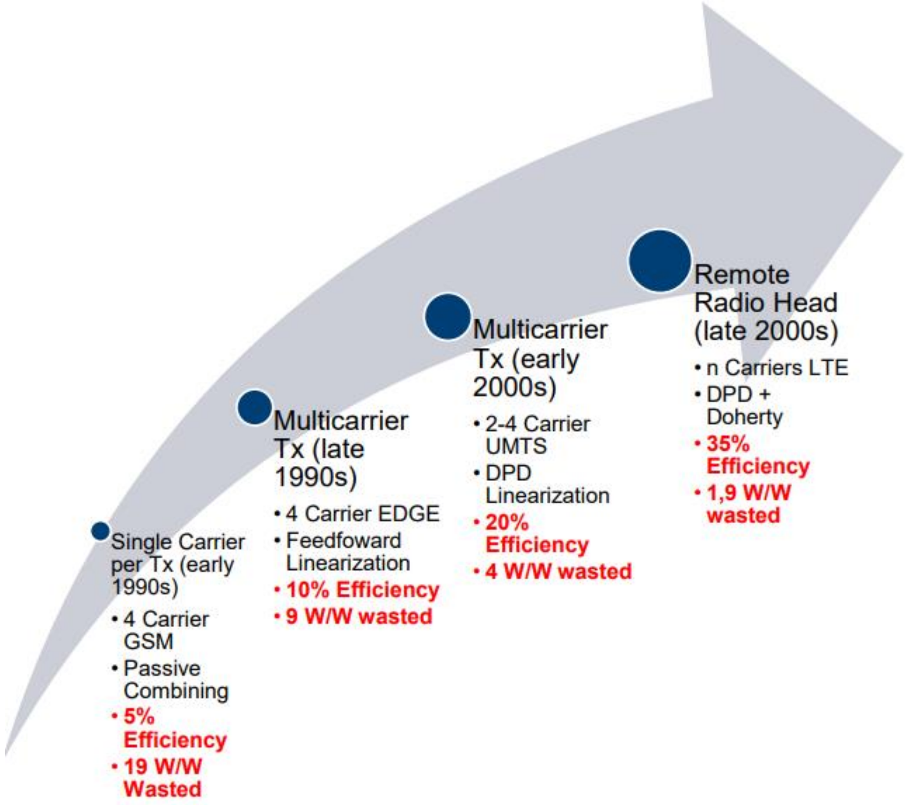
Tuner Auto De-embedding





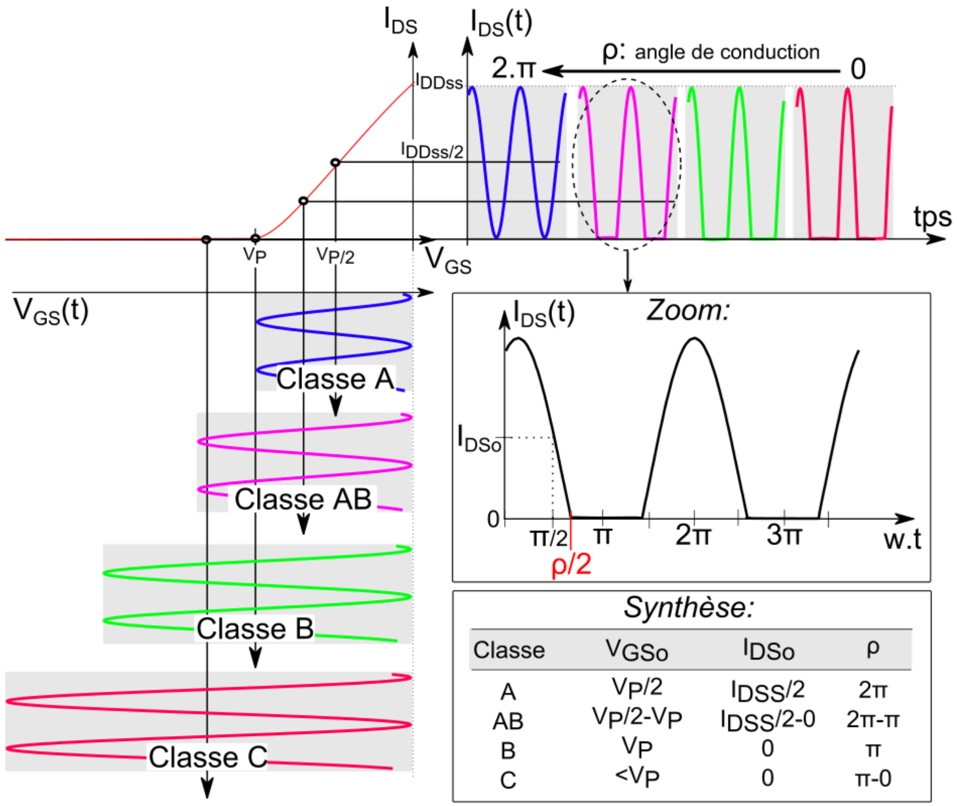
Energy Efficiency

- Radio Frontend (RFFE) performance is defined by 4 headline parameters:
  - Output Power
  - Bandwidth/Frequency
  - Linearity
  - Efficiency
- The first three of those are governed or dictated by specification or regulation
- Efficiency is the market differentiator.
- In battery powered applications, it drives time between-charges, in prime- or higher-powered applications, it drives cooling requirements; size and weight.

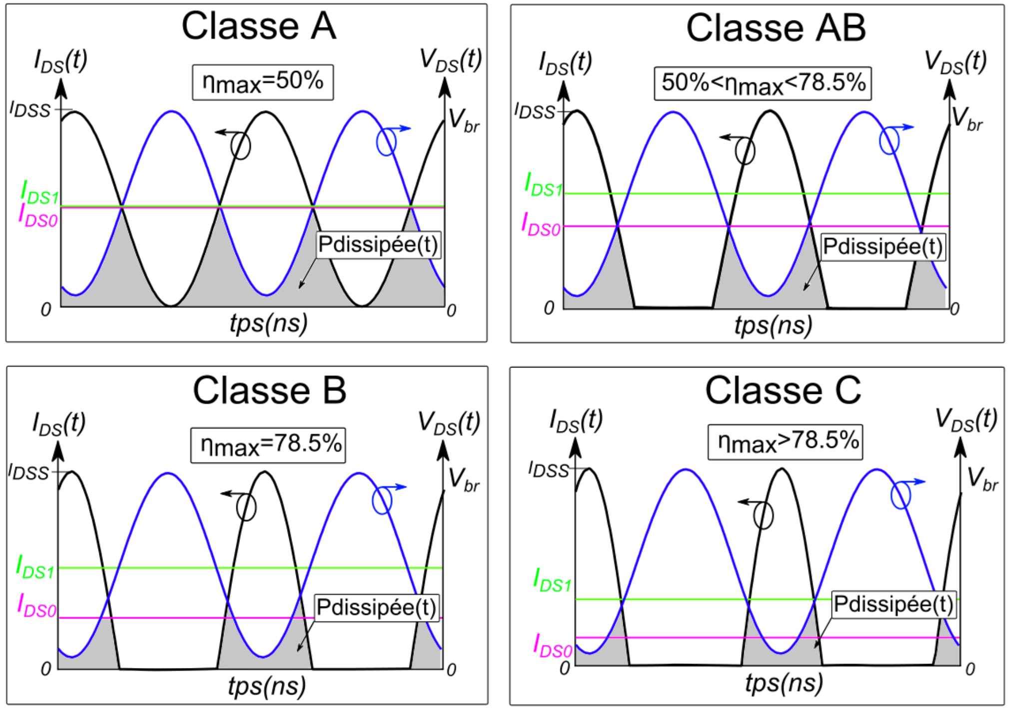


Maximum Efficiency of Transistor

Continuous Mode: Class A, AB, B & C based on Biasing point

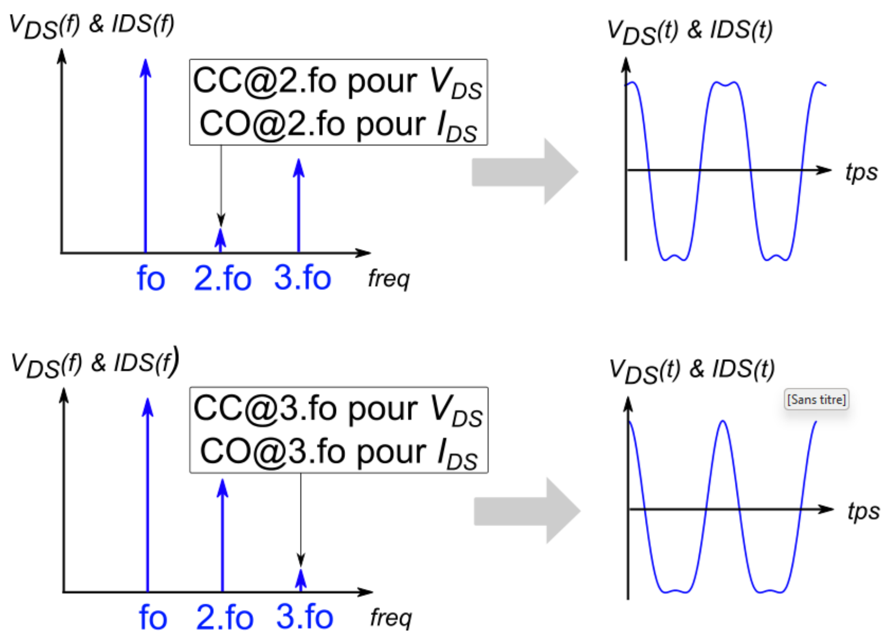


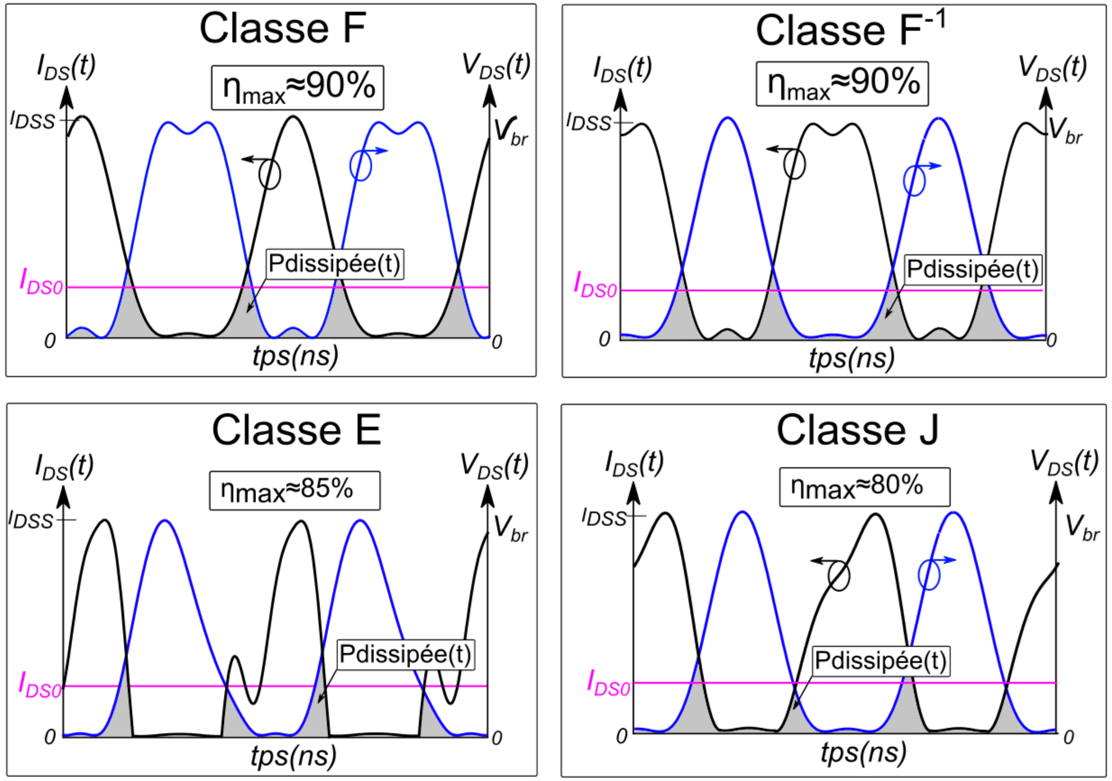
Classe	VGSo	IDSo	ρ
A	VP/2	IDSS/2	2π
AB	VP/2-VP	IDSS/2-0	2π-π
B	VP	0	π
C	<VP	0	π-0



Maximum Efficiency of Transistor

Switching Mode : Class F, E, J … Harmonics controlled



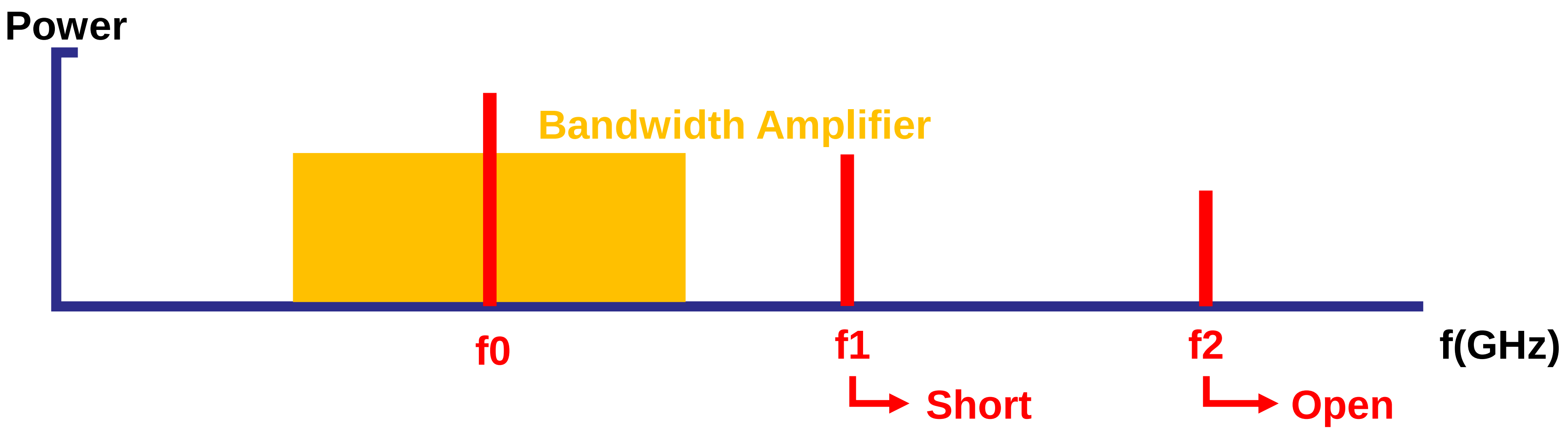


Maximum Efficiency of Transistor

Harmonics Load-Pull measurement, over a range of bias condition can explore the device efficiency potential to find the best design topology.

Harmonic VRLP … when?

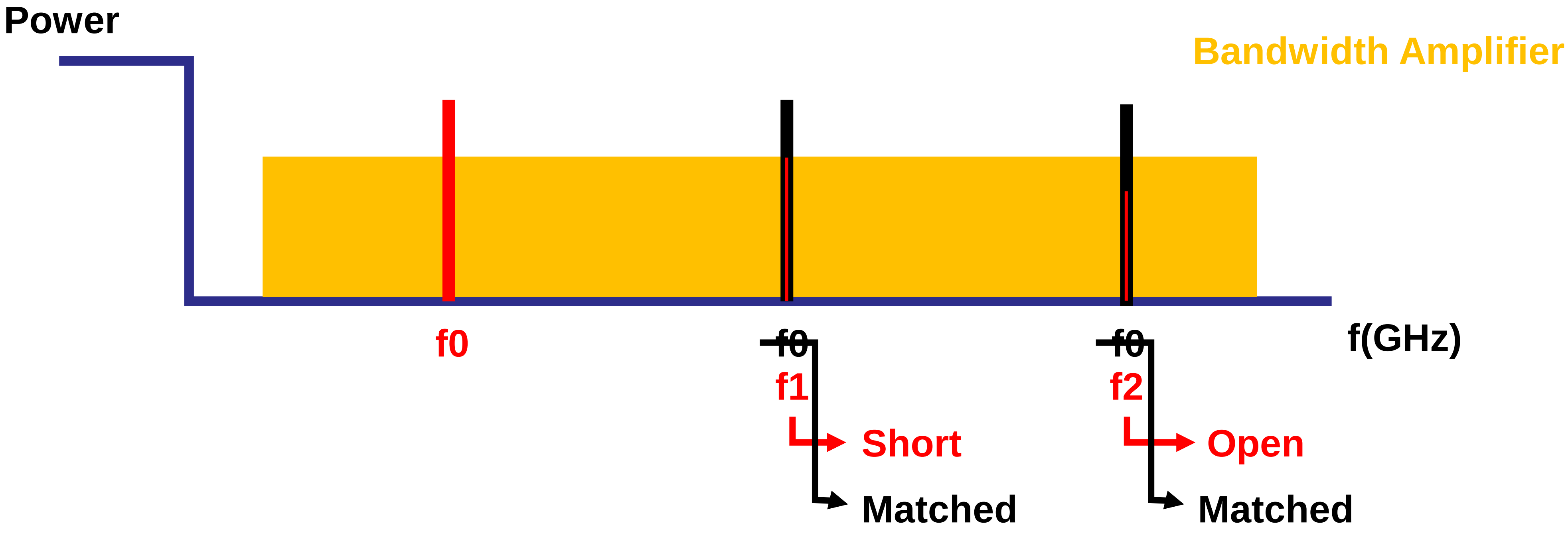
- Amplifiers operating under linear (small signal) conditions **do not** produce power at harmonic frequencies, and the output power of a device under test is **linearly proportional** to its input power.
- Highest efficiency is achieved under non-linear (large signal) conditions. Highly non-linear PAs operating in advanced classes (E, F, G, J and their inverses) are commonly used in modern wireless communication systems.
- Amplifiers operating under non-linear (Large signal) conditions **do** produce power at harmonic frequencies, and the output power of a device under test is **non-linearly proportional** to its input power.



Harmonic VRLP -> Wide band amplifiers

It may occur harmonic frequencies (2fo, 3fo…) of the lower frequency band overlap a fundamental frequency in the middle or upper portion of the frequency band.

For a fundamental frequency of, a theoretical ClassF amplifier would require a short at the second and an open on the third harmonic. This will yield in low performance for second- and third fundamental frequencies.



Harmonic LP, does it have effect?

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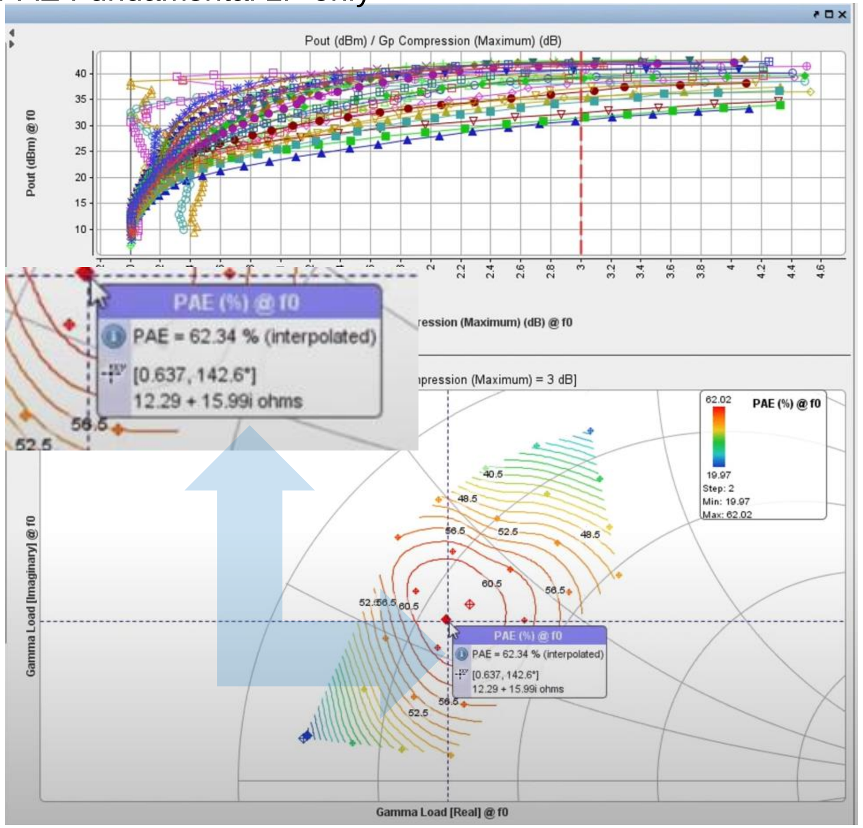
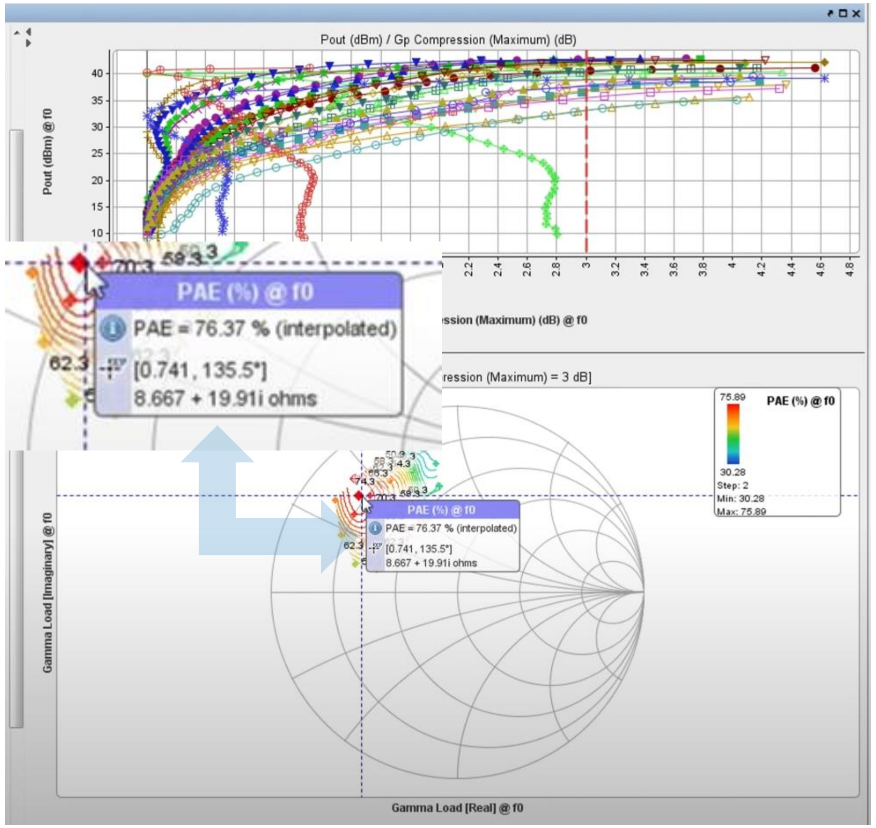
PAE Fundamental LP only



PAE Fundamental plus f2 and f3 harmonic LP

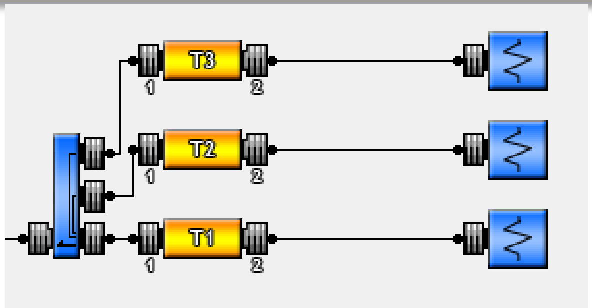


Increase of PAE of 14% by tuning f2 and f3 on optimum load

How to control Γ_{load} Harmonics

- Harmonic Load Pull with passive tuner One mechanical tuner per frequency
   To tune f0, 2f0 & 3f0 at the same time = 3 tuners

Multiplexer

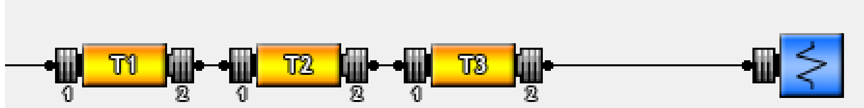


- Filters use to separate the f0 & harmonics signal

 f0 & harmonics may be tune independently

 Triplexer as filter
  - f0 = low pass filter
  - 2f0 = band pass
  - 3f0 = high pass filter

Cascaded



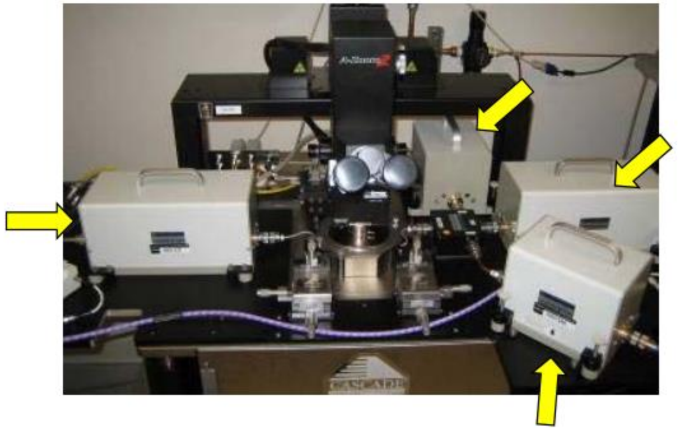
- Two or three cascaded tuners

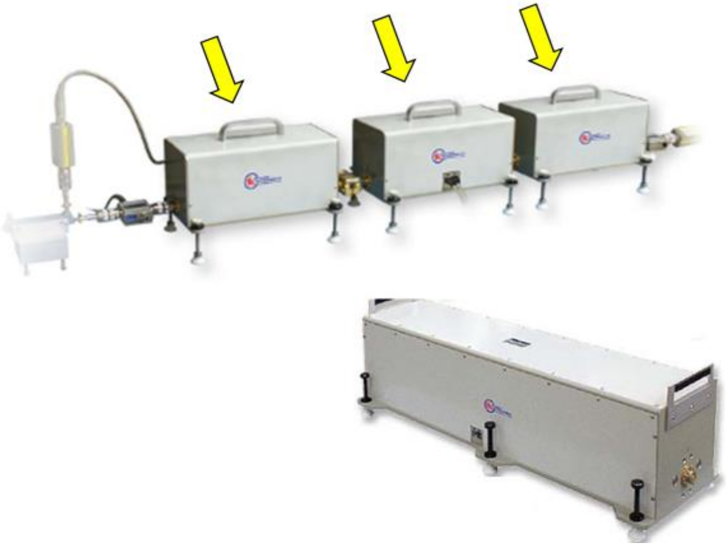
 ≈240,000,000 available impedances states

 Multiple states produce any specified f0 impedance & variety of f2, f3 impedances

 Robust and advanced algorithm to achieve the combination targetted

How to control Γ_{load} Harmonics

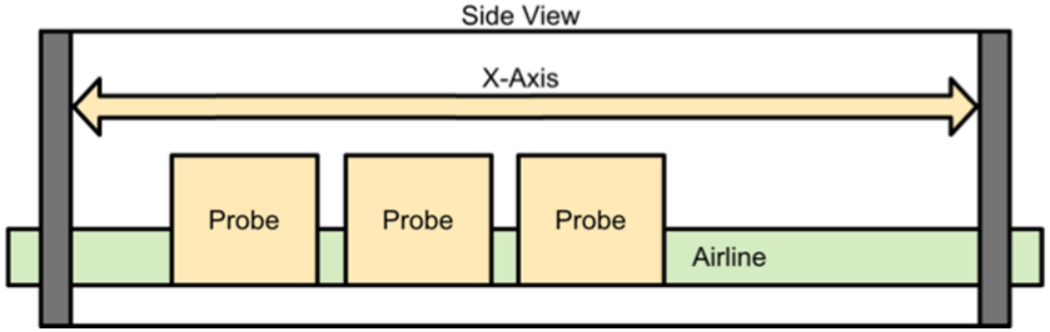


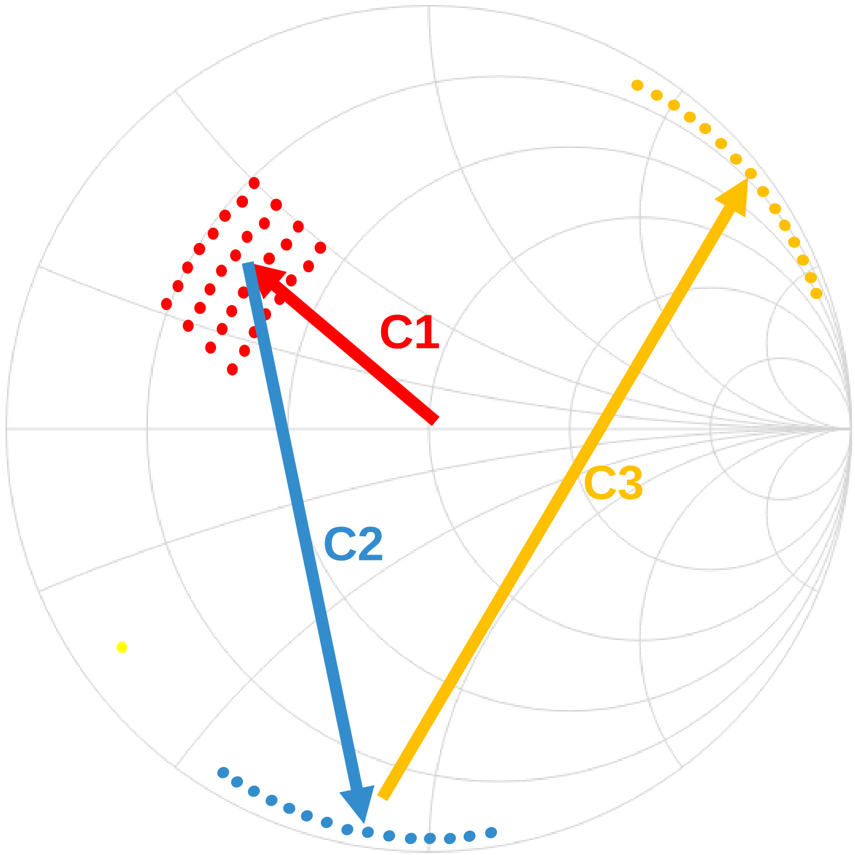


Harmonic Tuning Method	Advantages	Disadvantages
Multiplexer	• High tuning isolation	• Insertion loss due to the triplexer, reduced matching range • Triplexer has to be characterized in S-parameters / narrow band
Cascaded Tuner	• Operates over full tuner BW with no setup changes • No loss in front of any tuners • Fast measurements	• Less tuning isolation

Cascaded Harmonic Tuner

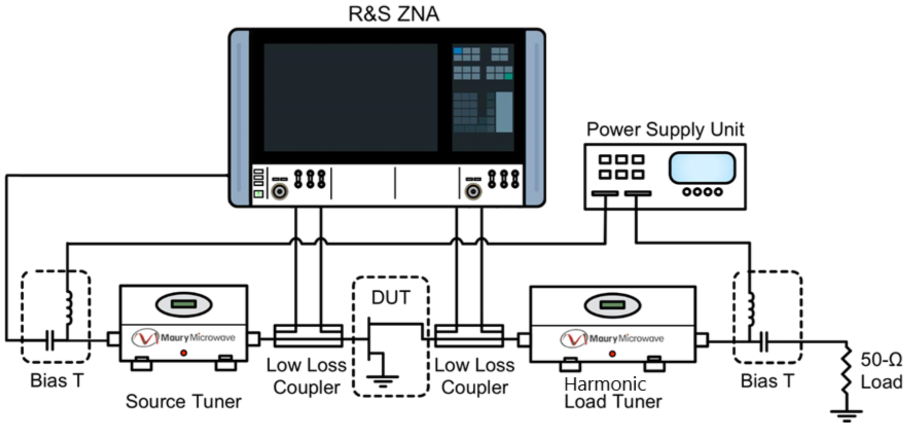
With harmonic tuners loads for f0, f1 and for a three-stage tuner also f2 independently controlled

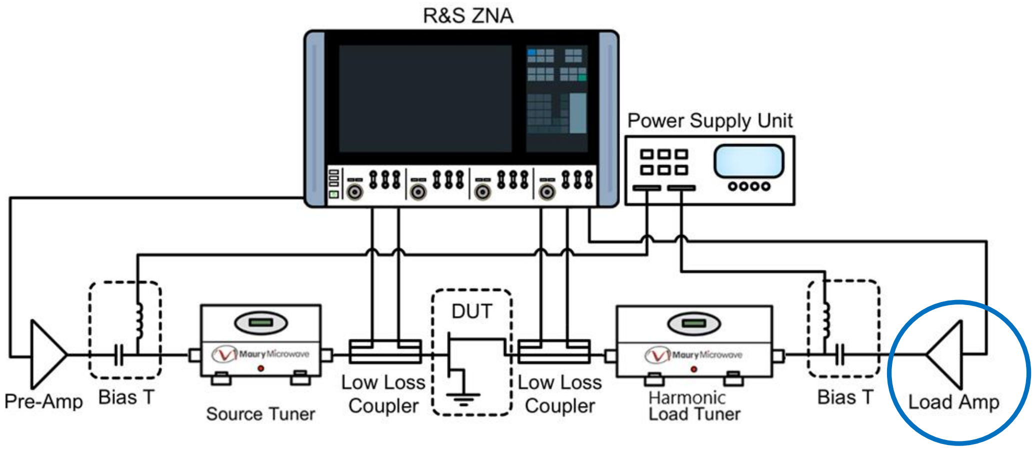




Harmonic passive & hybrid active VRLP

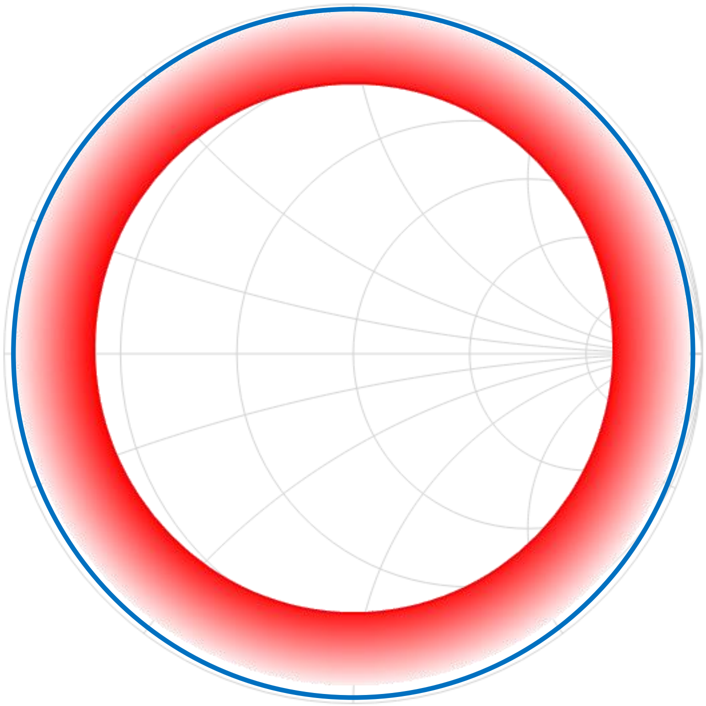
Advantage: Available (2-port VNA's) like ZVA / ZNA can be used with Harmonic tuners





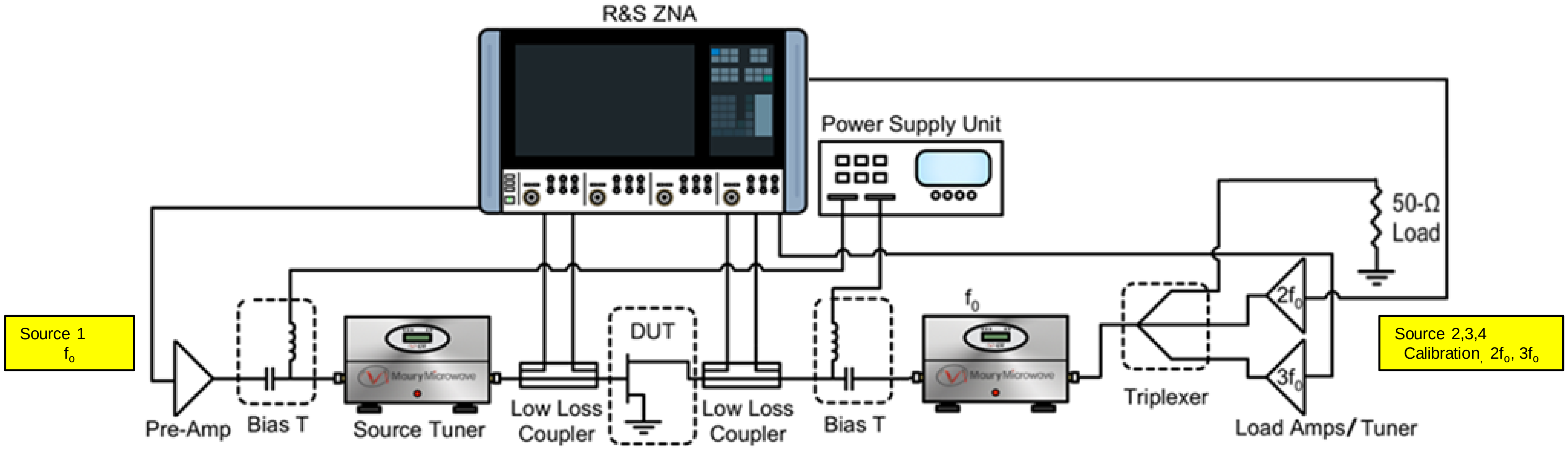
Maximum reflection of f2 and/or f3 depends on combination of device and setup.

The use of an amplifier overcome losses and the outside of the Smith chart can be reached. Recommended for high power devices



Hybrid active harmonic VRLP with 4-Port ZNA

Power and phase can be controlled independently with a ZNA with four sources. Fundamental control using passive tuners and harmonics using active injection (hybrid load pull)



Advantages:

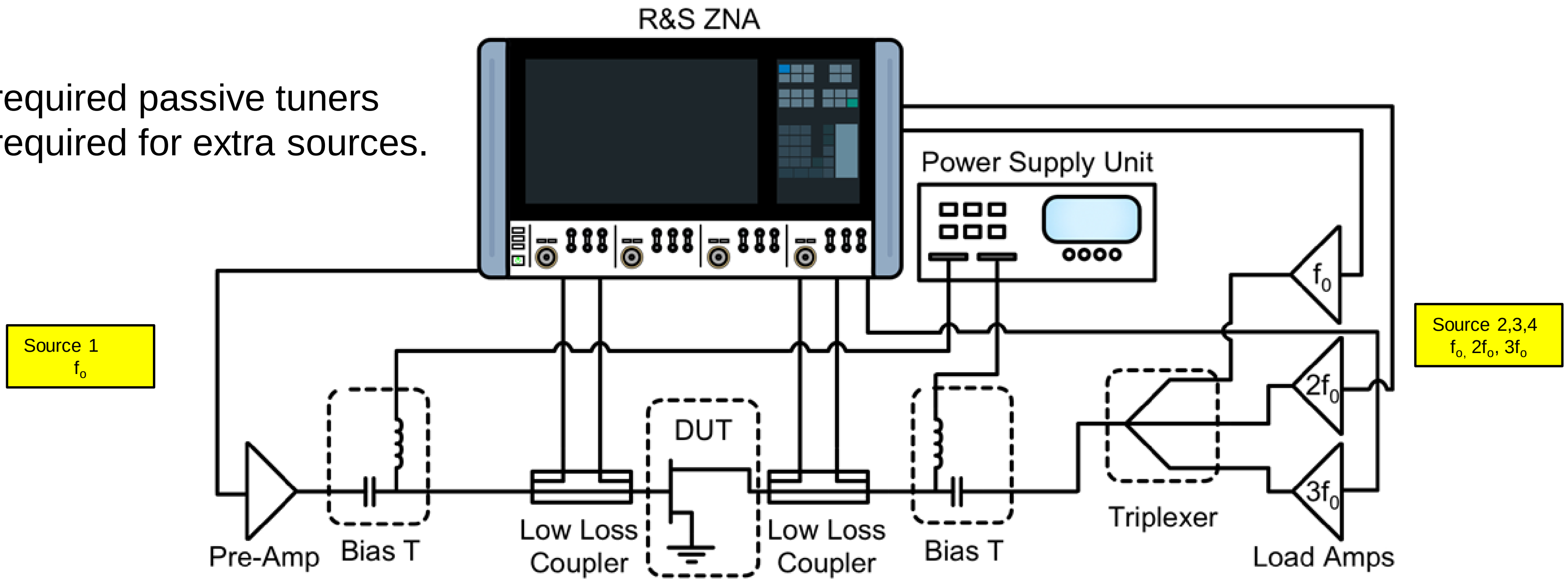
- No extra investments are required for harmonic tuner tuners
- No extra investments are required for extra sources.
- Most power is handled by passive fundamental tuner. Therefore, very suitable for high power devices.
- Very flexible and stable one-box solution.

Active harmonic VRLP with R&S 4-Port ZNA

Fully active impedance control using multiple signal generators and load amplifiers (active load pull)

Advantages:

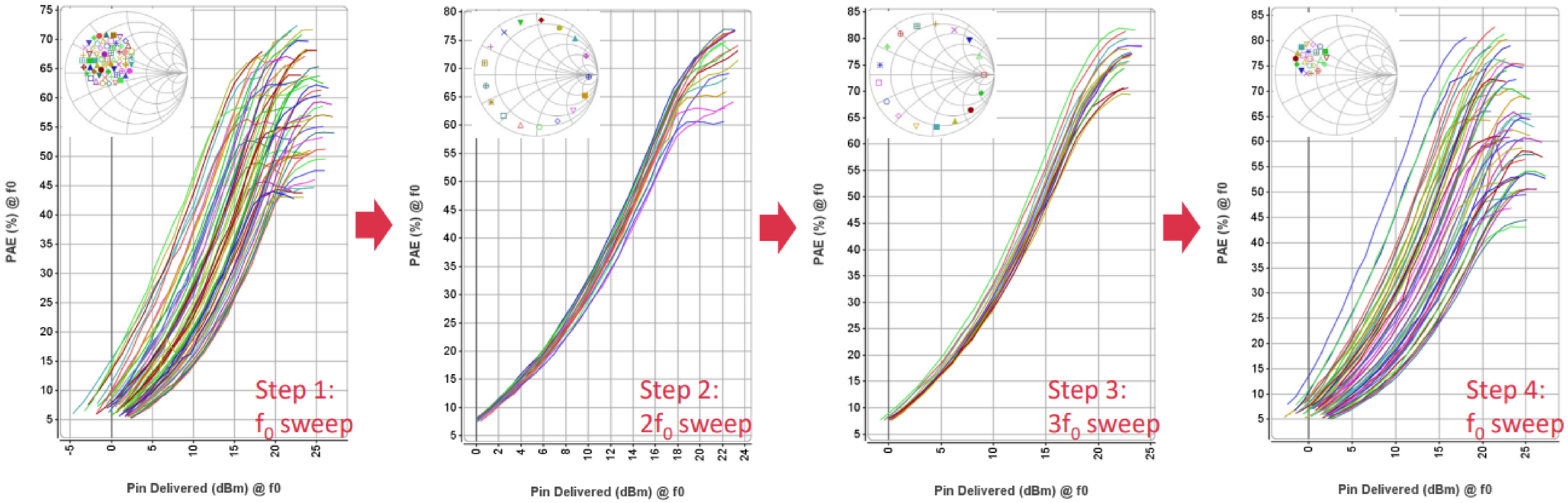
- No extra investments are required passive tuners
- No extra investments are required for extra sources.



Depending on the output power of the DUT, a high-power amplifier may be required to tune the load for f0 at high gammas!

Harmonic LP to maximize Efficiency

- Multiple load-pull measurements for PAE optimization:
    1. Swept impedances at f_0; $2f_0$ and $3f_0$ fixed at 50 Ω
    2. Swept impedances at $2f_0$; f_0 fixed for optimum PAE at 3 P_{3dB}, $3f_0$ fixed at 50 Ω
    3. Swept impedances at $3f_0$; f0 and $2f_0$ fixed for optimum PAE at 3 P_{3dB}
    4. Swept impedances at f_0; $2f_0$ and $3f_0$ fixed for optimum PAE at 3 P_{3dB}
- Measurements performed at the transistor package plane



Waveform Engineering

At RF and microwave frequencies, such conditions can be achieved using current and voltage waveform shaping at the drain level.

Thanks to the understanding **waveform shaping, designers have now widely adopted Power Amplifier (PA) design methodologies** which employ high efficiency class of operating conditions, such as Class F or inverse Class F amplifiers

Waveform Engineering & Behavioral Modelling request cross-harmonics phase relationship

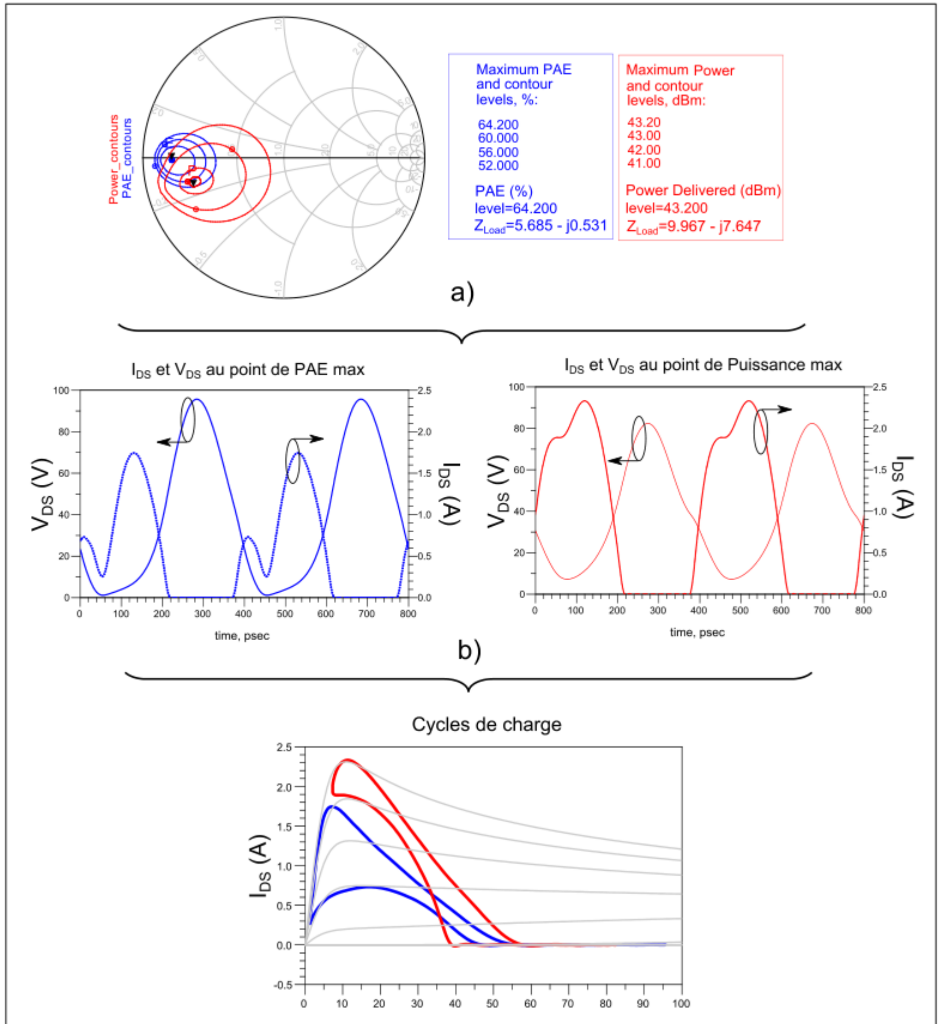


Figure III-12 : Simulation load-pull à puissance disponible d'entrée constante (f_0=2.5 GHz). a) Rouge : Contours de puissance de sortie (dBm). Bleu : Contours de PAE (%). b) Formes d'ondes de tension et courant pour la PAE maximale (bleu) et pour la puissance maximale (rouge). c) Cycles de charge pour la PAE maximale (bleu) et pour la puissance maximale (rouge).

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