Sub-Terahertz Noise Parameter Measurement

D / W-Band On-Wafer Capabilities

Focus Microwaves – An MPI Company

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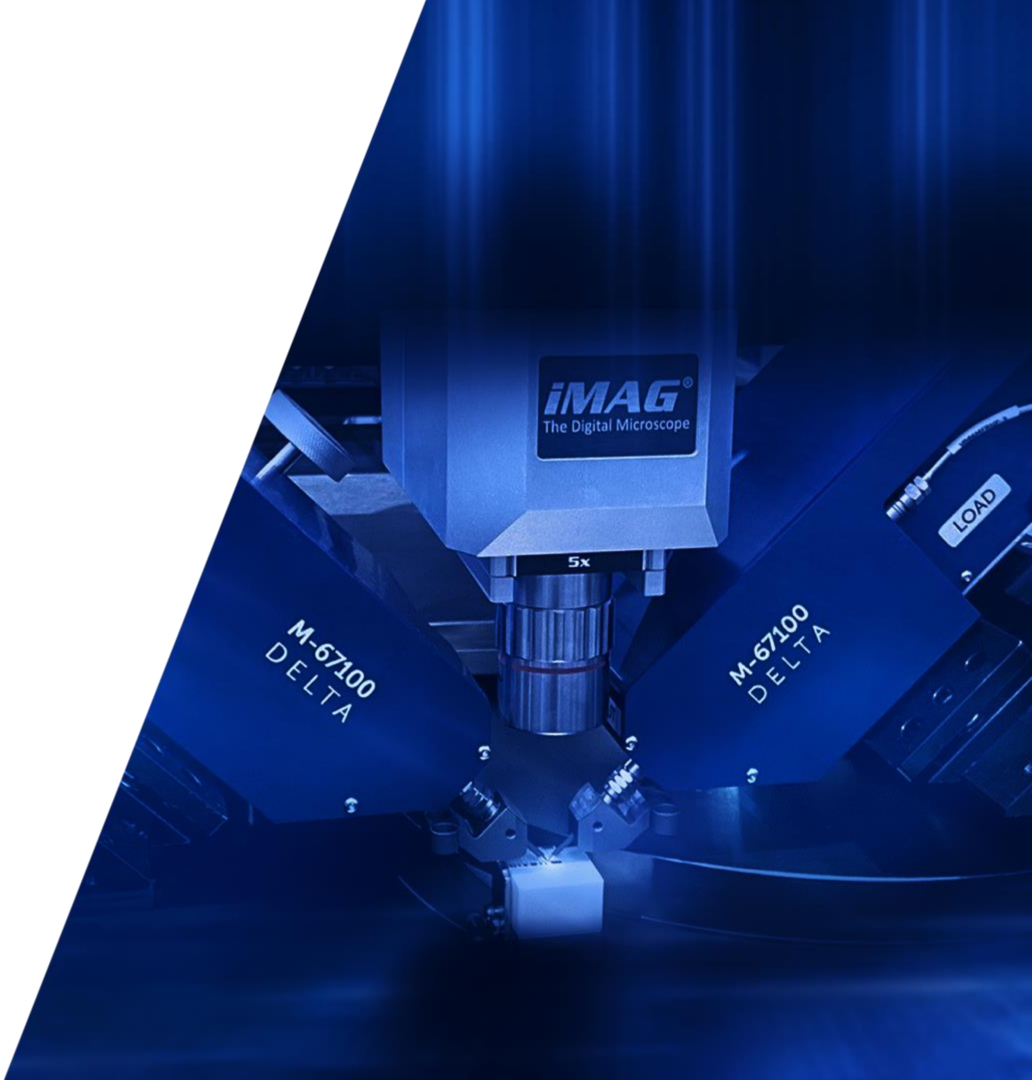
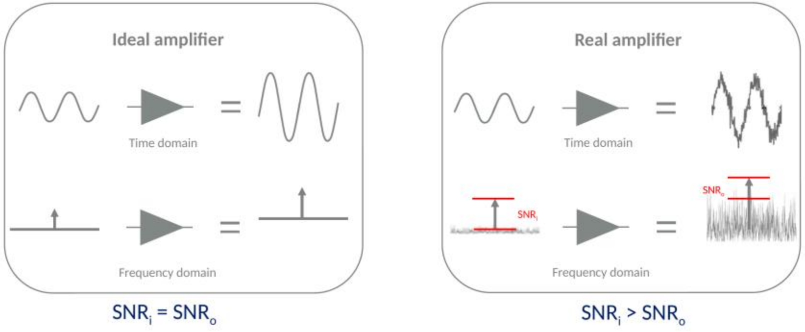


What is Noise in RF?

- **Any unwanted, random electromagnetic fluctuations**
- **Every component adds noise** – thermal (Johnson), shot, flicker. At mmWave, thermal noise dominates.
- **Noise sets the receiver's floor** – the smallest signal you can still detect.
- **The key metric is SNR** (signal-to-noise ratio).
- An *ideal* amplifier raises signal and noise equally → SNR unchanged.
- A *real* amplifier adds its own noise → SNR degrades.



Ideal: $SNR_{in} = SNR_{out}$ Real: $SNR_{out} < SNR_{in}$

From Noise to Noise Figure (the 50 Ω story)

Noise Factor & Noise Figure

$F = SNR_{in} / SNR_{out}$ (linear)

$NF = 10 \cdot \log_{10}(F)$ dB at 50 Ω, T_0 = 290 K

Friis: the first stage rules

$F_{tot} = F_1 + (F_2 - 1)/G_1 + (F_3 - 1)/G_1 G_2 + \dots$

- The LNA (stage 1) dominates the whole receiver's noise.
- Minimize its NF and you minimize the system NF.

A receiver chain

But NF is only the 50 Ω answer

- NF fully describes noise ***only*** for a fixed 50 Ω source.
- Real designs are ***not*** 50 Ω → we need noise **parameters**

Beyond 50 Ω: the Four Noise Parameters

A device's noise figure depends on the **source impedance** presented to it. It is minimized at just one point – ***Γ*opt**.

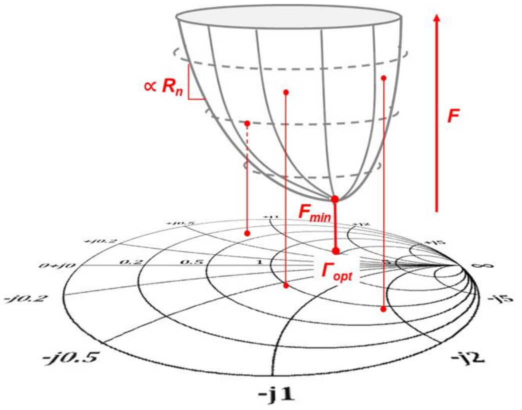
NFmin Minimum noise figure the device can reach

|Γopt| Optimum source reflection – magnitude

ϕopt Optimum source reflection – phase

Rn Noise resistance – how fast NF rises off Γopt

Noise figure over the Smith chart

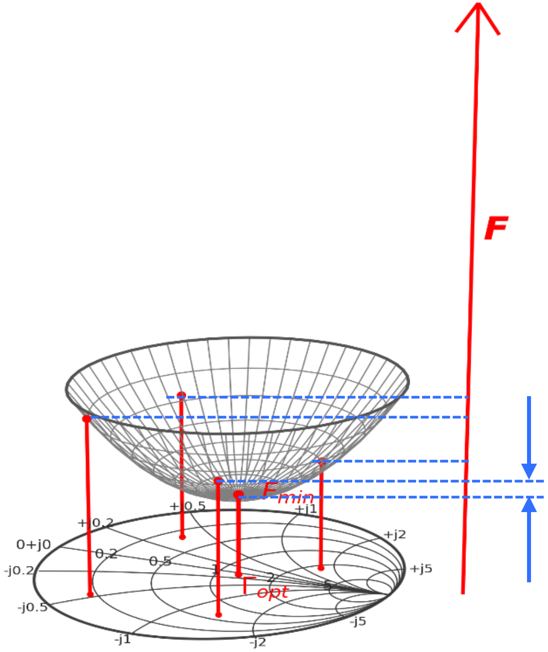


$$F(\Gamma_s) = F_{min} + \frac{4R_n\,|\Gamma_s - \Gamma_{opt}|^2}{Z_0\,|1+\Gamma_{opt}|^2(1-|\Gamma_s|^2)}$$

Red bars mark F at each source impedance; the surface minimum is F_{min} at Γ_{opt}.

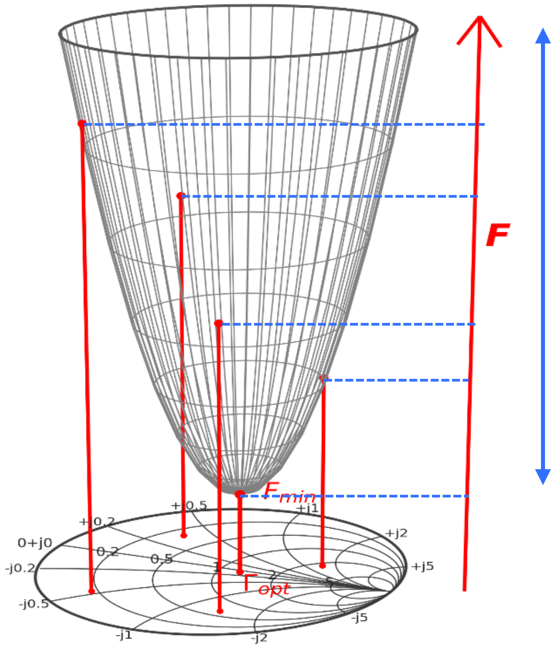
Noise Parameters Measurement Challenges

Low R_n DUT



Receiver accuracy & tuner repeatability becomes important

High R_n DUT



Needs higher dynamic range

Why receiver & LNA designers need Noise Parameters

Noise match ≠ power match

To hit datasheet NF, the LNA input must see Γ_{opt}. That 'noise match' is usually different from the conjugate (gain) match – designers must trade the two off.

You can't optimize what you can't see

With only 50 Ω NF you're blind to Rn and Γ_{opt}. The full noise parameters let you design the input matching network deliberately.

Trustworthy device models

Foundry / PDK LNA and transistor models need measured noise parameters to be validated at mmWave and sub-THz.

Predict system noise

Feed Γ_{opt}, Rn and NFmin into Friis-based budgets to predict real receiver NF – not just the 50 Ω figure.

Two ways to measure noise; Why cold-source

Hot–Cold (Y-factor)

- Switch a noise source between hot (ON) and cold (OFF); read the power ratio Y. ENR inaccuracy in high gammas
- A noise source needs to be turned on and off at every impedance state. Measurement speed
- Measuring Hot and Cold powers requires higher dynamic range for the receiver and even the DUT.

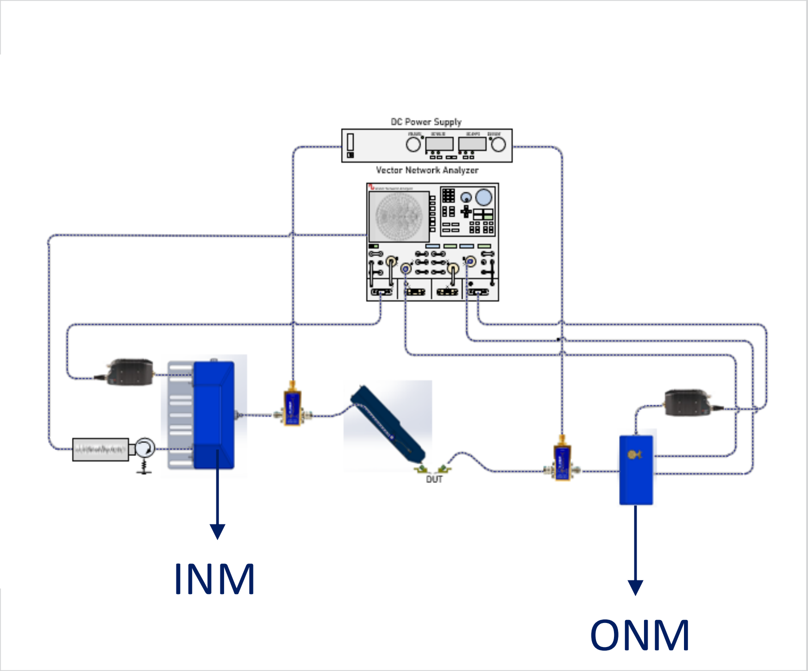
Inaccuracy due to possible nonlinearity

Cold-Source (our method)

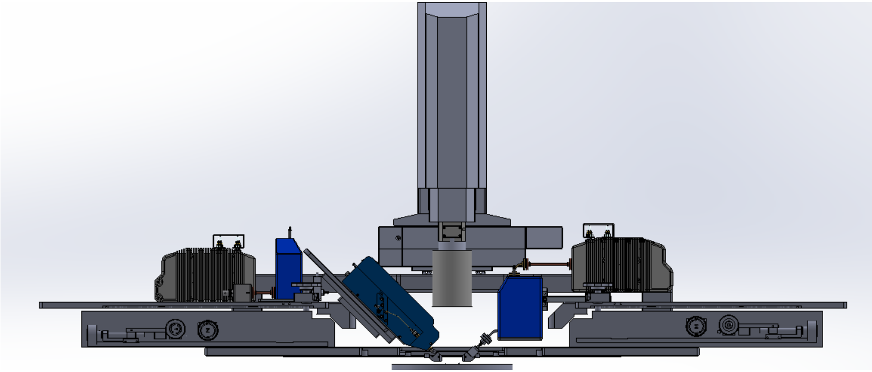
- **DUT input is terminated (cold)**; measure absolute noise power with a calibrated receiver.
- Noise source used ***once at 50 Ω***, only to calibrate the receiver – not per DUT point.
- Higher dynamic range available ***without the ENR***.

Bottom line: Cold-source eliminates ENR uncertainty at high Γ (mismatched transistors, non-50-Ω measurements) and preserves receiver dynamic-range headroom; less compression and non-linearity. The result: faster, more accurate noise parameters.

Our on-wafer Noise Setup



- **VNA + dedicated noise receiver** (PNA-X) – best wideband receiver.
- **Focus Delta tuner** presents source higher VSWR @ 67GHz; with direct probe mounting capability.
- **Delta Noise modules:** ONM direct-mounted at the probe; integrated bias-Ts at the INM and ONM.
- **Noise source, DC supply**; MPI low-loss Titan probes.



Why Focus setup measures better

Wider impedance coverage

- Focus Delta tuners reach higher Γ; due to the direct-mounted probe feature. Using the low loss MPI titan probes pushes the tuner gammas even further.
- Better-conditioned noise-parameter extraction for high opt gamma DUTs.

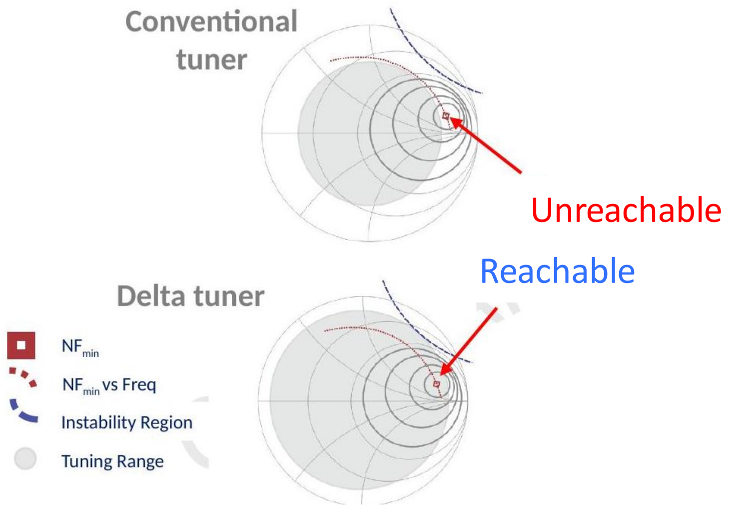
Higher receiver sensitivity

- The ONM6700 body can be mounted directly to the probe, cutting cable loss and lowering receiver NF by 4–5 dB (50–67 GHz).
- Positive gain-slope LNA copes with DUT gain roll-off and cable losses across wide bands.

Integrated & automated

- Bias-tees built into the modules – no external add-ons.
- Full software / API control and automated wafer traversal.

Wider impedance coverage



Conventional vs. Delta tuner – reachable region on the Smith chart

- A conventional tuner's lossy path shrinks the reachable region – it **can miss reaching Γopt**.
- **The Delta tuner reaches it**, so NFmin and Γopt are measured directly, not extrapolated.
- **Higher Γ = better-conditioned fit** = lower uncertainty on all four noise parameters.

Measured tuning range – C6720 + T67MA MPI probe

|Γ| ≈ 0.8

(VSWR-equivalent)

held across 30–50 GHz – coverage to the Smith-chart edge

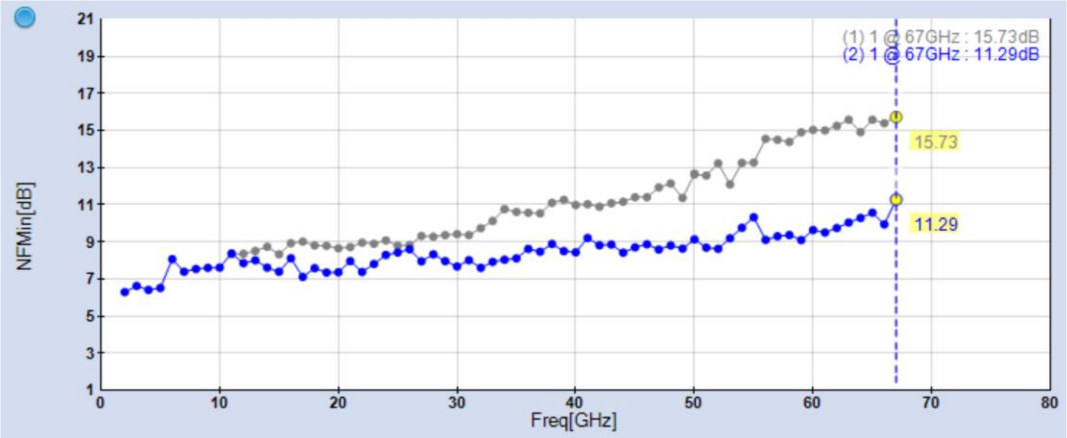
Measured tuning range – C110500 + T110LL MPI probe

|Γ| ≈ 0.7

(VSWR-equivalent)

held across 50–110 GHz – coverage to the Smith-chart edge

Higher receiver sensitivity



Receiver NFmin vs. frequency – cabled (grey) vs. direct-mount (blue)

4–5 dB

lower receiver NFmin, 50–67 GHz

- **Direct connection at the probe** removes cable loss ahead of the LNA.
- **Lower receiver noise → more dynamic range** to see a quiet DUT.
- **More accurate DUT noise**, especially where DUT gain is low at high frequency.

The measurement procedure (cold-source)

1
VNA & Tuner Calibration
VNA cal; tuner S-parameters at every impedance state

2
System S-Parameters
Characterize the network around the DUT

3
Cold / KBG Calibration
Noise source ON/OFF, no DUT – get receiver gain·bandwidth

4
Receiver Noise Calibration
NF at many tuner impedances → receiver's 4 noise params

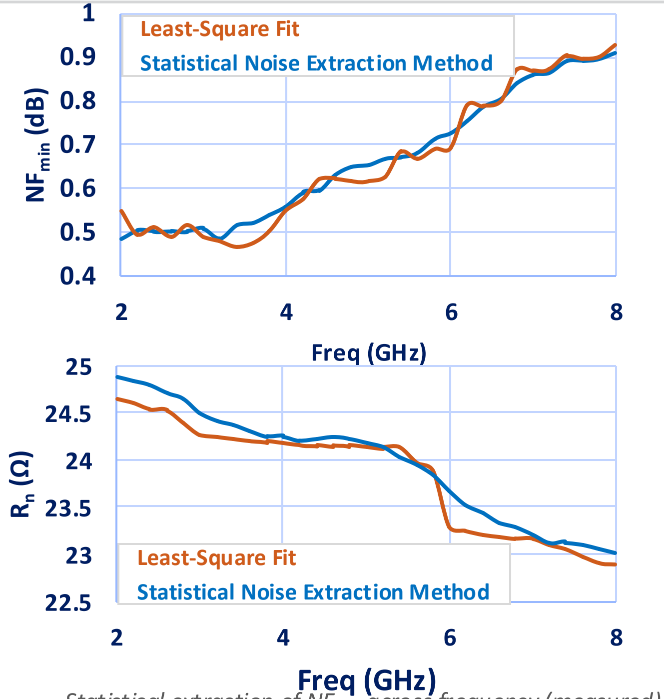
5
DUT Noise Measurement
NF vs. source impedance → DUT's 4 noise params

?

Cold-source – so why do we still need a noise source?

- The noise source is used ***once***, in Step 3 (ON/OFF at 50 Ω), to set the receiver's absolute gain·bandwidth (K·B·G) from its known ENR.
- After that, every DUT point is a **cold measurement** – so the noise measurement can be performed with higher speed.

Better data with our extraction software



Statistical extraction of NF_{min} across frequency (measured)

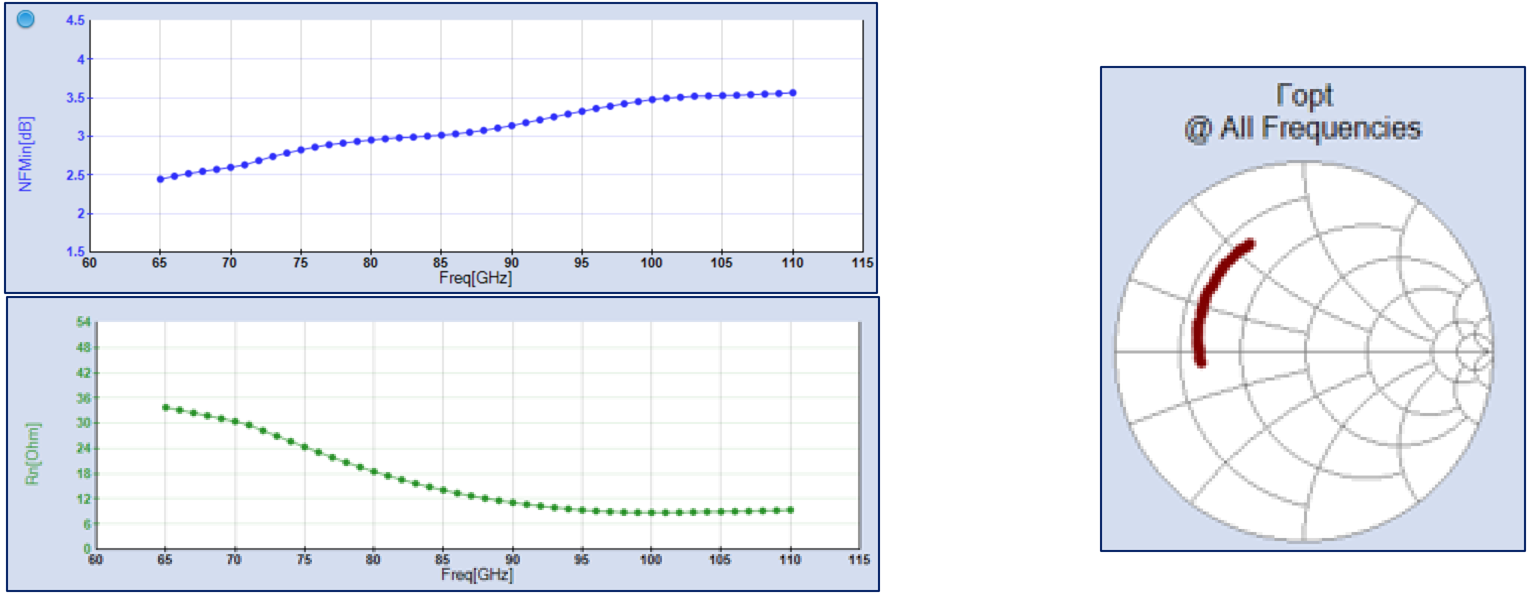
Classical least-squares (LSQ)

- Fits each frequency independently.
- Sensitive to measurement scatter; can fail when NF is dispersed (Lane's method).

Focus statistical extraction

- Analyzes many combinations of measured points and continuity across frequency.
- Rejects outliers → smoother, more continuous, more repeatable wideband NFmin & Rn.

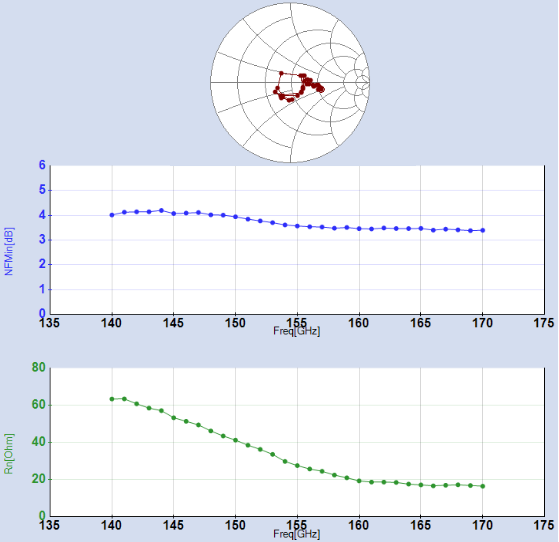
Measurement examples-W Band



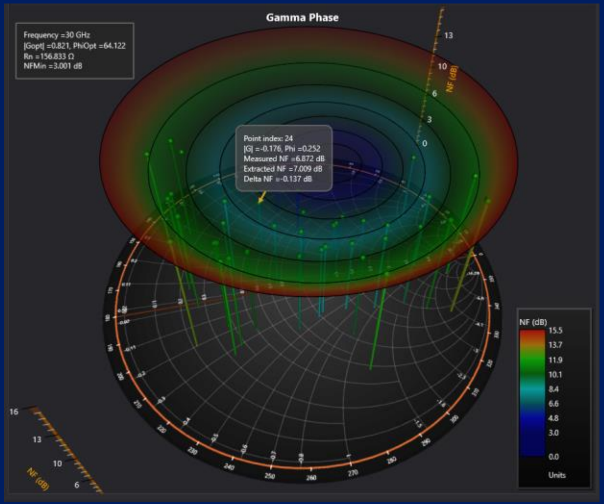
Extracted noise parameters vs. frequency

W-Band noise measurement example

Measurement examples-D band



Extracted noise parameters vs. frequency (example)



3D noise-figure surface – diagnostic view

D-Band noise measurement example

* N. Messaoudi *et al.*, "Enhanced Accuracy in On-Wafer Noise Figure Measurements at Sub-Terahertz Frequencies," *2024 IEEE/MTT-S International Microwave Symposium - IMS 2024*, Washington, DC, USA, 2024, pp. 1024-1027, doi: 10.1109/IMS40175.2024.10600359.

Key takeaways

Full noise parameters, not just NF

We measure NFmin, Γopt and Rn on-wafer – the complete picture receiver and LNA designers actually need.

Coverage + sensitivity = accuracy

Delta tuners widen Smith-chart coverage; the direct-mount ONM6700 lowers receiver NF by 4–5 dB at mmWave.

Cold-source + statistical extraction

A cold-source method with outlier-rejecting statistical extraction gives accurate, repeatable results.

A complete, automated platform

Focus + MPI integrate tuners, modules, probes, software and automation – demonstrated to 67 GHz and scaling into W / D-band.

1) N. Messaoudi *et al.*, "Enhanced Accuracy in On-Wafer Noise Figure Measurements at Sub-Terahertz Frequencies," *2024 IEEE/MTT-S International Microwave Symposium - IMS 2024*, Washington, DC, USA, 2024, pp. 1024-1027, doi: 10.1109/IMS40175.2024.10600359.
2) N. Messaoudi *et al.*, "An Early Comparison of D-Band and G-Band On-Wafer Noise Figure Measurements," 1-4. 10.1109/ARFTG65332.2025.11168143.

Thank You.

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