# ON-WAFER NOISE-PARAMETER MEASUREMENTS, CHECKS, & UNCERTAINTIES AT NIST

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## OUTLINE

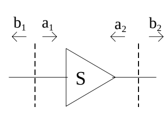
- Background
- NIST Measurement Methods
- Uncertainty Analysis
- Some Measurement Results & Comparisons
- (Checks & Verification)
- Simulations & Possible Improvements

# BACKGROUND

- NIST has been working with RFMD & IBM in "Kelvin Project," aimed at better understanding & measurement of noise in CMOS devices, 0.13 µm gate length. [1,2]
- NIST focus is on measurement (& uncertainties), particularly for 1 – 12.4 GHz.
- Measurement Challenges:
  - Very low minimum noise figure or noise temperature
  - Very poorly matched; $|S_{11}|$, $|S_{22}|$, and $|\Gamma_{opt}|$ can all be greater than 0.7, and are often greater than 0.9.
  - Probe characterization (at least for $T_{\text{in}}$), on-wafer cal
  - Even probe contact to pads (Al) can be problematic if vibration present.

# NIST MEASUREMENTS [3]

- Our methods based on measurements of output noise temperatures. Nothing fundamentally advantageous about noise *temperature* (available power) as opposed to power; it's just what we're set up to do.
- Work in terms of noise correlation matrix in wave representation (flexibility, convenience for some purposes).[4,5]

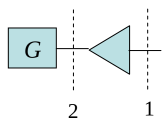



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

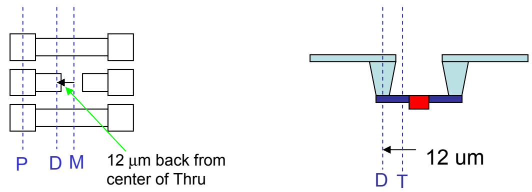
$$k_B X_1 \equiv \left\langle |c_1|^2 \right\rangle, \quad k_B X_2 \equiv \left\langle |c_2 / S_{21}|^2 \right\rangle, \quad k_B X_{12} \equiv \left\langle c_1 (c_2 / S_{21})^* \right\rangle$$

(Can transform back & forth between $X$'s & IEEE parameters.)

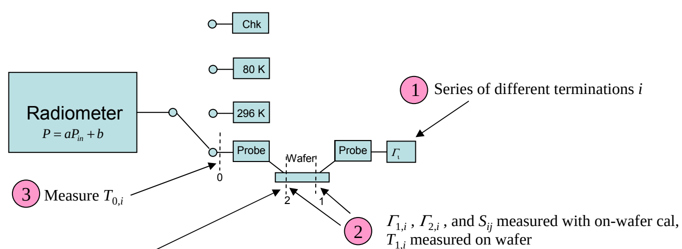
- Measurement method is fairly standard (vary input states, measure output, fit), except:
  - have primary cryogenic standard & very well calibrated diode sources
  - include a reverse noise measurement




  - use an on-wafer cal set, multiline TRL at D [6]




- Measurement Procedure:




4 Compute $T_{2,i}$: $T_0 = \alpha_{02} T_2 + (1-\alpha_{02}) T_{amb}$ so $T_{2,i} = \frac{T_{0,i} - (1-\alpha_{02,i}) T_{amb}}{\alpha_{02,i}}$

where $\alpha_{02.i} \equiv \frac{P_0^{avail}}{P_2^{avail}} = \frac{|S_{21}(02)|^2 \left(1-|\Gamma_{2,i}|^2\right)}{|1-\Gamma_{2,i} S_{11}(02)|^2 \left(1-|\Gamma_{0,i}|^2\right)}$

5 Measure $T_{rev}$ = $\mathrm{T}_1$ in reverse configuration

6 (Weighted) Fit to $T_{2,i} = \frac{|S_{21}|^2}{\left(1-|\Gamma_{2,i}|^2\right)} \left\{ \frac{\left(1-|\Gamma_{1,i}|^2\right)}{|1-\Gamma_{1,i} S_{11}|^2} T_{1,i} + \left| \frac{\Gamma_{1,i}}{1-\Gamma_{1,i} S_{11}} \right|^2 X_1 + X_2 + 2\,\mathrm{Re}\left[ \frac{\Gamma_{1,i} X_{12}}{1-\Gamma_{1,i} S_{11}} \right] \right\}$

and

$$T_1(rev.config) = \frac{1}{\left(1-|\Gamma_1|^2\right)} \left\{ \frac{|S_{12}|^2 \left(1-|\Gamma_{2,L}|^2\right)}{|1-\Gamma_{2,L} S_{22}|^2} T_{2,L} + \left| \frac{S_{12} S_{21} \Gamma_{2,L}}{1-\Gamma_{2,L} S_{22}} \right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[ \frac{S_{12} S_{21} \Gamma_{2,L} X_{12}{}^*}{1-\Gamma_{2,L} S_{22}} \right] \right\}$$

## UNCERTAINTY ANALYSIS [5,7]

- Follow ISO Guide to Uncertainty in Measurement (GUM) [8]
- Type A (statistical): obtained in the fitting process, from the covariance $V_{ij}$

$$u_A(i) = \sqrt{V_{ii}}$$

- Fit is done for *X*'s, so the type-A uncertainties are for the *X*'s. To get type-A uncertainties for the IEEE parameters,

$$u_i(IEEE) = \sqrt{V_{ii}(IEEE)} \qquad V_{ij}(IEEE) = \sum_{i',j'=1}^{5} D_{ii'} D_{jj'} V_{i'j'}(X's)$$

- Type-B uncertainties are all other uncertainties, i.e., not evaluated by statistical means.
- We "know" uncertainties in underlying quantities ($T_{G,i}$ , $\Gamma_{G,i}$ , $T_{out,i}$ , $S$, $T_{amb}$ , …); want the resulting uncertainties in noise parameters.
- Estimate them with a Monte Carlo program
  - use measured values as hypothetical "true" values
  - input uncertainties (& distributions) in reflection coefficients, noise temperature of non-ambient source, ambient temperature, measurement of output noise temperature (or power), correlations, ...

- MC Program (cont'd)
  - generate set of simulated measurement data for $T_{G,i}$ , $\Gamma_{G,i}$ , $T_{out,i}$ , $S$, and $T_{amb}$ , *e.g.*, $T_{meas} = T_{true} + \varepsilon_T$ where $< \varepsilon_T > = 0$, $< \varepsilon_T^2 > = u_T^2$
  - analyze simulated data as if it were real data, compute the "measured" noise parameters & $G$
  - repeat (simulate, analyze, repeat)
  - compute type-B uncertainties,

$$u(y) \approx RMSE(y) = \sqrt{Var(y) + (\bar{y} - y_{true})^2} \; .$$

- Standard (combined) uncertainty: $u_c = \sqrt{u_A^2 + u_B^2}$

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- Values used for underlying uncertainties:

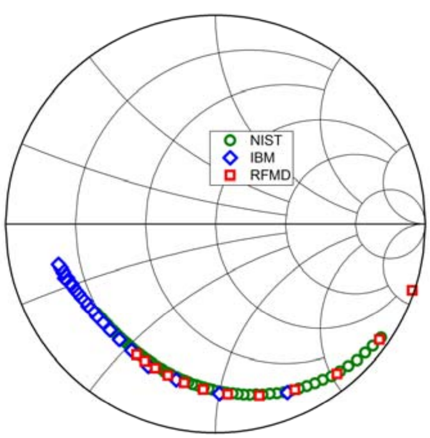
| | $\sigma_{cor}$ | $\sigma_{uncor}$ |
|---|---|---|
| $\Gamma_{G,i} \leq 0.005$ : | 0.003 | 0.004 |
| $\Gamma_{G,i} > 0.005$ : | 0.003 | 0.004 |
| $S_{21}$: | 0.003 | 0.004 |
| $T_{amb}$ : | 0.0 | 0.5 K (rect. distr.) |
| $T_{in,hot}$ : | | 1 % |
| $T_{out,meas}$ : | 0.8 % | 0.6 % |

- Will see resulting uncertainties in noise parameters below.

# SOME RESULTS

- Measurements & comparisons done as part of "Kelvin Project," with IBM & RF Micro Devices (RFMD) [1,2]
- 128×3×0.12 NMOS device
  - 128 fingers of polysilicon over
  - 3 µm wide active channel
  - 0.12 µm gate length
  - fabricated in 0.13 µm technology (by IBM)
- Bias:
  - drain voltage $V_{ds}$ = 1.2 V
  - $J$ = 25 µA/µm

# *S* Parameters




$S_{11}$ at plane D

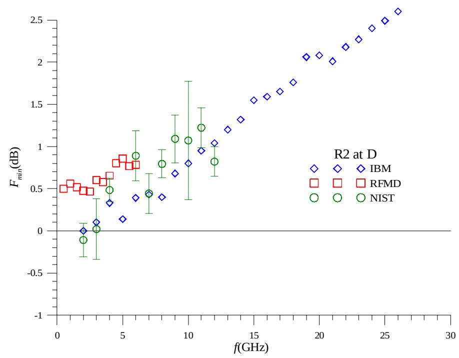
Generally agree well,
but some small differences.

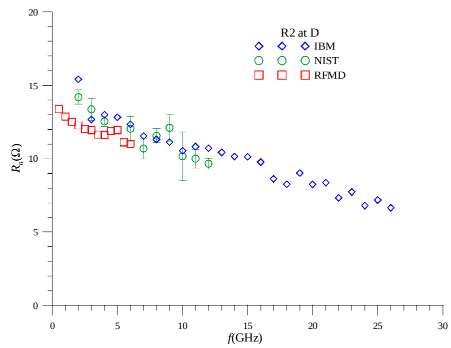
Frequency ranges

RFMD 0.5 – 6 GHz (to cover cellular bands)
IBM: 2 – 26 GHz
NIST: 1 – 12 GHz

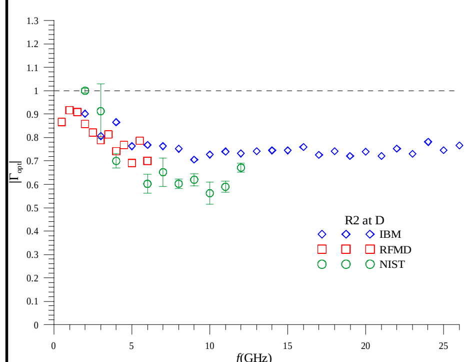
# Noise Parameters (at D):

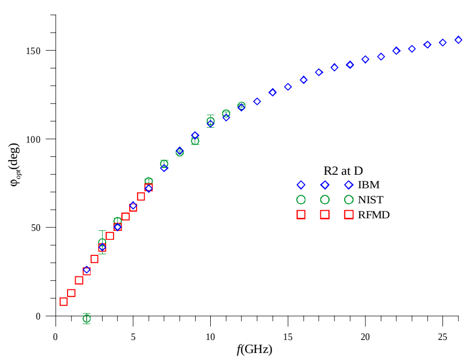
All labs used TRL cal at D.




Results are probably consistent within expected uncertainties, but it is clear that the device performance is better than our ability to measure it.



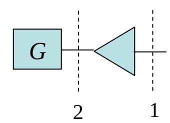



## SIMULATIONS & POSSIBLE IMPROVEMENTS

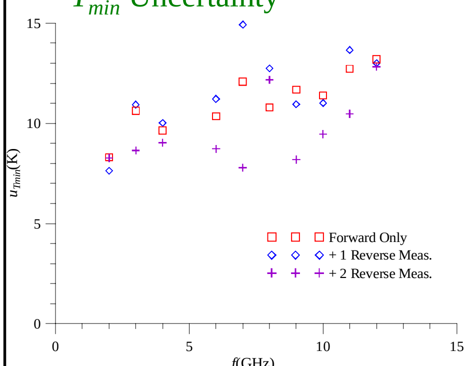
- Can also use the Monte Carlo uncertainty program to test possible improvements.
- Caution: results are for NIST methods & system.
- Expect similar results for other systems, but …
- We're working to extend program to more common or more general systems & methods.
- Consider two possible improvements here:
  - Inclusion of one or more reverse noise measurements.[2]
  - Use of a cold (i.e., significantly below ambient) input noise source.

## Reverse Noise Measurement(s)

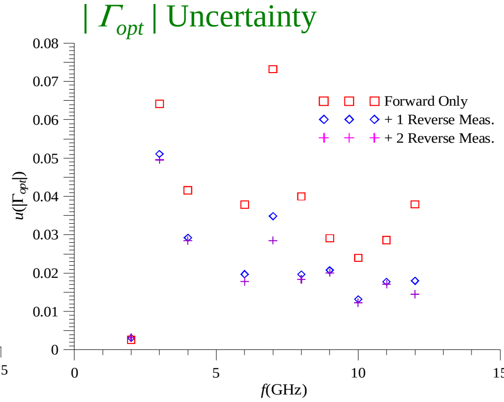
• Inclusion of one or more reverse noise measurements improves uncertainties, especially for $|\Gamma_{opt}|$




$T_{min}$ Uncertainty

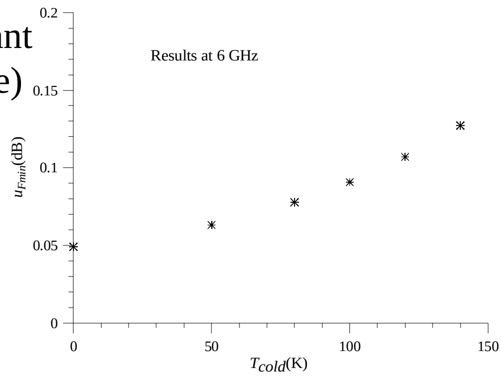



$|\Gamma_{opt}|$ Uncertainty

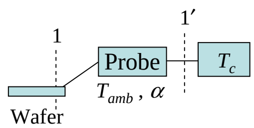


## Cold Input Noise Source

- For maximum effect, want $T_{cold}$ as low (and accurate) as possible.




- Probe causes problems: $T_1 = \alpha T_{1'} + (1-\alpha)T_{amb}$

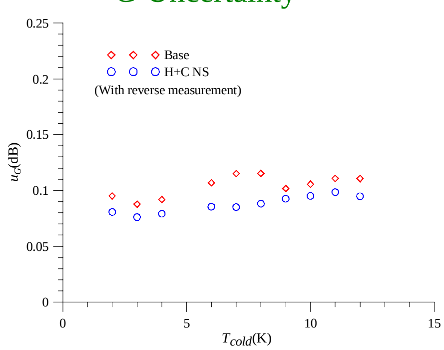



- If probe has 1 dB loss, $(1-\alpha)T_{amb} \approx 62$ K at $T_{amb} = 296$ K.

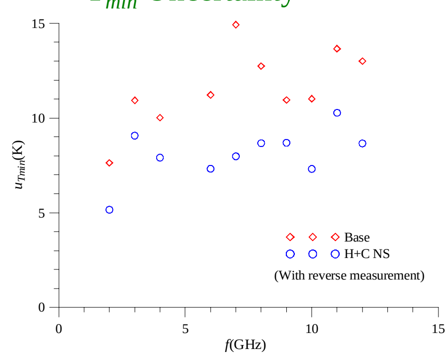
## Cold Input Noise Source (cont'd)

- With reasonable, "good" values for $\alpha$, $T_{cold}$, $u_{Tcold}$, etc., significant improvement if use cold source *in addition to* (not instead of) hot source.

$G$ Uncertainty




$T_{min}$ Uncertainty




($u_{Fmin} \approx 0.15$ dB $\rightarrow$ 0.10 dB)

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NIST publications & presentation slides available at
http://boulder.nist.gov/div818/81801/Noise/index.html

## References

[1] J. Randa, S.L. Sweeney, T. McKay, D.K. Walker, D.R. Greenberg, J. Tao, J. Mendez, G.A. Rezvani, & J. Pekarik, "Interlaboratory comparison of noise-parameter measurements on CMOS devices with 0.12 μm gate length," *66th ARFTG Conference Digest*, pp. 77-81, Dec. 2005.

[2] J. Randa, T. McKay, S.L. Sweeney, D.K. Walker, L. Wagner, D.R. Greenberg, J. Tao, & G.A. Rezvani, "Reverse Noise Measurement and Use in Device Characterization," 2006 IEEE RFIC Symposium Digest, San Francisco, June 2006.

[3] D.K. Walker & J. Randa, "On-wafer noise-parameter measurements at NIST," submitted to Conference on Precision Electromagnetic Measurements, Torino, Italy, July 2006.

[4] S. Wedge and D. Rutledge, "Wave techniques for noise modeling and measurement," *IEEE Trans. Microwave Theory & Tech.*, vol. 40, no. 11, pp. 2004-2012, Nov. 1992.

[5] J. Randa, "Noise-parameter uncertainties: a Monte Carlo simultation," *J. Res. NIST*, vol. 107, pp. 431-444, Sept. 2002.

[6] R. Marks, "A multi-line method of network analyzer calibration," *IEEE Trans. Microwave Theory & Tech.*, vol. 39, no. 7, pp.1205-1215, Jan. 1991.

[7] J. Randa, "Simulations of noise-parameter uncertainties," 2002 IEEE MTT-S International Microwave Symposium Digest, pp. 1845 – 1848, Seattle, WA, June 2002.

[8] *ISO Guide to the Expression of Uncertainty in Measurement*, International Organization for Standardization; Geneva, Switzerland; 1993.

[9] J. Randa & D.K. Walker, "Amplifier noise-parameter measurement checks and verification," 63rd AFRTG Conference Digest, pp. 41 – 45, Ft. Worth, TX, June 2004.

# Extra Slides

## $X$'s $\rightarrow$ IEEE

$$t = X_1 + |1+S_{11}|^2 X_2 - 2\,\mathrm{Re}\left[(1+S_{11})^* X_{12}\right],$$

$$T_{e,\min} = \frac{X_2 - |\Gamma_{opt}|^2 \left[X_1 + |S_{11}|^2 X_2 - 2\,\mathrm{Re}(S_{11}^* X_{12})\right]}{\left(1+|\Gamma_{opt}|^2\right)},$$

$$\Gamma_{opt} = \frac{\eta}{2}\left(1 - \sqrt{1 - \frac{4}{|\eta|^2}}\right),$$

$$\eta = \frac{X_2\left(1+|S_{11}|^2\right) + X_1 - 2\,\mathrm{Re}(S_{11}^* X_{12})}{(X_2 S_{11} - X_{12})}.$$

## IEEE $\rightarrow$ $X$'s

$$X_1 = T_{e,\min}\left(|S_{11}|^2 - 1\right) + \frac{t|1 - S_{11}\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

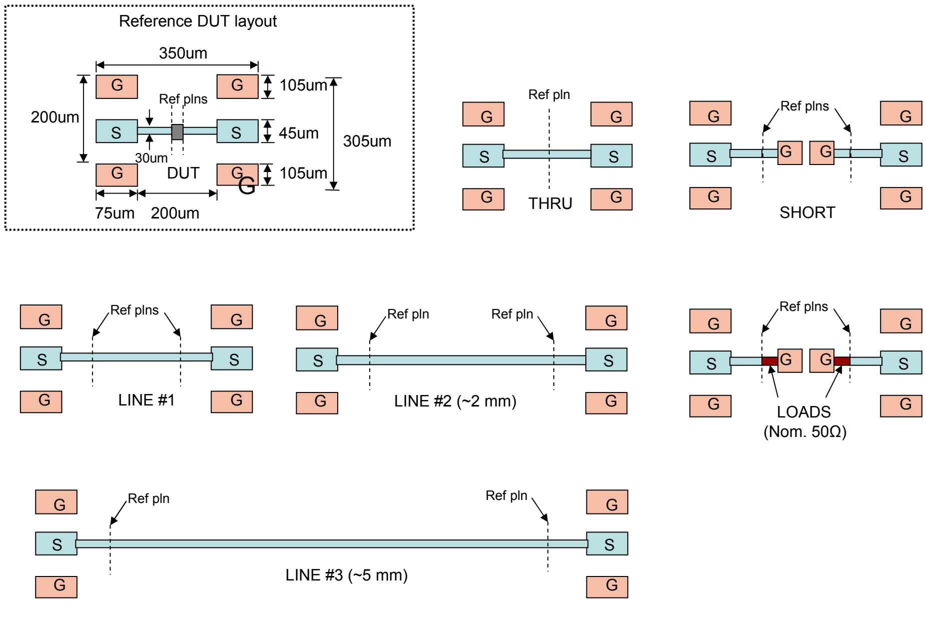
$$X_2 = T_{e,\min} + \frac{t|\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

$$X_{12} = S_{11} T_{e,\min} - \frac{t\Gamma_{opt}^*\left(1 - S_{11}\Gamma_{opt}\right)}{|1+\Gamma_{opt}|^2}.$$

Notes: $X_2 = T_{e,0}$

Bound implied by $X_1 \geq 0$

# TRL Calibration Set



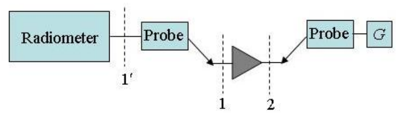

$$u_i(IEEE) = \sqrt{V_{ii}(IEEE)}$$

$$V_{ij}(IEEE) = \sum_{i',j'=1}^{5} D_{ii'} D_{jj'} V_{i'j'}(X's)$$

$$D = \begin{pmatrix} \frac{\partial T_{\min}}{\partial X_1} & \frac{\partial T_{\min}}{\partial X_2} & \frac{\partial T_{\min}}{\partial \operatorname{Re} X_{12}} & \frac{\partial T_{\min}}{\partial \operatorname{Im} X_{12}} & 0 \\ \frac{\partial t}{\partial X_1} & \frac{\partial t}{\partial X_2} & \frac{\partial t}{\partial \operatorname{Re} X_{12}} & \frac{\partial t}{\partial \operatorname{Im} X_{12}} & 0 \\ \frac{\partial \operatorname{Re} \Gamma_{opt}}{\partial X_1} & \ldots & \ldots & \ldots & 0 \\ \frac{\partial \operatorname{Im} \Gamma_{opt}}{\partial X_2} & \ldots & \ldots & \ldots & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

# CHECKS

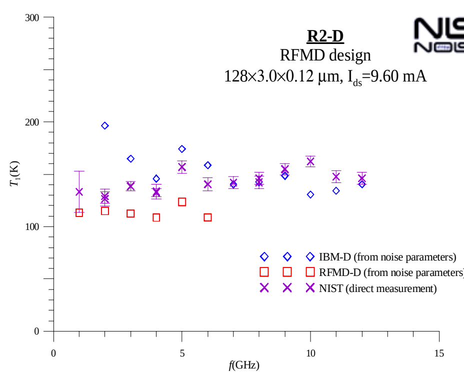
- Can directly measure reverse noise $T_1$

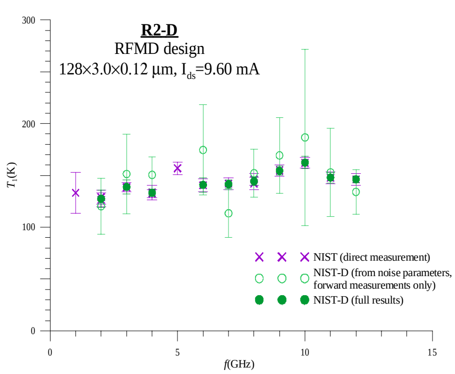



- And can compute $T_1$ from noise parameters

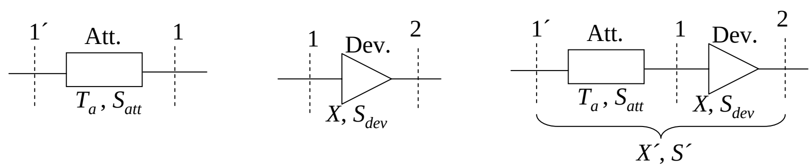
$$T_1 = \frac{1}{\left(1-|\Gamma_1|^2\right)}\left\{\frac{\left(1-|\Gamma_G|^2\right)|S_{12}|^2}{|1-\Gamma_G S_{22}|^2}T_G + \left|\frac{S_{12}S_{21}\Gamma_G}{1-\Gamma_G S_{22}}\right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[\frac{S_{12}S_{21}\Gamma_G X_{12}^*}{1-\Gamma_G S_{22}}\right]\right\}$$

- So do both & compare [9]



## Cascade Test




- Measure $S_{att}$, $X$, $S_{dev}$ ; predict $X´$ & compare.
- Have used this test with an isolator for connectorized amplifiers; very successful. [9]
- About to use it on-wafer with an attenuator & transistor.