(RMO4D-2 )

# Reverse Noise Measurement & Its Use in Device Characterization

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## Logos

## Outline

- Kelvin Project
- Wave Representation of Noise Correlation Matrix & Noise Parameters
- Reverse Noise Measurements
- Benefits of Reverse Noise Measurements
  - As a check
  - To improve uncertainties in noise parameters & reduce occurrence of unphysical results
  - Direct implications for model parameters
- Summary

## The Kelvin Project

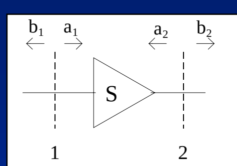
- Collaboration between small groups at IBM, RFMD, and NIST to explore noise in deep submicron CMOS (starting with 0.13 μm)
- Aims
  - Improve noise data quality & measurement methods.
  - develop & test new designs for devices, circuits, test structures
  - explore implications for modeling
  - ….

## The Kelvin Project

- Participants:
  - – IBM: device design, fab, modeling, test
  - – RFMD: device & circuit design & test, modeling, product knowledge
  - – NIST: RF & microwave test & standards

## Noise Correlation Matrix in Wave Repr.

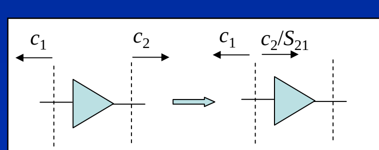
- Linear two-port described by




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

$|c|^2$ = spectral power

- Define (intrinsic) noise correlation matrix $\hat{N}_{ij} = \langle c_i c_j^* \rangle$
- For convenience, scale $c_2 \rightarrow c_2/S_{21}$




$$k_B X_1 \equiv \left\langle |c_1|^2 \right\rangle = \hat{N}_{11}$$

$$k_B X_2 \equiv \left\langle \left| \frac{c_2}{S_{21}} \right|^2 \right\rangle = \frac{\hat{N}_{22}}{|S_{21}|^2}$$

$$k_B X_{12} \equiv \left\langle c_1 \left( \frac{c_2}{S_{21}} \right)^* \right\rangle = \frac{\hat{N}_{12}}{S_{21}^*}$$

- *X*'s have dimensions of temperature.

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

- Can relate *X*'s ↔ IEEE (through *S* parameters)

**$X$'s → IEEE**

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

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

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

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

Note: $t = \dfrac{4R_n T_0}{Z_0}$

**IEEE → $X$'s**

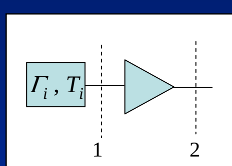
$$X_1 = T_{e,\min}\left(|S_{11}|^2 - 1\right) + \frac{t\,|1 - S_{11}\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

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

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

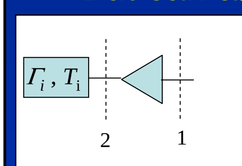
## "Reverse Noise"

- Normally:




$$T_{2,i} = \overbrace{\frac{|S_{21}|^2}{\left(1-|\Gamma_{2,i}|^2\right)}\left\{\frac{\left(1-|\Gamma_i|^2\right)}{|1-\Gamma_i S_{11}|^2}\right.}^{G_{av}} T_i + \left|\frac{\Gamma_i}{1-\Gamma_i S_{11}}\right|^2 X_1 + X_2 + 2\,\mathrm{Re}\left[\frac{\Gamma_i X_{12}}{1-\Gamma_i S_{11}}\right]\left.\vphantom{\frac{1}{1}}\right\}$$

- But can also:



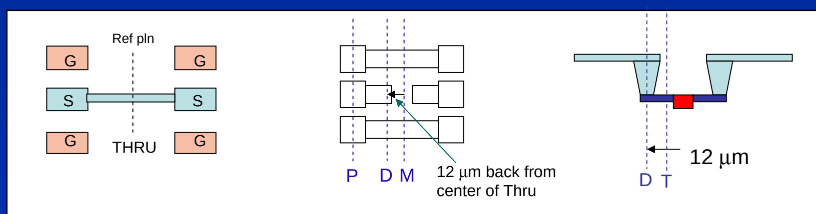

$$T_{1,i} = \frac{1}{\left(1-|\Gamma_{1,i}|^2\right)}\left\{\frac{\left(1-|\Gamma_i|^2\right)|S_{12}|^2}{|1-\Gamma_i S_{22}|^2} T_i + \left|\frac{S_{12}S_{21}\Gamma_i}{1-\Gamma_i S_{22}}\right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[\frac{S_{12}S_{21}\Gamma_i X_{12}^*}{1-\Gamma_i S_{22}}\right]\right\}$$

note: for $\Gamma_i = 0$,

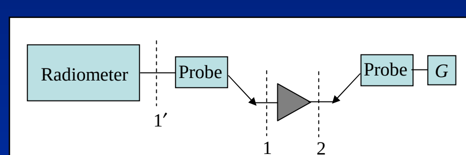
$$T_{1,i} = \frac{1}{\left(1-|S_{11}|^2\right)}\left\{\frac{|S_{12}|^2}{1} T_i + X_1\right\} \rightarrow \frac{X_1}{\left(1-|S_{11}|^2\right)} \quad \text{for small } |S_{12}|^2$$

## Measurement Method (at NIST)

- One-port noise-temperature measurement (on-wafer)
- Most commercial noise-parameter systems not set up for this.
- NIST method:
  - – Two-tier multiline TRL cal (with on-wafer cal set)




- NIST method:
  - ✓ Two-tier multiline TRL cal (with on-wafer cal set)
  - – Noise temperature measurement at plane 1′ (in coax)




  - – Correct for probe as an adapter

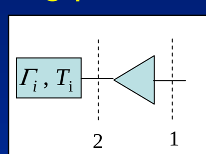
$$T_{1'} = \alpha_{1'1}T_1 + (1-\alpha_{1'1})T_{amb} \Rightarrow T_1 = \frac{T_{1'} - (1-\alpha_{1'1})T_{amb}}{\alpha_{1'1}}$$

$$\alpha_{1'1} = \frac{|S_{21}(1'1)|^2\left(1-|\Gamma_1|^2\right)}{|1-\Gamma_1 S_{11}(1'1)|^2\left(1-|\Gamma_{1'}|^2\right)}$$

- Ok, you can measure it.
- But why would you want to?
  - As a check
  - Better noise-parameter uncertainties
    - and fewer unphysical results
  - Direct insight into device properties (or parasitics)?

## Application 1: As a Check of Noise-Parameter Measurements

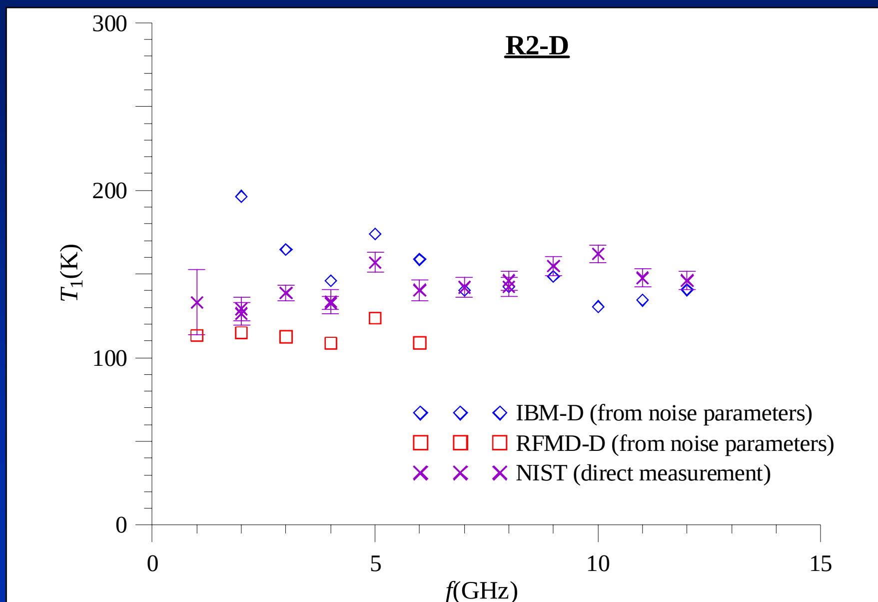
- If noise & scattering parameters have been measured, can predict $T_1$



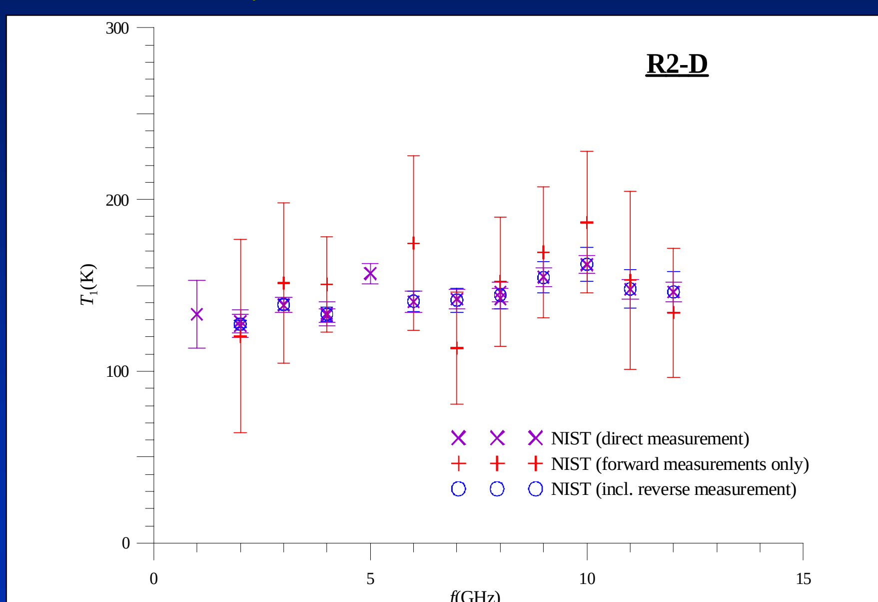

$$T_{1,i} = \frac{1}{\left(1-\left|\Gamma_{1,i}\right|^2\right)}\left\{\frac{\left(1-\left|\Gamma_i\right|^2\right)\left|S_{12}\right|^2}{\left|1-\Gamma_i S_{22}\right|^2}T_i + \left|\frac{S_{12}S_{21}\Gamma_i}{1-\Gamma_i S_{22}}\right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[\frac{S_{12}S_{21}\Gamma_i X_{12}^*}{1-\Gamma_i S_{22}}\right]\right\}$$

- So predict it, measure it, & compare the two sets of results.

- Example: $\Gamma_i \approx 0$



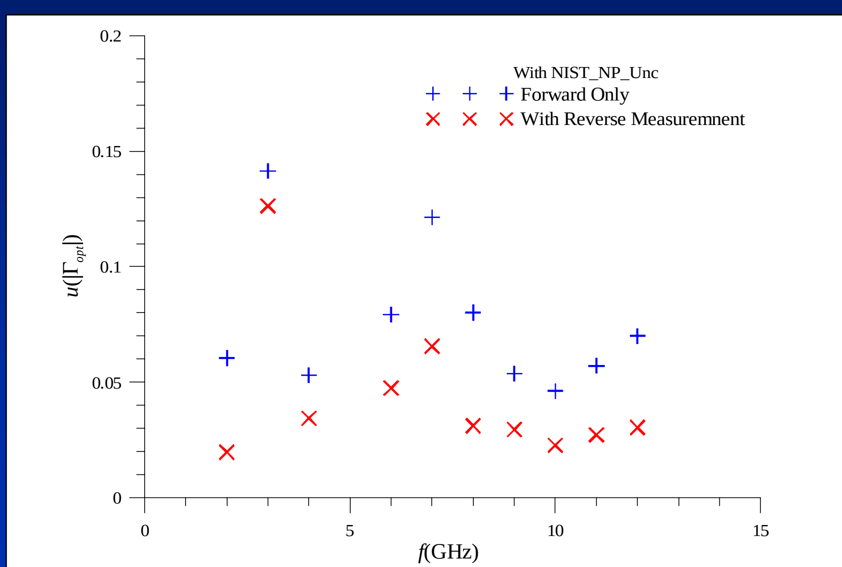

- Example: $\Gamma_i \approx 0$



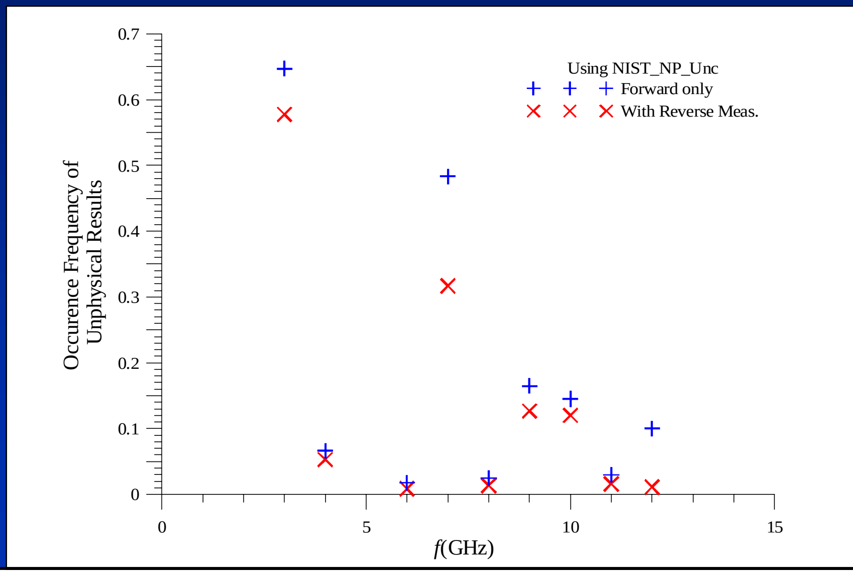
## Application 2: To Improve Noise-Parameter Uncertainties

- Can also include reverse measurement(s) in the set of data to be fit to determine the noise parameters.
- NIST does so for on-wafer noise-parameters.
- 1 reverse measurement results in a significant reduction in the uncertainty in $|\Gamma_{opt}|$; doesn't help much for others.
- Can improve other uncertainties by using 2 reverse measurements (or by using a cryogenic source in addition to hot and ambient on input).

- Example (Caution: particular case, NIST sets of input states.)

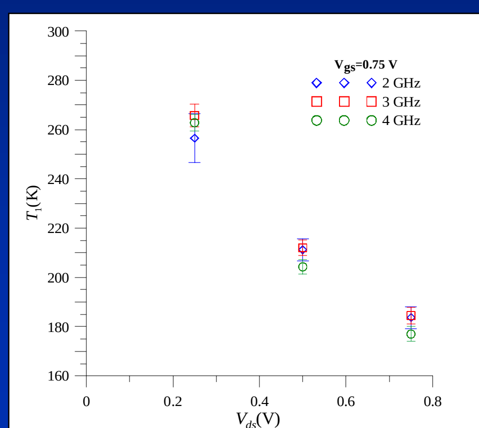


- Also reduces the frequency of unphysical results.
- Example (Caution: particular case, …)




## Application 3: "Direct" Implications for Modeling (?)

- Besides determination of noise parameters, reverse noise could have direct implications for model parameters.
- This application is still in progress.



## Summary

- Reverse noise measurements are not normally done, but they are not so difficult, & they can be useful:
  - They can serve as a check of noise-parameter measurements.
  - They can be used to improve the uncertainties in noise-parameter measurements & to reduce the occurrence of unphysical results.
  - They could have direct implications for model parameters.

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