Characterisation of L-band Differential Low Noise Amplifiers

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Motivation

• The Square Kilometre Array telescope will have unsurpassed sensitivity
• Sensitivity of Radio Telescopes is defined as the ratio of two critical parameters

\[
\text{Sensitivity} = \frac{\text{Aperture Area}}{\text{System Temperature}}
\]

• For high sensitivity it is imperative to ensure low noise contribution from the receiver system
• The SKA will consist of three antenna topologies
  – Sparse Aperture Array
    • Dual Polarisation Dipoles
  – Parabolic Reflector Antennas
    • Focal Plane Arrays or Dual polarisation single pixel horn feeds
  – Dense Aperture Array
    • Tiles of Differentially fed antennas
Motivation

• Most Precursor and Pathfinder Telescopes incorporate Differentially fed antennas

• Loss introduced by any passive component placed between antenna feed and LNA adds directly to the system temperature

• Implementing Differential LNAs
  – Removes the need for lossy baluns - effectively reducing the system temperature
  – Suppresses interference coupling in the common-mode (Common-Mode Rejection)
  – Increases the complexity of the design and characterisation of LNAs
    • Nearly all commercially available noise figure analysers/meters are single ended - Complicating Differential Noise Figure measurement
How does the signal and noise performance of a Differential LNA compare to that of Single-ended LNAs?
• Differential LNA Design
• Differential- and Common-mode (Mixed-mode) S-Parameters
• Single-ended Noise Figure Measurement
• De-embedding the Differential Noise Figure from Single-ended Measurements
• Conclusion
Differential LNA Topology

• Balanced Topology
  – Operating at the mid frequency band of the MeerKAT system (1 – 1.75 GHz)
  
  ![Diagram](image)

  – Two single-ended LNAs feeding a wideband 180°-Hybrid Ring Coupler
  – Allows the design of the constituent single-ended LNAs to be considered separately
Single-ended LNA Design

• The performance of the single-ended LNAs should be well matched

• Paired GaAs pHEMTs manufactured by AVAGO (MGA-16516)
  – Operating Bandwidth 500 MHz – 1.75 GHz
Single-ended LNA Design

Simulated Noise Figure

< 35 K @ 290 K Ambient
Differential LNA Design

- Combines the two output signals of the LNAs differentially.

- Realised using FGCPW with no bottom ground plane.

- Incorporates a 180° phase shift by interchanging the centre and ground conductors along one of the signal paths.
Differential LNA Design

- Integrating the single-ended LNA design and the wideband Hybrid Coupler
  - LNA design implements CPW with ground plane on the bottom layer to ensure device stability
  - Hybrid coupler is implemented using FGCPW with no ground plane on the bottom layer in order to achieve wideband phase inversion
- CPW with Ground plane to FGCPW with no Ground plane transition
Differential LNA Design

- Differential LNA realised by integrating the two single ended LNAs, the CPW transition and the wideband 180°-Hybrid Ring Coupler

- Differential- and Common-mode signals can propagate in any Multi-Port Network

- Instead of using single-ended Scattering Parameters, use Mixed-Mode Scattering parameters to characterise differential-mode and common-mode circuit performance
Mixed-mode Scattering Parameters

- Mixed-Mode Performance of Three-port Differential LNA Design
  - Three Port Transformation Matrix.
  
  \[
  [M] = \frac{1}{\sqrt{2}} \begin{bmatrix}
  1 & -1 & 0 \\
  1 & 1 & 0 \\
  0 & 0 & \sqrt{2}
  \end{bmatrix}
  \]
  
  - Solve the mixed-mode S-Parameters
  
  \[
  [S_{mm}] = [M] [S] [M]^{-1}
  \]

  \[
  S_{s2d1} = \frac{1}{\sqrt{2}} (S_{31} - S_{32})
  \]

  \[
  S_{s2c1} = \frac{1}{\sqrt{2}} (S_{31} + S_{32})
  \]

  \[
  S_{d1d1} = \frac{1}{2} (S_{22} - S_{21} - S_{12} + S_{11})
  \]

  \[
  S_{c1c1} = \frac{1}{2} (S_{22} + S_{21} + S_{12} + S_{11})
  \]

  - Common-Mode Rejection Ratio

  \[
  CMRR = \frac{S_{s2d1}}{S_{s2c1}}
  \]
Mixed-mode Scattering Parameters

- Reflection Coefficients
  - Differential-mode Input Reflection Coefficient similar to single ended LNAs
Mixed-mode Scattering Parameters

- Differential Gain
  - Differential Gain equals the Gain of the single ended LNAs

![Graph showing differential gain compared to single ended gain](image-url)
Mixed-mode Scattering Parameters

- **CMRR**
  - Determined by the isolation of the Coupler
  - Highly dependent on Amplitude imbalance and Phase Difference

![Graph showing CMRR vs Frequency](image)
Mixed-mode Scattering Parameters

- Amplitude and Phase Imbalance
  - Amplitude imbalance less than 1 dB across most of the band
  - Phase Difference deviates from 180° by less than 5°
Single-ended Noise Figure Measurement

- In order to perform accurate noise figure measurements the DUT has to be well matched to both the Noise source and the NFA using a component with a low insertion loss.
Single-ended Noise Figure Measurement

- Narrowband Noise Figure of DUT (1.15 – 1.45 GHz)
• Majority of techniques proposed for measuring/de-embedding differential noise figure require the use of baluns – placed before and after the DUT

• Using baluns to de-embed the differential noise figure is only applicable to “Fully”-differential LNAs (Differential Input and Output)

• Since this differential LNA design has a single ended output, the differential noise figure is de-embedded from two single ended noise figure and gain measurements
De-embedding The Differential Noise Figure from Single-ended Measurements

Define the noise contribution of the two single ended LNAs by Equivalent noise Temperatures $T_{e1}$ and $T_{e2}$

For equal noise contribution $T_{e1} = T_{e2} = T_e$

\[ F_d = 1 + \frac{T_{e1} + T_{e2}}{2T_0} \]

\[ F = 1 + \frac{T_e}{T_0} \]
De-embedding The Differential Noise Figure from Single-ended Measurements

Determine $T_{e1}$ and $T_{e2}$ from two single ended noise figure measurements

- $F_{31}$ and $G_{31}$: Measured with port 2 terminated
- $F_{32}$ and $G_{32}$: Measured with port 1 terminated

In terms of equivalent noise temperatures

$$F_{31} = 1 + \frac{T_{e1}}{T_0} + \frac{G_{32}}{G_{31}} \left( 1 + \frac{T_{e2}}{T_0} \right)$$

$$F_{32} = 1 + \frac{T_{e2}}{T_0} + \frac{G_{31}}{G_{32}} \left( 1 + \frac{T_{e1}}{T_0} \right)$$

Solve the equivalent noise temperatures

$$T_{e1} = \frac{(F_{31} - 2) T_0}{2}$$

$$T_{e2} = \frac{(F_{32} - 2) T_0}{2}$$

Differential Noise Figure

$$F_d = \frac{F_{31} + F_{32}}{4}$$

Assumes no deviation in the measured gains
De-embedding The Differential Noise Figure from Single-ended Measurements

Take deviation in measured gains into account by defining two constants

\[ k_0 = \frac{1}{2} \left[ \frac{G_{32}}{G_{31}} + \frac{G_{31}}{G_{32}} \right] \]

\[ \frac{G_{32}}{G_{31}} = k_0 + \Delta \]

\[ \frac{G_{31}}{G_{32}} = k_0 - \Delta \]

Differential noise figure – taking gain deviation into account

\[ F_d = \frac{(2 + \Delta)F_{31} + (2 - \Delta)F_{32}}{2(k_0 + 1)^2} \]

Note that for \( G_{31} = G_{32} \), \( k_0 = 1 \), \( \Delta = 0 \)

\[ F_d = \frac{F_{31} + F_{32}}{4} \]
De-embedding The Differential Noise Figure from Single-ended Measurements

De-embedded Differential Noise Figure

- Measured Differential
- Measured Single Ended
- Simulated Single Ended
- Simulated Differential

Plot showing Noise Figure (dB) vs Frequency (MHz)
Motivation

? How does the signal and noise performance of a Differential LNA compare to that of Single-ended LNAs?
Conclusion

• A differential LNA realised using a balanced topology has been demonstrated

• Using mixed-mode Scattering parameters it was shown that the performance of the differential LNA is very similar to that of its constituent single ended LNAs – Provided there are little deviation in the gains along the two signal paths

• Using two single ended noise figure and gain measurements the differential noise figure has been de-embedded and shown to be nearly equal to that of the single-ended LNAs incorporated in the differential LNA design
Thank you for your Attention

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