Integration of the General Network Theorem in ADE and ADE XL

Toward a Deeper Insight Into Circuit Behavior

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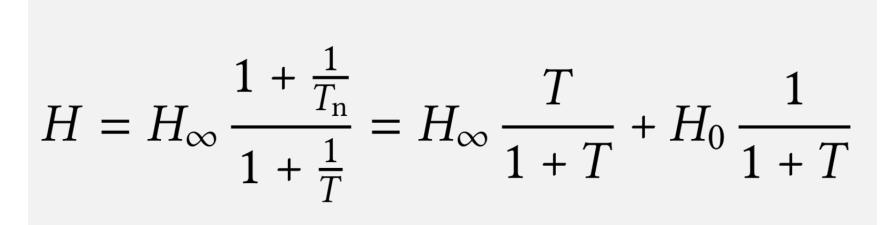
Integration of the General Network Theorem in ADE and ADE XL

> General Network Theorem Integration in ADE (XL) Application example

General Network Theorem

Decomposition of transfer function in simpler parts: lower-level transfer functions, *useful for design*

Using test signal injection and nulling techniques



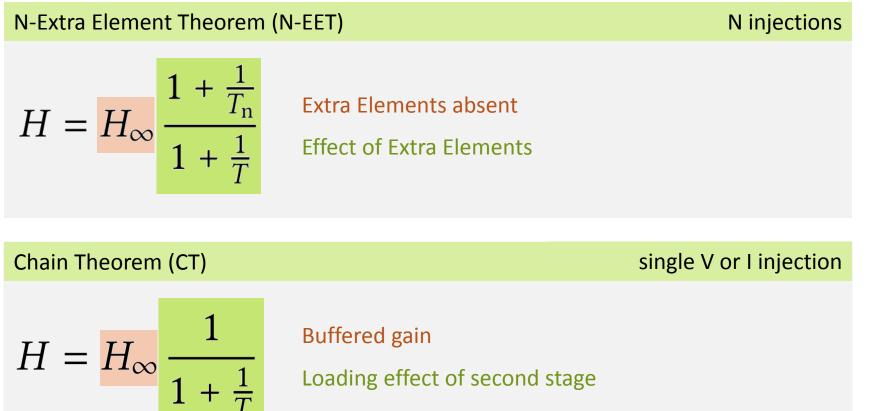
Using multiple injections T, Tn and H0 can be further factored

Ref: R. D. Middlebrook 2006, IEEE Microwave Magazine

General Network Theorem: N-EET and CT

Injection points determine decomposition and interpretation

GNT morphs into three interpretations



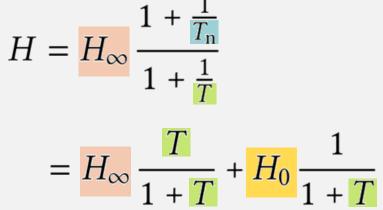
Loading effect of second stage

General Network Theorem: GFT

Injection points determine decomposition and interpretation

GNT morphs into three interpretations

General Feedback Theorem (GFT) $1 + \frac{1}{\tau}$



- 'Ideal' transfer function, infinite loop gain
- Loop gain
- Null loop gain
- Direct feedthrough, zero loop gain

V and I injection

Lower-level TF factorization example: loop gain T

$$T = \frac{T_{\text{fwd}}}{1 + T_{\text{rev}}}$$
$$T_{\text{fwd}} = T_{\text{v,fwd}} || T_{\text{i,fwd}}$$
$$T_{\text{rev}} = T_{\text{v,rev}} || T_{\text{i,rev}}$$

Compare to *stb* loop gain T_t

 $T_t = T_{\rm fwd} + T_{\rm rev}$

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> General Network Theorem Integration in ADE (XL) Application example

Integration in ADE (XL): motivation

GNT advantages

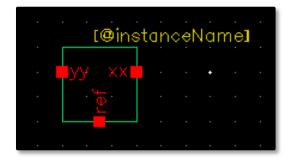
General framework

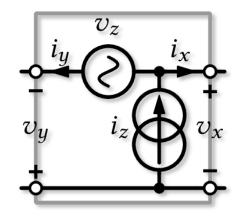
Same techniques for different applications, hand calculations Well-known results derive cleanly from GNT Results are useful for design Divide-and-conquer approach

Integration in Virtuoso

Application of GNT to real-world designs
Deeper insight into complex circuit behavior
Find out dominant lower-level TFs (a priori)
Validate hand-analysis results (a posteriori)

Integration in ADE (XL): circuit setup





Insert GNT Probes in schematic at appropriate points

Inject small-signal test signals: voltage and/or current

Uninvasive

Does not interfere with other analyses Layout XL and Calibre LVS tools supported

GNT in ADE (XL)

Integration in ADE (XL): analysis setup

| | Cho | osing Analys | es ADE L (1) | |
|--|--|---|--------------|--|
| Analysis | 🔾 tran | 🔾 dc | 🔾 ac | 🔾 noise |
| | 🔾 xf | 🔾 sens | 🔾 dcmatch | 🔾 stb |
| | 🔾 pz | 🔾 sp | 🔾 envlp | 🔾 pss |
| | 🔾 pac | 🔾 pstb | 🔾 pnoise | ⊖ p×f |
| | 🔾 psp | 🔾 qpss | 🔾 qpac | 🔾 qpnoise |
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| Sweep Ra | inge | | | |
| | | | | |
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| ● Start-S ○ Center | | Start 1 | s | itop 100M |
| Center | r-Span | Start 1 | s | itop 100M |
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New analysis 'gnt' in Choosing Analysis...

Same use model as stb, ac, ...

Familiar options

Sweep variable, sweep range, sweep type

• Source instance, output net or probe

Indicates the transfer function H to decompose

(Nested) GNT analyses

GNT Probe instance(s) Analysis type: GFT, N-EET, CT

Integration in ADE (XL): internals

| | Cho | bsing Analys | es ADE L (1 | \odot \odot \odot | \otimes |
|---|---|---|-------------|---|-----------|
| Analysis | 🔾 tran | 🔾 dc | 🔾 ac | 🔾 noise | |
| | 🔾 xf | 🔾 sens | 🔾 dcmatch | 🔾 stb | |
| | 🔾 pz | 🔾 sp | 🔾 envlp | 🔾 pss | |
| | 🔾 pac | 🔾 pstb | 🔾 pnoise | 🔾 pxf | |
| | 🔾 psp | 🔾 qpss | 🔾 qpac | 🔾 qpnoise | |
| | 🔾 qpxf | 🔾 qpsp | 🔾 hb | 🔾 hbac | |
| | 🔾 hbnoise | i 🔾 hbsp | 🥑 gnt | | _ |
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| Shoop na | | | | | |
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| | top | Start 1 | | Stop 100M | |
| ● Start-S ○ Center | top -Span | Start 1 | | Stop 100M | |
| ● Start-S ○ Center Sweep Ty | itop -Span pe | Start 1 | | Stop 100M | : |
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| Start-S Center Sweep Ty Automatic Add Specifi Source Inst Output Type Output Net Remove Analysis Ty | e bottom ana | /I4 voltage /o lysis 2GFT /I2 1EET 2GFT | | Select Select nested analysis Select | |
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Internally always flat N-EET calculated

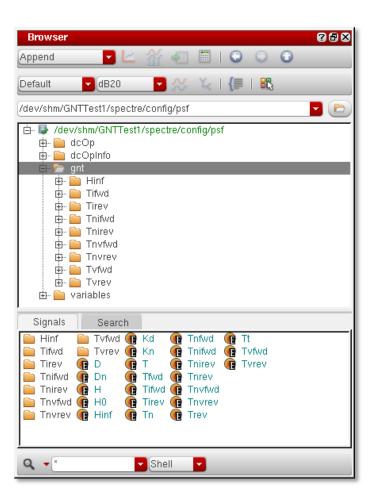
Using AC analysis per injection

Data to be saved optionally

Flat N-EET results

Any possible permutations of nested analyses

Integration in ADE (XL): results



Results included in psf data

Nested results as folders

Accessible in the usual ways

ViVa's Results Browser getData() SKILL API

GFT Tt identical to *stb* loop gain Given identical reference nodes

Integration in ADE (XL): ADE support

| 44 (i) | ADE L (1) - Test1 GNTTest1 config | \odot \otimes |
|--|--|-------------------|
| Launch S <u>e</u> ssion Set <u>u</u> p <u>A</u> | nalyses <u>V</u> ariables <u>O</u> utputs <u>S</u> imulation <u>R</u> esults »Cād | епсе |
| Daaine Vaniahlaa | 👌 🎾 🖆 🗹 🏷 Analyses 📀 🖗 | x = |
| Design Variables Name Value 1 1K | Type Enable Arguments 1 dc | C Trans |
| | Outputs ? € Name/Signal/Expr Value Plot Save Save Option 1 H_dc_mag wave ✓ ■ | |
| > Results in /dev/shm/GNTT | Plot after simulation: Auto Plotting mode: Replace us: Ready T=27.0 C Simulator: spectre State: spectre_C | |

| No Parasitics/LDE 📃 🔦 | th » | Monte | e Carlo S | Sampling 🔽 » Reference | se: | | - , |
|-------------------------|------|------------|-------------|--------------------------------------|----------|----------|-----|
| Data View ? ₽ × | Outp | outs Setup | F Co III | Results Diagnostics | | | |
| 🛱 🗞 Analyses | Test | Name- | Туре | Expression/Signal/File | EvalType | Plot | Sa |
| - 🗹 dc t | gnt | Tn | expr | db20(getData("/Tn" ?result "gnt")) | point | | |
| - 🗹 gnt 2GFT 1 1G Aut | gnt | Т | expr | db20(getData("/T" ?result "gnt")) | point | V | |
| - Click to add analysis | gnt | Hinf | expr | db20(getData("/Hinf" ?result "gnt")) | point | | |
| 🗄 🎰 Design Variables | gnt | Н | expr | db20(getData("/H" ?result "gnt")) | point | V | |
| - Click to add test | gnt | Dn | expr | db20(getData("/Dn" ?result "gnt")) | point | V | |
| 🗄 🗔 🦀 Global Variables | gnt | D | expr | db20(getData("/D" ?result "gnt")) | point | | |

ADE L

Incl. parametric sweep

ADE (G)XL

Corners

Parameters

Monte Carlo sampling

Sensitivity analysis

Optimization

Worst-case corners

...

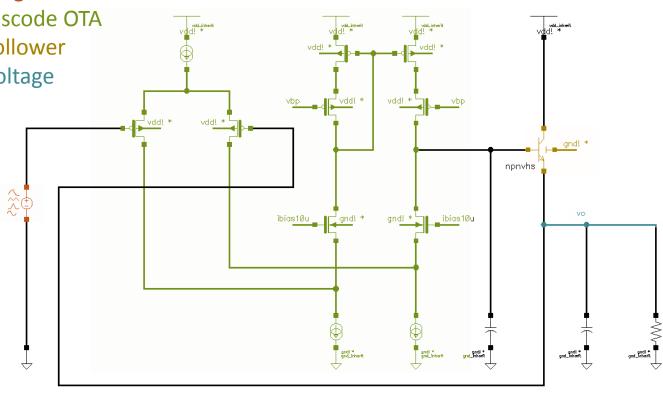
Tested in IC 6.1.5 and IC 6.1.6

Integration of the General Network Theorem in ADE and ADE XL

> General Network Theorem Integration in ADE (XL) Application example

Application example: voltage regulator

- Input voltage source
- Folded cascode OTA
- Emitter follower
- Output voltage



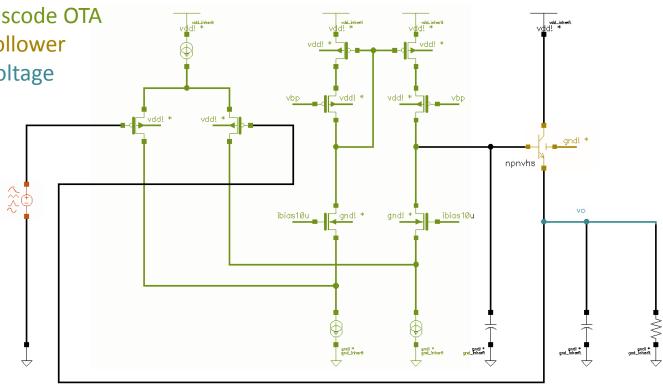
GNT in ADE (XL)

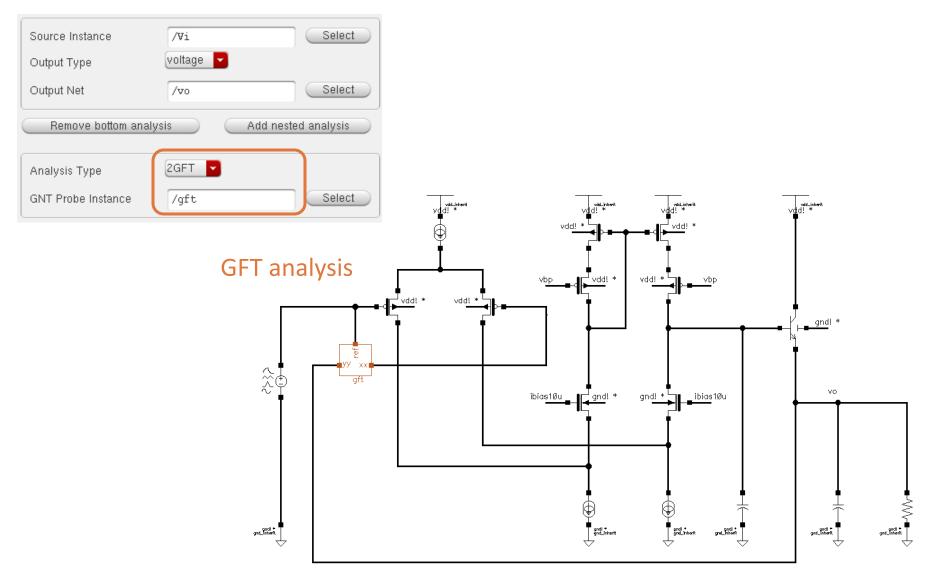
Application example: voltage regulator

Problem

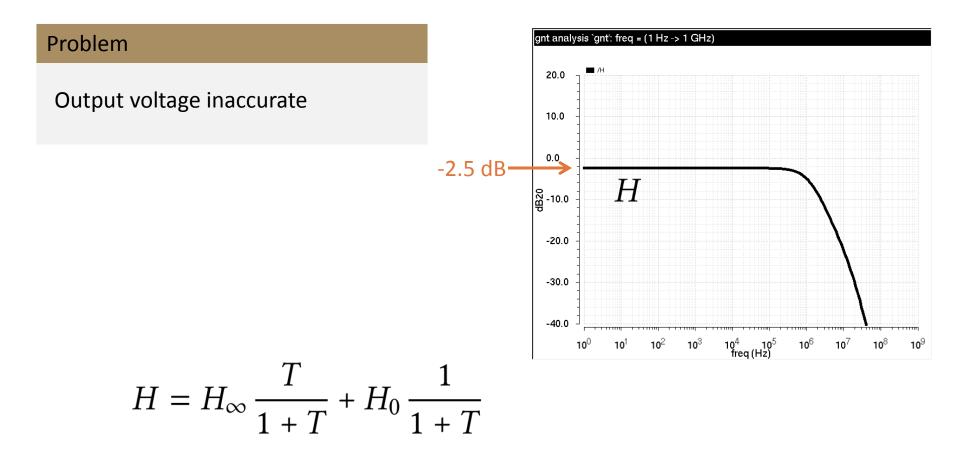
Output voltage inaccurate

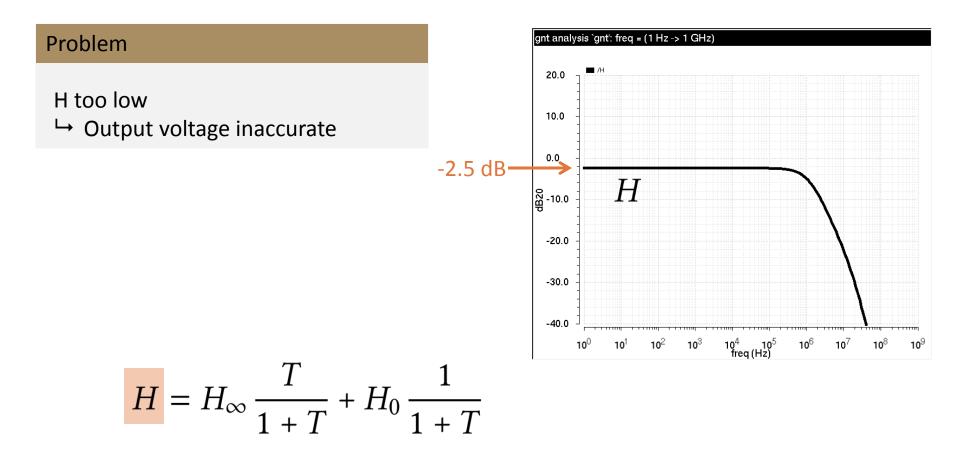
- Input voltage source
- Folded cascode OTA
- Emitter follower
- Output voltage

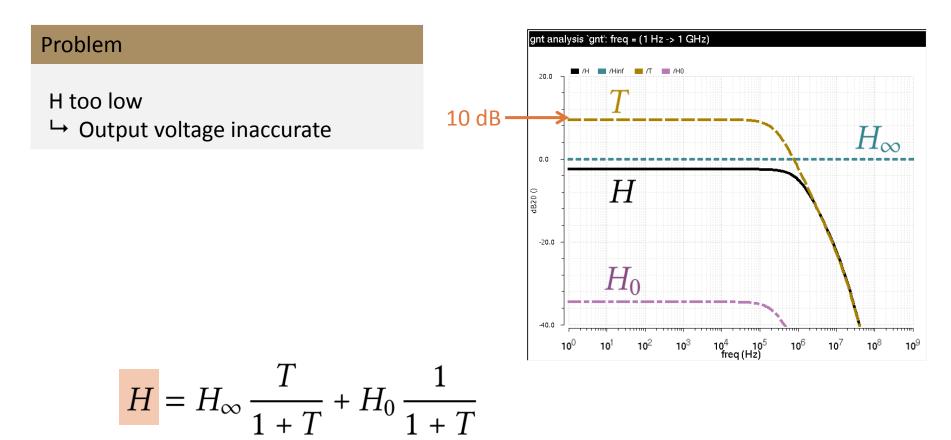




GNT in ADE (XL)



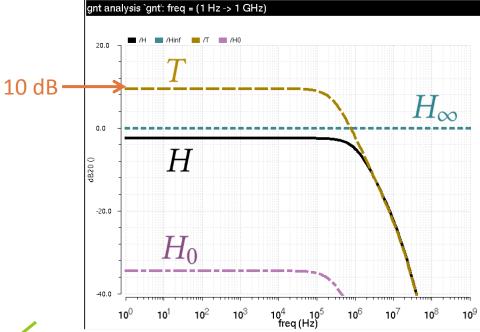




Problem

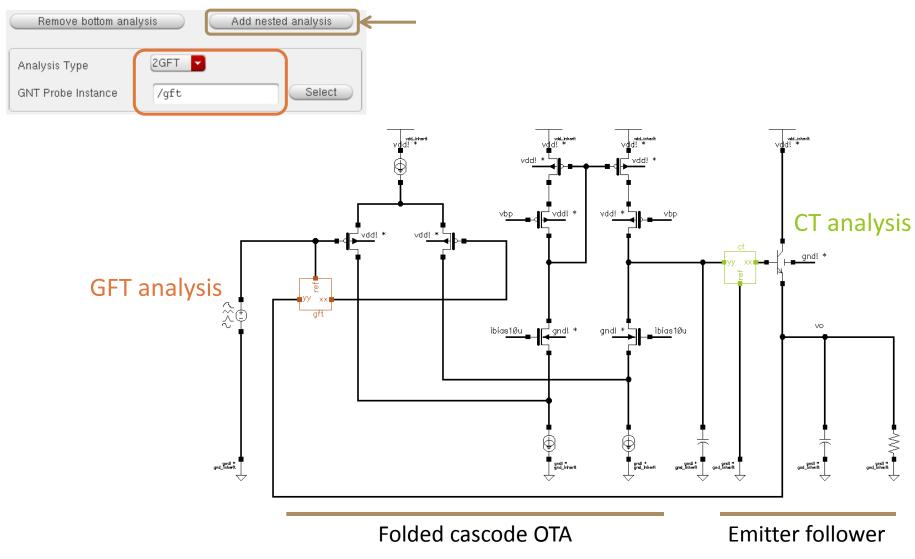
Forward voltage loop gain insufficient

- \mapsto H too low
 - → Output voltage inaccurate

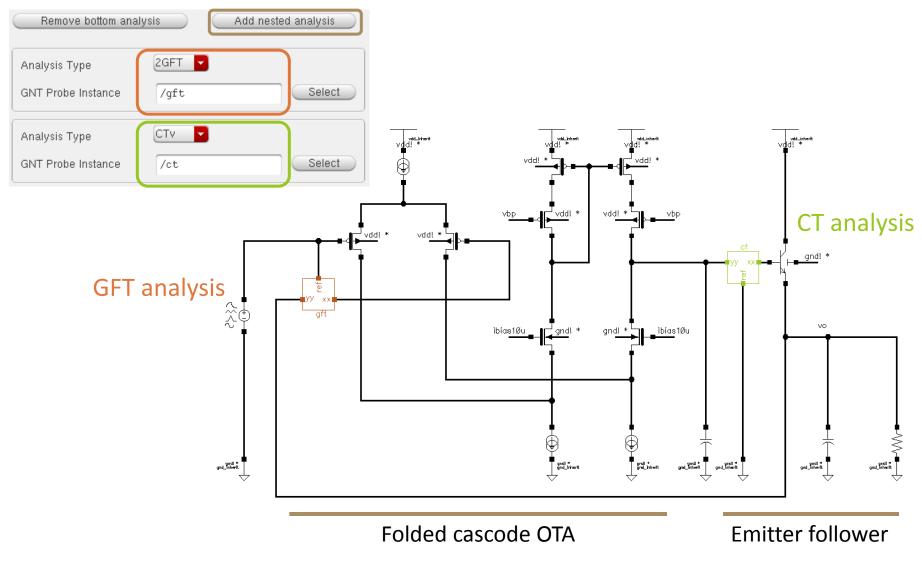


$$H = H_{\infty} \frac{T}{1+T} + H_0 \frac{1}{1+T}$$
$$T \approx T_{\rm v, fwd}$$

Application example: CT analysis nested in GFT analysis - setup



Application example: CT analysis nested in GFT analysis - setup

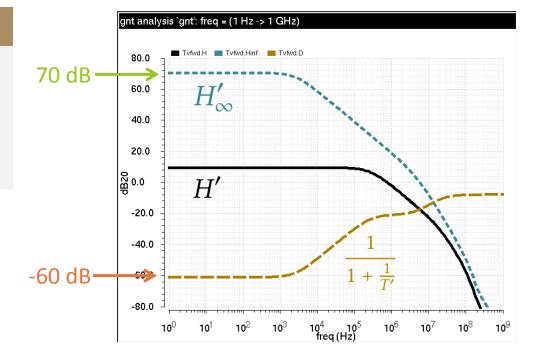


Application example: CT analysis nested in GFT analysis - results

Problem

Forward voltage loop gain insufficient

- \mapsto H too low
 - → Output voltage inaccurate



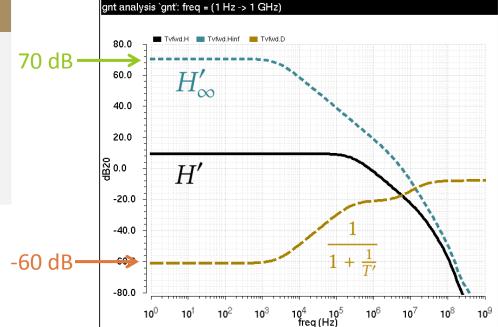
$$T_{\rm v,fwd} = H'$$
$$H' = H'_{\infty} \frac{1}{1 + \frac{1}{T'}}$$

Application example: CT analysis nested in GFT analysis - results

Problem

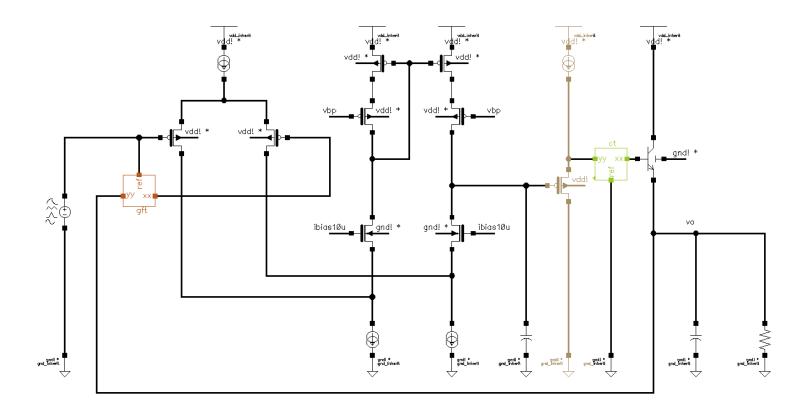
Excessive interaction between stages

- → Forward voltage loop gain insufficient
 - \mapsto H too low
 - → Output voltage inaccurate



$$T_{\rm v,fwd} = H'$$
$$H' = H'_{\infty} \frac{1}{1 + \frac{1}{T'}}$$

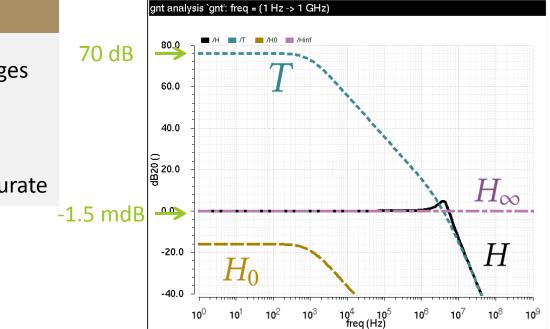
Insert a PMOS source follower



Problem

Excessive interaction between stages

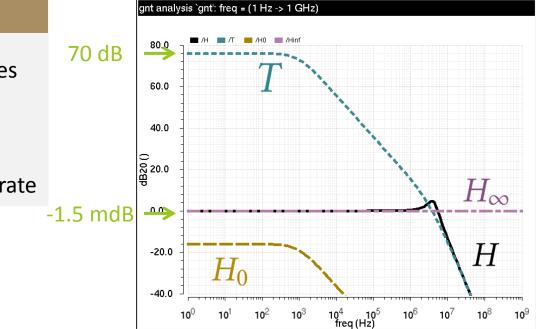
- → Forward voltage loop gain insufficient
 - \mapsto H too low
 - → Output voltage inaccurate



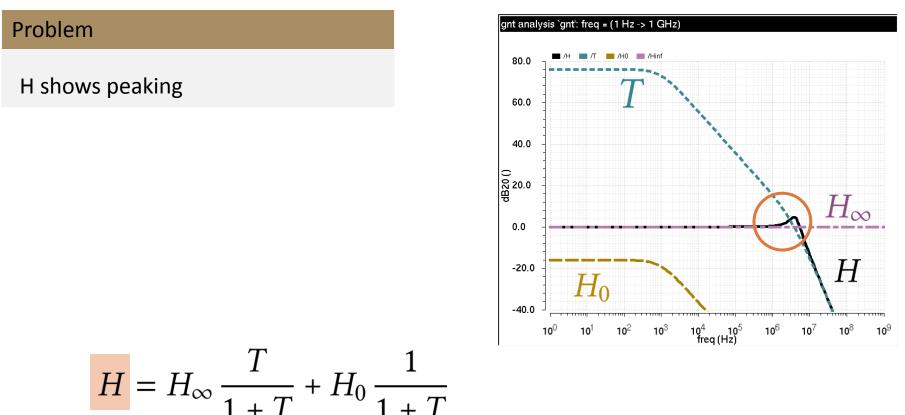


Excessive interaction between stages

- → Forward voltage loop gain insufficient
 - \mapsto H too low
 - → Output voltage inaccurate

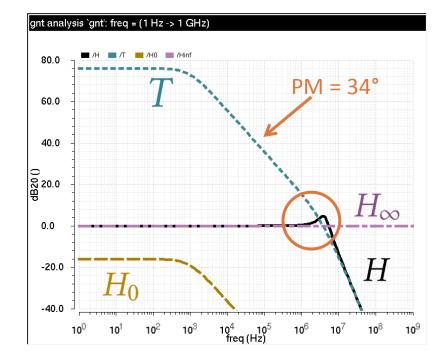






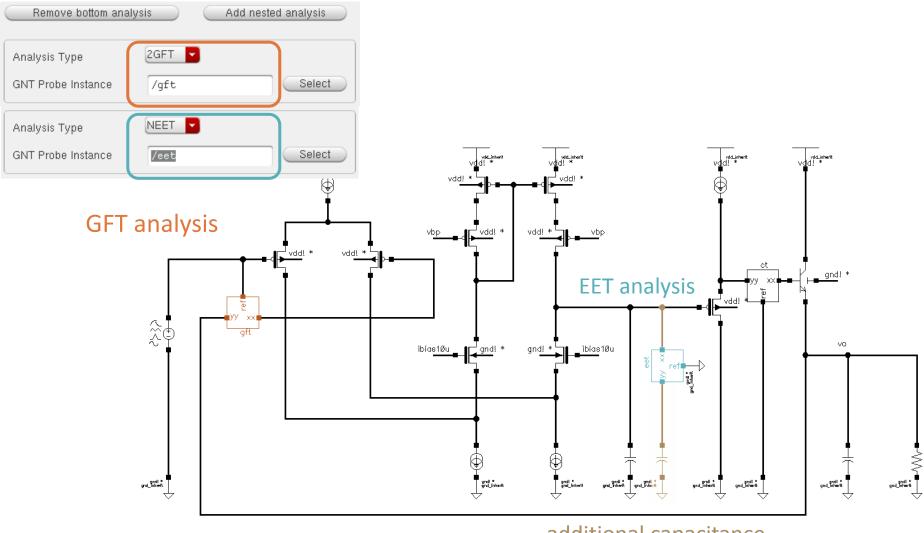
Problem

Forward voltage loop gain insufficient phase margin → H shows peaking



$$H = H_{\infty} \frac{T}{1+T} + H_0 \frac{1}{1+T}$$
$$T \approx T_{v,fwd}$$

Application example: reducing peaking, EET analysis nested in GFT analysis - setup



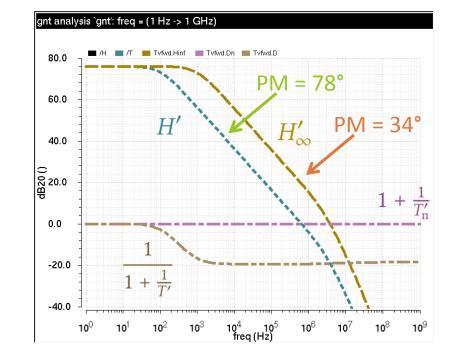
additional capacitance

GNT in ADE (XL)

Application example: reducing peaking, EET analysis nested in GFT analysis - results

Problem

Forward voltage loop gain insufficient PM → H shows peaking



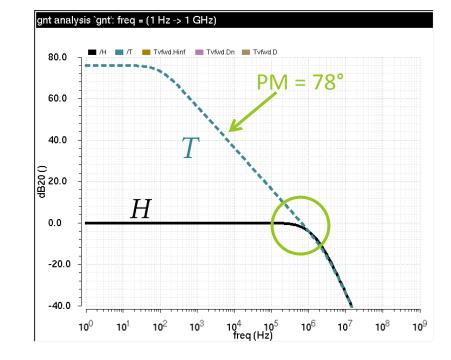
$$T_{v,fwd} = H'$$

$$H' = H'_{\infty} \frac{1 + \frac{1}{T'_n}}{1 + \frac{1}{T'}}$$

Application example: reducing peaking, EET analysis nested in GFT analysis - results

Problem

Forward voltage loop gain insufficient PM → H shows peaking



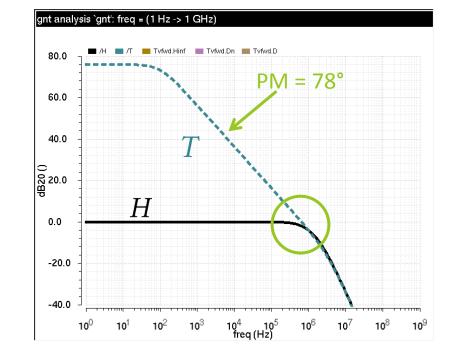
$$T_{\text{v,fwd}} = H'$$
$$H' = H'_{\infty} \frac{1 + \frac{1}{T'_n}}{1 + \frac{1}{T'}}$$

Application example: reducing peaking, EET analysis nested in GFT analysis - results

Problem

Forward voltage loop gain insufficient PM → H shows peaking

$$T_{\rm v,fwd} = H'$$
$$H' = H'_{\infty} \frac{1 + \frac{1}{T'_{\rm n}}}{1 + \frac{1}{T'_{\rm n}}}$$





GNT analysis integrated in ADE and ADE XL

Allows direct application of theorem

Valuable to increase insight, provides design guidance

Helpful instrument for design and analysis of electronic circuits and education of future designers

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GNT in ADE (XL)

References and acknowledgement

- R. D. Middlebrook, "The general feedback theorem: A final solution for feedback systems," IEEE Microwave Magazine, vol. 7, no. 2, pp. 50+, April 2006
- V. Vorpérian, Fast analytical techniques for electrical and electronic circuits. 2002
- R. D. Middlebrook, "The DT and the CT: The Dissection Theorem and the Chain Theorem." [Online]. Available: http://www. rdmiddlebrook.com/D-OA-Rules&Tools/index.asp
- R. D. Middlebrook, "Null double injection and the extra element theorem," IEEE Transactions on education, vol. 32, no. 3, pp. 167-180, August 1989
- R. D. Middlebrook, V. Vorperian, and J. Lindal, "The N Extra Element Theorem," IEEE Trans. Circuits Syst. I Fundam. Theory Appl., vol. 45, no. 9, pp. 919–935, 1998
- J. Verbrugghe, B. Moeneclaey, "Implementation of the Dissection Theorem in Cadence Virtuoso", International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design, pp. 145-148, September, 2012
- M. Tian, V. Visvanathan, J. Hantgan, and K. Kundert, "Striving for small-signal stability," IEEE Circuits & Devices, vol. 17, no. 1, pp. 31-41, january 2001
- F. Wiedmann. Loop gain simulation. [Online]. Available: http://sites.google.com/site/frankwiedmann/loopgain

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