Recent advances in the efficient small- and large-signal stability analysis of microwave circuits

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Stability detection and control of nonlinear circuits in large-signal regime by the conversion matrix approach

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Motivation

- Nonlinear circuits, when driven in large-signal regime, may be prone to the appearance of spurious oscillations

- A design-oriented approach, aimed at ensuring the stability in large-signal regime, is desirable

- An extension to the nonlinear regime of linear methods for stabilisation, making use of the conversion matrix, is a possible solution
Outline

• The conversion matrix approach

• Paralleled-transistor amplifiers – a possible approach exploiting symmetry

• Extension of linear design concepts to the nonlinear regime – $K$ factor, stability circles, etc.

• Application: intentional design of unstable amplifiers
The Conversion Matrix approach

Mixer, Power Amplifier
(Frequency Divider)

Small-signal amplifier
(Oscillator)

Large signal only
The Conversion Matrix approach

Large + small signal (stable)

Mixer, Power Amplifier
(Frequency Divider)

Small-signal amplifier
(Oscillator)
The Conversion Matrix approach

Mixer, Power Amplifier
(Frequency Divider)

Large + small signal (unstable)

Small-signal amplifier
(Oscillator)
The Conversion Matrix approach

Large (DC) + small (RF) signals

Amplifier

S-parameters

DC
The Conversion Matrix approach

Large (DC+RF) + small (RF) signals

Conversion matrix

Mixer

DC

LO

Conversion matrix

f_s

f_LO

f_s

f_LO - f_s

f_LO + f_s

f_s

f_LO - f_s

f_LO + f_s
The Conversion Matrix approach

Conversion Matrix

= Linear(ised) frequency-converting N-port Matrix

Linear stabilisation approaches
The Conversion Matrix approach

Reduction to a two-port network

K, Stability circles, etc.
Paralleled-transistor amplifier

Example: 4-transistor amplifier

Even and Odd modes

Odd modes are not observable from the input and output ports
Paralleled-transistor amplifier

Equivalent even-mode analysis
Paralleled-transistor amplifier

Modes are identified from symmetries in the S parameters of input and output networks

\[
\begin{align*}
    b_1 &= S_{i,R} \cdot a_1 + S_{i,MN} \cdot a_2 + S_{i,MF} \cdot a_3 + S_{i,MF} \cdot a_4 \\
    b_2 &= S_{i,MN} \cdot a_1 + S_{i,R} \cdot a_2 + S_{i,MF} \cdot a_3 + S_{i,MF} \cdot a_4 \\
    b_3 &= S_{i,MF} \cdot a_1 + S_{i,MF} \cdot a_2 + S_{i,R} \cdot a_3 + S_{i,MN} \cdot a_4 \\
    b_4 &= S_{i,MF} \cdot a_1 + S_{i,MF} \cdot a_2 + S_{i,MN} \cdot a_3 + S_{i,R} \cdot a_4.
\end{align*}
\]

Eigenmodes

\[
\begin{align*}
    m_1 &= [1 \quad 1 \quad 1 \quad 1]^T \\
    m_2 &= [1 \quad -1 \quad 1 \quad -1]^T \\
    m_3 &= [1 \quad 1 \quad -1 \quad -1]^T \\
    m_4 &= [1 \quad -1 \quad -1 \quad 1]^T.
\end{align*}
\]

Even mode

Odd modes
Paralleled-transistor amplifier

\[
\begin{align*}
m_1 &= [1 \quad 1 \quad 1 \quad 1]^T \\
m_2 &= [1 \quad -1 \quad 1 \quad -1]^T \\
m_3 &= [1 \quad 1 \quad -1 \quad -1]^T \\
m_4 &= [1 \quad -1 \quad -1 \quad 1]^T.
\end{align*}
\]

Example: mode 3

\[
b = (S_{i,R} + S_{i,MN} - 2S_{i,MF}) \cdot a = \Gamma_{i,m3} \cdot a
\]

Conversion matrix

Equivalent single-transistor analysis
Paralleled-transistor amplifier

Example: 8-transistor power amplifier

Stable for small signal

Unstable for higher input power
Paralleled-transistor amplifier

For each mode the conversion matrix is computed at increasing input power levels.

For each mode the conversion matrix is computed at increasing input power levels.

8 symmetry modes
Paralleled-transistor amplifier

Possible stability analysis: Nyquist

15 dBm – 20 dBm

20 dBm – 25 dBm
Paralleled-transistor amplifier

Conversion matrix reduction to a 2-port network

- For each mode
- For different port pairs
- For increasing input power levels
Paralleled-transistor amplifier

- Mode 2
- Input $f_s$, output $f_{in} + f_s$
- For increasing input power levels

\[
\Gamma(f_s) \quad \Gamma(f_{in} + f_s)
\]
Paralleled-transistor amplifier

Stability check by the pole-zero identification method

Output stability circles

Input reflection coefficient

Output load

Stability check by the pole-zero identification method

Imag

Real

Stability

15 dBm

16 dBm

17 dBm

18 dBm

19 dBm

20 dBm

International Microwave Symposium
6 - 11 June 2021, Atlanta, GA
Paralleled-transistor amplifier

Same analysis for Mode 5:

Output stability circles

Potential instability

Stability

Input reflection coefficient
Paralleled-transistor amplifier

Same analysis for Mode 3:

Potential instability

Instability

Output stability circles

Output load

Input reflection coefficient

$P_{in}=16\text{dBm}$
Paralleled-transistor amplifier

Frequency sweep

Increasing input power levels

Unit circle

Real Part

Imaginary Part

-10dBm

13dBm
Paralleled-transistor amplifier

Example: intentional synthesis of unstable amplifier

Stable single-ended amplifier at 600MHz

Unstable single-ended amplifier (even mode)

Unstable balanced amplifier (odd mode)
Paralleled-transistor amplifier

Stable and unstable (even mode) single-ended amplifiers

Moved a load in the unstable region

Other loads almost unchanged

Circles: stable

Triangles: unstable
Paralleled-transistor amplifier

Stable and unstable (even mode) single-ended amplifiers

Measured S parameters

Simulated output power
Paralleled-transistor amplifier

Stable and unstable (even mode) single-ended amplifiers

Measured output power

Measured spectrum
Paralleled-transistor amplifier

Stable and unstable (odd mode) balanced amplifiers

Schematic – redesigned input network

Simulated output power

![Graph showing simulated output power for stable and unstable amplifiers](image)

- **Input Power (dBm)**: -15 to 15
- **Output Power (dBm)**: 0 to 30

- **Stable amplifier (dBm)**
- **Unstable amplifier (dBm)**

**Components list**

- **BJT**: BFR92A
- **Rstab**: 47 Ω
- **L1**: 9.1 nH
- **L2**: 6.2 nH
- **L3**: 1.5 nH
- **L4**: 8.2 nH
- **L5**: 47 nH
- **L6**: 47 nH
- **L7**: 39 nH
- **C1**: 0.5 pF
- **C2**: 1.5 pF
- **C3**: 1.5 pF
- **C4**: 5.6 pF
- **C5**: 6.8 pF
- **R1**: 39 kΩ
- **R2**: 60 Ω
Paralleled-transistor amplifier

Stable and unstable (odd mode) balanced amplifiers

Measured output power

-20 -15 -10 -5 0 5 10
Input Power (dBm)

0 10 20
Output Power (dBm)

Fundamental frequency (Unstable)
Subharmonic frequency (Unstable)
Fundamental frequency (Stable)

Measured spectrum

Output power (dBm)

0 10 20
Frequency (GHz)

Subharmonic amplifier
Stable amplifier
Conclusions

• An approach has been described for the control of instabilities in the design / redesign phase

• Standard linear stabilization methods have been extended to the nonlinear regime via the conversion matrix

• Examples have been given