The S-Probe
A New, Cost-Effective, 4-Gamma Method for Evaluating Multi-Stage Amplifier Stability

Ken Wang, Marty Jones, and Steve Nelson

Texas Instruments Incorporated
PO Box 665474, Dallas, TX, 75265

ABSTRACT

This paper describes a generalized, automated, noninvasive, "4-Gamma" technique for stability analysis of multi-stage active circuits. It operates directly in the circuit-simulator environment and eliminates all off-line calculations. This technique can be extended to n-port networks and works equally well with circuit models or s-parameter descriptions. Most importantly, it can detect special cases of instability involving "active" terminations. These are often missed using conventional stability analysis approaches.

INTRODUCTION

Stability analysis can be such a tedious task for microwave designers that it tends to discourage rigorous analysis; promoting assumptions, approximations and dangerous shortcuts. Costly amplifier redesign may be avoided if a time-saving method is available and a rigorous stability analysis is performed.

Rollett's stability factor K was introduced in 1962 [1]. The standard procedure for most designers has been to use some combination of K-factor and stability-circle evaluation to determine an amplifier's tendency to oscillate. The generally-accepted method for ensuring stability of microwave amplifiers is as follows:

For a single two-port network, shown "not unconditionally stable" by s-parameter calculations, the designer has two basic options: (1) Circuit techniques may be applied to render the network unconditionally stable. This will often sacrifice performance. (2) The designer can show by analysis that the source and load impedances presented to the device will not cause oscillation. This is a multi-step procedure. After terminating the device with the load impedance presented by the circuit, the device input reflection coefficient is checked against the source reflection coefficient to see if it overcomes circuit losses and supplies power. A similar analysis is performed using the circuit-supplied source impedance and device output reflection coefficient.

Multi-stage amplifiers are often analyzed by separating the amplifier's active stages into a cascade of two-port networks, then evaluating K-factor and stability circles for each. The designer looks for stages within the cascade that are not unconditionally stable. If any are found, the designer then faces the previously-mentioned options of: (1) rendering each stage unconditionally stable or (2) proving that the terminating impedances will not cause oscillation.

Several issues limit the usefulness of conventional techniques in a multi-stage circuit:

Separating stages in a multi-stage amplifier always involves approximations. Stage-to-stage feedback, intentional or inadvertent (such as common bias feeds), can invalidate results obtained from the "cascaded-network" analyses. For some topologies there is no clear representation as a cascade.

An "unconditionally-stable" device (as defined by common practice) is stable if presented with source and load reflection coefficients less than one. Embedded in a multi-stage amplifier, a device may frequently be presented with reflection coefficients greater than one.

Conversely, a "not unconditionaly-stable" device (as defined by common practice) will not oscillate if the input and output stability indices (to be defined in the 4-gamma discussion) are less than one.

None of the conventional techniques used for multi-stage amplifier analysis are completely integrated with the circuit-simulation tools. A time-consuming off-line analysis and comparison of the data is required. The stability analysis *should be performed over the entire frequency range where the active devices are capable of oscillation. For multi-stage amplifiers, it must also be performed over a representative range of overall amplifier terminations, as this will affect the internal circuit impedances because of imperfect isolation between stages.*

"Loop-gain" analysis techniques [2] avoid the need to separate stages, but require reconfiguration of the circuit model to accommodate injection of external signals and recovery of returned voltages.

An automated procedure, preferably operating directly in the reflection-coefficient domain, is needed.

THE NEW "4-GAMMA" STABILITY INDEX METHOD

See Figure 1 for conventions used in the following discussion.

A linear active two-port is stable in a given environment if the input stability index:

mag[GammaS] * mag[GammaS11'] * cos[θ1+θ2] < 1

and the output stability index:

mag[GammaL] * mag[GammaS22'] * cos[θ3+θ4] < 1

θ1	=	Ang[GammaS]
θ2	=	Ang[GammaS11']
θ3	=	Ang[GammaL]
θ4	=	Ang[GammaS22']

THE S-PROBE

To implement this 4-Gamma stability check, we created a reflection-coefficient-probing analysis tool (S-Probe) using the TouchstoneTM circuit simulator. This S-Probe may be inserted anywhere in a complex circuit to measure reflection coefficients in either direction. Circuit operation is unaffected by insertion of the probe.

The S-Probe and 4-Gamma stability-analysis techniques offer the following advantages:

Direct implementation in the circuit file results in 85% reduction in stability-analysis time due to elimination of off-line processing.

The S-Probe technique recognizes stability problems caused by active loads presented to "unconditionally-stable" devices.

Because the noninvasive technique does not involve circuit separation, all modelled feedback paths are simultaneously accounted for.

The technique can be extended to n-port devices.

The simulator output maps noninvasively-determined circuit reflection coefficients against stability circles of the active devices. This output occurs in real time, giving the designer physical insight into the internal circuit behavior during the design process.

Figure 2 is the netlist of a sample S-Probe TouchstoneTM circuit file, with explanation and comments. Table 1 shows the results from this circuit file.

CONVENTIONAL METHODS MAY OVERLOOK SPECIAL CASES

During evaluation of the S-Probe analysis tool, we discovered regions of instability that were previously overlooked when using conventional techniques on multi-stage designs. These conditions occurred when "unconditionally-stable" stages faced active sources or active loads. Conversely, devices with source or load reflection coefficients in unstable regions were sometimes revealed not to oscillate when the S-Probe technique was used to evaluate the simultaneous application of both interface reflection coefficients.

S-PROBE EXAMPLE: OSCILLATION CAUSED BY FEEDBACK THROUGH BIAS CIRCUITS

Figure 3 is a simplified diagram of a three-stage power amplifier design centered at 15 GHz. The gate-bias networks are combined on-chip to reduce external parts count. By implementing the S-Probe and subjecting the design to the 4-gamma stability check, problems were detected at 0.8, 2.0, and 7.5 GHz. This is illustrated in Table 2a. Instability occurs when the stability index is positive and greater than one.

Isolating the gate-bias networks with separate off-chip bypassing eliminated the instability problem. Table 2b illustrates the results of analyzing the modified configuration.

Without the improved analysis technique, this problem would not have been discovered during the design cycle.

Conventional analysis techniques failed to reveal the instability.

CONCLUSION

An automated, generalized, 4-Gamma stability-analysis method has been developed. It operates in the reflection-coefficient domain and is incorporated in the circuit-simulation netlist. We can detect special instability cases which are often overlooked by using conventional methods. Because it can be extended to n-port networks, the S-Probe can be useful for designing oscillators, mixer amplifiers, matrix amplifiers, etc.

Using the S-Probe and 4-Gamma techniques, we achieve an 85% reduction in stability-analysis time for multi-stage amplifier designs. Long term, design-cost savings can be significant. Additional savings are realized by eliminating redesigns of unstable products. Late product introductions may cost market share that can never be recovered.

REFERENCES

[1] J. M. Rollett, "Stability and Power-Gain Invariants of Linear Twoports"; IRE Trans. Circuit Theory, vol. CT-9, pp. 29-32, Mar. 1962.

[2] Douglas J. H. Maclean, "Stability Margins in Microwave Amplifiers"; IEEE Trans. on Microwave Theory and Techniques, vol. MTT-32, No. 3, pp. 237-242, 1984.

Figure 1. Conventions Used in Discussion of the 4-Gamma and S-Probe Analysis Techniques

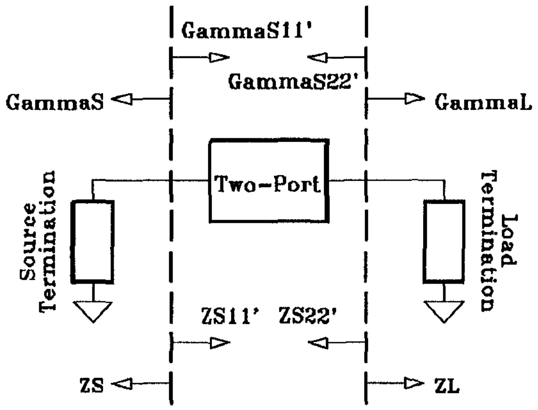

Figure 2.
This circuit file demonstrates the usage of the S-Probe in a simple circuit. Due to space constraints, compressed notation is used in some of the circuit-file blocks. The two-port in this example is a 50-ohm resistor. In addition to reflection coefficient data, the S-Probe can also compute voltage, current and impedance at any point in a circuit. Reflection coefficients and stability circles may be simultaneously output on the same Smith chart.

```
CKT
RES      1 2            R=0.0001
VCVS     1 777 2 0      M=-10000   A=0     R1=1E6     &
         R2=1E-6        F=0        T=0     !Current
VCVS     2 888 0 0      M=-1       A=0     R1=1E6     &
         R2=1E-6        F=0        T=0     !Voltage
DEF4P    1 2 777 888    SPROBE

RES      1 2            R=50       !50-ohm resistor
DEF2P    1 2            DUT

!These are defined for the circuit, can be any impedance
RES      1 0            R=50
DEF1P    1              TERM_S     !Source termination
RES      1 0            R=50
DEF1P    1              TERM_L     !Load termination

SPROBE   20 10 101 102             !Source reflection coefficient
SPROBE   20 30 201 202             !Device input reflection coefficient
DUT      30 40
SPROBE   50 40 301 302             !Device output reflection coefficient
SPROBE   50 60 401 402             !Load reflection coefficient
DEF10P   10 60 101 102 201 202 301 302 401 402          NET

!Current into GammaS, driven from NET output node 60
NET      10 60 101 102 201 202 301 302 401 402
TERM_S   10
DEF2P    60 101         I_S
!Voltage at GammaS, driven from NET output node 60
NET      10 60 101 102 201 202 301 302 401 402
TERM_S   10
DEF2P    60 102         V_S
!Current into GammaS11, driven from NET input node 10
NET      10 60 101 102 201 202 301 302 401 402
TERM_L   60
DEF2P    10 201         I_S11
!Voltage at GammaS11, driven from NET input node 10
NET      10 60 101 102 201 202 301 302 401 402
TERM_L   60
DEF2P    10 202         V_S11
!Current into GammaS22, driven from NET output node 60
NET      10 60          101 102 201 202 301 302 401 402
TERM_S   10
DEF2P    60 301         I_S22
!Voltage at GammaS22, driven from NET output node 60
NET      10 60 101 102 201 202 301 302 401 402
TERM_S   10
DEF2P    60 302         V_S22
!Current into GammaL, driven from NET input node 10
NET      10 60 101 102 201 202 301 302 401 402
TERM_L   60
DEF2P    10 401         I_L
!Voltage at GammaL, driven from NET input node 10
NET      10 60 101 102 201 202 301 302 401 402
TERM_L   60
DEF2P    10 402         V_L

TERM
I_S      TERM_L   0 0       I_S22    TERM_L   0 0
V_S      TERM_L   0 0       V_S22    TERM_L   0 0
I_S11    TERM_S   0 0       I_L      TERM_S   0 0
V_S11    TERM_S   0 0       V_L      TERM_S   0 0

OUTVAR   !Define the variables for calculations in the OUTEQN block
IS       =        I_S       S21
VS       =        V_S       S21
IS11     =        I_S11     S21
VS11     =        V_S11     S21
IS22     =        I_S22     S21
VS22     =        V_S22     S21
```

Figure 2. Cont.

```
IL          =        I_L          S21
VL          =        V_L          S21

OUTEQN     !Compute impedances and reflection coefficients
ZS          =        VS/IS
ZS11        =        VS11/IS11
ZS22        =        VS22/IS22
ZL          =        VL/IL
GAMMAS               =            (ZS-50)/(ZS+50)
GAMMAS11             =            (ZS11-50)/(ZS11+50)
GAMMAS22             =            (ZS22-50)/(ZS22+50)
GAMMAL               =            (ZL-50)/(ZL+50)

!Compute stability indices at both ports
SBINDEX1 = MAG((GAMMAS*GAMMAS11))*
                     COS(ANG(GAMMAS*GAMMAS11))
SBINDEX2 = MAG((GAMMAL*GAMMAS22))*
                     COS(ANG(GAMMAL*GAMMAS22))

FREQ
STEP       2

OUT
!Stability indices at source and load interfaces
OUTEQN    RE[SBINDEX1]          OUTEQN    RE[SBINDEX2]
!Interface reflection coefficients
!OUTEQN   GAMMAS                !OUTEQN   GAMMAS22
!OUTEQN   GAMMAS11              !OUTEQN   GAMMAL
!Stability circles for the two-port under analysis
!DUT      SB1         DUT       SB2
!Impedance data (in MAG/ANG form)
!OUTEQN   ZS          !OUTEQN   ZS22
!OUTEQN   ZS11        !OUTEQN   ZL
!Voltage and current data at source interface
!OUTVAR   VS          !OUTVAR   IS
!OUTVAR   VS11        !OUTVAR   IS11
!Voltage and current data at load interface
!OUTVAR   VS22        !OUTVAR   IS22
!OUTVAR   VL          !OUTVAR   IL
```

Table 1. Stability Indices and Reflection Coefficients Generated By the Circuit File of Figure 2

FREQ-GHZ	SBINDEX1 OUTEQN RE	SBINDEX2 OUTEQN RE
2.00000	-8.3e-06	-8.3e-06

FREQ-GHZ	GAMMAS OUTEQN MAG	GAMMAS OUTEQN ANG
2.00000	2.5e-05	180.000

FREQ-GHZ	GAMMAS11 OUTEQN MAG	GAMMAS11 OUTEQN ANG
2.00000	0.333	0.000

FREQ-GHZ	GAMMAS22 OUTEQN MAG	GAMMAS22 OUTEQN ANG
2.00000	0.333	0.000

FREQ-GHZ	GAMMAL OUTEQN MAG	GAMMAL OUTEQN ANG
2.00000	2.5e-05	180.000

Table 2a. Stability Indices For 1st Stage of 15-GHz Amplifier With On-Chip-Combined Bias

FREQ-GHZ	SBINDEX1 OUTEQN RE	SBINDEX2 OUTEQN RE
0.80000	1.104	-0.244
2.00000	1.018	1.191
7.50000	1.198	-0.848

Table 2b. Stability Indices For 1st Stage of 15-GHz Amplifier With Off-Chip-Isolated Bias

FREQ-GHZ	SBINDEX1 OUTEQN RE	SBINDEX2 OUTEQN RE
0.80000	-0.618	-0.299
2.00000	0.066	-0.722
7.50000	0.003	0.549

Figure 3. Diagram of the 15-GHz Amplifier Using On-Chip-Combined Bias Networks