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Assessment for the Stabilization of a Front-end Circuit

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ABSTRACT

An assessment for the stabilization of a front-end circuit is described in terms of a scattering matrix, where the key issue is unconditional stability. A CMOS preamplifier, designed for a silicon micro-strip detector, is evaluated concerning its quality of unconditional stability.

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In the most recent and future applications, such as the B-factory experiment and/or LHC, front-end circuits are required to have a wider frequency bandwidth than before, where radiation-measurement circuits merge with micro-wave-circuit technology. The stability issue of front-end circuits has so far been easily overlooked. It is quite common to check the input impedance in either a SPICE simulation or in practice with a network analyzer.^{[1][2][3][4]} When the circuit design is inadequate for stabilization, the input impedance could be a good measure of the stability/instability. In the design of microwave circuits it is quite common to use a scattering-matrix approach instead of an impedance matrix. The instability of a circuit and/or blocks of circuits has been evaluated and checked out in terms of the stability coefficient. The toughest instability is , associated with the packaging and/or assembly , which can be resolved using the scattering-matrix formalism et al.,^[5]. We would like to call the attention of circuit designers to the stability-assessment issues in addition to noise analysis, linearity/dynamic-range issues, and classical gain/phase analysis.^[6] Chapter 2 deals with a general theory of unconditional stability. Chapter 3 shows the availability of the K-factor formalism for a CMOS preamplifier circuit employed for the B-factory experiment, BELLE^[7]. Chapter 4 concludes the discussion.

2. Theory of stability analysis

2.1. DEFINITION OF UNCONDITIONAL STABILITY

A definition of unconditional stability reads as follows. A two-port network is said to be unconditionally stable at a given frequency if the real part of the input impedance (Z_{in}) and the output impedance (Z_{out}) are greater than zero for all passive-load and source impedances. If the two-port network is not unconditionally

stable, it is potentially unstable. The impedance matrix $\mathbf{Z}$ is defined as

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}, \quad (2.1)$$

where v_1 and v_2 are the voltages appearing at terminals 1 and 2, respectively, and i_1 and i_2 are the in-coming currents to terminals 1 and 2, respectively. Assuming that the output node, i.e. designated as 2, is terminated by a passive load of Z_L , we obtain

$$\begin{pmatrix} v_1 \\ -Z_L i_2 \end{pmatrix} = \mathbf{Z} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}, \quad (2.2)$$

which can be reorganized as

$$Z_{in} = \frac{v_1}{i_1} = Z_{11} - \frac{Z_{12}Z_{21}}{Z_L + Z_{22}}. \quad (2.3)$$

In the same context, the output impedance will be

$$Z_{out} = Z_{22} - \frac{Z_{12}Z_{21}}{Z_S + Z_{11}}, \quad (2.4)$$

where Z_S is the source impedance. The reflection coefficients at the input and output nodes are defined as

$$\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (2.5)$$

and

$$\Gamma_{out} = \frac{Z_{out} - Z_0}{Z_{out} + Z_0}, \quad (2.6)$$

where Z_0 is a real positive number, which normalizes the impedance of the measurement system. We employ $Z_0 = 50\Omega$ for the later analysis in chapter 3. Since $|\Gamma_{out}|$ is described as

$$|\Gamma_{out}|^2 = \frac{|Z_{out}|^2 + Z_0^2 - 2Z_0 \text{Re}Z_{out}}{|Z_{out}|^2 + Z_0^2 + 2Z_0 \text{Re}Z_{out}}, \quad (2.7)$$

the condition $|\Gamma_{out}| < 1$ is equivalent to $\text{Re}Z_{out} > 0$. Similarly, we also find that $|\Gamma_{in}| < 1$ is equivalent to $\text{Re}Z_{in} > 0$. Since the condition requested by Eqs.

(2.5) and (2.6) still includes source and load impedances, it is inconvenient to use in practice. In the next section we eliminate Z_L and Z_S with the aid of the scattering-matrix formalism.

2.2. STABILITY IN TERMS OF THE SCATTERING MATRIX

Since details concerning the scattering matrix for the microwave circuit appear elsewhere^{[8],[9]}, we only outline the theory here. The reflection coefficients (Γ_{out} and Γ_{in}) relate to each other through the scattering matrix ($\mathbf{S}$) as

$$\begin{pmatrix} P_{in}\Gamma_{in} \\ P_{out} \end{pmatrix} = \mathbf{S} \begin{pmatrix} P_{in} \\ P_{out}\Gamma_L \end{pmatrix}, \quad (2.8)$$

where P_{in} is the in-coming power for port-1, and P_{out} is the out-going power for port-2. The reflection coefficient at the load impedance (Z_L) is defined as

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}. \quad (2.9)$$

Eliminating P_{in} and P_{out} , we obtain

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \rightarrow \frac{S_{11} - \Delta\Gamma_L}{1 - S_{22}\Gamma_L}, \quad (2.10)$$

where Δ is the determinant of matrix $\mathbf{S}$. In a similar procedure, we have

$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} \rightarrow \frac{S_{22} - \Delta\Gamma_S}{1 - S_{11}\Gamma_S} \quad (2.11)$$

where Γ_S is the reflection coefficient at the source impedance (Z_S). The above two equations can be derived from Eqs. (2.5) and (2.6) with the aid of the conversion relations appearing in Eqs. (A.4), (A.5) and (A.6). The unconditional stability requires that the above-two equations have absolute values of less than 1. The

unconditional stability condition is described as

$$K = \frac{1 + \Delta^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{12}S_{21}|} > 1 \quad (2.12)$$

and

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1. \quad (2.13)$$

The actual derivation of Eqs. (2.12) and (2.13) appears in Appendix (B) and (C), which supplement the discussion. K and Δ take an essential part in the discussion given in the next chapter.

3. Potential instability of a front-end circuit

3.1. EXTRACTION OF S- PARAMETERS

The configuration for measuring the impedance matrix is shown in Figure 1. Applying an AC current (I_1) at input node 1 with an open load at output node 2 ($I_2 = 0$), the voltages appearing at the input node (V_1) and the output node (V_2) are measured. By applying the impedance matrix defined in Eq. (2.1) we obtain

$$Z_{11} = \frac{V_1}{I_1} \quad (3.1)$$

and

$$Z_{21} = \frac{V_2}{I_1}. \quad (3.2)$$

In a similar way, by applying an AC current (I_2) at output node 2 with an open-source impedance at input node 1 ($I_1 = 0$), we obtain

$$Z_{22} = \frac{V_2}{I_2} \quad (3.3)$$

and

$$Z_{12} = \frac{V_1}{I_2}. \quad (3.4)$$

By employing these impedance elements we can extract the S-parameters according to the conversion formula appearing in Appendix A.

3.2. PRACTICE FOR CIRCUIT ANALYSIS

Circuit for evaluation

Figure 2 shows a circuit schematic of the CMOS preamplifier employed for stability analysis. The preamplifier is a single-stage, single-ended charge-sensitive amplifier with a cascode configuration. The feed-back capacitor is 0.2pF, which is discharged by an nMOS switch (NM47). NM75 is used to compensate for any feed-through from the gate electrode upon the event that RESET is released. The size of the input FET (NM05) is $W/L=1200/2$ in μm . Under typical operation conditions of $I_d = 120\mu A$, the transconductance of the input FET is about 3mS. The circuit is biased by three voltages (VHI, VMI, and VLO), which are generated by a separate circuit block. Being biased by VHI and VMI, pMOS transistors PM08 and PM07 provide a constant-current load. The nMOS transistor NM06 serves as a cascode transistor for the input FET (NM05). The nominal voltage of the output node (SGOUT) is about 2.5V, which allows a swing to either polarity of the input signal. The nMOS transistor (NM51) provides a DC-voltage shift between the output node (SGOUT) and the input node (SGIN) during the reset procedure. The preamplifier has a test-pulse input (TPLS), which is enabled by an nMOS switch (NM07).

Check for unconditional stability

Since we have recognized that the CMOS preamplifier circuit could oscillate during the reset procedure^[10], we have a good reason to examine the preamplifier circuit while being reset, i.e. RESET=H and RESETB=L. In order to evaluate the impedance matrices, we employ a SPICE simulator (HSPICE, version h93a.02, from Meta-Software, Inc.). The parameters for MOS transistors are compatible with the Level=3 MOS model of a 1.2 μm n-well CMOS process from Seiko Instr., Inc. Figure 3 shows the stability coefficients with parameterization for the gate width (W) of the source follower transistor (NM51). The typical transistor size for NM51 is $W/L=40/36$ in μm . While the Δ 's satisfy $|\Delta| < 1$ over the entire frequency region, the K 's exhibit an irregularity in the 1 to 10 MHz region, which

indicates that there exists some particular types of loading conditions which can move the circuit to oscillate. We can find additional insight from Figure 3, in that the larger gate width for NM51 improves the stability.

Check for conditional stability

Under the actual operating conditions of the preamplifier circuit, the load impedances are predominantly capacitive. It would be desirable that the circuit be stable for the actual capacitance loads. We first examine the real part of the input impedance (ReZ_{in}) for load impedances of 4, 8, and 16pF (Figure 4), where it is found that the real part of the input impedance shows no negative resistance. The typical value of the load capacitance is 8pF, which comes from the sample-and-hold capacitors of analog memories which are in a tracking mode while being reset. Figure 5 is for examining the real part of the output impedance (ReZ_{out}). We employ source (or detector) impedances of 10, 20, and 40pF, for which we have recognized that the circuit is stable in practice.

4. Conclusions

The stability theory developed in the area of microwave circuits provides a more stringent idea than the common practice in the area of radiation-measurement instrumentation. It may frequently happen that a circuit is stable in a laboratory test, but not at the installation site, which is possibly due to differences of loading conditions. Once the circuit is qualified in terms of unconditional stability and fixed so as to be stable, the trouble never happens in principle. We can relax the constraint for the integrated-circuit design of the front-end circuit as long as the output load of the front-end amplifier is located on a chip, and has no reason to appreciably drift. For the particular case of a CMOS integrated-circuit preamplifier, we have demonstrated that the circuit is stable for a wide variety of loading conditions, while still residing in a potentially instable region. Once we recognize an assessment for stabilization, we should proceed through a recipe for the up-and-coming procedure.

APPENDIX A

Impedance matrix and scattering matrix

In terms of the impedance matrix $\mathbf{Z}$, the scattering matrix $\mathbf{S}$ appears as

$$\mathbf{S} = \frac{\mathbf{Z} - Z_0 \mathbf{I}}{\mathbf{Z} + Z_0 \mathbf{I}}, \quad (\text{A.1})$$

where matrix $\mathbf{I}$ is an unit matrix. Denoting $\mathbf{z}' = \mathbf{Z}/Z_0$, we describe matrix $\mathbf{S}$ as

$$\mathbf{S} = \frac{\mathbf{z}' - \mathbf{I}}{\mathbf{z}' + \mathbf{I}} = \frac{1}{\Delta_1} \begin{pmatrix} (z'_{11} - 1)(z'_{22} + 1) - z'_{12}z'_{21} & 2z'_{12} \\ 2z'_{21} & (z'_{11} + 1)(z'_{22} - 1) - z'_{12}z'_{21} \end{pmatrix}, \quad (\text{A.2})$$

where

$$\Delta_1 = (z'_{11} + 1)(z'_{22} + 1) - z'_{12}z'_{21}. \quad (\text{A.3})$$

The inverse relation between matrices $\mathbf{Z}$ and $\mathbf{S}$ is

$$\mathbf{z}' = \frac{\mathbf{I} + \mathbf{S}}{\mathbf{I} - \mathbf{S}}, \quad (\text{A.4})$$

which leads to

$$\frac{1}{\Delta_2} \begin{pmatrix} (1 + S_{11})(1 - S_{22}) + S_{12}S_{21} & 2S_{12} \\ 2S_{21} & (1 - S_{11})(1 + S_{22}) + S_{21}S_{12} \end{pmatrix}, \quad (\text{A.5})$$

where

$$\Delta_2 = (1 - S_{11})(1 - S_{22}) - S_{12}S_{21}. \quad (\text{A.6})$$

APPENDIX B

Necessray and sufficient condition for unconditional stability

By requesting $1 - |\Gamma_{out}|^2 > 0$ and $1 - |\Gamma_{in}|^2 > 0$ in Eqs. (2.10) and (2.11) under the subsidiary conditions $1 > |\Gamma_L|$ and $1 > |\Gamma_S|$, we can reorganize the stability conditions as

$$||S_{22} - \Delta S_{11}^*| - |S_{12}S_{21}|| > ||S_{22}|^2 - |\Delta|^2| \quad (\text{B.1})$$

and

$$||S_{11} - \Delta S_{22}^*| - |S_{12}S_{21}|| > ||S_{11}|^2 - |\Delta|^2|. \quad (\text{B.2})$$

Taking the squares of the above equations and applying the identities

$$|S_{11} - \Delta S_{22}^*|^2 = |S_{12}S_{21}|^2 + (1 - |S_{22}|^2)(|S_{11}|^2 - |\Delta|^2) \quad (\text{B.3})$$

and

$$|S_{22} - \Delta S_{11}^*|^2 = |S_{12}S_{21}|^2 + (1 - |S_{11}|^2)(|S_{22}|^2 - |\Delta|^2), \quad (\text{B.4})$$

we obtain

$$2|S_{12}S_{21}| + (|S_{22}|^2 - |\Delta|^2)(1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2) > 2|S_{12}S_{21}||S_{22} - \Delta S_{11}^*| \quad (\text{B.5})$$

and

$$2|S_{12}S_{21}| + (|S_{11}|^2 - |\Delta|^2)(1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2) > 2|S_{12}S_{21}||S_{11} - \Delta S_{22}^*|. \quad (\text{B.6})$$

By applying $K = 1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2$ on the left-hand side of the above equations and dividing by $|S_{12}S_{21}|$ under an assumption that $|S_{12}S_{21}| \neq 0$, we obtain

$$|S_{12}S_{21}| + (1 - |S_{11}|^2)K - 2|S_{12}S_{21}|K^2 > 2|S_{12}S_{21}||S_{22} - \Delta S_{11}^*| \quad (\text{B.7})$$

and

$$|S_{12}S_{21}| + (1 - |S_{22}|^2)K - 2|S_{12}S_{21}|K^2 > 2|S_{12}S_{21}||S_{11} - \Delta S_{22}^*|. \quad (\text{B.8})$$

Taking squares on each side of the equation and applying the identities appearing

in Eqs. (B.3) and (B.4) again, we obtain

$$(|S_{22}|^2 - |\Delta|^2)^2(K^2 - 1) > 0 \quad (\text{B.9})$$

and

$$(|S_{11}|^2 - |\Delta|^2)^2(K^2 - 1) > 0. \quad (\text{B.10})$$

Moving back to Eqs. (B.7) and (B.8), we can add additional constraints. The condition $K^2 > 1$ should be consistent with

$$|S_{12}S_{21}| + (1 - |S_{11}|^2)K - 2|S_{12}S_{21}|K^2 > 0 \quad (\text{B.11})$$

and

$$|S_{12}S_{21}| + (1 - |S_{22}|^2)K - 2|S_{12}S_{21}|K^2 > 0. \quad (\text{B.12})$$

These constraints require that $K > 1$ together with reorganized presentations for the constrains

$$1 - |S_{11}|^2 > |S_{12}S_{21}| \quad (\text{B.13})$$

and

$$1 - |S_{22}|^2 > |S_{12}S_{21}|. \quad (\text{B.14})$$

The unconditional stabilities are presented in some modified forms, as listed in Table 1. These statements are mutually equivalent. We provide a proof in Appendix C.

APPENDIX C

(P1) $K > 1 \rightarrow B_1 B_2 > 0$

By employing B_1 and B_2 appearing in Table 1, we obtain $B_1 B_2$ as

$$B_1 B_2 = (1 - |\Delta|^2)^2 - (|S_{11}|^2 - |S_{22}|^2)^2, \quad (\text{C.1})$$

which is reorganized as

$$B_1 B_2 = (1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2)(1 + |\Delta|^2 + |S_{11}|^2 + |S_{22}|^2) - 4(|\Delta|^2 - |S_{11}|^2 |S_{22}|^2). \quad (\text{C.2})$$

By applying $K > 1$ for the first term, and

$|\Delta|^2 \leq |S_{11} S_{22}|^2 + |S_{12} S_{21}|^2 + 2|S_{11} S_{22}| |S_{12} S_{21}|$ for the last term, we obtain

$$B_1 B_2 > 4|S_{12} S_{21}|(|S_{11}| - |S_{22}|)^2 \geq 0. \quad (\text{C.3})$$

(P2) $|\Delta| < 1 \leftrightarrow B_1 + B_2 > 0$

By employing the relation

$$B_1 + B_2 = 2(1 - |\Delta|^2), \quad (\text{C.4})$$

we find that $|\Delta| < 1$ is equivalent to $B_1 + B_2 > 0$.

(P3) $K > 1, |\Delta| < 1 \leftrightarrow K > 1, B_1 > 0, B_2 > 0$

From (P1) and (P2), $B_1 > 0$ and $B_2 > 0$ are equivalent with $|\Delta| < 1$ as long as $K > 1$.

(P4) $K > 1, B_1 > 0, B_2 > 0 \rightarrow A_1 > 0, A_2 > 0$

A_1 and A_2 appearing in Table 1 are reorganized as

$$2A_2 = B_1 + 2(K - 1)|S_{12} S_{21}| > 0 \quad (\text{C.5})$$

and

$$2A_1 = B_2 + 2(K - 1)|S_{12} S_{21}| > 0, \quad (\text{C.6})$$

which are positive when $K > 1$, $B_1 > 0$, and $B_2 > 0$.

(P5) $A_1 > 0, A_2 > 0 \rightarrow B_1 + B_2 > 0$

$B_1 + B_2$ is reorganized as

$$B_1 + B_2 = 1 - |S_{11}|^2 |S_{22}|^2 - |S_{12} S_{21}|^2 - 2|S_{11} S_{22} S_{12} S_{21}|. \quad (\text{C.7})$$

By employing $A_1 > 0$ and $A_2 > 0$ for the second term, we obtain

$$B_1 + B_2 > 2|S_{12} S_{21}|(1 - |S_{11}| |S_{22}|) > 0, \quad (\text{C.8})$$

where we employ $|S_{11}| < 1$ and $|S_{22}| < 1$, which are directly implied by $A_1 > 0$ and $A_2 > 0$.

(P6) $K > 1, A_1 > 0, A_2 > 0 \leftrightarrow K > 1, B_1 > 0, B_2 > 0$

From (P4) and (P5), $A_1 > 0$ and $A_2 > 0$ are equivalent to $B_1 > 0$ and $B_2 > 0$ as long as $K > 1$.

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TABLE CAPTIONS

1: Presentation for unconditional stability

Table. 1 Presentation for unconditional stability

(A)	$K > 1$ $A_1 = 1 - S_{11} ^2 - S_{12}S_{21} > 0$ $A_2 = 1 - S_{22} ^2 - S_{12}S_{21} > 0$
(B)	$K > 1$ $B_1 = 1 + S_{11} ^2 - S_{22} ^2 - \Delta ^2 > 0$ $B_2 = 1 + S_{22} ^2 - S_{11} ^2 - \Delta ^2 > 0$
(C)	$K > 1$ $ \Delta < 1$

FIGURE CAPTIONS

- 1) a) Setup for Z_{11} and Z_{21} measurements
b) Setup for Z_{22} and Z_{12} measurements
- 2) Circuit schematic of the CMOS preamplifier circuit for evaluation
- 3) Stability coefficients for the size of the nMOS transistor (NM51, $W = 20, 40,$ and $80 \mu m$)
a) for K , and b) for Δ
- 4) Real part of Z_{in} for load capacitances of 4, 8, and 16pF
- 5) Real part of Z_{out} for source capacitances of 10, 20, and 40pF

Figure 1

FIGURE 2

Figure 3

Figure 4

Figure 5