Best Practices to Ensure the Stability of SiGe HBT Cascode Low Noise Amplifiers

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***Abstract* — This work provides a detailed examination of the stability of SiGe cascode low noise amplifiers (LNAs). The upper base is identified as a problematic node for stability. S-probe simulations are used to extract reflection coefficients internal to the circuit and provide insight on how to improve the stability of a cascode amplifier and thereby establish "best practices" for designers. These techniques are incorporated into a cascode LNA design fabricated on a 180 nm, 150 GHz f_T SiGe BiCMOS technology. The measured SiGe LNA has a gain of 16.5 dB and a noise figure of 2.1 dB at a center frequency of 9.2 GHz. A series of measurements using tuners at both the input and output confirm the LNA is stable for all impedances covered by the tuners ($|\Gamma| < 0.8$).**

***Index Terms* — Stability, stability analysis, silicon-germanium, SiGe HBT, low-noise amplifier, LNA.**

I. Introduction

The cascode topology has become a popular architecture for low noise amplifiers as well as power amplifiers. Cascode amplifiers provide high gain, good isolation between ports, and a reduction in the effect of the Miller capacitance on the lower transistor [1]. The cascode topology is becoming increasingly important as device breakdown voltages naturally decrease with technology scaling. To overcome the limitations of the decreasing breakdown voltage and to achieve higher output voltage swings (higher power), transistors are often stacked in the cascode topology.

While this topology offers several benefits, it is more difficult to analyze in terms of stability than a single transistor amplifier. The common Rollett "K-factor" analysis may give some indication of possible instabilities, but it is not a sufficient test for amplifiers with multiple active devices [2]. In some special cases, additional information may be gained by running the K-factor analysis separately on each amplifier stage [3]. However, in the cascode topology, the two transistors have significant loading effects on each other and cannot be separated. An alternative approach to Rollett's K-factor is the S-probe analysis [4]. The S-probe analysis extracts the reflection coefficients looking into and out of an arbitrary node to determine if the node is stable.

The present work analyzes in detail the stability of the cascode configuration implemented using silicon-germanium (SiGe) HBTs, by utilizing the S-probe approach, and offers "best practices" for designers. The results of the analysis are used to design an X-band SiGe cascode LNA. The LNA achieves 16.5 dB of gain with a NF of 2.1 dB at a center frequency of 9.2 GHz and is stable in measurement for the entire range of the tuners with $|\Gamma_s|$, $|\Gamma_L| < 0.8$.

II. Theoretical Analysis

In the cascode topology, the stability at the base of the cascode device (upper base) is of particular concern because of the capacitive loading of the lower transistor. Similar to the CMOS cascode structure [5], a negative resistance can appear looking into the base of the upper transistor. Unfortunately, the K-factor analysis is designed to test for stability at the input and output of the circuit and does not indicate the value of the reflection coefficient at the upper base node. If the lower transistor of a basic cascode pair is modeled as a resistor in parallel with a capacitor as shown in Fig. 1, the impedance looking into the base can be derived from the small-signal model as Equation (1).

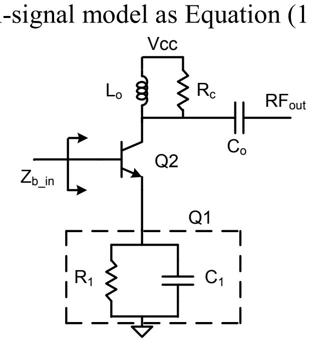

Fig. 1. Simplified cascode topology used for circuit analysis.

$$Z_{b\_in} = \frac{r_\pi}{1+j\omega C_\pi r_\pi} + \frac{R_1}{1+j\omega C_1 r_1}\left(1 + g_m \frac{r_\pi}{1+j\omega C_\pi r_\pi}\right) \quad (1)$$

$$R_{b_{in}} = \frac{g_m r_\pi R_1(1-\omega^2 C_\pi r_\pi C_1 R_1)}{(1+\omega^2 C_\pi^2 r_\pi^2)(1+\omega^2 C_1^2 R_1^2)} + \cdots$$

$$\cdots + \frac{r_\pi}{1+\omega^2 C_\pi^2 r_\pi^2} + \frac{R_1}{1+\omega^2 C_1^2 R_1^2} \quad (2)$$

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The real part of the impedance is given in Equation (2) and shows that for $\omega^2 C_\pi r_\pi C_1 R_1 > 1$, the impedance looking into the upper base can be negative. Equation (2) also indicates that biasing at higher current densities where g_m is large increases the likelihood that the impedance is negative.

As a result, it is very important to develop a methodology to determine the stability at the upper base. Circuit analysis shows that this node is prone to instabilities, but it is difficult to apply this theory to the design of an actual circuit. The additional parasitics and coupling associated with any layout would make such an analysis unreasonably complicated. Furthermore, the simple parallel resistor and capacitor used to model the lower transistor change significantly with frequency and bias conditions.

The S-Probe or Gamma-Probe is a technique which extracts the reflection coefficients looking into and out of internal nodes without affecting the circuit response [4]. This is very beneficial in the present context because it allows for stability analysis without breaking any feedback loops. S-Probe components are now available in many simulation tools and are easily utilized. Fig. 2 shows that using the S-probe, the entire circuit can be represented by a small loop.

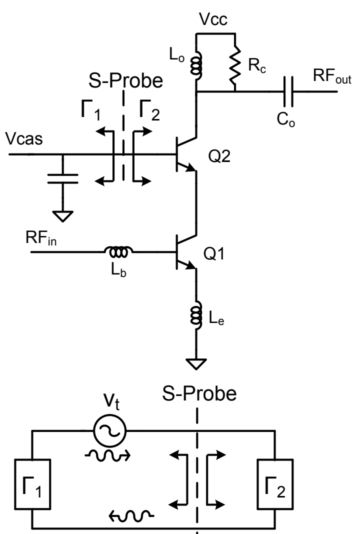

Fig. 2. S-probe applied to the cascode node.

Fig. 2 can be thought of as a loop containing Γ_1 and Γ_2 connected over an infinitely short transmission line. A small noise source V_t is included to highlight that oscillations may occur without an RF source. If the loop gain is greater than unity and in phase, the thermal noise of the networks associated with Γ_1 and Γ_2 may induce oscillations. It can be shown using the Nyquist stability test that the number of closed-loop right-half plane poles is equal to the number times $\Gamma_1(\omega)*\Gamma_2(\omega)$ encircles the point (1,0) in a clockwise fashion [6]. Thus, any node where the product of the reflection coefficients encircles (1,0) may cause oscillations.

III. Stability Improvements

An X-band cascode LNA was designed using a 180 nm, 150 GHz peak-f_T SiGe BiCMOS technology. The design was based on the simultaneous noise and power matching approach presented in [1]. The current density was selected to balance the tradeoff between noise and gain at a center frequency of 9.2 GHz. The transistors were sized to match the real part of the optimum noise impedance to 50 Ω. The base and emitter inductors were chosen for noise and power matching at the input.

The S-Probe was applied to the cascode node of the LNA, as shown in Fig 2. To get a sense of circuit robustness for unconditional stability, the S-Probe analysis was run for a large number of source and load terminations. In simulation, it was determined the worst case impedances for the stability of the LNA were $\Gamma_S = 0.95 \angle 330°$ and $\Gamma_L = 0.95 \angle 210°$. Fig. 3 plots the product of the reflection coefficients for these terminations over frequency on a polar plot. The critical point (1,0) is encircled in a clockwise fashion, indicating that the node is potentially unstable.

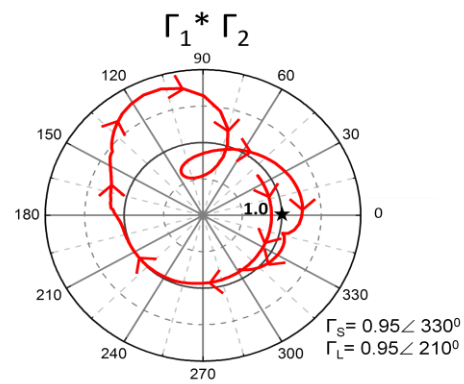

Fig. 3. Product of the reflection coefficients at the cascode node from 10 MHz to 80 GHz.

As predicted by the theoretical analysis, Fig. 4 shows the reflection coefficient looking into the base can be larger than unity, corresponding to a negative resistance. While this negative resistance is highly undesirable, it does not necessarily mean the circuit will be unstable. The reflection coefficient looking out of the base must also be analyzed to determine if there is a possibility for circuit oscillations. Looking to the left of the cascode base, there is a DC bias node which is typically RF grounded with a decoupling capacitor. This appears as a short circuit at high frequencies and presents a reflection coefficient very close to -1. As a result, it is quite possible the product of the two reflection coefficients will be greater than unity.

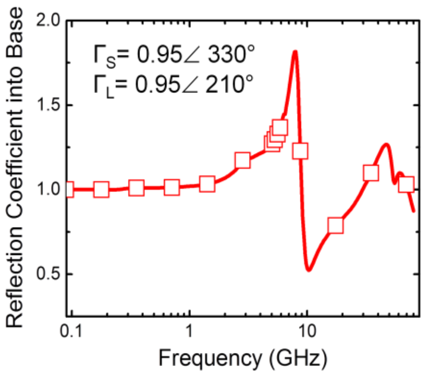

Fig. 4. Reflection coefficient looking into the upper base.

One way to reduce the reflection coefficient looking into the cascode base is to decrease the bias current and the g_m of the transistor and thus reduce the negative resistance (refer to (2)). However, the current density of the transistor core is normally chosen to balance noise and gain requirements. Reducing g_m to improve stability would decrease the amplifier gain and is hence an undesirable solution. Another option is to include a small resistor between the cascode base and the decoupling capacitor to reduce the reflection coefficient looking out of the upper base. Since the current flowing into the upper base is very small, this burns very little power and does not significantly change the operating point. However, the resistor should be kept small to minimize the noise added to the circuit and allow large voltage swings across the cascode device [7]. For the LNA presented in this work, a 10 Ω resistor was selected to decrease the reflection coefficient. Fig. 5 demonstrates that this change improves the stability at the cascode node so the product of reflection coefficients no longer encircles the (1,0) point and therefore should not cause oscillations.

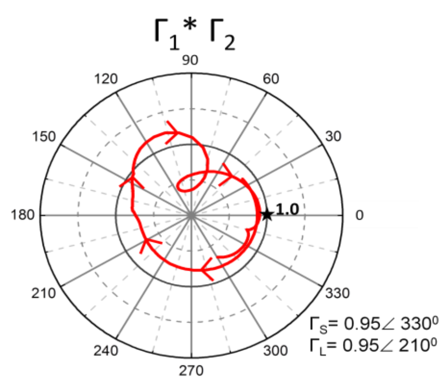

Fig. 5. Nyquist plot after design improvements.

IV. X-Band Cascode LNA Design

The final schematic with the improved cascode bias network is shown in Fig. 6.

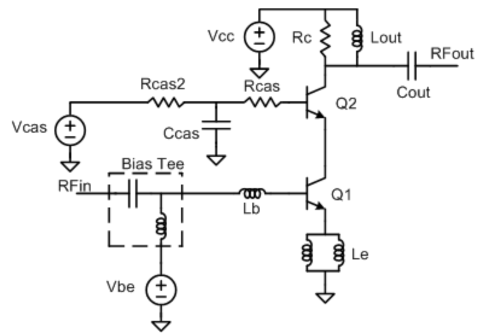

Fig. 6. Final schematic of the X-Band cascode LNA.

The emitter degeneration inductor was split into two parallel inductors to create better symmetry and improve the current distribution to the SiGe HBTs in the amplifier core. Fig. 7 shows the photomicrograph of the fabricated SiGe LNA. The final layout is 1.1 mm x 0.8 mm.

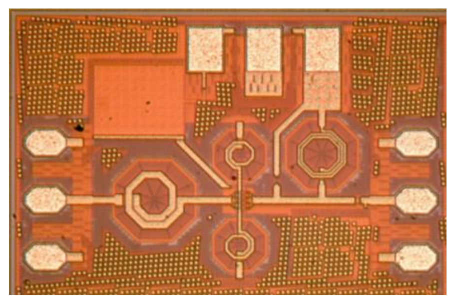

Fig. 7. Photomicrograph of the SiGe cascode LNA.

The S-parameters of the LNA were measured using an Agilent E8363B Vector Network Analyzer (VNA) from 1-20 GHz with co-planar ground-signal-ground (GSG) probes. Fig. 8 shows that the measured and simulated S-parameters are in good agreement. The total power consumption of the LNA is 13.75 mW.

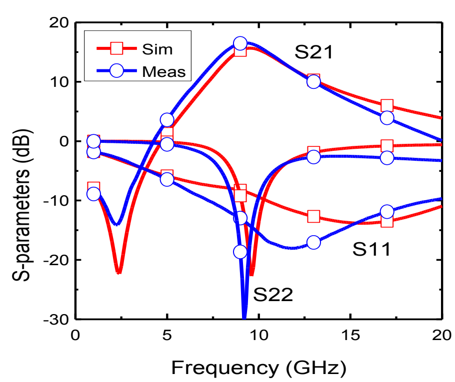

Fig. 8. Simulated and measured S-parameters.

The noise and power measurements were performed on a custom built integrated S-parameter, noise figure, and load-pull probing station which provides RF switching between the network analyzer, signal sources, and spectrum analyzer. Fig. 9 shows the LNA achieves a noise figure of less than 2.4 dB from 8-12 GHz and is in reasonable agreement with the simulated results.

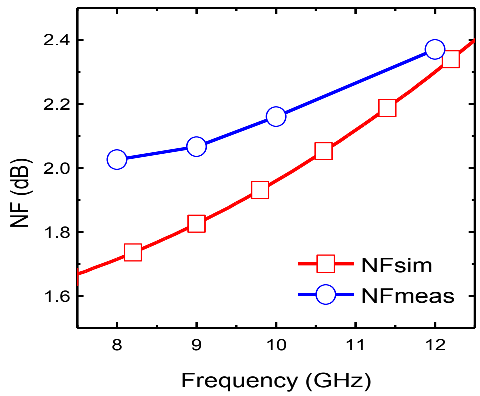

Fig. 9. Simulated and measured noise figure.

To verify the robustness of the stability of the fabricated LNA, a series of measurements were completed with tuners at the input and output. Source and load terminations on the edge of the Smith chart were thoroughly investigated since they reflect more energy back towards the amplifier and are prone to instabilities. A load pull was performed for $|\Gamma_s| = 0.8$ at every 60°. Fig. 10 shows the measured gain contours for $|\Gamma_s| = 0.8\angle 330°$, which was the worst case source termination for stability in simulation. Similar to Fig. 10, the load pull contours for all the measured source impedances had smooth gain contours with no spikes or drops in current, which would suggest instability. To further ensure stability, a coupler was used during load pull measurements to simultaneously view the output spectrum on the spectrum analyzer. The spectrum analyzer showed no indications of oscillation.

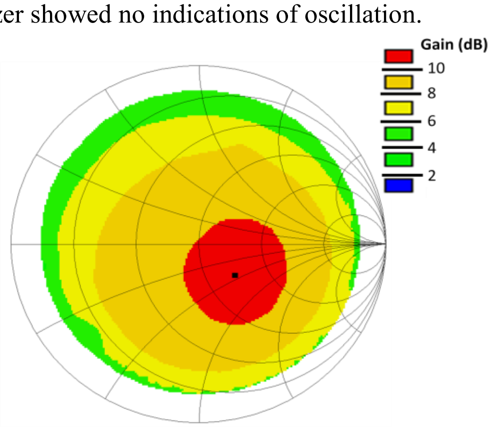

Fig. 10. Measured load pull at Γ_S=0.8∠ 330^0.

The techniques presented in this work have provided insight to "best practices" for the cascode topology. First, a small resistor should be included at the upper base to reduce reflections at that node. In addition, the trace length from the cascode device to the resistor and decoupling capacitor should be kept to a minimum. This reduces the parasitic inductance and pushes the resonance of the LC network to higher frequency. While this work focuses on the problematic cascode node, the S-probe analysis should be run at all terminals of the active devices. At each location, the S-probe should be used with a large number of source and load terminations from low frequency up to the f_{max}. It is also wise to run these simulations over temperature and process variations to ensure oscillations cannot occur.

VII. Summary

This work has analyzed the stability of the SiGe cascode architecture in detail. The potential for internal node instabilities has been shown through circuit analysis. The S-probe simulation technique was utilized to improve the bias network at the cascode node to achieve unconditional stability. In measurement, a series of load pulls were performed at different source impedances to confirm the stability of the amplifier. The LNA achieves 16.5 dB gain with a noise figure of 2.1 dB at 9.2 GHz while consuming 13.75 mW of power. The approach presented in this work to ensure stability can be applied to a variety of RF circuits.

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