

Noise-Figure Optimization of a Multi-Stage Millimeter-Wave Amplifier with Negative Capacitance Feedback

Shota KOHARA[†] Shuhei AMAKAWA[†] Takeshi YOSHIDA[†] and Minoru FUJISHIMA[†]

[†]Graduate School of Advanced Sciences of Matter, Hiroshima University,

1-3-1 Kagamiyama, Higashihiroshima, Hiroshima, 739-8530 Japan

E-mail: [†]skohara@fis.hiroshima-u.ac.jp

Abstract In a low noise amplifier, a source-degeneration inductor is commonly used to reduce noise figure (NF), which also degrades the gain. Thus, the inductance of source degeneration for NF minimization in a single stage amplifier not always results in NF minimization in a multistage amplifier, because a small gain in the first stage influences a total NF. In this study, a local feedback by a negative capacitance is discussed to compensate the gain degradation due to a source-degeneration inductor for minimizing the NF of multi-stage amplifier. It is shown that the circuit parameters of local feedbacks are optimized, and the negative capacitance between the gate and the drain works effectively reduce the total NF of a multi-stage amplifier.

Keyword millimeter wave, low-noise amplifier, noise figure, local feedback

1. Introduction

In a low noise amplifier (LNA) using a MOSFET, a source-degeneration inductor is commonly used to reduce a noise figure (NF) [1]. However, the source-degeneration inductor degrades gain. Here, reactive components between a gate and a drain as well as a source inductor can be used as local feedback [2]. These local feedbacks change not only a NF but also a gain. The circuit parameters for minimum NF of a single-stage amplifier not always minimize the NF of a multi-stage amplifier, because gain reduction of the first stage degrades total NF, where the NF's of the succeeding stages play nonnegligible roles. In the millimeter wave band, especially, a NF degradation due to gain reduction becomes stringent, because the maximum available gain (MAG) and the maximum stable gain (MSG) of a silicon MOSFET decrease. In this study, it is discussed that the circuit parameters in local feedback of the amplifier stage to minimize the total NF of the millimeter wave band multi-stage amplifier.

2. NF in a Single-Stage amplifier

A schematic of a single-stage amplifier is shown in Fig. 1. In this study, it is assumed that input and output of a common-source stages comprise ideal matching networks satisfying conjugate matching at 80 GHz with 55nm CMOS process. In this case, a gain of a common-source amplifier is equal to a MAG. First, NF and MAG of a single-stage common-source amplifier are simulated as functions of an inductor at the source L_f and a capacitor between the gate and the drain C_f . It is noted that negative C_f can be realized, for example, by cross couple capacitors in a differential network [3]. The NF of a common-source amplifier is derived from

$$F = F_{\min} + \frac{4R_n}{Z_0} \frac{|\Gamma_S - \Gamma_{\text{opt}}|^2}{(1 - \Gamma_S)|1 + \Gamma_{\text{opt}}|^2}, \quad (1)$$

where $F_{\min}$ is minimum noise factor, R_n is equivalent noise coefficient, Γ_S is input circuit reflection coefficient, Γ_{opt} is noise matching reflection coefficient, and Z_0 is reference impedance

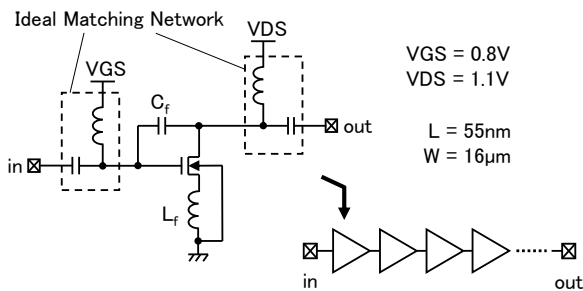


Fig. 1. A schematic of a single-stage LNA.

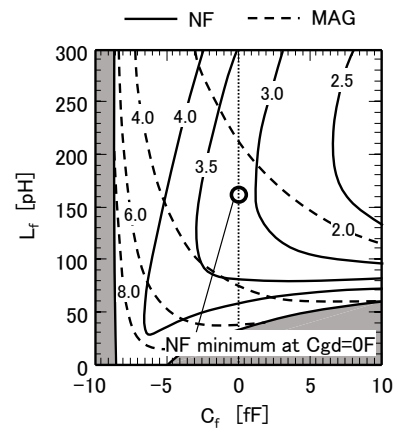


Fig. 2. NF / MAG [dB] of a single-stage LNA.

equal to 50Ω . In this case, Γ_S is equal to simultaneous conjugate matching impedance Γ_{MS} .

In Fig. 2, NF and MAG are shown by a solid line and a broken line, respectively. The conditionally stability region is removed, shown in gray. For $C_f = 0$ F, the NF becomes minimum at $L_f = 162$ pH. On the other hand, the NF is monotonically decreasing with increasing C_f . However, the MAG also decreases in this case.

3. Theoretical Discussion: NF in an Infinite-Stage Amplifier

Next, a multi-stage amplifier is discussed, where the identical common-source amplifiers shown in section 2 are cascaded. For simplicity, it is assumed that all the circuit parameters are same. In this case, a noise figure of a n -stage amplifier $F_{total,n}$ is given by a sum of geometric series from the Friis formulas with the noise figure (F) and the gain (G) of single stage.

$$F_{total,n} = F + \sum_{k=1}^n \frac{F-1}{G^k} = \frac{(F-1)(1-G^{-n})}{1-G^{-1}} + 1. \quad (2)$$

And the NF of an infinite-stage amplifier is derived as

$$F_{total,\infty} = \frac{F-1}{1-G^{-1}} + 1, \quad (3)$$

as shown in Fig. 3 when n is infinite in Eq. (2). It is noted that the first term of $F_{total,\infty}$ is known as a noise measure [4]. In an infinite-stage amplifier, the optimum values of L_f and C_f are determined uniquely at $C_f = -7$ fF, $L_f = 15$ pH. It is shown that negative capacitances are not only reducing a total NF but also increasing gain in an infinite-stage amplifier.

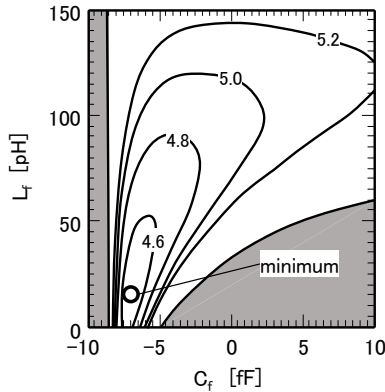


Fig. 3. NF of an infinite-stage LNA.

4. Practical Case: NF of a Four-Stage Amplifier

Since an infinite-stage amplifier is impossible for actual designs, the case of a four-stage amplifier is discussed. The NF in a four-stage amplifier is derived from Eq. (2) as shown in Fig. 4. The cases of the single-stage and infinite-stage amplifiers are appeared in the regions of positive and negative C_f , respectively. The total NF is reduced in both cases.

The total NF reduces with increasing C_f when $C_f > 0$, as shown in a single-stage amplifier. It also reduces the total NF with decreasing C_f in the case of $C_f < 0$, as shown in an infinite-stage amplifier. Since an amplifier with a higher gain is preferred, the case of $C_f < 0$ should be chosen. In this case, the circuit parameters realizing the minimum NF are equal to those of the infinite-stage amplifier.

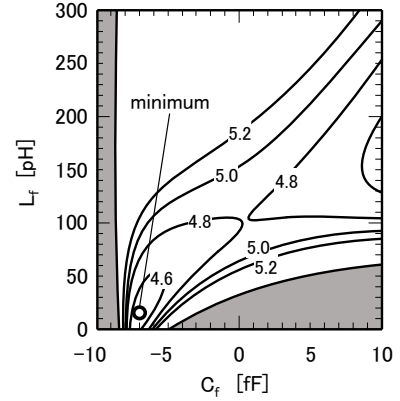


Fig. 4. NF of a 4-stage LNA.

5. Conclusion

Circuit parameters of a common-source amplifier with local feedbacks have been discussed for minimizing a NF of a multi-stage small-signal amplifier in millimeter wave. In the multi-stage amplifier, it is necessary to consider not only a NF but also a gain in each common-source stage. As a result, it is shown that the circuit parameters for minimizing a NF are different for a single-stage and a multi-stage amplifier. Finally, a negative capacitance feedback is effective to reduce the total NF in a multi-stage amplifier.

Acknowledgement

A part of this study is based on collaboration with Mie Fujitsu Semiconductor, Ltd.

References

- [1] D. K. Shaeffer, Thomas H. Lee, "A 1.5-V, 1.5-GHz CMOS low noise amplifier," *IEEE J. Solid-State Circuits*, vol. 32, no. 5, pp. 745–759, May 1997.
- [2] C. Cheng, "Neutralization and unilateralization," *IRE Trans. Circuit Theory*, vol. 2, no. 2, pp. 138–145, June 1955.
- [3] J. A. Mataya, G. W. Haines, and S. B. Marshall, "IF amplifier using C_c compensated transistors," *IEEE J. Solid-State Circuits*, vol. 3, no. 4, pp. 401–407, Dec. 1968.
- [4] H. A. Haus, R. B. Adler, "Optimum Noise Performance of Linear Amplifiers," *Proc. of the IRE*, vol. 46, no. 8, pp. 1517–1513, Aug. 1958.