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A 16-43 GHz Low-noise Amplifier with 2.5-4.0 dB Noise Figure

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Abstract—This paper presents an ultra-broadband low-noise amplifier (LNA) operating from 16 to 43 GHz in a 0.25 μm SiGe:C BiCMOS technology. Across this band, the LNA achieves simultaneous low-noise performance (2.5-4.0 dB) and power matching ($S_{11} < -10$ dB) using dual-LC tank matching. The measured minimal noise figure is 2.5 dB at 26 GHz with an average value of 3.25 (± 0.75) dB from 16 to 44 GHz. The best gain is 10.5 dB at 26 GHz with a 3-dB gain bandwidth from 16 to 43 GHz (90% fractional bandwidth). The measured input 1-dB compression point and input IP3 are better than -8.5 dBm and 1.8 dBm over the 16-43 GHz band, respectively, for a total power consumption of 24 mW.

Keywords—LNA; ultra-broadband; dual-LC tank; SiGe

I. INTRODUCTION

Broadband systems at millimeter-wave (mm-wave) frequencies have recently received a great deal of interest since their bandwidth is sufficient for high-data rate communication, such as the fifth generation (5G) wireless communication system [1] and typical K band (20-40 GHz) applications [2, 3]. With the development of silicon based technology, a high performance mm-wave front-end with complex system integration is feasible in SiGe BiCMOS technology [3]. However, it is still challenging for a mm-wave front-end system to cover the entire bandwidth from 20 to 40 GHz to support K band and 5G communication systems.

In such a broadband system, the low-noise amplifier (LNA) design is one of the biggest challenges, expected to provide significant low-noise (i.e. noise figure (NF) around 3 dB), sufficient power matching ($S_{11} < -10$ dB), and small gain variation (3-dB gain bandwidth, $BW_{3dB} > 20$ GHz). Various wide band designs are proposed for broadband systems. For instance, the common-base (CB) structure could provide broadband input matching, but its noise performance is poorer than the common-emitter (CE) structure [4]. Shunt resistive feedback with inductive series-peaking is employed in [5] to provide large gain bandwidth, but both power matching and noise performance are limited. CE structure with inductive degeneration and inductor matching is used in [6] to achieve low-noise performance, however, it is limited by both power matching and gain bandwidth (26-31 GHz). An LC-ladder is used in [7] to achieve a wideband power matching (3-10 GHz) but the operating frequency is below 10 GHz. In this paper, an ultra-broadband LNA with 2.5-3.5 dB NF and $S_{11} < -11$ dB

over the complete K band is presented. To achieve both broadband power matching and low-noise performance, a dual-LC tank matching method is proposed and employed in a cascode structure.

This paper is organized as follows. In section II, the proposed method of dual-LC tank matching is analyzed. The implemented LNA is presented in the Section III. The measurement results are provided in section IV. Conclusions are presented in Section V.

II. LNA CIRCUIT DESIGN

A. Dual-LC Tank Matching Network

The equivalent small-signal model of the dual-LC tank matching network is shown in Fig. 1, which consists of a shunt tank (L_1, C_1), a series (L_2, C_2) tank and an equivalent resistance (R_{EQ}). Both shunt and series tanks are resonant at the same frequency ω_C . The input impedance, Z_{IN} , can be expressed as a function of frequency (ω) and R_{EQ} in (1).

$$Z_{IN} = \left[j\omega C_1 \left(1 - \frac{\omega_C^2}{\omega^2} \right) + \frac{1}{j\omega L_2 \left(1 - \frac{\omega_C^2}{\omega^2} \right) + R_{EQ}} \right]^{-1} \quad (1)$$

The Z_{IN} curves are plotted on the Smith chart in Fig. 1 with R_{EQ} from 30 to 70 Ω . The blue dashed circle indicates the region for return loss (Γ_{IN}) better than -10 dB, where Γ_{IN} is defined in (2).

$$\Gamma_{IN} = 10 \log(|S_{11}|^2) = 10 \log \left| \frac{Z_{IN} - Z_0}{Z_{IN} + Z_0} \right|^2 \quad (2)$$

As shown in Fig. 1, the S_{11} bandwidth is extended when R_{EQ} is decreased. The bandwidth of $S_{11} < -10$ dB can be derived by solving ω from (1) under the condition that the imaginary part of $Z_{IN}(\omega)$ is zero. Equation (1) has three roots: ω_C at the central frequency, ω_L at a lower frequency and ω_H at a higher frequency with the relation $\omega_H \cdot \omega_L = \omega_C^2$. The real parts of Z_{IN} at these three frequencies are:

$$R_{IN}(\omega) = \begin{cases} R_{EQ}, & \omega = \omega_C \\ \frac{L_1 L_2 \omega_C^2}{R_{EQ}}, & \omega = \omega_L, \omega_H \end{cases} \quad (3)$$

Fig. 1. The simulated Z_{IN} of dual-LC tank matching network in the Smith chart ($Z_0 = 50 \Omega$) for different values of R_{EQ} (30/50/70 Ω). Frequency increases from 10 to 50 GHz by 5 GHz per step (shown by an arrow). The dashed circle indicates the region of $S_{11} < -10$ dB.

Therefore, the S_{11} is completely determined by $R_{IN}(\omega)$ at these frequencies. Note that (3) also indicates $R_{IN}(\omega_L) = R_{IN}(\omega_H)$ (designated as R_I), which means S_{11} has the same value at these frequencies. The boundary conditions of R_{EQ} and R_I is obtained by solving (2), which leads to $26 < R_{EQ} < R_I < 96 \Omega$. As a result, the S_{11} bandwidth is given by (4).

$$\omega_H - \omega_L = \frac{\sqrt{R_I R_{EQ} - R_{EQ}^2}}{L_2} \quad (4)$$

B. Dual-LC tank as Noise Matching

The Dual-LC tank can also be applied for broadband noise matching. The output impedance of the matching network (Z_S) is shown in Fig. 2, where R_0 is the source resistance. The minimal noise figure (NF_{MIN}) of a transistor is achieved under the noise matching condition of $Z_S = Z_{OPT}$ [6], where Z_{OPT} is the optimal noise impedance of the transistor. If $Z_S = Z_{OPT} = Z_{IN}^*$, then the transistor achieves simultaneous noise and power matching [8]. For an inductively degenerated CE stage (Fig. 2), Z_{OPT} and Z_{IN} are expressed in (5) and (6), respectively.

$$Z_{OPT} \approx \frac{1}{\omega(C_{BE} + C_{BC})} \left[\sqrt{\frac{g_m}{2}(R_E + R_B)} + j \right] \quad (5)$$

$$Z_{IN} \approx \frac{g_m L_E}{C_{BE}} + \frac{1}{j\omega(C_{BE} + C_{BC})} \quad (6)$$

where C_{BE} and C_{BC} are the base-emitter and base-collector capacitance; R_E and R_B are emitter and base resistance; g_m is the transconductance and L_E is the degeneration inductance. Z_S , Z_{IN} , Z_{IN}^* and Z_{OPT} are plotted in the Smith chart from 10 to 50 GHz in Fig. 2. It can be shown that the rotation direction of Z_{IN} in the Smith chart is similar to a series RC circuit, therefore Z_{IN} and Z_S constitute the dual-LC tank. By applying the dual-LC tank matching method, Z_S and Z_{IN} can be matched ($S_{11} < -10$ dB) at ω_L , ω_C and ω_H , which means Z_S curve follows Z_{IN}^* curve between ω_L and ω_H .

Fig. 2. The simulated input impedance Z_{IN} , its conjugate matching Z_{IN}^* and optimal noise impedance Z_{OPT} of an inductively degenerated common-emitter transistor; the simulated output impedance Z_S of the dual-LC tank matching network in the Smith chart ($Z_0 = 50 \Omega$). Frequency increases from 10 to 50 GHz by 5 GHz per step (shown by arrows).

At the same time, Z_S is required to follow Z_{OPT} for broadband noise matching. This is challenging because Z_{IN}^* and Z_{OPT} deviate from each other at all frequencies [4]. In fact, the noise matching at ω_H is more important because of the higher NF_{MIN} . Therefore, the input matching network Z_S can be designed to follow Z_{OPT} only at the higher frequencies instead of the full band.

C. Gain bandwidth

The gain flatness is achieved by tuning the output LC tank above the highest working frequency (i.e. 40 GHz) [7]. The input impedance is close to a broadband 50 Ω by using the double-LC tank matching, which sets the input signal current (I_{IN}) almost constant at all frequencies (at the same input power level). Thus the input voltage ($V_{BE} = I_{IN}/(sC_{BE})$) and the output current ($I_{OUT} = g_m V_{BE}$) decrease at 20 dB per decade due to the capacitive input impedance of the transistor. An inductive load can compensate this drop and flatten the output voltage. An extra transmission line is used for fine tuning.

III. CIRCUIT IMPLEMENTATION

The schematic of the proposed LNA is shown in Fig. 3. The cascode structure (Q_1 and Q_2) is chosen to alleviate the Miller effect and improve the reverse isolation. The method of dual-LC tank matching network is implemented through L_1 , C_1 , L_2 and transistor Q_1 . The pad capacitance C_{PAD} , the shunt inductor L_1 and the shunt capacitor C_1 form the first tank. The series inductor L_2 , together with the input capacitance of transistor Q_1 (C_{BE}) and L_3 form the second tank. L_3 is a degeneration inductor to generate the required real part of the input impedance for power matching. The transistor Q_1 is biased at 3.5 mA/ μm^2 current density for optimal noise performance.

Fig. 3. The schematic of the proposed LNA.

The size of Q_1 and value of L_3 are selected to generate the required input impedance ($R_{IN} = 35 \text{ } \Omega$) and noise matching ($R_{OPT} = 45 \text{ } \Omega$) based on the dual-LC tank matching method at 30 GHz. The transistor Q_2 provides extra power gain and isolation and its size is selected to improve the noise matching between two transistors [6]. The inductor L_4 and transmission line T_1 provide a broadband inductive load to achieve the flat gain. Passive structures including inductors, transmission lines and bond pads are all simulated using electromagnetic (EM) software (Agilent Momentum).

IV. MEASUREMENT

The circuit is implemented in NXP's 0.25 μ m SiGe:C BiCMOS technology with a peak f_T/f_{MAX} of 177/216 GHz [6]. The measurement setup and the die photo are shown in Fig. 4 with a total die area of 0.7 $\times$ 0.6 mm².

The measured input return loss is less than -10 dB from 20 to 50 GHz and the reverse isolation is better than 25 dB at 40 GHz, as shown in Fig. 5. The gain and noise performance are shown in Fig. 6. The best S_{21} is 10.5 dB at 26 GHz and the 3-dB gain bandwidth covers 16 GHz to 43 GHz, corresponding to a 90% fractional bandwidth. The measured minimal NF is 2.5 dB at 20 and 26 GHz and the average NF is 3.25 (± 0.75) dB from 16 to 44 GHz. The linearity performance is shown in Fig. 7 for input IP3 ($IIP3$) and input 1-dB compression point (ICP_{1dB}) respectively. The group delay and phase of S_{21} are shown in Fig. 8 for wideband applications. The LNA draws 10 mA from a 2.4-V power supply (24 mW in total).

Table I shows a benchmark with other silicon-based LNAs operating in the K band. The proposed work achieves the best performance in a combination of low average noise, wide gain bandwidth and sufficient S_{11} bandwidth, covering the full K band from 20 to 40 GHz.

Fig. 4. Die photo and measurement setup.

Fig. 5. Comparson of measured and simulated S_{11} and S_{12} .

Fig. 6. Comparison of measured and simulated noise figure and S_{21} .

Fig. 7. Measured Lineary performance.

Fig. 8. Comparison of measured and simulated group delay and phase of S_{21} .

TABLE I. PERFORMANCE SUMMARY AND COMPARISON

	This work	TMTT 2015 [3]	RFIC 2012 [6]	JSSC 2010 [9]	TMTT 2012 [10]	MWCL 2010 [11]
Central Frequency (GHz)	29.5	30*	27.5*	27.5*	36.5*	36*
3-dB Gain BW (GHz)	27	10.5	7	9	15	14
Peak Gain (dB)	10.5	25.3	12.4	12	13.8	14.2
NF (dB)	2.5-4.0	2.5-3.2	1.8-2.2	4.5-6.3	3.8-6*	2-3.3
$S_{11} < -10$ dB BW (GHz)	17-50	N/A	29-33*	20-35*	29-50*	29-43*
IIP3 (dBm)	1.8 to 5.9	-13.8@ 31GHz	-1.3 @ 30GHz	-4.5 to -6.3	-1 @ 37GHz	N/A
Power (mW)	24	21	98	13	18	38
Technology	0.25 μ m SiGe	0.25 μ m SiGe	0.25 μ m SiGe	0.18 μ m Bi-CMOS	90 nm CMOS	0.15 μ m InGaAs pHEMT

*Calculated from Paper

V. CONCLUSION

In this paper, the design of an ultra-broad band LNA with 90% fractional bandwidth is presented in a 0.25 μ m SiGe:C technology. The input matching is the most crucial part to achieve a broadband noise and power matching. A dual-LC tank matching method is proposed and applied to the LNA design. The measured NF is 2.5-4.0 dB from 16 to 44 GHz. To our knowledge, this work achieves the best average noise performance for silicon based mm-wave broadband LNA designs (fractional bandwidth up to 90%). This LNA also enables a mm-wave front-end system integrated in a low cost silicon based technology for K band and future 5G communication systems.

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