Step Gain Amplifier with impedance unchanged in gain control

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Abstract —**A novel gain control method without impedance alternation in a gain control action has been developed. The method was based on the traditional current switch gain control scheme. A low gain mode has not only a DC feed-through as in the conventional method but also an RF feed-through with an RC network and a common-base transistor. An implemented differential Low Noise Amplifier exhibited the complete suppression of the impedance alternation effect. The details of the circuit topology are presented in this paper.**

INTRODUCTION

Low Noise Amplifiers (LNAs), which constitute the front-end (F/E) of mobile communication systems, should have at least 15dB power gain to suppress the noise characteristic for the latter stages. However, when the signals with about −30 dBm, the standard specification of usual communication systems, are amplified by such high gain LNAs, the output of the LNAs exceed the input dynamic range of the following mixer. This would then result in undesired distortion of the mixer output, i.e. inter-modulation. Therefore, in the cellular phone requiring high sensitivity, a variable gain control function should be given to the LNA. At the time of a weak input, the LNA is set at a high gain mode to achieve the required high sensitivity, while at the time of a strong input the LNA is set at a low gain mode in order to keep the signal within the input dynamic range of the following mixer.

Fig. 1 shows the schematic of the conventional current switch gain control amplifier [1]. The emitters of the two common-base transistors Q2 and Q3 are connected to the transconductance stage, which consists of the common-emitter transistor Q1. The collector of Q3 is connected to Vcc, while the collector of Q2 is connected to a load and gives the RF output. The current determined by the transconductance stage flows into the transistor Q2 or Q3. Q2 and Q3 are switched by the base bias and one of the transistors with a higher base bias voltage is turned on. If Q2 turns on, the current switch gain control amplifier acts as an usual cascode amplifier and has a high gain, while if Q3 turns on most RF power is thrown away into Vcc through Q3 and it leaks only the little power set by the isolation characteristic of Q2 to the output. Thus, the variable gain function is realized by switching Q2 and Q3.

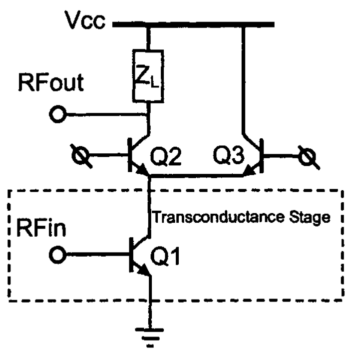

Fig. 1. The schematic shows the conventional current switch gain control amplifier.

However, this traditional gain control method has a disadvantage of alternation of the LNA output impedance due to the switching action of the gain control itself. Such impedance alternation or "impedance hopping (IH)" necessitates the corresponding change of the matching state of the mixer of the F/E block, which affects the noise figure and the F/E gain. In addition, stability of the F/E mixer would be significantly affected by this matching-state alternation, in the worst case, possibility resulting in mixer oscillation.

In this work, we present a novel method to suppress such impedance-hopping (IH) effect in the gain control action of a LNA. We introduce an additional transistor, Q4, of which base node is synchronously controlled with Q3 base node in parallel with the common-base transistor, Q1, of the cascode circuit of the LNA. We also insert a feedback resistor at the emitter node of Q4. With this configuration, the noise figure (NF) of 1.6 dB and the input third order intercept point (IIP3) of -4.5 dBm were achieved at 2GHz with 10 mA current flows in a differential LNA.

II. METHOD OF SUPPRESSING IMPEDANCE-HOPPING

Figure 3 shows the schematic of the present method of impedance-hopping suppression. The new circuit has an additional current path to the traditional one. The added current path consists of a resistor R_{Q4} and a common-base transistor Q4. The same base bias of Q4 is identical to that of Q3, and the gain control is realized by switching the height of the base bias of VB_{Q2} and $VB_{Q3,4}$. Although the LNA with the new gain control method works as a usual cascode amplifier when Q2 is turned on, when Q3 and Q4 are turned on, some current determined by Q1 flows into Q3 and Q4.

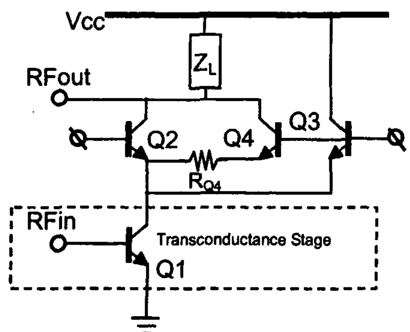

Fig. 3. The schematic shows the step gain amplifier that improves an impedance-hopping characteristic of the conventional current switch gain control amplifier.

The emitter potential of Q4 is determined by the voltage feedback of the R_{Q4}. Therefore, the transconductance of the common-base transistor Q4 can set by R_{Q4}. It means that although, with the conventional current switch amplifier, it is difficult to freely give the gain that a communication system requires in low gain mode, the developed amplifier can easily control a gain by R_{Q4}

TABLE I
5GHZ SIMULATION RESULTS

R_{Q4} [ohms]	Modes	Nfmin [dB]	MAG [dB]
50	High Gain	2.2	21.9
	Low Gain	9.5	-0.9
100	High Gain	2.1	22.0
	Low Gain	13.7	-7.3
200	High Gain	2.1	22.1
	Low Gain	20.0	-15.0

Table I shows the summary of the simulation results for the current impedance-hopping free Low Noise Amplifier (IHF-LNA) in Fig. 3 with the various resistances of R_{Q4}. The simulation was conducted for 5GHz and the SPICE parameters were of the Matsushita SiGe BiCMOS process. The current that flows into Q1 was 5 mA and the load impedance was 1.7 nH. The table shows that the gain for the low gain mode can be set almost freely by the feedback resistance R_{Q4} which doesn't affect the noise figure in high gain mode. While in low gain mode, the noise figure deteriorates with the higher R_{Q4}. This feature that the noise figure in high gain mode does not depend on the feedback resistance value is quite important for the step gain amplifier when that is applied for a LNA.

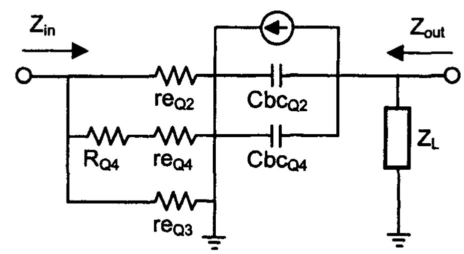

Fig. 4. The schematic shows an RF equivalent circuit for the step gain amplifier without transconductance stage.

Figure 4 shows the RF equivalent circuit of the amplifier shown in Fig. 3, which doesn't include the transconductance stage. The circuit consists of the feedback resistance R_{Q4}, the set of the emitter resistors (re_{Q2}, re_{Q4} and re_{Q3}), the set of base-collector capacitors (Cbc_{Q2} and Cbc_{Q4}), the voltage controlled current source and the load resistance Z_L. The input and output are uncorrelated because the transistors Q2 and Q4 are configured as common-base. Therefore, the input impedance is determined by the emitter resistance set while the output impedance is determined by the base-collector capacitance set and the load impedance Z_L. It should be noted that the input impedance of the equivalent circuit of Fig. 4, Z_{in}, should be as low as possible in order to minimize the Miller effect of the above impedance Z_{in} on the input of the transconductance stage.

In the high gain mode, the input impedance is approximately determined by re_{Q2} because Q3 and Q4 are tuned off and the rest of the emitter resistances are high value. While in the low gain mode, R_{Q4}, re_{Q4} and re_{Q3} affect the input impedance because Q2 turns off and re_{Q2} is high value. When a sufficiently high current flows into Q3, the sum of R_{Q4} and re_{Q4} are negligible because re_{Q3} is low. As a result, in the high gain mode, Z_{in} is characterized by re_{Q2}, while, in the low gain mode, it is represented by re_{Q3}. Therefore, in order to suppress the Miller effect on the input of the transconductance stage, Q1, we control the current flowing into Q1 high enough to achieve the required low value of re_{Q2} and re_{Q3}.

As the output impedance, the load impedance with Cbe_{Q2} and Cbe_{Q4} approximately decide that. If the transistors Q2 and Q4 have the same emitter size, the total junction capacitance remains constant regardless of the gain mode (high/low) of the LNA because the on-state Cbe_{Q2} and the off-state Cbe_{Q4} are equal to the off-state Cbe_{Q2} and the on-state Cbe_{Q4}. Thus, the desired feature of the circuit, i.e. impedance-hopping free (suppressed) has been realized.

III. IMPLEMENTATION FOR LNA

The developed gain control method was implemented in a differential type LNA for 2GHz and 5GHz bands. The Matsushita 0.25µm SiGe BiCMOS process was used for LNA design, which offered the peak ft of 50GHz. Fig.5 shows the schematic of the implemented IHF-LNA for 5GHz band. The LNA was designed for the power supply voltage of 3V and the consumption currents were 10mA for 2GHz and 13mA for 5GHz. The emitters of Q1 and Q2 are directly connected to obtain a sufficient gain for the 5GHz LNA while the 2GHz LNA has spiral inductors (not shown in the figure) connected to each emitter of Q1 and Q2 for degeneration.

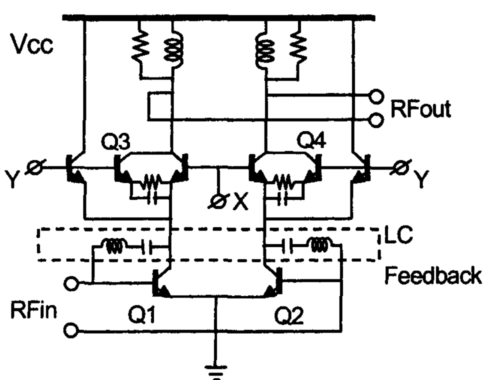

Fig. 5. The schematic shows an implemented differential Low Noise Amplifier for 5GHz band with the developed gain control function.

Although, for the 5GHz LNA, simultaneously matching cannot be achieved without the emitter degeneration technique, it was realized by the series LC networks acting as a neutralization or feedback between the collector and the base of Q1 (and Q2).

The collector loads comprised of RL parallel networks were used for realizing high stability and high gain. RC parallel networks were used for the controllability of the gain in low gain mode. Although only a resistor could suppress the gain as can be seen in the Table I, a strong dependence on the resistance was observed especially in a low value regime of R_{Q4} in Fig. 1, resulting in poor gain controllability. Since the RC networks allow RF power to leak through the capacitor, the dependence of the gain on the resistance in the RC networks can be reduced.

In the implemented amplifier, the gain was controlled by switching the statuses of X and Y nodes: X high/ Y low in the high gain mode and X low/ Y high in the low gain mode.

A die photograph is shown in Fig. 6. In order not to collapse the differential signal, the careful symmetric layout was employed. The die size was 0.9X1.7 mm^2.

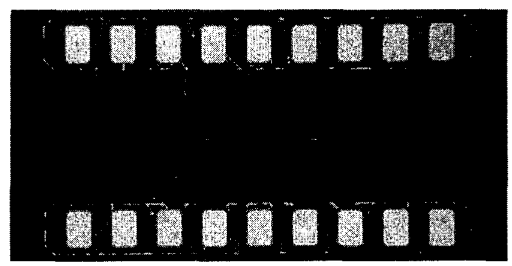

Fig. 6. The die photograph of the differential LNA with the step gain control function is shown.

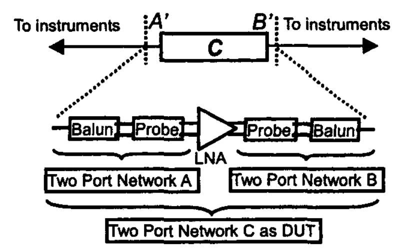

Fig. 7. The configuration of the measurement system is shown for the implemented differential LNA.

We investigated the impedances of the high gain and the low gain states as well as the noise figure and the two-tone intermodulation characteristics of the implemented LNAs.

The measurements were carried out by an on-wafer measurement system as shown in Fig 7. We used two GSGSG RF probes and two baluns in order to transform the differential input and output into those with single ends. The conventional single end measurements were conducted on the reference planes A' and B' and after that the additional components for transformation were de-embedded.

TABLE II

DIFFERENTIAL LNA MEASUREMENT RESULTS

Bands	Modes	NF [dB]	Gain [dB]	IIP3 [dB]
2GHz	High	1.6	14	-4.5
	Low	12	-4	-2
5GHz	High	3.2	14.3	-2
	Low	4.2	6.3	-8

Table II shows the results of the measurements for the implemented LNAs. It shows that the 2GHz band LNA achieves about 18 dB gain difference between high gain and low gain modes with 1.6 dB of NF and –4.5dBm of IIP3 in the high gain mode. Unfortunately, in the 5GHz band LNA sufficient gain difference cannot be observed. The reason for the insufficient results of 5GHz band LNA is now under investigation. However, a dynamic improvement in suppressing IH was confirmed with both 2GHz and 5GHz LNAs, as follows.

Figures 8a and 8b show the input and output IH characteristics in the gain control action for the 2GHz and 5GHz band LNAs, respectively. Markers show the two impedance states of the high and low gain modes for input and output impedances, respectively. In Fig. 8a the makers point 2GHz impedances and in Fig. 8b the makers point 5GHz impedances. As can be seen in Fig. 8a, the impedance difference between the two states cannot be distinguished, i.e. IH in the gain control is completely eliminated. Although such complete elimination of the IH effect could not be achieved with the 5GHz band LNA, we infer this result would have an extrinsic origin such as a layout issue. Currently, investigation with an improved layout is under way.

However, it was found that with this novel method a gain control could be achieved without any impedance alternation at 2GHz band.

IV. CONCLUSION

A gain control method without impedance change was presented. The method is based on the conventional current switch gain control scheme. The low gain mode has not only a DC feed-through as in the conventional method but also an RF feed-through with an RC network and a common-base transistor. The base-emitter bias of the common-base transistor is choked by the resistance of the RC network. This specifies the gain in the low gain mode. The residual current is bypassed through the DC feed-through. The input impedances are stable upon the gain control action because the emitter resistances of the common-base transistors for both modes can be neglected by a sufficient high current that flows into these common-base transistors.

Also the output impedances in the both modes were insensitive to the gain control action because the total base-collector capacitances of both modes are the same due to the identical emitter sizes of the common-base transistors connected to the output. Significant suppression of the IH effect was obtained with both 2GHz and 5GHz LNAs. Especially with the former, complete elimination of the IH was achieved.

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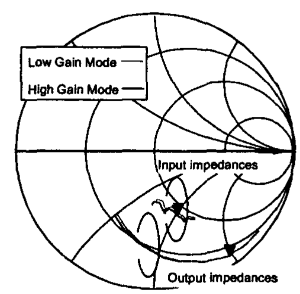
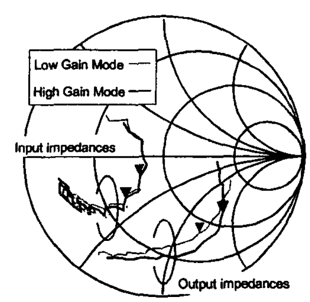


freq (1.500GHz to 3.000GHz)

(a)



freq (4.000GHz to 8.000GHz)

(b)

Fig. 8. Smith charts are shown for the input and output impedances in the High and Low gain modes.