A 1.4-dB-NF Variable-Gain LNA with Continuous Control for 2-GHz-band Mobile Phones Using InGaP Emitter HBTs

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Abstract — **We designed a continuously variable-gain low-noise-amplifier (VG-LNA) circuit with a noise figure (NF) of 1.4 dB. This VG-LNA has a diode-loaded emitter follower and a variable-current source. The diode-loaded emitter follower enables gain control without NF degradation at the maximum gain; the variable-current source improves the linearity and widens the range of gain control. It was fabricated by using InGaP-emitter hetero bipolar transistors (HBTs) and has an NF of 1.4 dB at maximum gain, 1.95 GHz, and a 3-V supply voltage. Its maximum gain is 15 dB, its input 3rd-order-intercept-point (IIP3) at the maximum gain is 3.4 dBm, and the gain-control range is 40 dB. The obtained of NF of 1.4 dB is the lowest so far reported for a continuously controlled VG-LNA.**

I. Introduction

To be able to provide Internet access from anywhere, mobile phones must be able to support high-bit-rate data communication at over 1 Mbps. The receivers of such mobile phones should have a wide dynamic range to ensure a sufficient bit-error rate for weak signals. To ensure such a wide dynamic range, Noise figure (NF) should be low and input 3rd-order-intercept-point (IIP3) should be high. However, NF and IIP3 are restricted by transistor performance. One promising way to widen the dynamic range is to build a variable-gain mechanism into the low noise amplifier (LNA). This enhances the IIP3 by decreasing the gain at a high input-power level. A continuous gain control is also required in order to obtain the optimum IIP3 for any input-power level.

Several types of variable-gain LNAs (VG-LNAs) have been developed. They include a step-control type that provides gain control by bypassing the LNA [1] and an LNA-VGA two-stage type that provides gain control through the VGA at the second stage [2]. However, none of these reported LNAs has a low NF, a high IIP3, and a continuously controlled gain at the same time.

Accordingly, we have developed a continuously controlled VG-LNA circuit that can operate with a variable gain in a single stage by minimizing NF degradation at the maximum-gain operation point. It also enables linear-gain control and a high IIP3 under small-gain operation. This VG-LNA was fabricated by using highly reliable InGaP HBTs, which have an excellent RF and noise performance, especially near the 50-Ω source impedance [3,4].

II. Gain-Control Circuit Concept

Figure 1 shows the design of the developed VG-LNA circuit. It has a diode-loaded emitter follower that enables gain control without NF degradation at the maximum-gain point. The emitter follower consists of an HBT (Q2) and a diode. The output end of the emitter follower is connected to another HBT (Q1) in the LNA core through a capacitor.

When gain is decreased, IIP3 can be increased. This is because the output IP3 (OIP3) of the VG-LNA does not change and IIP3 is defined as *OIP3 (dBm) – gain (dB)*. When gain-control voltage (V_{GC}) is increased, the output impedance of the diode-loaded emitter follower decreases. The input RF signal bypasses to the ground through this impedance, so the overall gain of the VG-LNA decreases without decreasing OIP3; consequently, IIP3 increases. This IIP3 increase in the small-gain region is one promising way to widen the dynamic-range.

At the maximum gain, the overall RF performance of the VG-LNA, in terms of gain and NF, is the same as the LNA-core performance. When V_{GC} is lower than the turn-on voltage of HBT Q2, the emitter follower is not active. Because HBT Q2 is cut off and there is no collector current, the diode is also cut off. As a result, there is no NF degradation at the maximum gain.

We compared the NF at the maximum gain of a VG-LNA using the proposed diode-loaded emitter follower with that of a VG-LNA using a conventional resistor-loaded emitter follower (Fig. 2). The minimum NF is 1.6 dB for a varying load resistance (R_E) because the maximum R_E is limited to 400 Ω by the 3-V supply voltage. We found that the NF decreases to 1.1 dB when the diode-loaded emitter follower was used.

To improve gain-control linearity and range, the designed LNA has an additional gain-control circuit that controls the base-bias of the HBT in the LNA core. Figure 3 shows the circuit schematic of this VG-LNA. The base-bias is controlled by a variable-current source consisting of HBT Q4 and resistor R3. The emitter follower for input bypassing consists of HBTs Q2 and Q3, where HBT Q3 acts as a diode by connecting the base to the collector.

The gain-control linearity was improved by using two reciprocal curves. The gain-control characteristics of input-bypassing are in the form of an upward convex curve. This is because the decrease in the output impedance of the emitter follower saturates to an emitter-parasitic resistance when the emitter-to-base voltage (V_{BE}) approaches the built-in potential. In contrast, the gain-control characteristics of the base-bias control are in the form of a downward convex curve because the HBT gain increases exponentially when V_{BE} increases. Consequently, the combination of the two gain-control methods improves the linearity of the gain-control characteristics because the upward convex curve and the downward convex curve are canceled out. This combination can also widen the gain-control range.

To enable single-terminal gain control, the emitter-follower output is connected directly to the base of HBT Q4. And to reverse the direction of the gain variation depending on the control voltage, an inverter HBT (Q1) is used.

III. Circuit Description

By optimizing resistors R3, R4, R5, and R6, we designed two kinds of VG-LNA, type A and type B, for 2-GHz-band mobile phones with a 3-V supply voltage. Type A was designed to increase the IIP3 in the low-gain operation region, whereas type B was designed to widen the gain-control range.

In simulation, the NF of the type-A VG-LNA was 1.35 dB and that of type B was 1.2 dB at 1.95 GHz.

Figure 4 shows the simulated gain, IIP3, OIP3, and current (I_{CC}) of the two VG-LNAs. The IIP3 of type A increases from 5 dBm at the maximum gain of 15 dB to over 10 dBm at the minimum gain of –5 dB. Type B has a wide gain-control range (40 dB) and an IIP3 of more than -2 dBm over the entire gain-control range.

IV. Measurement Results

We fabricated two VG-LNA chips by using highly reliable InGaP-emitter HBTs. These chips consist of SiN MIM capacitors, resistors with a base epitaxial layer, and two layers of Au wiring.

A photomicrograph of the type-B VG-LNA chip, measuring 0.6 x 0.7 mm, is shown in Fig. 5.

The chips were assembled into 2.0 x 1.25-mm 6-pin super mini-mold packages, which were then mounted on a printed wiring board with off-chip matching circuits, and tested. At the maximum gain of 15 dB, the NF is 1.4 dB. This is the lowest NF reported for continuously controlled VG-LNAs. Figure 6 shows the gain-control characteristics of the type-B VG-LNA at 1.95 GHz with a 3-V supply voltage. The gain-control range is 40 dB while the IIP3 remains over -2 dBm, and the current consumption is 12 mA at maximum gain.

V. Summary

We designed a VG-LNA circuit, with InGaP-emitter HBTs, for 2-GHz-band mobile phones. The circuit has a diode-loaded emitter follower and a variable-current source: the diode-loaded emitter follower enables gain control without NF degradation at the maximum gain; the variable-current source improves the linearity and widen the range of gain control. The fabricated VG-LNA had an NF of 1.4 dB at a maximum gain of 15 dB. Its gain-control range with an IIP3 of -2 dBm over the entire gain range is 40 dB. This is the lowest NF of an L-band continuously controlled VG-LNA with HBTs on GaAs so far reported. It is concluded that the developed VG-LNA be applied to 2-GHz-band mobile phones for high-bit-rate data-communication services.

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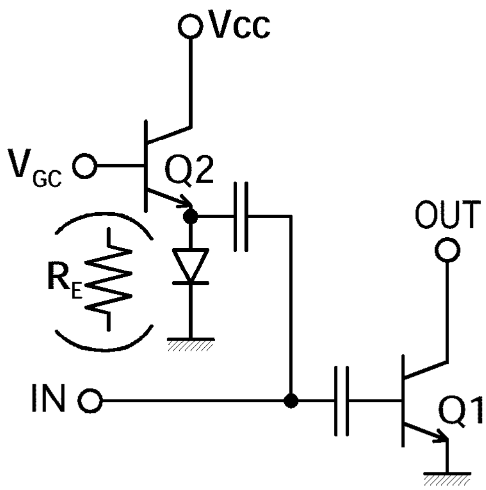


Fig. 1. VG-LNA circuit with input-bypassing by using a diode-loaded emitter follower.

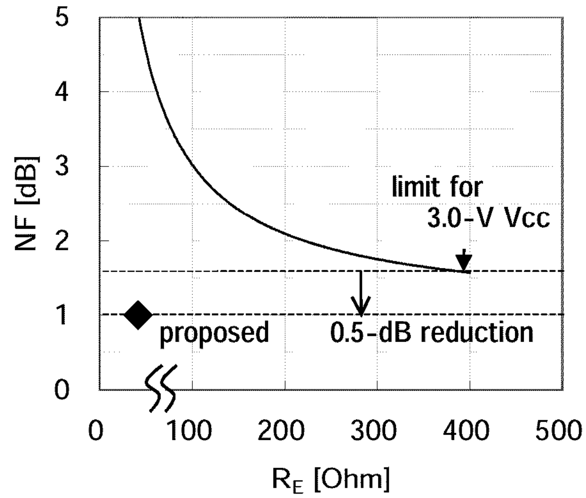


Fig. 2. NF at maximum gain in a VG-LNA with a diode-loaded emitter follower (developed) and a resistor-loaded emitter follower (conventional).

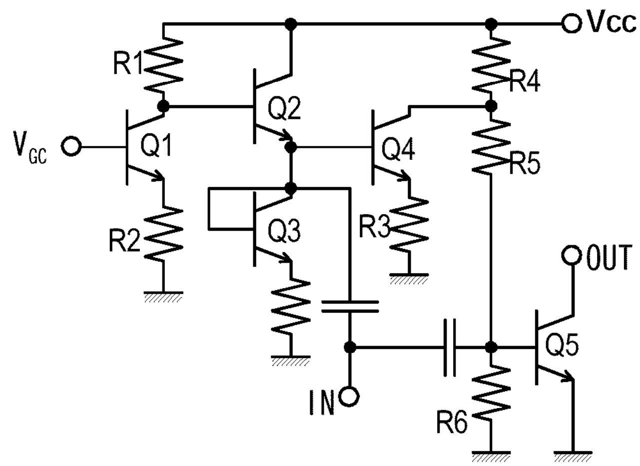
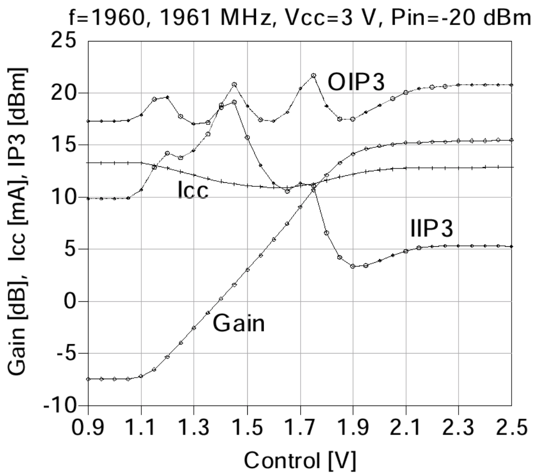
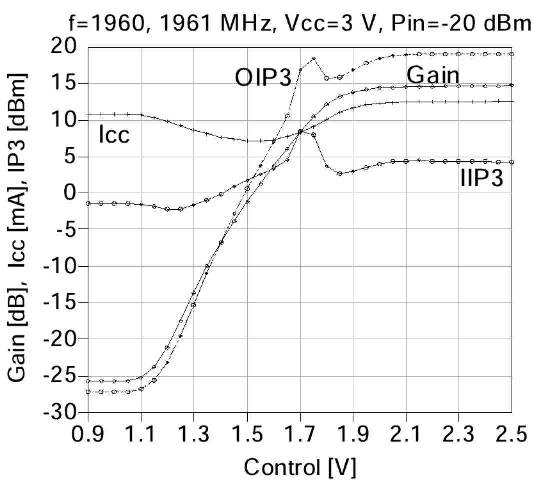


Fig. 3. Circuit schematic of a variable-gain LNA.



(a) Type A: High-IIP3 design



(b) Type B: Wide-gain-control-range design

Fig. 4. Simulated gain, IIP3, OIP3, and I_{CC} of designed VG-LNA.

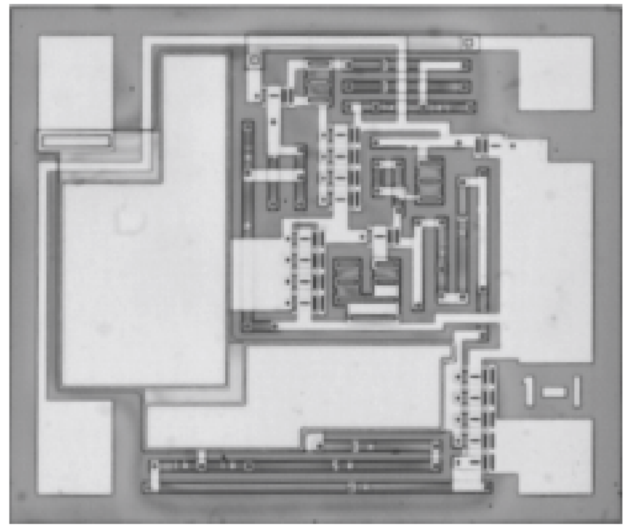


Fig. 5. Chip photomicrograph of designed VG-LNA (0.6 x 0.7 mm).

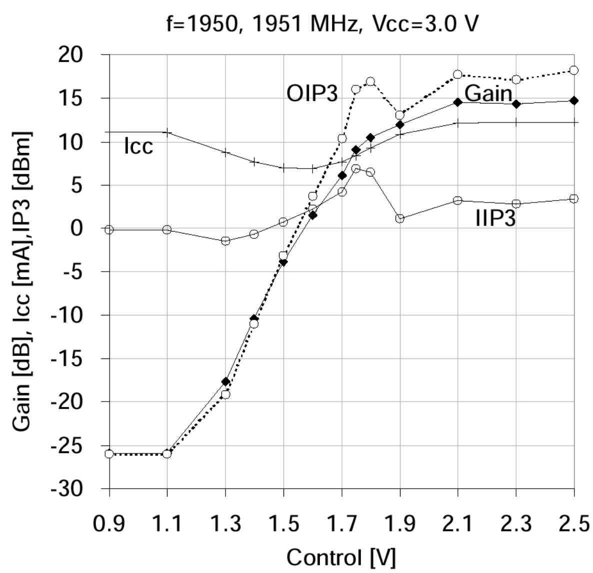


Fig. 6. Measured gain, IIP3, OIP3, and I_{CC} of fabricated VG-LNA (type B).