A Millimeter-Wave Linear Low Noise Amplifier in SiGe HBT Technology with Substrate Parasitic Model

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***Abstract* — This paper outlines the design and implementation of a monolithic millimeter-wave low noise amplifier (LNA) fabricated in a 200 GHz SiGe HBT technology. A simple analytical model of electromagnetic and substrate parasitic effects inherent at millimeter-wave frequencies is also included. A measured gain of 13.3 dB at 45 GHz, with an associated 3 dB bandwidth of 6.7 GHz, is exhibited by the LNA, along with a noise figure of 4.5 dB. The LNA provides linear performance with an IIP_3 of −8 dBm and it dissipates 18 mW.**

I. INTRODUCTION

Silicon-germanium (SiGe) technology has emerged as a strong contender in the field of very high frequency monolithic circuit design [1]. Circuit designers attempting to utilize the potential of SiGe HBT technologies must therefore face the difficulties associated with low resistivity silicon substrates at millimeter wavelengths. Traditionally, the use of III-V processes in millimeter wave system design avoids substrate parasitic effects in large measure by using semi-insulating substrates. This is clearly not possible in Si-based technologies. Thus the increasing use of SiGe technologies in the mm-wave design space warrants a closer look at circuit design in conjunction with substrate effects, and is addressed in this paper using an LNA designed in state-of-the-art SiGe HBT technology.

The SiGe HBT technology is 100% Si compatible, and employs a novel, reduced thermal cycle, "raised extrinsic base" structure, and utilizes conventional deep and shallow trench isolation, an *in-situ* doped polysilicon emitter, and an unconditionally stable, 25% peak Ge, C-doped, graded UHV/CVD epitaxial SiGe base, all fabricated on an 8 Ωcm p-type Si substrate [1]. A peak f_T of 208 GHz (f_{max} = 285 GHz) for a 0.12 x 2.5 μm^2 geometry structure has been achieved.

This paper is divided into four sections. A brief description of the design of the 45 GHz LNA and parasitic model is presented in section II. In section III, a comparison between measured results and simulations including high frequency substrate effects are presented, followed by a summary.

II. LNA DESIGN

A. Circuit Design

The LNA was designed using a state-of-the-art 200 GHz SiGe HBT technology on a low resistivity substrate. This technology provides linear, wideband operation in the desired mm-wave region of the spectrum (40-60 GHz). The design employs a 2-stage topology with a common-emitter common-base cascode for the first stage. It functions as a monolithic amplifier with all matching components being realized by microstrip-like inductive elements [2]. The bias currents to the two stages are supplied by current sources designed on chip. Degeneration in the first stage is avoided since the associated parasitics might destabilize amplifier operation.

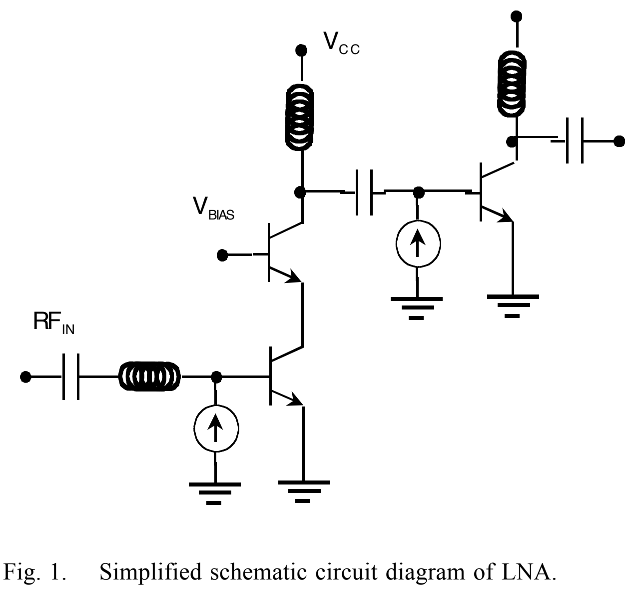

Fig. 1. Simplified schematic circuit diagram of LNA.

Fig. 1 shows a simplified schematic of the LNA, illustrating its topology. For clarity, distributed parasitic models and substrate impedances are not shown in this view. Such a configuration is chosen to provide optimum gain, along with linear unilateral operation.

B. Parasitic Model

Electromagnetic coupling between circuit components on chip is in most cases undesirable and difficult to predict. The methods used here may be employed to analytically determine performance and relieve the designer of the need to conceive of and design separate test structures [3]-[5] to measure and isolate these effects prior to actual circuit design. A major source of deviations from simulated behavior is the coupling to the substrate associated with device collector-to-substrate junctions and the accompanying coupling between devices through a low resistivity substrate. As an example, a collector-substrate junction in a SiGe HBT presents a strong possibility of feedback between the transistor output and input. This effect is remarkably enhanced in magnitude at mm-wave frequencies and thus problematic despite the usage of numerous substrate contacts [2].

An important consideration in the modeling of electromagnetic effects in the mm-wave regime is to approximate interconnects by distributed transmission line equivalents. When present in the load or degenerative circuitry of amplifiers, these may cause severe shifts in frequency of operation, reduction in gain, and potential instability. A simple but adequate distributed transmission line model using analytical expressions [6]-[8] is employed to represent the microstrip-like interconnects on chip. The equivalent models resulting from these had inductances and capacitances of the order of 10-30 pH and 10-20 fF respectively. At 50 GHz, passive elements of even such small magnitudes can alter circuit operation significantly.

Since the Si substrate is low resistivity (8-10 Ωcm), coupling between various nodes in the circuit is clearly possible. With an eye towards robustness, the entire substrate underlying the device components was represented as a mesh of resistors. The grid resistances were each of the order of 100 Ω. A minimum grid dimension of 60 μm was used in the mesh model. The length of the inductors used in the layout being comparable to the dimensions of the die, the parasitic capacitances to the device base-junction from either end was estimated to be significantly different from the other.

In the proximity of the substrate cutoff frequency given by

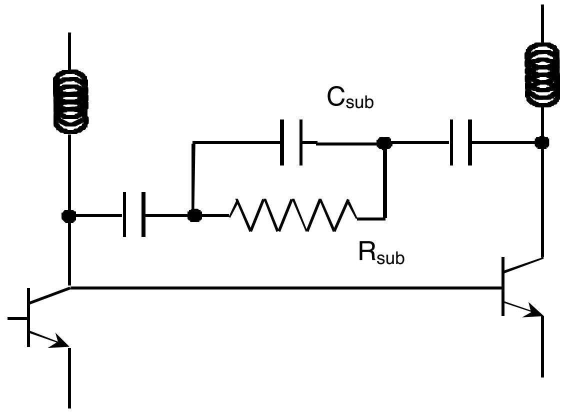

Fig. 2. An example of substrate induced feedback as incorporated in the LNA design.

$$\omega_c = \frac{2\pi}{\rho_{sub}\varepsilon_{sub}} \tag{1}$$

apart from resistances, capacitive effects must also be considered. Capacitances estimated were of the order of a few hundreds of fF. A typical example is shown in Fig. 2.

III. Results

Measured gain of the LNA is shown in Fig. 3 along with the simulation results in the presence and absence of our high-frequency coupling models. A large migration in the frequency response as a result of feedback and alteration of matching conditions due to the presence of substrate and electromagnetic effects can be clearly observed.

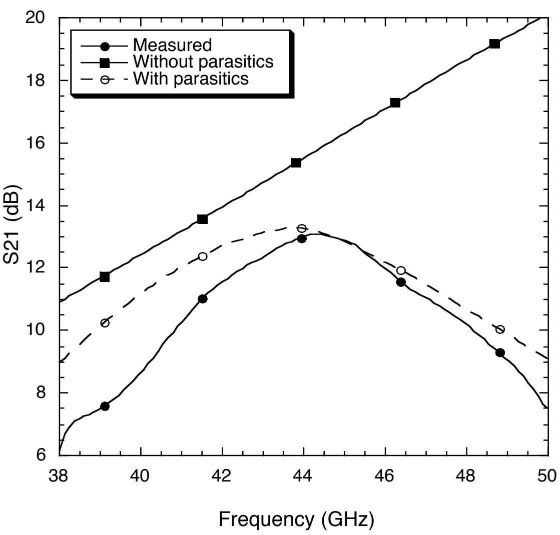

Fig. 3. Measured and simulated S_{21} of LNA.

Fig. 4 shows the return loss at either port of the LNA and compares measured results with simulations. Simulation curves for both the presence and absence of parasitic models are included in the graph. Parasitics have a deleterious effect on broadband noise, accounting for about 0.5 dB increase in noise figure. This is recorded in Fig. 5. Linearity measurements performed on the amplifier revealed a 1dB compression point of –17.5 dBm as shown in Fig. 6. The associated IIP_3 of the LNA is –8 dBm. The circuit operates from a supply voltage of 1.9V and consumes 9.5 mA current.

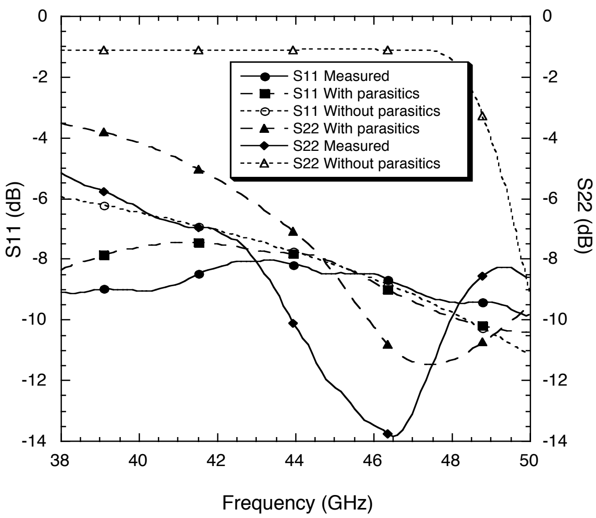

Fig. 4. Measured and simulated (with and without parasitics) return losses at the ports of the LNA.

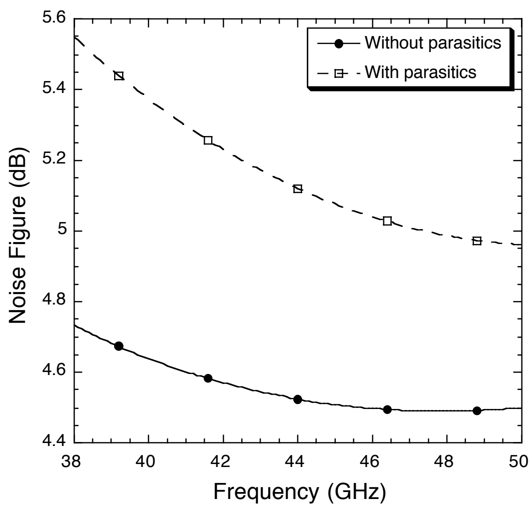

Fig. 5. Broadband noise of the LNA.

A die photograph of the LNA is shown in Fig. 7. The die occupies 625 μm x 480 μm.

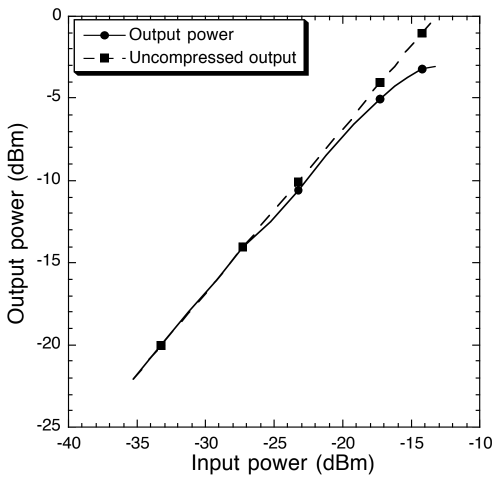

Fig. 6. 1-dB compression point of the LNA.

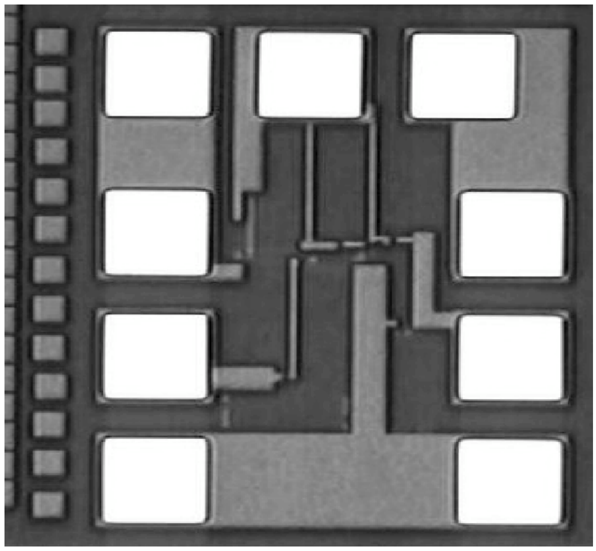

Fig. 7. Microphotograph of the LNA.

IV. CONCLUSION

The design and measurement of a 45 GHz monolithic linear LNA in 200 GHz SiGe HBT technology has been presented. A simple, yet adequate model of substrate coupling and distributed effects in the design of monolithic millimeter wave circuits on low resistivity substrates has been demonstrated. Correlation between the measured results and simulations based on parasitic effects serves as an illustration of the principles presented, and should help enable designers to achieve successful first-pass designs of monolithic circuits at mm-wave frequencies on low resistivity substrates.

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