A Broadband Indirect-Feedback Power-to-Current LNA

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***Abstract*—A dual-loop resistive-feedback power-to-current amplifier circuit to be implemented in SiGe or GaAs IC technology is presented. Simulation results indicate that any technology process with NFmin < 0.3 dB and f_T> 20 GHz is able to achieve an overall noise figure less than 0.5 dB, an input return loss less than -15 dB and flat gain over a frequency range from 0.6 GHz to 1.6 GHz.**

I. INTRODUCTION

The Netherlands Foundation for Research in Astronomy (NFRA) is currently developing a new radio telescope, the Square Kilometer Array (SKA), which is 100 times as sensitive as the best telescopes up to now [1]. High sensitivity is obtained by increasing the collecting area to approximately one square kilometer and a low noise temperature of the entire receiver chain. This requires better low noise amplifiers (LNAs) than currently available. Compared to LNAs that are employed in, e.g., cell phones, wireless LANs and other radio-astronomy applications, their noise figure and noise temperature must be lower (approximately 0.5 dB and 35 K, respectively) and remain low over the entire frequency band from 0.6 GHz to 1.6 GHz, in the presence of a complex source (antenna) impedance that varies with frequency. As a huge number of such amplifiers will be required for SKA, on chip design and realization will significantly reduce the overall cost of the system.

To realize the LNA on a chip for the desired RF frequency range, a negative feedback amplifier is preferred. Of the 16 possible negative-feedback amplifier topologies, we choose a dual-loop power-to-current (P-I) amplifier, since it offers a well defined input impedance [2] that can be properly matched to the source, being an antenna. Direct feedback topologies require a transformer to extract the output quantity. However, when a physical transformer is present in the feedback loop, non-idealities of the transformer will deteriorate the performance (especially noise) of the amplifier [3]. In this paper, we propose a resistive indirect-feedback power-to-current amplifier (here referred to as RPIA), which is able to achieve good power matching, flat gain and low noise over a wide bandwidth. Section II introduces the circuit diagram and operation of the RPIA. The influence of bond wires is analyzed in Section II. To mitigate their effect on the transfer function and the input impedance, frequency compensation is applied. Section IV deals with the noise and bandwidth performance of the RPIA. Simulation results are presented in Section V. Finally, Section VI presents the conclusions.

II. CIRCUIT DESIGN

Fig. 1 shows the circuit diagram of the RPIA, employing current-to current feedback (by R_1 and R_2) and series current-to-voltage feedback (by R_f). A SiGe HBT bipolar process has been assumed. Since both output terminals of the output stage (Q3 and Q4) are used for feedback, in order to extract the output signal, an indirect feedback output stage (Q5 and Q6) is introduced. In order to reduce the negative impact of the bond wires, which increase the input impedance, an inductor (L_1) in series with R_1 and a Miller capacitor (C_{miller}) at the second stage are applied. As the Miller capacitor will degrade the reverse isolation, a current follower is necessary to reduce this effect, resulting in a cascode for the first stage (Q1 and Q2). To accomplish proper biasing of the amplifier, overall current feedback, by means of R_b and R_{C4}, is employed. The bias collector resistor of the first stage (R_{C1}) is chosen large with respect to the noise resistance of the second stage.

III. INFLUENCE OF BOND WIRES

Without bond wires, the input impedance for the RPIA topology is defined by

$$Z_{in}(\omega) = R_f(R_1 + R_2) / R_1 = \alpha \cdot R_f\,, \tag{1}$$

while the signal transfer function is determined by

$$H(\omega) = I_O / V_S = 1/(2R_f)\,. \tag{2}$$

However, the bond wire (L_{bondwire}) in series with R_f will introduce a low frequency zero in the input impedance and a (phantom) zero in the loop gain of the amplifier. When we take the bond wire and its countermeasure L_1 into account, (1) changes to:

$$Z_{in}(\omega) = (R_f + j\omega L_{bondwire})(R_1 + R_2 + j\omega L_1)/(R_1 + j\omega L_1) \tag{3}$$

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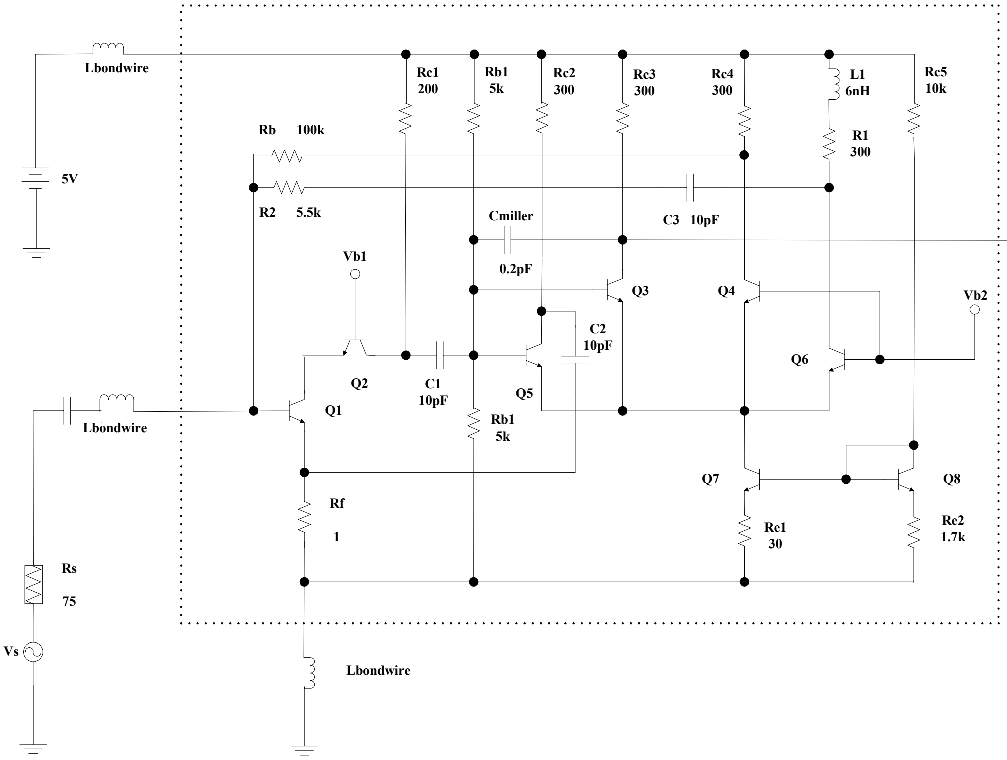

Figure 1. Circuit diagram of the RPIA

which contains a pole at $p1$=-R_1/L and two zeros at $n1$=-$R_f/L_{bondwire}$ and $n2$=-$(R_1+R_2)/L_1$, respectively, as shown in Fig. 2a. Fig. 2b shows the simulation result of the frequency response of Z_{in}, with the simulated S_{11} in Fig. 2c.

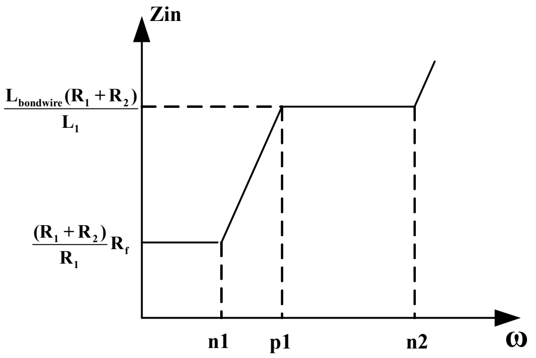

Figure 2a. Frequency response of the input impedance from analysis of the RPIA topology

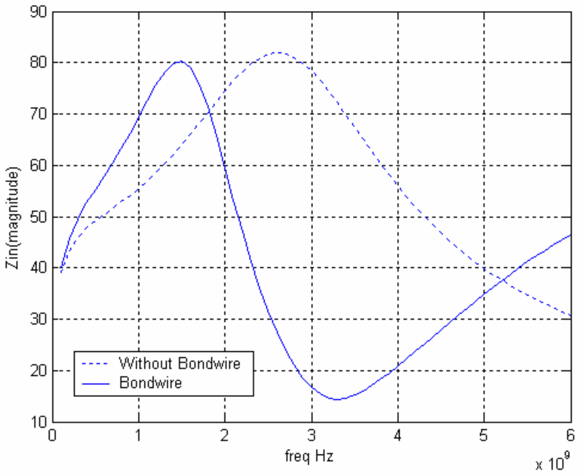

Figure 2b. Circuit simulation of the input impedance with and without bond wires

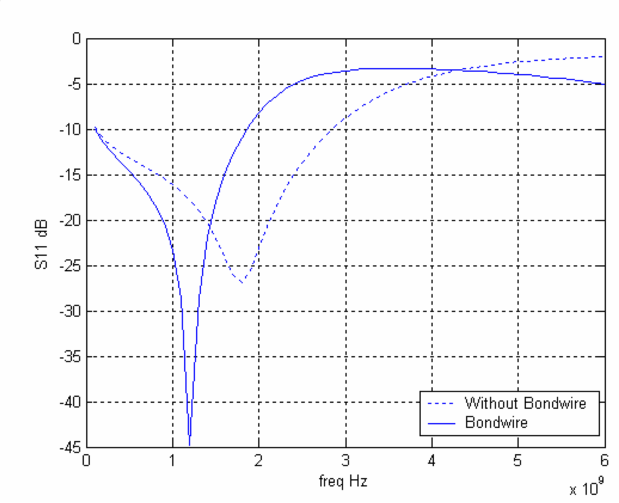

Figure 2c. Circuit simulation of S_{11} with and without bond wires

Including the bond wire the signal transfer function (2) becomes:

$$H(\omega)=\frac{R_1+R_2+j\omega L_1}{R_s(R_1+j\omega L_1)+(R_f+j\omega L_{bondwire})(R_1+R_2+j\omega L_1)} \tag{4}$$

As can be deduced from (4), L_1 and L_{bondwire} introduce a zero $n1$' and two poles $p1$' and $p2$', which is illustrated in Fig. 3a. Fig. 3b presents the simulation results for the frequency response of the signal transfer function and shows that the influence of the bondwire has been effectively reduced in the frequency band of interest by the introduction of L_1 and C_{miller}.

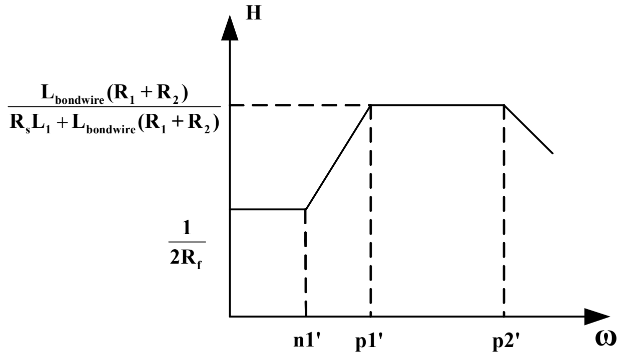

Figure 3a. Frequency response of the signal transfer function from analysis of the RPIA topology

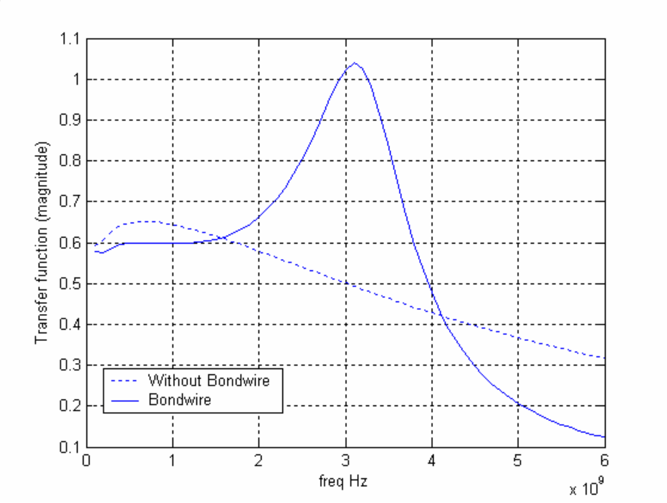

Figure 3b. Circuit simulation of the signal transfer with and without bond wires

IV. NOISE AND BANDWIDTH

The noise parameters of the RPIA, viz. its optimum source admittance $Y_{S,opt}$, the minimum noise factor $F_{\min}$ and the minimum noise resistance R_n, follow from taking into account the dominant noise sources, being the base current shot noise, the collector current shot noise, and the base resistance thermal noise of the input stage and the noise originating from the feedback network. After proper transformation of these noise sources to the input of the RPIA, the noise parameters become:

$$Y_{S,opt}\approx\frac{g_m(\sqrt{1+2g_m(R_f+R_B)}/\beta_f+jf/f_T)}{1+2g_m(R_f+R_B)}, \tag{5}$$

$$F_{\min}\approx 1+\frac{\sqrt{1+2g_m(R_f+R_B)}/\beta_f+(1/\beta_f+jf/f_T)R_B}{1+2g_m(R_f+R_B)} \tag{6}$$

and

$$R_n\approx 1/(2g_m)+R_f+R_B, \tag{7}$$

where R_B, g_m, β_f and f_T are the base resistance, transconductance factor, forward current gain and cut-off frequency of the SiGe HBT respectively [4]. Equations (5)-(7) indicate that a small R_B and R_f, and a relatively large collector current are optimal for good noise performance.

The bandwidth of the amplifier is determined by its loop-gain pole product and can be approximated by

$$BW \approx \sqrt{f_{T1} f_{T2} / \alpha} \tag{8}$$

where f_{T1} and f_{T2} are the transistor's cut-off frequency of the first stage and the second stage, respectively. For f_T = 30 GHz and α= 40, the bandwidth of the amplifier is about 4.7 GHz, which is large enough for this application. Equation (8) also defines $f_T > 20$ GHz for the RPIA.

V. SIMULATION RESULTS

Fig. 4 shows the noise figure of the proposed power-to-current amplifier. Using a SiGe HBT BiCMOS process, the circuit exhibits a NF<1.2 dB, S_{11}<-15 dB and gain>23 dB across the band, at a power consumption of 110 mW.

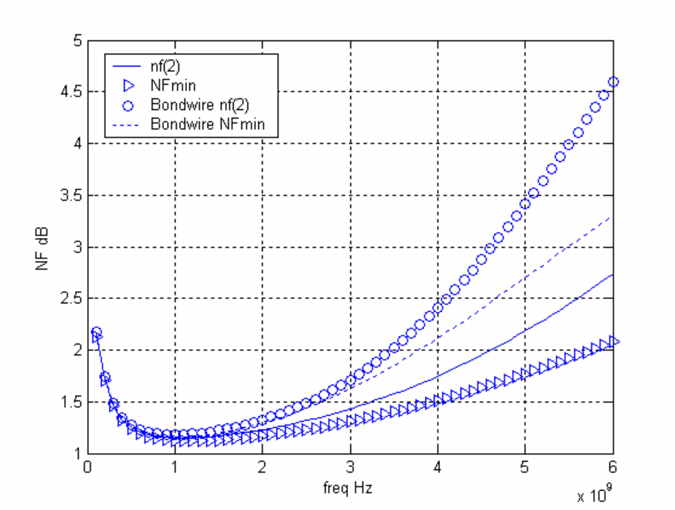

Figure 4. Circuit simulation results of the noise figure of the RPIA circuit, with and without bond wires

The noise contribution from of each circuit element is listed in Table 1, showing the dominance of the IC process. The noise analysis suggests that for any technology with NFmin<0.3dB, the RPIA may obtain an overall NF<0.5 dB.

Table 1. Noise contributions in the RPIA circuit

Elements	Equivalent noise voltage (pV)	Noise figure (dB)	Noise contribution (%)
The input stage (Q1, Q2)	225	0.7	64%
The output stage (Q3, Q4)	140	0.2	14%
Indirect feedback (Q5, Q6)	84	0.1	8%
Dual-loop feedback	79	0.1	6%
Biasing	100	0.1	8%
Total	251	1.2	100%

To demonstrate the validity of this conclusion, this circuit topology has, albeit with slightly modified bias circuitry, also been simulated with a 0.2 µm GaAs p-HEMT technology process (NFmin<0.2 dB and f_T >60 GHz). The circuit shows NF<0.46 dB, S_{11}<-18 dB and gain >17 dB, a power consumption of 290 mW (Table 2) and is unconditionally stable up to 30GHz.

Table 2. Performance of the RPIA circuit using SiGe HBT and GaAs pHEMT IC processes

Element	Specification				Simulation results	
	Min	Typ	Max	Unit	0.35µm SiGe	0.2µm GaAs
Power consumption			300	mW	110	290
Power gain (Signal transfer function)		20		dB	S21>23dB 0.6	S21>17dB 0.33
Noise figure			0.5	dB	1.2	0.46
Output IP2	15			dBm	18	15
Output IP3	5			dBm	5.7	7.4
Input reflection coefficient	-10			dB	< -15	< -18

VI. CONCLUSIONS

The indirect-resistive feedback power-to-current (RPIA) amplifier design shows good input power matching and noise performance over a wide bandwidth from 0.6 GHz to 1.6 GHz. In addition, its chip area is much smaller than of amplifiers that, e.g., use. transformer feedback. Performance results are presented, including the effect of bond wires. A noise contribution analysis suggests that any technology process with NFmin<0.3 dB and $f_T > 20$ GHz may result in an overall NF of 0.5~0.6 dB in the band of interest. This makes the RPIA topology a good candidate for the LNAs to be employed in the square kilometer antenna array.

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