Ultra-Wideband Low-Noise Amplifier Design Using Reactive Feedback

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Abstract— **The inherent ability of Ultra-Wideband (UWB) to resolve multi-path radio-wave propagation components makes it attractive for use in a Wireless Personal Area Network (WPAN). To harness the advantages of UWB in a WPAN, the transceiver circuitry will have to be low power and fabricated in a high-yield, silicon-based commercial process to maintain reasonable cost for end-user devices. In this paper, a broadband LNA simulated using in a commercial SiGe process operating in the range from 3-10.6GHz is presented. Reactive feedback [1] reduces excessive thermal noise and keep the noise figure below 3dB. An on-chip transformer stabilizes the gain to 16.6dB (within 1dB ripple) across the band, with a power consumption of 4mW from a 1V supply.**

Keywords— **Wideband Amplification, Low Noise Amplifier, Reactive Feedback, UWB Communiction.**

I. INTRODUCTION

The input signal of an UWB Low Noise Amplifier (LNA) can be characterized by Gaussian mono-cycle pulses (or derivatives), thereby emphasizing a tighter constraint for group delay and a greater demand for frequency compensated input matching networks (IMN) [1]. Such a broadband amplifier could also be used for multi-carrier OFDM applications. Aside from the apparent difficulty in achieving low-loss lumped components for an UWB IMN, on-chip capacitors have an approximate +/-10% tolerance, which adversely affects characteristics including group delay and introducing mismatch for both gain and noise [2]. Uniformity in phase as well as gain in the band of interest suppresses group delay.

There is an array of design topologies for the realization of broadband amplifiers. Each topology has limitations such as power consumption, frequency range as well as gain and noise. The UWB architecture poses unique implementation challenges for the proposed system specifications as listed in Table I.

TABLE I
UWB LNA SPECIFICATIONS

Parameter	Target Specification	SiGe HBT UWB LNA Results [3]
Gain (S21)	16dB	21dB
Noise Figure	<3dB	∈ [2.5dB, 4.5dB]
Group Delay	+/-10ps	N/A
IIP3	-5dBm	-5.5dBm
Power Consumption	4mW (at 1V)	27mW (at 2.7V)

A design using reactive feedback can overcome some of these difficulties, providing moderate gain and low noise, over the specified band (3GHz-10.6GHz), complete with a $50\,\Omega$ input match for maximum power transfer. The amplifier topology presented in this paper also maintains high linearity while dissipating just 4mA from a 1V supply.

II. BROADBAND AMPLIFIER TOPOLOGY

Three broadband topologies such as: distributed traveling wave amplifier (TWA), resistive feedback amplifier (RFA), or a reactive feedback amplifier (XFA) are compared in Table II.

TABLE II
BROADBAND AMPLIFIER TECHNIQUES

Topology	Advantages	Disadvantages
TWA	Wide Bandwidth, Group Delay	Power Consumption, Chip Area
RFA	Stability Enhancement	Noise Figure
XFA	Power Consumption, Linearity	Chip Area (Still Less Than TWA)

Reactive feedback does not add thermal noise and provides an increase in linearity in narrowband designs [1]. For broadband amplifiers, this effect is further pronounced as broadband amplifiers attain higher noise figures than their narrow-band counterparts. A traveling wave configuration is far superior to both the resistive and reactive feedback counterparts in terms of bandwidth. However, with large power consumption and a nominal noise figure > 3dB due to multiple devices and distributed passives, it is not suitable for an UWB LNA.

A. The LNA Topology

The LNA topology presented for a potential UWB application is illustrated in Fig. 1. The reactive feedback network includes a current-current transformer, which above all, allows for a high impedance output node unlike its voltage-voltage counterpart [4].

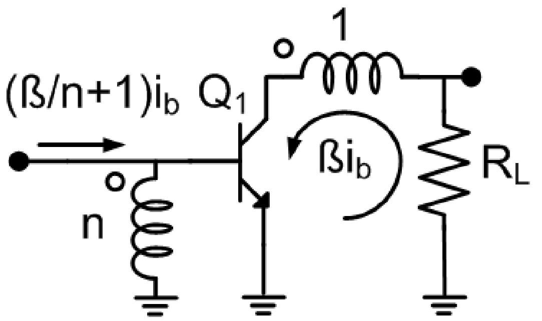

Fig. 1. LNA Configuration Including Current-Current Transformer Feedback.

Modeling the transformer for an input match of approximately 50Ω is a formidable task for any broadband application. The absence of a resonant IMN ensures that the noise figure has the potential to remain constant over the band, if the noise figure of the device is nearly constant. Assuming an ideal transformer, the input impedance of the LNA can be approximated as:

$$Zin \simeq r\pi \,//\, C\pi \,//\, \frac{n}{gm}\frac{(1+sR_L C_\mu)}{(1+sn^2 gmR_L C_\mu)} \qquad (1)$$

In this ideal case, $\Re\{Zin\}$ is dominated by the (n/gm) term. Furthermore, the broadband input match is attained by setting turns ratio (n) sufficiently large. In effect, the ratio (β/n) should be large. The turns ratio is limited by the chip area of a monolithic transformer as well as the parasitics that it will present to the circuit. The capacitive parasitics to the substrate degrade the noise figure and linearity as well as the gain-bandwidth product [5]. One technique that overcomes this problem is to design the non-ideal transformer with a low coupling (k) coefficient while making the self-inductance ratio between the secondary and the primary windings very high. Intrinsically, this will satisfy the requirement for a high effective turns ratio (n'), which is related by:

$$n' \equiv {}^{n}\!/_{k} \qquad (2)$$

A counterpoint to this technique is the difficulty in achieving a low coupling factor.

On-chip transformers are susceptible to coupling from other IC components. Thus, weakly coupled transformers are more prone to interferers than highly coupled transformers. In addition, a large (n') value corresponds to an even greater inductance ratio as:

$$n' \propto \sqrt{\frac{Ls}{Lp}} \qquad (3)$$

A large ratio between the winding self-inductances creates a geometric bottleneck in terms transformer layout. If the turns ratio required is too large, an overlay configuration may be the only viable geometry. Although, the overlap design reduces on-chip area, it is more sensitive to perturbations in the substrate (i.e., crosstalk, eddy-currents)[5].

An auxiliary to yielding a high effective turns ratio while maintaining a high coupling coefficient is to add self-coupled leakage inductance to one of the windings. From the perspective of the compact transformer model [6], this design entails the same electrical transfer characteristics as a weakly coupled transformer with winding inductances that are closer in value, and hence, area. A small-signal model including first-order parasitics of the transformer and device is depicted in Fig. 2.

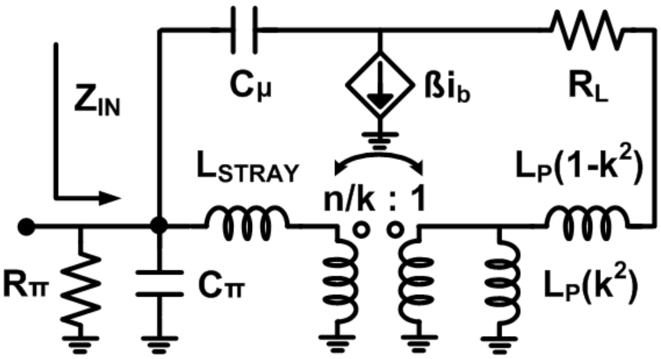

Fig. 2. Simplified Small-Signal LNA Model.

Modeling the transformer given a 4mA bias current and a device size of $6.4\,\mu m^2$ yields the input matching results as seen in Fig 3. At 3GHz the input impedance is $45 + j3\,\Omega$, while at 10.6GHz, it is $38.3 - j9\,\Omega$. Thus, the insertion loss for the circuit lies within the range of [0.01dB, 0.12dB].

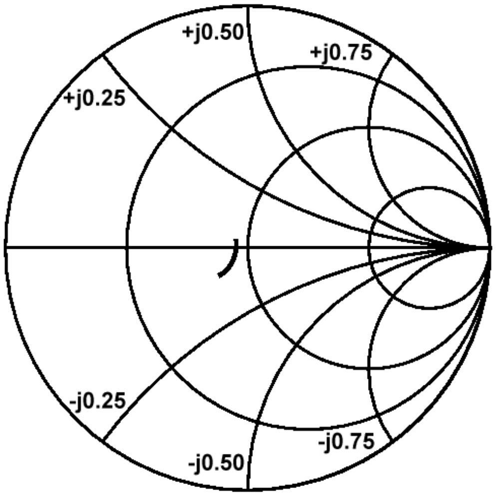

Fig. 3. Input Impedance Match (3GHz < f < 10.6GHz).

The noise sources in the transistor are not diminished through reactive feedback. However the contributions of the noise sources in the feedback network can be minimized [4].

To realize a suitable noise figure while sustaining adequate gain for the LNA, the device is biased between optimum noise and f_T points. With the bias current already chosen, the lone variable is the device area. A double base contact is incorporated to reduce the base resistance of the device. The results for both gain and noise figure are illustrated in Fig. 4.

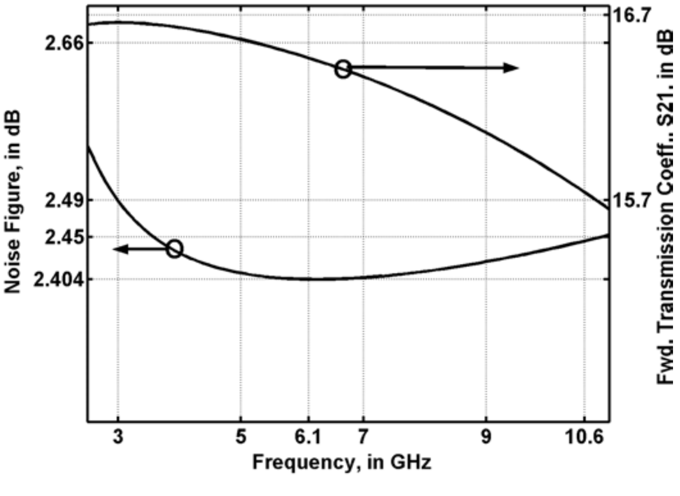

Fig. 4. Noise Figure, Transducer Gain vs. Frequency.

As seen in Fig. 4., the gain of the circuit (S21) peaks at 16.6dB and stays within 1dB throughout the operational band. Also, the noise figure peaks at the lower end of the band at 2.49dB and swings to 2.45dB at the upper band. The noise figure sensitivity is greater at the lower end of the spectrum. Primarily, this is due to the operation of the transformer at lower frequencies. Namely, the transformer is producing less mutual flux linkage and mutual inductance at the lower frequencies. The amplifier has negligible reactive feedback, and operates as a common-emitter amplifier with high input impedance. The reduction in transducer gain is attributed to feed-forward via $C\mu$, as well as the attenuation due to $C\pi$.

Another figure of merit for any LNA is its linearity. The input third-order intercept point (IIP_3) of the amplifier is a measure of the amount of power that the input can withstand before producing equal amounts of power at both the fundamental and third order inter-modulation frequencies. Intuitively, the linearity of the amplifier should degrade with an increase in frequency. However, the effects are not so profound with transformer feedback, which aids in neutralization of the feed-forward path [1]. Results for the IIP3 at various frequencies within the band are shown in Fig. 5.

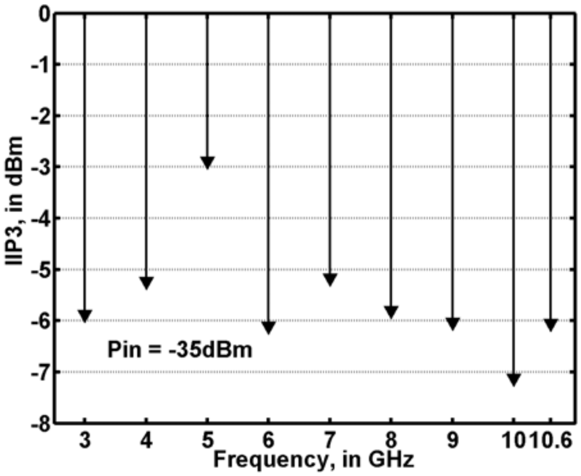

Fig. 5. IIP_3 vs. Frequency.

Fig.5. presents the degradation trend in linearity for frequencies above the center frequency. These values were obtained under a two-tone test at each point shown with a 10MHz spacing between adjacent frequencies.

The group delay measurement is paramount in broadband amplifier design. The consequences for an amplifier with non-linear group delay include phase distortion. Specific to the UWB amplifier, phase distortion is detrimental, as the signal is comprised of picosecond duration Gaussian monocycles pulses. Fig. 6. depicts the group delay of the LNA as well as the deviation from the group delay at the geometric center frequency (5.6GHz).

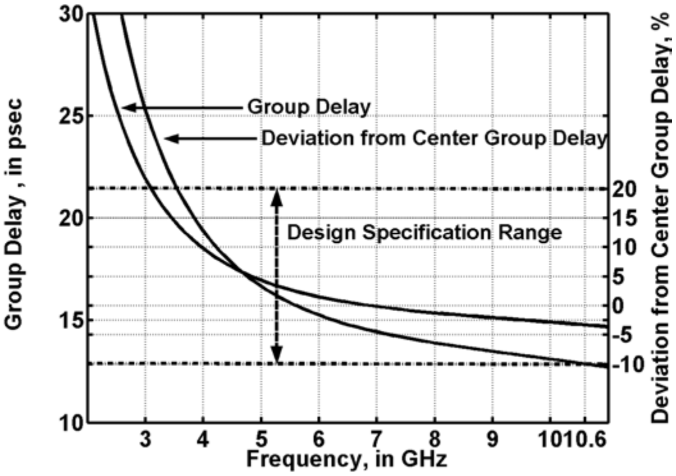

Fig. 6. Group Delay, Deviation from Center Group Delay vs. Frequency.

The group delay of the LNA is within 5% of the group delay at the center frequency from [5GHz, 10.6GHz]. Prior to 5GHz, the rate of change of the group delay is high and exponential; indicating that distortion may become apparent. Fig. 7. depicts the input and output time-domain signals for an applied Gaussian mono-cycle of approximately 130 psec in pulse width. Any measure of distortion due to non-linear group delay in the frequency domain would be revealed in the time-domain. The output waveform in Fig. 7. is amplified, inverted and illustrates a slight time-delayed response (~7 psec) relative to the input waveform as expected in a transistor amplifier circuit. However, the trough width of the output signal has slightly more breadth than that of the crest width indicating the (minimal) effects of distortion due to group delay.

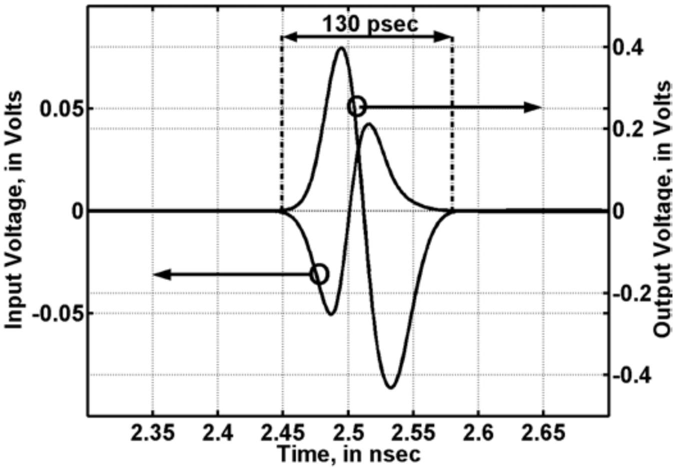

Fig. 7. Input, Output Voltage Waveforms vs. Time.

III. CONCLUSION

A reactive feedback SiGe bipolar is presented as a potential topology for future UWB applications. The transducer gain is simulated to be 16.6dB with < 1dB ripple across the frequency band while the noise figure was simulated to be 2.4dB with 0.1dB variation across the band. Reactive feedback is supplied by an on-chip current-current transformer and does not consume DC power. Total dissipation is 4mW from a 1V supply.

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