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AREA AND POWER OPTIMIZATION OF 802.15.4A UWB PULSE LOW NOISE AMPLIFIERS BY GENETIC ALGORITHMS

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Abstract—An Ultra Wide Band (UWB) Low Noise Amplifier (LNA) for 802.15.4a UWB PHY (physical layer) is proposed. The amplifier is designed using IHP Microelectronis CMOS 0.25 µm technology for lower price. The LNA area, power, and performance was optimized using the Genetic Algorithm (GA). The optimization goals included inductance values, power consumption, and performance in the frequency domain using S-parameters, then fine tuned in the time domain using the reference UWB pulses of the 802.15.4a standards. The LNA consumes around 10 mW excluding the output buffer stage, has a gain of 11 to 15 dB, a 1 dB compression point of −9 dBm, and five inductors with a total value around 10 nH.

1. INTRODUCTION

The motivation behind UWB is presented by the following argument. The capacity of a channel in terms of bit-rate is given by the Claude Shannon famous Eq. (1)

$$C = B\log_2\left(1 + \frac{S}{n_o B}\right) \tag{1}$$

where B is the bandwidth, n_o the noise power density, S the signal power, and C the maximum data rate of the channel. As indicated, the capacity increases as a log of the signal power, and linearly as bandwidth. Thus, UWB channels can support larger data rates for the same signal to noise ratio (SNR).

Several authors addressed UWB LNA in their work, but they mostly stressed constant gain over the entire frequency band of

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operation, power consumption, and noise figure (NF) [1–3]. In this paper, the author stresses chip area (mostly the inductor's area), as well as gain, power consumption, NF, and time-domain pulse response for the 802.15.4a UWB standards [4]. These standards specify operation from 3 GHz to 10 GHz, using around 500 or 1200 MHz channel bandwidth. This fact is exploited here to reduce chip area which is mainly composed from inductors. The gain only needs to be approximately constant over each channel band, and not over the 7 GHz UWB. Further gain can be provided by amplifier stages with higher NF.

The proposed LNA consists of an inductively degenerated cascode amplifier, with an all pass equalization section for the input, and a shunt peaking inductor and a resistor load, as shown in Figure 1. Design challenges were faced at the edge of the UWB around 10 GHz due to the relatively low unity current gain frequency of the 0.25 μm technology as compared to 0.18 μm or smaller channel length technologies.

2. UWB LNA DESCRIPTION

The cascode amplifier consists of a common source (CS) amplifier, M1, with a common gate (CG) as its load, M2. The CG amplifier has low

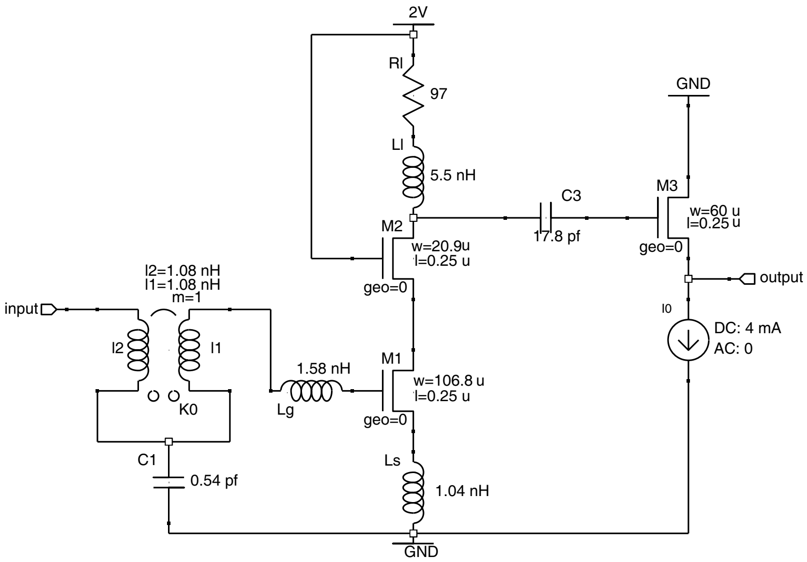

Figure 1. UWB cascode amplifier.

input impedance, thus it reduces the load impedance for the CS and thus reduces the Miller effect. Further reduction at high frequencies is countered by the shunt peaking inductor, L_l. The load resistor, R_l, is used to further flatten the gain over the UWB. The inductor at the source degenerates into a real impedance at the resonant frequency in case of a narrow band amplifier, or to a nonuniform complex impedance with a constant real part over the wideband, as given by Eq. (2).

$$Z_{\text{in}}(\omega) = \omega_T L_s + j\omega \left(L_s + L_g\right) + \frac{1}{j\omega C_{gs}} \tag{2}$$

with the unity gain radian frequency $\omega_T = g_m/C_{gs}$, the source inductor is set to

$$L_s = R_s C_{gs}/g_m \tag{3}$$

The voltage reflection coefficient is given by

$$\rho_v\left(\omega\right) = \frac{\left(Z_l - Z_s\right)}{\left(Z_l + Z_s\right)} \tag{4}$$

At resonance, the input impedance is real and equals the source impedance, and the reflection coefficient, as given by Eq. (4) is zero.

The real component of the impedance is constant, as given by Eq. (3), but the imaginary component is varying over the frequency band. Thus, a second order all pass equalization section is added at the amplifier input, consisting of the input matching network ($L_{\text{in}1}$, $L_{\text{in}2}$, C_1) to help in flattening the reflection coefficient over a wider band. However, the reflection coefficient can't be made exactly zero, and most authors assume a sufficient requirement that the return loss $S_{11} \leq 10\,\text{dB}$. This means that 99% of the incident power is consumed by the amplifier and thus amplified. For a LNA, the assumption is that the antenna impedance is constant and usually is $50\,\Omega$, which is close for the case for UWB antennas that are designed with the same assumption of $S_{11} \leq 10\,\text{dB}$.

The output buffer in the proposed LNA can represent the input stage of a mixer, or another amplifier for further gain. The design requirements for the 802.15.4a UWB standards can be further simplified by the fact that the selected channel is not changed during the transmission, thus simplifying the design. The work presented here utilizes this fact to reduce the chip area requirements of the LNA. The process is iterative. The Inductances are constrained not to exceed certain values, and further tuning, or inductance value constraints, are obtained after a minimization process. The final goals are not of a constant S_{21} over the UWB, but rather the distortion of the reference pulse for the channels of the LNA. This relaxes the requirements on the S-parameters, while it requires more effort for the transient response computations for the LNA, as discussed in Section 4.

For a simple input matching network, such as used here, the input impedance, or the reflection coefficient, can be easily expressed as a ratio of two polynomials, or poles and zeros [1,5]. While this can provide more insight into the process of flattening the variations of the impedance, it poses more work into the minimization of the inductor values.

The noise figure requirements pose more challenges. Since the optimum power reflection impedance is different than the minimum NF impedance, which requires some compromise in the design. The sources of noise are the CG load resistor, and the noise due to the transistors. The NF of a CS, input matched $R_s = R_{\text{in}}$, transistor amplifier is given by

$$F \geq 2 + \frac{4\gamma}{\alpha} \frac{1}{g_m Rs} \tag{5}$$

where γ, α are technology, frequency, and bias dependent parameters, taken here as $\gamma = 2$, $\alpha = 0.85$ [6]. Thus, the NF of a CS amplifier with optimal power is given by

$$F_{\min,p} \approx 1 + 2.4 \frac{\gamma}{\alpha} \frac{\omega}{\omega_T} \tag{6}$$

while the absolute minimum NF is given by

$$F_{\min} \approx 1 + 2.3 \frac{\omega}{\omega_T} \tag{7}$$

While a CG input amplifier has a more uniform real component impedance, it suffers from higher NF than a CS input stage. Thus, the choice of a cascode architecture of the LNA. Further noise reduction is accomplished by the Q-factor of the series resonant section at the CS input, composed from the equivalent gate capacitance C_{gs}, and the inductor L_g.

The source of the signal is assumed to be a wideband antenna with a constant impedance of 50 Ohms over the frequency band of operation. If the antenna impedance is not uniform, the LNA can be matched directly with the antenna as in [7].

3. LNA DESIGN PROCEDURE

Initial design is carried out as a narrow band LNA using the linear simple model of the NMOS transistors. Several procedures are available, including design of CS channel width for optimal NF [6], or optimal matching of input impedance [8]. Using the manufacturer's data of $\omega_T = 40\,\text{GHz}$, and designing for $\text{NF} = 3\,\text{dB}$, and a center frequency of $\omega_c = 7\,\text{GHz}$, we obtain the following values for the CS

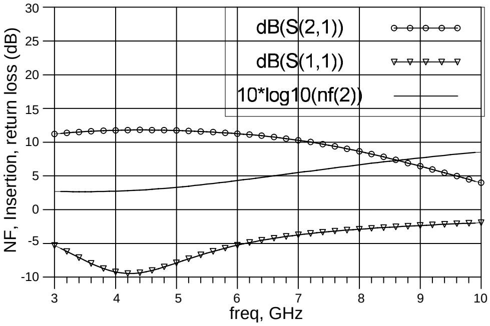

Figure 2. UWB cascode amplifier NF and S parameters before optimization.

Table 1. Design requirements.

Pulse distortion	cross correlation with reference pulse
Input impedance	$S_{11} < 9\,\mathrm{dB}$
Gain: S_{21}	$10 < S_{21} < 15\,\mathrm{dB}$
Power consumption	$P < 10\,\mathrm{mW}$
Inductors	$L < 10\,\mathrm{nH}$

amplifier: $L_s = 0.2\,\mathrm{nH}$, $L_g = 1.8\,\mathrm{nH}$, $W = 225\,\mu\mathrm{m}$. The power consumption is estimated as 20 mA, and the frequency response is shown in Figure 2. To broaden the bandwidth, an all pass section consisting of a coupled transformer with a capacitor at center is added. The final design is shown in Figure 1. Several goals are attempted as shown in Table 1. Other authors used numerical optimizations for UWB LNA amplifier design with good results [9].

The main goal is not the S_{11} or S_{21}, rather, the performance is the measure of the distortion of the reference pulse, as discussed in Section 4. The standards call for 15 channels with 499.2 MHz bandwidth except channels 4, 7, 11, and 15 with bandwidth around 1300 MHz [4], covering the range from 3.25 GHz to 10.25 GHz. Except for channel 0 which is centered at 499.2 MHz.

3.1. Optimizations

Several algorithms are implemented in today's design tools. These include classical, and numerical robust algorithms that overcome the local minima traps. While the optimizers in the tools running fast multicore machines are very powerful, they are not guaranteed to converge to the best solution. Thus, the initial pencil and paper design is necessary. Reference [1] provides an analytical derivations for a similar cascode LNA, and the analysis can be used as a good starting point. The procedure here is a little different, since the input match is a first order allpass section rather than a second order bandpass filter.

Sub-micron transistor models are very complex [10]. It is required that the circuit is simulated using the SPICE models or the BSIM models for shorter channel length devices for accurate results. Keep in mind that the amplifier still needs to be tuned using a simulator to include the above mentioned effects. The Genetic Algorithm was chosen to do the optimization for this LNA. The GA is a very robust algorithm that has been discussed extensively in the literature [11].

In summary, the genetic algorithm employs several randomly generated designs, known as parents, measures their performance, and then combines the best designs into a new set of available designs (off-springs). The algorithm then generates some more designs and includes them in the set. A new set is formed by combining good performance designs, in a process known as cross-over, and sometimes randomly changing some properties, known as mutation. The algorithm converges once the performance of the set is not providing better solutions.

4. RESULTS AND DISCUSSIONS

Simulations were carried out for the S-parameters with a Harmonic Balance simulator, and for the transient response using a SPICE simulator, with 802.15.4a root raised cosine reference pulse. Figure 3 shows the optimized LNA S-parameters.

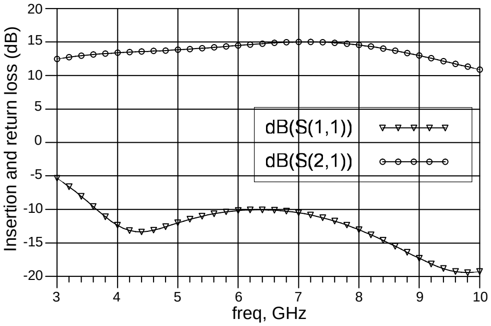

Figure 3. UBW cascode amplifier S-paremeters.

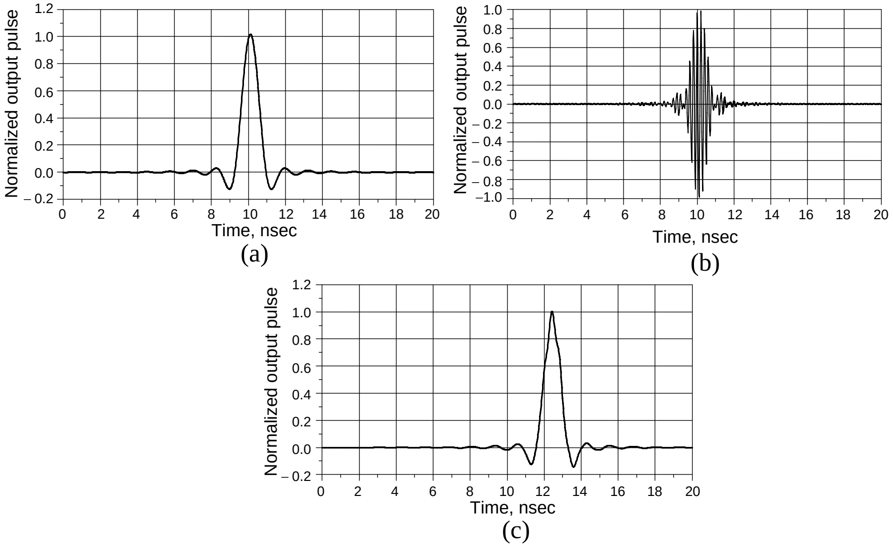

Figure 4. UWB cascode amplifier reference pulse response (normalized, for 5 GHz carrier). (a) Input pulse, (b) input RF pulse, (c) output pulse.

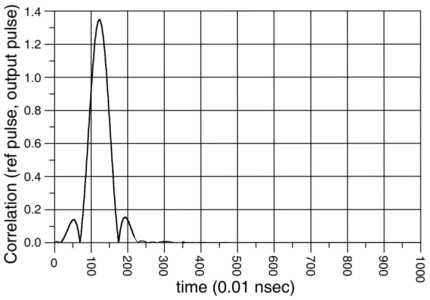

Figure 5. Cross correlation of LNA output and reference pulse against time for 5 GHz carrier.

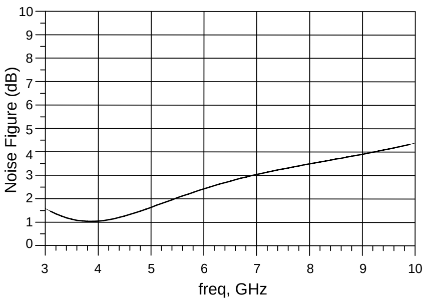

Figure 6. UBW cascode amplifier noise figure against frequency.

In UWB systems, phase response, including group delay, is of great importance, since different bands need to be grouped in phase to produce time-domain reference pulses. The designed LNA was simulated using transient analysis with the reference raised cosine time domain signal. The input is shown in the top of Figure 4. The output is shown at the botom section of the same figure.

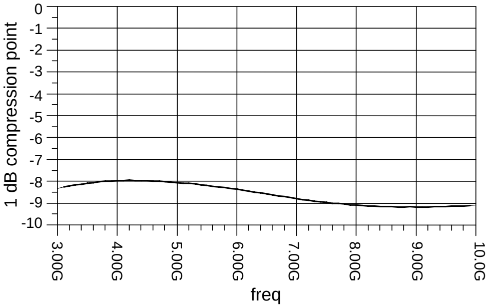

Figure 7. UWB cascode amplifier 1 dB compression point.

Table 2. Performance and comparisons to other publications.

Reference	This work	[13]	[1]	[14]	[12]	[3]
Power Consumption	9 mW	35	9	10	4.5	13.5
Tech. CMOS (µm)	0.25	0.25	0.18	0.18	0.18	0.18
Bandwidth (GHz)	7	1.6	7	2	7	9.5
NF	4.5	1.9	4.0	4.57	5.5	5.2

The standards require the cross correlation of the output of the UWB transmitter to be conformant using the reference signal cross correlation with certain requirements, such as the sidelobe to main lobe magnitude ratio and the pulse spreading. Figure 5 shows the cross correlation of the output signal to that of the reference signal for the 5 GHz carrier. In this paper, the transmitter requirement was used for the receiver LNA. For example channel 7 is a 0.92 ns pulse. The cross correlation function should have a width of at least 0.2 n sec for a threshold of 0.8, which is clearly satisfied. Also, the sidelobes are required to be at most 0.3 of the normalized cross correlation. In the design, the sidelobes are at 0.1. The figures clearly indicate excellent results.

Figure 6 shows the noise figure against the frequency for the whole band of operation. The NF is less than 3 dB up to 7 GHz, with a minimum of 1 around 4 GHz, and maximum of 4.5 dB at 10 GHz. It should be kept in mind that the NF has less effect on the channel capacity in UWB systems than narrowband systems as indicated in Eq. (1).

Figure 7 shows the 1 dB compression point for the LNA, which is around -9 dBm over UWB frequency range. Table 2 lists some LNA's for comparison purposes. The performance of this LNA made with the 0.25 μm technology is comparable to some 0.18 μm LNA technology.

5. CONCLUSION

The design of receivers for the 802.15.4a UWB PHY can be greatly simplified using the UWB channel organization and robust numerical optimization algorithms, such as the GA. The die area of a receiver is mostly due to the large size spiral inductors, which can be reduced as a compromise to the gain uniformity over the frequency operating range. A significant factor that needs to be addressed for the size reduction in UWB pulses is the pulse distortion requirements of the standards. In this paper, pulse distortion using correlation of the raised cosine reference pulse and amplified LNA output pulse as given in the standards was used.

ACKNOWLEDGMENT

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