A Brief Summary of Recent Advancements for the Design of Semiconductor Low Noise Amplifiers for Ultra-Wideband Technology

Introduction

Rapid communication has been in existence since the days of classical antiquity. In the early stages of development, it was implemented using means such as light (such as obtained from fire) or smoke in combination with topography and/or manmade structures. These modes of operation were commonly used in military applications. For example, Greek historian and cryptographer Polybius, developed a method using torches in approximately 150 B.C.—a type of semaphore communication—to indicate the contents of a message as well as when a message was ready to be sent and to be received between watchtowers [1]. Semaphore remained the dominant method of rapid relay of information among groups of people until about the 18th century except for the use of carrier pigeons in Asia and the Middle East during approximately 1100-1200s. Close to the mid 1800s semaphore reached its climax with the further development of a system, by Claude Chappe, that was distributed throughout all of France. The next milestone was the first transcontinental telegraph invented by Samuel F.B. Morse and his associates in approximately 1850. It replaced the memorable Pony Express and outdated semaphore. Advances in rapid communications continued and in the 1930s the father of information theory Claude E. Shannon began publishing research in the areas of communications and coding among others, which led to his theorem regarding channel capacity, i.e., $C = W[\log_2(\mathrm{SNR}+1)]$. It is by this formula that we understand that the rate of data transmission in bits/second C, is directly proportional to the bandwidth W of the channel. Hence, the significance of ultra-wideband technology (UWB).

[1]In 2002 the Federal Communications Commission (FCC) approved the ultra-wideband unlicensed spectrum usages of 1.99-10.6 GHz, 3.1-10.6 GHz and 22-29 GHz for commercial applications [2]. This announcement attracted the interest of both academia and industry leading to a flurry of research in this relatively new domain. In industry, Freescale Semiconductor was the first company to avail itself of UWB: it received the first FCC certification for this technology. Until relatively recently (2002) little has been discussed regarding wideband low noise amplifiers (LNAs) [3]. This article will present a brief overview of UWB, its applications, important LNA design parameters and an update on some of the latest developments for semiconductor LNA design for UWB.

Overview of UWB

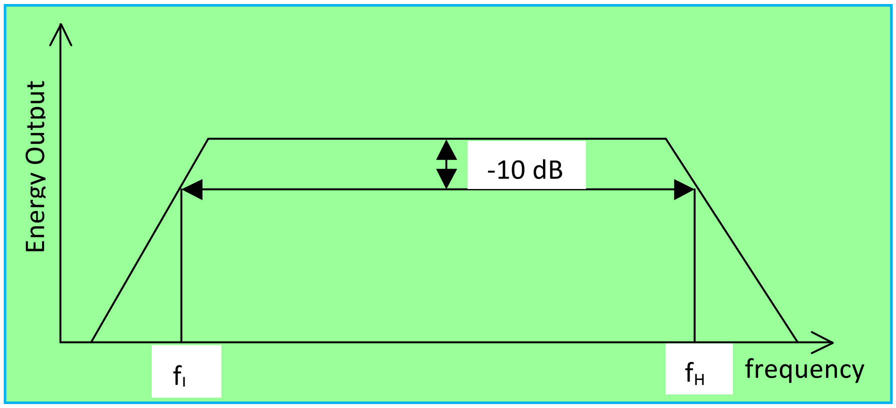

Figure 1 Illustration of the definition of UWB frequency range.

The definition of UWB according to the FCC is either (a) a fractional bandwidth greater than 0.2

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[1] FCC also allocated 57-64 GHz for commercial use but to limit the length of the article this frequency range will not be discussed.

or (b) a bandwidth greater than 500 MHz. The fractional bandwidth is calculated as $2(f_H-f_L)/(f_H + f_L)$ where f_H and f_L are defined in **Error! Reference source not found.**. The concept of UWB is not entirely new and its history can actually be traced to the days of the Hertz, Marconi and Tesla spark gap transmitter, when in 1901, Marconi used it to transmit Morse code across the Atlantic Ocean. The spark gap transmitter was essentially a resonant antenna subject to an applied impulse. For UWB antennas the most prevalent input signals are monocyles, impulses and steps [4]. Hence UWB systems are capable of transmitting over a large frequency bands and can do so with very low power and high data rates [5]. Other advantages are coexistence with other radio services, resistance to jamming and multipath fading, excellent signal penetration properties and simple transceiver architecture.

Applications

The applications for UWB bandwidth are many**:** imaging systems: ground penetrating (3.1-10.6 GHz), through-wall radar (1.99-10.6 GHz) and medical imaging (3.1-10.6 GHz); electronic surveillance and detection (1.99-10.6 GHz); personnel and asset tracking, e.g., buried victim rescue (3.1-10.6 GHz); automotive radar (anti-collision) and sensors(22-29 GHz); high-speed mobile local area networks (3.1-10.6 GHz) and wireless personal area networks (3.1-10.6 GHz). It is anticipated that UWB will supplant almost every wireline connection in an office or at home with a wireless connection that accommodates hundreds of megabits of data per second [6]. Shown in Figure 2 is a typical application of an LNA in a receiver.

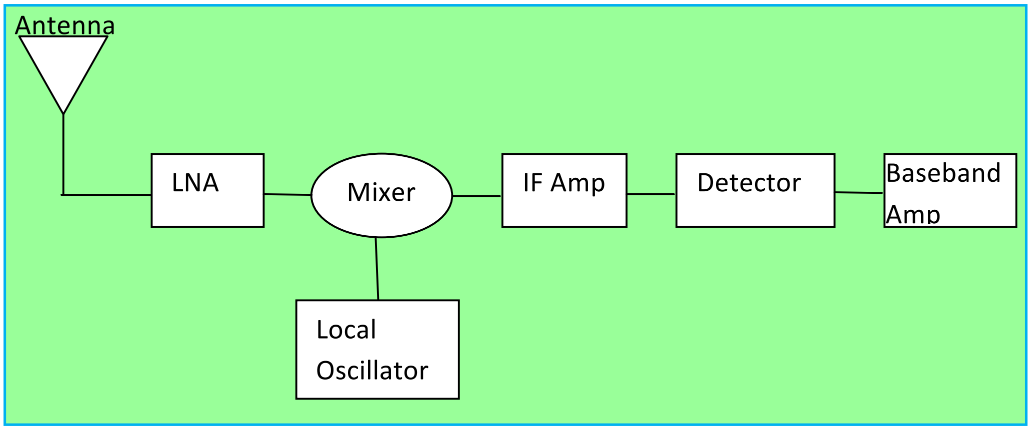

Figure 2 The functionality of an LNA in a superheterodyne receiver.

Overview of Design Parameters

Some of the key parameters in the design of an LNA are low noise figure, sufficient gain over the frequency band of interest, low power dissipation, third order intercept point and proper input and output impedance matching (S11, S22 parameters) [7]. S parameters of an LNA are also used to specify power/voltage gains, insertion loss, assess the stability and provide insight into the design. Another important parameter, though not always discussed, is group delay, which measures how evenly the Fourier components of a time domain signal travel through a linear time invariant system. Where there is considerable group delay variation versus frequency, time domain signals will be distorted particularly for UWB pulse signals that take up a bandwidth of several GHz [8]. Thus in addition to the parameters above, the UWB LNA needs to be characterized by a constant group delay (frequency components of interest have same transit time through the system) within the allocated bandwidth.

Recent Developments

Many LNA designs for UWB have been carried out in seven categories or variations thereof: common source (CS-LNA), common gate (CG-LNA) and resistive feedback [9], [10]; a ladder filter at the input of the LNA [11], [12]; use of feedback [13], [14]; current reuse [10], [15]; distributed amplifier [16], [17]; noise cancelling [18], [19] and Darlington configuration [20], [21]. The following paragraphs will briefly highlight some advantages and/or disadvantages of each topology.

Earlier elementary topologies developed for LNAs with uniform gain and wideband matching were common gate and the resistive feedback LNAs [9], [13], [22]. Common-gate amplifiers, however, [23], [24] are generally characterized by a higher noise figure i.e., their noise performance is poor. Shunt resistive feedback amplifiers can achieve matching over a broad frequency range, however, low power dissipation, constant gain and low noise figure are difficult to obtain over a wide frequency band [25], [26], [27]. As to the CS-LNA, it has been often implemented for narrow-band applications because of high gain and low noise figure as a result of input matching [22], [28]. Also, the CS-LNA tends to increase die size since a minimum of two inductors are used for input matching [22]**.**

The advantage of the ladder topology—which is a modification of a narrow band LNA—compared to a conventional wideband resistor amplifier based on resistor feedback, is that a higher gain and lower noise factor is achieved over a broader frequency range [29]. On the negative side for the UWB ladder approach, is that the signal can undergo a significant group delay variation [30]. In addition, the noise figure and gain are negatively affected by the high insertion loss introduced by the filter and the ladder design tends to increase the die size as a result of the inductor [30].

To alleviate the area concern, to break the tradeoff between the noise factor and impedance matching while maintaining low power consumption, inductorless topologies—many of them using feedback—were introduced by improving upon elementary wide band amplifiers such as a common gate configuration and the simple resistor feedback structure [19], [31]. Many feedback topologies have been categorized according to shunt-shunt active and passive feedback topologies with the active portion being often a source follower [14], [31], [32] and in the case of passive feedback being often a resistor, capacitor or inductor or reactance. The reactance may not decrease area but can introduce less noise than a feedback resistor or the ladder filter topology or increase the gain and reduce power consumption, or simply reduce power consumption, flatten the gain or provide wideband input matching and high gain [9], [30], [33], [13]. Other feedback topologies that have employed shunt feedback technology have taken the form of reactive cascode with input transformer [13] and active dual feedback [32] to improve the noise figure and return loss and passive dual feedback [34] to broadband impedance matching while keeping the noise figure relatively constant over the entire band of interest**.** As to the source follower its advantage is that it reduces noise, distortion and return loss [31], [32] compared to an elementary resistive feedback amplifier.

The fourth topology, current-reuse LNA(CRLNA) schemes show good potential for competitive low-power designs because they reuse the same DC bias current in multiple gain stages, i.e., they achieve high bias current-efficiency and therefore reduce power consumption [10]. A simple example of current reuse is illustrated in **Error! Reference source not found.** for a DC coupled LNA employing shunt-peaking using BJT technology. The amplifier cascade on the left uses approximately twice as much current as the cascode on the right for approximately the same gain. One advantage of bipolar transistors over CMOS transistors in LNAs is that CMOS requires higher DC current to obtain the same input-referred third-order intercept point [35].

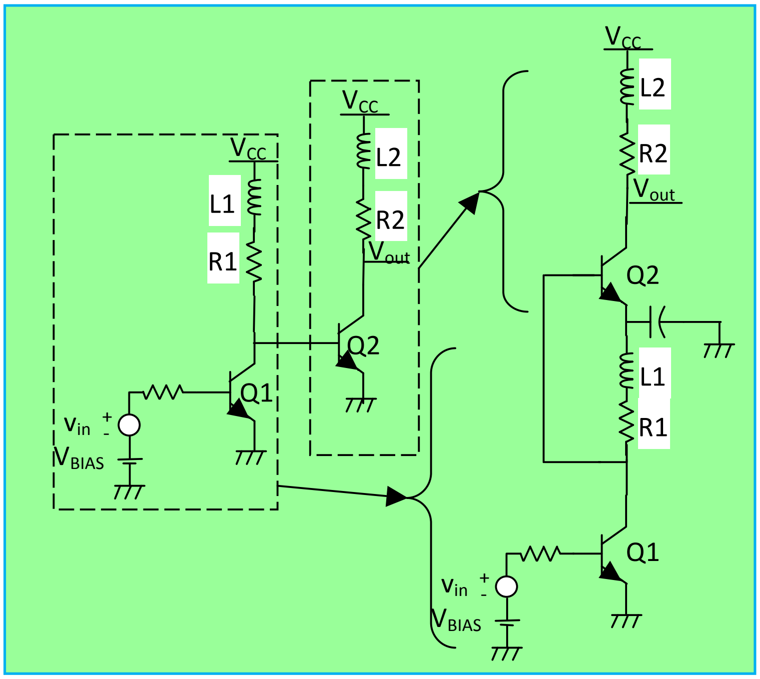

Figure 3 BJT LNA circuit showing current reuse.

The fifth topology, the distributed amplifier, invented by William S. Percival of Great Britain in 1936, consists of multiple transistors whose inputs arrive from one transmission line i.e., a tapped delay line and whose outputs feed into another transmission line i.e., another tapped delay line. To avoid reflections, the terminations of the input line and output line are terminated with the characteristic impedance of the input and output lines respectively, such that the forward travelling wave is absorbed by the termination on the input transmission line and the backward travelling wave is absorbed by the termination on the output transmission line**.** Multiorder LC ladder networks can also be used to form transmission lines [36]; the networks often take the form of T-type or π-type constant-k sections (k-sections) [37]. An example of a distributed amplifier using such networks is shown in **Error! Reference source not found.**. Distributed amplifiers have traditionally provided constant gain over a broad frequency range, wide input impedance matching, and often higher third order input intercept point [38]. However distributed amplifiers are

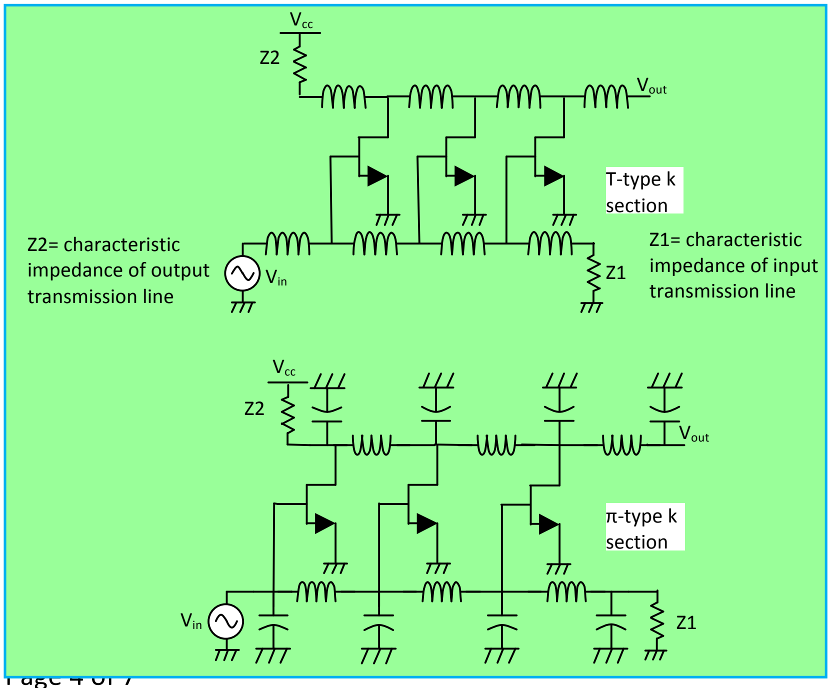

Figure 4 Distributed amplifier using π and T-type k-sections.

disadvantageous for low cost and low power applications because they consume significant area and power. Power consumption can be high because of a the multi-stage nature of the designs [30].

Noise cancelling and the Darlington configuration are the last topologies that will be mentioned. Noise cancelling was developed as a means to reduce the noise figure in inductorless topologies namely LNAs that rely on resistive feedback for broadband input matching. The idea behind noise cancelling is to generate noise signals with opposite phase polarities in different output paths such that polarities of the noise signals cancel out at the output without degrading the RF signal transmission [39]. Finally Darlington configurations were used to increase the gain of the LNA compared to the distributed amplifier topology over the operating bandwidth while dissipating low power [20].

Another important factor— not covered in this article because of publishing constraints—yet critical for the design, is whether an elemental or compound semiconductor process is used. The type of semiconductor affects among others frequency response, noise performance, power capability, cost, yield, integration and others [40] (Popular compounds include groups III-V and IV[11]). Also we could see non semiconductor materials used in the near future [41].

Conclusion

Once the topology has been selected, DC biasing would be the next step in the design followed by a stability analysis, noise matching, input return loss, and output matching. To complete the design, one needs to be knowlegeable of the parametric trade-offs and variables to modify parameter values. Finally LNA amplifiers are typically operated in class A regime which is characterized by a quiescent point more or less at the center of maximum current such that the small signal is present during the entire output cycle.

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