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IMPEDANCE MATCHING TECHNIQUES FOR CMOS LOW NOISE AMPLIFIERS

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Abstract. This paper reviews the main impedance matching techniques proposed in literature during the last two decades and widely used at CMOS low noise amplifiers. Trying to offer good insights on the impedance matching issue, the paper presents considerations on the trade-off between matching, gain, noise, linearity, chip area and power consumption. Such review is of great help when having to choose between narrowband and wideband matching techniques.

Key words: CMOS; impedance matching; low noise amplifier; RF.

1. Introduction

Impedance matching is critical for RF receivers, especially in wireless devices such as mobile phones, any impedance mismatch between two consecutive blocks deteriorating the overall SNR (signal to noise ratio). Due to the low power level of the signal received by antenna, the significant number of matching points on the signal path (≤ 6 for super-heterodyne and ≤ 3 for homodyne receivers) and the thermal noise generated by all RF active devices, SNR is continuously degraded from antenna to ADC (analog to digital converter). This is not the case of transmitters where a fixed matching network

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is usually inserted between the power amplifier (PA) module and antenna (Li *et al.*, 2006) or RF filter. The second matching point (RF filter – LNA) from a receiver represents also the scope of this paper. Dedicating a review article to impedance matching addressing low noise amplifiers is welcome taking into account that there are more than 1,500 articles in the literature proposing different topologies of CMOS LNAs (designed for particular frequency bands) and at least 1,000 dedicated to RF CMOS transceivers (and reporting also LNA structures).

For a straightforward review, these matching techniques are split in two categories, corresponding to narrowband and broadband amplifiers. To clarify the narrowband and wideband concepts, it is worth mentioning that the bandwidth allocated for each common wireless standard is less than 5% of the center frequency. Thus, the bandwidths regulated for the common wireless standards are: 25 MHZ (GSM 850), 35 MHz (GSM 900), 60 MHz (GSM/CDMA 1900, 3G 1900/2100), 75 MHz (GSM 1800) and 83.5 MHz (Bluetooth/WLAN). Since the bandwidth allocated for UWB applications is larger than 500 MHz or 20% of the center frequency, all these wireless standards are hereinafter considered as narrowband applications.

The importance of impedance matching network consists not only in the fact that it sets the noise figure (NF) but also that it changes the bandwidth. Thus, beside S_{21} that defines actually the amplifier bandwidth, S_{11} shapes also the overall frequency response of the amplifier. As it will be noticed, there are different techniques used in case of matching networks either to select or enlarge and shape a particular frequency band, according to the design constraints. Besides, it is interesting to note that its frequency performances are achieved despite of its compactness, for a particular single stage chip size, one LNA offering a good trade-off between space, gain, noise figure, power consumption and bandwidth.

2. Impedance Matching Techniques for Narrowband LNA

CS (common source) amplifiers are preferred for narrowband applications thanks to their low NF (noise figure), yet with the price of larger chip area and increased power consumption & nonlinearity compared with CG (common gate) stages. In order to change the capacitive input impedance (because of C_{gs}) into a resistive one, two supplementary inductors are added to the gate and source of the CS buffer, as shown in Fig. 1 (Pärssinen *et al.*, 1998). This is the single solution for CS–LNA impedance matching (no matter which technology is used) and the final structure is known as *inductively-degenerated common source LNA*. The equivalent input impedance is expressed by

$$Z_{\text{in}}(s) = s(L_g + L_s) + \frac{1}{sC_{g,t}} + R_g + \frac{g_{m1}}{C_{g,t}} L_s \tag{1}$$

and the noise figure by

$$F_{\text{CS-LNA}} = 1 + \frac{2}{3} \cdot \frac{1}{R_S g_m Q_g^2} \,. \tag{2}$$

In (1), $C_{g,t}$ represents the total gate to source capacitance and R_g – the gate parasitic resistance (widely neglected in literature for Z_{in}). It is obvious that Z_{in} can be easily adjusted to 50 Ω by tuning g_m correspondingly. Both inductors, L_g and L_s, are implemented on-chip, usually requiring a chip area larger than the active one, the entire chip area being increased significantly. In addition, L_s deteriorates the gain since $g_m = 1/(2\omega_0 L_s)$ at the resonant frequency, in many cases L_s being chosen as small as possible and even much smaller than L_g. Besides, the transistor must be sufficiently large in order to increase the parasitic capacitance and decrease L_g (since $L_g = 1/(\omega^2 C_{g,t}) - L_s$). This is another trade-off that must be taken into account. In addition, the transistor transconductance must be sufficiently large (drawback) in order to decrease the noise factor while the resonant tank at the input must have high quality factor (drawback), mostly dependent on L_g. Finally, since impedance matching is implemented by external means, a problem that the designer has to deal with is the DC biasing. In this regard, several biasing schemes are mentioned in literature for CS–LNAs such as using a DC feed/bias tee (Floyd *et al.*, 1999), gate bias resistors inserted after (Hayashi *et al.*, 1998) or before L_g (Abdelghany *et al.*, 2011) and a voltage reference (Wong-Sun Kim *et al.*, 1999). It is interesting to note that this basic topology is almost a standard when implementing narrowband LNAs, being used in most papers focused on narrowband applications.

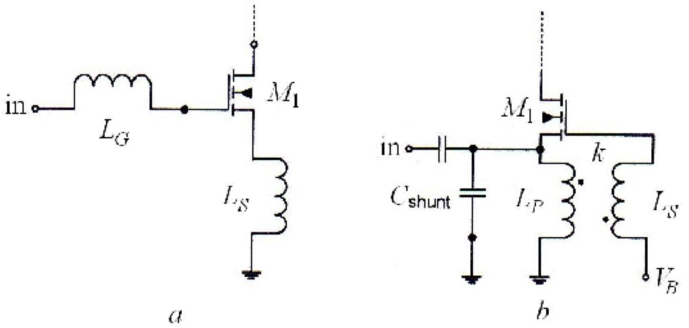


Fig. 1 – Inductively-degenerated CS–LNA (*a*) and transformer coupled g_m-boosted CG–LNA (*b*).

Beside CS amplifiers, the CG buffer can be used to design narrowband LNAs, too. Such topology, making use of a transformer for biasing purposes (*transformer coupled g_m-boosted CG–LNA*), is shown in Fig. 1 (Allstot *et al.*, 2005) and has the noise factor given by

$$F_{\text{CG-LNA},g_m\text{-boosting}} = 1 + \frac{\gamma}{\alpha} \cdot \frac{1}{1+A} \,, \; A = nk. \tag{3}$$

It is obvious that NF is improved (< 2 dB) with the main advantage of lower power consumption but with the price of increased nonlinearity, IIP3 decreasing.

3. Impedance Matching Techniques for Wideband LNAs

The most common, simplest and well known wideband amplifier is the CG one (Fig. 2 *a*), with the input impedance approximated by

$$Z_{\text{in}}(s) \approx \frac{1}{sC_{gs}} \left\| \frac{1}{g_m + g_{mb}} \right. . \tag{4}$$

It is obvious that Z_{in} is resistive over a large frequency range, usually up to 1…2 GHz (depending on the particular technology). Different biasing schemes were reported in literature, such as using passive inductors (Fig. 2 *a*) (Shin & Bult, 1997), transformers (Liscidini *et al.*, 2006), current sources (Tsung-Te Liu & Chorng-Kuang Wang, 2005), resistors (Merkin *et al.*, 2006), shunt *LC* resonators (Wei Wu *et al.*, 2009) and even negative resistances for differential topologies (Yoon *et al.*, 2010). All these components are used to ground the transistor source terminal. Besides, *reactive matching* can be skillfully used in conjunction with CG–LNAs in order to increase their bandwidth and improve the impedance matching (Fig. 2 *b*) (Chen Chun-Chieh

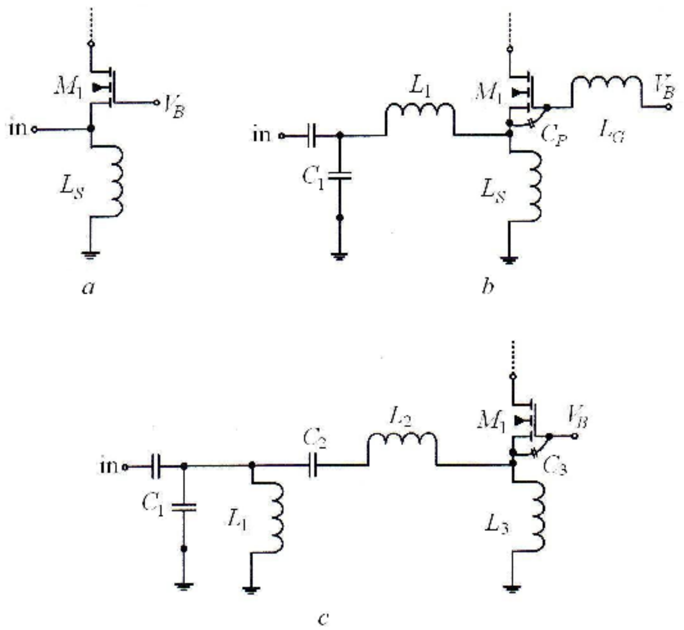
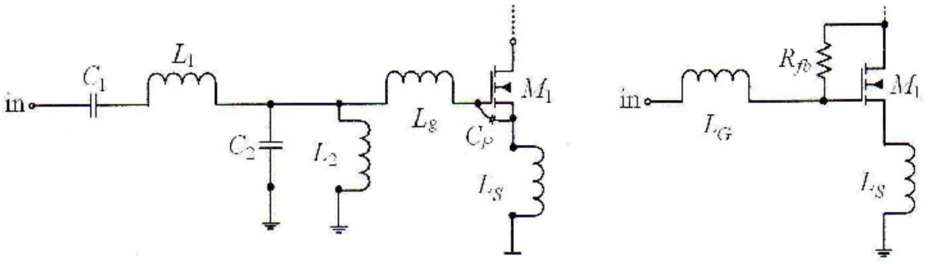


Fig. 2 –CG–LNA (*a*), CG–LNA with reactive matching (*b*) and CG–LNA with 3rd order bandpass filter input matching network (*c*).

et al., 2006). Another CG–LNA using a 3rd order Butterworth bandpass filter as matching network was also proposed in literature (Yao Huang Kao & Chia Hung Hsieh, 2007; Fan *et al.*, 2005) (Fig. 2 *c*).

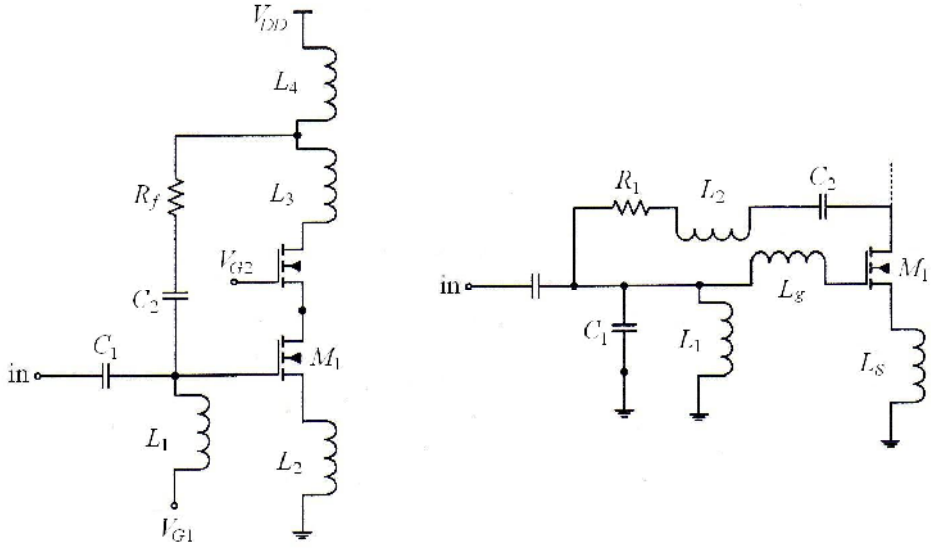
Secondly, CG–LNAs can exhibit wideband properties with the price of some frequency compensation methods if particular operation band are envisaged. Two such methods are *reactive matching* (Bevilacqua & Niknejad, 2004) (Fig. 3 *a*) and *resistive feedback* wideband matching applied to CS–LNAs (Wei-Hsiang Hung *et al.*, 2011) (Fig. 3 *b*), a DC feed being used to bias M_1 in the second case.



a *b*

Fig. 3 – CS–LNA with reactive matching (*a*); CS–LNA with resistive feedback (*b*).

Two other methods are *shunt resistive feedback* (Pou-Tou Sun *et al.*, 2011) (Fig. 4 *a*) and feedback series *RLC* tank LNA with reactive matching (Khalaf, 2011) (Fig. 4 *b*). Offering the advantage of low noise figure, their main drawback is the large chip area (due to the presence of inductors).



a *b*

Fig. 4 –Shunt resistive feedback CS–LNA (*a*) and CS–LNA with feedback series *RLC* tank and reactive matching (*b*).

Instead of a passive feedback network, an active one including a MOS transistor may be used (Dores *et al.*, 2011), as shown in Fig. 5 *a*. A third wideband prototype is the CS–CG LNA (Blaakmeer *et al.*, 2011) (Fig. 5 *b*). The advantage of such topology is that the circuit is intrinsically input matched thanks to the CG input stage while converting the single-ended input to differential output and offering low noise figure (being compensated). In addition, the circuit supplements the role of a balun.

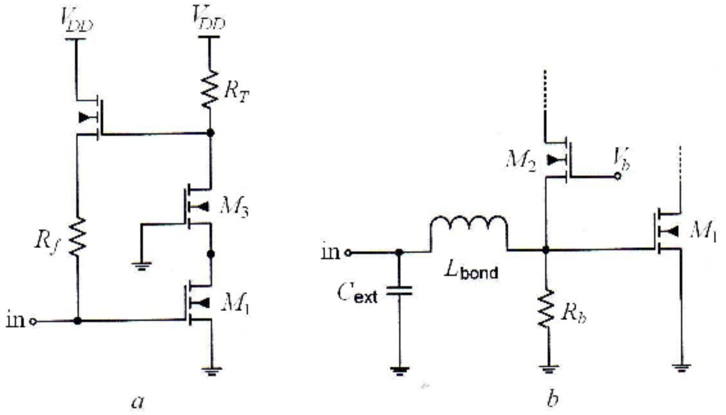


Fig. 5 –CS–LNA with feedback transistor (*a*) and CS–CG–LNA (*b*).

All these artifices extend the amplifier bandwidth and insure a flat response for gain and noise figure together with wideband matching. Bandwidths up to 7 GHz can be achieved by using these feedback networks while keeping the noise as low as possible (NF < 4 dB).

4. Conclusions

Two classes of low noise amplifiers, together with some basic prototypes of matching networks, were reviewed in this paper. It is clear from this review that for narrowband applications there are very few possibilities to implement an LNA (with respect to the impedance matching), while a great number of prototypes are available for wideband applications. In any case, the frequency capability of an LNA is strongly influenced by the matching network and this is the reason why particular attention must be paid to this input stage.

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TEHNICI DE ADAPTARE A IMPEDANȚEI PENTRU AMPLIFICATOARELE LNA DE TIP CMOS

(Rezumat)

Se rezumă cele mai importante tehnici de adaptare a impedanței propuse în literatură în ultimele două decenii şi cu largă utilizare la amplificatoarele cu zgomot mic de tip CMOS. Încercând să ofere nişte repere utile cu privire la problematica adaptării de impedanță, se prezintă unele considerații cu privire la compromisul dintre adaptarea de impedanță, câştig, zgomot, liniaritate, aria ocupată şi puterea consumată. Un asemenea „review” este un ghid util pentru situația în care trebuie alese tehnici de adaptare de bandă îngustă sau largă.