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A SiGe HBT low noise amplifier using on-chip notch filter for K band wireless communication

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ABSTRACT

In this paper a new notch filter topology has firstly been described. In order to improve the input match as well as enhance the gain on the operating frequency of 20.5 GHz, extra capacitor has firstly been added in the passive base-collector notch filter forming a new scheme, eliminating the operating-frequency (*op*) input mismatch in formal base-collector notch filters. EM simulations have shown that the LNA obtained 14.1 dB gain at 20.5 GHz and high image-rejection ratio (IRR) of 33.5 dB at image frequency of 15 GHz, and S_{11} of -15 dB was obtained compared to -8 dB without notch filter at operating frequency, *NF* was below 5 dB at gain peak frequency, power consumption was 18 mW at 3 V voltage supply, and *IIP*3 was 3.43 dBm ensuring a high linearity in SiGe bipolar process.

1. Introduction

The increasing demand for larger bandwidth and high image rejection has been grown up rapidly in recent years [1–3]. In the superheterodyne wireless communication transceivers, suppression of image-frequency signals is one of the most fundamental performances, image signals should be filtered out so as not to deteriorate the operating signals. External high-Q filter, such as surface-acoustic wave (SAW) filters or ceramic filters can be used for image rejection [4]. However, these filters are large and incapable in integration monolithically [5]. To address these problems, on-chip integrated filters are carried out to attenuate the unwanted image signals by means of IR filter or IR architectures [6–11]. Active filters are preferred since it can degrade the parasitic resistances of on-chip inductor [2–3] [12–20], compensating the small Q of on-chip inductors (about 3–6) [21]. However, the Q of the small inductors—in the range of about 0.05 nH to 0.4 nH—is often sufficient enough to satisfy the performance of passive filters. Based on this, many research works have been devoted to design a base-collector passive notch filter to fulfill the desired outcome [1,22–24]. The most intriguing advantage using this topology lies in the fact that no extra power is used for filter function. In Ref. [1,22] a notch-filter between base and collector in LNA is introduced which shows great IRR. However, S_{11} in these LNAs are unsatisfying, that is, about -8 dB. Good IRR can ensure a good image rejection, but poor input match at operating frequency may degrade the useful signal injection performance [6,23]. Attention should be made that [24] adopts an extra capacitor to tune the operating frequency without affecting the image frequency, this is, theoretically, can also be utilized in passive filters. In order to optimize the input match as well as the save power [10], a new passive IR filter is introduced.

This paper demonstrates the design principles and analytical derivation of proposed IR LNA which is organized as follows. Section 2 introduces the general design principles of IR LNA, focusing on the facts of image rejection and input match. Section 3 describes the proposed LNA. Section 4 discusses the results of proposed LNA and compares them with other previous works, which is followed by conclusion in Section 5 and acknowledgment.

2. Principles of image rejection low noise amplifier

In CECB topology, there are several passive IR structures which can filter out the unwanted image signal to ac ground whereas the operating frequency signal is maximally maintained. This is implemented by the characteristic of notch filter: the impedance of notch filter is lowest at image frequency and highest at operating frequency, Fig. 1 shows two topologies of passive notch filter [1,22]. Fig. 1a uses two capacitors (C_1 and C_2) and one inductor (L_1) to form the notch filter network, and in Fig. 1b the circuit adopts the same components only at a difference that the

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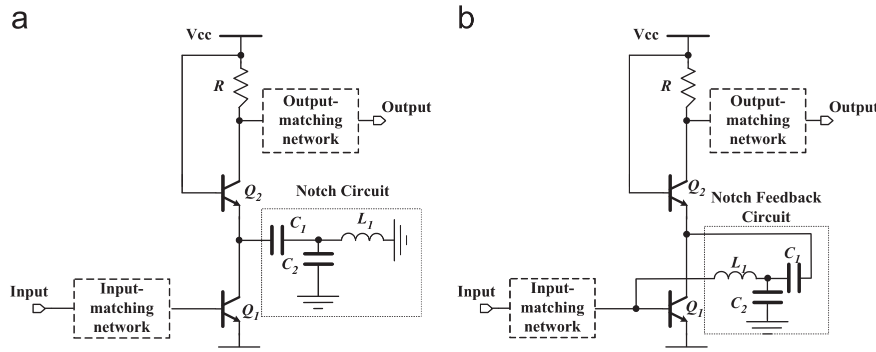

Fig. 1. Schematics of low noise amplifier with image rejection function. (a) Conventional notch filter. (b) Improved notch feedback.

terminals of notch filter are tied at base and collector of one transistor, whereas in Fig. 1a one terminal of notch filter is tied to the ground. The transformation from Fig. 1a to Fig. 1b has lots of benefits: high IRR and good linearity. A feedback topology ensures that at image frequency it provides low impedance looking from the collector-node, but also provides low impedance at base node, this means that mismatch exists at image frequency making image signal reflect back to antenna and image gain of LNA is attenuated, lowering down the image signal's amplifying amplitude. This dual attenuation can maximally attenuate the image signal. Besides, it is shown that no dc path exists in both filters which mean no power consumption is wasted.

The image frequency f_{im} and gain peak frequency f_{op} shown in Fig. 1a are

$$f_{im} = \frac{1}{2\pi\sqrt{L_1(C_1+C_2)}} \tag{1}$$

$$f_{op} = \frac{1}{2\pi\sqrt{L_1C_2}} \tag{2}$$

By tuning C_1, C_2 and L_1, good IR performance can be satisfied. As shown in Fig. 1b there still exist some problems. This can be explained in two facts: one is that notch filter's impedance may deteriorate the input match and transconductance of input transistor, leading to more effective power's' reflection and gain degradation. This will low down the IRR. The other fact is that because one terminal shown in Fig. 1b is tied to base-node, the formal analysis is invalid: impedance looking out of this node is not an ac zero, making the image and operating frequency tuning harder.

To ensure a good IRR a good input match is essential; Ref. [24] adopts extra capacitor to tune the operating frequency which is shown in Fig. 2. Capacitor C_t is adopted to tune the impedance of notch filter. The image and operating signal can be expressed as

$$f_{im} = \frac{1}{2\pi\sqrt{L_fC_{eq}}} \tag{3}$$

$$f_{op} = \frac{1}{2\pi} \times \sqrt{\frac{C_t+C_{eq}}{L_fC_tC_{eq}}} \tag{4}$$

$$\frac{1}{C_{eq}} = \frac{1}{C_{gs3}} + \frac{1}{C_f} \tag{5}$$

From Eq. (4), it can be seen that by adding C_t, operating frequency can be tuned. This can increase the flexibility for choosing the frequency with maximum filter impedance, and wanted gain can be ensured with the minimum influence caused by notch filter. C_t is often small because as it grows bigger, image and operating frequency will overlap. Performance of this active filter is satisfying that about 35 dB of IRR can be achieved only at a cost of power; assumption is made that by adding this extra capacitor into passive counterpart, good performance and no power may be achieved. This has been proved in the following section.

3. Circuit design

3.1. Circuit topology

Fig. 3 shows the proposed LNA with CECB topology and notch circuit. Two feedback loops exist: global feedback caused by resistor R_F and capacitor C_F and local feedback introduced by notch circuit. Global feedback determines the equivalent input impedance made by R and R_F and local feedback connecting base and collector of transistor Q_1 determines the image and operating frequency. The design method is to first determine the input impedance by global feedback with the assumption that local feedback introduces minor impact on input match at *op* frequency; the other step is to tune the notch filter to optimize the circuit performance. The following part will discuss the design flow in detail.

3.2. Input match and notch filter design

In the design of wideband LNA, much of input match topologies can be used. Traditional *LC* ladder input match [25] can easily implement the wideband match; however, about two or three inductors are used, which means a large die cost. To overcome this problem, resistor feedback for wideband match topology is introduced [26,27]. Elements of C_{in}, L_G and C_{BE1} form the input π matching network to fulfill the wideband input match as well as low noise requirement [28]. The notch circuit does, however, exist in the input match which should be included.

Fig. 4 shows the small signal equivalent circuit of input match network. L_G and C_{in} are real elements which are shown in Fig. 3. R_{Zin} and C_M are the equivalent impedance formed by global feedback and load. Extra capacitor C_{Extra} splits into C_{Ex1} and C_{Ex2} and locates in π network and notch circuit whose function will be discussed later. C_{BE1} is the base–emitter capacitance of Q_1; C_3 and R_{BE2} are the impedance looking into Q_2. Our first step is to determine the π network and R_{Zin} without impact of notch circuit, and then quantify the impact of notch filter and optimize. The corresponding values are [28,29]

$$R_{Zin} = \frac{R_MC_M^2}{(C_M+C_\pi)^2+(R_MC_MC_\pi\omega)^2} \approx R_M\left(\frac{C_M}{C_M+C_\pi}\right)^2 \tag{6}$$

$$C_M \approx C_{BC} \times 2 \tag{7}$$