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A low-noise mixer with an image-reject notch filter for 2.4 GHz applications

Nam-Jin Oh *

Department of Electronic Engineering, Chungju National University, 123 Geomdan-ri, Iryu-myeon, Chungju, Chungbuk 380-702, Republic of Korea

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ABSTRACT

This paper presents a low noise first down-conversion mixer with a notch filter for the heterodyne receiver. The notch filter connected to the output node of the mixer driver stage plays a role of image rejection at an image frequency, thereby suppressing the sideband image noise and improving the mixer noise performance. Targeted for 2.4 GHz industrial–scientific–medical band applications, a simple source-degenerated down-conversion single balanced mixer with the filter is implemented. The measurement results of the proposed down-conversion mixer shows about 3.0 dB improvement of single-side band noise figure, about 2.9 dB power conversion gain improvement, and 25 dB image suppression compared to those without the filter dissipating 4 mA from a 2.5 V supply voltage.

1. Introduction

While research and development for a direct conversion radio transreceiver has been active recently, heterodyne radio architecture has been widely adopted for several decades, and is still prevalent for many commercial products.

Fig. 1 shows a conventional heterodyne radio receiver front-end which comprises an radio frequency (RF) band pass filter (BPF), a low-noise amplifier (LNA), an image rejection filter (IRF), a down-conversion mixer, and an intermediate frequency (IF) filter. The down-conversion mixer is used for frequency translation of a RF signal down to an IF by mixing the RF signal from the LNA with the local oscillator (LO) signal. The front-end blocks such as LNA and down-conversion mixer mainly affect the receiver noise figure (NF). Since the LNA predominantly affects the receiver NF, it is required to have a low NF to receive very weak signals. The next noise contributor is a down-conversion mixer. A low NF mixer relaxes the gain requirement of the preceding LNA. A mixer with high-power gain reduces the noise contribution from the following IF stages [1]. Usually, the filters are implemented externally. They make several decibels of signal losses in the signal path and thereby degrade the overall receiver NF.

In this paper, a simple down-conversion single balanced mixer (SBM) with a notch filter [2,3] targeted at 2.4 GHz applications is presented to achieve low NF, high-power gain, and an image rejection. The emphasis is on the image rejection filter implementation, and the noise analysis of the proposed mixer.

2. Mixer design considerations

For a cascaded system as shown in Fig. 1, it can be shown that the LNA must have enough gain to suppress the noise contribution by the following stages such as down-conversion mixer and IF filter. The system noise factor expressed in linear scale can be written as

$$\mathrm{NF} = \frac{1}{L_{\mathrm{RF}}} + \frac{\mathrm{NF}_{\mathrm{LNA}} - 1}{L_{\mathrm{RF}}} + \frac{(1 - L_{\mathrm{IR}})}{L_{\mathrm{RF}} G_{\mathrm{LNA}} L_{\mathrm{IR}}} + \frac{\mathrm{NF}_{\mathrm{MIX}} - 1}{L_{\mathrm{RF}} G_{\mathrm{LNA}} L_{\mathrm{IR}}} \tag{1}$$

where L_{RF} and L_{IR} are the insertion losses of the RF filter and the image rejection filter, respectively, $\mathrm{NF}_{\mathrm{LNA}}$ and $\mathrm{NF}_{\mathrm{MIX}}$ are the NFs of the LNA and the down-conversion mixer, respectively; and G_{LNA} is the power gain of the LNA.

Based on the typical heterodyne receiver specifications and assuming $L_{\mathrm{RF}} = 3$ dB, $\mathrm{NF}_{\mathrm{LNA}} = 1.5$ dB, $G_{\mathrm{LNA}} = 15$ dB, $L_{\mathrm{IR}} = 6.0$ dB and $\mathrm{NF}_{\mathrm{MIX}} = 13$ dB, the calculated overall system NF is 8.9 dB. If the NF of the mixer $\mathrm{NF}_{\mathrm{MIX}} = 10$ dB, the system noise performance can be significantly improved to 7.22 dB.

Analyzing the linearity for the cascaded system, the linearity of the latter stages becomes increasingly important and hence sufficiently high linearity of a mixer is required. To improve the receiver linearity, the gain of the LNA also should not be too high, which in turn leads to the NF degradation of the receiver. Lowering the mixer NF can compensate the degradation of the receiver NF.

The next consideration is an image problem. Many heterodyne receivers adopt double conversion architecture with high IF over several hundred megahertz to provide an inherent image rejection, and employ low-side mixing (LO has lower frequency than

* Tel.: +82 43 841 5162; fax: +82 43 841 5160.
E-mail address: onamjin@cjnu.ac.kr

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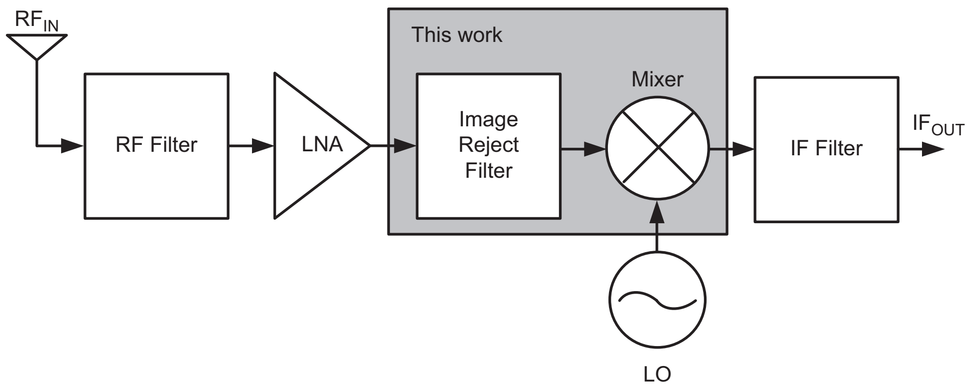

Fig. 1. Conventional heterodyne radio receiver front-end.

RF) for the first down conversion [4,5]. However, the image rejection ratio cannot be obtained enough at GHz range high frequencies. So, an integrated image reject mixer for the first down conversion has advantage of suppressing the image frequency and noise furthermore.

3. Mixer noise analysis

Usually, the active mixers (in silicon technology) have a single-side band (SSB) NF greater than 10 dB. The mixer is noisy because side band noise is translated from multiple frequency bands to the output and the input RF signal power is translated to multiple frequency bands by frequency mixing as shown in Fig. 2. Thus, the mixer inherently has high NF compared to those of amplifiers.

The mixer noise contributing components consist of driver stage noise, switching pair noise, LO signal noise and thermal noise from the load resistor. Among the noise contributing components, the driver stage noise dominates the mixer noise performances.

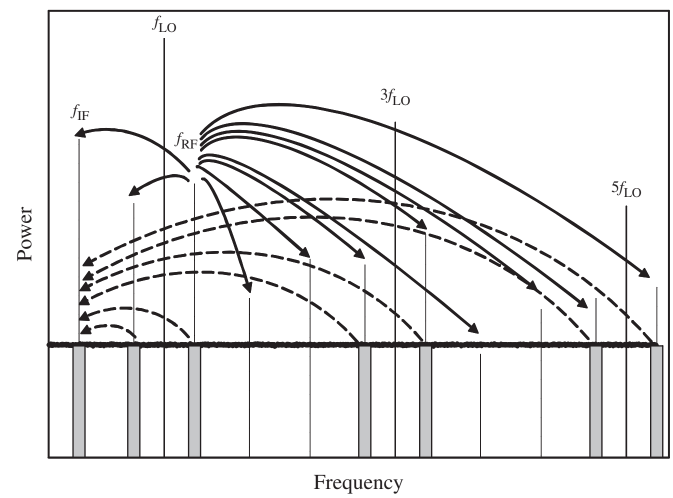

Fig. 2. Frequency translations of white noise in the driver stage (dotted line) and RF signal translations by mixing with LO (solid line).

3.1. Noise for a nondegenerated single balanced mixer

Fig. 3 shows a nondegenerated active SBM, and a small-signal equivalent circuit of the RF input driver stage. The noise sources are modeled in the input and output. Assuming that the gain of the driver stage and its output noise are constant across all frequencies, the total output noise current spectral density at the drain of the driver stage is

$$S_a = 4kT[(R_s + R_g)g_m^2 + \gamma(\kappa + \xi)g_{d0}] \tag{2}$$

where k is Boltzmann's constant, T is the absolute temperature, R_s is the source resistance, R_g is the gate resistance, g_m is the transconductance, γ is a bias-dependent factor, g_{d0} is the zero-bias drain conductance, κ is the combined parameter for the drain channel current noise and the correlated induced gate noise, and ξ is the parameter for the uncorrelated induced gate noise [6]. From (2), the first term is due to the source resistance and polysilicon gate resistance, the second term is due to the induced gate noise and drain channel current noise.

Assuming the LO switching is square wave-like, the LO frequency and its odd harmonics will downconvert the respective noise components to the IF. Since the mixer conversion gain is $2/\pi$, the mixer output noise current spectral density is

$$\overline{i^2_{no,M1}} = nS_a\left(\frac{2}{\pi}\right)^2 \tag{3}$$

where

$$n = 2\left(1 + \frac{1}{3^2} + \frac{1}{5^2} + \cdots\right) = \left(\frac{\pi}{2}\right)^2 \tag{4}$$

is the noise increase factor and originates from the harmonic amplitudes of the square-wave [7,8].

From (3), it can be shown that the mixing process increases the noise contribution by a factor of $(\pi/2)^2$ or 3.9 dB. As shown in Fig. 2, the first term of (4) is noise at $f_{LO} \pm f_{IF}$ downconverted by the fundamental LO, the second term is noise at $3f_{LO} \pm f_{IF}$ down-converted by the third harmonic of the LO, and so on. The first and second term account for 81% and 9% of the noise transferred to the output, respectively. The remaining 10% comes from the higher-order LO harmonics $\pm f_{IF}$ [9].

The output noise current spectral density due to the switch noise and the output load resistor (if two load resistors R_L are used) is

$$\overline{i^2_{no,sw,R_L}} = 8kT\left(\frac{\gamma I}{\pi A} + \frac{1}{R_L}\right) \tag{5}$$

where I is the tail fixed current, A is the LO amplitude [7]. In (5), the noise contribution of the switches can be minimized with a large LO signal.