A Highly Integrated GaAs pHEMT Active Mixer for Wideband SAR Systems

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Abstract — **This paper presents the design and performance of a GaAs pHEMT active mixer for wideband Synthetic Apertur Radar (SAR) systems. The active mixer is highly integrated and includes active baluns on the RF/LO ports, active combiner on the IF port and a Gilbert Cell mixer core. The active mixer demonstrates a 10 dB conversion gain over a 9.5 GHz RF port bandwidth. A conversion gain variation of $\pm 0.25dB$ is achieved over a 800 MHz signal bandwidth for frequency conversion between C- and L-band making the active mixer suitable for SAR systems.**

I. Introduction

High performance monolithic microwave integrated circuits are required for frequency conversion of wideband linear FM-modulated signals in next generation SAR systems. To achieve operation over multiple frequency bands with good phase linearity and conversion gain flatness as required in wideband SAR systems, GaAs pHEMT technology is preferred for realizing these circuits [1].

Several highly integrated active mixers based on FET technologies have previously been reported [2], [3], [4]. These active mixers have mostly been optimized for downconversion performance. Typical such mixers are capable of frequency conversion of narrowband signals over a wide range of RF frequencies to a fixed low IF frequency. This differs from the demands on active mixers for wideband SAR systems. Here the active mixers should be optimized for wideband operation at both the RF and IF ports in order to provide undistorted frequency conversion of wideband linear FM-modulated signals.

In this paper the design of a highly integrated GaAs pHEMT active mixer for a wideband SAR system is presented. Special design consideration for the balance in a highly integrated active mixer is discussed in details. Good balance over a wide bandwidth is assured by including wideband active baluns on both the RF and LO port as well as a wideband active combiner at the IF port. The experimental results demonstrates the usefulness of the highly integrated GaAs pHEMT active mixer for wideband SAR systems.

II. Balance Considerations

The schematic of a GaAs pHEMT active mixer suitable for monolithic integration is shown in Fig. 1. It consist of RF balun, LO balun, Gilbert Cell mixer, and IF combiner. Ideally the points where the drains of the upper devices are connected represents a virtual ground for the RF and LO signals, and the drains of the lower devices are virtual ground for the LO signal [5]. Thus, the Gilbert Cell mixer ideally suppres the LO leakage to the RF and IF ports as well as leakage from the RF port to the IF port. Due to the unavoidable device mismatch and balun imperfections the RF and LO signal will leak to the IF port. The LO leakage is a serious concern in a SAR system as this signal may cause passband ripples due to AM/PM conversion in the non-linear parts of the system [1]. The effect of mismatch has been investigated previously in [6] and will not be considered here. Instead the effect of balun imperfections on the performance of the GaAs pHEMT active mixer shown in Fig. 1 will be discussed with emphasis on the mechanism leading to LO leakage.

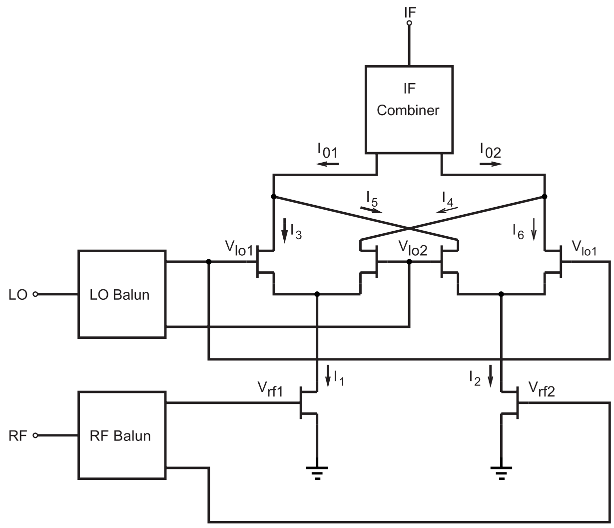

Fig. 1. Active mixer including RF/LO baluns and IF combiner.

A. RF Balun Imperfections

Integrated baluns will have both gain and phase unbalance, resulting in non-ideal signal drive for the Gilbert Cell mixer. The effect on the mixing process due to RF balun imperfections can be investigated assuming a gain unbalance a and phase unbalance ϕ. If single-ended output current ($I_{01} = I_3 + I_5$) is taken and higher order terms are neglected the mixing process results in

$$I_{01} = g_m V_{rf}\sqrt{a^2+\phi^2}\cos(\omega_{rf}t) + \frac{2}{\pi}g_m V_{rf}\left(1+\frac{a}{2}\right)\cos\left((\omega_{lo}\pm\omega_{rf})t \pm \frac{\phi}{2}\right) \quad (1)$$

for small gain and phase unbalance. Here g_m is the small-signal transconductance of the lower devices of the Gilbert Cell mixer, V_{rf} is the amplitude of the applied RF signal, and ω_{rf} and ω_{lo} are the angular frequency of the applied RF and LO signal respectively. This equation shows RF leakage along with upper and lower sidebands at $\omega_{lo} \pm \omega_{if}$. The LO leakage is fully suppressed in this case. If instead differential output current ($\Delta I_0 = (I_{01} - I_{02})/2$) is considered the RF leakage is suppressed and the mixing process is represented as

$$\Delta I_0 = \frac{2}{\pi} g_m V_{rf} \left(1 + \frac{a}{2}\right) \cos\left((\omega_{lo} \pm \omega_{rf})t \pm \frac{\phi}{2}\right). \tag{2}$$

It is observed that any gain and phase unbalance in the RF balun are transferred to the frequency converted signals. If either the gain unbalance or phase unbalance varies over the frequency band of interest transfer function distortion occurs and degrades the performance of the SAR system.

B. LO Balun Imperfections

LO balun imperfections are modeled similar to RF balun imperfection with a gain unbalance a and phase unbalance ϕ. The single-ended output current which result from the mixing process in this case becomes

$$\begin{aligned} I_{01} = \quad & \gamma \sqrt{a^2 + \phi^2} \cos(\omega_{lo} t) + \\ & \tfrac{2}{\pi} g_m V_{rf} \cos((\omega_{lo} \pm \omega_{rf})t) \end{aligned} \tag{3}$$

for small gain and phase unbalance. The LO leakage coefficient γ describes the forward transmission path through the gate-drain capacitances of the upper devices of the Gilbert Cell mixer. If differential output current is considered the mixing process is represented as

$$\Delta I_0 = \frac{2}{\pi} g_m V_{rf} \cos((\omega_{lo} \pm \omega_{rf})t). \tag{4}$$

and the LO leakage is fully suppressed.

In order to verify the modeling of LO balun imperfections simulation on a GaAs pHEMT active mixer has been performed with ideal RF balun. The LO balun is modeled with gain and phase unbalance, and the resulting LO leakage to a single-ended IF port is observed. The LO-IF isolation at 6.65 GHz LO frequency versus phase unbalance is shown in Fig. 2 for three different values of gain unbalance. Fig. 2 is used to specify the amount of gain and phase unbalance allowed in the LO balun in order to meet the requirements on LO-IF isolation. If a combiner is applied at the IF port the requirements on LO-IF isolation can be met at relaxed LO balun specifications, depending on the gain and phase unbalance for the combiner.

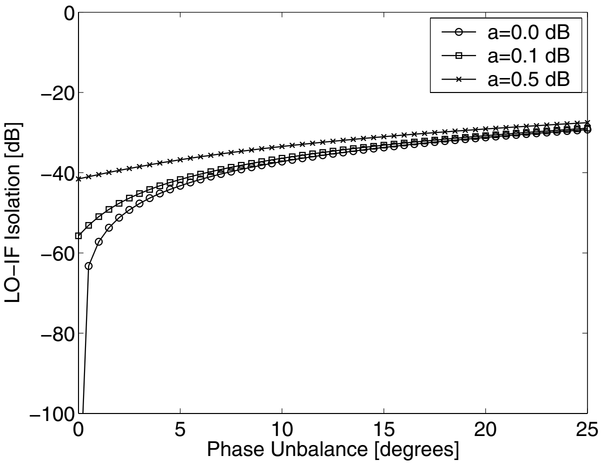

Fig. 2. LO-IF isolation at $6.65GHz$ LO frequency versus LO balun phase unbalance for different values of gain unbalance.

III. Circuit Design

An active balun for the GaAs pHEMT active mixer should in addition to requirements on gain flatness and phase linearity exhibit good wideband impedance match, low noise figure and low gain and phase unbalance. Following the previous discussion, also the variation of the gain and phase unbalance over the frequency range of interest should be low in order to prevent transfer function distortion. A schematic of an active balun design based on the phase inverter configuration [7] is shown in Fig. 3. A device in a common-gate configuration provides wideband active impedance match to 50Ω. An peaking inductance is included in series to the gate of the phase inverter device to extend the usable frequency range for the active balun. The value of this inductance is carefully optimized for gain flatness and phase linearity. A transmission line following the source output of the phase inverter device implements a phase adjustment circuit.

In Fig. 4 a schematic of the Gilbert cell mixer and an active output combiner circuit is shown. Inductors are added in series with the load resistors of the Gilbert Cell mixer to compensate the high-frequency degradation of the conversion gain due to capacitive loading at the output. An active combiner is needed at the output of the Gilbert Cell mixer in order to reduce the LO leakage, caused by LO balun imperfections, from reaching the output port. An active combiner design based on source follower stages and a differential amplifier output stage is shown in Fig. 4. Level shift diodes are inserted in the source follower stages to provide the necessary bias for the differential amplifier stage. The series resistance components of the level shift diodes degrades the frequency response of the source follower stages. Therefore a capacitor is shunted across the diodes to provide a short for the high-frequency signal. This permits an increase in high-frequency gain and expansion of the bandwidth [8]. The differential amplifier stage is degenerated with source resistors for increased linearity and wideband operation. An open drain arrangement is used at the output because this allows for the beneficial use of the bond inductance for further extension of the output port bandwidth.

IV. Experimental Results

The designed active mixer was realized in a 0.2μm, 63 GHz f_T GaAs pHEMT process with a maximum transconductance of 680 mS/mm. A photograph of the active mixer is shown in Fig. 5. The die size is 1.5 mm by 2.0 mm. The on-wafer measured downconversion gain and LO-IF isolation for the active mixer versus RF frequency at fixed IF frequency of 1.25 GHz are

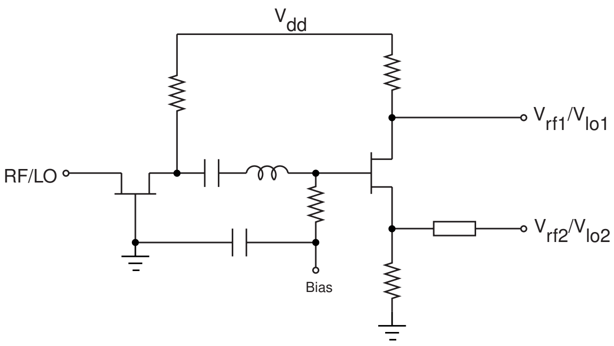

Fig. 3. Active Balun based on the FET phase inverter configuration.

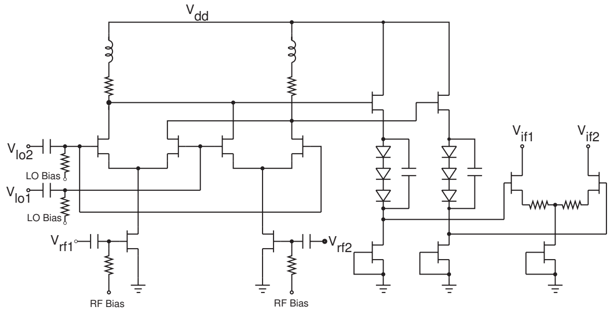

Fig. 4. Gilbert Cell mixer with reactive loads and active output combiner.

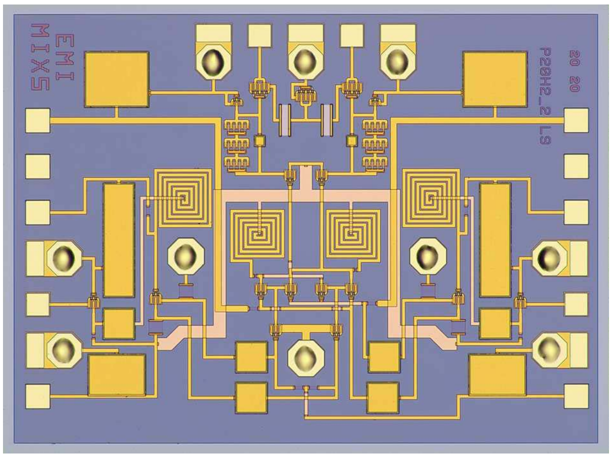

Fig. 5. Photograph of the active mixer.

shown in Fig. 6. A conversion gain of approximately 10 dB with a 3 dB bandwidth of 9.5 GHz is obtained at a LO power of 10 dBm. The bandwidth is limited by the self-resonance frequency of the peaking inductors in the active baluns. The LO-IF isolation is around -25 dBm over the RF bandwidth which indicates asymmetry in the layout or LO balun imperfections. The power consumption of the circuit is 320mW when biased at +5 V. The 1 dB conversion gain compression point occurs at an input power of -5 dBm.

In order to demonstrate the usefulness of the designed GaAs pHEMT active mixer for wideband SAR systems, the conversion gain was measured versus RF frequency with fixed LO frequency at 6.65 GHz as shown in Fig. 7. The conversion gain variation over an 800 MHz bandwidth is within ± 0.25dB. Thus the active mixer is

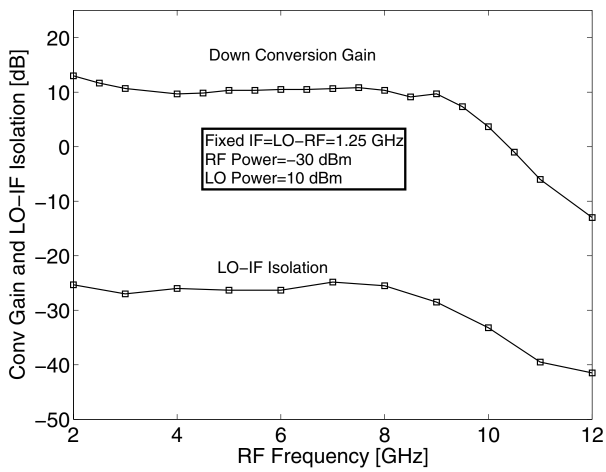

Fig. 6. Measured downconversion active mixer performance.

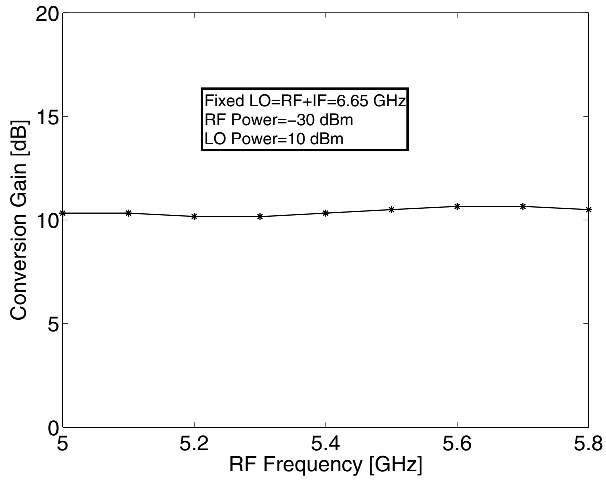

Fig. 7. Measured wideband downconversion active mixer performance.

capable of frequency conversion of linear FM-modulated signals from C- to L-band over a large bandwidth as required in wideband SAR systems.

V. Conclusions

The design and performance of a highly integrated GaAs pHEMT active mixer for wideband SAR systems has been reported. Experimental results demonstrates the usefulness of the design for downconversion of wideband linear FM-modulated signals.

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