The Wideband High-Linearity Mixers for Cable Television Tuner Application

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Abstract—The wideband high-linearity mixers for a double conversion cable TV tuner is presented. The up-conversion mixer converts the input signal from 100MHz to 1000 MHz to the intermediate frequency (IF) of 1 GHz above. And the down-conversion mixer converts the frequency back. The degeneration resistors are used to improve the linearity. The tuner is implemented in a 0.35μm SiGe technology. Input power at 1dB compression point can reach +14.23dBm. The lowest noise figure is 17.5dB. The two mixers consume 103mW under a supply voltage of 5 V.

I. INTRODUCTION

The tuner in front of the TV Set-Top-Box is a necessary part of the product. Due to the difference of the transmission, there are terrestrial digital TV, satellite digital TV and cable digital TV, which decides the distinct performance of the tuners. As the terrestrial signal is comparatively weak, the tuner should be sensitive with the noise figure, and have a much higher gain in a wide band. The satellite tuner is familiar with the former. However, the cable tuner is linked directly to the cable, so the signal is much stronger. The tuner requires input impedance match in the whole wide band. Any way, all tuners need a low phase noise, and high linearity will be always a critical demand [1].

Nowadays, the TV tuners are mostly realized through two frequency conversions. Firstly, the input signal is amplified by an auto gain control (AGC) or a low noise amplifier (LNA). Then the radio frequency (RF) signal is up converted to a certain intermediate frequency (IF). This uses a SAW filter outside the chip to reject the image of the down conversion. The received signal is down converted to a much lower IF, which is amplified and transmitted out of the chip for modulation. This paper focuses on the design and analysis of both the up and down conversion mixers [2].

II. CIRCUIT ANALYSIS

A. Up and Down Conversion Mixer Topologies

For the mixer input frequency is from about 100MHz to 1000 MHz, linearity is rather important for the wide band design. Compared various kinds of the mixers, the Gilbert mixer structure is selected, which has a better isolation, low noise figure, and larger conversion gain [3]. The structure of the mixers is illustrated in Fig.1.

![Figure 1. Structure of mixers for tuner application](image)

B. Input Impedance match

For the RF input frequency is a wide band, the input impedance match should be achieved without any inductance. The small signal model of the RF input stage is shown in Fig.2.

Since the RF input stage uses resistor as emitter degeneration, its input impedance could be expressed as (1).

$$R_i = [r_{be} + (1 + \beta)R_e]/2$$  \hspace{1cm} (1)
So the RF input impedance of the mixers will be fairly high, typically in the order of a kilohm. If the input sources, such as LNA or the SAW filter have low output impedance, the wide-band match is realized by the high impedance matching with the low source impedance. In most situations, the LNA output impedance will be 50 Ω, and the SAW filter output impedance will be 200 Ω differential, so the source impedance is low enough to satisfy the condition.

C. Current Injection Structure

Usually, the LO input need not be linear, since the LO is clean and of know amplitude. In fact, the LO input is always designed to switch the upper quad. More formally, if \( v_{LO} > 2V_T \), then the operation of the LO signal can be treated as a switch function \( u(v_{LO}) \), which is

\[
u(v_{LO}) = \begin{cases} 1 & \text{if } v_{LO} \text{ is positive} \\ -1 & \text{if } v_{LO} \text{ is negative} \end{cases}
\]

\( u(v_{LO}) \) can be expressed as a Fourier series. If \( v_{LO} \) is a sine wave with frequency \( \Omega_{LO} \), then

\[
u(v_{LO}) = \frac{4}{\pi}v_{RF} \sin(\Omega_{RF}t) + \frac{4}{3\pi}v_{RF} \sin(3\Omega_{RF}t) + \frac{4}{5\pi}v_{RF} \sin(5\Omega_{RF}t) + \ldots
\]

In the frequency domain, the function of the mixer is using each of the Fourier components of the square wave to modulate the RF signal. So the output amplitude of the product of the fundamental component of square wave is

\[
v_i = \frac{4}{\pi}v_{RF} \sin(\Omega_{RF}t) \sin(\Omega_{LO}t) = \frac{1}{2} \frac{4}{\pi}v_{RF} \sin(\Omega_{RF} + \Omega_{LO})t + \frac{1}{2} \frac{4}{\pi}v_{RF} \sin(\Omega_{RF} - \Omega_{LO})t
\]

\( v_i \) is the output voltage of the mixer, \( v_{RF} \) is the input voltage to the mixer, \( v_{RF} \) is the input voltage to the mixer, \( \Omega_{RF} \) is the fundamental component of square wave and \( \Omega_{LO} \) is the LO frequency component.

Thus, a useful estimate of gain in a mixer (at one output frequency component) is the following:

\[
\frac{v_i}{v_{RF}} = \frac{2}{\pi} \frac{R_c}{r_e + R_E}
\]

(5)

Here, \( R_c \) is the load resistor of the mixer, such as \( R_t \) and \( R_e \) in Fig. 1. \( r_e \) is the emitter resistor of the RF transistors.

Note that in (5), the voltage conversion gain is in direct proportion to \( R_c \), so \( R_c \) is hoped to be large to get a considerable conversion gain. Simultaneously, the bias current in \( Q_t \) and \( Q_e \) should be large to increase the linearity and to diminish the noise from the RF stage. However, this will lead to increase the voltage drop on the load resistors and switch transistors, and result in excursion of the bias.

To allow independent values of collector currents in \( Q_4 \sim Q_4 \) and \( Q_5 \sim Q_5 \), a current injection structure can be added as shown in Fig. 1. If, for example, \( I_i \approx 0.8I_{C5} \), then the collector currents of \( Q_1 \) and \( Q_3 \) are lowered by a factor of 5. Furthermore, for a given allowable voltage drop across \( R_t \), the value of the load resistors can be increased by a factor of 5, which raises the voltage conversion gain.

III. PERFORMANCE ANALYSIS

A. Linearity

In the wide-band situation, such as tuner for TVs, the linearity is the most important characteristic for mixer. The mixer analyzed in this paper is a high-linearity mixer and the most important contributions to the linearity come from the degeneration resistors and the attenuation resistors. The presented linearity analysis is valid under the small signal condition. Accurate linearity analysis can be obtained using techniques such as Volterra series [4].

In this analysis, third-order intercept point (IIP3) is used to scale the linearity of the mixer. Mathematically, any nonlinear transfer function can be written as a series expansion of power terms:

\[
v_{out} = k_0 + k_1v_{in} + k_2v_{in}^2 + k_3v_{in}^3 + \ldots
\]

(6)

In most situations, the input power at the IIP3 point (IIP3) is used to express the linearity. The input voltage at the third-order intercept point is used to discuss the linearity in this paper. The relation between the coefficients in (7) with the input voltage at the third-order intercept point is as follows:

\[
v_{IP3} = 2\sqrt[3]{\frac{k_1}{3k_3}}
\]

(7)

Fig. 3 shows the small signal model of the input stage. In this paper, the single side input stage is analyzed. The coefficients \( k_1 \) and \( k_3 \) should be determined from the model.
The output voltage is in proportion to $v_{be}$. The expression for $v_{be}$ can be achieved from the small signal model as follows:

$$v_{be} = V_T \ln \left(1 + \frac{i_e}{I_c}\right) = V_T \left[\frac{i_e}{I_c} - \frac{1}{2} \left(\frac{i_e}{I_c}\right)^2 + \frac{1}{3} \left(\frac{i_e}{I_c}\right)^3 + \ldots\right]$$

(8)

The expression of $i_e$ can be got from small signal model. Then the coefficients $k_1$ and $k_3$ can be achieved:

$$k_1 = \frac{1}{R_e + \frac{R_b}{\beta} + r_e}$$

$$k_3 = \frac{1}{(R_e + \frac{R_b}{\beta} + r_e)^3} \left[2I_e^2 (R_e + \frac{R_b}{\beta} + r_e) - \frac{r_e^2}{3I_e^2}\right]$$

(9)

(10)

The $r_e$ represents the emitter impedance of the bipolar transistor. The coefficients $k_1$ and $k_3$ in (7) is replaced by (9) and (10). The input voltage at the third-order intercept point is achieved.

$$v_{IP3} = 2\sqrt{2} V_T \left(\frac{R_e + \frac{R_b}{\beta} + r_e}{3I_e}\right)^3$$

(11)

For the differential input stage, the input voltage at the third-order intercept point has an extra factor of 2. The (11) shows that the degeneration resistor $R_e$ can improve the linearity dramatically. The attenuation resistor $R_e$ in the down-conversion mixer can also improve the linearity.

B. Noise Figure

Noise figure will be largely determined by the choice of the topology of the mixer. And the simultaneous matched design could keep the noise at the lowest level. However, some other factors cannot be avoided to add noise to the output. The noise components mainly exist in the RF stage before the conversion and IF stage after the conversion.

As depicted in Fig.5, in the RF stage, the primary components contributing noise are the thermal noise due to the base resistances of $Q_3$ and $Q_6$, and the emitter resistor, $R_3$ and $R_4$. In the IF stage, the load resistors $R_2$ and $R_5$ will introduce thermal noise. All noise sources are assumed to be white and uncorrelated. The resulting noise power spectral (S) of components are [5]:

$$S(v_b) = 4kTb$$

(12)

$$S(v_e) = 4kTR_e$$

(13)

The equations (12) and (13) show how much noise power spectral the attenuation resistor and the degeneration resistor produce.

C. Voltage Conversion Gain

The current injection structure could increase the load resistor of the up-conversion mixer, $R_1$ and $R_2$, but for the consideration of linearity, a much larger emitter degeneration resistor is applied. So, the gain of the up-conversion mixer is reduced as shown in (5), the estimate of gain.

For the down-conversion mixer, in Fig.3, the single side input stage is analyzed. An equation for the estimate of the gain is

$$A_c \approx \frac{\beta R_e}{\beta R_c + R_b + R_e}$$

(14)

Here, $R_c$, $R_e$, $R_b$ stand for the attenuation resistor, degeneration resistor and the load resistor respectively.

The result shows that both the degeneration resistor and the attenuation resistor reduce the voltage conversion gain.

IV. MEASURED RESULT

The wideband high linearity mixers for tuner applications are fabricated in 0.35um SiGe BiCMOS technology. Fig.2 shows that the measured input power at 1dB compression point of up-conversion mixer is 12.16dBm when the IF is 1.5GHz. The measured input power at 1dB compression point of down-conversion mixer can reach +14.23dBm which is shown in Fig.3.
TABLE I. MEASURED RESULT OF THE MIXERS

<table>
<thead>
<tr>
<th></th>
<th>Up-Conversion</th>
<th>Down-Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage conversion gain (dB)</td>
<td><a href="mailto:0.7@1.9GHz">0.7@1.9GHz</a></td>
<td>8.31@700MHz</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>17.5(min)</td>
<td>17.5(min)</td>
</tr>
<tr>
<td>P_{1db} (dB)</td>
<td>12.16</td>
<td>14.23</td>
</tr>
<tr>
<td>IIP3 (dB)</td>
<td>+21.76</td>
<td>+23.83</td>
</tr>
<tr>
<td>Power Consumption (mW)</td>
<td>47</td>
<td>54</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The paper introduced the wideband high-linearity mixers for cable tuner application. The experimental results show that the linearity of the mixers is improved dramatically by the degeneration and attenuation resistors. The degeneration and the attenuation resistors should be added according to the gain and noise demand of the whole system. In the allowable range, the resistors can improve the linearity remarkably and have little influence on the voltage gain and the noise figure. Also, the current injection structure has improved the gain. The die area displayed in Fig. 6 occupies 1.15mm X 0.47mm.

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REFERENCES