Research article
DOI: https://doi.org/10.18721/JCSTCS.14403
UDC 621.374.44

HIGH LINEARITY UP-CONVERSION MIXER

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Abstract. Mixer is a fundamental block of the transmitter path exerting great influence on the transmitter linearity level. This article is concerned with a method to enhance the linearity of the Gilbert cell mixer using several parallel-connected differential pairs in an attempt to reduce a variation in incremental transconductance with respect to an input signal amplitude. As part of the study, a Gilbert cell with two parallel-connected differential pairs and a Gilbert cell with three parallel-connected differential pairs were designed and simulated. Both concepts demonstrate an increase in *OIP*3 value in comparison with a classical Gilbert cell. We used a Si-Ge component library with a design rule of 130 nm. The simulations were conducted in the CAD Advanced Design System.

Keywords: mixer, Gilbert cell, BiCMOS, nonlinear distortion, multi-tanh principle, *OIP*3

Citation: Panovitsin N.E., Balashov E.V. High linearity up-conversion mixer. Computing, Telecommunications and Control, 2021, Vol. 14, No. 4, Pp. 29–36. DOI: 10.18721/JCSTCS.14403

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Научная статья
DOI: https://doi.org/10.18721/JCSTCS.14403
УДК 621.374.44

ПОВЫШАЮЩИЙ СМЕСИТЕЛЬ С ВЫСОКОЙ ЛИНЕЙНОСТЬЮ

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Аннотация. Смеситель является основным блоком тракта передатчика и во многом определяет линейность передатчика в целом. Рассмотрена методика повышения линейности смесителя Гильберта за счет использования нескольких параллельно включенных дифференциальных пар для уменьшения зависимости передаточной проводимости от амплитуды входного сигнала. В ходе исследования разработаны и промоделированы смеситель Гильберта с двумя параллельно включенными дифференциальными парами и смеситель Гильберта с тремя параллельно включенными дифференциальными парами. Оба схемотехнических решения продемонстрировали увеличение параметра *OIP*3 по сравнению со стандартной схемой Гильберта. При разработке использовалась библиотека компонентов, выполненная по Si-Ge технологии с проектной нормой 130 нм; анализ работы проводился в САПР Advanced Design System. Полученные результаты могут применяться при разработке смесителя в составе приёмо-передающей системы, когда необходимо выполнение высоких требований по уровню нелинейных искажений.

Ключевые слова: смеситель, ячейка Гильберта, БиКМОП, нелинейные искажения, мультитангенсальный принцип, *OIP*3

Для цитирования: Panovitsin N.E., Balashov E.V. High linearity up-conversion mixer // Computing, Telecommunications and Control. 2021. Т. 14, № 4. С. 29–36. DOI: 10.18721/JCSTCS.14403

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Introduction

Frequency mixer is one of the key blocks in radio frequency paths of receivers and transmitters, with its functional parameters determining the performance of the radio frequency path as a whole. A good example of this is wireless communication systems for the civil use, which should demonstrate enhanced functional parameters as the working frequency range is limited, while the simultaneous number of communication channels belonging to this range is growing. In this case, there are special requirements posed to the linearity characteristics of the up-conversion mixer, because the neighboring channels may overlap due to intermodulation distortions leading to degradation of the communication quality. This paper is devoted to the development of an up-conversion mixer with high linearity for the Ku frequency band.

The purpose of this article consists in designing a high-linearity up-conversion mixer. To achieve this goal, the paper solves the following tasks: development of the circuit diagram for the high-linearity mixer; simulation of the circuit diagram for the high-linearity mixer; comparison of the modified Gilbert cell mixer with the parameters of the standard Gilbert cell mixer.

Gilbert cell

To realize the high-linearity mixer, we chose Gilbert cell circuit as a prototype [1–6]; its diagram is presented in Fig. 1. A mixer of the Gilbert cell circuit has double balanced structure, which allows canceling parasitic harmonics at the input signal frequency, local oscillator frequency and direct-current components [7, 8].

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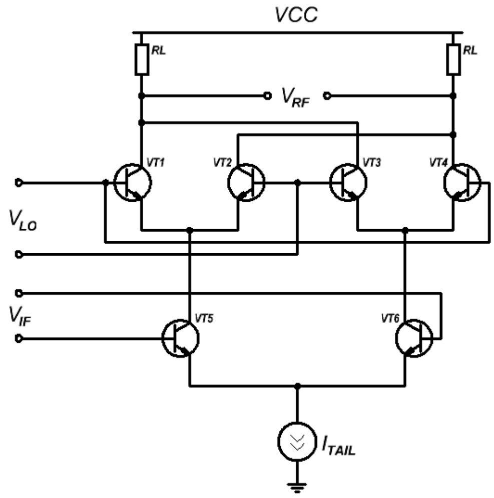

Fig. 1. Circuit diagram of Gilbert cell

We assumed the following operation mode of the mixer: four upper transistors $VT1$–$VT4$ work in the large-signal mode; the differential pair ($VT5$, $VT6$) works in the small-signal mode. In this mode, the output signal voltage of the mixer has the form:

$$v_{RF}(t) = -i_{OUT}(t) R_L = -R_L I_{TAIL} \tanh\left(\frac{v_{IF}}{2\phi_T}\right) \times s_{LO}(t),$$

where $s_{LO}(t) = \pm 1$ – local oscillator signal; v_{IF} – voltage of the desired input signal at the intermediate frequency; R_L – ohmic part of load impedance; $\phi_T = 26$ μV – thermodynamic potential at $T = 300$ K. After analyzing the expression, we can see the local oscillator signal $s_{LO}(t)$ ensures the current switching between two arms and is not the source of non-linearity; the voltage of the desired signal $v_{IF}(t)$ is an argument of a non-linear function, which describes the output signal of the differential pair. Thus, as the linearity parameter of the differential pair increases, so does the overall linearity of the mixer, and as a result the non-linear distortions decrease.

Multi-tanh principle

The task of enhancing the linearity of the differential pair is achieved by means of introducing the so-called multi-tanh principle to the Gilbert topology [9–12]. The circuit realization of this principle lies in parallel connection of N differential pairs to the input and the output. Each pair is characterized by coefficient of proportionality $A = A_1/A_2$, where A_1 and A_2 are the areas of the base-emitter p–n junction of the first and the second transistors in the differential pair, and the value of the differential pair biasing current. Using transistors with different emitter areas, we can change the input voltage providing maximum transconductance of the differential pair. The transconductance function of the differential pair depending on the input voltage for this case has a form:

$$g_m(V_{IN}) = \frac{dI_{OUT}}{dV_{IN}} = \frac{I_{EE}}{2\phi_T} \operatorname{sech}^2 \frac{(V_{IN} + \Delta V_{BE})}{2\phi_T},$$

where ΔV_{BE} – difference between base-emitter voltages of the differential pair transistors; V_{IN} – voltage of the input differential signal; I_{EE} – bias current of the differential pair; ϕ_T – thermodynamic potential; I_{OUT} – differential current at the differential pair output. The ΔV_{BE} voltage defines the V_{IN} voltage at which

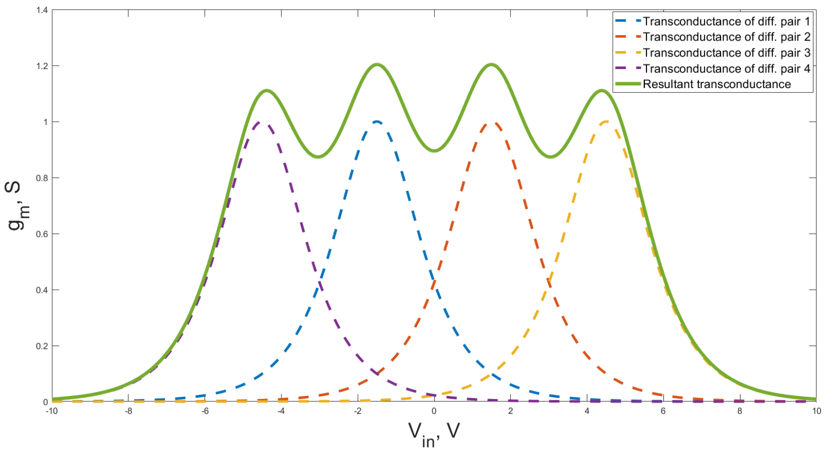

Fig. 2. Resultant transconductance function depending on input voltage

the transconductance of the differential pair reaches its maximum. With the parallel connection of N differential pairs, the resultant transconductance is composed of the transconductances of each differential pair. If the maxima of the transconductances of the differential pairs are achieved at different values of the input signal, then a decrease in transconductance of one differential pair is compensated by an increase in another pair. This smooths the dependence of the resultant transconductance in a certain range of the input voltage reducing non-linear distortions. Fig. 2 shows this effect for a case of $N = 4$.

Development and modeling of the mixer circuit diagram

In the course of the study, we carried out a comparative analysis of the circuits of up-conversion mixers with and without the use of the multi-tanh principle. For this, we developed and modeled three mixer circuits: a conventional Gilbert cell and mixers with two and three differential pairs. The parameters of greatest interest that were obtained during the simulation are the point of intersection of the linear dependences of the output powers of the fundamental component and third-order intermodulation distortion (OIP3) [13–15] and the bias current value of the differential pair. The OIP3 parameter is calculated by analyzing the power of the fundamental tone at the ω_{RF} frequency and the power of the third-order intermodulation distortion in the output signal when a two-tone signal is supplied to the mixer input. For comparative analysis, all topologies have the same supply voltage $V_{EE} = 3.3$ V, the ohmic part of the load impedance $R = 100$ Ohm, and the bias current of each differential pair.

At the first stage of development, we built and simulated a standard Gilbert cell circuit. The performance indicators of the classical Gilbert cell are presented in Table 1. As a result of the DC analysis of the circuit, the transconductance function g_m was obtained in dependence on the input signal voltage V_{IN}. The resulting dependence shown in Fig. 5 corresponds to the mathematical description of a standard differential pair. The linear properties of the mixer are characterized by a point value of $OIP3 = 2.3$ dBm.

At the second design stage, we developed another mixer circuit by introducing two differential pairs connected in parallel. Each differential pair carries a bias current of $I_{TAIL} = 2.4$ mA, which is equal to the bias current of the differential pair in the classical Gilbert cell. We chose 32 as the ratio of the emitter areas A of the differential pairs transistors. The circuit diagram of the resulting mixer is shown in Fig. 3.

The bias voltages of the transistors of the differential pairs were determined using optimization according to the criterion of maximizing the OIP3 parameter. The resulting function of the transconductance of the NPN differential pair in dependence on the input voltage was obtained after the DC analysis, the results are shown in Fig. 5. The curve is characterized by two distinct maxima of the transfconductance corresponding to each differential pair; we can observe that the region of a relatively weak change in the

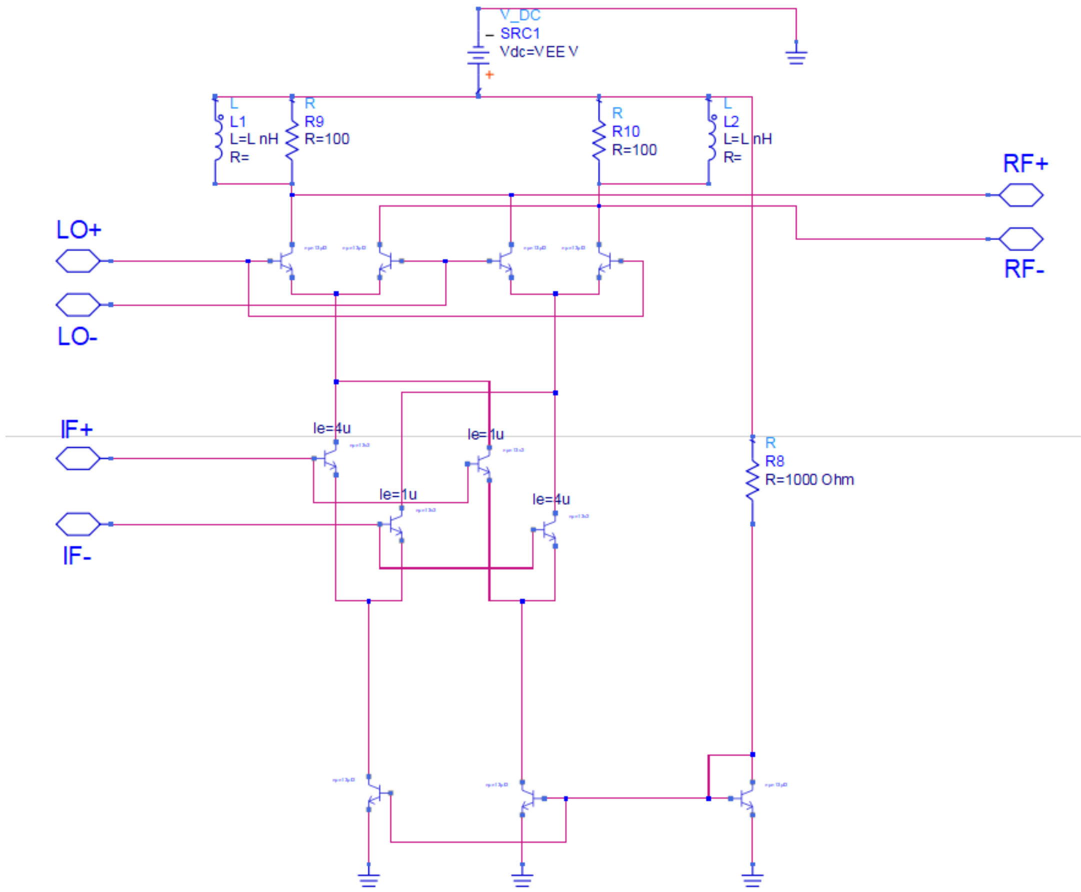

Fig. 3. Circuit diagram of mixer with two differential pairs

value of the transconductivity g_m is expanding, which indicates an increase in linearity. The linearity of this mixer after analysis with a two-tone signal is $OIP3 = 7.71$ dBm.

At the third stage, we designed an um-conversion mixer circuit employing three differential pairs connected in parallel at the input and output. The circuit diagram of the developed device is shown in Fig. 4.

In the presented diagram, the left and right differential pairs have a coefficient of proportionality of the emitter areas $A = 32$, due to which the voltage ΔV_{BE} is approximately equal to 200 mV; the central differential pair is formed by transistors with the same emitter area, due to which the maximum transconductance is achieved at zero input voltage. The resulting transconductance function depending on the input signal is shown in Fig. 5.

The function is characterized by a relatively flat transconductance section for the amplitude of the input signal in the range of $\Delta V_{IN} = 500$ mV. The bias current of the outermost differential pairs is the previous value of $I_{TAIL} = 2.4$ mA. The bias current of the middle differential pair has been slightly increased to 2.65 mA to reduce the ripple of the $g_m(V_{IN})$ function, which further improves linearity. The indicator of the level of nonlinear distortion $OIP3 = 8.81$ dBm.

Fig. 5 shows the transconductance functions g_m versus the input signal voltage V_{IN} for the three developed mixer topologies. The graph clearly shows the extension of the input voltage range V_{IN}, in which the transconductance g_m changes relatively slightly, as the circuitry solution becomes more complex: from turning on an ordinary differential pair to turning on three parallel differential pairs. The results of the three mixers are shown in Table 1.

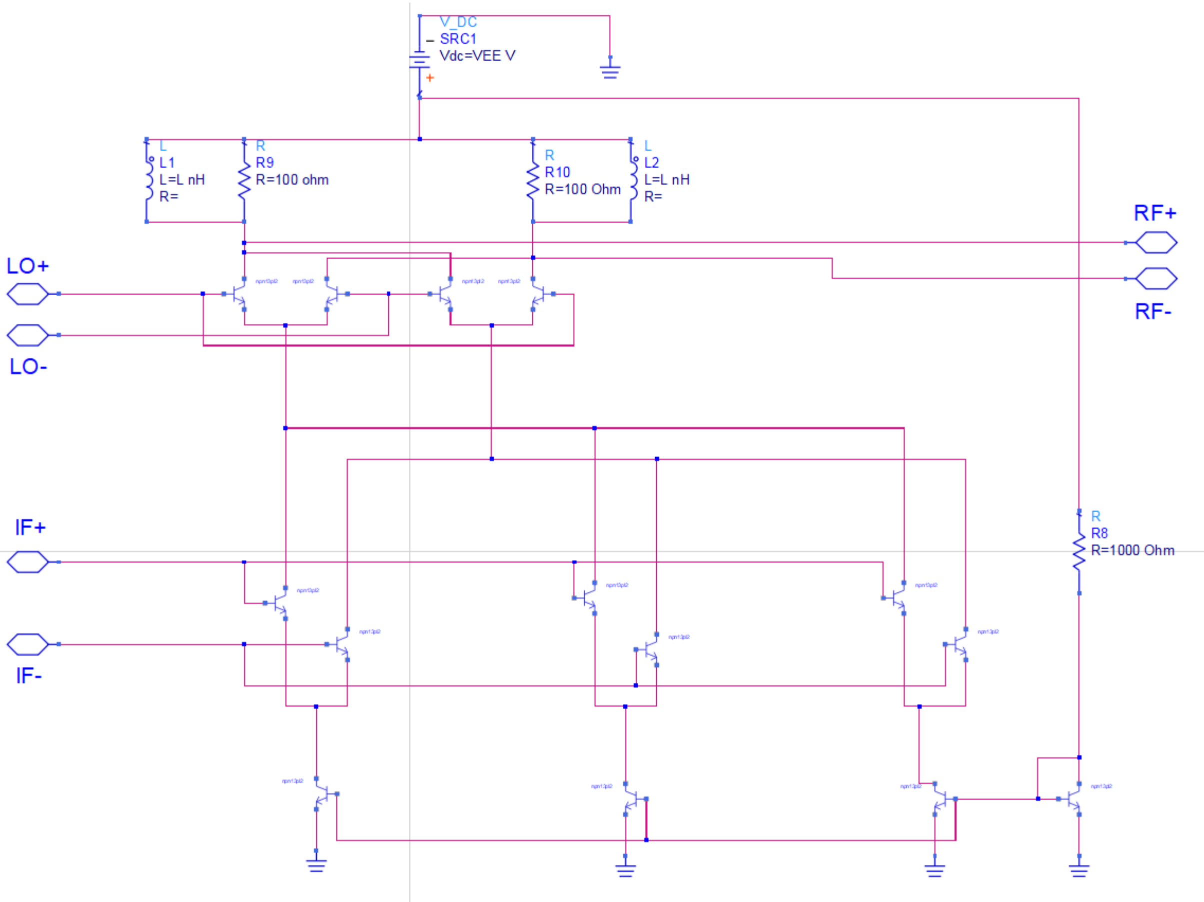

Fig. 4. Circuit diagram of mixer with three differential pairs

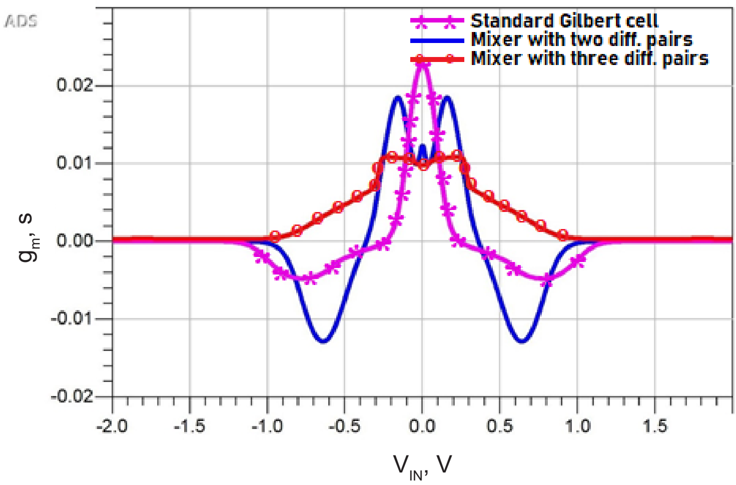

Fig. 5. Transconductance functions of three different mixers

Table 1

Results of mixers modeling

	V_{CC}, V	$OIP3$, dBm	G, dB	I_{TOTAL}, mA
Standard Gilbert cell	3.3	2.3	9.2	2.38
Mixer with two diff. pairs	3.3	7.71	5.39	4.76
Mixer with three diff. pairs	3.3	8.81	4.88	7.14

Conclusion

The results show a 6.51 dB improvement in $OIP3$ with a three differential pair mixer and 2.41 dB with a two differential pair mixer. With an increase in the degree of linearity, there is a natural decrease in the conversion gain; for a circuit with three differential pairs, the gain dropped by 4.32 dB. As the circuitry becomes more complex, the total mixer current increases, which is determined by the sum of the bias currents I_{TAIL} of each differential pair.

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The article was submitted 30.11.2021; approved after reviewing 15.12.2021; accepted for publication 22.12.2021.
Статья поступила в редакцию 30.11.2021; одобрена после рецензирования 15.12.2021; принята к публикации 22.12.2021.