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Research Article

Analysis and design of an active CMOS mixer with low non-linear effects (Second and third order)

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ABSTRACT

In this paper the non-linear effects in the output of the synchronic mixer has fallen by using a transitional guidance class with low second and third-order distortion. Analysis of structure using Taylor nonlinear analysis led the some equations which make the optimum design of the circuit possible. Simulation results carried out in ADS simulator in 0.18um CMOS technology, show that in radio frequency of 900MHz, IIP2 and IIP3 values of the mixer which indicate linearity of the circuit, have improved by 16 dB and 6dB over the base model with the proposed method and the supply voltage provided in the mixer is approximately 1.8V. The results show that in the provided structure, the IIP2 and IIP3 have increased simultaneously while in other articles just one of the values of IIP2 or IIP3 increased or provided a structure in which the second and third order nonlinearity reduce at the same time but increment of the noise due to the addition of capacitors was one of their disadvantages which was solved in the proposed model. The results of the proposed and provided structures are investigated for 4 mA bias current. Compared with previous models, the main advantages of this structure are the simultaneous increase of IIP2 and IIP3 and low power.

Keywords: Gilbert Cells , IIP2, IIP3, IM2, IM3, Second and third order nonlinear effects

INTRODUCTIO

Demands for wireless communication systems has increased significantly in recent years and one of the most important components used in Zero-IF receivers is mixer (Pozar, 1997). The main function of a mixer is frequency conversion. Using CMOS technology in radio frequency RF circuits to remove the intermediate modulation class (IF) creates some challenges, one of which is non-linearity. Since the mixer circuits are nonlinear, when two frequency enters the mixer, several different frequency distortions will be produced in the mixer output. Although most of the distortion components are outside of the desired signal and can be eliminated by the filter in the receiver circuit, but some of the harmful effects maintain within the signal bandwidth and cause data disruption. If the two input frequencies are close together, the components of second and third intermodulation (IM2 & IM3) are located near or within the signal bandwidth and linearity of circuit performance decreases (Rofougaran, 1997).

Various methods have been tried to solve this problem. A number of the ways of reducing the nonlinear effects are as follows.

Injecting controllable, nonlinear current is into the output of the mixer (Vahidfar and Shoaei, 2008)

In this method, the generator block of the IM2, converts the produced $I_{IM2,cm}$ in the transconductance to the differential mode and by controlling it by Gm, injects a differential current equal and against the second order non-linear effects to the output of the and as a result, second order nonlinear effects will be decreased. The disadvantages of the proposed structure includes: not increment of (IIP3) complexity of the structure, and high power consumption due to the calibration system of injecting the noise of calibration system into the output and increment of output noise.

Injecting Second order nonlinear effects to the output of the pseudo-differential transconductance (Vahidfar and Shoaei, 2007)

In this method, since most non-linear effects are produced in, second order nonlinear effects will be deleted by injecting the second order nonlinear effects into the the transconductance output and the current is controlled by a wide bandwidth feedback loop. This elimination method is suitable for wide bandwidth applications of multi-standard mixers.

Linearization by adding a multiplier blocks (Bautista et al, 2000)

In this method, by adding high-frequency multiplier blocks, nonlinear elements and interference signal are transmitted to higher frequencies outside the baseband signal and removed by the filter. The problems of this structure are thermal noise increase due to a rise in the number of transistors and that the sqµAre signals in real terms may not be in the same phase and this decreases the (IIP2).

- *DS Method*

In this method which third order nonlinear effects are reduced, two parallel main and auxiliary transistors with different gate-source voltage are used and the amount of transconductance is set ate the point in which a total third order nonlinear effects is zero.

Fusion method (Brandolini et al, 2006)

The procedure shown in figure 1 is to simultaneous reducing the second and third order nonlinear effects. In this method, the transistors because of the low common gain, have high IIP2 and due to the voltage leakage of source to the gate, their IIP3 is low at low frequencies and because of high common gain have low IIP2 and high IIP3, but in the proposed structure, the noise is increased because the size of the capacitors are large.

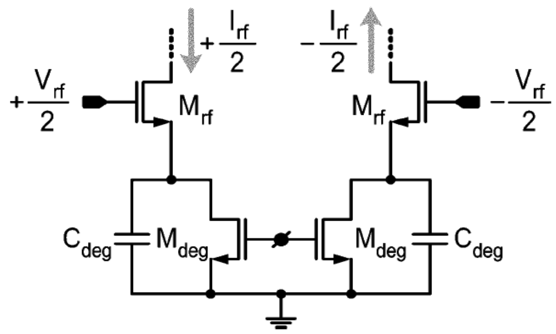


Figure1. Transconductance of Fusion circuit

The purpose of this article is designing a low conversion mixer with high linearization. Therefore, the main focus is on designing a transconductance with reduced second and third order harmonic distortion. Some measures are provided to bring down the non-linear effects (IM2 and IM3) in differential mixers (DCR).

Theory and analysis

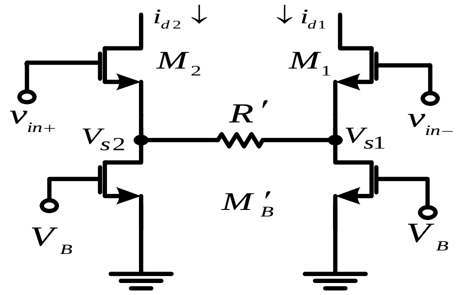


Figure2. Differential couple with resistance degeneration

In Figure2, the Taylor series expansion of nonlinear transistor output current according to the input signal (V_{RF}=V_{in}) and (-V_{RF}= -V_{in}) are expressed due to Eq1 in which A'_1, B'_1 are first order transconductance, A'_2, B'_2 second order transconductance and A'_3, B'_3 the third order transconductance of differential couple.

(1)

$$i_{d1} = A'_1\left(-v_{in}\right) + A'_2\left(-v_{in}\right)^2 + A'_3\left(-v_{in}\right)^3 + ..$$
$$i_{d2} = B'_1\left(+v_{in}\right) + B'_2\left(+v_{in}\right)^2 + B'_3\left(+v_{in}\right)^3 + ..$$

Current-voltage characteristics of the transistors using a Taylor series expansion is expressed as Equation 2.

$$i_{d1} = g'_m(-v_{in}-v_{s1}) + g'_2(-v_{in}-v_{s1})^2 + g'_3(-v_{in}-v_{s1})^3 + ...$$
$$i_{d2} = g'_m(v_{in}-v_{s2}) + g'_2(v_{in}-v_{s2})^2 + g'_3(v_{in}-v_{s2})^3 + ... \quad (2)$$

And first, second and third order transconductance of transistors are shown in Eq3. (3)

$$g'_m = \frac{\partial I_D}{\partial V_{GS}} \quad , \quad g'_2 = \frac{\partial^2 I_D}{\partial^2 V_{GS}} \quad , \quad g'_3 = \frac{\partial^3 I_D}{\partial^3 V_{GS}}$$

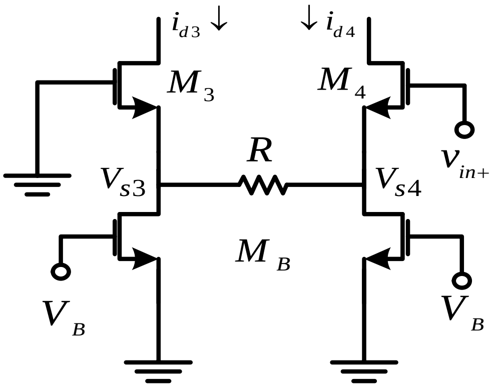
Applying the Kirchhoff's law to the V_{S1} and V_{S2} due to Eq4:

$$v_{s1} = \frac{r'_d \left(i_{d1} R' + r_d \left(i_{d1} + i_{d2}\right)\right)}{R' + 2 r'_d}$$
$$v_{s2} = \frac{r'_d \left(i_{d2} R' + r_d \left(i_{d1} + i_{d2}\right)\right)}{R' + 2 r'_d} \quad (4)$$

Taylor series expansion coefficients are obtained according to equation 5

$$A'_1 = -B'_1 = \frac{g'_1 (R' + 2r'_d)}{R' + r'_d (2 + g'_1 R')}$$
$$A'_2 = B'_2 = \frac{g'_2 (R' + 2r'_d)^2}{(R' + r'_d (2 + g'_1 R'))^2 (1 + g'_1 r'_d)}$$
$$A'_3 = -B'_3 = \frac{(R' + 2r'_d)^4 \left(g'_3 (g'_1 r'_d + 1) - 2 g_2'^2 r'_d\right)}{(R' + r'_d (2 + g'_1 R'))^4 (1 + g'_1 r'_d)} \quad (5)$$

If we connect the figure2 from both sides to a circuit like figure3 circuits such that is connected to V_{in} and - V_{in} from one side and on the other hand is grounded, so according to equations 6, 7 and 8 we have:



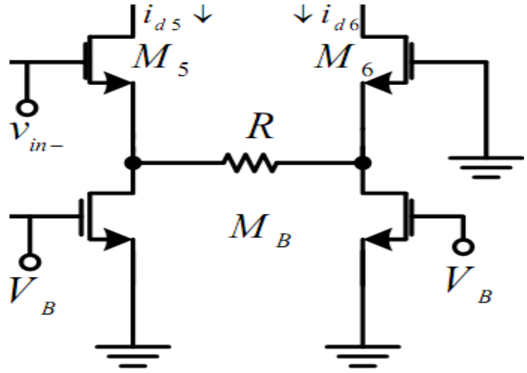


Figure3. Differential Couple with resistance degeneration and a grounded terminal

$$i_{d3} = A_1(+v_{in}) + A_2(+v_{in})^2 + A_3(+v_{in})^3 + ...$$
$$i_{d4} = B_1(+v_{in}) + B_2(+v_{in})^2 + B_3(+v_{in})^3 + ...$$

$$i_{d5} = B_1(-v_{in}) + B_2(-v_{in})^2 + B_3(-v_{in})^3 + ...$$
$$i_{d6} = A_1(-v_{in}) + A_2(-v_{in})^2 + A_3(-v_{in})^3 + ... \quad (6)$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \quad , \quad g_2 = \frac{\partial^2 I_D}{\partial^2 V_{GS}} \quad , \quad g_3 = \frac{\partial^3 I_D}{\partial^3 V_{GS}} \quad (7)$$

$$v_{s3} = \frac{r_d \left(i_{d3} R + r_d (i_{d3} + i_{d4})\right)}{R + 2r_d}$$
$$v_{s4} = \frac{r_d \left(i_{d4} R + r_d (i_{d3} + i_{d4})\right)}{R + 2r_d} \quad (8)$$

So, $A_1, B_1, A_2, B_2, A_3, B_3$ coefficients are obtained from Eq12 and provided in attachments.

The simplest method of linearization is source degeneration with a linear resistor. As we know degeneration reduces the swing between the gate and source of the transistor and thereby makes the input-output characteristic of the transistor more linear [8].

A structure that consists of three differential couples with resistive degeneration is used to increase linearization in transconductance, as shown in Figure 4. As can be seen one of the left and right differential couple's terminals are grounded and the overall structure of the transconductance is differential.

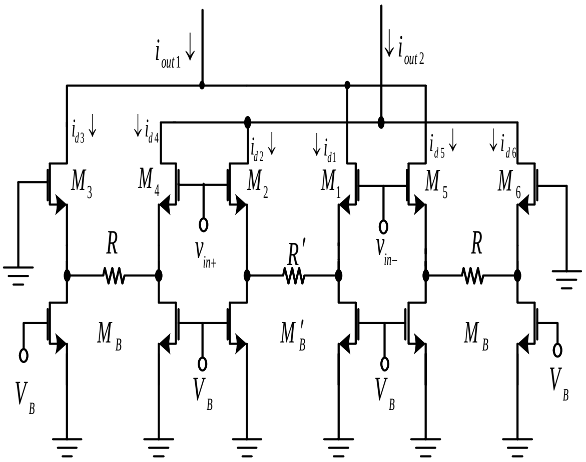


Figure4. Structure of the proposed transconductance circuit

According to Figure4 the output current of transconductance will be

$$i_{out1} = i_{d1} + i_{d3} + i_{d5} = G_m v_{in} + G_2 v_{in}^2 + G_3 v_{in}^3 + ...$$
$$= \left(A_1'(-v_{in}) + A_1(+v_{in}) + B_1(-v_{in})\right)$$
$$+\left(A_2'(-v_{in})^2 + A_2(+v_{in})^2 + B_2(-v_{in})^2\right)$$
$$+\left(A_3'(-v_{in})^3 + A_3(+v_{in})^3 + B_3(-v_{in})^3\right) \quad (9)$$

Coefficients of the overall Taylor expansion of the transconductance G_3, G_2, G_m according to Taylor coefficients of differential couples $B_1, B_2, B_3, A_1', A_2', A_3'$ and A_1, A_2, A_3, are

$$G_m = (-A_1' + A_1 - B_1)$$
$$G_2 = (A_2' + A_2 + B_2)$$
$$G_3 = (-A_3' + A_3 - B_3)$$

(10)

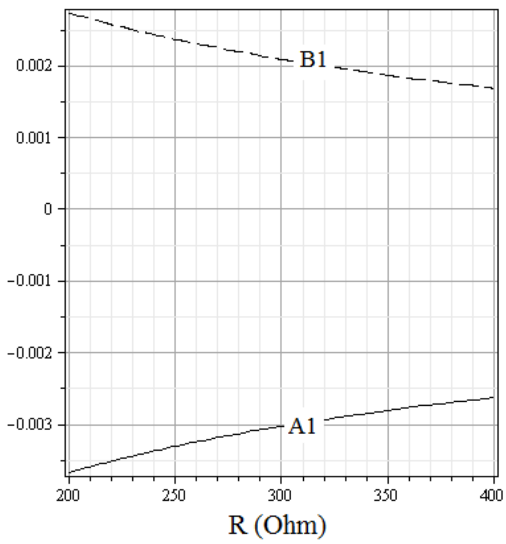
According to coefficients signs, the Taylor expansion coefficients G_3, G_2, G_m are totally obtained as

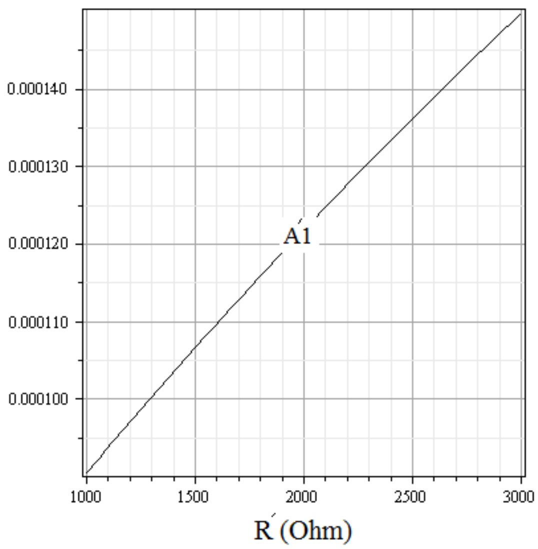
$$G_m = (-A_1' + A_1 - B_1) = -\left(|A_1'| + |A_1| + |B_1|\right)$$
$$G_2 = (A_2' + A_2 + B_2) = +\left(|A_2'| - |A_2| + |B_2|\right)$$
$$G_3 = (-A_3' + A_3 - B_3) = \left(|A_3'| - |A_3| - |B_3|\right) \quad (11)$$

As it is shown, by cumulating the coefficients into G_m, the value of G_m is increased and with decreasing the coefficients G_3, G_2 are decreased.

Simulation and Results

Simulations have carried out by ADS in 0.18um CMOS technology and coefficients g_3', g_2', g_m', g_3, g_2, g_m and r_d, r_d' are obtained with it. The bias current of the right and left differential couples is 1.85 mA and of the middle section is 150µA. In radio frequency of 900 MHz, the values of g_3, g_3' are negative therefore A_3', A_3 are negative and B_3', B_3 are positive. By placing them in the equations, the values for figure5 are obtained.





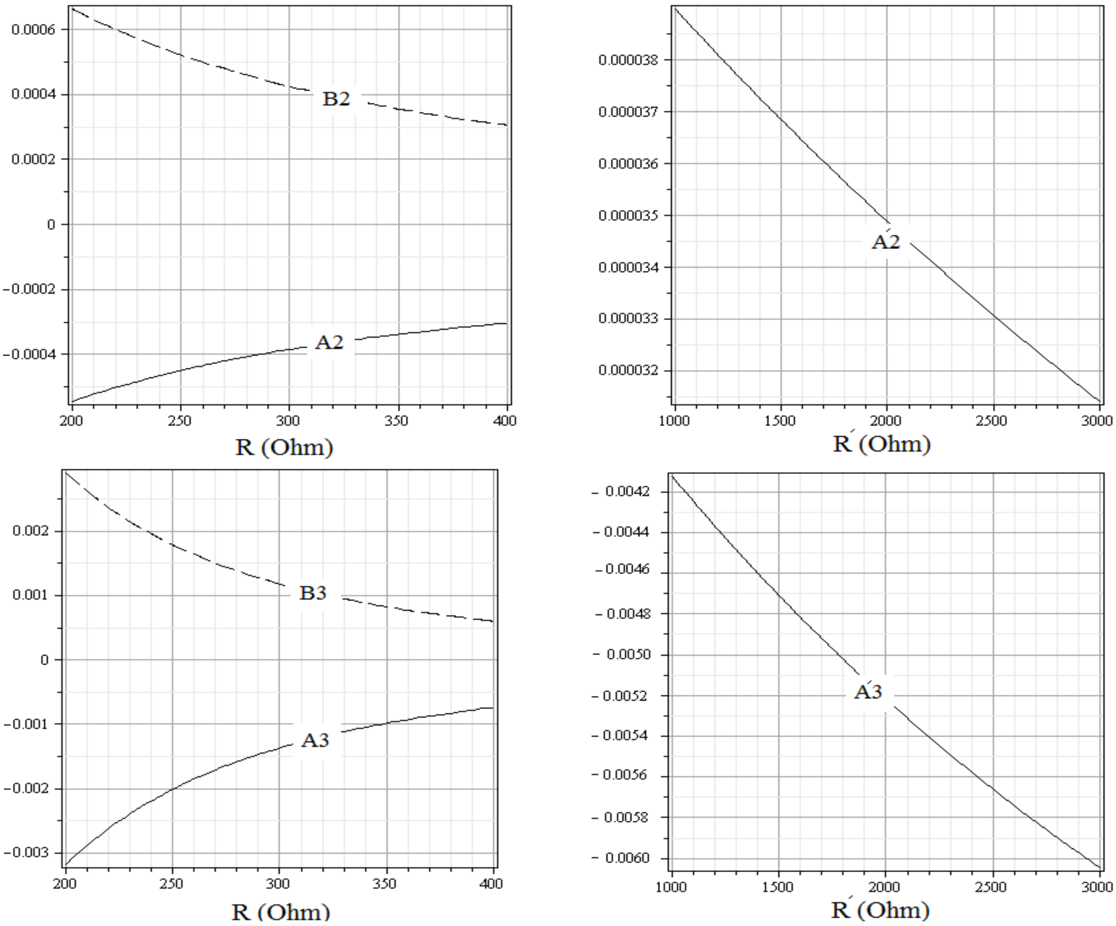
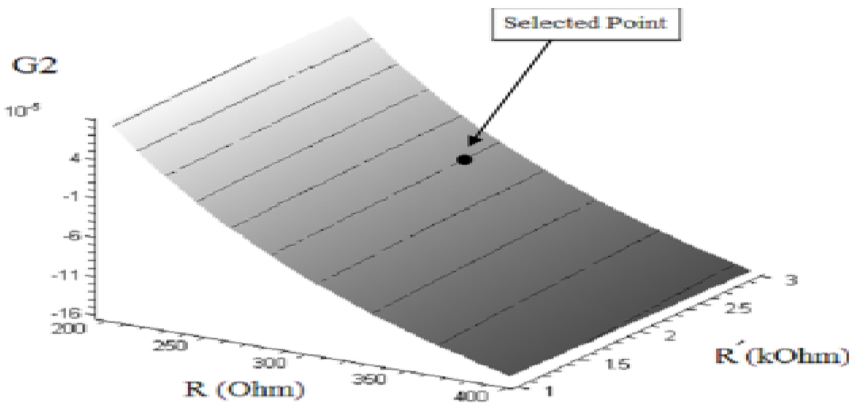


Figure5. Main, Second and third order transconductance for middle and side differential couples according to R and R'

Figure 6 shows the theoretical results of Main, Second and third order transconductance according R and R'. As it is shown, by choosing the appropriate values for the resistors R and R' $(R' = 2.5k\Omega \ , R = 300\Omega)$ such that G_3, G_2 stay minimum and G_m stay maximum, the optimum values are extracted for G_3, G_2, G_m. In this condition $G_3 = 2\times10^{-4}, G_2 = 2\times10^{-5}$. As it is obvious, second and third order transconductance coefficients is decreased compared to transconductance coefficients of single differential couples. Also, G_m is risen to 5×10^{-3}.



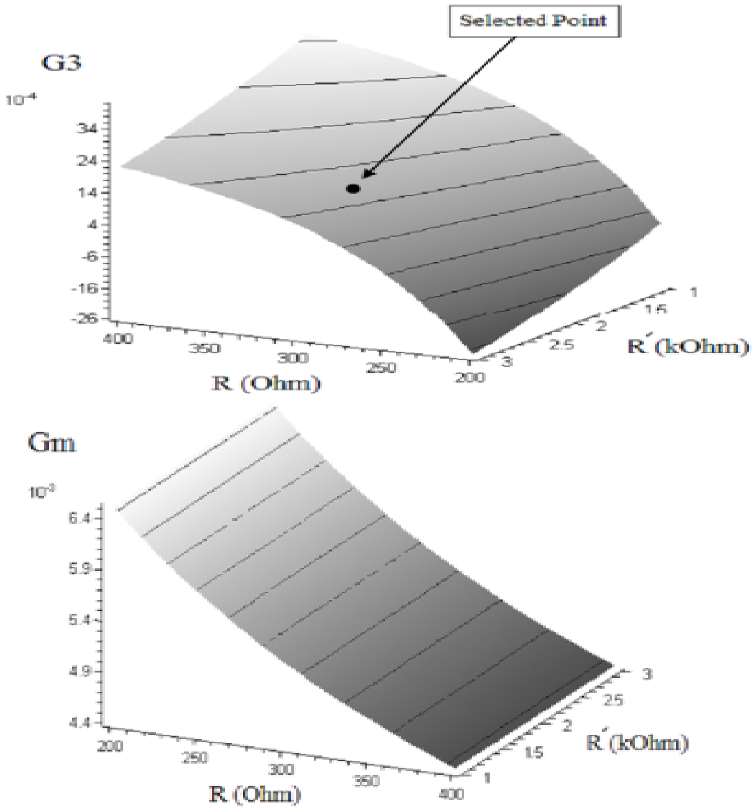


Figure 6. Main transconductance couples according to R and R'

Figure 7 shows the main structure of a mixer with transconductance part. The bias current is 2 mA and the transistors M4, M4, M5 and M6 are 100µm/0.25µm and biased in a current of 925µA. And the bias voltage V_B is 0.8V. The size of transistors M1 and M2 are lower than M3 and M4 and equal to 10µm/0.25µm and biased with a 150µA current.

The power of oscillator signal connected to the switch is 6 dB and the size of the transistors is 300µm/0.25µm. the values of resistors are $R' = 2.5\,k\Omega, R = 300\Omega$. The source capacitor is 0.6pF. The value of the L_s inductor for filtering the main frequency and LO side band is about 30nH. Also, the mismatch between switch transistors is modeled with a voltage offset of 2mV.

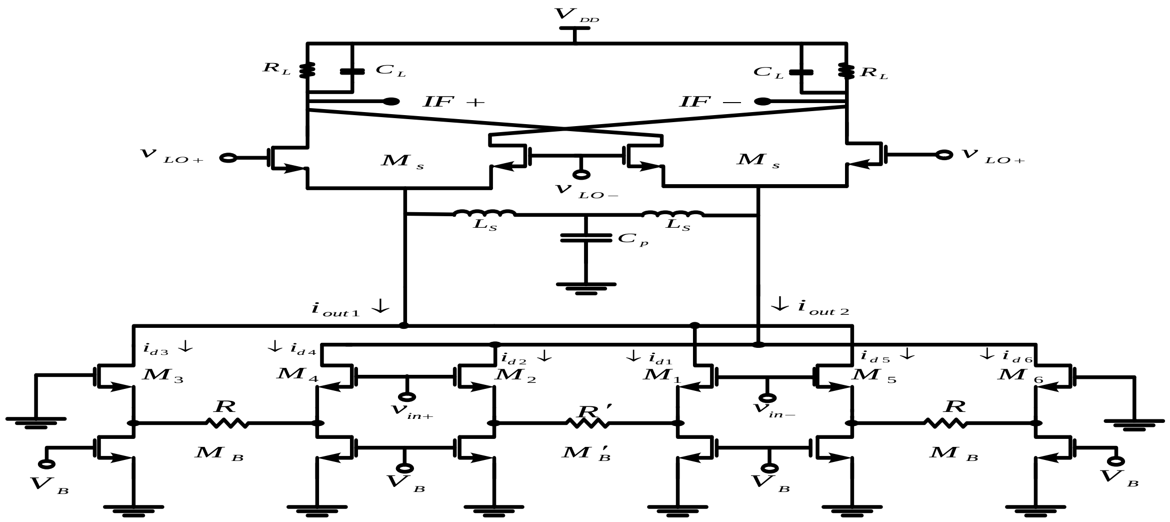


Figure7. Main structure of the mixer

Comparing the Results

In order to assess linearity improvement resulting IM2 injection in the mixer, IIP2 and IIP3 results of proposed and base models are shown in Figure8 and Figure9.

IIP2 and IIP3 results of proposed and base models show that in the proposed model, IIP2 and IIP3 are improved by 16dB and 6dB respectively.

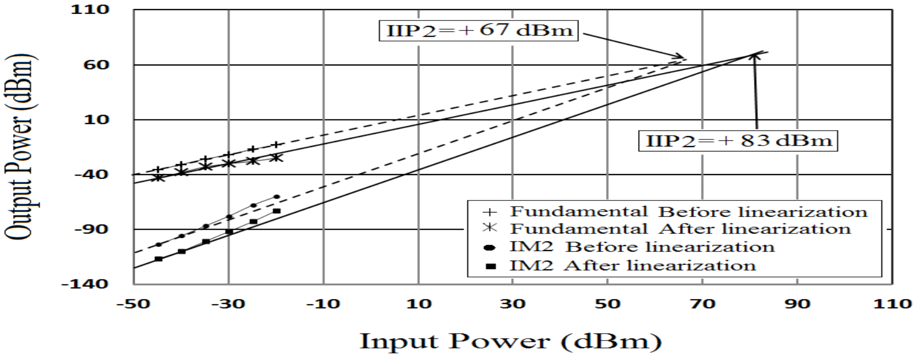


Figure8. IIP2 values of the proposed and based mixer

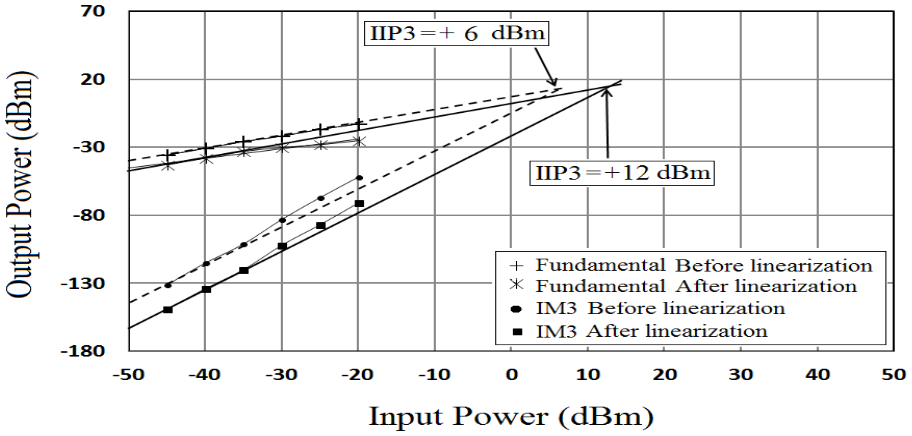


Figure9. IIP3 values of the proposed and based mixer

Important parameters resulted from the proposed and provided structures for a 2mA current bias are shown in table1. Simultaneous increment of IIP2 and IIP3 is one of the proposed structure and as it is shown the power consumption of this structure is lower than the provided ones.

Table1. Important parameters for proposed and provided structures.

REF	This Work	[3] 2008	[5] 2000	[6] 2008	[7] 2006	[8] 2011	[9] 2012
Process	0.18 µm	65 nm	0.35 µm	0.18 µm	0.18 µm	65 nm	0.18 µm
W/L	300/0.25	400/0.24	400/0.24	200/0.3	200/0.3	300/0.3	400/0.3
Biasing current (mA)	2	2	3	2	2	3	2
Freq (GHz)	0.9	2.1	0.9	2.4	2.1	0.8	1-3
IIP2 (dBm)	+83	+90	+78	N/A	+88	N/A	N/A
IIP3 (dBm)	+12	+8	+2.4	+14.5	+9	13.3	10
Power (mW)	7.2	8	10.8	7	7.2	8.75	5.25
Gain (dB)	15	15	14.5	14	16	9.2	9.5
NF (dB)	15	17.5	12	15	18	9	16.5

Chart1 shows the results for the proposed and provided structures. As it is expressed, in the proposed structure the IIP2 and IIP3 are increased simultaneously while in [3] and [5] just IIP2 and in [6] just IIP3 is increased. As it mentioned before, in the circuit structure provided in [7], second and third order nonlinear effects has fallen at the same time. The disadvantage of this structure is increment of noise due to adding some capacitors.

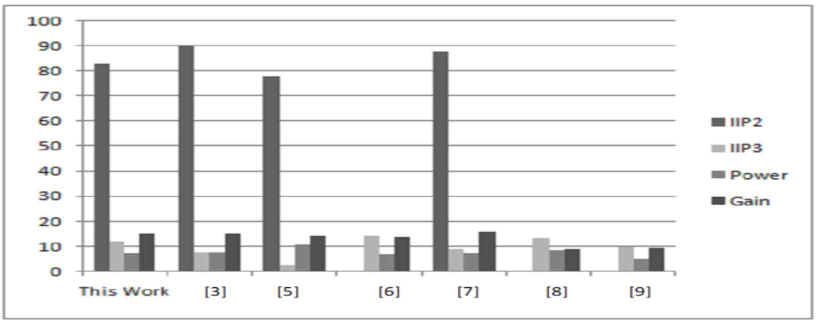


Chart1. Results of provided and proposed structures.

In this paper the non-linear effects in the output of the synchronic mixer has fallen by using a transitional guidance class with low second and third-order distortion. Analysis of structure using Taylor nonlinear analysis led the some equations which make the optimum design of the circuit possible. Simulation results carried out in ADS simulator in 0.18um CMOS technology, show that in radio frequency of 900MHz, IIP2 and IIP3 values of the mixer which indicate linearity of the circuit, have improved by 16 dB and 6dB over the base model with the proposed method

APPENDIX A

$$A_1 = -\frac{g_1^2 r_d^2}{(1+g_1 r_d)(R+g_1 r_d R+2r_d)}$$

$$A_2 = -\frac{g_2 g_1 r_d^{\,2}\left(R+g_1 r_d R+2r_d+g_1 r_d^2\right)}{(1+g_1 r_d)^3 (R+g_1 r_d R+2r_d)^2}$$

$$B_1 = \frac{g_1\left(R+g_1 r_d R+2r_d+g_1 r_d^2\right)}{(1+g_1 r_d)(R+g_1 r_d R+2r_d)}$$

$$B_2 = \frac{g_2\begin{pmatrix} R^2+2g_1 R^2 r_d+g_1^{\,2} R^2 r_d^{\,2}+3Rg_1^{\,2} r_d^{\,3} \\ +3g_1^{\,2} r_d^{\,4}+6g_1 r_d^{\,3}+4r_d^{\,2}+7R+4Rr_d \end{pmatrix}}{(1+g_1 r_d)^3 (R+g_1 r_d R+2r_d)^2}$$

$$A_3 = -\frac{\begin{pmatrix} g_2^{\,2}R+g_2^{\,2}r_d+4g_2^{\,2}g_1Rr_d+2g_2^{\,2}g_1R^2+2g_1^{\,2}g_2Rr_d+2g_1^{\,2}g_2^{\,2}r_dR^2 \\ +4g_1^{\,3}g_2^{\,2}r_d^{\,3}R+g_1^{\,3}g_2^{\,3}r_d^{\,3}R^2+g_1^{\,3}g_2^{\,2}R^4+g_1^{\,2}g_2^{\,3}r_d^{\,2}R^2+6g_1^{\,3}g_2^{\,3}r_d^{\,2}R^3 \\ -g_3\left(5g_1R+g_1^{\,2}R^2+16g_1^{\,3}r_d^{\,3}+24g_1^{\,2}Rr_d+6g_1^{\,2}R^2r_d+g_1r_d+2g_2^{\,2}R\right) \end{pmatrix}}{(1+g_1R)^4(1+g_1R+2g_1r_d)^5}$$

$$B_3 = \frac{\begin{matrix} g_1r_d\left(g_1R+g_1r_d+1\right)\left(4g_2^{\,2}r_d+2g_2^{\,2}R-g_3\left(1+g_1R+g_1r_d\right)\right) \\ \left(2g_1^{\,2}r_d^{\,2}+2g_1r_d+2g_1^{\,2}Rr_d+2g_1R+g_1^{\,2}R^2+1\right) \end{matrix}}{(1+g_1R)^4(1+g_1R+2g_1r_d)^5} \qquad (12)$$

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