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A 900 MHz High Gain Low Noise Figure Down Converter Mixer for Wireless Applications

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ABSTRACT: A high gain low noise figure double balanced down conversion mixer is presented for RF frequency of 900 MHz, IF frequency of 45 MHz and LO frequency of 855 MHz. This work focus upon design of single ended double balanced down conversion mixer with high gain, low noise figure and low input reflection coefficient for 900 MHz frequency band. The mixer design is based upon the Gilbert cell architecture. RF transconductance stage MOSFETS are inductively source degenerated to enhance the linearity of the mixer. Pi type impedance matching is used at RF transconductance stage, to enhance the input matching of the designed mixer. Output is taken across differential resistive load. Single ended RF signal is used at RF port and differential LO signal is used at LO port. The mixer is simulated in a 180 nm CMOS technology using Keysight Advanced Design System (ADS) software. The mixer achieves maximum conversion gain of 13.95 dB, 1 dB compression point (P1dB) of -19.91 dBm, the third order Input Intercept point (IIP3) of -12.287 dBm, single sideband (SSB) noise figure of 4.786 dB and S_{11} of -33.307 dB.

Keywords: Down conversion mixer, Gilbert Cell, Source degeneration, Pi type impedance matching, CMOS, Conversion Gain, Noise figure.

I. INTRODUCTION

Mixer is an essential block of wireless transceiver systems. In homodyne receiver or Zero-IF receiver, RF frequency is directly converted to base band frequency without no IF frequency conversion [1-3]. In heterodyne transceiver architecture, RF frequency is down converted to low IF frequency using LO frequency with the use of mixer. Heterodyne receiver preferred over homodyne due to higher selectivity [4-7]. Being a nonlinear system, Mixer dominantly affects total performance of the transceiver system. Basic function of mixer is shown in Fig. 1.

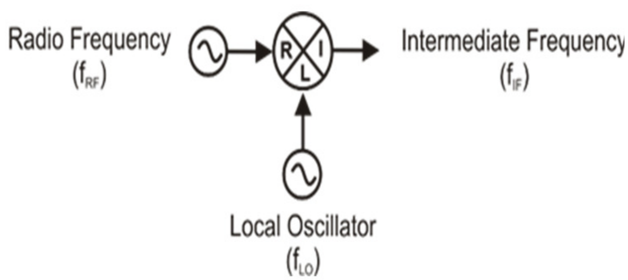

Fig. 1. Frequency conversion using mixer.

In literature various active and passive mixer topologies are reported. Passive Mixers have lesser complexity and higher linearity but and they produce mix products with conversion loss [8-12]. In active mixer, Gilbert cell mixer architecture is most preferred due to its advantages including double balance feature which results in LO-IF isolation and low even order distortion due to its double differential pair architecture for both RF and LO ports [13-19]. Fig. 2 shows the schematic of basic Gilbert cell mixer circuit topology.

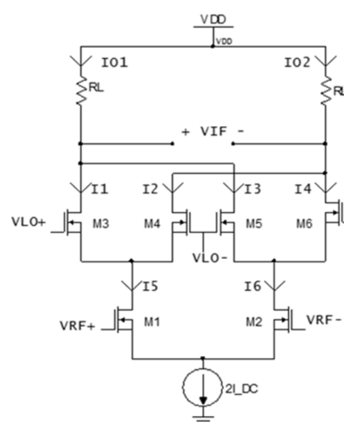

Fig. 2. Schematic of basic Gilbert mixer circuit.

This circuit operates as an alternating switch, in which the top four MOSFETs (M3-M6) are turned on and off alternatively with half-cycles of the LO voltage. Due to the differential mode operation, the common node of the sources of the MOSFETs (M3-M6) works as a virtual ground for the LO voltage. These LO stage MOSFETs are biased slightly higher than pinch off so that each MOSFET can conduct for slightly more than half of each LO cycle. During the positive half-cycle of *VLOp,* the MOSFETS (M3-M4) switched on with a low resistance, and they turn off during the negative half cycle of VLOm. The MOSFETs (M5-M6) turned on during the positive half cycle of *VLOm,* this occurs simultaneously during the negative half cycle of *VLOp*. Thus, It is ensured that at one time one of the MOSFETs (M3-M6) always conducts. The lower two MOSFETs (M1-M2) works as transconductance amplifier stage which amplifies RF voltage and provides amplified RF current through the upper switches circuit paths. In this way RF signal is switched periodically with the frequency of RF signal and mix frequency is obtained across load resistors R_L in differential form. The expression of output current in Gilbert mixer can be found as follows with reference to circuit shown in Fig. 2. Principle of operation of mixer is described as following equations

$$I_5 = I_{DC} + I_{RF}\ cos\omega_{RF}t \quad (1)$$

$$I_6 = I_{DC} - I_{RF}\ cos\omega_{RF}t \quad (2)$$

$$I_1 - I_2 = I_5\ s(t) \quad (3)$$

$$I_4 - I_3 = I_6\ s(t) \quad (4)$$

Where s(t) denotes LO switching function.

$$s(t) = \frac{4}{\pi}[sin\omega_{LO}t + \frac{1}{3}sin3\omega_{LO}t + \frac{1}{5}sin5\omega_{LO}t + \cdots] \quad (5)$$

$$I_{O1} = I_1 + I_3 \quad (6)$$

$$I_{O2} = I_2 + I_4 \quad (7)$$

$$I_{OUT} = I_{O1} - I_{O2} \quad (8)$$

$$I_{OUT} = (I_1 + I_3) - (I_2 + I_4) \quad (9)$$

$$I_{OUT} = (I_1 - I_2) - (I_4 - I_3) \quad (10)$$

$$I_{OUT} = I_5\ s(t) - I_6\ s(t) \quad (11)$$

$$I_{OUT} = (I_5 - I_6)\ s(t) \quad (12)$$

$$I_{OUT} = 2\ I_{RF}\ cos\omega_{RF}t\ s(t) \quad (13)$$

$$I_{OUT} = \frac{4}{\pi}I_{RF}[sin(\omega_{LO} - \omega_{RF})t + sin(\omega_{LO} + \omega_{RF})t + \frac{1}{3}sin(3\omega_{LO} - \omega_{RF})t + \frac{1}{3}sin(3\omega_{LO} + \omega_{RF})t \ldots] \quad (14)$$

Where $\omega_{LO} - \omega_{RF} = \omega_{IF}$ the required IF is output frequency. After passing through low pass filter I_{Out} is given by Eqn. (15)

$$I_{OUT} = 2\ I_{RF}\ cos\omega_{RF}t\ s(t) \quad (15)$$

Many authors including [20-25] are reported design of Gilbert mixer for 900 MHz. Most of the mixer not reported to provide high gain with low noise figure also matching is also not provided at the input port.This work attempts to provide optimized design of input matched single ended down conversion mixer with high gain as well as low noise figure operating as 900 MHz frequency.

II. PROPOSED WORK

This paper presents a high gain double balanced down conversion mixer for RF frequency of 900 MHz, IF frequency of 45 MHz and LO frequency of 855 MHz. Down converter mixer converts RF frequency (f_{RF}) to lower IF frequency (f_{IF}) with help of local oscillator frequency (f_{LO}), where f_{IF} is difference of f_{RF} and f_{LO} ie $f_{IF}= |f_{RF}-f_{LO}|$. In this work, intermediate frequency is given as $f_{IF}=$ | 900-855 |= 45 MHz.

Schematic of designed mixer circuit is shown in Fig. 3. Mixer design is based uses Gilbert cell topology as core of the mixer. Voltage conversion gain (A_V) of the mixer is given by Eqn. (16)

$$A_V = \frac{2}{\pi}g_m R_L \quad (16)$$

Where g_m is the transconductance of RF stage MOSFETs and R_L is the load resistance. Transconductance gm is given by Eqn. (17)

$$g_m = \mu_n C_{OX}\frac{W}{L}(V_{GS} - V_{th}) \quad (17)$$

Current through RF stage transistors is given by Eqn. (18)

$$I_D = \mu_n C_{OX}\frac{W}{2L}(V_{GS} - V_t)^2 \quad (18)$$

From Eqns. (17) and (18) transconductance gm is given by equation (19)

$$g_m = \frac{2I_D}{(V_{GS} - V_{TH})} \quad (19)$$

It is indicated from Eqn. (15) that for given gm, the voltage conversion gain (A_V) an be maximized by increasing load resistor RL but consequently this decrease the voltage headroom (V_{DS}), This decrease in voltage headroom can result can violate the condition ($V_{DS}>V_{GS}-V_{Th}$) and force the transistor to come out of saturation which result in distortion of the output IF waveform. Let the maximum output voltage across resistor R_L is V_{Lmax} for maintaining the transistors in saturation. In this case maximum value of R_{Lmax} is given by Eqn. (20)

$$R_{Lmax} = {2V_{Lmax}}/{I_D} \quad (20)$$

In the proposed design of mixer, the gain is maximized for maximizing R_L satisfying the condition given by Eqn. (20).

Equation (18) clearly indicates that g_m is dependent on V_{gs}, this dependence of g_m on V_{gs} produces non linearity in the circuit. This nonlinearity in the mixer results in harmonics and intermodulation distortion products. To minimize this nonlinearity of g_m, source degeneration technique is used.. In designed mixer, sources of M1 and M2 are inductively degenerated using inductors L1 and L2.

Effective transconductance (G_m) after applying resistive source desecration is given by

$$G_m = \frac{g_m}{1+g_m R_s} \text{ if } g_m r_o >> 1 \quad (21)$$

r_o is the output impedance of RF stage MOSFETs.

$$G_m = \frac{1}{R_S} \text{ if } g_m R_s >> 1 \quad (22)$$

Eqn. (22) indicates that effective transconductance depends on Rs ie it becomes independent of biasing. Trade-off of resistive source degeneration is that, it increases the thermal noise but use of inductor in place of resistor has the same effect as resistor on linearity and it does not contribute to noise but at the expense of larger area.

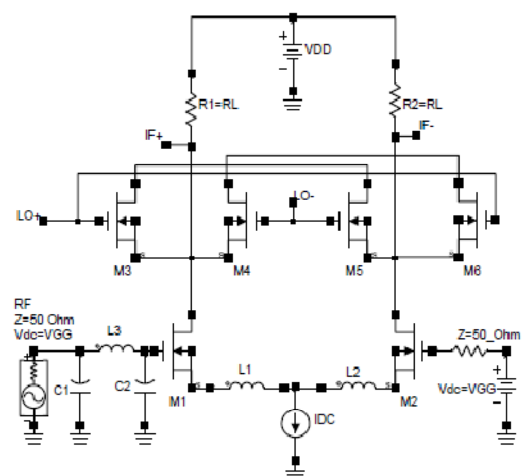

Fig. 3. Schematic of designed mixer.

To minimize the input reflections at RF port, single ended three element pi type CLC matching circuit (C1, L3, C2) is used at RF port. Three elements matching is preferred over two element matching due to flexibility in choosing the bandwidth for matching along with centre matching frequency at 900 MHz. All the components of the mixer are well optimized for required results.

III. RESULTS AND DISCUSSION

Designed mixer is simulated in 180 nm CMOS technology in Keysight Advanced Design System (ADS) Software. Harmonic balance simulation is done to observe distortive effects in mixer due to nonlinearity in designed mixer. Order of LO signal frequency is chosen as 7 and order of RF signal frequency is chosen as 3. Maximum Intermodulation (mix) frequency order is chosen as 5.

Results of conversion gain with input RF power is shown in Fig. 4. RF power is varied from -60 dBm to higher power levels to observe gain compression phenomenon. It is observed that gain is decreased at higher power RF power levels. Maximum conversion gain is observed as 13.95 dB.1 dB compression point of the mixer, at which the gain of the mixer is reduced by 1 dB from maximum value is observed as -19.91 dBm. This value of P1dB reveals that mixer maintains sufficient amount of linearity.

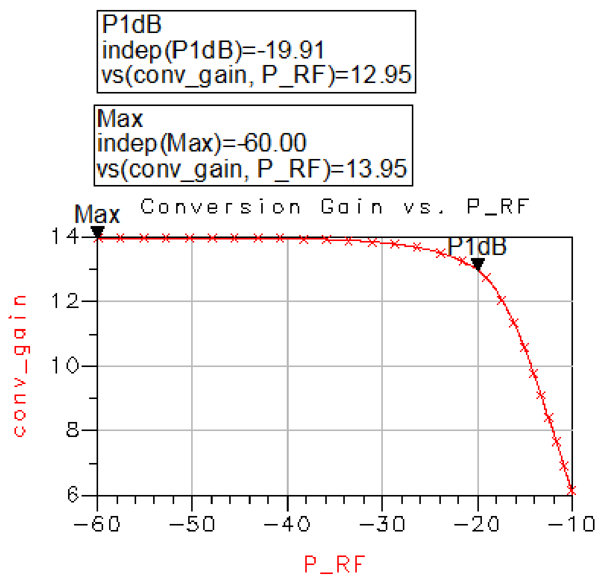

Fig. 4. Conversion gain versus RF signal power.

Simulation of IF power output delivered with reference to ideal IF power is shown in Fig. 5. Ideal IF output power behavior is shown with straight line with assumption that mixer is perfectly linear. Curved line shows the delivered IF output power at load. It is noticed that gain starts declining from ideal value at higher power levels of RF power level. This behavior of conversion gain confirms gain compression phenomenon as also depicted in Fig. 4.

Results of IF output voltage versus input RF power level is shown in Fig. 6. Results shows that magnitude of IF voltage initially increases with increase in RF power levels and further ceases to increase at higher power levels which further validates gain compression phenomenon as shown in Figs. 4 and 5.

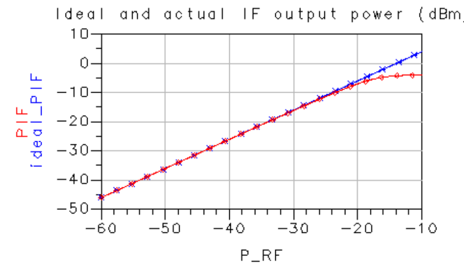

Fig. 5. IF power versus RF power.

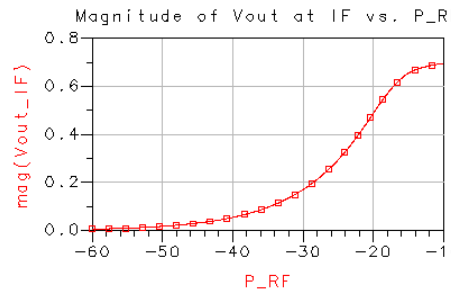

Fig. 6. Magnitude of IF voltage versus RF power.

Results of input reflection coefficient (S_{11}) versus RF signal frequency is shown in Fig. 7.

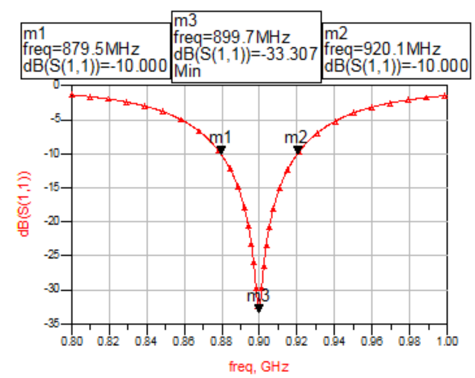

Fig. 7. S_{11} versus RF frequency.

Result shows minimum value of S_{11}as -33.307 dB at required RF frequency of 900 MHz. Further it is observed that value of S_{11} remains less than -10 dB for frequency ranging from 879. 5 MHz to 920.1 MHz, this reveals that mixer is suitably matched at 900 MHz RF frequency with sufficient bandwidth.

Intermodulation distortion (IMD) performance of the mixer is measured with the third order input intercept point (IIP3) parameter. For IMD simulations, two frequencies are set as $f_1 = f_{RF} + fspacing/2$ and $f_2 = f_{RF} - fspacing/2$. The value of *f spacing* should be chosen such that mix frequency products corresponding to IMD products should lie within IF bandwidth. It is ensured in the by taking the low value of fspacingas 20 KHz for IMD simulations of the mixer. Simulations results IIP3 and conversion gain versus V_LO (LO signal voltage) are shown in Fig. 8 and in Table 1. It observed that conversion gain does not change significantly and IIP3 decreases significantly for values of V_LO above 0.2 V so V_LO of voltage 0.2 V is chosen for mixer design.

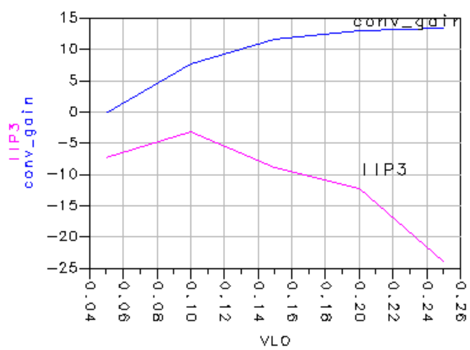

Fig. 8. Conversion gain and IIP3 with LO Volatge.

Table 1: IMD Simulations Results.

S.No.	IMD Simulations Results		
	V_LO (V)	IIP3 (dBm)	Conversion Gain (dB)
1.	0.50	-7.390	-0.234
2.	0.100	-3.253	7.593
3.	0.150	-8.855	11.702
4.	0.200	-12.287	13.039
5.	0.250	-23.772	13.468

Noise figure simulation output is shown in Fig. 9. Noise power output at 45 MHz IF frequency is observed as -46.89 dBm for RF signal power 0 -60 dBm. Single side band noise figure (NF SSB) is observed as 4.786 dB. This low amount of noise figure reveals that the mixer justifies low noise behavior of mixer circuit.

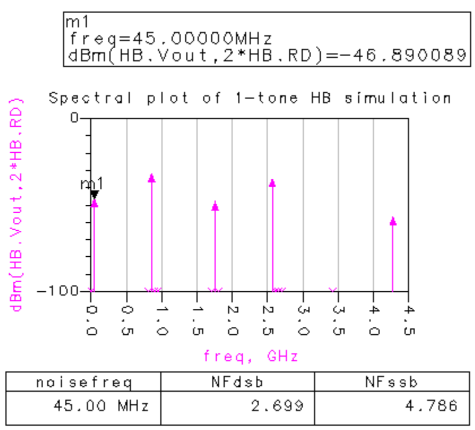

Fig. 9. Noise figure simulation output.

Table 2 presents the component values and transistor sizing of the designed mixer.

Table 2: Final component Values.

Component	Value
Load (R_L)	300 Ω
Length of MOSFETs	0.18 μm
Width of MOSFETs	90 μm
L1, L2	10 nH
C1,L3,C2	1.61 pF, 115.5 nH, 0.1298 pF

IV. CONCLUSION

A low noise figure high gain down conversion mixer is designed for RF frequency of 900 MHz, IF frequency of 45 MHz and LO frequency of 855 MHz. Mixer is simulated in 180 nm CMOS process technology using ADS software. Mixer design is configured upon Gilbert Cell as a core of the mixer. Inductive source degeneration is used to improve the linearity of the mixer without adding additional noise to the circuit. High linearity of the circuit reflected through high value of P1dB of -19.91 dBm and IIP3 of -12.287 dBm. CLC type pi matching is employed at RF port for matching the RF port which results in very low value of S_{11} as -33.307 dB at frequency of 900 MHz with sufficient bandwidth. Designed mixer is optimized for a high value of conversion gain as 13.95 dB and low noise figure (SSB) as 4.786 dB. This mixer is useful for wireless applications utilizing 900 MHz band spectrum including emerging IOT applications.

V. FUTURE SCOPE

Proposed mixer is designed for single band operating at a frequency of 900 MHz. Further this work can be extended to provide multiband support operating at 900 MHz frequency spectrum

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Conflict of Interest. The author declare no conflict of Interest associated with this work.

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