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A 2.4 GHz Op-Amp Based Up-Conversion Mixer for Zigbee Front-end Transmitter

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***Abstract*—This paper illustrates up-conversion mixer with very high linearity and improved conversion gain. CMOS Operational amplifier is used to enhance the overall conversion gain of the proposed mixer circuit. The derivative Superposition technique is applied to improve the linearity of the proposed Up-conversion mixer circuit. The operating frequency of this circuit is 2.4 GHz and it is applicable for the Zigbee transmitter front-end. In this proposed Up-conversion mixer, passive balun circuit is used to convert unbalanced base-band signal to differential balanced signal. The proposed up-conversion mixer converts input base band signal of 100 MHz to radio frequency output signal of 2.4GHz. The local oscillator frequency is 2.3 GHz and a local oscillator power is considered at 2 dBm. The conversion gain of this mixer is 18.86 dB, IIP3 and OIP3 are 15.9708 dBm and 16.4053 dBm respectively. The circuit is simulated on cadence analog and digital design tool at 45nm CMOS technology and rail to rail power supply is ±1.2 V.**

***Keywords*— Base-Band Signal, Local Oscillator (LOSC), Inter mediate frequency (IF), Radio-frequency (RF), Input Intercept Point (IIP), Output Intercept Point (OIP), Conversion Gain (CG), Complementary Metal Oxide Semiconductor (CMOS).**

I. INTRODUCTION

The demands for single chip transceiver are increasing due to the requirement of energy efficient wireless communication systems. Circuit fabrication cost minimization, power dissipation and chip area reduction are now becoming possible only due to advancement in CMOS technology. The RF - mixer is the most significant component in modern communication systems transmitter and receivers. Mixers convert signals from one frequency band to another. The output of the mixer consists of multiple images of the mixer input signal where each image is shifted up or down by multiples of the local oscillator (LOSC) frequency.

Up-conversion mixer is one of the key building block of transceiver generally used to convert an incoming low frequency baseband signal to a higher frequency RF signal for reliable transmission in the RF transmitter front-end. The most significant performance parameters for designing of mixers are linearity, conversion gain (CG), Local oscillator power, noise figure (NF) and power consumption. These parameters depend upon each other and change in one parameter affects another. Therefore, it is difficult to find a suitable mixer topology, which can achieve a high linearity, low power, low noise figure, and high conversion gain simultaneously [1]. Zigbee IEEE 802.15.4 assigns three frequency bands of operation: the 868-MHz, 915-MHz, and 2.4-GHz unlicensed ISM bands. Among the three, the 2.4-GHz band is the most commonly used unlicensed bands. Typical applications of this low data rate standard are in industrial and commercial uses, home automation, PC peripherals, consumer electronics, and personal health care appliances. Battery life time is the key factor. Zigbee Transmitter employs Direct Sequence Spread spectrum and used OQPSK as a modulation scheme. An IEEE 802.15.4-based 2.4 GHz PHY can support 250 Kb/s data rate. Sixteen channels are available for 2.4-GHz band applications, with channel spacing of 5 MHz.

Mixer is a three port device which multiplies two signals in time domain. If both sinusoidal type signals input to a multiplier, then the output of the multiplier can get sum frequency component and difference frequency component, which can be expressed as [1]:

$$(A_1\cos\omega_A t) * (B_1\cos\omega_B t) = \frac{A_1B_1}{2}[\cos(\omega_A - \omega_B)t + \cos(\omega_A + \omega_B)t] \quad \textbf{(1)}$$

One of input sinusoidal signals is a fixed rate of the vibration signal (LO), provided by a local oscillator, and the other is the received RF signal or the transmitted low-frequency signal. You can get a difference frequency component of frequency $(\omega_A - \omega_B)$ and sum frequency component of frequency $(\omega_A + \omega_B)$.

The magnitudes of difference frequency component and sum frequency component are proportional to the magnitude of the input signal by controlling the local oscillator signal amplitude. The band pass filter can be applied at output to select proper frequency band.

Active mixer is generally used as an up-conversion mixer. It has a privilege of better conversion gain and low noise figure. But its power consumption is higher than passive mixers. Better performance parameters can be achieved if the power supply voltage is increased. However, low power consumption is mandatory for the mixer to use in energy efficient transmitter. In this proposed Up-conversion Mixer derivative superposition theorem is applied to increase linearity of the mixer and two operational amplifiers are used in both of the base band signal input to improve the overall voltage conversion gain of the mixer. Passive balun is used to convert unbalanced baseband signal to balanced two input base band signal of equal magnitude and 180 deg out of phase. Conversion gain and linearity are both contradictory to the improvement of each other, so an optimum value for conversion gains and IIP3 is chosen to design of proposed Up-conversion Mixer.

II. Gilbert-Cell Mixer Design

A. Gilbert cell Mixer Topology

Gilbert mixer [1] is a conventional structure which is commonly used in implementing active mixers. It has several advantages. Gilbert mixer achieves a definite conversion gain with appropriate load. Very low Local Oscillator power is required to operate Gilbert Cell Mixer. Double-Balanced Gilbert cell structure leads to very good port-to-port isolation and low noise figure. The Gilbert topology is the most commonly implemented using CMOS technology. It operates on the concept of translinear configuration. Techniques like pre-distortion and emitter degeneration are necessary to obtain a reasonable linearity. The CMOS double balanced structure cancels out the quadratic even order term of the MOS transistor. These mixers have not only a limited linearity which highly depends on matching; even more important is their limited frequency range. The input transistors of these mixers can only be biased with a relatively small $V_{GS} - V_{TH}$, in order to keep them in saturation region at all times. Structure of Gilbert mixer is shown in Figure 1. NM5 is the tail current transistor. It remains in saturation region and controls the total current of the Gilbert cell. Transistors NM6 and NM7 are a pair of Transconductors. They operate in saturation and transform the baseband input voltage to current. The conversion gain and linearity of the Mixer mainly depends on these two transistors. NM1, NM2 and NM3, NM4 are two pairs of switches. They operate in saturation region and mix LOSC signal current with signal current from Transconductors NM6 and NM7 [4].

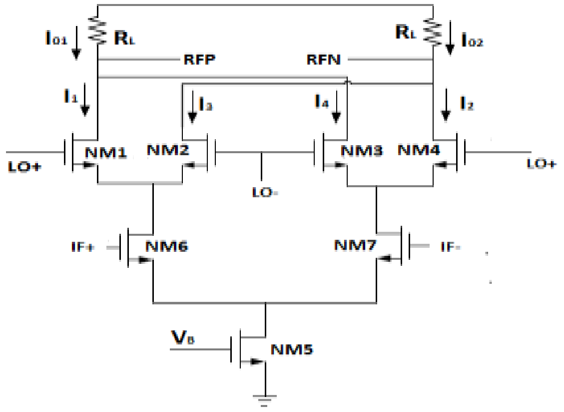


Fig.1. Schematic of the Conventional Mixer

The Gilbert mixer output current can be expressed as follows [3]:

$$\begin{aligned} I_{out} &= I_{out1} - I_{out2} = (I_A - I_B) - (I_C - I_D) \\ &= \mathrm{sgn}(\cos\omega_{LOSC} t)(I_B + i_s) - \mathrm{sgn}(\cos\omega_{LOSC} t)(I_B - i_s) \\ &= 2\,\mathrm{sgn}(\cos\omega_{LOSC} t) i_s \end{aligned} \tag{2}$$

The Fourier transform of the square wave signal $\mathrm{sgn}(\cos\omega_{LOSC} t)$ is as below

$$\mathrm{sgn}(\cos\omega_{LOSC} t) = \sum_{n=1}^{\infty} A_n \cos n\omega_{LOSC} t \tag{3}$$

Where

$$A_n = \frac{\sin\frac{n\pi}{2}}{\frac{n\pi}{2}} \tag{4}$$

Considering Transconductance of NM6 and NM7 is g_m:

$$g_{m_{NM6}} = g_{m_{NM7}} = g_m \tag{5}$$

The output of the Transconductors i_s

$$2i_s = g_m V_{IF} \cos\omega_{IF} t \tag{6}$$

Substituting equation (4), (5), (6) into the equation (2), the output

Current of Gilbert mixer is:

$$I_{out} = g_m V_{IF} \sum_{n=1}^{\infty} \frac{\frac{\sin n\pi}{2}}{\frac{n\pi}{2}} [\cos(n\omega_{LOSC} + \omega_{IF})t + \cos(n\omega_{LOSC} - \omega_{IF})t] \qquad (7)$$

The Voltage conversion gain of Gilbert mixer is expressed by:

$$G_{CB} = \frac{V_{RF}}{V_{IF}} = \frac{I_{out} R_L}{V_{IF}} = g_m R_L \sum_{n=1}^{\infty} \frac{\frac{\sin n\pi}{2}}{\frac{n\pi}{2}} [\cos(n\omega_{LOSC} + \omega_{IF})t + \cos(n\omega_{LOSC} - \omega_{IF})t] \qquad (8)$$

Where R_L is the Load resistance of the Gilbert-cell mixer. If LOSC is strong enough, the conversion gain of Gilbert mixer is: $G_{CB} = \frac{2}{\pi} g_m R_L$

(9) A Gilbert-cell mixer is preferred than other type of mixer in reference of better RF LOSC isolation and dynamic range. The Gilbert mixer having two single-balanced circuits with the RF transistors which are connected in parallel and the switching pair in anti- parallel. The LOSC terms sum to zero and the IF signal doubled in the output. This configuration provides a high degree of LOSC-RF isolation, which satisfies filter requirements at the output. Due to differential IF signal double balanced mixers are less prone to noise than single balanced mixer. There are two key factors that control the linearity of the mixer circuit [12]. (i). If the applied signal at the driver stage is greater than the maximum differential input (Overdriving Voltage), the first compression will take place. By decreasing the driver stage transistor ratio (W/L), or enhancing the bias current, linearity of the mixer can be increased. (ii). When load resistor R_L is too large, the voltage across V_{DS} of switching transistor will decrease, resulting the switching transistors out of saturation region and switch to triode region ($V_{DS} \leq V_{GS} - V_{TH}$). If the size of load resistor R_L is reduced the dc output voltage will reach a higher level resulting the gain to a lower value.

B. Methodology for the Proposed Up-conversion Mixer

To design a highly linear mixer, it is necessary to know the sources of nonlinearities in mixers. The two dominant nonlinear sources in CMOS are the transconductance and output conductance. The Taylor series is used due to its simplicity for weakly nonlinear circuits. The drain current of a MOS in the Taylor expansion can be expressed as follows [11]:

$$\begin{aligned} i_{ds}(v_{GS,} v_{DS}) &= I_{DS}(V_{GS}, V_{DS}) + g_m v_{gs} + g_d v_{ds} + g_{m2} v_{gs}^{2} + g_{md} v_{gs} v_{ds} + \\ & g_{d2} v_{ds}^{2} + g_{m3} v_{gs}^{3} + g_{md2} v_{gs}^{2} v_{ds} + g_{md2} v_{gs} v_{ds}^{2} + g_{d3} v_{ds}^{3} \end{aligned} \qquad \textbf{(}10)$$

g_m is the small signal Transconductance and higher order coefficients (g_{m2}, g_{m3}) define the strengths of the corresponding non-linearities. Assuming that the drain current is shorted at the signal frequency, then all the output conductance terms and cross modulation terms are vanished and only the Transconductance terms are left. Among higher order coefficients g_{m3} is particularly important because it controls the 3rd order Intermodulation distortion (IMD_3) at low signal levels and thus determines the IIP3 which is expressed by the equation [4].

$$A_{IIP3} = \sqrt{\frac{4}{3}\left|\frac{g_m}{g_{m3}}\right|}$$

However, the model equations described above is not properly due to

(11)

exclude output Transconductance nonlinearity. Another model, which includes the nonlinearity added by output conductance expressed below .According to this model the third-order intermodulation current caused by the Transconductance and output conductance nonlinearities, is given by [11]

$$i_{IM3,trans} = \frac{3}{4} g_{m3} A^3 \frac{G_{load}}{g_d + G_{load}}$$
$$i_{IM3,cond} = \frac{3}{4} g_{d3} v_{ds}^{\ 3} \frac{G_{load}}{g_d + G_{load}} \qquad (12)$$

Where A is the fundamental amplitude at the gate and v_{ds} is the fundamental voltage at the drain and can be expressed by

$$v_{ds} = \frac{g_m A}{G_{load} + g_d}$$

(13)

The transconductance nonlinearity becomes a significant source at higher frequencies. The internal capacitances don't effect nonlinearity; but the conversion gain and output swing are reduced at higher frequencies. The output transconductance is a major source of nonlinearity especially at low frequencies. The transconductance can become more linear by proper selection of technology scaling, but the output conductance nonlinearity is increased.

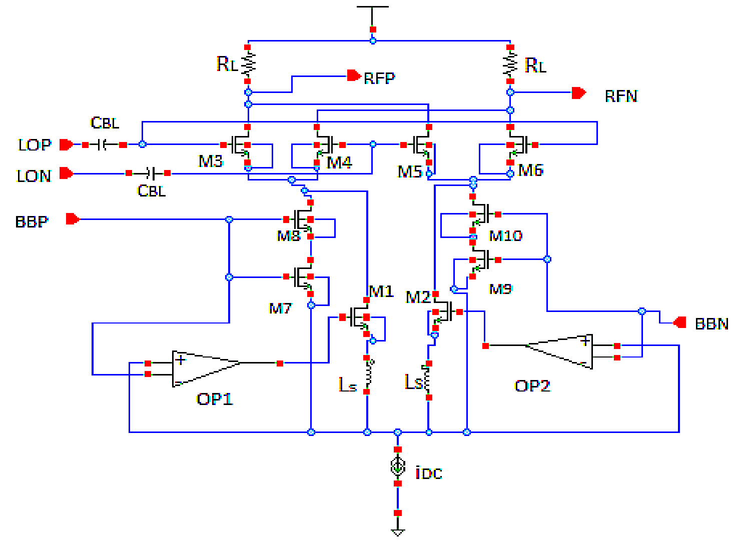


Fig. 2. Schematic of the Proposed Up-Conversion mixer Circuit

In the proposed mixer circuit as depicted in Fig 2, transistor M1 and M2 are differential pairs. They act transconductors pair converts baseband signal or IF signal voltage to current. NMOS transistors M3, M4 and M5, M6 acts as two pair of switching cores, which modulates the current supplied by transconductance pairs M1and M2 which is the basic principle of double balanced Gilbert cell mixer topology. These Four switching transistors act as ideal switch and biased in the saturation region close to triode region. The derivative superposition method is implied in the transconductance stage of this proposed up-conversion mixer by connecting four transistors. These transistors M7, M8 and M9, M10 are connected parallel to transconductance pair transistors M1 and M2. These four transistors are working in weak inversion region. The W/L ratio of these transistors is small compared to Transconductance pairs because

$$R_{ON} = \frac{1}{\mu_n c_{ox} \frac{W}{L}(V_{GS} - V_T)} \tag{14}$$

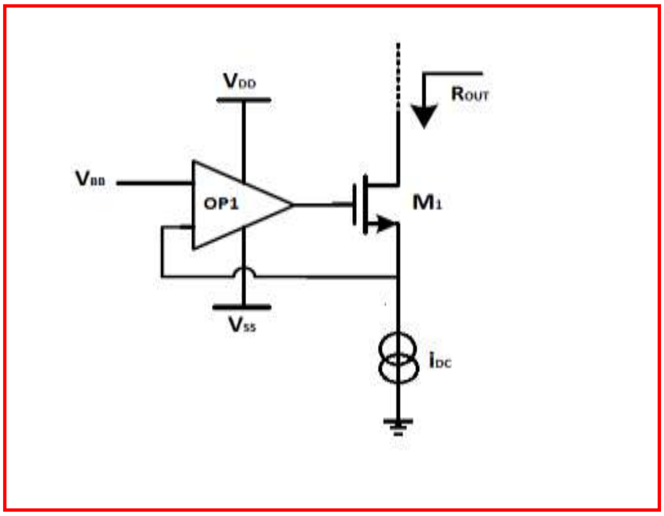
So two transistors are connected M7 and M8 in series to reduce W/L ratio, which indirectly improve R_{ON} resistance of these transistors. By a proper W/L ratio and gate bias transistors M7-M10 are applied to the weak inversion region and transistors M1 and M2 are working in the strong inversion region. The value of IIP3 depends on the third-order coefficient of transconductance g_{m3}. The parameter g_{m3} depends [9] on V_{GS} in such a way that when g_{m3} changes from positive to negative when V_{GS} changes from transit from weak inversion into the strong inversion region. If a positive g_{m3} with certain g_{m3}(V_{GS}) curvature of one NMOS transistor is aligned with a negative g_{m3} with a similar but mirror image curvature of another NMOS transistor by offsetting their gate biases and the g_{m3} magnitudes are equalized through a relative MOSFET scaling , the cumulative composite g_{m3} will be close to zero and the theoretical value of A_{IIP3} will be increased effectively Source degeneration spiral inductor is used in the circuit to improve the linearity of the circuit. The value of the A_{IIP3} depends on the source degeneration impedance [5],

$$|A_{IIP3}| \infty |1 + j\omega\omega_{gs} Z_s|$$

The value of source degeneration inductance is chosen at the resonant frequency. Capacitors C_{BL} are used as blocking capacitors to isolate the input and output port from the DC sources. The operational amplifier is used to improve conversion gain of the Up-conversion mixer. If the gain of the Op-amp OP1 is A then the output resistance looking for the drain of M1 is

$$R_{out} \approx A g_m r_1 .$$

Where g_m the transconductance of transistor M1and r_1 is the small signal equivalent resistance. So the overall conversion Gain of the mixer improved. The load resistors (R_L) stacked on the top of LO switch transistors which is optimized to obtain a low power dissipation and good conversion gain.



III. SIMULATION RESULTS

The proposed Up-conversion mixer is simulated in a Cadence analog design environment gpdk45 nm technology. Passive balun is used for conversion of unbalanced baseband signal to two balanced signal of equal magnitude and 180 degree out of phase. The effects of parasitic aroused due to the spiral inductor and capacitors are taken into consideration during the simulation. Rail to Rail Power supply used for core mixer is ±1.2 V.

The baseband signal is of the frequency 100 MHz and the Local Oscillator (LO) signal is 2.3 GHz. The proposed Up-conversion converts 100 MHz Baseband to 2.4 GHz Radio frequency (RF) signal. The baseband signal power is chosen at -40 dBm and Input LO power 2 dBm. The voltage conversion gain vs. Local oscillator power is 18.86 dB is shown in Fig, 4. The 1 dB compression point is achieved at 2.4 GHz frequency is -8.53054 dBm as depicted shown in Fig.5. The IIP3 of the proposed mixer is 15.9708 dBm and Output IP3 is 16.4053 dBm which is shown in Fig.6 and Fig.7 respectively. The Value of IIP3 of this proposed mixer is 8dBm better than the conventional mixer. The noise figure of simulated mixer is 18.10 dB. The transient response of the mixer is depicted in Fig 8. The operational amplifier used in the circuit with 73.2 dB gain and 57.6 deg phase margin as shown in Fig.9. The performance summary of simulated mixer and cross platform performance comparison respect to previous research works on Up-conversion mixer are shown in the table 1 and table 2 respectively.

IV. CONCLUSION

The proposed UP-Conversion mixer is suitable for Zigbee and Wireless Sensor Network applications. Linearity and conversion gain are contradictory performance parameters. In previous research works linearity achieved by sacrificing conversion gain. In the proposed mixer, linearity and Conversion Gain is sufficient enough at low supply voltage. The IIP3 of the proposed mixer is 8 dB higher than conventional mixer and it provides a very good conversion gain of 18.86 dB at ±1.2 V power supply. So it is suitable for applying in energy efficient low power Zigbee transmitter front-end.

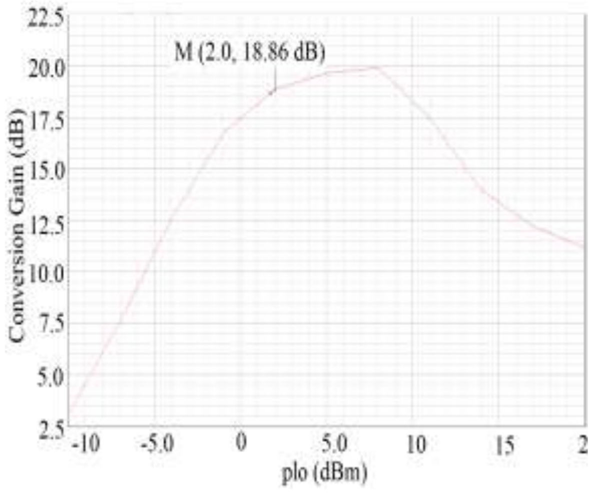


Fig.4. Voltage conversion Gain vs LO Power

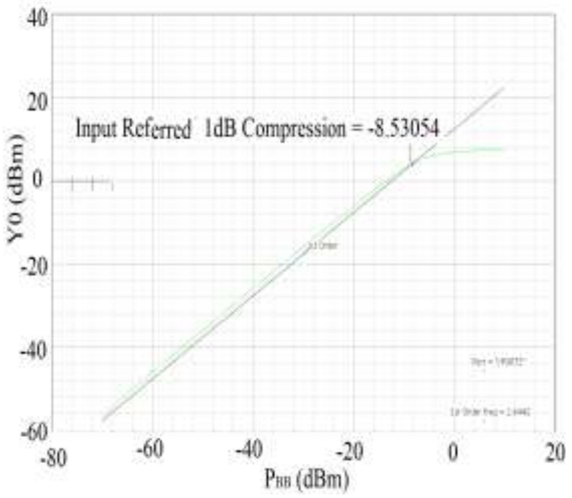
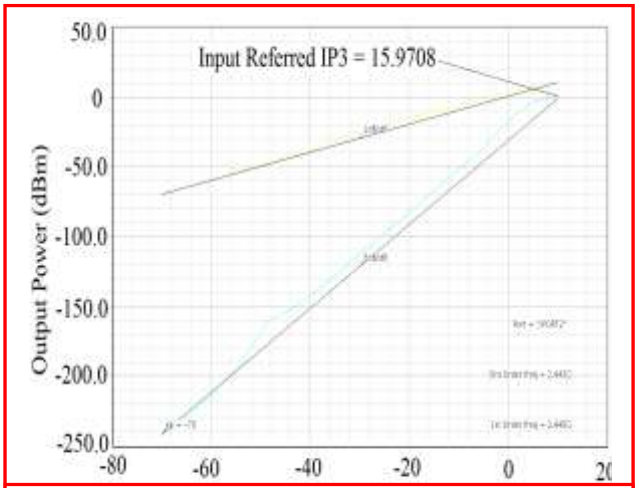
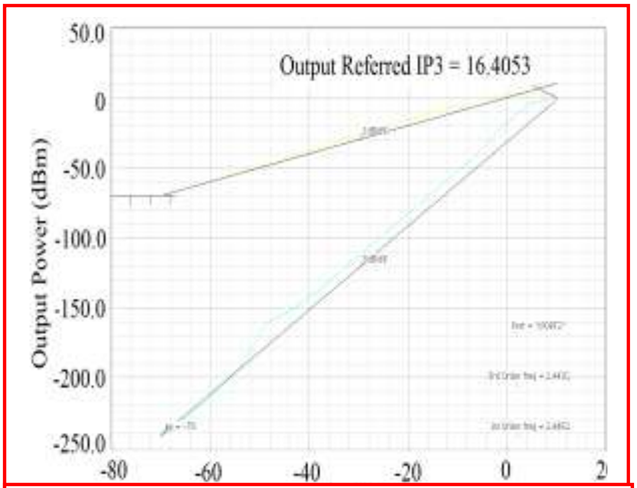


Fig.5. 1dB compression point





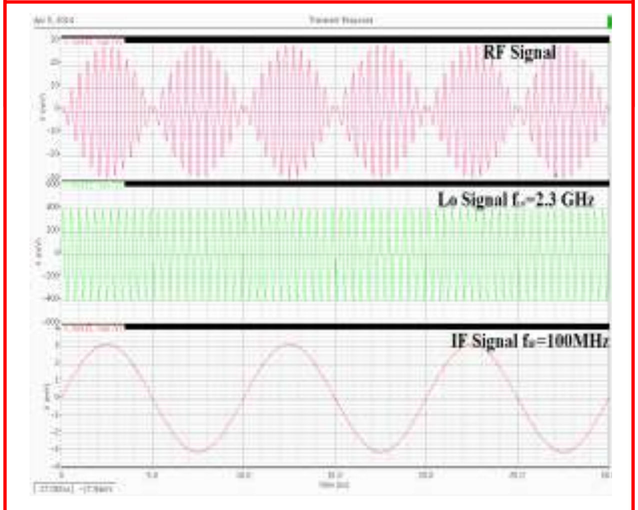


Fig.8. Transient Response

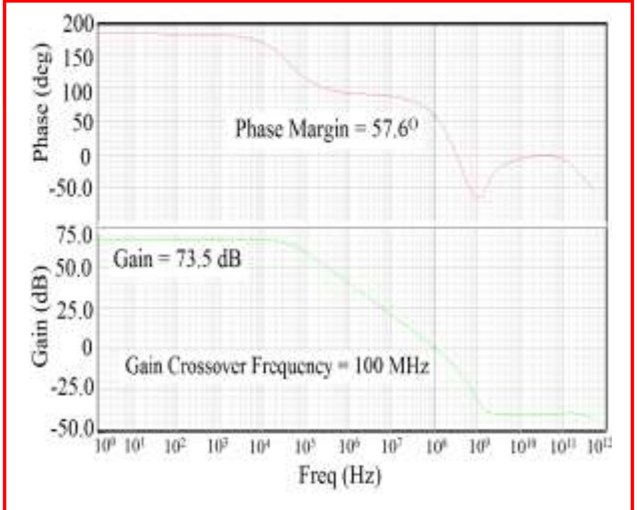


Fig.9. AC gain of proposed op-amp

Parameter	Value
Technology	**45nm**
Power Supply	**±1.2 V**
Base-band Signal Frequency	**100 MHz**
Local Oscillator Frequency	**2.3 GHz**
RF Signal Frequency	**2.4 GHz**
Voltage Conversion Gain	**18.86 dB**
Input 1 dB compression Point	**-8.53054 dBm**
IIP3	**15.9708 dBm**
OIP3	**16.4053 dBm**
Noise Figure	**18.10 dB**
Port to Port Isolation	**>58 dB**
Power Consumption	**3.65 mW**

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Table .2

Cross platform comparative performance

Parameter	[2]	[3]	[4]	[5]	[6]	This work
Technology	0.18µm	0.13 µm	0.18 µm	0.18 µm	0.18 µm	45nm
Power Supply(V)	1.2	1.2	1.8	1.8	1.8	1.2
IF Freq(MHz)	100	10-400	1	100	100	100
LO Freq(GHz)	1.8	1.8-2.6	2.419	5.1	5.1	2.3
RF Freq(GHz)	1.9	1.810	2.42	5.2	5.2	2.4
IF Power(dBm)	-30	-30	-40	-30	-30	-50
LO Power(dBm)	0	-3	1	-5	2	2
Conversion Gain (dB)	5	1.1	16.2	6	6	18.86
Input 1dB compression Point (dBm)			-20.7			-8.5304
IIP3(dBm)	14.68	6.45		8	15.7	15.9708
Noise Figure(dB)			18.6	26	24	18.10
Power Consumption (mW)	9.45	10		8.6	7.5	3.65

REFERENCES

[1] B.Razzavi, "Mixer Design Chapter 6," in RF Micoelectronics 2nd edition.

[2] Yuan-Hao Shu, and Jeng-Rern Yang. "Low voltage, high linearity CMOS up-conversion mixer for LTE applications," in Proc. IMFEDK – IEEE, 2013, pp-44-45.

[3] Xiaopeng Sun et.al. , "A 1.8-2.6GHz RF CMOS Up-Conversion Mixer for Wideband Applications," in Proc. IMWS-IEEE MTT-S International, 2012, pp-1-4.

[4] Wu Chenjian and Li Zhiqun, "A 0.18µm CMOS Up-Conversion Mixer for Wireless Sensor Networks Application," in Proc.WCSP IEEE, 2011, pp- 1-4.

[5] S.A.Z Murad et.al., " A Design of 5.2 GHz CMOS Up-conversion Mixer with IF Input Active Balun," in Proc. ISWTA IEEE, 2011, pp- 1-4.

[6] S.A.Z Murad et.al. , "High Linearity 5.2GHz CMOS up-conversion Mixer Using Super Derivative Superposition Method" in Proc. TENCON IEEE, 2010, pp-1509-1512.

[7] A. Saberkari et.al. ,"A low voltage highly linear CMOS up conversion mixer based on current conveyor," IEICE Electronics Express, vol.6, pp. 930-935, 2009.

[8] G.Sapone and G. Palmisano, "A 1.5V 0.25 µm CMOS up converter for 3-5 GHz low power WPANs," Microwave & Optical Technology Letter,vol. 49, no. 9, pp. 2209-2212, Sept. 2007.,

[9] S. H-L. Tu and S.C-H. Chen, "A 5.26-GHz CMOS up-conversion mixer for IEEE 802.11a WLAN", in Proc. of 4th IEEE International Conference on Circuits and Systems for Communications (ICCSC), 2008, pp. 820-823.

[10] Aparin, V et al. , "Modified Derivative superposition method for linearizing FET low –noise amplifiers," IEEE Microwave Theory and Techniques, vol. 53, pp. 571-581, Feb. 2005.

[11] Ghulam Mehdi, "Highly Linear Mixer for On-Chip RF Test in 130nm CMOS" Master thesis performed at division of Electronic Devices at Linköping Institute of Technology.

[12] Shengchang Gao. "A High-Linearity Low-Noise Figure Active Mixer in 0.18 um CMOS", 2009 5th International Conference on Wirelesssommunication Networking and Mobile computing.