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Fully-Integrated Tunable Q-Enhanced Linear Low Noise Amplifier for Wireless Receivers

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***Abstract:** This paper presents the design of a fully-integrated tunable Q-enhanced LNA resonator filter designed to tune the circuit center frequency and quality factor Q. The proposed circuit achieves a 600 MHz 3dB bandwidth tunable center frequency at 2.4 GHz with a 5.5 dB Quality Factor Q tuning range. The proposed circuit utilize a distortion transistor compensator to improve linearity of the circuit. The results show an 18 dBc of third order intermodulation IM3 cancellation. The overall proposed circuit peak gain is 16.5 dB and the minimum NF is 0.94 dB at 2.4 GHz frequency with power consumption of 5.2 mA*.

***Keywords:** Low noise amplifier, Tunable Q-enhanced coupled-inductors, Negative resistance and linearization, Wireless communications.*

I. INTRODUCTION

In practical down conversion radio frequency receivers lossy bulky off-chip filters are used to provide filtering of unwanted out of band interference. However, such off-chip filters degrade the overall noise figure of the system. Using on-chip inductors with high quality factors Q are difficult to obtain. A technique called Q-enhancement for increasing the Q of on-chip resonators can be applied to improve the Q factor of the on-chip inductors by placing a negative resistance across the inductors. However, linearity problems exist in these Q-enhanced circuits that degrades the overall dynamic range of the system. The main idea of the proposed circuit is to compensate the loss of coupled-inductors by using active devices transistors to create negative resistance. With this Q-enhanced resonator tuning circuit the resistance of the coupled-inductors is partially cancelled and the effective Q is increased. In this paper, a tunable Q-enhanced LNA resonator filter design circuit architecture is presented based on coupled resonator filter by means of mutual inductance coupled transformer. The proposed tunable Q-enhanced resonator filter designed to tune the quality factor Q and center frequency and is combined together with a distortion transistor compensator to improve linearity of the circuit. Other published tunable Q-enhanced LNA filter design [1] and [2] and [3] have a high noise figure of over 5 dB. And other Q-enhanced LNA filter [1] and [4] and [5] and [6] and [7]. Other published tunable RF LNA Q-enhanced Bandpass filter [8] have degraded linearity of -33 dBm input compression point and -17 dBm [9] do not employ distortion compensation circuit.

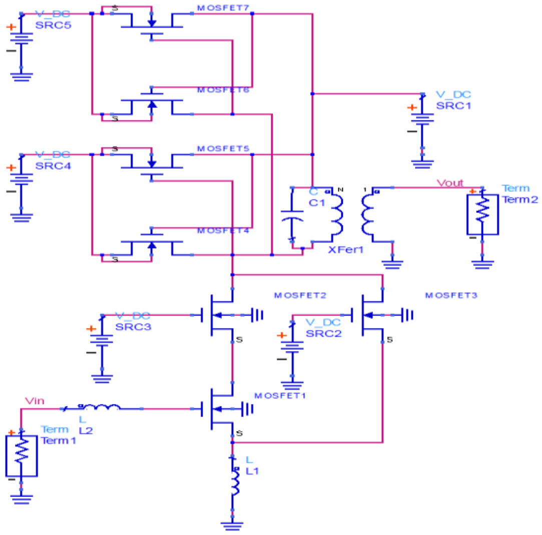

Fig. 1.Proposed fully-integrated tunable Q-enhanced LNA resonator circuit with distortion transistor compensator.

II. Q-ENHANCED COUPLED RESONANCE FILTER

A. Q-Enhancement LC resonator tuning circuit

Resonance LC filter require tuning mechanism to tune the center frequency with quality factor Q of the circuit. A Q-enhancement tuning mechanism is created from pairs of cross-coupled FET transistors. The main idea is to compensate the loss of inductors by negative resistance. A simple Q-enhanced circuit shown below in Figure 2 where the negative resistance of a cross-coupled pair FET transistors are utilized to partially cancel the parasitic resistance of the on-chip coupled inductor resonator thus enhancing its quality factor Q.

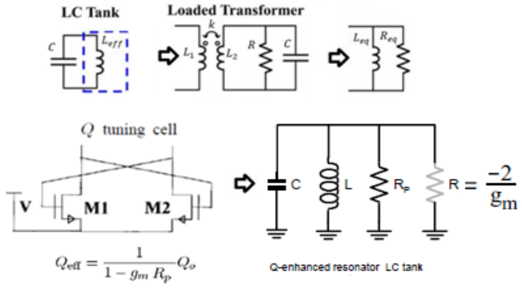

Fig. 2.A basic Q-enhancement LC resonator tuning circuit with cross coupled pair.

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The quality factor Q is related to Rp by the following equation. Where transconductance g_m is the Q-enhanced MOSFET in cross-coupled pair and Rp is the resistance in parallel with filter

$$Q = \frac{R_p//(-\frac{1}{gm})}{\omega oL}$$

Re-arranging the quality factor Q above equation we get the following equation

$$Q = \frac{R_p/gm}{\omega_o L.(\frac{1}{gm} - R_p)}$$

The bandwidth BW is related to the center frequency ωo and the quality factor Q by this equation

$$BW_{3dB} = \frac{\omega_o}{Q}$$

The center frequency ωo is given by

$$\omega_o = \frac{1}{\sqrt{LC}}$$

This circuit arrangement partially cancels inductors series resistance and improves boosting Q factor, where Q is the parallel resistance Rp and inductor reactance at resonant frequency by

$$Qo = \frac{Rp}{\omega oL}$$

The effective Q_{eff} is adjusted by modifying the cross-coupled pairs transconductance g_m of the given by equation [7], [8],

$$Q_{eff} = \frac{Q_o}{1 - g_m R_p}$$

Q_o is the resonant circuit base quality factor.

This the cross-coupled pair circuit behaves as a negative resistance and the amount of negative resistance generated is given by

$$R = \frac{V_{ds1} - V_{ds2}}{i} = \frac{-2}{g_m}$$

The cross-coupled pair negative resistance at high frequencies is given by equation

$$R = \frac{-2}{g_m}\left(1 - \frac{1}{g_m r_o}\right) + \frac{j\omega}{2}(C_{gs} + C_{db} + 4C_{gd})$$

The filter total capacitance can be regulated tuning the resonance frequency of the resonator filter.

III. PROPOSED Q-ENHANCED COUPLED-TRANSFORMER TUNING CIRCUIT TECHNIQUE

The proposed fully-integrated tunable Q-enhanced coupled-transformer resonator circuit CMOS design consists of two pair of cross-coupled transistors connected in parallel configuration where the gates of each device are connected to the drains of the opposite device as shown in Figure 3. The complementary –Gm circuit with supporting bias circuits is a result of using both nMOS and pMOS cross coupled pairs in parallel to generate the total negative resistance tuning mechanism. Hence with proper bias voltage and through suitable setting of the cross-coupled pairs transconductor g_m the effective Q_{eff} can in theory be tuned as high as desired.

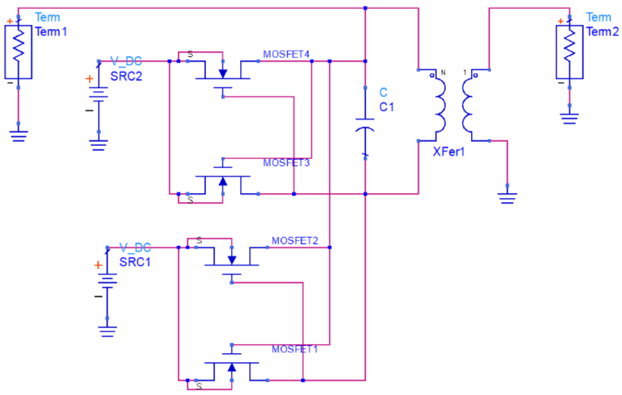

Fig. 3.Proposed Q-enhancement coupled-transformer tuning circuit.

The proposed fully-integrated tunable Q-enhanced coupled-transformer resonator circuit provides a filter 3dB bandwidth tuning range of 600 MHz from 2.1 GHz to 2.7 GHz as shown in center frequency tuning response of the proposed Q-enhanced LNA circuit in Figure 4. The proposed Q-enhanced resonator provides center frequency tuning range and larger 3dB bandwidth then the Q-enhanced LNA filters in [1], [4], [5], [6] and [7].

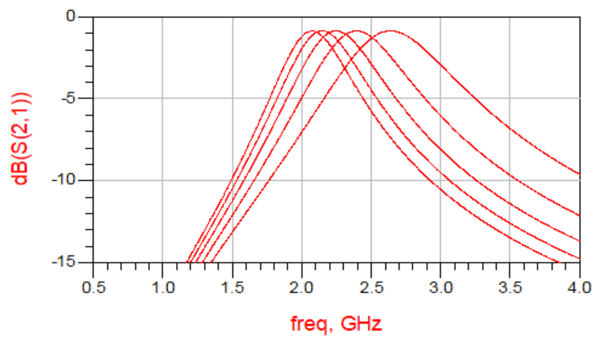

Fig. 4.Center frequency tuning response of the proposed Q-enhanced LNA circuit.

The proposed fully-integrated tunable Q-enhanced LNA coupled resonator filter circuit provides a forward gain S21 of 16.5 dB and NF of 0.94 dB at frequency 2.4 GHz as shown in Figure 5. And provides a reflection coefficient of -30.7 dB.

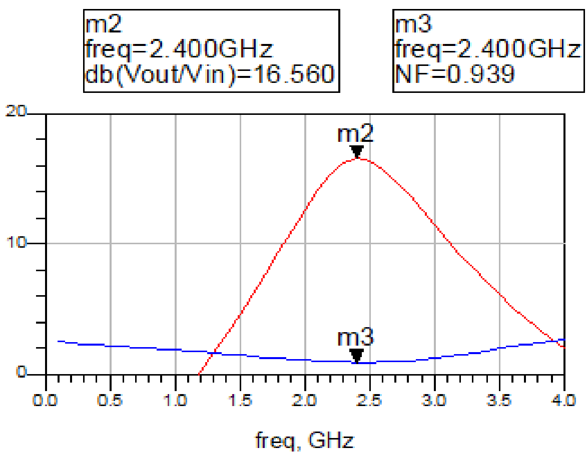

Fig. 5.Response for the proposed Q-enhanced LNA circuit Forward Gain S21 and Noise Figure at frequency 2.4 GHz.

The width of the fully-integrated tunable Q-enhanced LNA design transistors can be determined by the following equation

$$W = \frac{1}{3\omega o L C_{ox} R_s}$$

Where ω is the operating frequency and L is the length of the FET transistor and C_{ox} is the transistor oxide capacitance and R_s is the source resistance.

$$R_s = \frac{L_s}{C} g_m$$

where L_s is the source inductance and transistor gate capacitance C and transconductance g_m.

The proposed fully-integrated tunable Q-enhanced LNA coupled resonator filter circuit provides a 5.5 dB quality factor Q tuning range as shown in Figure 6.

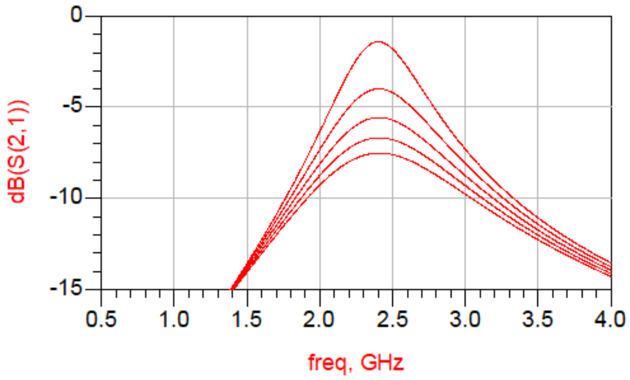

Fig. 6.The Q-enhanced LNA filter Q-tuning response at 2.4GHz.

IV. PROPOSED Q-ENHANCED LNA FILTER WITH DISTORTION TRANSISTOR COMPENSATOR

If The proposed fully-integrated tunable Q-enhanced LNA design utilize a distortion transistor compensator MOSFET3 shown in Figure 1 providing third order intermodulation IM3 distortion cancellation.

The transistor FET drain current is given by Taylor series as [12], [13],

$$i_d = g_{m1} v_{gs} + g_{m2} v_{gs}^2 + g_{m3} v_{gs}^3$$

where g_{m1} and g_{m2} and g_{m3} are the first transconductance derivative and second transconductance derivative and third transconductance derivative, respectively, with respect to the gate to source voltages.

The third-order intercept amplitude A_{IIP3} is a measure of the circuit nonlinearity and is given by [12], [13],

$$A_{IIP3}^2 = \left|\frac{4g_{m1}}{3g_{m3}}\right|$$

The LNA circuit third order intercept point amplitude A_{IIP3} can be written in terms of power and is given by [12], [13],

$$P_{IIP3} = 20\log(A_{IIP3}) + 10dbm$$

The LNA circuit 1-dB compression point amplitude A_{1dB} where g_{m1} and g_{m3} the first and third transconductance derivatives is given by [12], [13],

$$A_{1dB}^2 = 0.145\left|\frac{g_{m1}}{g_{m3}}\right|$$

The circuit dynamic range DR that can be achieved in a radio frequency receiver with respect to 1dB compression point is given by [9], [10],

$$DR = \frac{P_{1dB}}{4KT(F+1)BQ^2} Q_o^2$$

where is the circuit P_{1dB} 1-dB compression point power measured at the LNA's output and Q_o is the base resonant circuit quality factors before and Q is the quality factor after enhancement. F_{op} is the circuit operational noise figure and G is the low noise amplifier gain. B is the bandwidth of the receiver and KT is the Boltzmann's constant times temperature in Kelvin.

With proper bias voltage v_{gs} and FET transistor size and through suitable setting of the distortion transistor compensator transconductor g_m the proposed Q-enhanced LNA circuit achieved a third order intermodulation IM3 distortion cancellation of 18 dBc at 2.4 GHz as shown in Figure 7 and Figure 8.

The proposed Q-enhanced LNA simulation response in Figure 7 and Figure 8 show an 18 dBc of IM3 distortion cancellation equivalent of 9 dB of IIP3 improvement at 2.4 GH with consumption of 5.2 mA from a 2.5 V.

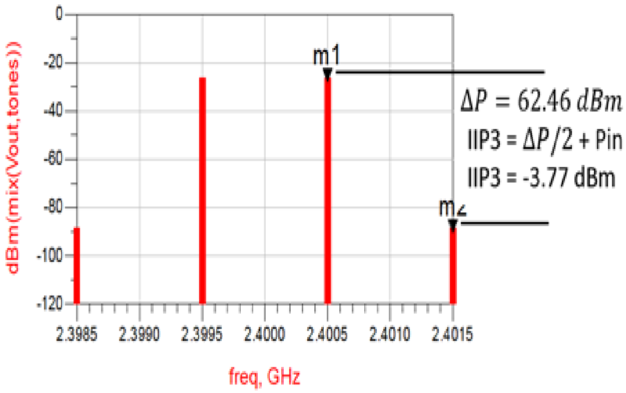

Fig. 7.Response of third-order intermodulation distortion of the proposed Q-enhanced LNA circuit at 2.4 GHz

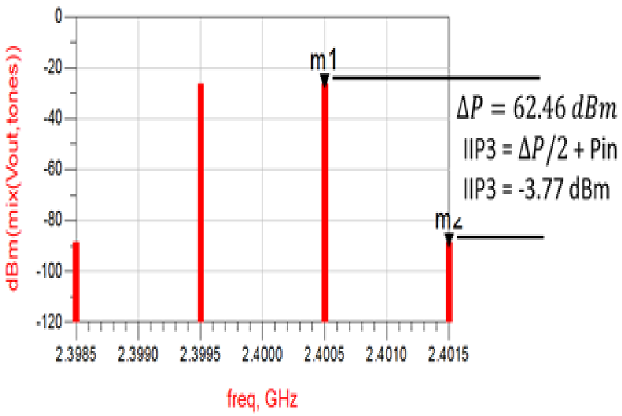

Fig. 8.Response of third-order intermodulation distortion of the proposed Q-enhanced LNA circuit at 2.4 GHz after distortion cancellation.

The IMD3 is improved by 18 dBc and the response of 1-dB Compression point of the proposed Q-enhanced LNA circuit at 2.4 GHz is shown in Figure 9.

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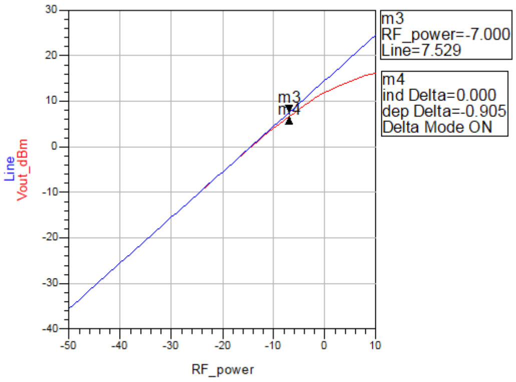

Fig. 9.Response of 1-dB Compression point of the proposed Q-enhanced LNA circuit at 2.4 GHz.

V. PROPOSED Q-ENHANCED LNA TRANSISTOR DIMENSIONS

The Q-enhanced LNA transistor dimensions are shown in Table I with MOSFET1 and MOSFET2 transistor width size of 100µm. The cross-coupled pair transistor width size is 50µm. The distortion transistor compensator is 100µm. The input matching inductor is 5.7 nH and source degeneration inductor is 1.2 nH shown in Figure 1.

Table- I: Transistor Sizes for the proposed Q-enhanced LNA circuit

MOSFET1 MOSFET2 MOSFET3	W/L: 100 µm / 0.25 µm
MOSFET4 MOSFET5 MOSFET6 MOSFET7	W/L: 50 µm / 0.25 µm

VI. RESULTS AND DISCUSSION

The simulation performance results for the proposed tunable Q-enhanced LNA circuit are shown in Table II.

Table- II: Simulation Performance results for the proposed tunable Q-enhanced LNA circuit

Process	RF CMOS
Center Frequency	2.4 GHz
Peak Gain	16.5 dB
Frequency tuning range	600 MHz
Q-Tuning	5.5 dB
Noise Figure	0.94 dB
Reflection Coefficient	-30.7 dB
Reverse Isolation	-44 dB
IM3 Tuning	18 dBc
IIP3 Tuning	9 dB
Power Consumption	5.2 mA

The comparison of performance of this work and previous Q-enhanced filter in literature is shown in Table III.

Table- III: Comparison between this work and integrated Q-enhanced filter previous work

REF	CENTER FREQ.	3DB FREQ TUNING RANGE	NF	PROCESS
[1]	942.5 MHz	940 MHz -982 MHz	6.4 dB	0.25µm
[3]	1640 MHz	1500 MHz -1780 MHz	2.3 dB	0.18µm
[5]	2 GHz	1.93 GHz -2.2 GHz	26 dB	0.35µm
[8]	2.4 GHz	31.57 MHz -32.76 MHz	14.2 dB	0.35µm
[11]	2.4 GHz	2.3 GHz -2.5 GHz	15.3 dB	0.18µm
THIS WORK	2.4 GHz	2.1 GHz-2.7 GHz	0.94 dB	0.25µm

VII. CONCLUSION

The design of a fully-integrated tunable Q-enhanced LNA filter circuit design is presented. The proposed circuit achieves a 600 MHz 3dB bandwidth tunable center frequency with a 5.5 dB Quality Factor Q tuning range. The proposed circuit utilize a distortion transistor compensator to improve linearity of the circuit. The results show 18 dBc of third order intermodulation IM3 cancellation. The overall proposed circuit peak gain is 16.5 dB and the minimum NF is 0.94 dB at 2.4 GHz frequency with power consumption of 5.2 mA.

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