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Bandwidth Extension of Constant-Q Bandpass Filter using Bandwidth Extension Techniques

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ABSTRACT: CMOS spiral inductors suffer from a number of drawbacks including a low Q factor, a low self- resonant frequency, and a small and non-tunable inductance and require a large chip area. On the other hand active inductor offers many unique advantages over their spiral counterparts including small chip area, large and tunable inductance and high quality factor. These active inductors have been used successfully in many applications such as in radio frequency (RF) front end integrated circuits, filters, and phase shifter and oscillator circuits. The effectiveness of these active inductors is however affected by a number of limitation including small dynamic range, a high noise level and high power consumption. High speed applications such as preamplifier of data transceiver require large bandwidth hence there is a need for technique that achieve larger bandwidth without increased power consumption and design complexity. In this paper, bandwidth extension techniques are used to extend the bandwidth of the bandpass filter. Active inductors are used in the designing of the bandpass filter. A swing independent quality factor, called constant-Q active inductor is used as an active element in the designing of the bandpass filter. Bandpass filter is implemented on both 0.5 µm and 0.35 µm CMOS process. Comparisons are made between resistive compensation technique and inductive series peaking technique. Simulation results shows that the bandwidth is improved by 72%.The operating frequency is also increases from 122.995 MHz to 194.276 MHz at 0.5 µm technology and operating frequency increases from 163.641 MHz to 259.189 MHz at 0.35 µm technology.

KEYWORDS: Bandpass filter, bandwidth extension, constant-Q active inductor, inductive series peaking, resistive compensation.

1 INTRODUCTION

In recent years, the demand of the wireless communication systems has led the IC design trend to low cost, low power, and high integration. An analog RF filter is an essential block in wireless receivers. Implementing on-chip high-Q IF/RF bandpass responses for band channel-selection filtering or image frequency rejection filtering is a very demanding problem, due to the extremely powerful specifications in terms of accuracy, stability, and dynamic range at very high operating frequencies. Typically, this requires the use of high quality spiral inductors with auxiliary active circuitry for compensation of inductor losses and achieving the necessary tuning ability.

Many circuits in literature are based on RLC realization using passive inductors [1]. Much architecture for active has been proposed [2], [3], [4]. Active inductors are realized by using the classical gyrator- C topology. Gyrators realized operational transconductors feature transconductance that can be adjusted with applied bias, thereby allowing for whose values can be adjusted, or “tuned”, electronically. Basic CMOS active inductor is described in section II. Various approaches for designing of bandpass filter using active inductor have been proposed [5], [6], [7], [8], [9]. Designing of bandpass filter using active inductor is described in section III.

Passive filtering (e.g. shunt and series peaking) has been used since the 1930s to extend amplifier bandwidth; it uses inductors to trade off bandwidth versus peaking in the magnitude response. Bandwidth extension techniques based on passive filtering as proposed in [10], [11], [12] is described in section IV.

In this paper, Inductive series peaking technique suggested in [12] is used for bandwidth enhancement of current mirror, is applied for bandwidth enhancement of active inductor. Comparisons are made between resistive compensation technique and inductive series peaking technique. Bandpass filter is implemented in both 0.5µm and 0.35 µm CMOS process.

2 ACTIVE INDUCTOR

Active inductors are realized by using the classical gyrator- C topology. The gyrator is a two port network that is designed to transform load impedance into input impedance where the input impedance is proportional to the inverse of the load impedance. Gyrator network can be used to transform a load capacitance into an inductance. When two transconductors are connected back to back, they form gyrator-C active inductor. Where one port of the gyrator is terminated with a capacitive load and the other port exhibits an inductive characteristic.

2.1 BASIC CMOS ACTIVE INDUCTOR

Figure 1 shows the Wu current reuse active inductor as proposed in [5], which in comparison to other topologies could use biasing current more efficiently. A common gate configuration of the positive transconductor along with a common source configuration of the negative transconductor creates the NMOS version of the active inductor.

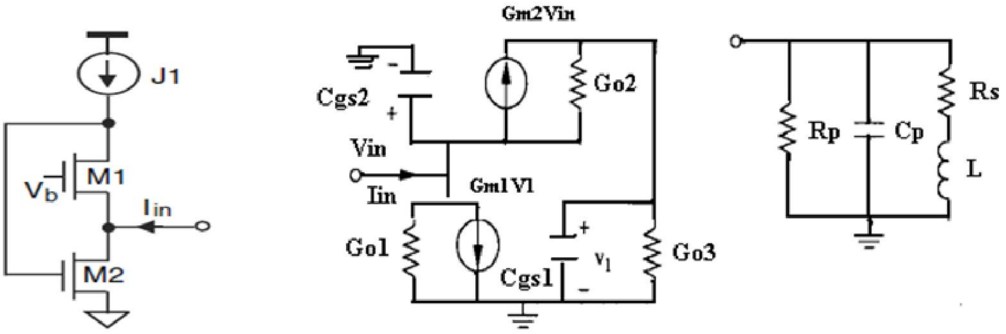


Fig. 1. Wu current reuse active inductor and its equivalent Small signal model and RLC circuit

Figure 1 shows the small signal equivalent circuit of the active inductor. Neglecting gate drain capacitance we have

$$C_p = C_{gs2} \tag{1.1}$$

$$R_p = \frac{1}{G_{o1}} \parallel \frac{1}{G_{m2}} \cong \frac{1}{G_{m2}} \tag{1.2}$$

$$R_S = \frac{G_{o1}}{G_{m1}G_{m2}} \tag{1.3}$$

$$L = \frac{C_{gs2}}{G_{m1}G_{m2}} \tag{1.4}$$

$$\omega_0 = \sqrt{\frac{G_{m1}G_{m2}}{C_{gs1}C_{gs2}}} = \omega_{t1}\omega_{t2} \tag{1.5}$$

$$Q \cong \sqrt{\frac{G_{m1}C_{gs2}}{G_{m2}C_{gs1}}} = \sqrt{\frac{\omega_{t1}}{\omega_{t2}}} \tag{1.6}$$

From above equations we can see that the inductance L, the parasitic series resistance R_S, and parasitic parallel resistance R_P all are functions of G_{m1} and G_{m2}, which are determined by the channel current of M1 and M2.The channel current of M2 is greatly affected by the input current I_{in}, especially when I_{in} is large. As a result both the inductance and quality factor of the active inductor are strong functions of the swing of the input current.

2.2 CONSTANT -Q CMOS ACTIVE INDUCTOR

Constant-Q CMOS active inductor consist Wu's active inductor and a current feedback network. In the applications, where the quality factor of the active inductor varies largely, such as LC-tank oscillators, the inductance, parasitic resistances, and quality factor of the active inductors all vary with signal swing.CMOS active inductor with nearly constant quality factor, called constant-Q active inductor is used as proposed in [13].

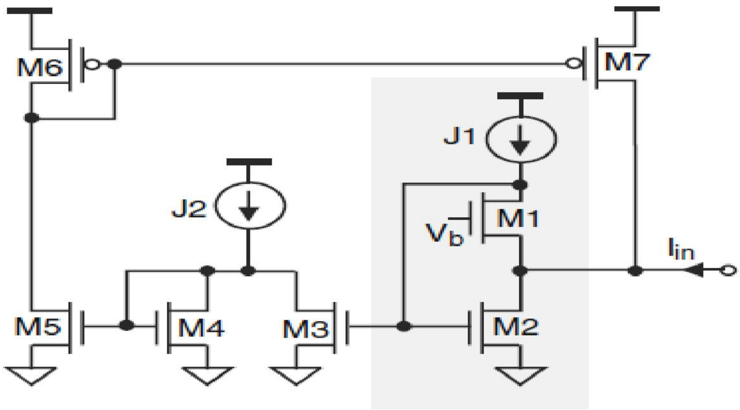


Fig. 2. Constant-Q CMOS active inductor

The transistors M2-M3, M4-M5, and M6-M7 form a current mirror pair having current gain k1, k2 and k3 respectively.J2 is set at maximum input current swing $i_{in,max}$.

3 FILTER ARCHITECTURE

A simple way of implementing a bandpass filter with the active inductor proposed in [9] is shown in Figure 3. The input transconductor Gm, realized by Min, converts the input voltage Vin to a current that is applied to the active inductor. The output voltage is taken at the inductor port. A source follower output buffer is included to drive the resistive loads and to prevent a load resistor and capacitor from reducing the resonant frequency and quality factor of the filter. The parasitic capacitors of the input Gm and the output buffer can be included in C1.

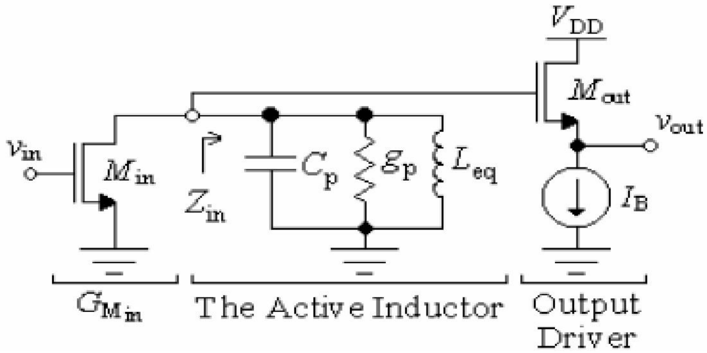
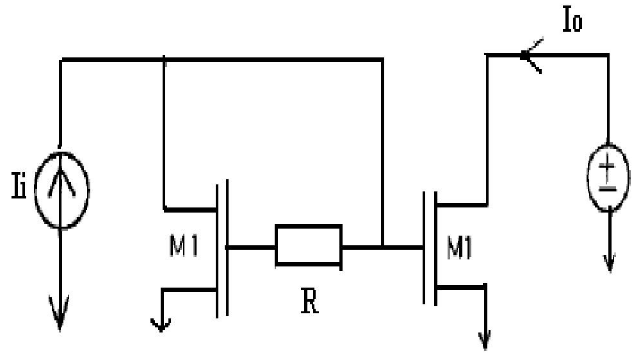


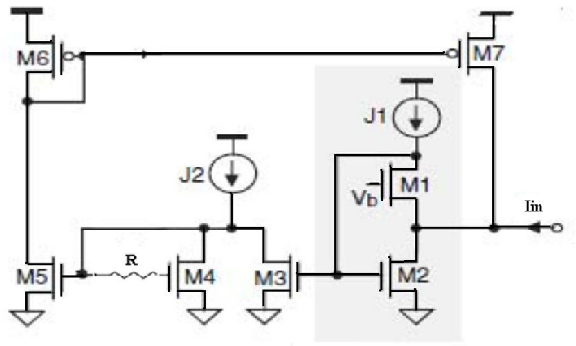
Fig. 3. Block diagram of the bandpass filter based on active inductor

4 BANDWIDTH EXTENSION TECHNIQUES

4.1 RESISTIVE COMPENSATION TECHNIQUE

Resistive compensation technique as proposed in [10] enhances the bandwidth of current mirrors without distorting the DC characteristics of the original circuits. In this a resistor is introduces between the gates of the input and output transistor of the basic current amplifier to introduce a zero in the system which cancels the dominant pole and increases the bandwidth.





(a) *(b)*

***Fig. 4.** (a) Simple current mirror (b) Constant-Q active inductor bandpass filter with resistive compensation*

However, the resistor eventually delays the response but also introduces a zero which cancels that delay. The addition of the zero makes the system faster and more oscillatory as the zero moves in the negative axis toward the origin. When R = $1/G_{m1}$ and $C_{gs1}= C_{gs2}$, zero cancels one of the poles, yielding a first order system with a frequency response determined by $\omega_0= G_{m1}/C_{gs2}$, which is twice the frequency of the uncompensated current mirror.

Figure3 (b) shows the constant Q active inductor with resistive compensation technique as proposed in [14]. Without compensation resistor the input impedance of the constant Q active inductor is given as

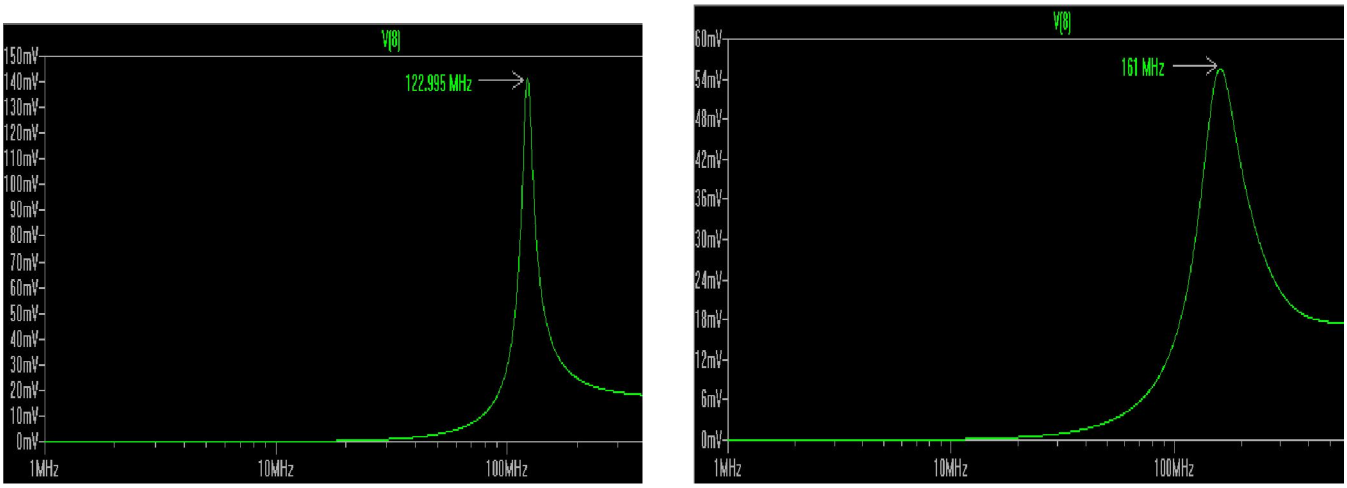
$$Z_{in} = \frac{\frac{s}{C_1}}{s^2+s\frac{G_{m1}}{C_1}+\frac{G_{m1}G_{m2}}{C_1C_2}} \quad (1.7)$$

By introducing a compensation resistor between the gates in one of the current mirror pair M4-M5, one zero two pole system is transposed into four zero five pole system.

$$Z_{in} = \frac{s^2(g+sC_3)/C_1C_3C_5}{s^4+s^3\left(\frac{g}{C_5}+\frac{G_{m1}}{C_1}\right)+s^2\left(\frac{G_{m1}g}{C_1C_5}+\frac{G_{m2}G_{m1}}{C_1C_2}\right)+ s\left(\frac{G_{m2}G_{m1}g}{C_1C_2C_5}+\frac{G_{m1}G_{m4}g}{C_1C_3C_5}\right)+\frac{G_{m1}G_{m2}G_{m4}g}{C_1C_2C_3C_5}} \quad (1.8)$$

At g = s/C_5 one pole and zero gets cancelled. Maximum bandwidth is achieved when zero cancels a pole.

Figure 5 shows the frequency curve of the constant Q active inductor bandpass filter at 0.5 µm technology. The frequency of the Constant Q active inductor bandpass filter is 122.995 MHz with a bandwidth of 21 MHz



(a) *(b)*

Fig. 5. (a) Frequency curve of constant Q active inductor bandpass filter with frequency 122.995 MHz and bandwidth is 21 MHz (b) Frequency curve of constant Q active inductor bandpass filter with resistive compensation with frequency 161 MHz and bandwidth is 69.61 MHz

After resistive compensation bandwidth of the constant Q active inductor bandpass filter is increased from 21 MHz to 69.61 MHz and frequency is also increased from 122.995 MHz to 161 MHz. The frequency curve of constant Q bandpass filter with resistive compensation is shown in Figure5 (b).

4.2 INDUCTIVE SERIES PEAKING TECHNIQUE

Inductive series peaking technique as proposed in [12], improves the bandwidth by utilizing the resonance characteristics of LC network. Because the dominant pole of CMOS current mode circuits is attributed to the gate source capacitances of the input and output transistors, a compensation inductor can be placed between the gates of the input and output transistors, and in series with C_{gs2} as shown in Figure 6.

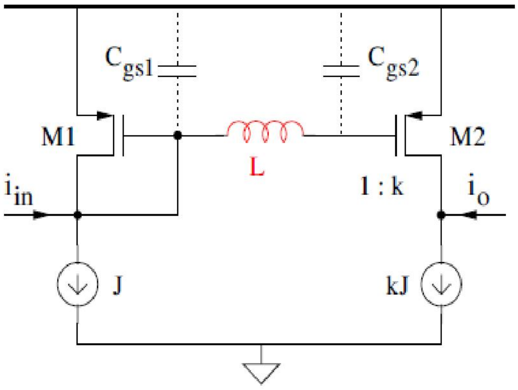
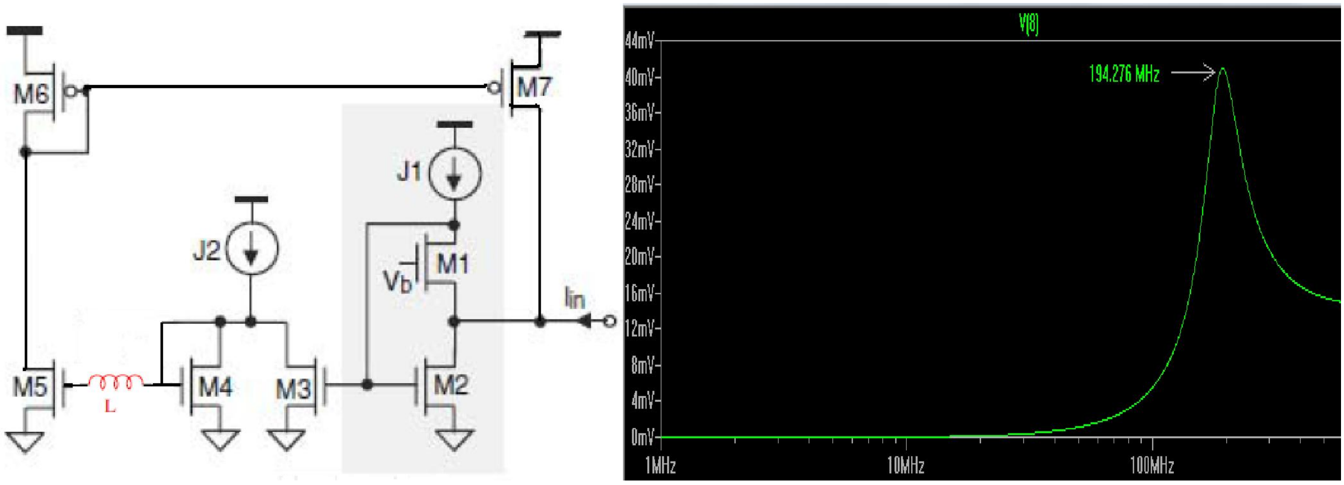


Fig. 6. Current mirror amplifier with series peaking inductor

The characteristics of the amplifier depend upon the value of the peaking inductor [18], as detailed in Table 1. To maximize the bandwidth and avoid ringing in time domain, the peaking inductor is sized based on the criterion of the critical damping, where $L = C_{gs2} / 4G^2_{m1}$, and the circuit has the bandwidth of $\omega 0 = 2G_{m1} / C_{gs2}$



(a) *(b)*

Fig. 7. ***(a) Modified constant Q bandpass filter with inductive series peaking (b) frequency response curve with frequency 194.276 MHz and bandwidth is 74.395 MHz***

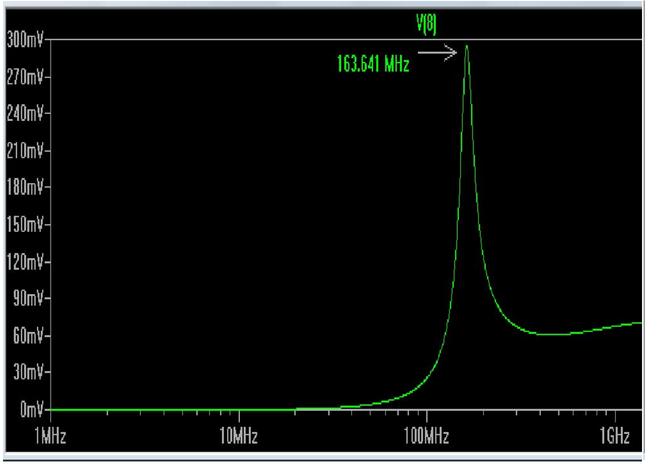
When constant-Q active inductor bandpass filter with inductive series peaking is simulated on 0.5 µm technology, then frequency is increased from 122.995 MHz to 194.276 MHz and bandwidth is increased from 21 MHz to 74.395 MHz. Figure 7(b) shows the frequency curve of constant-Q bandpass filter with inductive peaking.

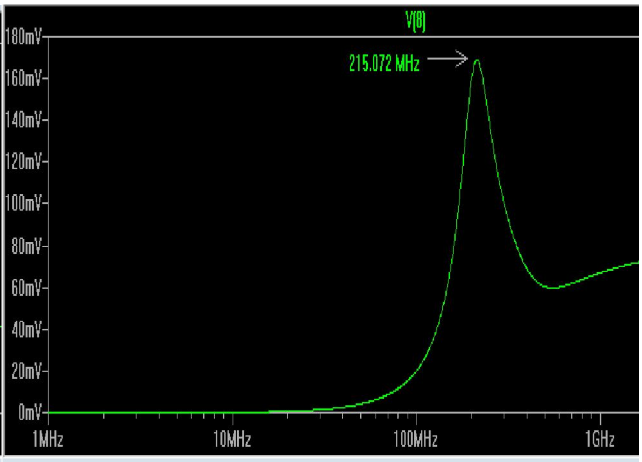
Now constant- Q active inductor bandpass filter is simulated on 0.35 µm technology. Frequency curves of bandpass filter with and without bandwidth extension are shown in section V.

Table 1. Damping characteristics

L	Poles	Damping characteristics	Responses
$L < C_{gs2}/4G^2_{m1}$	Two distinct negative real poles	Over-damped	Small bandwidth Large rise time No ringing
$L = C_{gs2}/4G^2_{m1}$	Two identical negative real poles	Critically damped	Large bandwidth Small rise time No ringing
$L > C_{gs2}/4G^2_{m1}$	Complex conjugate poles with negative real part	Under-damped	Large bandwidth Small rise time Ringing

5 Simulations on 0.35 µm Technology





(a) *(b)*

Fig. 8. (a) Frequency curve of constant-Q active inductor bandpass filter with frequency is 163.641 MHz and bandwidth is 26 MHz
(b) Frequency curve of constant-Q bandpass filter with resistive compensation: frequency 215.072 MHz and bandwidth is 89 MHz

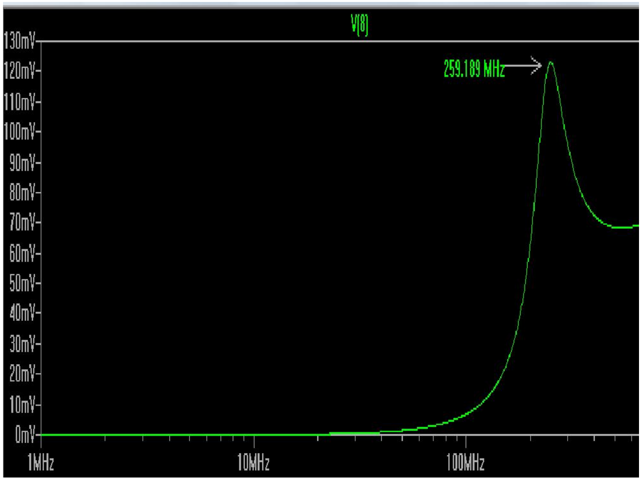


Fig. 9. Frequency curve of constant-Q active inductor bandpass filter with inductive series peaking: frequency is 259.189 MHz and bandwidth is 94 MHz

6 Simulation Results

Simulation is done on 0.5 µm and 0.35 µm technology. With inductive series peaking technique bandpass filter has maximum bandwidth 74.395 MHz with frequency 194.276 MHz at 0.5 µm technology. With resistive compensation technique bandpass filter has frequency 161 MHz and bandwidth is 69.61 MHz. Simulation results of bandpass filter at 0.35 µm technology are better than the 0.5 µm technology. With inductive series peaking, frequency of the bandpass filter is 259.189 MHz with 94 MHz bandwidth bandwidth. With resistive compensation technique, frequency is 215.072 MHz with bandwidth 89 MHz.

Table 2. Comparison of bandwidth extension techniques

Parameters	Without extension technique at 0.5 µm [14]	Resistive compensation at 0.5µm[14]	Inductive series peaking at 0.5µm	Without extension technique at 0.35µm	Resistive compensation at 0.35 µm	Inductive series peaking At 0.35µm
Frequency	122.462 MHz	148.59 MHz	194.276 MHz	163.641 MHz	215.072 MHz	259.189 MHz
Bandwidth	16 MHz	60 MHz	74.395 MHz	26 MHz	89 MHz	94 MHz

7 CONCLUSION

Constant Q active inductor bandpass filter with and without bandwidth extension techniques are described. Bandpass filter is simulated on both 0.5 µm and 0.35 µm technology. From simulation results we can say that inductive series peaking is best for bandwidth extension in bandpass filter. With the help of bandwidth extension techniques, bandwidth of the bandpass filter is extended more than thrice of the bandwidth of the bandpass filter without any extension technique.

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