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Optimization of Bandwidth and Insertion Loss using Currents of CMOS Quadrature LC Oscillators

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Abstract

This paper presents analytical approaches for estimation of the Bandwidth and Insertion loss related to LC-Tanks quadrature oscillators. In parallel coupled quadrature oscillators, transconductances due to the currents of switching and coupling transistors in LC tank effects on the quality factor (Q). Equations are obtained from Q which is considered as a loaded Q (Q_L). The transconductances due to the currents of switching and coupling transistors effect on the Q_L and consequently, the bandwidth. In this way, the bandwidth is adjustable by the currents of CMOS transistors of quadrature oscillators. The insertion loss becomes important when a resonant circuit is as a matching network or band-pass filter. A new estimation for insertion loss of LC tanks as matching networks of quadrature oscillators is obtained rely on loaded Q (Q_L) and also Q_U which refers only to the each passive component itself, apart from rest of the circuit. The proposed analysis, have critical roles for quadrature oscillator's applications which the bandwidth is imperative and also avoiding the excessive casualties is considered. To evaluate, a 5 GHz Parallel Coupled Quadrature Oscillator implemented using RLC tank as resonator and practical TSMC 0.18μm technology. The results confirm the proposed analysis.

Keywords: Quadrature Oscillator, LC Tank, RF CMOS, Loaded Q, Adjustable Bandwidth, Unloaded Q, Insertion Loss, Transconductance

Introduction:

Nowadays, many researches and studies have been performed to improve wireless communication systems and networks which have been widespread everywhere. The full integration of transceivers implies the use of low intermediate frequency (IF) or zero-IF architectures that require local quadrature oscillator (LQO) signals for image rejection and the modulation (Ghonoodi, H., and Miar-Naimi, 2014).

There are different ways to generate quadrature outputs; a more common topology with higher performance is the two coupled LC-Tank CMOS oscillators. Different ways have been proposed to couple two CMOS LC-Tank oscillators, but the first and the best method is the parallel coupling (Rofougaran, A. et al, 1996).

These types of quadrature oscillators (QOs) generally consist of two coupled LC oscillators and their performance depends on the quality factor (Q) (Ghonoodi, H., and Miar-Naimi, 2014).

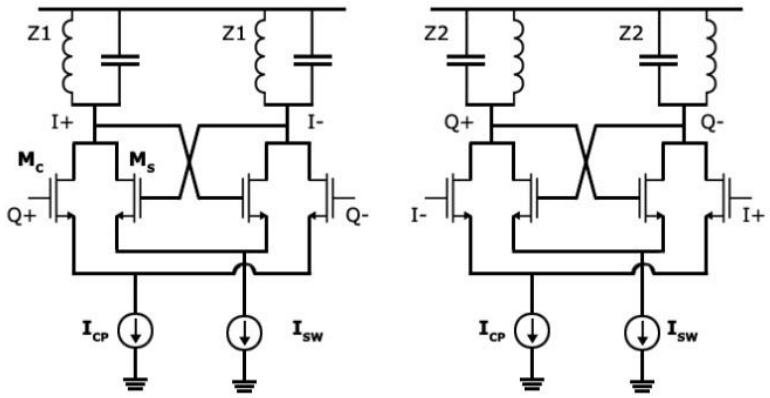
The Q gives a figure of merit for inductors and capacitors; it is the ratio of reactance to resistance. Transmission methods are traditionally used for making quality factor (Q) measurements on LC circuits. In LC parallel circuit, when a signal coupled into the LC tanks using a low value capacitor and extracts the output signal using the same value of capacitor. The inductive coupling is also possible, as used in transmission line resonators (ve2azx.net). The bandwidth is measured at the resonant frequency ω_0, and by the loaded Q. The bandwidth is obtained as a function of coupling and switching currents, but another calculation is required to get the unloaded Q (Q_u) to calculate the insertion loss. The transmission method is applied to propose analytical approaches of LC-Tank quadrature oscillators. The paper is organized as follows: In Parallel Coupled Quadrature Oscillator, this topology is explained briefly, a simple analysis under fully matched devices and component is represented for the parallel coupled topology in A simple analysis of LC-Tank quadrature oscillator, a novel analytical approach is proposed in Loaded Q and Adjustable Bandwidth, based on loaded Q and related to the transconductance and the currents of CMOS transistors, in Unloaded Q and Insertion loss, the unloaded Q is considered in order to obtain the insertion loss and that is also related to Q_L, and the currents, consequently a new analytical approach is presented in this section, too. In Simulation Results, in Order to show the confirmation of proposed analysis a parallel coupled quadrature oscillator implemented using RLC tank as a resonator. Adjusting the Currents of switching and coupling pairs of this oscillator affect the bandwidth to have good capability to use in RF application and also to reduce the insertion losses. All the circuit implemented and simulated using practical TSMC 0.18μm technology and the results show the agreement.

Parallel Coupled Quadrature Oscillator (PC-QO):

One of the most significant sections of many communication systems are oscillators with quadrature outputs (Razavi, Behzad,1997). There are different ways to generate quadrature outputs. A straightforward way is using a four-stage differential ring oscillator. Ring oscillators have the capability of generating quadrature outputs, but they suffer from poor phase noise/power tradeoff (Maneatis, J. G., and Horowitz, M. A, 1993) (Kinget, P. et al, 2002), a more common with higher performance topology is two coupled LC-Tank CMOS oscillators. Different ways have been proposed to couple two CMOS LC-Tank oscillators. The first and best method is parallel coupling (PC) proposed by A. Rofougaran (Mirzaei, A. et al, 2007).

In Parallel Coupled Quadrature Oscillator‘s topology, two additional transistors are added in parallel to one transistor of the oscillator (Rofougaran, A. et al, 1996). Using the gates of the parallel transistors, the oscillators are coupled as shown Figure 1.

Figure 1: The parallel coupled quadrature oscillator



In fully matched parts, applying Barkhausen's phase criterion implies the 90 degrees phase difference between outputs. Mismatches, like device mismatch, layout asymmetries and parasitic effects cause phase error (Mirzaei, A. et al, 2007) (Mazzanti, A. et al, 2006) (Chamas, I. R., and Raman, S., 2007). The phase error affects the overall performance of the systems incorporating the quadrature oscillators (Hsieh, Y. H et al, 2005). Some references investigate the phase noise of the oscillators in Figure1 and some other study the phase error using simulation. The tradeoff has been mentioned in several papers (Romanò, L. et al, 2004) (Chamas, I., and Raman, S., 2009). In this paper, an ideal condition without any mismatches is considered for the quadrature oscillator which is analyzed and some of the attractive aspects of the oscillator are used.

A simple analysis of LC-Tank quadrature oscillator:

LC-Tank quadrature oscillators have the topology shown in Figure 1. In this figure using coupling transistors, shown as M_C, the outputs of each oscillator are fed to the inputs of another. A simple analysis is performed under fully matched devices and components. In oscillation under mentioned condition, Equations (1), (2) obtained for four voltages shown in Fig.1 (Naimi, H., and Ghonoodi, H., 2010).

$$\mathrm{os}(\omega t) \tag{1}$$

$$\mathrm{os}(\omega \quad \theta) \tag{2}$$

In above equations, each block generates differential outputs so 180° phase difference is considered for single ended outputs of each block. Because of differential inputs each block experiences, the source of transistor have a constant voltage equivalent to a small signal ground. So the current of each transistor can be written as:

(3)

Where G_m is the transconductance of each transistor. In node V_{Q+}, a simple equation is written as follow:

$$\left(I_{I-} + I_{Q-}\right).Z \tag{4}$$

In above equation, Z is the impedance of LC tank at oscillation frequency. Writing Equation (4) in term of phasor leaves to Equation (5):

$$(G \qquad). \tag{5}$$

In (5) G_{mc} and G_{ms} are transconductances of coupling and switching transistors of the oscillator. Equation (5) can be simply expressed as Equation (6):

$$\text{———} \tag{6}$$

Same equations for node V_{I+} can be written that reduced to equation (9):

$$(I_{Q^+} + I_{I^-}). \tag{7}$$

$$(G \qquad). \tag{8}$$

$$\text{———} \tag{9}$$

Multiplying (6) and (9) concludes the following significant equation, proving the quadrature nature of the single ended outputs. One can simply show that two differential outputs are also quadrature:

$$\pi/2 \tag{10}$$

Equations (4) and (7) also conclude the significant point that providing the identical condition for LC tanks which will be used for the proposed analysis of this paper. The mentioned Equations are performed when two LC tanks have no mismatches. Under such a condition the phase difference between outputs is 90°. Z_1 and Z_2 are supposed as impedances for two tanks as shown in Figure1. For a general solution, following expressions for four single ended outputs are taken into account (Naimi, H., and Ghonoodi, H., 2010):

$$os(\omega t) \tag{11}$$

$$os(\omega \qquad) \tag{12}$$

$$os(\omega \qquad) \tag{13}$$

$$os(\omega \qquad) \tag{14}$$

The current voltage relation for V_{I+} is as (15):

$$(I_{Q^+} + I_{I^-}). \tag{15}$$

os(ωt) , (ss s s_s) (16)

A (c os(ω)) , —— (17)

The current of (17) passes through Z_1 and builds up V_{I+} (Naimi, H., and Ghonoodi, H., 2010). From Equations (16) and (17) can conclude that the currents of each tanks has a linear proportional to G_{ms} and specially G_{mc}.

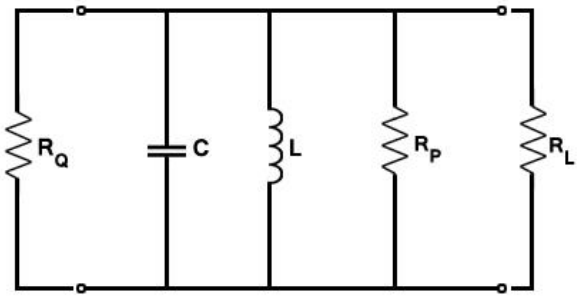
Loaded Q and Adjustable Bandwidth:

The Q factor gives a figure of merit for inductors and capacitors which are reactive components. It is the ratio of reactance to resistance. For oscillators, higher Q leads to lower phase noise production. In the case of antennas, a lower Q is generally preferred for a larger SWR bandwidth. The term "VSWR bandwidth" (or "SWR bandwidth") generally is defined as that bandwidth over which the antenna system has a VSWR of 1.1:1 or less (5 percent reflection coefficient). The antenna system includes the radiating elements, the interbay transmission line, matching devices and the transmission line. VSWR bandwidth generally is measured at the input to the transmission line (or the output of the transmitter) (www.radioworld.com).

The resonator can be used as a band-pass filter or matching network. Considering this resonant RLC as matching networks of quadrature oscillators when $\omega=\omega_0$, in LC-Tank quadrature oscillators, a signal coupled into an LC parallel circuit. The bandwidth (BW) is measured at the resonant frequency ω_0. Since the resonant circuits are connected to the coupling and switching transistors, the Q is loaded (Q_L) which is determined when the resonant circuits are connected to the outside world. As shown in Figure 2, the LC tanks consist of C, L and R_P, so the total Q_L is as:

. (R) (18)

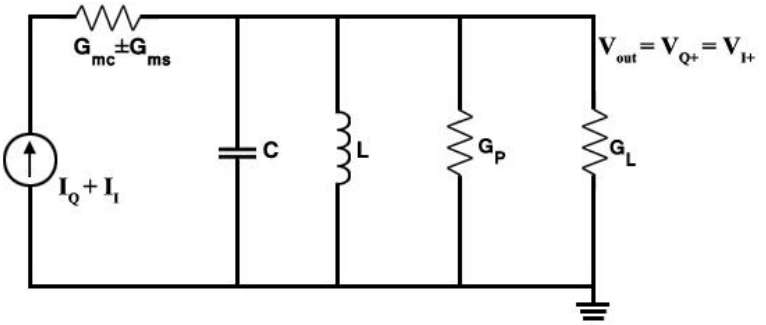
Figure 2: The parallel resonant circuit (C, L, RP)



Where R_P is the equivalent parallel resistor in LC tanks, R_L is the load resistance, R_Q is the external impedances level coupled to intrinsic resonator, that arising from the parallel coupled quadrature mechanism, here. On the other hand, it is easier to show Q_L rely on Q_L=suseptance/conductance for a parallel resonant circuit, so Q_L can be expressed by equation (19), proposed equivalent circuit of Fig.2 shown in Figure 3.

(G (G)) (19)

Figure 3: The proposed parallel resonant circuit of a quadrature oscillator



G_{mc} and G_{ms} present the transconductances of coupling and switching transistors which are related to their currents as equation (16). A gathering of these currents pass through the impedance of LC tanks. So, according to equation (19), the amount of Q_L depends on switching and coupling transistor's currents. Large Capacitance (C) increases the loaded Q_L, whilst boosting transistor's currents can reduce it.
The significant point obtained from mentioned Equations and statements that Q_L is on the contrary proportional to $(G_{mc} \pm G_{ms})$ and consequently, contrary proportional to the switching and coupling currents. So the bandwidth is adjustable for LC-Tank quadrature oscillators by Q_L and Gm depends on the currents of switching and coupling transistors rely on the following equation:

— (20)

Where $\omega_0=1/\sqrt{LC}$. The higher Q_L leads to narrower bandwidth, so the bandwidth is predictable. But the most important point is setting the $(G_{mc} \pm G_{ms})$, because of differential inputs of each block experiences as described in the previous section, the source of transistor have constant voltage equivalent to a small signal ground, so the current of each transistor is as Equation (3) (I=Gm.V) and it could be concluded that based on currents in equations (16) and (17), $(G_{mc} \pm G_{ms})$ is related to the coupling and switching currents and can be set by I_I and I_Q which are the currents of switching and coupling transistors. Consequently, the bandwidth can be set and adjusted by these currents. The authenticity of this is proved-up by the following proposed equations:

$$\frac{}{(G_P + G_L + (G_{mc} \pm G_{ms}))} \quad (21)$$

Equation (21) can be expressed by (22).

$$\underline{(G_P + G_L + (G_{mc} \pm G_{ms}))} \quad (22)$$

Small value of the C based on Equation (19) reduces the Q_L and increased the bandwidth according to Equation (22), but it was proof of that bandwidth can be adjustable based on the currents of switching and coupling transistors for parallel coupled quadrature oscillators. They have direct effects on Q_L by the ($G_{mc}\pm G_{ms}$). When the currents of each transistors increased, a gather of these currents pass through the impedance of the tanks (Z) and builds up the V_{I+} or V_{Q+} as shown in Figure 1. Increasing the currents effects on the ($G_{mc}\pm G_{ms}$) and also the bandwidth. It is obvious that increasing the currents cause to wider bandwidth and better coupling while it starts a tradeoff between the quality factor and the bandwidth.

Unloaded Q and Insertion Loss:

When the resonator used as a band-pass filter or matching network in RF applications, the insertion loss can be important. In previous section, according to the proposed Equations, the loaded Q (Q_L) is calculated based on the transconductances of coupling and switching transistor's currents. The bandwidth as a function of the currents and their conductances is adjustable. Another calculation is required to get is unloaded Q, when a signal coupled into the LC tanks of quadrature oscillators. For estimating the insertion loss unloaded Q is necessary. When Q refers only to the passive component (the capacitor or inductor) itself, apart from the rest of the circuit is unloaded Q (Q_U). The higher unloaded Q leads to the lower loss and affects G_P, ($G_P=G_C+G_{ind}$). If L and C changed, Q_U will be changed. In each LC tank of quadrature oscillators, the unloaded Q of capacitor is as:

(c itor) —— (23)

The unloaded Q of inductor is given by:

(in r) ——— (24)

Considering the RLC tank circuit in Figure 3, when $\omega=\omega_0$, the gain of oscillator should be considered ≥ 1. Typically, ($G_{mc}\pm G_{ms}$) $=G_L=G$ and to determine insertion loss of LC tanks, S_{21} should be found. $|S_{21}|^2$ is transducer gain=power delivered to the load/available power from the source of transistors that have the constant voltage equivalent to small signal ground in parallel coupled LC-Tank quadrature oscillators. First, consider the following Equation (25):

— $\overline{(G \quad 2(G \quad))}$ (25)

And also,

$\left(1 \quad —\right) \quad \frac{2(G \quad)}{(G \quad 2(G \quad))}$ (26)

So, insertion loss (dB) is as:

$$\text{og}\left(1 \quad —\right) \tag{27}$$

Thus, the wider bandwidth has smaller loss and in narrower bandwidth, when Q_L and Q_U are close, the LC tank losses would be large. So, the currents of switching and coupling and the related transconductances can reduce the insertion loss. The mentioned equations prove-up that Q_L and insertion loss can be set up by adjusting these currents and also the transconductances improves the insertion loss. So to avoid excessive losses, should be ensured that $Q_U \gg Q_L$ and this can be achieved depends on the transconductances and by adjusting the switching and coupling currents.

Simulation Results:

To verify the studies of this paper, this section explain the results of simulation. As described in analytical parts of this idea, based on changing in currents of switching and coupling pairs of parallel coupled oscillator's transistors, changing the bandwidth of circuit will occur. G_{mc} and G_{ms} are two key parameters which affect the loaded Q and simultaneously affect the bandwidth. By increasing the currents of coupling transistor to show the desired changes, the value of G_{mc} increased respectively. Here in this paper, a 5GHz parallel coupled quadrature oscillator based on circuit Figure 1 is considered. The circuit implemented using TSMC 0.18µm technology in order to show the results. The coupling and switching transistor aspect ratio is same with ratio of 10µm/0.18µm. The RLC tanks includes the inductor (L=1nH), the capacitance (C=1.01pF) and parallel resistor (Rp=500ohm). The switching transistor current considered a fixed value with 1mA but the current of coupling transistor sweep from 1mA to 2.5mA to see the results. In order to show the Insertion Loss value, the S-parameter of RLC tank illustrated in Figure 4. According to context and Equation (27), this value is proportional with loaded and unloaded Q. The value of unloaded Q must be greater than loaded Q. Increasing the gathered coupling and switching currents leads to increase the transconductances and consequently decrease the loaded Q. This phenomena cause to changing and improving the Insertion Loss as it can be seen in Table 1 obviously. Also the SWR bandwidth plotted in Figure 5 to show bandwidth across the frequency range.

Figure 4: S-parameter S21 of RLC tank

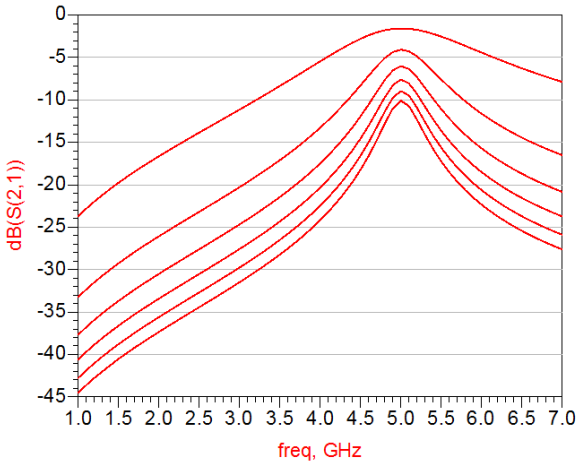


Figure 5: SWR bandwidth of RLC Tank

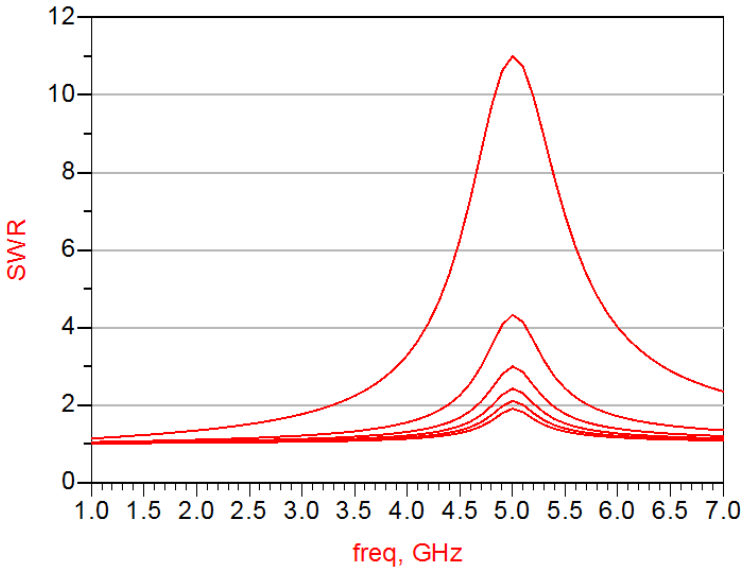


Table 1 is detailed simulation of circuit parameters and values. It is obvious that all the analytical study proved by this numerical values.

Table 1

I_{CP} (mA)	1	1.5	2	2.5
Gm (S)	G_{ms}= 0.00368 G_{mc}= 0.00368	G_{ms}= 0.00368 G_{mc}= 0.00415	G_{ms}= 0.00368 G_{mc}= 0.00442	G_{ms}= 0.00368 G_{mc}= 0.005
Vgs (V)	Vgs,s = 0.884 Vgs,c = 0.884	Vgs,s = 0.884 Vgs,c = 0.937	Vgs,s = 0.884 Vgs,c = 0.985	Vgs,s = 0.884 Vgs,c = 1.031
Gp (S)	0.002	0.002	0.002	0.002
BW(GHz)	11.24	11.71	11.98	12.14
Q_L	2.799	2.687	2.627	2.591
IL(dB)	-1.683	-1.609	-1.570	-1.546

To show the adjusting Bandwidth and Insertion Loss by using the idea of this paper Figure 6 and Figure 7 are illustrated. These diagrams are the illustration of simulated Bandwidth and Insertion Loss while coupling current is changing.

Figure 6: plot of Bandwidth vs. Coupling Current

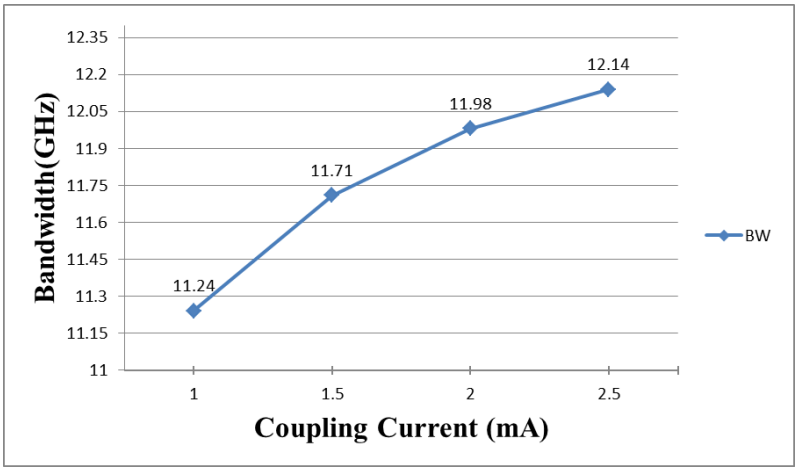
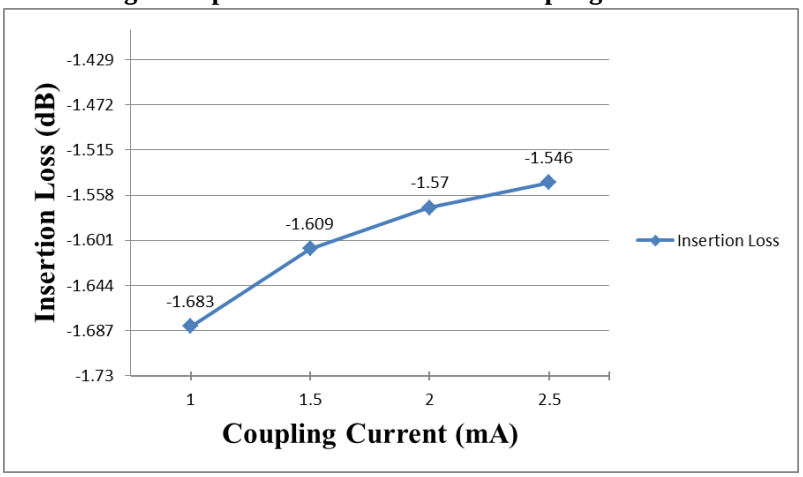


Figure 7: plot of Insertion Loss vs. Coupling Current



Conclusion:

Different method and analysis can be used for improving the parameters of an LC-tank oscillator. These parameters are vital to produce a desired output with precision value. Study on this parameters need to be well-organize in order to achieve this goal and employ it in RF circuit. In this paper, new analytical approaches have been proposed to estimate the bandwidth and the insertion loss for LC-Tank quadrature oscillators and new closed form equations are introduced. All proposed analysis has been estimated by the applied parallel coupled quadrature oscillator and its results could be seen in simulations. In this case of study, all the simulations has been done using TSMC 0.18µm technology to show how the bandwidth and insertion loss are affected by changing in current of LC-Tank by considering the idea of this paper. The bandwidth can be set and the insertion loss can be reduced and the results show the efficiency of the proposed equations and confirm the proposed idea.

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