A 2.5 GHz CMOS LC VCO with Improved Phase Noise Based on the Transformer Feedback Scheme

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ABSTRACT — **This paper demonstrates a circuit technique to improve the phase noise of a GHz-range CMOS differential LC VCO. The VCO has two on-chip transformers; primary of each transformer is used as an inductor of the LC tank. A signal current, whose frequency is the same and phase is 90 degrees in advance of the primary coil, is produced in the secondary coil so that the series resistance of the primary coil is cancelled out. As a result, Q-value of the LC tank is increased and the phase noise of a VCO is reduced. The measured phase noise of the 2.5 GHz VCO with a 100 KHz offset was -103 dBc/Hz, and the phase noise improvement in comparison with the conventional VCO at a 100 KHz frequency offset was 10 dB from a 2 V power supply.**

Index Terms — **CMOS VCO, LC VCO, phase noise, GHz range, transformer coupled.**

I. INTRODUCTION

On-chip high-frequency VCOs commonly incorporate on-chip inductors as elements of LC tuning circuits. However, the phase noise characteristics of on-chip VCOs are poor because the Q-values of the on-chip inductors remain low.

Attempts have been made to improve the Q-value of on-chip inductors by changing the LSI process, materials, and inductor structure [1]. However, the desired outcome is that the Q-value should be improved using the circuit approach with no LSI process change. [2] and [3] verified that the Q-value of the primary inductor of an on-chip transformer is greatly improved by applying the current 90 degrees in advance of that of the primary inductor to the secondary inductor. However, they only introduced the basic concept.

In [4], Soorapanth and Wong applied the above concept to realize a band-pass filter and oscillator. The oscillator used highly frequency selective characteristics realized by the Q-enhancement technique in a positive feedback loop. However, they did not give design details or measurement results for the oscillator circuit. The oscillator needed two RF chokes and two transformers to implement. As RF chokes occupy a large area on the LSI chip, it is desirable for them to be eliminated. Therefore, the purpose of this paper is to design an effective VCO circuit without RF chokes.

II. BASIC CONCEPT OF THE TRANSFORMER FEEDBACK Q-ENHANCEMENT TECHNIQUE

Fig. 1 shows a conventional high-frequency LC oscillator circuit. It is a positive feedback circuit from the Vout terminal to the positive input terminal of a GM amplifier. In Fig. 1, the single-ended version of the circuit is used for explanation purpose. In order to calculate the open loop gain of this feedback circuit to see the loop characteristics, the feedback line is cut at point X. Simple calculation shows the open loop gain to become,

$$T_{loop,conv}(s) = \frac{V_{out}(s)}{V_{in}(s)} = G_M \frac{R_P + sL_P}{1 + sCR_P + s^2 L_P C} \quad (1)$$

where Rp and Lp are the series resistance and the inductance of the coil, and iC and iLp are the current flowing through a capacitor C and a coil L of the LC tank, respectively.

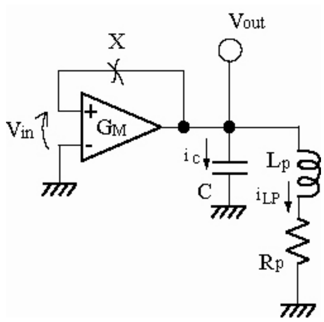


Fig. 1 Conventional LC oscillator circuit.

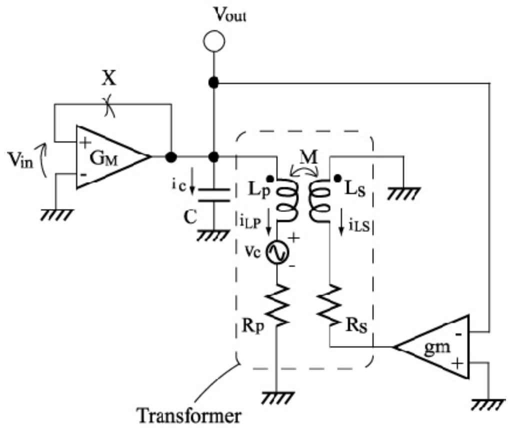


Fig. 2 The Q-value enhancement circuit having the external feedback path.

Oscillation frequency and the GM necessary to maintain the oscillation are calculated as,

$$\omega_{0,conv}{}^{2} = \frac{1}{L_P C} - \left(\frac{R_P}{L_P}\right)^2$$
$$G_{M,conv} = \frac{CR_P}{L_P} \qquad (2)$$

(2) shows that the oscillation frequency changes due to the influence of the Rp and we need the certain amount of GM to maintain oscillation.

Fig. 2 explains the basic idea to realize the Q-value enhancement with an on-chip transformer. We can eliminate the RF choke by having another gm to apply the feedback of the oscillator's output to the secondary inductor of a transformer. Fig. 2 again is the half of the differential circuit and the connection line at point X is cut for the open loop analysis.

In Fig. 2, Lp and Rp, and Ls and Rs are an inductor and a series resistor of the primary coil, and an inductor and a series resistor of the secondary coil of the transformer, respectively. The vc is the feedback signal appeared in the primary coil, which is generated by the feedback signal that is applied to the secondary coil of the transformer via the coupling of the mutual inductance M. In Fig. 2, the oscillator part consists of a GM amplifier, a capacitor C and a primary coil of a transformer (Lp and Rp). GM amplifier supplies the negative resistance. The feedback part consists of the gm amplifier and a secondary coil of the transformer (Ls and Rs). The feedback signal is taken at Vout.

Fig. 3 shows the phase relationships among voltages and currents appeared in Fig. 2. The phase relationship among iLP, Vout, and iC are usual.

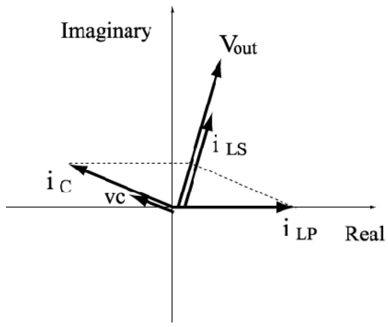


Fig. 3 Phase relationship of voltages and currents in Fig. 2.

They differ by almost 90 degrees. In the circuit shown in Fig. 2, iLS increases when Vout increases, therefore, Vout and iLS are in phase. As a result, vc becomes in phase with iC due to the mutual coupling established between Ls and Lp of the transformer. The vc becomes out of phase with iLP, and this means that vc cancels the voltage across Rp, which causes Q-value increase. We calculate the open loop gain of the oscillator in Fig. 2 to confirm the result shown in Fig. 3. As the following relations holds,

$$v_{out} = \frac{i_C}{j\omega C}$$
$$i_{LS} = g_m v_{out}$$
$$v_{out} = (R_P + j\omega L_P) i_{LP} + j\omega M i_{LS}$$
$$G_M v_{in} = i_C + i_{LP} \qquad (3)$$

The open loop gain becomes,

$$T_{loop,new}(s) = \frac{V_{out}(s)}{V_{in}(s)} = G_M \frac{R_P + sL_P}{1 + s(CR_P - Mg_m) + s^2 L_P C} \qquad (4)$$

When the circuit is oscillated in a stable condition, the imaginary part of (4) becomes zero and the real part becomes one. From these constraints, the oscillation frequency becomes,

$$\omega_0^2 = \frac{1}{L_P C} - \left(\frac{R_P}{L_P}\right)^2 + \frac{R_P M g_m}{L_P{}^2 C} \qquad (5)$$

$$G_{M,new} = \frac{1}{L_P}(CR_P - Mg_m) \qquad (6)$$

The (6) shows the effect of the feedback. Mgm is the feedback factor, and GMnew, which is the transconductance that supplies the negative resistance, becomes zero when CRp equals to Mgm. This means that negative resistance is not necessary to maintain oscillation. Even in this case, we recognize from (5) that the oscillation frequency does not change much. In reality, however, the capacitor value C in Fig. 2 increases due to the additional connection of the gm amplifier to form the external feedback.

III. CIRCUIT IMPLEMENTATION

We designed the circuit shown in Fig. 4, in which the oscillator part and the feedback part are separated. Cross-coupled transistors are used in the oscillator part. The cross-coupled pair supplies a negative conductance that is constant in frequency, more suitable for a VCO than that in [4]. LP1 and LS1 form one transformer, and LP2 and LS2 form another; both have mutual inductance coupling. The direction of coupling is shown by black circles for one and by black triangles for the other. Tuning capacitors Cv1 and Cv2 are simple reverse-biased PN junction diodes, and their capacitances are adjusted by using the external voltage Vbias. Cp1 and Cp2 are bypass capacitors. Io is a constant current source, and Iv is an externally adjustable constant current source. LP1, Cv1, LP2, Cv2, and the cross-coupled transistor pair of M1 and M2 form a differential LC oscillator. The oscillation waveforms at nodes A and B are monitored through the drain terminals of M5 and M6. M3 and M4 receive voltage waveforms at nodes A and B, and convert them into currents that are fed to LS1 and LS2. The voltage-to-current conversion gain, that is gm, can be adjusted by changing the current Iv.

IV. EXPERIMENTAL RESULTS

The VCO circuit shown in Fig. 4 was fabricated using a 0.35 um MOS devices from the 0.1 um CMOS process. Fig. 7 is the chip microphotograph. The supply voltage was 2 V. One of two VCOs on the chip is the one shown in Fig. 4, called a pMOS-type VCO. The other is for reference purposes, and we refer to this as a ref-type VCO. The ref-type VCO does not have the feedback loop consisting of M3, M4, LS1, LS2, Cp2, and Iv shown in Fig. 4. The current value of Io in the ref-type VCO is doubled to equate the current consumption for both VCOs.

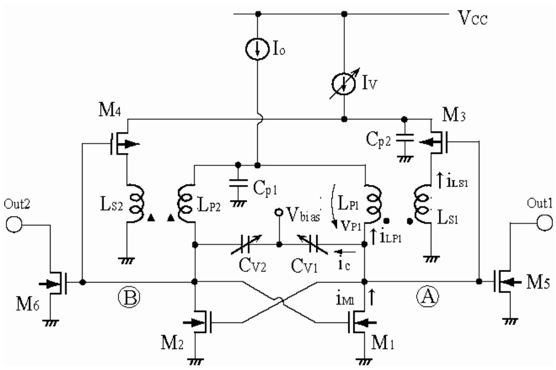
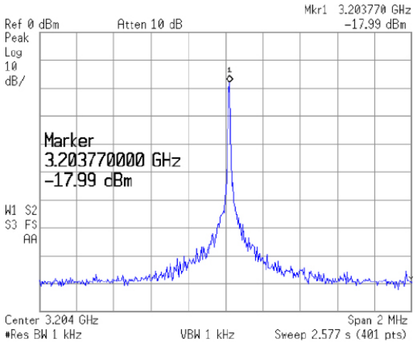


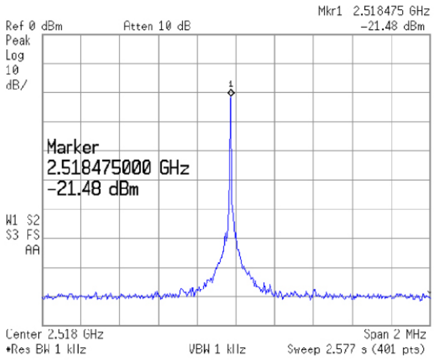
Fig. 4 Schematic of the Q-value enhancement VCO circuit.

Fig. 5 compares the frequency spectrum of the oscillation waveforms between the ref-type VCO and the pMOS-type VCO. Io=4 mA for the ref-type VCO, and Io=Iv=2 mA for the pMOS-type VCO. Vbias is set to 2 V for both. This setup equates the power consumption for both the pMOS-type and ref-type VCOs. The oscillation frequency and power measured in the pMOS-type VCO are 2.52 GHz and -15.5 dBm, respectively, and in the ref-type VCO they are 3.2 GHz and -12 dBm, respectively. A 6 dB pad was used at the input of the spectrum analyzer. The output power of the ref-type VCO is about 3 dB larger than that of the pMOS type VCO, because Io is doubled for the ref-type VCO compared with the pMOS-type VCO. Therefore, currents flowing through M5 and M6 of the ref-type VCO becomes double of currents flowing through M5 and M6 of the pMOS-type VCO. Stray capacitors of additional circuits decrease the oscillation frequency of the pMOS-type VCO and this might be the reason why the oscillation frequency of the pMOS-type VCO is low. The most important difference, however, is the spectral purity. The noise sideband nearby the oscillation becomes small in pMOS-type VCO.

Figure 6 directly compares the phase noise between pMOS-type and ref-type VCOs. The horizontal axis is the frequency offset from the center oscillation frequency, and the vertical axis is the noise power. The curve in dark black shows the phase noise of the ref-type VCO, while the curve in light black shows the one of the pMOS-type VCO. About 10 dB and 5 dB of phase noise improvement are measured at the offset frequency of 100 KHz and 1 MHz, respectively, and these values are large even when we consider the 1.27 times of oscillation frequency difference between these two VCOs. For the pMOS- type VCO, -103 dBc/Hz and -119 dBc/Hz of phase noise were measured at 100 KHz



(a) Frequency spectra of the ref-type VCO.



(b) Frequency spectra of the pMOS-type VCO.

Fig. 5 Spectral difference between conventional-type and feedback-type VCOs.

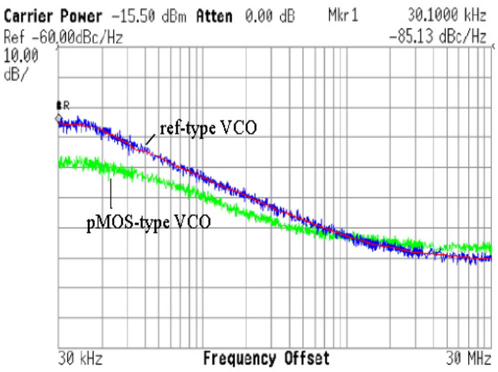


Fig. 6 Phase noise comparison.

and 1 MHz offsets, respectively. However, the phase noise of the pMOS-type VCO becomes larger than that of the ref-type VCO at frequencies larger than 3 MHz offset and there is no improvement in

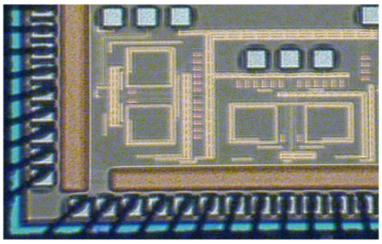


Fig. 7 Chip microphotograph of the pMOS-type (left) and ref-type (right) VCOs.

this region. This is considered that the noise generated by additional transistors to form the feedback loop is added. However, the noise behavior at this -130 dBc/Hz level is not clear because of the noise limit of our measurement system and the phase noise issue at frequencies larger than 3 MHz offset is left for further study in the future.

V. Conclusion

A new GHz-range VCO circuit that adopts a Q-enhancement technique by using the separate feedback circuit was examined, and the phase noise improvement was verified at frequencies up to the 3 MHz offset.

Acknowledgement

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