A Highly Stable CMOS Self-Compensated Oscillator (SCO) Based on an LC Tank Temperature Null Concept

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***Abstract*—A highly stable all silicon Self-Compensated Oscillator (SCO) reference source is presented. Self compensation across temperature is achieved using a newly discovered phenomenon in LC-tanks named the Temperature Null (TNULL) which has been described and briefly analyzed. A quadrature oscillator architecture has been used to implement the SCO in a 0.18μm CMOS technology. The SCO has on-chip infrastructure facilitating low cost trimming and frequency calibration at room temperature. Excellent frequency stability of ±50ppm has been measured across temperature (0 – 70°C), 3.0 – 3.6V supply and 1 – 15pF load. The SCO has a programmable frequency range of 1 – 133MHz, consumes 7.1mA at 25MHz and has an RMS period jitter of 2ps at 125MHz.**

I. Introduction

The demand for clocks has been continuously fueled by increased consumption of many feature rich consumer gadgets. A clock is generated from a reference frequency source which has to date been dominantly based on a quartz crystal. This industry de-facto of quartz crystals has been rightfully earned through reliable performance of quartz crystal oscillators (XO) in terms of excellent frequency stability across temperature, low power consumption and low noise. Moreover, quartz crystals enjoy very high manufacturing maturity that has been gained over the past decades which has helped sustain a steady, yet slow, decrease in the price of quartz crystal-based products. As new applications emerge, a need for new reference frequencies arise which unfortunately require long lead times of up to 14 weeks to be developed in quartz crystals leading to longer development cycles and slower market deployment. There has been always a need, thus great value, in decreasing the size of any solution through higher levels of integration while adding more features and functionality. The initial trend of decreasing package footprint and thickness has gained acceptance and interest. However, the benefits of having a monolithic CMOS timing solution are unbeatable. Such a solution will benefit from the continuously decreasing price of CMOS technologies that can produce thousands of reference clocks from a single wafer in comparison to hundreds of quartz crystals from a panel. This is directly translated into lower cost and very high volume capability.

The dominant deterring factor in clock selection for very high volume consumer products will be price as long as the required performance is secured. The most important performance metric is frequency stability across temperature, supply, load and aging. A total frequency stability of ±100ppm across a temperature range of 0 – 70°C and -20 – 70°C is considered the critical threshold that gives access to a large percentage of the market with heavy emphasis on very high volume consumer applications. Aggressive price reduction can only be achieved through a quantum reduction in the cost structure of clocks which requires the search for alternative technologies to quartz. The cost of an XO is composed of: Quartz Crystal, CMOS die, Ceramic Package, Assembly and Test. A programmable reference clock based on a silicon micro-electro mechanical system (MEMS) resonator, [1], [2] has merits in lowering the lead time but fails to address higher integration levels. The cost of a MEMS resonator is lower than a quartz one owing to very high number of resonators on a single MEMS wafer yet still requires wafer level packaging to conserve its performance and reliability. Expensive ceramic packaging is also dropped to low cost plastic packaging [3], [4]. However, the assembly cost of a MEMS-based solution requires stacking of the wafer level packaged MEMS die and CMOS die. In addition, the CMOS die in a MEMS-based solution is larger, compared to the die in an XO, thus more expensive. Furthermore elaborate production testing is required to trim each part to the required performance. Overall, the cost benefits of a MEMS-based solution is not evident thus cannot easily compete in the price sensitive lower performance consumer market.

Another alternative technology is an all silicon CMOS reference clock using an on-chip LC-tank. Recently several solutions have been reported [5], [6], [7] and commercialized. Such solutions are by definition highly integrated and have short lead times due to their programmability. Furthermore, the cost structure is very promising since it has been reduced to: CMOS die, low cost plastic package, simple assembly and production testing. The die in this case is still larger than the one found in an XO yet smaller than the die in a MEMS-based solution. It is then obvious that such a solution is conceptually of lowest cost as long as the production test cost is low. This work presents a new all silicon CMOS reference clock that uses an on-chip LC-tank designed to operate at a very specific low temperature-sensitivity phase operating point thus self compensating across temperature. The part is trimmed using a low cost single insertion at room temperature test procedure. Such a solution is promising very low cost and has achieved a total frequency stability of ±50ppm that can address a large

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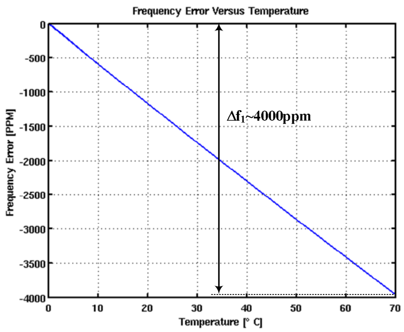


Figure 1. Temperature dependence of an LC-tank resonance frequency.

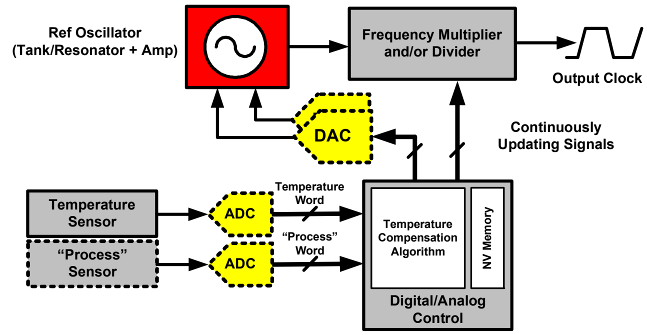


Figure 2. Generic block diagram of open loop temperature compensation.

percentage of high volume consumer applications such as SATA, PCI-E, HDD, LCD TV, printers and many others.

II. Temperature Compensation Techniques

The frequency stability of classical LC-tank based oscillators is highly dependent on temperature and typically may have a temperature coefficient ranging from -50ppm/°C to 100ppm/°C. The main source of temperature dependence comes from the LC-tank and in particular the inductive part. Fig. 1 shows simulation results of the frequency variation of an LC-tank across a 0 – 70°C temperature range of ~4000ppm which is not acceptable as a reference source. This large temperature dependence of LC-tanks has been the main challenge in designing an LC-tank based reference which requires sophisticated compensation techniques to neutralize the frequency variation. There are two main types of compensation techniques; either an open loop technique or a closed loop technique. Closed loop techniques are commonly used in oven-compensated oscillators where the ultimate objective is to tightly control the oscillator temperature by placing it in a temperature controlled oven and in turn stabilizing its frequency. Alternatively, one may opt to design the frequency determining element of the oscillator, the resonator mainly, to be temperature insensitive thus the oscillator becomes self-compensated.

A. Open Loop Compensation

An open loop temperature compensation technique aims to negate the temperature generated frequency shift of the oscillator by imposing a frequency shift in the opposite direction of equal magnitude. To achieve this one can modify the oscillation frequency using one or more frequency tuning controls of the oscillator. Alternatively one can follow the oscillator with a frequency multiplier and control the multiplication factor such that the output frequency is temperature independent. In all cases one must measure the temperature accurately using a suitable sensor and use it to generate the temperature dependent control(s) of the oscillator or frequency multiplier. To successfully achieve the required accuracy in compensation it is imperative not just to have an accurate temperature measurement but to also have precise knowledge of the oscillator frequency across temperature and its frequency tuning control(s). Fig. 2 shows a generic block diagram of an open loop compensation system indicating different variations of where the temperature sensor analog output may be directly used or converted to a digital word. Similarly the temperature compensation algorithm may be implemented using analog or digital circuitry and can generate analog or digital controls which may be converted back to analog signals to control the oscillator.

Clearly this is a knowledge based process since exact cancellation of the temperature dependence will require deterministic knowledge of the complete system behavior to build an effective compensation algorithm. Otherwise one must rely on characterization of the system performance across temperature for every oscillator unit to generate the required data. However, this may still not provide perfect cancellation of frequency shifts unless the system has the ability of synthesizing controls with high accuracy. Inevitably this adds to the overall system complexity that may be translated into cost due to a large die size and/or long production test times using two or more temperature insertions. Nonetheless, open loop compensation has been used to compensate MEMS-based clocks [3] which uses a fractional-N Σ-Δ PLL frequency multiplier that is digitally temperature controlled. On the other hand, a CMOS LC-tank based reference oscillator reported in [6] uses a digital open loop compensation technique that utilizes an integrated microprocessor and [5] uses analog temperature dependent circuitry to control the behavior of the oscillator across temperature. All open loop techniques will require the storage of calibration coefficients on-chip during the calibration process for future retrieval during the lifetime of the oscillator.

B. Self Compensated Oscillator

A self-compensated oscillator across temperature has intrinsically low temperature sensitivity. Such oscillators do not require any real time compensation and temperature sensors and are thus simpler. Usually self compensated oscillators have a specific temperature range where the oscillation frequency has tolerable variation. An excellent example of a self compensated oscillator is an XO built using a quartz crystal. An AT-cut quartz crystal if designed and manufactured correctly can exhibit low temperature sensitivity. This is achieved by selecting the exact cutting angle that achieves lowest temperature sensitivity. This was made possible by excellent control on the manufacturing process of quartz crystals which is today a very mature and stable technology. Similarly there have been trials for producing MEMS resonators that are self compensated by designing stiffness compensated and geometric compensated resonators as noted by [1] and summarized in Fig. 3. Such

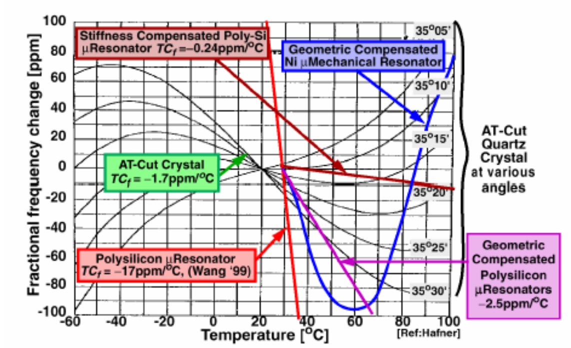
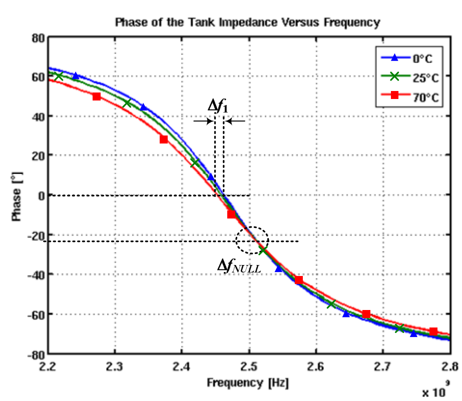


Figure 3. Frequency stability over temperature of self-compensated AT-cut quartz crystal and MEMS resonators.

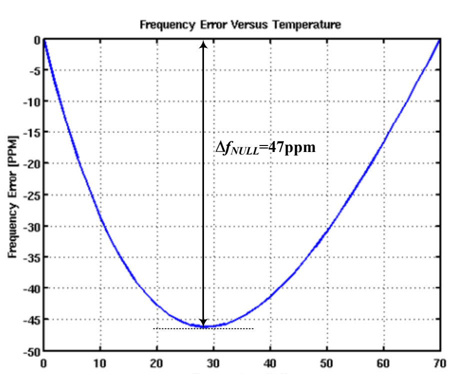
designs depend on materials with opposite temperature coefficients to cancel. However, the manufacturing accuracy and purity of the materials may impact the overall temperature dependence resulting in a wide variation in performance that is not industrially accepted. Such resonators end up with very non-linear temperature dependence of wide variation that make the use of open loop compensation techniques to correct them very challenging. In effect commercially viable self compensated MEMS resonators up to date are not available.

III. LC-Tank Temperature Null Concept

Building an oscillator operating at the LC-tank resonance frequency with variation over temperature shown in Fig. 1

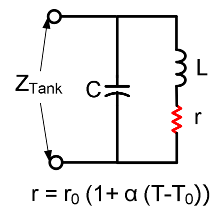


(a)

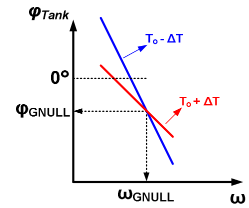


(b)

Figure 4. (a) LC-Tank impedance phase versus frequency for different temperatures and (b) frequency variation at TNULL.



(a)



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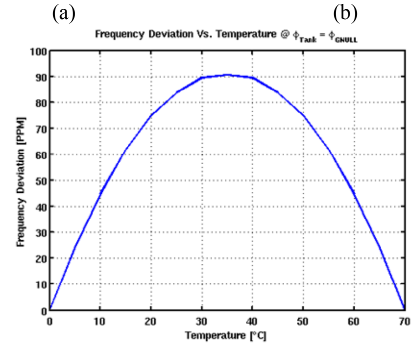


(c)

Figure 5. (a) Simple first order model of an LC-tank, (b) Global Null of an LC-tank and (c) Frequency deviation at GNULL phase.

would result in very poor frequency stability. This may be easily understood by studying the tank impedance Z_{Tank} phase versus frequency at different temperatures shown in Fig. 4(a). A classical oscillator operates with almost zero phase across the tank. A zero phase intersection with the tank phase curves over temperature results in a large frequency variation Δf_1. However, studying the tank impedance phase curves carefully one can notice that tank phase curves across temperature intersect at a negative phase where frequency variation across temperature is minimized by a factor of ~100 to be Δf_{NULL}=47ppm as shown in Fig. 4(b). This phenomenon of minimum temperature sensitivity of frequency will be named as the LC-tank Temperature Null (TNULL) and the phase across the tank as φ_{NULL}. This non-traditional phase operating point is very desirable since it is an example of a Self Compensated Oscillator (SCO) across temperature. The challenge is to design an LC-tank with a TNULL that exhibits good frequency stability and to successfully oscillate at φ_{NULL}.

The TNULL phenomenon may be mathematically derived using a simple first order model of an LC-tank shown in Fig. 5(a) where the only temperature dependent element is r, the ohmic losses of the inductor with a first order temperature coefficient α. The tank impedance phase φ_{Tank} is given by:

$$\varphi_{Tank} = \angle Z_{Tank} = \tan^{-1}\left(\frac{\omega L}{r}\right) - \tan^{-1}\left(\frac{\omega r C}{1-\omega^2 LC}\right) \quad (1)$$

The Global Null (GNULL) is defined across a temperature range of interest as the intersection of the tank phase curves at the temperature extremes as shown in Fig. 5(b). The operating phase φ_{GNULL} is the point of minimum temperature sensitivity across this temperature range. For a temperature range of $2\Delta T$ around T_0 using the simple first order tank model GNULL phase and frequency are given by:

$$\omega_{GNULL} = \frac{1}{\sqrt{LC}}\sqrt{1+\left(\frac{1-\alpha^2\Delta T^2}{L/Cr_o^2}\right)}, \quad \varphi_{GNULL} = -\tan^{-1}(2r_0 C\omega_{GNULL}) \quad (2)$$

Fig. 5(c) shows the frequency deviation across temperature at the GNULL phase. Since the simple first order model does not take into consideration many second order affects one can note the difference between plots in Fig. 4(b) and Fig. 5(c) yet the TNULL concept is evident.

IV. SCO Implementation Based on TNULL

This section illustrates the architecture of the SCO based on the aforementioned LC-tank TNULL concept. The SCO functional block diagram is shown in Fig. 6. The main objective of the architecture is to operate the LC-tank at precisely the TNULL phase. The oscillator is formed of a transconductor stage and a phase shift stage. At steady state, the transconductor and phase shifter provide a phase that is the negative of the required TNULL phase. Thus, at steady state, the LC-tank is forced to oscillate at the required non-zero TNULL phase. One of the most important design aspects of the phase shift circuitry is to provide a phase that is accurate and temperature independent, otherwise frequency deviation will increase. Phase magnitude is controlled via a digital phase control signal ($\varphi_{Control}$) the accuracy of which will determine how close the final operating point to the GNULL will be. The value of $\varphi_{Control}$ is trimmed to tune the phase operating point and is stored on chip.

Fig.7 illustrates one of the methods of injecting a positive phase into the oscillator loop using a quadrature oscillator architecture with variable coupling *m* between the two oscillators in quadrature. Two identical LC oscillator tanks are forced to oscillate at the same frequency but in quadrature phase with respect to one another. Transconductor stages *a* and *c* inject two quadrature currents g_m*V and $g_m*V\angle 90$ into their respective tanks *I* and *Q* while stages *b* and *d* couple the oscillators together by injecting $m*g_m*V\angle 90$ and $-m*g_m*V$ currents into tanks *I* and *Q* respectively. The value of the coupling factor *m* is variable and is controlled via a digital control word. A gain block produces a 180 degrees phase shift to force both oscillators to be in quadrature. Therefore, the tank total current phase shift φ is a simple function of the coupling ratio *m* and is given by:

$$\varphi = \tan^{-1}(m) = -\varphi_{GNULL} \quad (3)$$

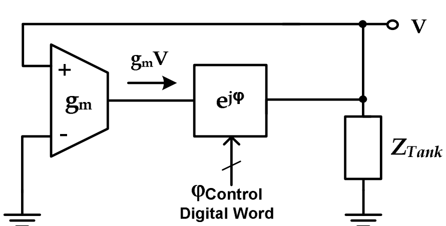
The value of *m* is varied by scaling the bias current of the transconductor stages and the dimensions of the active devices. This guarantees producing a stable temperature independent coupling ratio and phase across both tanks.

The architecture includes an automatic amplitude control (AAC) block. The AAC block senses the oscillation amplitude of both tanks and compares it to a reference voltage (V_{REF}). The amplitude level is adjusted such that at steady state oscillator amplifiers or transconductor stages operate at a fairly linear region. This minimizes the oscillation harmonic content and the impact of this harmonic content on frequency stability. The AAC block controls all four amplifier stages to ensure that all stages have a tracking gain and a constant coupling ratio *m* during operation.

The SCO is trimmed using a low cost room temperature only (RTO) trimming and frequency calibration algorithm. The algorithm modulates the temperature of the LC tank using on-chip resistors, varies the value of *m* and detects the phase with minimum oscillator temperature sensitivity (zero slope) which may be related to the required GNULL phase. The trimming and calibration routines are done only once during production testing and the value of *m* is stored on chip. At power-up, the value of *m* is loaded to operate the oscillator at the TNULL to become a self-compensated oscillator.

V. Measured Performance

The SCO architecture described has been fabricated in a 0.18µm CMOS process with thick aluminum top metal. A set of programmable dividers produce a CMOS output frequency from 1 to 133MHz. The chip has been packaged in a standard 4-pin package. A large number of parts have been tested and characterized. Tests include total frequency stability across temperature, supply and load, single side band (SSB) phase noise, current consumption and period jitter.



$$Z_{Tank} = \frac{1}{g_m} e^{-j\varphi}$$

Figure 6. SCO functional block diagram.

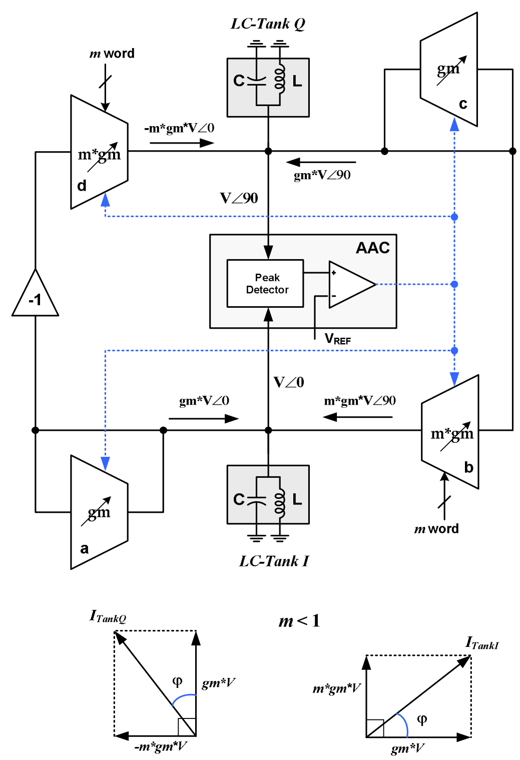


Figure 7. Block diagram of an SCO implemented using a quadrature oscillator architecture.

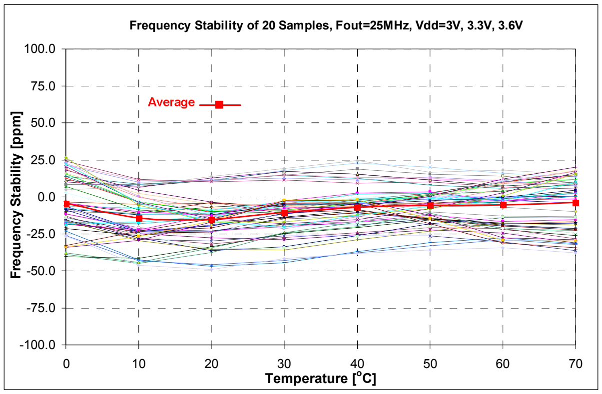


Figure 8. Frequency stability of 20 randomly selected samples.

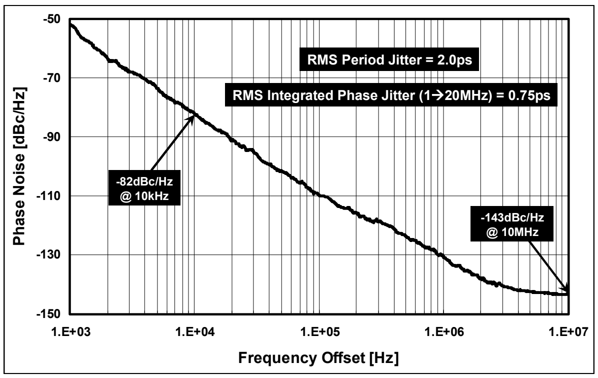


Figure 9. Phase noise measurement of a 125MHz output clock

Parts were randomly selected from a single wafer, trimmed and calibrated to a frequency of 25MHz at the CMOS output. Parts were inserted in a temperature chamber where the frequency was measured from 0 to 70°C in steps of 10°C. The power supply was varied by ±10% relative to a nominal 3.3V value. The measured total frequency stability for 20 parts is plotted in Fig. 8. Results show very good correlation between measurements and simulations indicating the robustness of the architecture and validity of the TNULL concept. Frequency stability across a capacitive load varying from 1pF to 15pF was tested and showed a maximum frequency variation across temperature of <10ppm. Frequency stability measurements illustrate clearly a very tight performance spread across the measured parts with an overall frequency stability of better than ±50ppm. It is to be noted that further improvements in the trimming and calibration routines can improve the initial accuracy to achieve an overall tighter frequency error of ±25ppm. The no load current consumption of the oscillator is 7.1mA at a 25MHz output frequency. The phase noise of a 125MHz output frequency was measured and is shown in Fig. 9 indicating a phase noise of -82dB/Hz at an offset of 10kHz. Processing the phase noise measurements yields 0.75ps RMS integrated phase jitter from 1MHz to 20MHz and a period jitter of 2ps. The performance of the SCO performance is compared to other all silicon CMOS LC-tank based commercially available oscillators in Table I. It is to be noted that the reported SCO frequency stability does not include aging while the other clocks include aging. It is expected that aging would increase the frequency stability by ±25ppm. Overall SCO performance is very competitive in terms of frequency stability and period jitter. Current consumption may be lowered by migrating to a smaller feature size technology such as a CMOS 0.13µm and use of higher quality factor copper integrated inductors will help decrease current and improve phase noise.

TABLE I. SCO PERFORMANCE COMPARISON

Specification	3CP0C02[8]	Si500S[6]	This work
CMOS Technology	0.13µm, Cu	0.13µm, Cu	0.18µm, Al
Frequency Range	4 – 133MHz	0.9 – 200MHz	1 – 133MHz
Total Freq Stability 0 – 70°C	±100ppm	±150ppm	±50ppm
No Load Current	2.2mA	9.7mA @ tri state o/p	7.1mA @ 25MHz
RMS Period Jitter	5ps @ 75MHz	1ps @ 200MHz	2ps @ 125MHz

VI. CONCLUSION

Self-compensation found in quartz crystals through precise selection of a mechanical cutting angle is analogous to the electrical TNULL phase. The LC-Tank TNULL concept has been analyzed, verified in simulation and validated by measurements. A Self Compensated Oscillator (SCO) has been successfully implemented based on the TNULL concept using a quadrature oscillator architecture which facilitated accurate temperature independent tank phase control and successful low cost trimming and calibration. The overall achieved frequency stability of ±50ppm across temperature (0 – 70°C), supply and load is very competitive with reported performance of all CMOS oscillators and may be further improved to achieve ±25ppm. Period jitter, phase noise and current consumption are reasonable and there is room for improvement by going to a smaller feature size technology such as a CMOS 0.13µm process with copper metal layers.

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