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Oscillators, crystal or silicon

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ABSTRACT

Reducing the size and cost with increasing reliability, are the main motivation to realizing the on-chip frequency reference. However, the main limitations of such references compared to their crystalline counterparts, is the effects of temperature, voltage and manufacturing process (PVT) on their output frequency. Over the many years, many efforts have been done for design silicon-based frequency references. So that these references have comparable frequency stability with crystals based oscillators. *In this paper the necessity of silicon oscillators and the limitations of quartz have been investigated and some of the silicon oscillators with temperature compensation have been introduced. These include LC, MEMS and ring oscillators. Finally, a comparison between these approaches have been presented.*

Keywords: frequency reference, silicon based oscillators, frequency stability, open loop temperature compensation, Ring oscillators.

INTRODUCTION

For decades, crystal oscillators have been the only meansof producing stable frequencies. Due to their relatively low cost, low temperature dependency and their wide commercially availability, they have adominant share of the frequency control market (more than 90%, equivalent to more than 4.5 billion dollars) [1].Quartz are available at different levels of stability. The non-compensated and voltage-compensated crystal oscillators are available with stability in the range of 20-100 ppm.Whereas the stability of TCXOsis in the0.1-5 ppm range, and OCXOs have been achieved very high stability of 1ppb [1, 2].

Apart from their high frequency precision, the crystal oscillators have also some drawbacks. Their main problem is thelarge space that occupy on the board, especially when more than one referenceon the board is needed. The other drawback is their sensitivity to the mechanical shocks and vibrations, this mainly effects on crystal because it is a mechanical unit. In comparison to electronic circuits that their performance is due to the electron movements, the crystal vibrate mechanically at the frequency of oscillation, so, any physical shocks can change their oscillation frequency. All the above mentioned limitations have been driven the researches for designing integrated frequency references that achieve the same stability as crystal oscillators. Such references are implemented on silicon and so they are referred to as silicon based frequency references [3, 4].

In this article testate-of-the-art implantation of silicon based frequency references with respect to architecture in system level and achieved stability is reviewed. Since this paper is about CMOS compatible frequency references, we have not a separate discussion about crystal oscillator, butwe compare their specification with other technology, wherever needed. As well as, MEMS based frequency references are not completely CMOS compatible and so, they will be considered briefly, compared to other technologies.

2. The electrical and mechanical resonators, the silicon and crystal oscillators - challenges and limitations

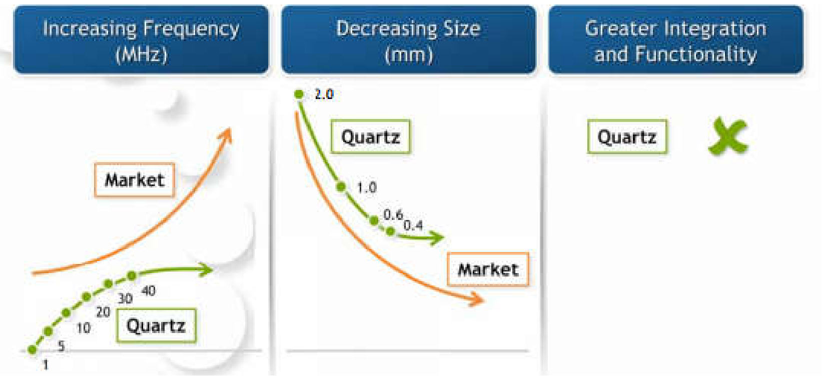
Reference oscillators (frequency references)play a prominent role in electronics systems. They have wide applications ranges from clock generation in wired and wireless data line, RF receivers and logical circuits. Oscillators can be classified into two main categories: mechanical and electrical oscillators [5]. The main differenceof them is the frequency selective unit. In the mechanical oscillators the frequency selective unit is a mechanical resonator which is made from quartz [6, 7]. But in the electrical oscillators

this part can be integrated in IC technology and includes RC or LC filters or a MEMS[1] resonator. Ring oscillators are also belong in this category, but due to their structure they don't need to a frequency selective unit. Generally, for each oscillator in any technology following features are of importance:
1- Deterministic and non-deterministic frequency stability.
2- Power consumption.
3- Integration and systems miniaturization (cost).
The main feature of a frequency reference is the frequency stability and depends on the application is different and can be ranged from several hundred ppm in a wire line data link such as USB, to a few ppm or less in a wireless application such as GPS or GSM [8, 9].Currently, the crystal oscillators produce the most stable frequencies and they are available commercially and reasonable price,a crystal oscillator frequency stability is excellent and their output frequency is very stable and accurate. So, what is the main problem of oscillator and why designers always try replacing them? Table 1 presents an overview of these characteristics.

Table 1. The pros and cons of crystal oscillators

manufacturing	Pros	Cost effective through economies of scale
	cons	2 to6 month for crystal growth alone
Scalability	Pros	Frequency and size are have improved historically
	cons	limits to scaling are imminent
Performance	Pros	Quartz is a very stable frequency reference
	cons	quartz is a rock; ckts are required for functionality
integration	Pros	quartz is small
	cons	quartz cannot be integrated; it's not silicon

Figure 1 shows the trends of market compared to that of crystals in terms of oscillation frequency, size reduction and integration capability. Timing market is so attractive and more than $4.5B, so each product should accompany this trend without sacrificing performance or increasing cost [3].



As can be seen from figure1, crystal oscillators cannot accompany the market trends and also, they cannot been integrated. In fact, quartz is the last and biggest hold out for microelectronic integration. Therefore in the near future we need products which replace quartz. In this regard, since early 80s with utilizing frequency synthesizers based on phase lock loop, the number of crystals on the board is decreased. This cause to degrade noise performance but on the other hand reduce the cost, and increase frequency and flexibility [3]. Current aim of researchers is complete removing crystals from board to achieving a fully integrated silicon frequency reference.

3. Silicon based oscillators

In the previous section we provided an overview of frequency references, also the need of having a fully integrated frequency reference was considered. In this regard, various activities have been carried out and silicon oscillator have been proposed. The rest of this paper introduce these structures. Challenges and problems which each technology encounters is briefly considered.

3.1silicon MEMS based oscillators

Over the years, with the aim of replacing crystals, a lot of research has been done on the developing of silicon MEMS based oscillators. As a results, the various commercial products are introduced bytwo

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[1] In practice, A MEMS oscillator also is operate on the basis of mechanical resonators, but because of integration capability of MEME, we have categorized them in the silicon oscillators.

pioneer companies, Discera and SiTime. The MEMS technology involves many of the processes that is used by CMOS technology as, lithography, deposition, etching etc. [10].So, because of large scale producing in IC technology is very cost effective. But because of some special processing required by MEMS technology, the MEMS resonator has to be made in a silicon die separate from the electronic circuitry. The quality factor of a resonator determines the stability of reference and for a MEMS resonator this factor is typically between 50,000 to 300,000. However, MEMS oscillators have faced some challenges both in resonator and electronic parts mainly in the frequency synthesizer [3, 11].The resonance frequency and quality factor may be affected by any gas molecules, Due to very low mass of a MEMS resonator (on the order 10^{-14} – 10^{-11}kg). So the resonator has to be encapsulated in a silicon vacuum cavity [12, 13, and 14]. The temperature dependency of the resonator is in the range of 20- 40 ppm/°C which is larger than that of quartz [11, 12]. The temperature dependence of the MEMS resonator is compensated by measuring the CMOS die with built in temperature sensors.So the reference can achieve to a stability about 10 ppm in the temperature range of -10°C to 85°C [3]. Another concern is about the aging of MEMS resonator. The reliability tests released by Discera shows a sub ppm aging in the first year of operation of these devises. Furthermore, because of smaller size and dimension, the MEMS resonators have better shock resistance than quartz crystals [15].So far, the commercially available MEMS based frequency references with sub ppm accuracy and programmable output frequencies make it possible to replace quartz crystals with MEMS based devices. Beside problems in the resonator, they have also have problems in the noise and jitter of fractional N-synthesizer. Also due to some special processing required for the MEMS resonator makes single die integration of these devices difficult. This means that the integration of such frequency references will usually result in a two-chip solution [3, 4].

3.2 LC oscillators

Another class of commercially available frequency references are LC oscillators. Such references operate at the resonance frequency of an LC tank and consist of passive elements such as capacitors and inductors as well as active elements such as transistors. so such an oscillator can be implemented in a standard CMOS process. The first steps for commercializing LC oscillator were taken at Mobius Microsystem.A fab-less company founded in 2004 with the aim of developing all-silicon frequency sources that replace quartz crystal oscillators. The goal of Mobius Microsystems was to produce a monolithic free running RF LC oscillator that did not require the frequency synthesizers used in MEMS frequency references (This was to avoid the effect of multiplication on the output frequency jitter). These efforts resulted in oscillators with 12 to 25 MHz oscillators with stability of 100ppm. [16, 20]. A simplified block diagram of an LC oscillator is shown on figure 2.It includes an LC tankwith their equivalent loss elements for the inductor and capacitor. Here the oscillation frequency is [16]:

$$\omega = \frac{1}{LC}\sqrt{\frac{L-C.R_L^2}{L-C.R_C^2}} \qquad (1)$$

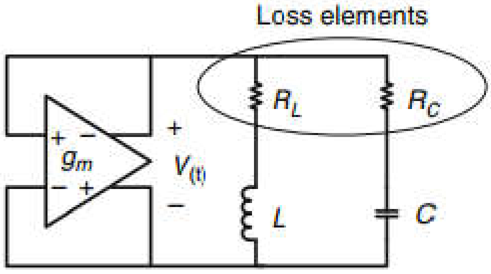


Figure 2. Block diagram of an LC oscillator with equivalent loss element

In (1) L and C,R_L , andR_C are the value of inductor, capacitor, equivalent loss of inductor and capacitor respectively. The frequency of an LC oscillator suffers not only from the losses but also due to change in the absolute values of passive elements (arising from temperature and process). Integrated inductors have a negligible temperature coefficient (TC) [17] but the temperature dependence of equivalent loss of inductor is determined by the material from which the inductor is made. Since, R_L is usually larger than R_C, the former's the temperature dependence will be dominant. Furthermore, the capacitor is affected bythe fringing capacitors due to interconnect and parasitic capacitance of transcondutor. Thelatter capacitance is significantly depended to temperature and bias. In factoutput frequency of an LC oscillator shows a concave negative temperature dependency whose sensitivity increases at high temperatures [17]. Also if a conducting material be in the nearby, the oscillation frequency of an LC oscillator will be varied, because the field lines of the inductor is affected due to changes in permeability or by EDDY current [17, 18]. The solution introduced by IDT is to build a faraday shield around the diein order to maintain the fringing lines and avoid disturbance. This is done by depositing a thick dielectric layeron the die of LC oscillator chip and electroplating several microns cupper in top of that. The back side of device is also protected by an aluminum layer [18].

The LC oscillator introduced in [19] has a 12 MHz output frequency and supply current of 9.5mA. The stability of this oscillator is 400ppm/℃. The main aim of Subsequent works was to reduce the power consumption of LC based oscillators. It has been done by making change in their compensation schemes [16, 17]. This compensation scheme initially was an active compensation block consists of PTAT generator and varactors in the LC tank which were connect to a control voltage. Later these modifications were turned into a passive compensation scheme. As a result of these efforts the 15mA supply current in [19] reduced to 2mA. But the recent production introduced by IDT by combination of the two previous techniques i.e. passive and active compensation and utilizing an improved faraday shield can achieve to accuracy of less than 50ppm in the temperature range of -20℃ to 70℃ [20]. Other than IDT products, the Si500 series have been introduced by Silicon labs. These oscillators are capable of producing programmable output frequency from 0.9 to 100 MHz and they have achieved to stability of 150ppm in the temperature range of 0℃ to 70℃.

Considering the temperature and process dependent parameters in LC oscillators and the probable lack of correlation between these parameters, at least a two point frequency trimming is needed to apply to this oscillators which is increased their cost. Furthermore these oscillators have a relatively narrow temperature range of -20℃ to 70℃ and limited their application over wide temperature ranges.

Ring oscillators

Ring oscillators is widely used as voltage-controlled oscillator in jitter sensitive applications such as phase lock loops and clock recovery circuits, they can achieve to high frequency and can be easily integrated in CMOS standard processes. Ring oscillators can be realized as a loop of serried inverter stages [3]. Ring oscillators can also be made by means of analog delay stages, this can be included a full differential stage or a differential pair and a symmetrical load [21].

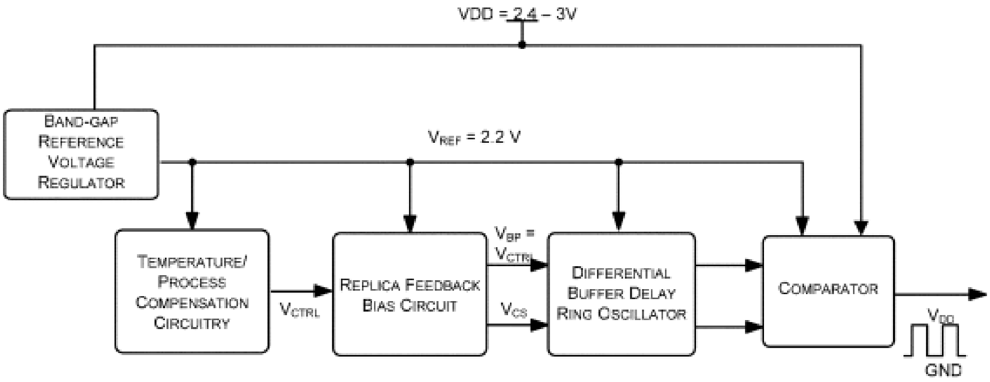
The oscillation frequency in a ring oscillator is determined by propagation delay at each stage and given by:

$$f_{osc} = \frac{I_{source}}{NC_{load}.Vdd} \qquad (2)$$

Where, I_{SOURCE} is the bias current of each stage, C_{load} is the equivalent capacitance in the output node of each stage, N is the number of inverter stages, and Vdd is the supply voltage of oscillator. The propagation delay at each stage and consequently oscillation frequency of a ring oscillator is a function of PVT [23, 24]. So the oscillation frequency is severely sensitive to temperature (as well as supply voltage and process). In order to reduce these effects two solution can be found in related references: open loop compensation and closed loop compensation. The first one, compensate PVT effects within the circuits, using voltage or current controlled ring oscillator in an open loop. The second approach embed a ring oscillator within a feedback loop. Our concentration will be mainly on the open loop compensation. About the closed loop compensation we will not more discussion and only introduce two works in this field. In [25] a frequency to voltage converter is used within a feedback loop to control the frequency of a voltage controlled ring oscillator. Also in [26] a frequency to voltage converter embedded in a feedback loop is used to control a voltage controlled ring oscillator. The temperature coefficient of these two works was 67 ppm℃ and 90 ppm/℃, respectively. In the following section the open loop compensation method of ring oscillator is considered.

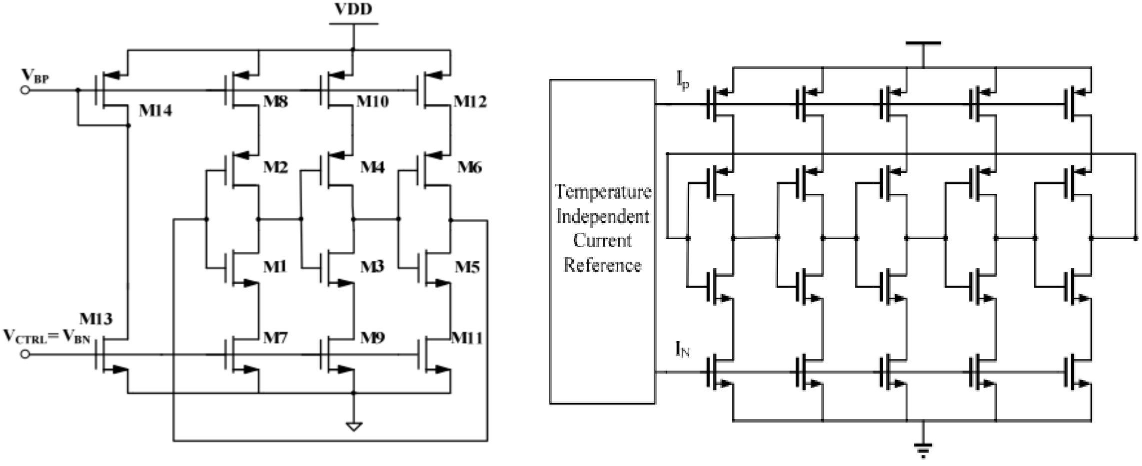
Open loop compensation in ring oscillators

A ring oscillator consists of number of gain stages which are connected in a loop. As mentioned before, these stages can be digital NOT gaits, analog delay stages like differential pair or CS stages etc. [27]. The method of applying open-loop compensation to a differential ring oscillator is described in [22]. The reference frequency is produced by three differential stages and stabilized by the reference current I_{ref} . This current is adopted from a control voltage produced by process and temperature compensated circuitry. Finally, analog output is converted to digital voltage levels by means of a comparator (figure3).



Figuire3. Block diagram of a differential ring oscillator of [22]

Another type of ring oscillators made using of NOT gate or digital inverters. This type is known as single-ended ring oscillator. The ***current starved*** inverters can be used for applying temperature (and process) compensation to a ring oscillators. Fundamentally, in this method, compensation can be obtained by controlling the charge and discharge current of inverters [28] current starved ring oscillators are made in the two types of voltage controlled or current controlled. The basis of both types is controlling the charge and discharge current of inverters, but in the former, a voltage signal is used for controlling the ring oscillator, whereas in the later a current signal directly used for controlling the ring oscillator (see figure 4). If we take a look to the figure 4.A, transistors M1-M5 form three inverter stages. M7-M9-M11 are the NMOS biasing transistors and determine the dischargetime or t_{pHL} , and also, transistors M8-M10-M12 are the PMOS biasing transistors and determine the charge time or t_{pLH} .the biasing transistors are often sizing so that these times are equal. Accordingly, the total delay time and oscillation frequency can be controlled by means of these currents. The vital temperature dependent parameters of MOS transistors are: carriers mobility μ and threshold voltage V_{th} .mobility have a negative temperature coefficient, whereas the temperature coefficient for threshold voltage is a positive value. The oxide capacitances are also temperature dependent, but they have a small temperature coefficient and can be neglected [23, 24].



A. voltage controlled ring oscillator B. current controlled ring oscillator

Figure 4. Using current starved inverters in ring oscillators

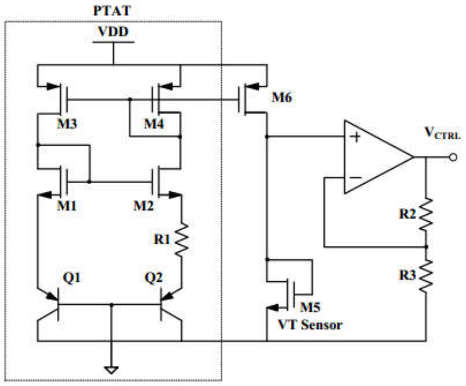
A. voltage controlled ring oscillators (VCRO)

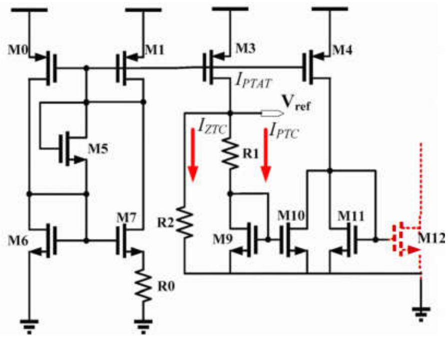
In this case, Control signal is voltage and applies to the oscillator from pin of VCTRL.Depending on how is the temperature dependence, a control voltage should be generated so that minimized the variation of frequency over temperature. The control voltage may depends on many of parameters, but in asimplified manner it can be given by:

$$VCTRL=V_{T0}+AT \tag{3}$$

$$A=V_{T0}\ \alpha V_{th}+\sqrt{\frac{f_{osc}N.Vdd.C_{Lo}}{\mu C_{ox}\frac{W}{L}}} \tag{4}$$

Where, V_T , αv_{th} , fosc, and N are threshold voltage, fractional temperature coefficient of threshold voltage, oscillation frequency and number of stages respectively. Other parameters are related to MOSbiasing transistors. In this equation of course, the effect of process variations have also been predicted and the temperature coefficients of load and oxide capacitances have been ignored. The control voltage here, follows a linear relationship. This control voltage can be easily produced by a PTAT voltage generator of figure 5.A. MOSFETs M1-M4, BJTsQ1 andQ2, and the resistor R1 form a conventional PTAT circuit. M6 copies the PTAT current into M5 so that the unbuffered control voltage is generated.The threshold voltage of M5 depends on process variations, the unbuffered control voltage will vary process parameters variations and so, the process compensation is done. A simple op-amp based voltage buffer is used to adjust temperature coefficient and deliver VCTRL [23]. Using this circuit and without any frequency trimming, the temperature variations over the temperature range of -40℃ to 125℃have been 4.29% and 2.29% at the frequencies 100MHz and 150MHz, respectively.





B. current controlled ring oscillators

A current signal is directly used to apply compensation. The structure of this oscillator is shown in figure 4.B. in which a current reference with appropriate specifications is used. The reference current should be such that its injection to the structure of current starved inverters caused to a frequency stability. The current reference of figure 5.B can be used to apply compensation in a CCRO. This current reference has been achieved to a stability of 6.8 ppm℃ and used MOS transistors in weak inversions [22]. So the reference voltage has been decreased to less than band gap of silicon. The operation of MOS transistors in weak inversion are like a BJT and on the other hand, because of having extremely low operating point they can produce voltages/currents under the silicon band gap [22, 27]. In this circuit transistors M6 and M7 are in the weak inversion and generate a PTAT current, finally, subtracting this current into zero TC and positive TC currents (I_{ZTC} and I_{PTC}, respectively), while reduces the reference current significantly, gives current with a low temperature coefficient. by applying this current to the CCRO, stability of 24 ppm/℃ over temperature range of -25℃ to 75℃ at frequency of 10MHz is obtained. Also, in [29], by modifying the temperature characteristics of the current reference by combining this current with a opposite characteristic curve current, the improved TC of 22.3 ppm℃ has been reported, over the same temperature range.

CONCLUSION

In this article, an overview of the need of replacing quartz and some of silicon based frequency references are presented. Efforts have been done in this field, caused to emergence of technologies such as MEMS, LC and ring oscillators. at this time, the LC and MEMS based silicon oscillators are commercially presenting and achieve best stability over temperature. But in recent years, ring oscillators with high integration capability, become of particularly in applications like mobile devices. By applying compensation and without any external elements and frequency trimming, ring oscillators have been able to achieve stability analogous other silicon technologies. Low power consumption, high integration capability, operating at low power supply voltages, make ring oscillators an appropriate choice in silicon frequency references market. Also, ability of achieving to high frequencies at range of several GHZ addition to above mentioned properties make ring oscillators an appropriate choice for mobile applications, but their frequency stability should still be improved and be in the order of tenth of ppm. At the end, a comparison between silicon oscillators is presented in table 2.

Table 1. Comparison of some state-of-the art all silicon frequency references.

Reference	[30]	[16]	[29]
Principle of operation	MEMS	LC	ring
Temperature range(℃)	-40 to 125	0 to 70	-25 to 75
Supply voltage (V)	1.8 ~ 3.3	1.8	1.8
Power consumption (or supply current)	3.2 – 20 mA	Less than 4mW	32 uW
Process	MEMS+CMOS	0.130 um	0.180 um
Temperature coefficient (ppm/℃)	0.12 to 0.62	8.6	22.3

REFERENCES

1. Lam CS, 2008, A review of the recent development of MEMS and crystal oscillators and their impacts on the frequency control products industry. In: IEEE ultrasonic symposium, pp. 694–704
2. Data sheets of high stability oscillators, available online at : www.vectron.com
3. Kashmiri,S.M, Makinwa K.A.A " Electro thermal frequency reference in standard CMOS" Springer, pp. 15-41
4. McCorquodaleMS, 2009, Silicon challenges quartz: precision self-referenced solid-state oscillators for frequency control and generation. In: IEEE Toronto section, University of Toronto, Canada, 2009.
5. J T M van Beek1 and R, 2012, "A review of MEMS oscillators for frequency reference and timing applications"JOURNAL OF MICROMECHANICS AND MICROENGINEERING, vol. 22
6. Frerking M., 1996, fifty years of progress in quartz crystal frequency standards Proc.IEEE Int. Freq.Control.Symp pp33–46
7. Fujishima S., 2000, the history of ceramic filters IEEE Trans. Ultrason. Ferroelectr. Freq. Control 47 1–7
8. Universal Serial Bus (USB) Specifications Rev 3.0, 2008. Available online at: www.usb.org
9. Allan DW et al, 1988, Ensemble time and frequency stability of GPS satellite clocks. In: IEEE annual frequency control symposium, pp 465–471.
10. Sadiku M, 2002, MEMS. IEEE Potential 21(1):4–5.
11. MEMS replacing quartz oscillators, SiTime application note AN10010, 2009, References 41.
12. Tabatabaei S. et al, 2010, Silicon MEMS oscillators for high-speed digital systems IEEE Micro 30(2): 80–89
13. Lutz M, 2007, MEMS oscillators for high volume commercial applications. In: IEEE transducers, pp. 49–52
14. Wan-Thai Hsu et al, 2007, the new heart beat of electronics - Silicon MEMS oscillators. In: IEEE electronic components and technology conference, ECTC, pp. 1895–1899
15. Wan-Thai Hsu, 2006, Reliability of silicon resonator oscillators. In: IEEE international frequency control symposium and exposition, pp. 389–392.
16. McCorquodale MS et al, 2008, A 25 MHz All-CMOS reference clock generator for XO-replacement in serial wire interfaces. In: IEEE international symposium on circuits and systems, ISCAS, pp 2837–2840
17. McCorquodale MS et al, 2009, A 25-MHz self-referenced solid-state frequency source suitable for XO-replacement. IEEE Trans Circ Syst I Regular Pap 56(5):943–956
18. McCorquodale MS et al, 2010, A silicon die as a frequency source. In: IEEE international frequency control symposium, pp. 103–108.
19. Hajimiri A (1999) Design issues in CMOS differential LC oscillators. IEEE J Solid-State Circ 34(5):717–724
20. McCorquodale MS et al, 2011, A history of the development of CMOS oscillators: the dark horse in frequency control. In: IEEE international frequency control symposium, pp. 437–442
21. Sundaresan K et al, 2006, Process and temperature compensation in a 7-MHz CMOS clock oscillator. IEEE J Solid-State Circ 41(2):433–442
22. Zheng-Yi Huang et al. ,2011, A New Temperature Independent Current Controlled Oscillator ,2011 international Symposium on Intelligent Signal Processing and Communication Systems (ISPACS) December2011
23. Panyai, S. et al, 2012, "Design and realization of a process and temperature compensated CMOS ring oscillator", (ECTI-CON), 2012 9th International Conference on
24. P. E. Allen and D. R. Holmberg, CMOS Analog Circuit Design. Oxford University Press, 2011.
25. Lee J et al ,2009, A 10 MHz 80μW 67 ppm/C CMOS reference clock oscillator with a temperature compensated feedback loop in 0.18 μm CMOS. In: IEEE symposium on VLSI circuits, pp. 226–227
26. Ueno K et al, 2009, A 30-MHz, 90-ppmC fully-integrated clock reference generator with frequency-locked loop. In: IEEE European solid-state circuits conference, ESSCIRC, pp. 392–395 References 43
27. B. Razavi, "Design of analog integrated circuits", McGraw-Hill Higher Education, international edition-2001 chapter 14, oscillators
28. E. SALMAN, "High performance integrated circuit design", chapter 13, MC GRAW HILL, 2012
29. Wei-Bin Yang et al ,2011, Temperature Insensitive Current Reference for the 6.27 MHz Oscillator, IEEE 2011, International Symposium on Integrated Circuits, pp. 559-562
30. SiTime's product selector sheet. Available online at: http://www.sitime.com/support/product-selector