A Colpitts-Based Frequency Reference Achieving a Single-Trim ±120ppm Accuracy from -50 to 170°C

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***Abstract*—A single-trim, high accuracy frequency reference is presented. The Colpitts LC-oscillator topology reduces the temperature dependencies of the LC-tank quality factor on the oscillation frequency. With a fractional divider for frequency compensation it can serve as crystal-replacement. Measurements of the prototype (16 samples) in a 0.13μm high-voltage CMOS SOI process show ±120ppm accuracy from -50 to 170°C. The oscillator dissipates 3.5mW from a 2.5V supply and has 220ppm/V supply-sensitivity without supply regulation.**

***Index Terms*—Frequency reference, Colpitts LC-oscillator, single-trim, temperature stability.**

I. Introduction

Frequency references compliant with e.g. wired communication standards like 10/100/1000 Ethernet, require ±100ppm absolute frequency accuracy over their operating temperature [1]. Wireless standards require even stricter accuracy. The de-facto solution is to use bulky and relatively expensive quartz crystal oscillators. These have ppm-level accuracy and very little temperature dependency, thus requiring no or at most a very simple single temperature (1T) trim. In an attempt to eliminate the bulky quartz crystal oscillator and move to fully integrated solutions, several on-chip frequency references have been published [1]–[7]. However, passive and active on-chip components in the processing front-end have a significant process spread and temperature (T) dependency. Absolute frequency accuracy hence requires trimming. The state-of-the-art either uses 1T-trimming but does not satisfy the absolute accuracy, or can achieve the required accuracy only with an expensive multi-temperature trim.

To our best knowledge, the best reported accuracy is obtained by a Colpitts LC-oscillator with ±1.7ppm over 80°C of operating range [2], but requires trimming at 16 temperatures per sample. The highest performing LC- [3] and RC-based [4] two-point temperature trimmed (2T) frequency references report an accuracy of ±50ppm over a temperature range of 105°C and ±200ppm over 130°C respectively. The best performing 1T-trimmed frequency reference is the Thermal-Diffusivity based reference [6] that uses the well-defined thermal diffusivity of silicon. Requiring high-accuracy temperature sensing (<0.1°C [6]) for frequency correction, the reported accuracy is only ±1000ppm over 180°C range.

A typical on-chip frequency reference consists of two parts: an oscillator and a temperature compensation block. To minimize cost (test time) only a single temperature trim per sample using a *fixed* temperature compensation polynomial is highly desired. This requires a well-defined temperature dependence of the oscillator. To achieve the latter, our design philosophy is to minimize the influence of doped semiconductors (such as poly-resistors, transistors, diodes) on the oscillation frequency. The class of LC-based oscillators therefore looks like the ideal candidate: the oscillation frequency f is mainly determined by the value of L and C, both of which can be easily implemented in the metal back-end. The general normalized temperature coefficient of the oscillation frequency ($\mathrm{TC_f}$) is given by:

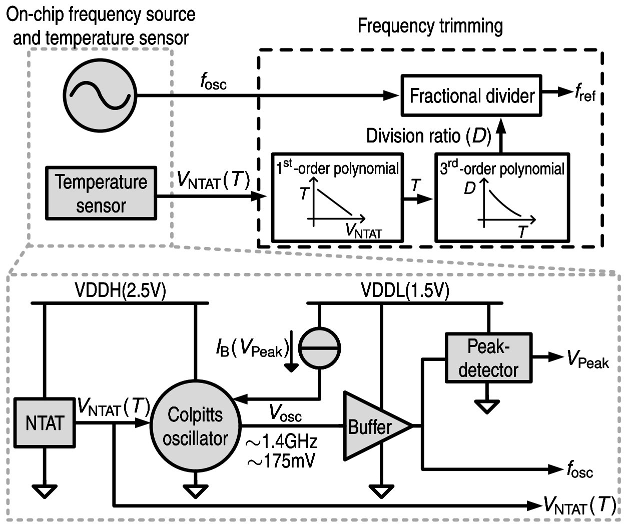


Figure 1. Functional schematic of the proposed frequency reference (integrated parts shown in grey).

$$TC_\mathrm{f} = \frac{1}{f}\frac{\partial f}{\partial T} = \frac{1}{f}\left(\frac{\partial f}{\partial L}\frac{\partial L}{\partial T} + \frac{\partial f}{\partial C}\frac{\partial C}{\partial T} + \frac{\partial f}{\partial Q}\frac{\partial Q}{\partial T}\right) \quad (1)$$

where Q is the quality factor of the LC-tank. The LC-based frequency references in [1], [3], [5] use the conventional cross-coupled LC-oscillator topology, where the oscillation frequency f depends significantly on Q [1]. In the low GHz-range (i.e., where $Q_\mathrm{L} \ll Q_\mathrm{C}$), $\mathrm{TC_f}$ is dominated by the process and temperature dependent quality factor of the inductor (Q_L) [1]. Thus for the cross-coupled LC-oscillator both the value and spread of $\mathrm{TC_f}$ are mainly proportional to $1/Q_\mathrm{L}^2$ [1]. Other contributors to $\mathrm{TC_f}$ are the temperature coefficient of the tank inductance ($\mathrm{TC_L}$) and capacitance ($\mathrm{TC_C}$), both of which are largely determined by interconnect/metal properties and thus show relatively low spread. As a result, the overall process spread of $\mathrm{TC_f}$ is mainly determined by process variation of Q_L, which therefore limits the achievable frequency accuracy over temperature after 1T-trimming.

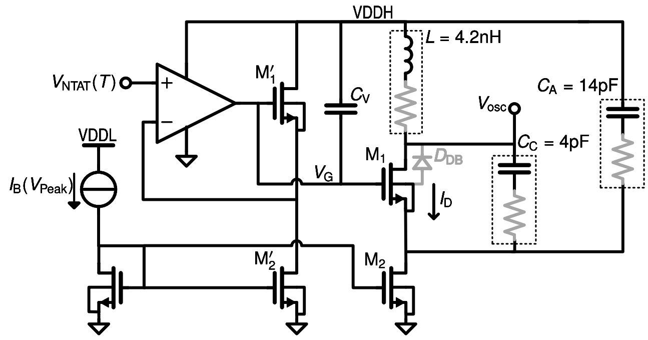
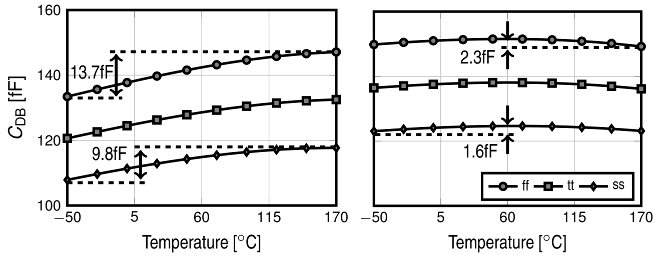


Figure 2. Circuit diagram of the presented Colpitts oscillator.



(a) With $V_\mathrm{G} = 1V$. (b) With compensation ($V_\mathrm{G}(T)$).

Figure 3. Simulation of C_DB with and without compensation for 3 process corners.

The work in [2] suggested that the $\mathrm{TC_f}$ of a Colpitts oscillator is less sensitive to variation of Q_L compared to that of the cross-coupled LC-oscillator. We derived mathematically that maximizing Q_C in Colpitts oscillators reduces the dependency of $\mathrm{TC_f}$ on Q_L even further. In this paper we leverage this property and present a Colpitts oscillator with a well-defined frequency behavior over temperature.

The oscillator in [2] includes varactors (driven from a PTAT source and a 9-bit DAC) for temperature compensation. Following our design philosophy, our oscillator itself is non-trimmable to exclude lossy and PVT-sensitive tuning/switching components, thereby minimizing the process spread of $\mathrm{TC_f}$ to enable 1T-trimming with sufficient accuracy. Similar to the work in [3], [7], nominal frequency trimming and temperature compensation are accomplished by adjusting the division ratio (D) of a fractional divider as illustrated in Figure 1. The focus of our demonstration vehicle is on the generation of f_osc itself. For measurement flexibility the frequency trimming, including fractional divider and compensation polynomial calculation, are implemented off-chip. The division ratio is obtained from a 3rd-order polynomial of the oscillator temperature. The temperature is determined from an integrated temperature sensor generating a voltage $V_\mathrm{NTAT}(T)$. For 16 samples a measured worst-case inaccuracy of 2.5°C over -50 to 170°C is achieved. Using only 1T-trimming, the presented frequency reference achieves a frequency accuracy on par with the 2T-trimming (at 0°C and 70°C) work presented in [3], but over the much wider temperature range of -50 to 170°C.

II. Circuit Implementation

Figure 2 shows the schematic of the Colpitts oscillator. The LC-tank is formed by inductor L in parallel with C_S, the series combination of the two capacitors C_A and C_C: $C_\mathrm{S} = C_\mathrm{A}C_\mathrm{C}/(C_\mathrm{A}+C_\mathrm{C})$. Capacitance C_V shorts the gate of the sustaining element M_1 to AC ground. From reactive power balance, the oscillation frequency is [8]:

$$f_\mathrm{osc} = \frac{1}{2\pi\sqrt{LC_\mathrm{S}}} \times \sqrt{1+\frac{1}{Q_\mathrm{L}}\left(\frac{1}{Q_{\mathrm{C_A}}}+\frac{1}{Q_{\mathrm{C_C}}}\right)-\frac{1}{Q_\mathrm{L}^2}\sum_{n=2}^{\infty}\frac{1}{n^2-1}h_n^2} \tag{2}$$

which depends on the natural resonance frequency $f_0 = 1/(2\pi\sqrt{LC_\mathrm{S}})$, the temperature-dependent quality factors of the LC-tank, as well as the n^th harmonic content $h_n = I_{\mathrm{D_n}}/I_{\mathrm{D_1}}$ in the sustaining current I_D. Frequency shift due to the harmonic content is known as the Groszkowski effect [8]. For the Colpitts oscillator the $\mathrm{TC_f}$ contribution from the temperature-sensitive quality factor of the LC-tank (assuming $Q_\mathrm{C} = Q_{\mathrm{C_A}} = Q_{\mathrm{C_C}}$) is proportional to $2/(Q_\mathrm{C}Q_\mathrm{L})$. This is inherently a factor $Q_\mathrm{C}/(2Q_\mathrm{L})$ better than the cross-coupled LC-oscillator at lower-GHz frequencies, where $Q_\mathrm{L} \ll Q_\mathrm{C}$. Consequently, to take advantage of this property, the layout of the LC-tank was optimized to maximize $Q_{\mathrm{C_A}}$ and $Q_{\mathrm{C_C}}$ (layout extracted to be $Q_\mathrm{C} \approx 300$ at 1.4GHz). For a $Q_\mathrm{L} = 12$, this gives an improvement of about $Q_\mathrm{C}/(2Q_\mathrm{L}) = 12$ times in the $\mathrm{TC_f}$ LC-tank quality factor term.

The integrated part of this prototype (see Figure 1) consists of the Colpitts oscillator core, a V_NTAT source/temperature sensor, a buffer, a peak-detector and a variable bias current source. The buffer is implemented by a conventional source follower and isolates the oscillator core from succeeding circuitry. Oscillation amplitude control is achieved by measuring the peak detector output V_osc and adjusting the bias current I_B accordingly. Low amplitudes of V_osc ensure that the sustaining element M_1 is kept close to its bias point and hence frequency drift due to the Groszkowski effect is minimized. Accordingly, for this prototype, the amplitude of V_osc is limited to 175mV. This degrades the figure of merit by >10dB compared to the case where maximum swing is used. For measurement flexibility, the control-loop is closed off-chip. Measurements indicated that small variations of V_osc, i.e. 10%, lead to negligible effects on the frequency (<10ppm).

By minimizing the contribution of the quality factor of the LC-tank and harmonic content on f_osc, the temperature-dependent tank inductance and capacitance dominate the residual $\mathrm{TC_f}$. The effective tank capacitance is influenced by PVT-sensitive parasitic capacitances of M_1 and M_2. The design choice of $C_\mathrm{A}/C_\mathrm{C} \approx 3.5$ is a compromise between the influence of the parasitic capacitances on C_A, and the necessary transconductance and current consumption of transistor M_1 for oscillation. M_1 contains a parasitic bulk-drain junction diode D_DB, of which its capacitance C_DB is PVT-sensitive and is in parallel with (the smaller) tank capacitance C_C. Figure 3 shows simulated C_DB versus temperature with constant 1-V gate voltage V_G over process corners. C_DB variations over temperature yield an additional frequency variation of 900ppm

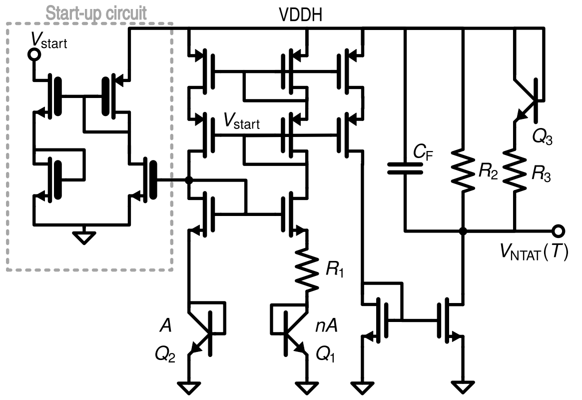


Figure 4. Schematic of the NTAT source. The bulk of NMOS and PMOS are connected to GND and VDDH respectively.

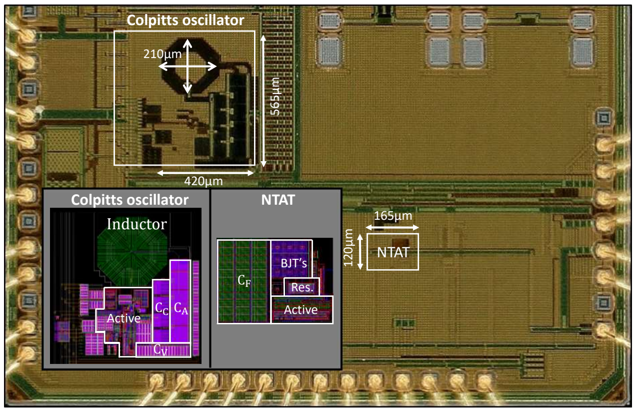
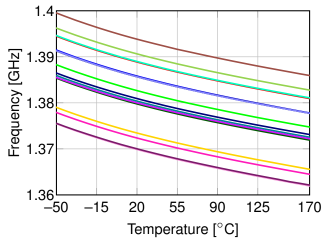


Figure 5. Die micrograph of the Colpitts based frequency reference.

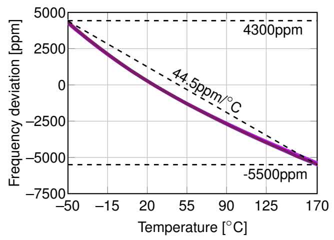
to 1300ppm from -50 to 170°C for the slow and fast corners respectively. In the presented oscillator, these dependencies of $C_{\rm DB}$ are canceled by forcing a suitable NTAT voltage $V_{\rm NTAT}$ on the source of $\rm M_1$, implemented by the replica circuit $\rm M_1'$, $\rm M_2'$ and the op-amp (see Figure 2). Figure 4 shows the $V_{\rm NTAT}$ generating circuitry. $V_{\rm NTAT}$ is given by:

$$V_{\rm NTAT} \approx V_{\rm DDH} - \frac{R_3}{R_2+R_3} \times \left(\frac{R_2}{R_1}\frac{kT}{q}\ln(n) + \frac{R_2}{R_3}V_{\rm BE,Q_3} \right) \quad (3)$$

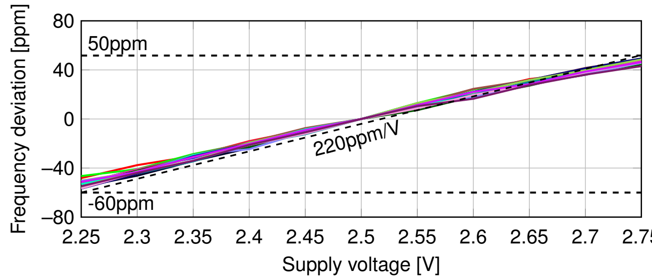
The absolute $V_{\rm NTAT}(T_{\rm trim})$ value and its temperature slope ($\mathrm{TC}_{V_{\rm NTAT}}$) can be independently set via the resistors R_2 and R_3. The $C_{\rm DB}$ compensation over temperature is achieved by applying a $\mathrm{TC}_{V_{\rm NTAT}}$ of about -3.1mV/°C. Simulations show that the $C_{\rm DB}$-variation over temperature is reduced by a factor 6 to within 2.3fF (see Figure 3b), which translates directly to a similar reduction of the frequency drift and its spread. The residual (well-defined) frequency drift of the oscillator is compensated using a 3$^{\rm rd}$-order polynomial in the temperature-to-division ratio compensation.



(a) $f_{\rm osc}$ over temperature.



(b) Frequency deviation of $f_{\rm osc}$ over temperature w.r.t. $f_{\rm osc}$ at 25°C.



(c) Frequency deviation of $f_{\rm osc}$ over supply voltage w.r.t. $f_{\rm osc}$ at 2.5V.

Figure 6. Measured temperature dependency of $f_{\rm osc}$ without polynomial correction (a,b) and frequency deviation over supply voltage (c).

III. Measurements

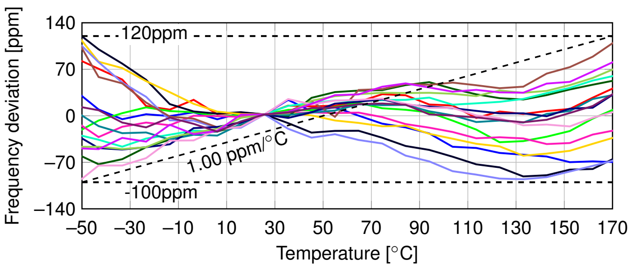
The prototype chip, shown in Figure 5, is fabricated in a 0.13μm high voltage CMOS SOI process and occupies an active area of $0.26\mathrm{mm}^2$. Sixteen samples in plastic packages were characterized. At 25°C the oscillator core and NTAT source dissipate 3.5mW from a 2.5V supply (VDDH), while the buffer and peak-detector draw 0.75mW from a 1.5V supply (VDDL). The output frequency $f_{\rm osc}$ was measured over a temperature range from -50 to 170°C using a thermo-streamer. The ambient temperature close to the chip was monitored by a PT100 thermometer. Figure 6 shows $f_{\rm osc}$ and its frequency deviation over temperature and supply voltage. The uncompensated frequency accuracy from -50 to 170°C is within ±5500ppm (see Figure 6b), yielding $\mathrm{TC_f} = 44.5$ppm/°C (box-method). Over a 2.25V-to-2.75V unregulated supply range, the frequency error is less than ±60ppm and equals 220ppm/V.

Based on the raw temperature measurements of $f_{\rm osc}$, a single 3$^{\rm rd}$-order polynomial was extracted for batch calibration. The 1$^{\rm st}$-order polynomial for the temperature sensor ($V_{\rm NTAT} \rightarrow T$) is also extracted from batch-calibration. Figure 7 shows measured frequency deviations after applying these temperature-correction polynomials and after 1T-trimming at room temperature for 16 samples. Using the internal temperature sensor, the worst-case frequency error stays within ±120ppm from -50 to 170°C, yielding $\mathrm{TC_f} = 1.0$ppm/°C (box-method). The measured frequency inaccuracy is partly limited by the spread of the temperature sensor, which is worst-case ±2.5°C across the 16 samples. With an external PT100 as temperature sensor, the frequency error stays within ±70ppm. Table I summarizes the measured performance and shows benchmarking against other integrated frequency references.

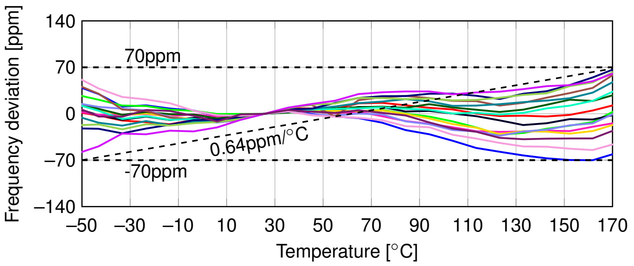
Table I
PERFORMANCE SUMMARY AND COMPARISON TO PRIOR WORK IN INTEGRATED FREQUENCY REFERENCES.

	This work	[2]	[5]	[3][a]	[4]	[7]	[6]
Reference principle	LC Colpitts	LC Colpitts	LC Cross-coupled	LC Cross-coupled	RC	Mobility	Thermal Diffusivity
Frequency [MHz]	1380	52	24	100	7	0.15	16
Temp. range [°C]	-50 to 170	0 to 80	0 to 70	-20 to 85	-45 to 85	-55 to 125	-55 to 125
TC_f [ppm/°C][b]	1.0	0.05	1.8	0.7	2.5	300	11.2
Trimming temp. [°C]	RT[c]	0, 5, ..., 80	NA	0 and 70	-35 and 75	RT[c]	RT[c]
VC_f [ppm/V]	220	4270	$\leq$ 8[d]	2.6[d]	1800	12000	NA
RMS Period jitter [ps]	0.5	3.2	6.5	12	24	NA	45
Number of samples	16	3	1	28	8	12	24
Power [mW]	4.25	14.25	49.5	14.85[e]	0.78	0.05	2.1
Area [mm^2]	0.26	2.3	2.25	0.2	1.59	0.2	0.5
Technology	130nm HV CMOS SOI	350nm CMOS	250nm CMOS	130nm CMOS	180nm CMOS	65nm CMOS	160nm CMOS

[a] LC-oscillator and fractional divider. Some numbers from private communication as not available from [3] itself [b] Box-method
[c] Room-temperature [d] On-chip voltage regulator [e] For a supply voltage of 2.7V NA = Not Available



(a) Using the internal temperature sensor.



(b) Using the external PT100 thermometer.

Figure 7. Frequency deviation over temperature with 3rd-order correction polynomial and 1T-trimming.

IV. CONCLUSIONS

This paper presents an on-chip Colpitts LC-oscillator that meets high accuracy over a large T-(and V-) range based on a single temperature trim. An LC-oscillator with its frequency mainly defined by the metal back-end allows for a well-defined temperature dependence of the oscillator. Remaining dependencies from active circuitry, like the Groszkowski effect and varying junction capacitance, are tackled with respectively amplitude control and NTAT biasing. The Colpitts topology is used since it has an inherently lower dependence on the quality factor of the LC-tank compared to the popular cross-coupled LC-oscillator.

The above-mentioned design choices and circuit techniques ensure a small residual temperature dependence, well-defined over all 16 samples. The residue is compensated off-chip by a fixed 3rd-order correction polynomial. The demonstration vehicle in a 0.13μm high-voltage CMOS SOI process achieves the highest stability over the largest temperature range of any published 1T-trimmed reference, improving frequency stability by 10x over the state-of-the-art without requiring high-resolution temperature sensors.

V. ACKNOWLEDGMENTS

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