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A 1.5 ± 0.39 ppm/ $^{\circ}\text{C}$ Temperature-Compensated LC Oscillator using Constant-Biased Varactors

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Abstract—This letter presents a temperature compensated oscillator for clock generation across a wide temperature range. The proposed technique deploys the characteristics of the constant-biased varactors to nullify the overall oscillator's temperature coefficient (TC), thereby reducing the temperature drift effect on the oscillator frequency output. Fabricated on a $0.18\text{-}\mu\text{m}$ CMOS technology, the proposed 2.09-GHz-gm-LC oscillator sees a mere $1.5\text{-ppm}/^{\circ}\text{C}$ frequency drift from -20°C to 120°C . The oscillator consumes 10.9 mW at 1.4-V supply, with phase noise of -119.4 dBc/Hz at a 1-MHz offset. The demonstrated technique is useful for providing accurate clock for a variety of applications, including those operating in harsh environment.

Index Terms—temperature sensor, temperature compensation, frequency source, phase-locked loop, frequency reference.

I. INTRODUCTION

MONOLITHIC oscillators functioning as clock generators and operating over wide temperature ranges are found in many applications such as wireless sensor nodes, food/chemical analysis and automotive electronics. To reduce the frequency drift in oscillators requires efficient temperature compensation techniques before the much desired precisely compensated clocks, which are vital for system operations, measurements and RF communications can be realized.

Various temperature compensation techniques for oscillators have been reported in literature, for example, in [1–3]; these temperature compensations are mainly implemented using temperature-dependent voltage biases and current sources, hence the resultant mismatches of the TCs between the biasing circuits and the oscillators limit their frequency accuracies to: $95.6\text{ ppm}/^{\circ}\text{C}$ [1], $64.3\text{ ppm}/^{\circ}\text{C}$ [2] and $85\text{ ppm}/^{\circ}\text{C}$ [3]. In [4,5], the minimization of the TCs of passive components using various types of $R\text{-}C$ components, have achieved similar performances of $86\text{ ppm}/^{\circ}\text{C}$ and $108\text{ ppm}/^{\circ}\text{C}$, respectively. In another recent technique [6], it is able to omit the temperature

effects from the transistors using a pulse-excited LC tank; but then again, it only succeeded to achieve a minimum frequency inaccuracy of $92\text{ ppm}/^{\circ}\text{C}$ [6]. To improve the performance beyond the prior arts, and down to $\text{ppm}/^{\circ}\text{C}$ level, complex trimming methods will require a control system with tenths of bits for the digitally controlled arrays as well as a lookup table in the non-volatile memory [7]. Consequently, additional hardware cost that is often unaffordable for many applications will also be incurred.

This letter presents a temperature compensation technique that makes use of constant-biased varactors, and this technique is demonstrated through application on a -gm-LC oscillator. Based on our analysis, the TC of a varactor can be regarded as a function of the bias voltage, and since the varactor is a component of the tank circuit, the TC of the -gm-LC oscillator can be directly minimized by adjusting the TC of the varactors through altering the constant bias voltage. Our proposed technique makes use of the intrinsic temperature characteristics of the varactors, so much so that the TC compensation mismatches between the oscillators and the temperature compensators can be significantly reduced when compared against prior works [1–6]. We demonstrated a 2.09-GHz LC oscillator based on a $0.18\text{-}\mu\text{m}$ CMOS process and achieves a frequency inaccuracy of just $1.5 \pm 0.39\text{ ppm}/^{\circ}\text{C}$, which outperforms most of the works that are referenced in this paper.

II. TECHNIQUE PRINCIPLE AND CIRCUIT DESIGN

A. Method to Vary TC of Varactors

The temperature characteristics of passive components are always undesirable for oscillator circuits. In our proposed technique, we are able to aptly deploy the temperature characteristics of the varactors for temperature compensation in LC oscillators. The capacitance of MOS varactors is dependent on the applied bias voltages [9], as demonstrated in the simulated curve in Figure 1(a), for a PMOS varactor. As temperature was varied from -20°C to 100°C , the capacitance curves were noted to shift simultaneously, and this phenomenon had been reported previously in [8]. In addition, we also observed that the temperature-induced capacitance variations are also different for different bias voltages, which implies that the TC of a varactor can be described as a function of the applied bias voltage. In Figure 1(b), the first order TC of the PMOS varactor is plotted against the applied bias voltage. Three distinct regions, showing positive TC, negative TC, and small TC can be markedly identified. With this observation, a

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Figure 1 (a) Simulated PMOS varactor's capacitance under different bias voltages and temperatures. (b) Simulated 1st order temperature coefficient (TC) of a PMOS varactor with different bias voltages at its gate.

desired varactor TC can subsequently be selected by applying the corresponding bias voltage, thus achieving the desired temperature compensation effect for the oscillator.

B. TC of Varactors for Temperature Compensation

The frequency output of our $-gm$ - LC oscillator, as shown in Figure 2, can be deduced from the LC tank example in [7]:

$$\omega_{OSC} \approx \omega_0 \sqrt{1 - \frac{C_{VAR} R_L^2}{L}} \quad \text{here } \omega_0 = \frac{1}{\sqrt{LC_{VAR}}} \quad (1)$$

where C_{VAR} , L and R_L represents the varactor, inductor and the lossy resistor of the inductor, respectively; ω_0 is the natural resonant frequency of the LC tank; and ω_{OSC} is the output oscillation frequency with consideration of the lossy R_L .

To determine the frequency drift of an oscillator, a deduction which includes the TCs of each component is impractical. Instead, the output frequency with consideration of temperature influences can be expressed using polynomials. First, we introduce an output frequency that is expressed as a function of the aggregate TCs of all components (excluding the varactor) as:

$$\omega_{OSC} = \omega_{OSC0} (1 + a_{OSC} \Delta T) \quad (2)$$

where ω_{OSC0} is defined at a referenced temperature and a_{OSC} is the first order TC. Note that only the first order TC is considered here to simplify the analysis. Next, we define an equivalent varactor capacitance C_{VAR_Eq} with an equivalent TC, a_{VAR_Eq} , to account for all the temperature influences on the output frequency:

$$C_{VAR_Eq} \approx C_{VAR0} (1 - a_{VAR_Eq} \Delta T) \quad (3)$$

where C_{VAR0} is the equivalent value of C_{VAR} at the referenced temperature (same reference temperature as ω_{OSC0}). From Equation 3, it becomes evident that if a compensation varactor with a TC of opposing gradient to Equation 2 is used, temperature compensation for zero first order TC can be achieved for the oscillator output.

Figure 2. The LC oscillator schematic and photograph of the chip.

The value of C_{VAR0} and a_{VAR_Eq} can be obtained by substituting Equation 2 into Equation 1, and using Taylor series expansion and Taylor approximation where $a_{OSC} \Delta T \approx 0$, thus arriving at:

$$C_{VAR0} = \frac{L_0}{R_{L0}^2 + L_0^2 \omega_{OSC0}^2} \quad \text{and} \quad a_{VAR_Eq} = \frac{2L_0^2 \omega_{OSC0}^2 a_{OSC}}{R_{L0}^2 + L_0^2 \omega_{OSC0}^2} \quad (4)$$

where L_0 and R_{L0} are defined the same way as C_{VAR0} for the values L and R_L . From Figure 1(b), the desired value of a_{VAR_Eq} can be tailored through the optimal choice of a suitable bias voltage between the positive and negative TC regions of the PMOS varactor.

C. Circuit Implementation

Using the proposed technique, the $-gm$ - LC oscillator, as depicted in Figure 2, was designed and fabricated. The on-chip 3.8-nH symmetrical chip-inductor was formed by merging the two inductors L , as shown in the schematic. The varactor, C_{VAR} , was designed using a 10×40 - μm^2 PMOS transistor. The sizes of the PMOS transistors $MP1$ and $MP2$ and the NMOS transistors $MN1$ and $MN2$ are 0.18×200 μm^2 and 0.18×96 μm^2 , respectively. The varactors' bias voltage is obtained through a resistor divider using resistors of the same type. The proposed design was fabricated on a 0.18- μm CMOS process. Excluding the bonding pads, the core circuit occupies an area of 0.35×0.45 - mm^2 . The oscillator operates on a 1.4-V supply and consumes 10.9 mW of power (including buffers).

III. MEASUREMENT RESULTS

To verify the theoretical analysis and the technical merits of our proposed temperature compensation technique, the oscillator output was measured at different bias voltages (from -0.5 V to 1.8 V, in 0.1 -V step increment) across a temperature range of -20°C to 120°C . The measured results are shown in the 3D graph in Figure 3; the vertical axis represents the relative frequency change with respect to the referenced frequency at 60°C . By calculating the frequency derivation with respect to temperature at each voltage step in Figure 3, it can be observed that the first order TC of the oscillation frequency shifts from negative to positive when bias voltage increases from -0.5 V to 1.8 V. This verifies that the TC characteristics of the varactor shifts from positive value to negative value with respect to a rising bias voltages as shown in Figure 1. In Figure 3, the plot

Figure 3. Measured frequency drift normalized with respect to that at 60°C under different temperatures and varactor's bias voltages.

Figure 4. (a) Measured oscillation frequencies from -20°C to 120°C at V_{Bias} of 0.1 V, 0.2 V, and 0.3 V. (b) Output frequency temperature dependence of LC oscillator versus the varactors' applied bias voltage on four measured samples.

exhibits a low fluctuation region (i.e., the green region with variation between 0 to 250 ppm) at around 0.2-V applied bias. This region gives the optimum performance in terms of temperature stability.

The temperature sweep of the output frequency and the absolute frequency error plot for different bias voltages are plotted in Figure 4. From the four measured samples in Figure 4(b), the measured frequency inaccuracy is only 1.5 ± 0.39 ppm/°C when the varactor bias voltage is set at 0.2 V. Even for a relative large fluctuation of bias voltage (± 0.1 V about the reference 0.2 V), the frequency error is still less than 6.9 ppm/°C. In addition, the oscillator also has phase noise performance of -101 dBc/Hz and -119.4 dBc/Hz at 100-kHz and 1-MHz offsets, respectively.

A performance summary of this temperature compensated LC oscillator is listed in Table I, with comparisons against the current state-of-the-arts. Using our proposed technique, the TC of the oscillation frequency is directly rectified towards zero through the constant-biased varactors, thus accurately reduces the frequency inaccuracy. Our demonstrated work achieved the lowest frequency inaccuracy among the state-of-the-arts [1–6]

TABLE I
PERFORMANCE COMPARISON

	This work	JSSC 06 [1]	TCAS-II 13 [2]	TCAS-I 11 [3]	JSSC 09 [4]	TCAS-I 13 [5]	ASSCC 11 [6]
Type	LC	Ring	RC	Ring	Wienbridge	RC	LC
Temp. Dependent Biasing Circuits	No	Yes	Yes	Yes	No	No	No
CMOS Node	0.18 μm	0.25 μm	0.18 μm	90 nm	65 nm	0.13 μm	0.13 μm
Osc. Freq. (GHz)	2.06	7 MHz	1.1 MHz	1.8	6 MHz	1 MHz	1.54
Freq. Inaccuracy (ppm/°C)	1.50	94.6	64.3	85	86	108	92
Temperature Range (°C)	-20 – 120	25 – 125	-20 – 80	7 – 67	0 – 120	25 – 200	-40 – 100
Phase Noise dBe/Hz							
100kHz	-101^*	N.A.	-79.48	-60^*	N.A.	N.A.	N.A.
1MHz	-119.4^*	N.A.	-74.2	-89^*	-94.6	N.A.	N.A.

* Theoretically, phase noise is decreased by $20\log(N)$ if the frequency is ideally divided by N .

for the same temperature range. In fact, this work is comparable to the design using computer aided trimming technique in [7] and discrete resonator based oscillator in [10].

IV. CONCLUSIONS

A temperature compensation technique using constant-biased varactors for LC oscillator is presented and the design has been successfully verified on a conventional 0.18- μm CMOS technology. The proposed technique compensates the overall temperature characteristic of an oscillator through altering the TC of MOS varactors using a constant bias voltage. This approach reduces the compensation mismatches, thus improving the overall temperature accuracy. The fabricated 2.09-GHz-gm-LC oscillator yields a 1.5 ± 0.39 -ppm/°C frequency inaccuracy over a temperature range of -20 to 120°C , which outperforms the state-of-the-arts. This technique is beneficial for clock generation that demands precise accuracy and for applications across wide temperature ranges.

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