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A 1.5±0.39 ppm/°C Temperature-Compensated LC Oscillator using Constant-Biased Varactors

Yong Wang, Student Member, IEEE, Kevin T. C. Chai, Member, IEEE, Xiaojing Mu, Minkyu Je, Senior Member, IEEE, Wang Ling Goh, Senior Member, IEEE

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-μm CMOS technology, the proposed 2.09-GHz–gm-LC oscillator sees a mere 1.5-ppm/°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 ppm/°C [1], 64.3 ppm/°C [2] and 85 ppm/°C [3]. In [4,5], the minimization of the TCs of passive components using various types of R-C components, have achieved similar performances of 86 ppm/°C and 108 ppm/°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 ppm/°C [6]. To improve the performance beyond the prior arts, and down to ppm/°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-μm CMOS process and achieves a frequency inaccuracy of just 1.5±0.39 ppm/°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
Instead, the output frequency with consideration of temperature which includes the TCs of each component is impractical. as:

the aggregate TCs of all components (excluding the varactor) temperature (same reference temperature as lossy resistor of the inductor, respectively; (TC) of a PMOS varactor with different bias voltages at its gate.

where

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

where \( C_{VAR}, L \) and \( R_L \) represents the varactor, inductor and the lossy resistor of the inductor, respectively; \( \omega_0 \) is the natural resonant frequency of the LC tank; and \( \omega_{OSC} \) 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:

\[ \omega_{OSC} = \omega_{OSC\ 0} \left(1 + \alpha_{OSC} \Delta T\right) \] (2)

where \( \omega_{OSC\ 0} \) is defined at a referenced temperature and \( \alpha_{OSC} \) 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, \( \alpha_{VAR\ Eq} \), to account for all the temperature influences on the output frequency:

\[ C_{VAR\ Eq} \approx C_{VAR\ 0} \left(1 - \alpha_{VAR\ Eq} \Delta T\right) \] (3)

where \( C_{VAR\ 0} \) is the equivalent value of \( C_{VAR} \) at the referenced temperature (same reference temperature as \( \omega_{OSC\ 0} \)). 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.

**B. TC of Varactors for Temperature Compensation**

The frequency output of our \(-gm\)-LC oscillator, as shown in Figure 1, can be deduced from the LC tank example in [7]:

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

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**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]:

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

\[ \omega_{OSC} = \omega_{OSC\ 0} \left(1 + \alpha_{OSC} \Delta T\right) \] (2)

\[ C_{VAR\ Eq} \approx C_{VAR\ 0} \left(1 - \alpha_{VAR\ Eq} \Delta T\right) \] (3)

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**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]:

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

\[ \omega_{OSC} = \omega_{OSC\ 0} \left(1 + \alpha_{OSC} \Delta T\right) \] (2)

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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].

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.

REFERENCES