A New Ring Oscillator with Dual Voltage/Current Control

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ABSTRACT:
A new Temperature compensated Ring Oscillator is presented. This CMOS ring oscillator consists of five current starved stage which is fed by a voltage and a current reference. In this paper a new method based on previous works has been proposed, in which required Temperature characteristic is imposed to the oscillator. The oscillation frequency of the proposed oscillator is 14.5 MHz and the simulation results in CMOS 0.18µm technology with a 1.8- V power supply showed that the temperature coefficient is 31.1 ppm/ºC in the Temperature range of -15 ºC to 65 ºC. The total power consumption of circuit is 587 µW.

KEYWORDS: Fully integrated frequency reference, Temperature compensation, Voltage references, Current references, Voltage/current controlled ring oscillator.

1. INTRODUCTION

High stability oscillators are one of the key elements in any digital or analog communication and processing systems. The required stability ranges from few PPM or less in a wireless system such as GPS or GSM, to a few hundred PPM in a wired link application [1]. In a reference frequency source the stability is typically provided by an external crystal oscillator.

In applications where stability may be tolerated to a few percent, a fully integrated circuit oscillator can be utilized resulting in lower cost and power consumption [1], [2]. A fully integrated circuit oscillator, nowadays, can be realized using LC, RC or Ring Oscillators circuits, in which, LC type provides best stability but the highest power consumption amongst all three types. RC and Ring Oscillators can also provide adequate stability in applications such as wireless sensor networks while meeting power consumption criteria as well [2]. Ring Oscillators, on the other hand, can be reduced in size and speed with the technology since they do not require neither large coils as in LC oscillators nor large resistor and capacitors as in RC oscillator circuits. They can be suitable candidates for full integration, low consumption, wide frequency adjustment range and medium stability reference development [2], [3].

Amongst many compensation and control techniques in the Ring Oscillator frequency stabilization, the current starved inverters are of importance [4]. Compensation methods in current starved Ring Oscillators for both open and closed loop circuits has been reviewed in [1].

A voltage controlled Ring Oscillator using current starved inverters has been designed and reported in [2], in which a control voltage is generated in such a way that the oscillator becomes insensitive to temperature and process variation. The circuit uses 0.18µm CMOS technology with a 1.8V supply voltage resulting in 4.49% frequency variation at 100 MHz and 2.29% at 150MHz, in the Temperature range of -40 to 125º C. The power consumption has also been reported as 437µW at 100MHz and 537µW at 150MHz operation.

A current controlled Ring Oscillator using current starved inverters has been reported in [5], where a current reference having combined two currents with positive and negative temperature coefficients are used. An overall temperature coefficient of 404ppm/ºC in the range of -40 to 100ºC has been obtained.

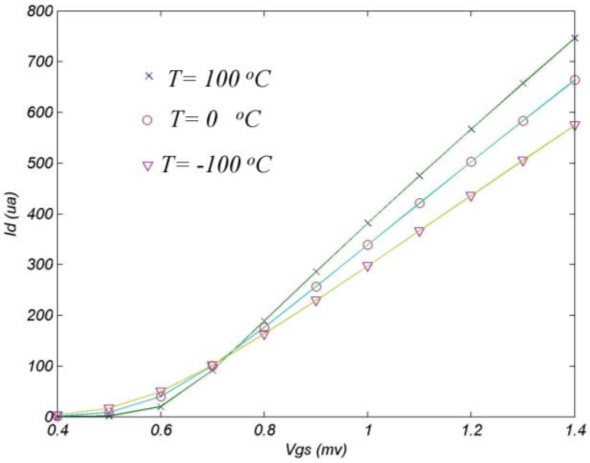

Fig.1. Dependency of drain current to temperature for several V_{GS}

A current reference with a small temperature coefficient for controlling an oscillator at frequencies of 10, 20, 30 and 40 MHz with temperature coefficients of 24, 32, 38 and 34ppm/ºC respectively has been reported in [6]. The Ref. [7] reports an improved version of [6] in which the current reference characteristics is improved by addition of a negative temperature coefficient hence reducing the overall oscillator temperature dependency to 22.3ppm/ºC. the operating temperature range is -25 to 75ºC in a 0.18µm CMOS technology.

In this research a single ended current starved Ring Oscillator controlled concurrently by both voltage and current references has been designed. In fact, one reference is used to impose a specific temperature dependency on the oscillator and the other for final compensation. The idea is based on an intrinsic property of MOS transistors.

Thermal characteristics of MOS transistors are discussed in next section, and the effect of these thermal behaviors on the performance of current starved ring oscillators is given in section 2. Design of a current starved Ring Oscillator and thermal compensation using above idea is discussed in section 3. Section 4. proposes the simulation results and finally section 5. deals with conclusion.

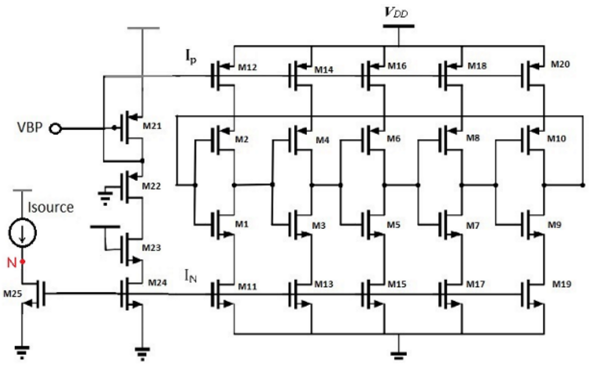

Fig.2. A current starved ring oscillator, structured for voltage/current control

2. THERMAL DEPENDENCY OF MOS TRANSISTORS

Thermal dependency of a MOS transistor can be obtained from its drain current equation, assuming that

$$I_D=1/2\ \mu\ C_{OX}\ (W/L)\ (V_{GS}-V_{TH})^2 \tag{1}$$

The transistor is working in saturation region:

Here, main temperature dependent parameters are threshold voltage Vth, electron and hole mobility µ. The temperature coefficient of threshold voltage for both NMOS and PMOS transistors are negative, (for PMOS transistors the absolute value of threshold voltage reduces). The mobility also reduces as temperature increases implying a negative temperature coefficient hence a direct reduction effect on trans-conductance constant (β) of the transistor [8], [9]. The threshold voltage and β are both reduced as the temperature rises, but reduction in threshold voltage raises drain current, as indicated in equation (1), but the reduction in β, on the other hand, causes a reduction in drain current. As depicted in Fig. 1, at low V_{GS} voltages, the effect of Vth is dominant and the drain current increases as temperature rises but at high values of V_{GS} voltages the effect of β becomes dominant and the drain current decreases as temperature increases.

3. CURRENT STARVED RING OSCILLATORS; IMPOSING A THERMAL CHARACTERISTICS

Compensation of thermal effects on current starved ring oscillators are generally performed by two control methods; by voltage (voltage controlled ring oscillators-VCROs) [2] and current (current controlled ring oscillators-CCROs) [7].

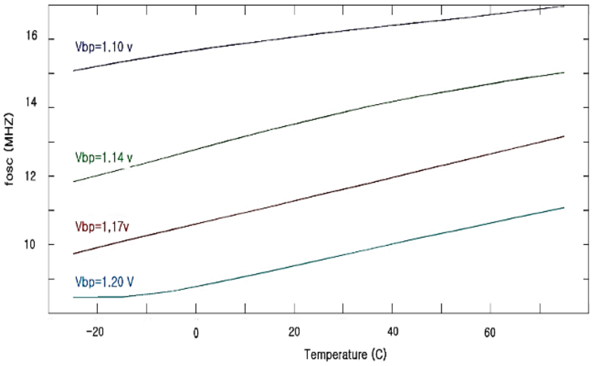

Fig.3. Imposing temperature characteritic to the oscillator by changing VBP

Both methods are relying on controlling the charging and discharging current of the inverters, former by voltage and in the latter directly by current. A ring oscillator with current starved inverters is shown in Fig .2. Transistors M1 to M10 constitute five stages of inverters. Transistors M11, M13, M15, M17 and M19 are NMOS biasing transistors determining the falling edge delay, T_{PHL}, and transistors M12, M14, M16, M18 and M20 are PMOS biasing transistors indicating the Rising edge delay, T_{PLH}. The sizing of biasing transistors are usually chosen such that $I_N = I_P = I_{SOURCE}$, hence equal rising and falling time is obtained. Accordingly, total delay time and oscillation frequency are controlled by these currents. The ring oscillator frequency is given by [7]:

$$f_{osc} = \frac{I_{source}}{N.C_{load}.VDD} \quad (2)$$

where I_{SOURCE} is the inverters bias current, N is the number of stages, Cload is the equivalent capacitance of each stage and VDD is the circuit supply voltage. The temperature dependency of oscillator frequency is mainly stemmed from the temperature dependency of I_{SOURCE} as the temperature dependency of C_{load} is minute. Compensation and frequency control is therefore obtained by this current.

The temperature dependency of drain current in a MOS transistor, as discussed in section II, can be positive or negative depending on its gate-source voltage. The gate-source voltage of the PMOS transistors in Fig. 2. is:

$$|V_{GSP}| = V_{DD} - VBP \quad (3)$$

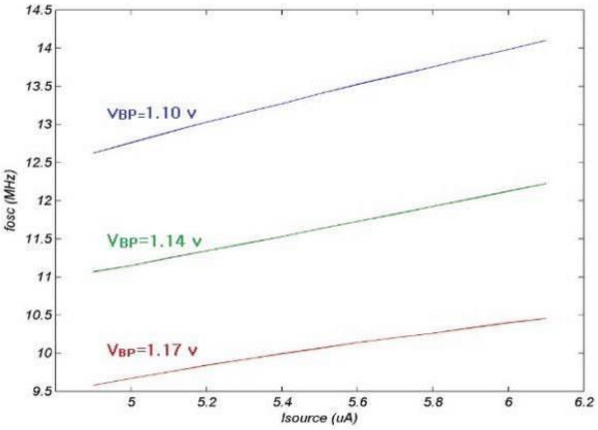

Fig.4. frequency versus reference current

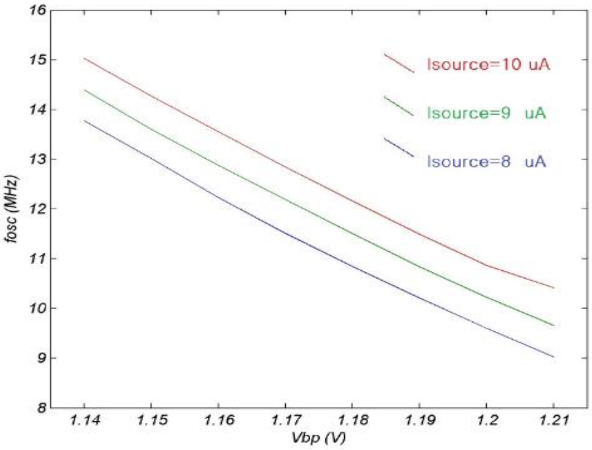

Fig.5. Frequency versus reference voltage

Changing the VBP can modify thermal dependency of the PMOS biasing transistors and consequently the thermal Characteristics of oscillator.

The idea is to tune the thermal characteristics of the oscillator to make it ready for applying temperature compensation.

In Fig. 3. as V_{BP} increases, it is predictable that the oscillation frequency is decreased, but also it causes a decrease in the slope of the temperature characteristic of oscillator. one should notice that the decrease in this can be utilize for implementing temperature compensation. So, this observation indicates that via a control voltage, one can control the rate of changes in thermal characteristics. To achieve optimum thermal compensation a trade-off between the reference circuit and thermal characteristics of the oscillator must be reached.

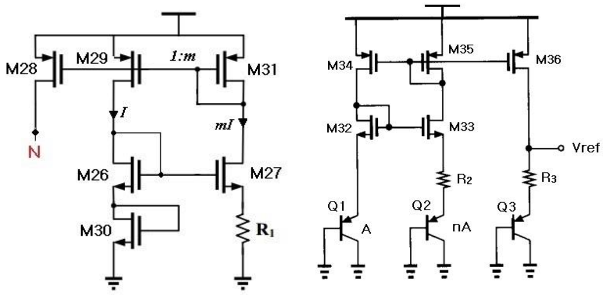

Fig.6. Standard current reference, Bandgap voltage reference

4. RING OSCILLATOR COMPENSATION USING BOTH VOLTAGE AND CURRENT CONTROL

In previous section it was shown that for a given voltage and current, frequency and temperature had an incremental relationship. The relationship between frequency and current and also voltage demonstrated in Fig. 4. and 5 at various amounts of VBP and I_{source} ,respectively. For a fixed frequency of oscillation, two types of reference sources are required. These are current and voltage references with positive thermal coefficients.

A CMOS current reference circuit [10] with a first order compensation and an ordinary band gap reference circuit [11] is used for current referees and voltage reference respectively. These reference circuits are illustrated in Fig. 6. respectively.

4.1. Current Reference with first order compensation

The circuit of Fig. 6. consists of two current sources connected in parallel. Transistors M28 and M30 maintain a constant ratio m between two parallel branches whilst, the

Widlar current mirror M26-M27-R_1 provides the reference current I. All the MOS transistors are working in saturation region and follow the square law relation as in (1). Using KVL in this circuit:

$$\sqrt{\frac{1}{\beta_{n0}}}\left(\frac{1}{\sqrt{\alpha_1}}+\frac{1}{\sqrt{\alpha_5}}-\sqrt{\frac{m}{\alpha_2}}\right)+V_{thN}-mR_1I=0 \qquad (4)$$

Where $\beta_n=1/2\mu_nC_{ox}$ and α_i is the aspect ratio of MOS transistors. The temperature dependent parameters in equation (5) are μ, V_{thn} and R_1. The voltage drop across R_1 is due to two components, the first one is due to gate-source voltage of transistors M1, M2 and M5 and have a positive temperature dependence, and the other is due to the MOS transistor threshold voltage which has a negative temperature gradient. R_1 and m can be utilized for changing the temperature characteristic of reference current and consequently the oscillation frequency. This indicates that we can control the gradient of the thermal characteristics of current reference by R_1.

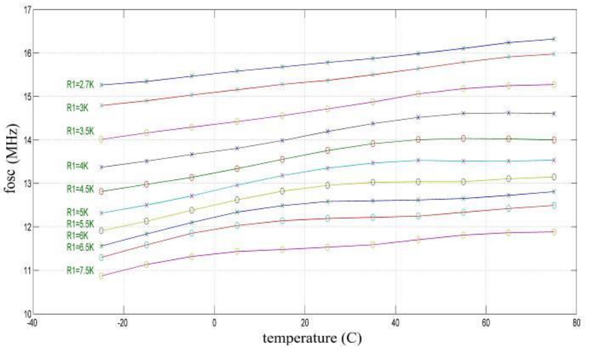

Fig. 7. The oscillator temperature characteristic after applying current reference, m=8, VBP=1.140 V

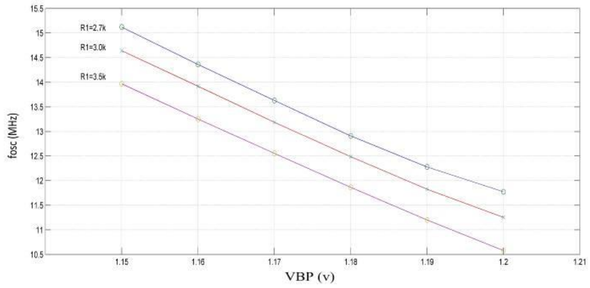

Fig.8. the dependency of frequency to the VBP, after applying current reference, m=8

4.2. Band gap voltage reference

In the band gap voltage reference circuit, the MOSFET transistors M32-M36, and BJT transistors Q1, Q2 and resistor R2 constitute an ordinary PTAT circuit and produce a PTAT current. This current is copied by M36 to create an un-buffered V_{ref} [11]. A simple op-amp based voltage buffer with a unit gain is used to turn the V_{ref} into the V_{BP}, as well.

Here our goal is not to generate a constant voltage and current which are not change over temperature range, but we need a voltage and current which are change in a desired scheme over temperature.

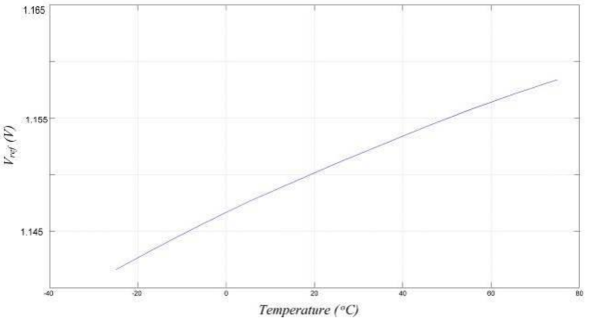

Fig. 9. The simulation plot of the output of voltage reference

The voltage and current references is now coupled simultaneously to the corresponding inputs of circuit in Fig. 2. It was shown in the previous section that thermal characteristics of the oscillator can be modified by applying controlling voltages and currents to the inputs,

therefore to obtain the relevant data about the temperature dependency of the circuit the reference current is applied to the current input and output frequency for different values of R1 is obtained. Fig. 7 shows temperature dependency of the circuit for a range of R1 values. Dependency of the oscillator frequency to the V_{BP} voltages has also been obtained for different values of R1, as illustrated in Fig. 8.

Typical values for temperature coefficients of resistors are also be considered. Resistor R1 is utilized here to control the slope of thermal characteristics of the oscillator.

5. SIMULATION RESULTS

By choosing a proper position for temperature characteristic of oscillator through the current reference and then applying the control voltage we were able to compensate the temperature effect on oscillation frequency. The behavior of the band gap circuit against temperature is shown in Fig. 9. The output voltage set point is about 1.140 and its growth for the temperature span is 16.8mV. The oscillator output frequency with and without thermal compensations has been obtained and shown in Fig. 10. Resistor R1 is the means by which the oscillators' thermal characteristics slope can be adjusted. The circuit output for R1 values around 3.5kΩ has also been obtained. Finally, by simultaneous setting the temperature characteristic of the oscillator (by R1) and the output of the voltage reference (by changing R3/R2), we can optimize the oscillator frequency in an appropriate temperature range. The result has been shown in Fig. 11. The circuit parameters are summarized in table I.

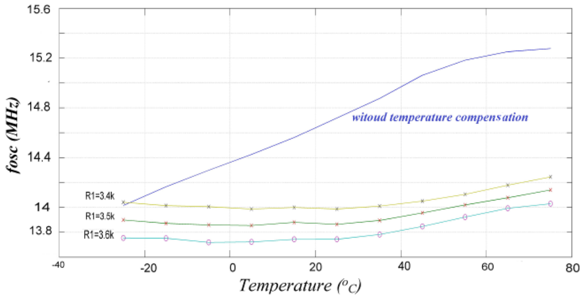

Fig. 10. The oscillation frequency with temperature compensation vs. without temperature compensation

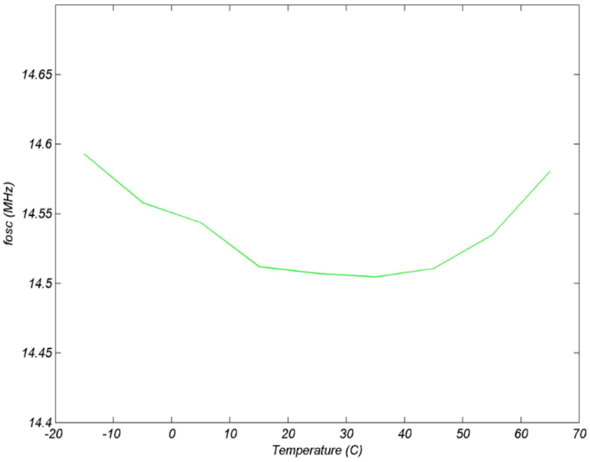

Fig. 11. The simulation plot of the output frequency after compensation

6. CONCLUSION

In this paper a CMOS ring oscillator with thermal compensation has been presented. The circuit is designed and simulated in a 0.18µm CMOS technology. Simultaneous voltage and current control for imposing a specific thermal behavior to an oscillator has been presented too.

Voltage and current reference circuits have been utilized to achieve this goal. Thermal characteristics of one reference is adjusted to a desired behavior, theother reference is used to tune the thermal characteristics of the oscillator circuit in such a way that the first reference can perform its compensation. After optimization and trade-off between temperature specification of frequency and output voltage of bandgap reference, the worst case frequency variation at 14.5MHz, was 0.447% across the temperature range of -15 ºC to 75 ºC (31.1 ppm/ºC). The overall circuit consumes 587µW. a comparison with other reference is presented in table 2.

Finally it should be noted that the main advantage of technique used here is adding flexibility to a current starved ring oscillator so that the temperature characteristic of oscillator can be set in desire points. In fact we present a way with several parameters (R1,m,) that can change the thermal characteristics of a ring oscillator.

Table 1. Design parameters of oscillator circuit

<table>
<tr><td rowspan="3">Fig. 2.</td><td colspan="6">(W/L) (µm/µm)</td></tr>
<tr><td>$M_{1\text{-}10}$</td><td colspan="3">$M_{11,13,15,,17,19,23,24,25}$</td><td colspan="2">$M_{12,14,16,18,20,21,22}$</td></tr>
<tr><td>2/1</td><td colspan="3">1/0.5</td><td colspan="2">4.5/0.5</td></tr>
<tr><td rowspan="3">Fig. 6.</td><td colspan="4">(W/L) (µm/µm)</td><td colspan="2">R1 (kΩ)</td></tr>
<tr><td>$M_{26,27,28,30}$</td><td colspan="3">M_{29}</td><td colspan="2" rowspan="2">3.1</td></tr>
<tr><td>1/0.5</td><td colspan="3">8/0.5</td></tr>
<tr><td rowspan="2">Fig. 7.</td><td colspan="2">(W/L) (µm/µm)</td><td colspan="2">n</td><td>R2 (kΩ)</td><td>R3 (kΩ)</td></tr>
<tr><td>$M_{32,33,34,35}$</td><td>M_{36}</td><td>Q1,</td><td>Q2</td><td>3.323</td><td>2</td></tr>
</table>

			3			
	16.3/1	81.5/1	1	8		

Table 2. Performance summary and comparison

Ref.	**This work**	**[2]**	**[3]**	**[5]**	**[6]**
Target frequency (MHz)	14.5	100	891	4	10
temperature range (^oC)	-15 ~ 75	-40 ~ 125	–40 ~ 85	-40 ~ 125	-25 ~ 75
Supply voltage(v)	1.8	1.8	1.2	3	1.8
process (nm)	180	180	65	350	180
Freq. variation %	0.447	4.49	0.708	6.64	0.24

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