THERMAL ANALYSIS OF CMOS VOLTAGE-CONTROLLED OSCILLATORS

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Abstract. *The paper presents impact of chip temperature on frequency generated by Voltage-Controlled Oscillators. Three different CMOS structures have been tested. Resonant cross-coupled oscillator was designed and fabricated in AMS 0.35 μm (3.3 V) technology and has at ambient temperature the frequency range from 2.2 to 2.5 MHz. Two different ring oscillators were designed in UMC 0.18 μm (1.8 V) technology and have at ambient temperature the frequency range respectively from 0.6 to 2.8 GHz and from 0.4 to 1.9 GHz. All circuits were designed using full-custom technique. Influence of temperature to tuning range and power consumption has been investigated.*

Keywords: VCO, LC, RO, CMOS, temperature

ANALIZY TERMICZNE GENERATORÓW PRZESTRAJANYCH NAPIĘCIEM

Streszczenie. *Artykuł przedstawia wpływ temperatury na działanie generatorów przestrajanych napięciem VCO. Przebadane zostały trzy różne struktury układów CMOS. Generator rezonansowy został zaprojektowany i sfabrykowany w technologii AMS 0,35 μm (3,3 V) i w temperaturze pokojowej generuje częstotliwości z zakresu od 2,2 do 2,5 MHz. Dwa odmienne generatory pierścieniowe zostały zaprojektowane w technologii UMC 0,18 μm (1,8 V) i generują częstotliwości z zakresu odpowiednio od 0,6 do 2,8 GHz oraz od 0,4 do 1,9 GHz. Wszystkie układy zostały zaprojektowane techniką full-custom. Przetestowane zostało oddziaływanie termiczne na zakres przestrajania oraz pobór mocy generatorów.*

Słowa kluczowe: VCO, układy rezonansowe, generatory pierścieniowe, CMOS, temperatura

Introduction

Work of every circuit depends on its temperature [5]. This impact is very important in case of integrated circuits where all elements are in the same silicon die and few elements dissipating large amount of power can influence big number of other elements. Because of that reason designers must take into account thermal aspects of circuit work.

Temperature dependence is especially significant factor in designing Temperature-Controlled Oscillators (TCOs). In these structures Voltage-Controlled Oscillators (VCOs) are tuned by the signal from temperature sensors. If frequency produced by generator is tuned by the chip temperature thermal behaviour of generator itself must be known. Favorable situation is when generated frequency changes with temperature monotonically, then this change can be predicted and included to design process. If so three cases are possible:

- frequency rising with temperature growth – generally higher clock frequency means higher dynamic power losses in the circuit and as a consequence higher die temperature. Such positive feedback is undesirable effect and must be compensated,
- frequency constant with temperature growth – very rare effect when generator work does not depend on thermal conditions, but can be obtained in some situations what will be presented in next sections,
- frequency falling with temperature growth – effect desirable in most of Dynamic Power Management (DPM) systems which can be combined with other methods, for example Dynamic Frequency Scaling (DFS) or Dynamic Voltage Scaling (DVS).

Another important issue is impact of temperature to power consumption of the generator.

In next sections three different CMOS generators will be described. First is LC cross-coupled structure and next are two ring oscillators. Resonant circuit was fabricated and tested in thermal chamber while in case of ring oscillators simulation results are presented. Some temperature dependencies will be defined. Obtained results can be helpful for engineers in designing TCOs or temperature-independent generators.

1. Resonant oscillator

Resonant cross-coupled generator was designed and fabricated in AMS 0.35 μm technology with 3.3 V supply voltage. LC circuits are widely used because of low phase noise and high frequency but they cover big area of the chip which can be a problem for some applications. Presented structure consists of 4 PMOS and 3 NMOS transistors. Resonant circuit is built of a spiral metal geometry which works as an inductor L, a capacitor between two polysilicon layers C_{CONST} and two varactors C_{VAR}.

Schematic diagram is presented in Fig. 1 [3, 6]. At each moment only one arm of the circuit is working and charging the LC circuit. Frequency generated by the structure is equal (1) and C represents combination of constant capacitance C_{CONST} and variable one C_{VAR}. In order to maximize tuning range part of the capacity coming from varactors should be more important [1].

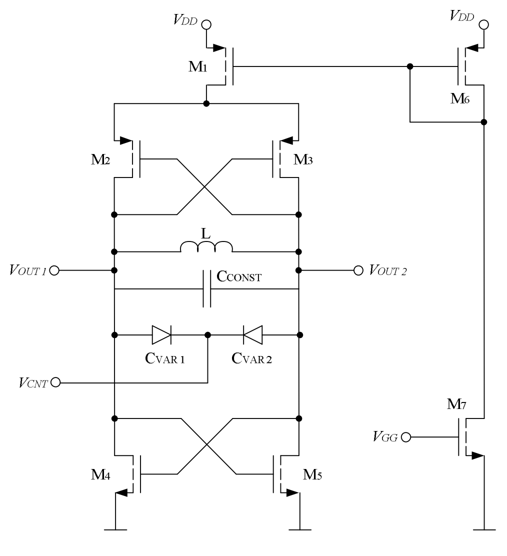

Fig. 1. Schematic diagram of the resonant VCO

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Measurements in thermal chamber showed that frequency generated by resonant VCO is not constant with changes of the chip temperature. Rising temperature caused higher frequency of oscillations. This can be only result of changes of LC elements parameters. Change of the transistors parameters was visible as smaller amplitude of the oscillations at hotter chip. Tuning characteristics of resonant VCO at different temperatures

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are presented in Fig. 2. At higher temperatures oscillations started fading. The shape of the characteristic is caused by the change of varactors capacity and is nonmonotone. Useful part of it which can be took under consideration while designing the circuit is o rising range from about 1.1 to 2.3 V. Temperature dependence of this part will be investigated in next parts of the paper.

Tuning parameters of presented VCO are gathered in Table 1. For low and medium temperature relative tuning range is approximately constant an equals 11 to 13% while for higher temperatures it starts to drop below 10%. At the same time range of tuning voltage is getting narrower with rising temperature and as a consequence the characteristics are more steep. This effect must be taken into account when designing VCO working at non-constant temperature of the chip.

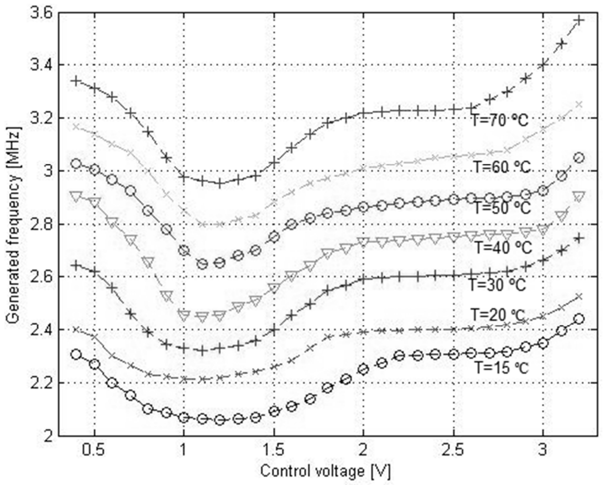

Fig. 2. Tuning characteristics of the resonant VCO for different temperatures

Table 1. Parameters of the resonant VCO for different temperatures

Temperature [°C]	Tuning range [MHz]	Relative tuning range [%]
15	0.244	11.84
20	0.278	13.11
30	0.282	12.16
40	0.291	11.88
50	0.228	8.60
60	0.238	8.50
70	0.278	9.42

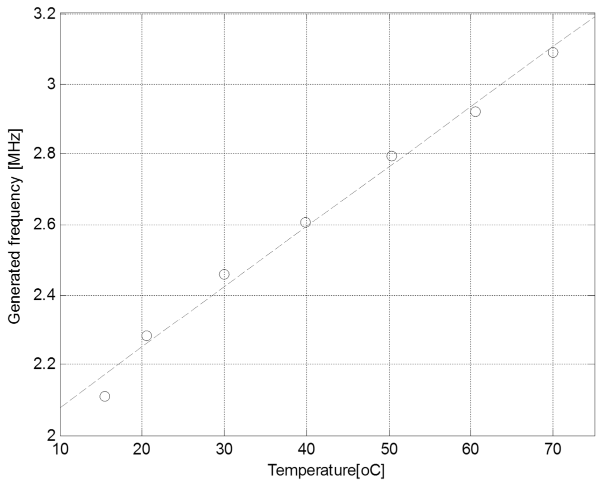

Fig. 3. Temperature dependence of frequency generated by the resonant generator for constant tuning voltage (1.6 V)

For constant tuning voltage characteristic of temperature dependence of generated frequency can be plotted, Fig. 3. This dependence is a linear function and can be described by (2) based on knowledge of frequency f_{T_A} at ambient temperature T_A = 20°C, where α and γ are proportionality coefficients.

$$f = \gamma\left(f_{T_A} + \alpha T\right) \tag{2}$$

In presented case $\gamma \approx 0.677$ and $\alpha \approx 0.116$ MHz/°C. This data can be used to calculate frequency generated by presented oscillator at every chip temperature without necessity of additional measurements.

2. Ring oscillators

Ring oscillators were designed and in UMC 0.18 µm technology with 1.8 V supply voltage. The structure consists of odd number (2n-1) of inverters connected in series, as presented in Fig. 4 [4]. Such circuit generates square wave of frequency described by (3). This frequency can be tuned by change of number of inverters N in the ring or by change of single inverter propagation time t_P.

$$f_0 = \frac{1}{2Nt_P} \tag{3}$$

Designed circuit consisted of five CMOS inverters which propagation time was controlled by change of their supply voltage. Lowering the supply value changes the time of recharging the parasitic capacitances of the structure and causes lowering of the oscillation frequency. For too low supply the oscillations will fade. Obviously on the output of the ring there has to be another inverter with constant supply which acts as a buffer for stable magnitude of output wave. Tuning characteristic of the ring oscillator for different temperatures (from 10 to 90ºC with 10ºC step) is presented in Fig. 5. Direction of temperature change is also marked.

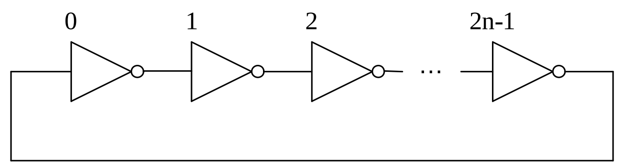

Fig. 4. Schematic diagram of the ring oscillator

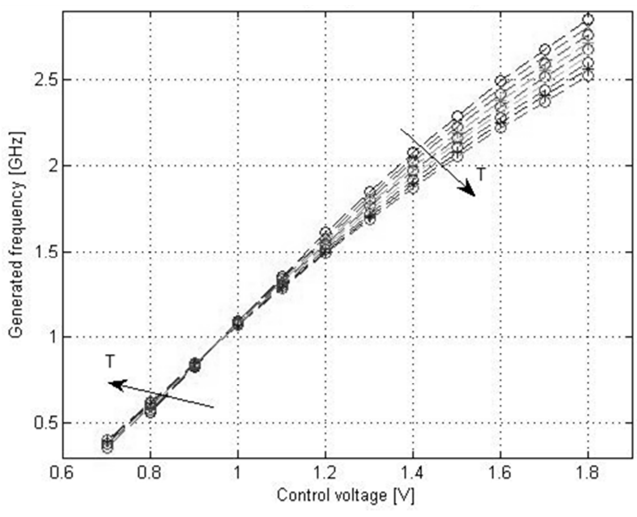

Fig. 5. Tuning characteristics of the ring oscillator for different temperatures

Thermal behaviour of the ring oscillator is quite complex issue. With change of the temperature parasitics change but also the carriers mobility changes (which affects currents). As an effect the direction of the characteristic change is not monotone. What is more, for higher temperatures the tuning range is narrower. Tuning ranges for different temperatures are gathered in Table 2. Despite the fact that they are getting narrower with temperature growth, they are still much larger then in case of resonant oscillator which is a great advantage of such ring oscillator. For higher control voltages the generated frequency is getting smaller with temperature growth. Such situation is desired for Dynamic Power Management systems to ensure thermal safety of the circuit. On the other hand at low control voltages the frequency is slightly rising. Special attention has to be paid to this region while designing the circuit. Between them there is a single point at about 0.93 V where generated frequency is independent on temperature. This information is very useful when integrated circuit designer wants to implement stable oscillator in the circuit with changing thermal conditions. In such situation presented ring oscillator with proper control voltage can be used. Dependence between generated frequency and temperature for three different control voltages is presented in Fig. 6. Every presented curve in figure below can be described by (2) because they are linear but for every temperature the coefficients α and γ would differ.

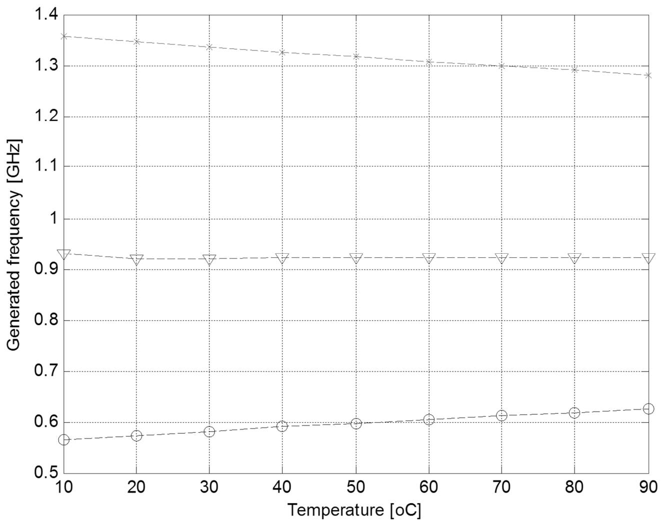

Fig. 6. Temperature dependence of frequency generated by the ring oscillator for constant tuning voltage (1.1 V - top; 0.93 V - middle; 0.8 V - bottom)

Table 2. Parameters of the ring oscillator for different temperatures

Temperature [°C]	Tuning range [GHz]	Relative tuning range [%]
10	2.286	80.21
20	2.231	79.56
30	2.178	78.94
40	2.127	78.28
50	2.078	77.68
60	2.030	77.04
70	1.984	76.43
80	1.940	75.84

Another important feature is relation between power consumption of the generator and temperature. It is crucial because too high power dissipated in the circuit can cause self-heating and further changes in circuit behavior. Fig. 7 presents gathered maximum power dissipated in the circuit in dependence of control voltage for different temperatures. Presented values are maximum ones, which can be observed only in short moments of changing the inverters state. Shape of the figure is tightly connected to tuning characteristic. Faster work of the circuit means higher power consumption.

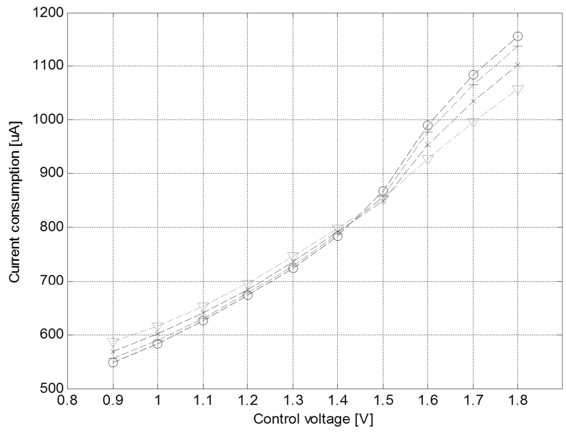

Fig. 7. Dependence of total power consumption with control voltage change of the ring oscillator for different temperatures (10ºC - top; 25ºC; 50ºC; 90ºC - bottom)

Because of power consumption minimization usage of circuit other than inverter in ring oscillator structure is possible [2]. For this reason five stage ring oscillator based on CMOS XNOR gates was implemented in UMC 0.18 μm technology. Schematic of such gate is presented in Fig. 8. When one of input of the XNOR gate is connected to the ground the circuit behaves like an inverter but without having direct path between supply and ground which results with power consumption decrease.

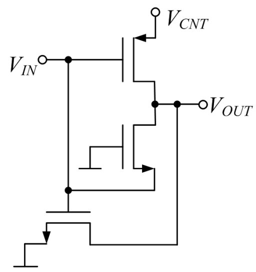

Fig. 8. Schematic diagram of the CMOS XNOR gate

The circuit Works very similar to previous one. Temperature change of tuning characteristic, presented in Fig. 9, is also not monotone – generated frequency is falling with temperature growth at higher control voltages and increasing with lower control voltages. The thermally stable point of the characteristic is about 0.9 V and 585 MHz. This dependence is clearly seen in Fig. 10. Tuning range is slightly smaller than in inverter-based structure and getting narrower for higher temperatures but still much larger than in resonant structure. Values of tuning ranges for different temperatures for XNOR ring oscillator are gathered in Table 3.

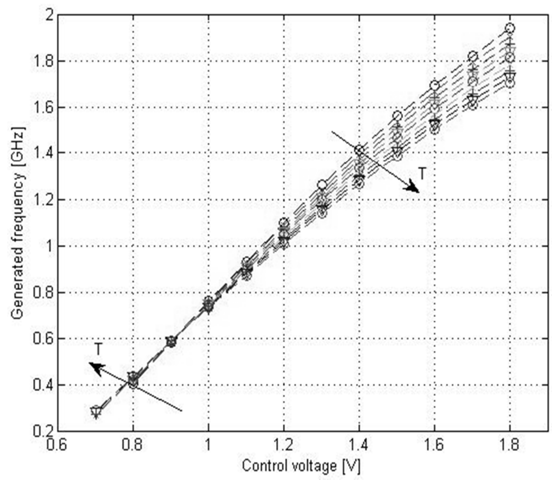

Fig. 9. Tuning characteristics of the XNOR ring oscillator for different emperatures

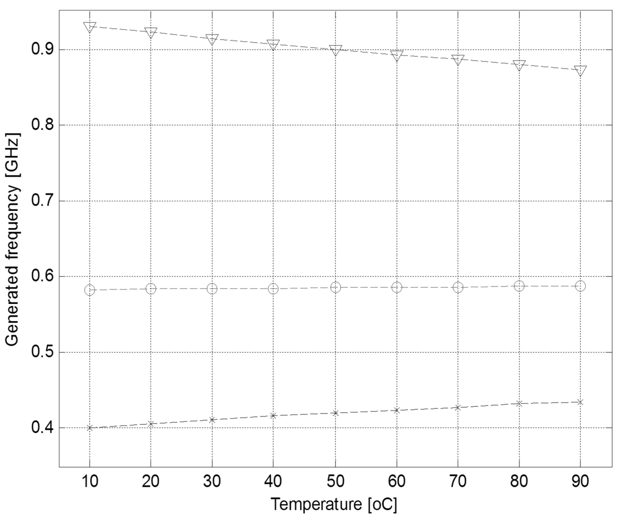

Fig. 10. Temperature dependence of frequency generated by the XNOR ring oscillator for constant tuning voltage (1.1 V - top; 0.9 V - middle; 0.8 V - bottom)

Table 3. Parameters of the XNOR ring oscillator for different temperatures

Temperature [°C]	Tuning range [GHz]	Relative tuning range [%]
10	1.536	79.30
20	1.498	78.68
30	1.462	78.06
40	1.426	77.42
50	1.393	76.83
60	1.360	76.23
70	1.329	75.64
80	1.298	75.03
90	1.269	74.47

Shape of the XNOR ring oscillator current consumption characteristic, Fig. 11, is similar to inverter-based case. The difference is that while using XNOR gates the circuit is less power-hungry which means smaller heat dissipation and less problems with self-heating of the structure. For this reason usage of presented structure is favorable choice.

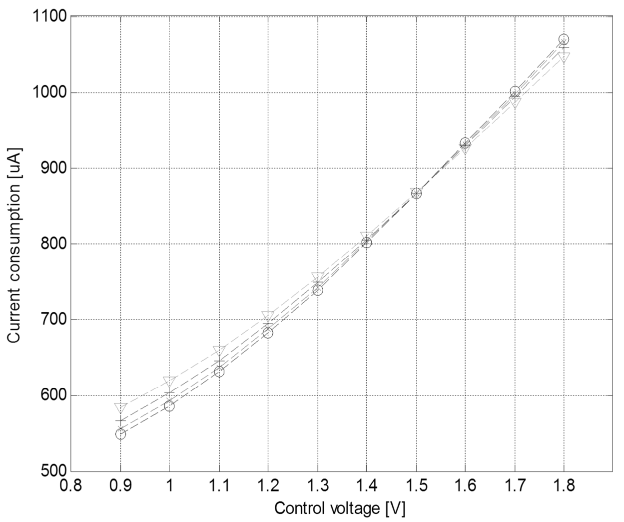

Fig. 11. Dependence of total power consumption with control voltage change of the XNOR ring oscillator for different temperatures (10ºC - top; 25ºC; 50ºC; 90ºC -bottom)

3. Summary

The paper presented thermal analysis of three different CMOS voltage-controlled oscillators. Resonant cross-coupled structure was designed and fabricated in AMS 0.35 μm technology. Frequency generated by this circuit is approximately linearly decreasing with temperature growth. The tuning range of LC oscillator is slightly narrower for higher temperatures. Two ring oscillator structures (inverter- and XNOR-based) were designed in UMC 0.18 μm technology. Thermal response of this structure is not monotone. For higher control voltages the generated frequency is decreasing while for lower control voltages is increasing with temperature growth. There is a single point on the tuning characteristic which is thermally independent. Tuning range of ring oscillators is getting narrower for higher temperatures but is a very large in comparison to resonant structure. Because of power consumption aspect the XNOR-based structure seems reasonable choice in comparison to inverter-based one.

Presented results will be used in authors work including design of dynamic power management systems using voltage-controlled oscillators. Obviously, the precise values of parameters would differ for each new design but the principles and direction of characteristics change should stay the same. As a result the presented measurements can be good reference for future works.

Acknolegements

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