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Improved Version of Gravitational Search Algorithm and its Application in Power Improvement of CMOS Ring Voltage Controlled Oscillator

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ABSTRACT

In this paper, a three-stage CMOS inverter-based ring Voltage Controlled Oscillator (VCO) is designed. Very low power consumption is an important feature of the designed VCO. The variables used in design of the presented oscillator are quantified using the improved Gravitational Search Algorithm (GSA) in order to minimize the power consumption of the oscillator. In this algorithm, the Boltzmann scaling function is used to control the exploration and productivity capabilities of GSA. Other advantages of the designed VCO are the high integration capability, simplicity of implementation and high frequency. The power dissipation of the VCO is 820 µW while its frequency range is between 1.25 and 2.5 GHz.

Keywords: Gravitational Search Algorithm, Boltzmann scaling, CMOS inverter, Ring Voltage Controller Oscillator

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1 Introduction

Ring VCOs are widely used as the building block in many communications and wireless systems because of their wide tuning range, small chip area occupancy and ability to generate multiphase signals [1]. For example, Phase Locked Loops (PLLs) need to ring VCO as one of the critical blocks for clock generation in transceivers [2]. Hence, in the recent years, more researches have been done to design different configurations of ring VCOs with high oscillation frequency and wide tuning range. Among different types of oscillators, ring VCOs and inductance-capacitance (LC) VCOs are more popular. Although, LC VCOs have good phase noise performance, they have narrow frequency tuning range [3].

A ring VCO can be configured by odd or even number of delay cells or gain stages. In the single-ended types, it must be used odd number of stages in a closed loop to generate multiphase signals. Considering N as the number of delay cells or gain stages, a number of N voltages will be generated with the phase differences of 360/N. In fact, each stage contributes 180/N frequency dependent phase shift and the dc phase shift of 180o is provided. Recently, a new method has been introduced to design the multiphase VCO by coupling two single-ended ring VCOs [4]. In this method, two single-ended ring VCOs have been coupled together as the crosswise scheme. Hence, 2N output voltages are generated with the phase differences of 180/N. The differential ring VCOs can be made with odd or even stages. Although, the single-ended ring VCOs show the higher phase noise compared to the differential types, they have some advantages such as low power dissipation, small chip area and easy implementation.

Employing different improvement approaches of the analog and RF integrated circuits in order to achieve optimum results are very effective. In various research studies, different single-objective and multi-objective optimization functions have been defined to determine appropriate values for the parameters in the given model circuit. Then, heuristic and meta-heuristic algorithms have been used to solve these objective functions. In [1], a five-stage ring VCO has been presented that has been optimized using the Genetic Algorithm (GA). In this algorithm, the objective functions are considered the phase noise and power consumption of the circuit. Another example of algorithm employed for optimization has been presented in [5]. In this work, the hybrid of Particle Swarm Optimization (PSO) and Many Optimizing Liaisons (MOL) algorithm is proposed. This algorithm has been used to calculate the size of MOS transistors to guarantee the appropriate DC operating conditions of an operational transconductance amplifier. Improvement algorithms can be used in optimizing of LC-VCOs. In [6], design of complementary LC-VCO has been optimized using multi-objective GSA. The objective of the designed VCO is to minimize the phase noise and the power dissipation simultaneously.

The remaining of this paper is organized as: the next section presents the description of designed VCO. In Section 3, the improvement algorithm is presented in details. The simulation results and the summary of the important points of this work are presented in Section 4 and 5, respectively.

2 Description of the Designed Ring VCO

Inverter based delay cell is popularly used for configuring of ring VCOs. Figure 1 shows the general configuration of CMOS inverter-based ring oscillator. As mentioned above, the number of inverters must be equal odd. In this circuit, similar to the other type oscillators such as LC oscillators, the Barkhuizen's criteria must be satisfied to create oscillation at the outputs. This means that the total phase shift around the closed loop must be equal to 360^oor a multiple of it and also, the loop gain must be unity.

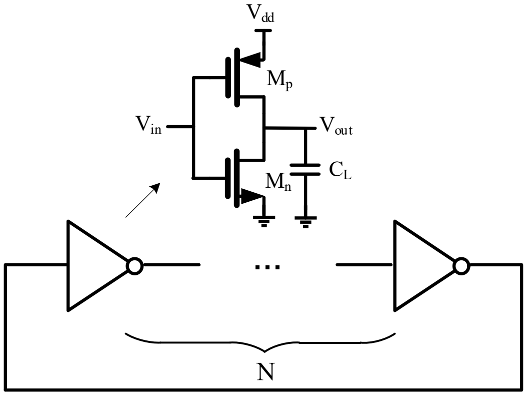

Figure 1. General structure of inverter-based ring oscillator

Figure 2 shows a three-stage CMOS inverter-based ring VCO. In each stage, the transistors M_n and M_p form a CMOS inverter and transistor M_c controls the current which discharges the output capacitance C_L. In fact, the gate-source voltage of M_c is equal to V_{ctrl}, varying the controlling voltage changes the drain-source current of this transistor. In other words, the oscillation frequency of circuit is controlled with V_{ctrl}.

The output frequency in the inverter based ring VCOs can be driven as [7, 8]:

$$f_{osc} = \frac{I_D}{\eta N V_{DD} C_{tot}}, \quad (1)$$

where N is the number of stages and η represents the characteristic constant. In the ring VCOs, η is chosen between 0.75 and 1. Also, I_D is the average current flows through the inverter stages. C_{tot} is the total capacitance appears on each output node. C_{tot} can be expressed as [7]:

$$C_{tot} = \frac{5}{2} C_{ox}\left(L_p W_p + L_n W_n\right), \quad (2)$$

where W_n and L_n are the width and length of NMOS transistors, respectively and also, W_p and L_p are the width and length of PMOS transistors, respectively. C_{ox} represents the gate-oxide capacitance of transistors per unit area.

Average power consumption of each stage is given by

$$P = V_{DD} I_D. \quad (3)$$

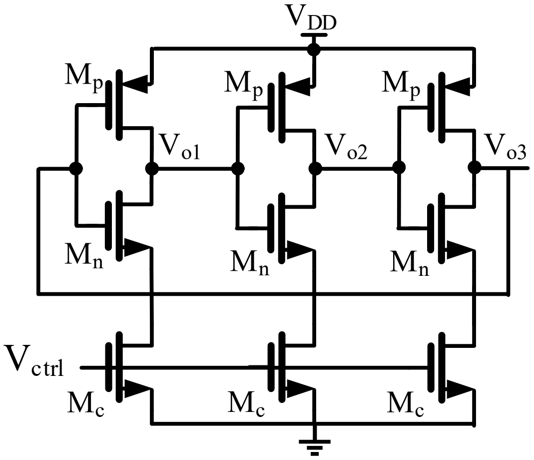

Figure 2. Inverter based ring VCO

The purpose of this article is to fine the sizes of transistors by minimizing the power consumption of the ring VCO. The objective function of the presented VCO is expressed by

$$Objective\ function = \underset{W_p,W_n}{\operatorname{argmin}} P. \tag{4}$$

In this objective function, W_n and W_p are decision variables for minimizing the power consumption of this VCO. It is proven that computing optimal values for this objective function is an NP-hard problem [9]. For solving NP-hard problems, the use of evolutionary algorithms, which can compute solutions close to optimal within a reasonable execution time, is a common and valid approach in scientific research and real-world industrial challenges [10].

3 Improved Gravitational Search Algorithm

The GSA (Gravitational Search Algorithm) is a popular metaheuristic algorithm used for solving optimization problems. It has demonstrated favorable efficiency compared to other existing algorithms [11]. In this Algorithm, the search agents are represented as masses, and their positions correspond to solutions for the problem at hand. The position of i^th agent is demonstrated by $X_i = (x_i^1, x_i^2, \dots x_i^n)$ where n states the search space dimensions. The weight of each agent is determined by the quality of its corresponding solution. It means that heavier masses correspond to better solutions, while lighter masses represent weaker solutions. According to Newton's law of gravity, all masses exert a gravitational force on each other that is proportional to their weight and the distance between them. In this algorithm, the gravitational force that acts on i^th object from object j in d^th dimension is calculated using the following equation.

$$F_{ij}^d = G(t) \frac{M_j \times M_i}{R_{ij}(t)+\varepsilon} (x_j^d - x_i^d), \tag{5}$$

where M_i and M_j show the mass values of i^{th} and j^{th} agents respectively. ε is a very small number defined to prevent division by zero. $R_{ij}(t)$ represents the Euclidean distance between agents i and j. $x_j^d - x_i^d$ calculates the distance between agents i and j in d^{th} dimension. $G(t)$ represents the gravitational constant, which is defined in this algorithm as a decreasing function of time. According to Newton's second law of motion, the force applied to an object will result in an acceleration in the direction of the applied force. This acceleration leads to changes in velocity and, consequently, changes in position. These relationships are expressed in the following equations.

$$a_i^d = \frac{F_i^d}{M_i}, \tag{6}$$

$$V_i^d(t+1) = rand.V_i^d(t) + a_i^d(t), \tag{7}$$

$$X_i^d(t+1) = X_i^d(t) + V_i^d(t+1)\,. \tag{8}$$

These equations pertain to the computation of the acceleration, velocity, and new position of agent i in dimension d. The weight of each agent in the GSA algorithm is calculated proportionally to its normalized fitness. The following equation illustrates how the weight of agent i at time t is determined:

$$M_i(t) = \frac{fit_i(t) - worst(t)}{\sum_{j=1}^{N}\left(fit_j(t) - worst(t)\right)}\ , \tag{9}$$

where worst(t) represents the fitness of the worst solution in the search space at time t.
The GSA algorithm is characterized by its simple idea and implementation, as well as its high execution speed. Despite its simplicity, it exhibits excellent performance and efficiency [12]. Despite these positive features, the GSA algorithm lacks the ability to control exploration and exploitation in multimodal problems that have multiple local optima. It may get trapped in local optima instead of finding the global optimum [13]. At the beginning of the computational process of GSA, the standard deviation of fitness values for agents are high. So, there are some heavy masses that attract other lighter ones. Thus, algorithm converge to better solution and cannot explore more regions in feasible area. On the other hand, at the end of the computational process of the algorithm, it should converge to the best solution and search around it to improve the best answer for the problem. But the mass values are close together. The selection pressure of the algorithm is low and the masses explore the search area to find new solutions. Therefore, in GSA, at the beginning of the algorithm, the selection pressure is high, which enhances the exploitation capability of the algorithm. Towards the end of the algorithm's execution, by reducing the selection pressure, the exploration capability of the algorithm increases. Indeed, these conditions contradict the definition of an ideal state for evolutionary algorithms [14]. In the GSA, the mass value of agents, which is determined based on the fitness of solutions, has a significant impact on the selection pressure and, consequently, the exploration and exploitation capabilities of the algorithm. By adjusting the mass values, the algorithm can be tuned to strike a balance between exploration and exploitation [15].

In this paper, Boltzmann scaling function is used for mass calculation. Improved version of GSA (ImGSA) can control the exploration and exploitation abilities using this scaling method. The value of masses in ImGSA are computed as follows:

$$M_i(t) = \frac{\exp\left(\frac{N\,fit_i(t)}{T(t)}\right)}{<\exp\left(\frac{N\,fi\ _i(t)}{T(t)}\right)>_t} \tag{10}$$

where $M_i\ (t)$ is the mass value for i^{th} agent in time t, $Nfit_i(t)$ is the normalized fitness value of the i^{th} agent in time t, $<.>$ shows the mean operation and computes the mean value for all agents in time t. Moreover, T is a function shows temperature in Simulated Annealing (SA) algorithm and be computed as follows [16]:

$$T(t) = \frac{0.2}{\ln(t)}\,. \tag{11}$$

In this equation, t shows the iteration number of the algorithm. $T(t)$ is a descending function. At the beginning of the algorithm, temperature is high and $T(t)$ returns high values. Hence, the values of masses are calculated close together using Eq. (10). So, ImGSA can explore the feasible area and find good solutions (exploration). At the end of algorithm, temperature is low and the standard deviation of the masses is high. The selection pressure is high and algorithm converge to the best solution. In this stage, ImGSA search around the best solution in order to improve it (exploitation). Thus, exploration and exploitation abilities are balanced in ImGSA using this method. ImGSA has better performance in complex optimization problems and can escape from getting trapped in local optima. In this paper, ImGSA is used to find a good solution for Eq. (4).

4 Simulation results

The designed ring VCO has been simulated with 0.18 µm RF-CMOS technology in cadence software. Voltage waveforms of the output nodes are drawn in Figure 3 at the oscillation frequency of 1.5 GHz. The power dissipation of the designed VCO is 0.85 mW. The designed VCO can oscillate from 1.25 GHz to 2.5 GHz by varying V_{ctrl} from 0.65 V to 1.2 V. Therefore, according to the simulation results, frequency tuning range of the presented VCO is 1.25 GHz.

The circuit phase noise has been plotted from the offset frequency of 1 kHz to 10 MHz in Figure 4. At 1 MHz offset frequency, the phase noise of the designed VCO is -91 dBc/Hz. The sizes of all components employed in the simulated VCO are presented in table1. To compare the performance of the designed VCO with some other ring VCOs, Table 2 is provided. In this comparison, the designed technology and the main characteristics of the VCO is summarized. In this table, the Figure of Merits (FoM) are reported based on the following equation.

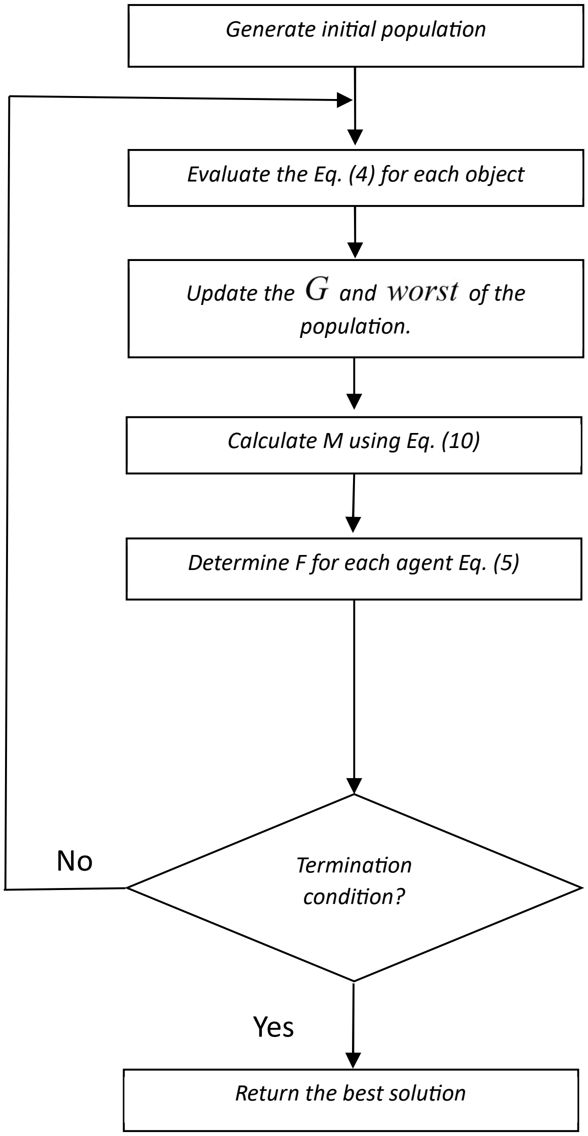

Figure 3. Flow chart of the ImGSA

$$FoM = L(\Delta\omega) + 10LogP_{DC} - 20Log\left(\frac{\omega_o}{\Delta\omega}\right) \tag{12}$$

where L(Δω) is the single side band phase noise at the offset frequency, Δω is the offset frequency, ω_o is the oscillation frequency, P_{DC} is the power dissipation of the oscillator in mW.

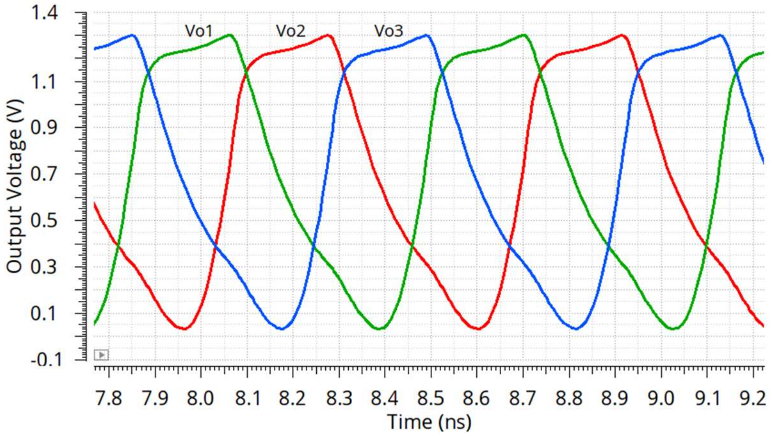

Figure 3. Output waveforms of the designed VCO

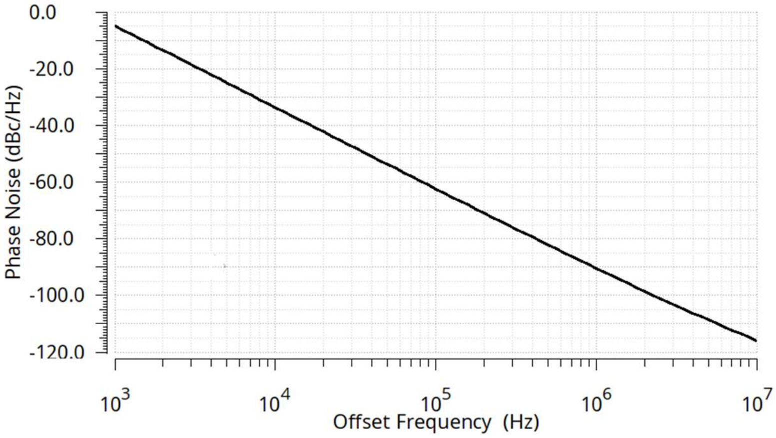

Figure 4. Simulated phase noise of the designed VCO

Table 1. Device sizes of the simulated VCO

Active Devices	M_n	M_p	M_c
W (µm)	10	40	10
L (µm)	0.18	0.18	0.18

Table 2. Performance summary of the presented VCO and some other published VCOs

VCO	**CMOS Tech.**	**V_{DD} (V)**	**$P_{dis.}$ (mW)**	**F_{osc} (GHz)**	**TR (GHz)**	**Phase Noise (dBc/Hz)**	**11**
[17]	0.18 µm	1.8	50.9	5	2.9 ~ 9	-82@1 MHz	-145.9
[18]	0.18 µm	1.8	8.1	5.4	4.9 ~ 5.9	-86.7@1 MHz	-149.7
[19]	0.18 µm	1.8	6.99	5	2.36 ~ 2.85	-112@10 MHz	-151.3
[20]	0.18 µm	1.8	6.521	2.02	6.687~6.39	-76.2@1 MHz	-149.43
This work	0.18 µm	1.25	0.85	1.5	1.25 ~ 2.5	-91@1 MHz	-155.2

5 Conclusion

A three-stage inverter based ring VCO was presented and designed with 0.18 µm RF-CMOS technologies. To improve the performance of this oscillator, the improved gravitational search algorithm was used to determine the variables and reduce the power consumption of this oscillator. In this algorithm, the Boltzmann scaling function was used with the aim of controlling the exploration capabilities and productivity in defining the mass of search agents. The designed VCO has the other advantage of high frequency tuning range. The designed VCO dissipates 0.85 mW power at the oscillation frequency of 1.5 GHz. Simulated phase noise of the designed VCO is -91 dBc/Hz at the offset frequency of 1 MHz.

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