Multi-Swarm Optimization of a Graphene FET Based Voltage Controlled Oscillator Circuit

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***Abstract*—The lack of well defined abstraction levels and immature design tools have made the custom design and optimization of analog circuits slow, complex and laborious. Furthermore, CMOS technology beyond 10 nm faces fundamental limits which may restrict its applicability for future devices. In this paper, a Graphene Field Effect Transistor (GFET) based cross-coupled LC circuit is used as case study to design a mixed-signal integrated circuit. A Multi-Swarm Optimization (MSO) algorithm is used for fast exploration of the design space for the GFET based LC-VCO to maximize its operating frequency given phase noise and power dissipation as optimization constraints. The length (L) and width (W) of the graphene channel are selected as the design variables. The phase noise is kept below -80 dBc/Hz and power dissipation is less than 16 mW. The design optimization flow results in a maximum frequency of 2.58 GHz for $L = 3.35\mu$m and $W = 1.82\mu$m and the phase noise and power dissipation constraints are well below the guard limits.**

***Keywords*-Graphene FET, LC-VCO, Multi swarm optimization (MSO)**

I. Introduction

Until recently, silicon based field effect transistors (FETs) were the only choice for the semiconductor industry. As complementary metal oxide semiconductor (CMOS) has hit the power wall i.e. non scaling of KT/q and hence of V_{th} and V_{DD}, it may not be the obvious choice for future smarter devices. With the recent discovery of graphene, the industry and academia have started focusing their attention to graphene based electronic systems. For technologies beyond the 10 nm node or below, graphene is considered to be a viable solution to the problem due to its high field-effect mobility (as high as 15000 cm$^2/(Vs)$ [1]–[4] and a high Fermi velocity ($\sim$10^8 cm/s) even at room temperature.

In this paper a design flow for graphene FET based analog circuits is presented. An LC oscillator is considered as a case study to present the fast design optimization flow for a mixed-signal integrated circuit design. Various optimization techniques have been used in the literature in optimizing analog circuits. Swarm optimization, simulated annealing, and evolutionary algorithms are common [5]–[7]. Bee colony optimization and particle swarm optimization are examples of swarm optimization techniques. However in this paper, a multi-swarm optimization algorithm is used to explore the design space of the GFET based LC-VCO, where the objective is to maximize the frequency with phase noise and power dissipation considered as constraints. The design variables for the optimization are the length (L) and width (W) of the graphene channel. Multiple swarms of particles are generated to search the design space. The oscillator is implemented in Verilog-A based on [8].

The rest of this paper is organized as follows: In section II new contributions are highlighted. In section III related research in the area of GFET based circuit design as well as swarm optimization techniques in optimizing analog circuits are discussed. In section V the proposed design and optimization flow of the LC oscillator circuit are presented. The baseline design of the LC-VCO is described in Section IV. The optimization results and final sized circuit are described in Section VI. In conclusion, some possible future directions are examined in Section VII.

II. Novel Contributions of this Paper

To the best of the authors' knowledge, this is the first attempt to propose a design flow for GFET based cross-coupled version of an LC oscillator. A new optimization algorithm called multi-swarm optimization (MSO) is used in the design flow, which is also a new attempt. The output of this optimization flow gives the proper sizing of the GFET device so as to achieve the maximum frequency within given constraints. Thus, this paper is a forward step in the design and optimization of GFET based RF circuits where an LC oscillator is used.

III. Related Prior Research

After the successful preparation of a two dimensional structure of carbon atoms, graphene has drawn a lot of attention from the electronic device community [9], [10]. In the previous works, graphene based devices like low noise amplifier [11], mixer [12], high frequency graphene amplifier [13], and a frequency doubler [14] have been presented. In [15], the design and simulation of a GFET based LC-VCO for WLAN applications along with its process variation analysis is presented. Optimization is necessary at the final stage of the circuit design so as to meet the design goal. Swarm optimization has been widely used in analog and RF circuits. In this paper, the MSO technique is used, which is a variation of particle swarm optimization (PSO). Instead of a single swarm, multiple swarms are used to find the best global solution for the optimization problem. In the literature, various versions of MSO have been used for tracking the best solution for global optima from the generated multiple swarm, [16]. In [17], speciation based approaches were used where the number and size of the swarms is dynamically adjusted so as to construct an ordered list of particles. In [18], MSO has been presented for a dynamic environment which keeps track of the changing optimum value over time.

IV. Design and Characterization of a Graphene LC-VCO

Unlike semiconductors, graphene lacks an intrinsic bandgap and hence it cannot be turned off completely. The typical transfer and output characteristics of the GFET show a "kink" at the saturation region, which is due to the transition of carrier type (either positive holes or negative electrons depending upon the gate voltage). Due to the zero bandgap, graphene shows ambipolar conduction depending on the top gate voltage. Exploiting the ambipolar characteristics of GFET, analog and RF circuits can be built such as frequency doublers, RF mixers, digital modulators and phase detectors. However as a case study, a cross coupled LC oscillator using GFET [1], [15] is designed as shown in Fig. 1, where the ambipolar property of graphene is exploited. Due to the high electron mobility of the GFETs, the phase noise is reduced and the linear response is improved.

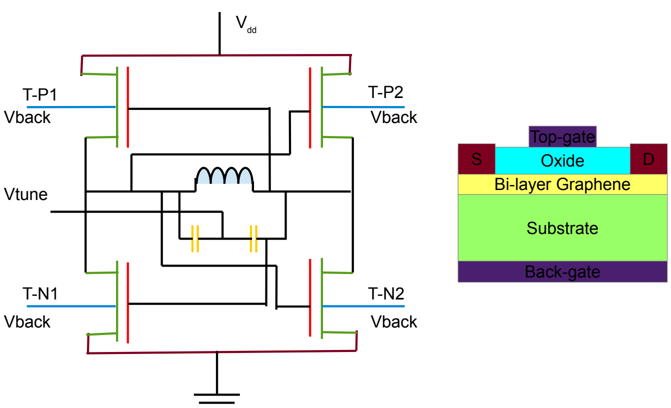
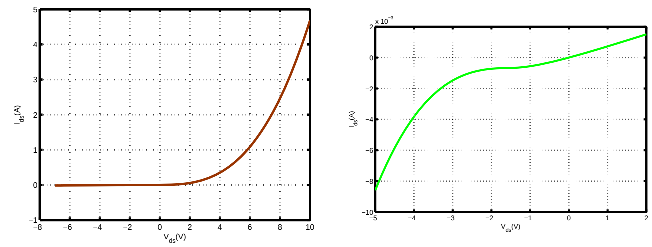


Fig. 1. GFET based LC-VCO with GFET-2D cross-section (left).

TABLE I
GFET device parameters [1], [15].

Device Parameters	Default Values
μ (Mobility)	0.3 $m^2/(Vs)$
Length	6.0 μm
Width	1.6 μm
R_s (p-channel)	600 Ω
R_s (n-channel)	4000 Ω
V_{supply}	9 V
I_{bias}	0.7 mA

In this paper, the GFET is modeled in Verilog-A. Fig. 2 shows the source drain $I - V$ characteristics for the NFET and PFET around the operating region. Table I summarizes the GFET parameters used for the baseline design in this paper where the values for channel length (L) and width (W) are selected heuristically. Table II summarizes the characteristics of the baseline oscillator. The phase noise performance and the tuning characteristics at the operating condition are shown in Fig. 3(a) and Fig. 3(b).



(a) I_{ds} Vs V_{ds}

(b) I_{ds} Vs V_{ds}

Fig. 2. $I - V$ curve of N-type and P-type GFET around operating region.

TABLE II
Characterization of Baseline GFET based LC-VCO

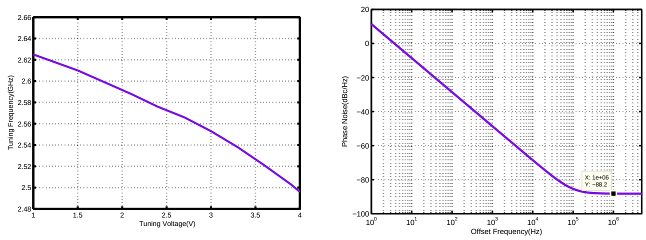
LC-VCO Characteristics	Estimated Values
f_{center}	2.56 GHz
$V_{tank,p-p}$	0.8 V
I_{bias}	0.77 mA
Tuning Range	4.88%
Phase Noise (1MHz offset)	-88.25 dBc/Hz

V. Proposed Design Optimization Flow for GFET based LC-VCO

A. *Overall Design Optimization Flow*

Fig. 4 shows the proposed design flow for the LC-VCO circuit. The design process starts with determining the approximate design points from the behavioral analysis. The baseline design of the circuit is performed from which a netlist is generated. Various figures of merits (FoMs) such as frequency, phase noise and power dissipation are chosen to characterize the oscillator. After choosing the FoMs for the circuit, design variables (length (L) and width (W)) of the GFET are selected. The netlist obtained from the baseline design is then parameterized with respect to these design variables. In order to obtain the distribution of the variation of the characteristics due to the variation of design parameters, parametric analysis is performed on the FoMs. This gives the variable range and the constraints are then chosen based on the design requirements. In the final step of the design, optimization is performed to obtain the maximum frequency for the given constraints. After the successful completion of optimization, a netlist is obtained from this final sized circuit.

The Multi-swarm optimization (MSO) algorithm is used in this paper for optimization. In MSO, several swarms of simulated particle are used to estimate the solution of the optimization problem. Any optimization problem starts with problem formulation which includes problem constraints and



(a) Fequency Vs Tuning Voltage (b) Phase Noise Vs Offset frequency

Fig. 3. Tuning range and Phase noise characteristics of the baseline GFET based LC-VCO.

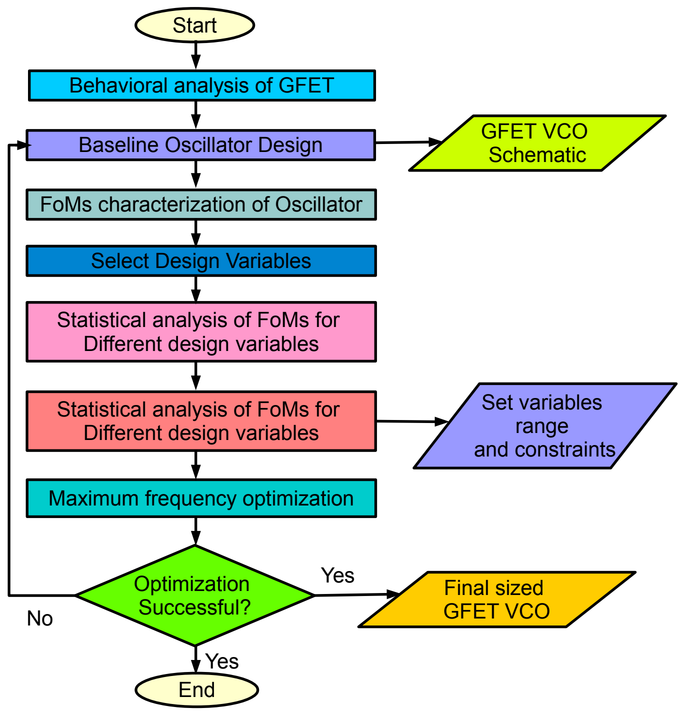


Fig. 4. Design Flow of GFET based LC-VCO Circuit Optimization.

the design variable ranges as the main step. In this circuit optimization, length (L) and width (W) of the graphene channel are chosen as the design variables which are represented by the particle positions. The cost function for each particle is then evaluated . The current position of each particle is compared with the previous best position in order to make a decision on whether to retain the current best position or update the value with the previous best position. Since the objective is to maximize the the frequency of oscillation, the current frequency is observed at each value set of the design variables. Accordingly the value set or the coordinate of the best design variable is decided, based on the present best value and previous best value. From each swarm, a best swarm particle is selected and the best global particle is chosen from the total number of swarms. The maximum frequency is now obtained in the first iteration.

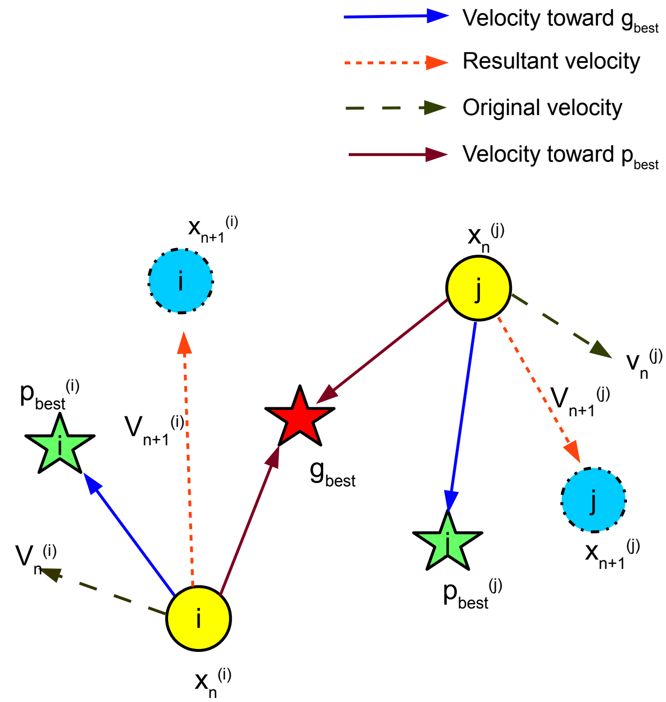


Fig. 5. Particle velocity updating where particles i and j are acceleretaed to wards their best location, g_{best} and p_{best}

B. Multi-Swarm Optimization (MSO) Technique

PSO is an efficient and powerful heuristic technique to solve the global optimization. It has drawn a lot of attention in recent years due to its ease of implementation, robustness and efficiency. The PSO system consists of a single swarm of potential solutions called particles, each of them being associated with a fitness value. These particles move towards the optimal solution with a specified velocity, keeping track of the best position obtained so far. The particles' personal best position is referred as p_{best} while the swarm's best position is referred as g_{best} (or global best). Thus in each iteration, the particle move towards its g_{best} as well as to its p_{best}.

In the second iteration, the best particle from the previous iteration is used to calculate the particle velocity in order to move closer to the optimum solution in each successive iteration. The particle velocity is updated using the following expression:

$$\begin{aligned} v_{t+1} \;=\; & w v_t + c_1 r_1 (x_i - p_{\text{best}}) \\ & + c_2 r_2 (x_i - s_{\text{best}}) + c_3 r_3 (x_i - g_{\text{best}}). \end{aligned} \tag{1}$$

The particle position is updated using:

$$x_i = x_i + v_{t+1}. \tag{2}$$

In Eqn. 1 and Eqn. 2, w is the inertia weight that tends to retain the previous velocity [19] and c_1, c_2 and c_3 are the constants that tend to retain the particle behavior to its own previous position, to its swarm behavior and to the global behavior of multiple swarms respectively. r_1, r_2 and r_3 are three random numbers generated each time which reflect the natural phenomenon of swarm intelligence. In each iteration, the particle moves towards the global best particle, the best particle in its swarm as well as to its previous best position. In constrained optimization, the design variables must be within a specified range. If some particles go beyond the range then those particles need to be reflected back from the boundary so as to maintain their position within the swarm. After a specific number of iterations, based on the convergence criteria or designer's intuition, convergence to a global optimum can be achieved and the simulation is stopped. The optimization process can be considered to be completed if a relatively constant best particle position is obtained or if the frequency of the oscillator does not improve or it swings back and forth around some average value.

VI. Experimental Results

The results obtained from the parametric analysis are shown in Fig. 6. Datas are extracted from this analysis and are then fed to the optimization algorithm to optimize the circuit. The values for phase noise and power dissipation are chosen to be less than -80 dBc/Hz and 16 mW respectively thus optimizing the circuit for maximum possible frequency.

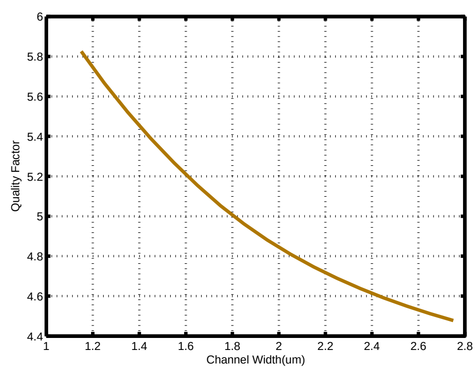


Fig. 7. Quality Factor of the GFET based LC-VCO.

Table III shows the design variable range used. As can seen in Fig. 6(a) and Fig. 6(b), there is a dip in the curves corresponding to a resonating condition. This dip is created in the tank circuit due to the GFET capacitances. The design variable range is selected in such a way that these variables avoid resonance. In Fig. 6(f), two peaks are observed.

In order to understand this behavior, it is necessary to analyze Fig. 6(d) and Fig. 7. In Fig. 7, the quality factor Q is measured as a function of varying channel width and it is observed that the Q value decreases with the channel width. However in Fig. 6(d), the reverse trend is seen with the power dissipation versus width. For an LC oscillator, the phase noise is dependent on both Q and signal power. Based on Leeson's equation, phase noise is proportional to the inverse of signal power and is inversely proportional to the square of Q [20]. So from Fig. 6(d) and Fig. 7, it becomes clear that phase noise has two peaks with channel width variation. Again the design variable width (W) is selected to avoid these phase noise peaks as well. Thus it becomes clear from Fig. 6 that the MSO approach does not allow the optimization problem to oscillate in local optima, unlike PSO. In MSO, due to multiple swarms, which explore for the global optimum independently, the chance of getting stuck in a local optimum is always lower than that in PSO.

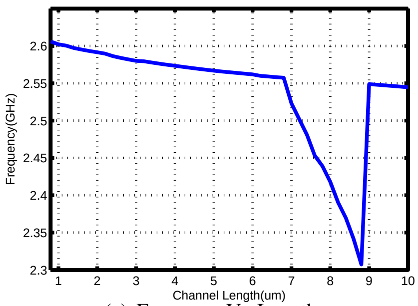
To facilitate the optimization, inertia constants need to be chosen based on the problem. In the absence of inertia constants, the particle may not converge [21]. When a small inertia constant is chosen then the algorithm becomes more like a local search algorithm. Similarly, a large inertia constant can make it a global search algorithm which tries to explore new areas. Both high and low values of inertia constant are not preferable. Thus there is need to have some balance between the local and the global search. For any optimization algorithm, it is generally preferred to have more exploitation ability at the beginning stages to find good seeds and then limit the search to the local area around these seeds. It is beneficial to make the inertia as constantly decreasing functions of time. In this paper, the value of inertia constant is gradually decreased form an initial value of 0.7 to a final value of 0.33. These values have been chosen after exhaustive trial and error until satisfactory results were obtained. Based on particle movement, the maximum iterations is set to be $N = 20$. Table IV summarizes the parameters in defining particle velocity.

TABLE IV
Multi-Swarm Optimization Algorithm Parameters.

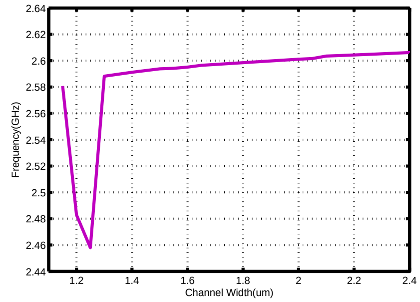
Algorithm Parameters	Values
w	0.7 - 0.33
$c1$	0.2
$c2$	0.2
$c3$	0.2

Similarly, critical parameters are the acceleration constants. Small values for these constants make the particles roam far away from the target global region and high values result in abrupt particle movement. The acceleration constants are chosen small compared to the values selected in [22] for a single swarm PSO. Table IV shows the values chosen for acceleration constant after several trial and error.

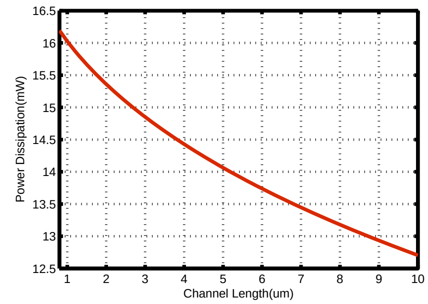
The optimization steps and results are shown in Fig. 8. The initial and final particle positions after 20 iterations are shown in Fig. 8(a) and Fig. 8(b), respectively. As can be seen in these figures, the initial particles are spread all over the design space but after 20 iterations, the particles of all swarms are converged around the global optimum particle position. The interpolated contours in Fig. 8(b) helps to visualize the convergence step where each line illustrates connected isometric values. The global best particle position is obtained by averaging across all steps and Table V illustrates the optimal oscillator values obtained after optimization. Fig. 9(a) and Fig. 9(b) show the tuning range and phase noise of the optimized LC-VCO.



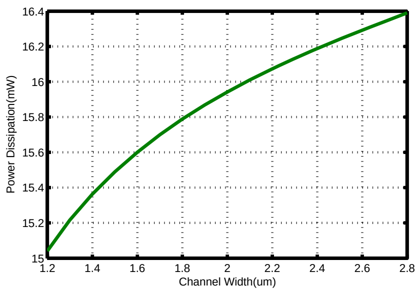
(a) Fequency Vs Length



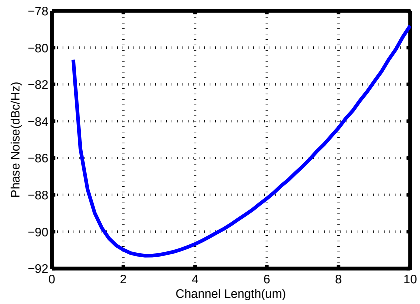
(b) Frequency Vs Width



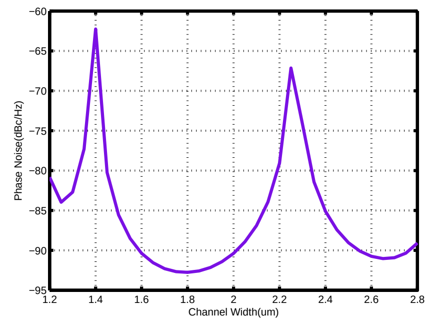
(c) Power Dissipation Vs Length



(d) Power Dissipation Vs Width



(e) Phase Noise Vs Length



(f) Phase Noise Vs Width

Fig. 6. Characteristics of the GFET based LC-VCO.

TABLE III
GFET-BASED LC-VCO DESIGN VARIABLES AND CONSTRAINTS.

LC-VCO Parameter	Parameter Type	Minimum Value	Maximum Value
L	Design Variable	$3\mu m$	$7\mu m$
W	Design Variable	$1.4\mu m$	$2.2\mu m$
Power Dissipation	Design Constraint	Minimize	$16mW$
Phase Noise	Design Constraint	Minimize	$-80dBc/Hz$

TABLE V
CHARACTERISTICS OF THE OPTIMAL LC-VCO.

LC-VCO Parameters	Estimated Values
Channel Length	3.35 μm
Channel Width	1.82 μm
Frequency	2.58 GHz
Power Dissipation	11.74 mW
Phase Noise (at 1MHz offset)	-92.92 dBc/Hz
Tuning range	4.26%
$V_{tank(p-p)}$	0.75 V
I_{bias}	0.83 mA

VII. CONCLUSIONS AND FUTURE RESEARCH

The required LC-VCO oscillator is successfully designed following the design flow and optimization algorithm presented in this paper, where the design constraints of phase noise and power dissipation are well met. The netlist obtained from the baseline oscillator is used to apply MSO for the given objective function, design variables and constraints. The baseline LC-VCO with center frequency of 2.56 GHz is initially designed and the final LC-VCO with center frequency of 2.58 GHz is obtained, where the power dissipation and phase noise are 26.625% and 16.15% below their maximum values.

As an alternate design approach, in future work, a surrogate model of the circuit will be created which will then be used to perform optimization instead of using a netlist, in order to reduce the optimization time. In order to perform parasitic aware design, parasitic extraction will be done and multi-objective optimization will be performed to obtain the final layout.

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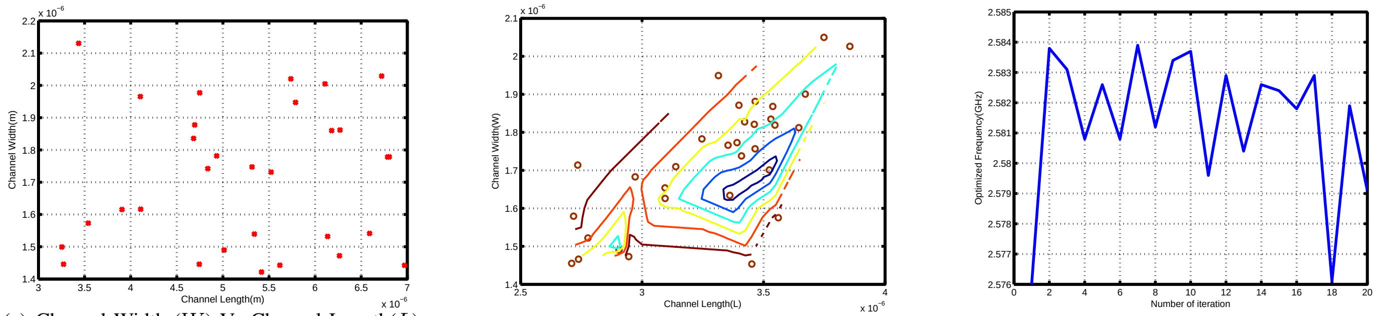
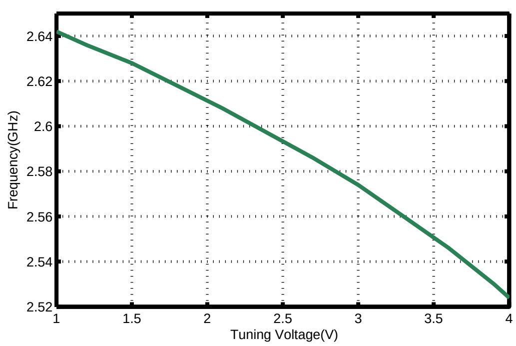
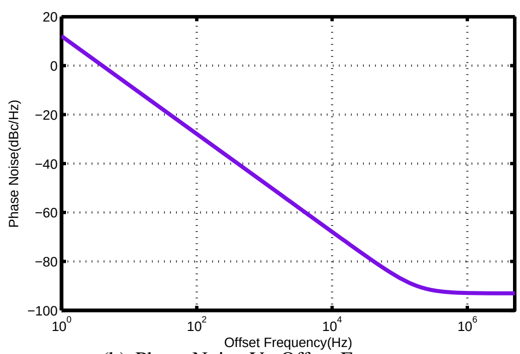


(a) Channel Width (W) Vs Channel Length(L) (b) Channel Width (W) Vs Channel Length(L) (c) Optimized Fequency Vs No. of Iteration

Fig. 8. GFET based LC-VCO Optimization: (a) Initial particles (x), (b) particles after 20^{th} iteration (o), (c) Optimized frequency.



(a) Fequency Vs Tuning Voltage



(b) Phase Noise Vs Offset Frequency

Fig. 9. Tuning range and Phase noise of Optimized GFET based LC-VCO.

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