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Design of GaAs HBT VCO Based on Response Surface Method

Zhisen Li, Min Liu*, Jincan Zhang, Kun Xu, Bowen Zhang, Tonghe Huang and Yiming Wang

Information Engineering College, Henan University of Science and Technology, Luoyang 471023, China

Abstract

In this paper, a differential cross-coupled Colpitts voltage control oscillator (VCO) based on 1 μm GaAs HBT technology is presented, and response surface method (RSM) is used to co-optimize the phase noise, center frequency, and tuning range of the VCO. The differential cross-coupled structure is used to provide negative resistance and the Colpitts structure is applied for achieving low phase noise. Then, we choose five parameters of the VCO circuit through establishing RSM model, in order to find the optimal combination of VCO circuit design parameters and to obtain the best performance. The results show that the frequency tuning range of VCO circuit is 11.59~15.39 GHz, the phase noise is -110.6 dBc/Hz at 1 MHz offset from center frequency of 13.49 GHz, the power consumption of the VCO core is 18.05 mW at 5.0 V supply voltage and the calculated figure of merit (FOM) is -189.628 dBc/Hz. The performance of the VCO is improved after the optimization of response surface method.

Keywords

Voltage Control Oscillator; GaAs HBT; Figure of Merit; Tuning Range; Phase Noise.

1. Introduction

Voltage control oscillator (VCO) is necessary component of RF transceiver system, and it can offer local oscillator signal for transmit chain and receive chain, so the performance of the VCO greatly influences the performance of RF transceiver system[1-2]. In recent years, VCOs are widely studied with the increasing development of integrated circuit, and the requirement for VCO circuit are getting higher and higher due to RF transceiver system demanding higher work frequency. GaAs HBT devices are a good choice for designing voltage-controlled oscillators, because GaAs HBT devices have small size, high process maturity, low cost and low 1/f noise compared to other devices that can be used in RF integrated circuit VCO, such as Si BJT, CMOS, InP HBT, etc[3-5].

The important performance of VCO based are phase noise and frequency tuning range, but the relationship of them is mutually restrictive. Most researchers devote to enhance the performance of the VCOs by improving VCO circuit structure in many literatures. For instance, the literature[4,6] proposed a VCO topology that combines the advantages of three circuit structures, which adopts the benefits of the Colpitts/class-C/NS structure and circumvents the deficiencies in them in a gradual evolutionary manner[4,6]. In [5], the gm-boosting technique was applied to relax oscillation start-up condition and the Collector-Emitter cross-coupling was proposed to reduce the phase noise[5]. The other approach of improving the performance of VCOs is to use the devices manufactured by better semiconductor process. In [7], a magnetic transformer is used to set positive feedback around a common-collector differential npn transistor pair, implementing the push-pull operation, which optimized the phase noise of the VCO circuit[7]. Literature [8] adopted a fully differential tuning varactor to reduce amplitude-to-phase noise[8].

As the circuit structure is becoming more and more complicated, meanwhile the layout area becomes larger. The performance indicators of the VCO circuit are usually related or restricted, and the experience-based simulation joint adjustment is not only cumbersome, but also has little effect. Therefore, in addition to improving the device technology, optimizing performance-related parameters is also a good way to improve the performance of the circuit[9]. For instance, literature [9] proposes an optimization method named Taguchi Design to optimize the circuit parameters. The response surface method (RSM) is an improved approach compared with Taguchi Design, which is a statistical experiment method to optimize the random process. The goal is to find the quantitative law between the experiment index and each factor, and to find the best combination of each factor[10-12].

In this paper, we present a low phase noise and wide tuning range VCO, the differential cross-coupled structure is used to provide negative resistance, and the Colpitts structure has an advantage of low phase noise. Then, we adopt response surface method to establish quadratic polynomial mathematical model between response variables (include phase noise, center frequency and tuning range) and circuit design parameters, in order to seek out the best combination of them for achieving optimal performance. To verify the proposed method, the FOM is regard as evaluation criteria. This Colpitts VCO with differential cross-coupled structure was designed in 1μm GaAs HBT technology. The results show that the FOM has significant improvement after optimization of the RSM.

2. VCO Circuit Design

The schematic of the VCO circuit is shown in Fig1. From the picture, the proposed VCO topology adopts differential cross-coupled structure and Colpitts structure. The differential cross-coupled structure is one of the negative resistance structures, it can not only supply differential output signal but can also suppress common mode noise and compensate for the phase shift between input and output in common emitter mode. The Colpitts structure has the effect of reducing phase noise[4]. All adopted components in this design are from 1 μm GaAs HBT PDK of WIN Semiconductor Crop. Usually inductors L, varactor diode C_{var} and constant capacitors(C_1、C_2) form a resonant circuit in low frequency, however, in the case of high frequency, the capacitor of the HBT device cannot be ignored in resonance, such as the base-collector junction capacitors, include external capacitor C_{bcx} and internal capacitor C_{bc}, which will affect the oscillation frequency[13]. Therefore, it is not easy to estimate the required component value using the traditional formula for calculating the oscillation frequency. We use the S-parameter method to determine the elements of the circuit. In order to reduce the influence of the parasitic elements of the inductors in high frequency, microstrip transmission lines are taken to replace inductors. What's more, the resistor R is used as a tail current source to adjust the static operating point of the transistor. C_{var1} and C_{var2} are varactor diode array, the range of tuning control voltage Vtune applied across them is 0.1~6 V, because the maximum voltage that the varactor diode this paper proposed can withstand is 7 V. After all components are selected, the frequency tuning effect is achieved by adjusting the control voltage Vtune. The design results show that the frequency tuning range of VCO circuit is 12.04~16.06 GHz, the phase noise is -105.5 dBc/Hz at 1 MHz offset from center frequency of 14.05 GHz, the power consumption of the VCO core is 20.75 mW at 5.0 V supply voltage.

3. Response Surface Method to Optimize VCO Circuit

RSM is a statistical experiment design method to establish the optimization process of continuous variable surface model. It evaluates the factors that affect the results and their interactions, and determines the optimal level range. This paper utilizes Box-Behnken Design to build the response surface model of the VCO circuit performance. Generally, the response surface model can be expressed by a regression equation in the form as follow[10-11]

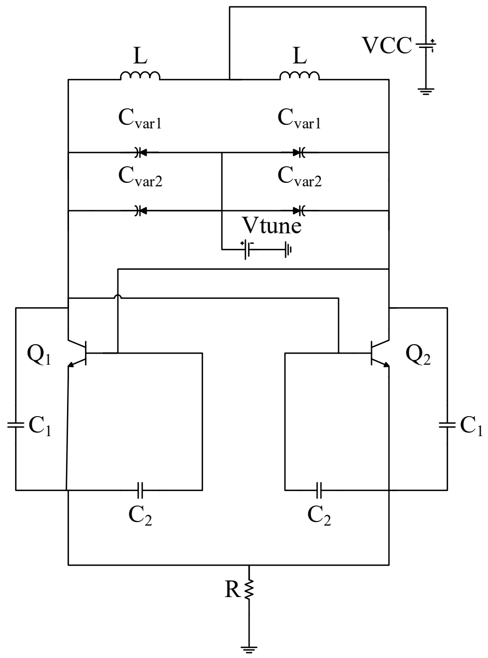

Fig 1. Schematic of the proposed VCO circuit

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1, j \le i}^{k} b_{ij} x_i x_j, \quad (k \in z) \tag{1}$$

Firstly, the impact factors level is decided by response surface analysis according to single factor simulation result. Impact factors affecting circuit performance are the length of the microstrip transmission lines(Mline), the number and area of the varactor diodes, the value of the constant capacitors and the resistor, the tuning voltage. After performing single factor simulation separately in the frequency range covering 15 GHz, it is found that the length of the microstrip transmission lines, the number of the varactor diodes, and the value of the constant capacitors are more sensitive to performance of the VCO circuit. According to design experience, the impact factor levels and codes based on Box-Behnken response surface method are shown in Table 1.

Table 1. Level and Code of impact factors

Actual values	factor		Level and Code	
		-1	0	+1
A	Mline(um)	300	325	350
B	C_{var1}(ge)	2	4	5
C	C_{var2}(ge)	2	4	5
D	C_1(pF)	0.036	0.0775	0.119
E	C_2(pF)	0.036	0.0775	0.119

Secondly, the optimization goals are determined as phase noise, center frequency and frequency tuning range based on circuit simulation results, which are completely important performance of the VCO. And they generally influence each other, all of them are selected as the values of the response. The experimental program and results are shown in Table 2.

Finally, the result was inserted in design Expert v10.0.3 statistical software, that is, the Box–Behnken design, to obtain the responses as a function of Mline, C_{var1}, C_{var2}, C_1 and C_2.

Table 2. Experimental design and results

Num	Factor1	Factor 2	Factor 3	Factor4	Factor 5	Respose1	Response 2	Response 3
	Mline	C_{var1}	C_{var2}	C_1	C_2	f_c	PN	TR
1	325	4	4	0.0775	0.0775	14.335	-108.437	3.55
2	300	4	4	0.119	0.0775	14.37	-106.628	3.79
3	300	5	4	0.0775	0.0775	14.6	-106.6	3.84
4	325	4	4	0.0775	0.0775	14.335	-108.437	3.55
5	325	4	4	0.0775	0.0775	14.335	-108.437	3.55
6	300	4	4	0.0775	0.119	14.55	-106.169	3.43
7	325	5	4	0.0775	0.036	14.375	-108.903	3.93
8	325	5	4	0.119	0.0775	13.61	-110.393	3.4
9	325	5	4	0.0775	0.119	13.61	-110.376	3.41
10	325	5	4	0.036	0.0775	14.375	-108.88	3.93
11	325	2	5	0.0775	0.0775	14.71	-107.138	3.4
12	300	2	4	0.0775	0.0775	15.76	-102.946	3.3
13	325	2	4	0.036	0.0775	15.6	-104.86	3.46
14	300	4	4	0.036	0.0775	15.38	-104.921	3.97
15	325	4	4	0.119	0.036	14.3	-108.391	3.52
16	325	4	2	0.0775	0.119	14.68	-106.568	2.92
17	325	4	5	0.036	0.0775	14.375	-108.86	3.93
18	325	4	2	0.036	0.0775	15.6	-104.86	3.46
19	350	5	4	0.0775	0.0775	13.415	-111	3.47
20	350	4	5	0.0775	0.0775	13.415	-111	3.47
21	325	4	4	0.119	0.119	13.58	-110.48	3.03
22	325	4	4	0.036	0.119	14.3	-108.391	3.52
23	325	4	4	0.0775	0.0775	14.335	-108.437	3.55
24	325	4	2	0.119	0.0775	14.68	-106.568	2.92
25	325	2	4	0.0775	0.119	14.685	-106.6	2.93
26	325	4	5	0.0775	0.119	13.61	-110.4	3.41
27	350	4	4	0.119	0.0775	13.37	-111.3	3.1
28	350	4	4	0.036	0.0775	14.16	-103.6	3.62
29	325	5	5	0.0775	0.0775	13.66	-110.4	3.76
30	325	4	5	0.0775	0.036	14.375	-108.9	3.93
31	325	2	4	0.119	0.0775	14.68	-106.568	2.92
32	350	4	2	0.0775	0.0775	14.53	-108.8	3.04
33	325	4	4	0.0775	0.0775	14.335	-108.437	3.55
34	325	5	2	0.0775	0.0775	14.71	-107.1	3.39
35	300	4	5	0.0775	0.0775	14.6	-106.437	3.84
36	325	2	4	0.0775	0.036	15.595	-104.9	3.45
37	300	4	2	0.0775	0.0775	15.76	-102.946	3.3
38	325	4	4	0.0775	0.0775	14.335	-108.437	3.55
39	325	4	2	0.0775	0.036	15.595	-104.9	3.45
40	325	2	2	0.0775	0.0775	16.095	-102.6	2.59
41	300	4	4	0.0775	0.036	15.38	-104.934	3.96
42	350	2	4	0.0775	0.0775	14.53	-108.8	3.04
43	325	4	5	0.119	0.0775	13.61	-110.4	3.4
44	325	4	4	0.036	0.036	15.235	-107.4	4.13
45	350	4	4	0.0775	0.119	13.37	-111.3	3.1
46	350	4	4	0.0775	0.036	14.155	-109.6	3.63

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4. Results and Analysis

4.1. Analysis of Variance

The significance of different impact factors is different. The analysis of variance (ANOVA) gives a detailed view that the significance of impact factors and their interaction effects on the responses and the accuracy of response surface quadratic model in Design Expert 10.0.3. The list of the ANOVA of the center frequency f_c is given in Table 3. Table 4 and Table 5 are the lists of the ANOVA of the phase noise and the tuning range.

F-value and P-value are crucial standards of the analysis of variance. The Model F-value of 1284.06 implies the model is significant. P-value less than 0.05 indicate model terms are significant. In this case A, B, C, D, E, AD, BC, BD, BE, CD, CE, DE, B^2, C^2 are significant model terms. P-values greater than 0.1 indicate the model terms are not significant. That the values of R-squared closed to 1 indicates regression models are more accurate. From the Table 3, R^2=99.90%, Adj R^2=99.82%, Pred R^2=99.61%, Lack of Fit=0.022, which indicate the regression model fits well. The insignificant model terms that have no effect on the regression model equation can be ignored, and the final regression model equation of f_c is:

$$\begin{aligned} f_c &= 14.335 - 0.590938A - 0.58125B - 0.580938C - 0.426563D - 0.414063E \\ &+ 0.055AD + 0.08375BC + 0.03875BD + 0.03625BE + 0.03875CD \\ &+ 0.0375CE + 0.05375DE + 0.229375B^2 + 0.228958C^2 \end{aligned} \tag{2}$$

The model F-value is 37.66 and P-value is 0.0001, which means the model is significant. Impact factors Mline, C_{var1}, C_{var2}, C_1, C_2 are significant model terms because their F-values are great than 1 and P-values are less than 0.05. R^2=82.48%, Adj R^2=80.29%, Pred R^2=76.40%, which indicate the regression model fits well and is accurate. But there are no interaction terms and square terms in Table 4, which implies the regression equation of the response is linear. The reason is that the Mline is from 300 μm to 350 μm in order to make sure the oscillation frequency above 10 GHz, since the phase noise increases with the reduction of the oscillation frequency, so do the others impact factors. Consequently, the regression model equation of the phase noise is linear as Eq (3):

$$PN = -107.66 - 2.11A - 1.83B - 1.82C - 1.18D - 0.77E \tag{3}$$

From the Table 5, the Model F-value of 72.57 and P-value of 0.0001 implies the model is significant. A, B, C, D, E, AD, BC, B^2, C^2 are significant model terms. R^2=98.31%, Adj R^2=96.95%, Pred R^2=93.23%, which indicates the regression model fits well and is accurate. The insignificant model terms that do not affect the regression model equation can be ignored; the regression model equation of the tuning range is given in Eq (4):

$$\begin{aligned} f_{TR} &= 3.55 - 0.185A + 0.2525B + 0.254375C - 0.24625D - 0.265625E \\ &0.085AD - 0.11BC - 0.133542B^2 + 0.134375C^2 \end{aligned} \tag{4}$$

4.2. Analysis of Response Surface

The 3D response surface plots for center frequency presented in Fig2, Fig 3 and Fig4 show the response surface plots for phase noise and tuning range respectively. These plots show the effect of impacts factors and their interaction on center frequency. The plots of Fig 2 indicates that with an increase in Mline, C_{var1}, C_1 and C_2 center frequency decreases because the increase in length of MLine represents an increase in inductance, the increase of inductance and capacitance lead to oscillation frequency reduction. C_{var2} has same effect with C_{var1}. From Fig 3, the response surface plot for phase noise is a flat. The value of phase noise increase with the linear increase of each impact factors. Fig 4 shows that, frequency tuning range decreases with the increase of Mline, C_1 and C_2, and increases with the increase of C_{var1} and C_{var2}.

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Table 3. Analysis of variance of response f_c

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	23.03	20	1.15	1284.06	< 0.0001
A-Mline	5.59	1	5.59	6229.47	< 0.0001
B-C_{var1}	5.41	1	5.41	6026.9	< 0.0001
C-C_{var2}	5.4	1	5.4	6020.42	< 0.0001
D-C_1	2.91	1	2.91	3245.89	< 0.0001
E-C_2	2.74	1	2.74	3058.44	< 0.0001
AB	5.06×10^{-4}	1	5.06×10^{-4}	0.56	0.4595
AC	5.06×10^{-4}	1	5.06×10^{-4}	0.56	0.4595
AD	0.012	1	0.012	13.49	0.0011
AE	5.06×10^{-4}	1	5.06×10^{-4}	0.56	0.4595
BC	0.028	1	0.028	31.28	< 0.0001
BD	6.01×10^{-3}	1	6.01×10^{-3}	6.7	0.0159
BE	5.26×10^{-3}	1	5.26×10^{-3}	5.86	0.0231
CD	6.01×10^{-3}	1	6.01×10^{-3}	6.7	0.0159
CE	5.63×10^{-3}	1	5.63×10^{-3}	6.27	0.0192
DE	0.012	1	0.012	12.88	0.0014
A^2	4.64×10^{-4}	1	4.64×10^{-4}	0.52	0.4786
B^2	0.46	1	0.46	511.94	< 0.0001
C^2	0.46	1	0.46	510.08	< 0.0001
D^2	6.40×10^{-5}	1	6.40×10^{-5}	0.071	0.7915
E^2	1.15×10^{-3}	1	1.15×10^{-3}	1.28	0.2691
Residual	0.022	25	8.97×10^{-4}		
Lack of Fit	0.022	20	1.12×10^{-3}		
Pure Error	0	5	0		
Cor Total	23.06	45			
S=0.03, R^2=99.90%, Adj R^2=99.82%, Pred R^2=99.61%					

Table 4. Analysis of variance of response PN

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	210.18	5	42.04	37.66	< 0.0001
A-Mline	71.48	1	71.48	64.03	< 0.0001
B-C_{var1}	53.44	1	53.44	47.87	< 0.0001
C-C_{var2}	53.26	1	53.26	47.71	< 0.0001
D-C_1	22.46	1	22.46	20.12	< 0.0001
E-C_2	9.54	1	9.54	8.55	0.0057
Residual	44.65	40	1.12		
Lack of Fit	44.65	35	1.28		
Pure Error	0	5	0		
Cor Total	254.84	45			
S=1.06, R^2=82.48%, Adj R^2=80.29%, Pred R^2=76.40%					

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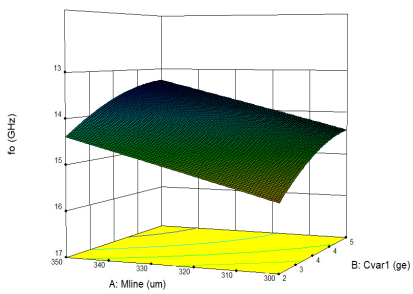
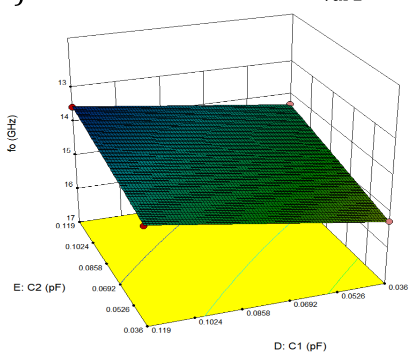
Table 5. Analysis of variance of response TR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	5.13	20	0.26	72.57	< 0.0001
A-Mline	0.55	1	0.55	154.82	< 0.0001
B-C_{var1}	1.02	1	1.02	288.41	< 0.0001
C-C_{var2}	1.04	1	1.04	292.71	< 0.0001
D-C_1	0.97	1	0.97	274.31	< 0.0001
E-C_2	1.13	1	1.13	319.17	< 0.0001
AB	3.03×10^{-3}	1	3.03×10^{-3}	0.86	0.3639
AC	3.03×10^{-3}	1	3.03×10^{-3}	0.86	0.3639
AD	0.029	1	0.029	8.17	0.0085
AE	0	1	0	0	1
BC	0.048	1	0.048	13.68	0.0011
BD	2.50×10^{-5}	1	2.50×10^{-5}	7.07×10^{-3}	0.9337
BE	0	1	0	0	1
CD	2.50×10^{-5}	1	2.50×10^{-5}	7.07×10^{-3}	0.9337
CE	2.50×10^{-5}	1	2.50×10^{-5}	7.07×10^{-3}	0.9337
DE	3.60×10^{-3}	1	3.60×10^{-3}	1.02	0.3227
A^2	3.64×10^{-4}	1	3.64×10^{-4}	0.1	0.751
B^2	0.16	1	0.16	44	< 0.0001
C^2	0.16	1	0.16	44.55	< 0.0001
D^2	4.67×10^{-3}	1	4.67×10^{-3}	1.32	0.2616
E^2	3.19×10^{-4}	1	3.19×10^{-4}	0.09	0.7666
Residual	0.088	25	3.54×10^{-3}		
Lack of Fit	0.088	20	4.42×10^{-3}		
Pure Error	0	5	0		
Cor Total	5.22	45			
S=0.059, R^2=98.31%, Adj R^2=96.95%, Pred R^2=93.23%					



(a) Effect of MLine and C_{var1} on f_c



(b) Effect of C_2 and C_1 on f_c

Fig 2. Response surface plot for center frequency

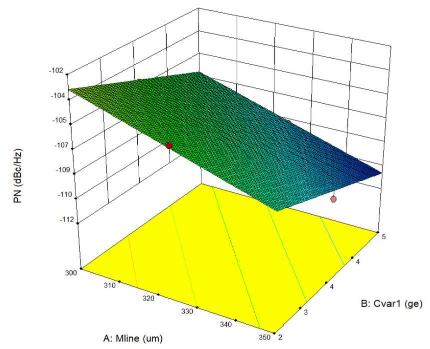
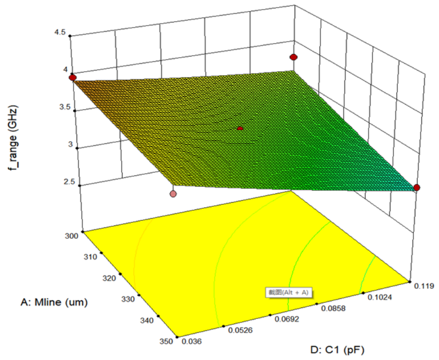
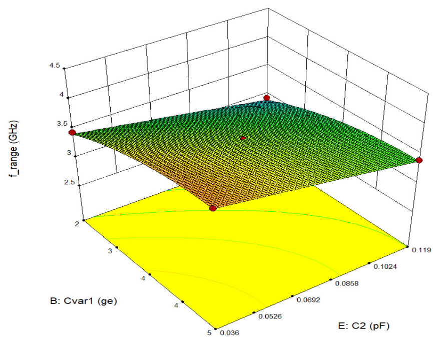


Fig 3. Response surface plot for phase noise



(a) Effect of MLine and C_1 on f_{TR}



(b) Effect of C_{var1} and C_2 on f_{TR}

Fig 4. Response surface plot for tuning range

4.3. Optimization Results of the VCO Circuit

Phase noise is an important parameter to characterize the frequency stability of oscillators. The result of the phase noise at 1MHz frequency offset, that changes with the tuning voltage, is provided in Fig 5.

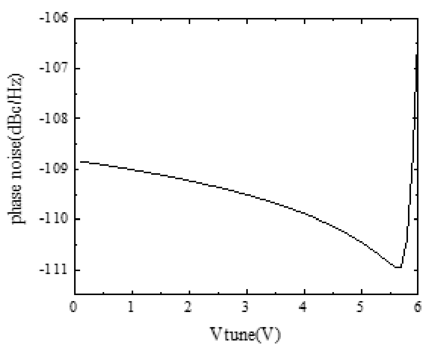


Fig 5. Phase noise at 1MHz frequency offset

In order to evaluate the overall performance of the VCO circuit, the figure of merit (FOM) is adopted to analyze the VCO circuit. Its definition is given by Eq (5)[8]

$$FOM = PN - 20\lg\left(\frac{f_c}{\Delta f}\times\frac{TR}{10\%}\right) + 10\lg\left(\frac{P_{vco}}{1mw}\right) \quad (5)$$

Where PN is phase noise, f_c is center frequency at 1 MHz offset from center frequency, Δf is offset frequency, P_{vco} is power consumption of the VCO, f_{TR} is frequency tuning range, and TR is defined as Eq (6)

$$TR = \frac{f_{TR}}{f_c}\times 100\% \quad (6)$$

RSM is used to seek the optimal combination of the VCO circuit design parameters for the best performance of the circuit, the results after RSM optimization show that, Mline is 348.5μm, C_{var1} and C_{var2} are 5, C_1 is 0.079 pF, C_2 is 0.039 pF, the frequency tuning range of VCO circuit is 11.59~15.39 GHz, the phase noise is -110.6 dBc/Hz at 1 MHz offset from center frequency of 13.49 GHz, the power consumption of the VCO core is 18.05 mW at 5.0 V supply voltage and the calculated figure of merit (FOM) is -189.628 dBc/Hz Compared with that before RSM optimization in section II, the phase noise is improved significantly, the power consumption is reduced by 2.7 mW, the FOM is increased by 5.217 dB because the calculated FOM before RSM is -184.411 dBc/Hz at 1 MHz offset. Therefore, the VCO circuit achieves better performance after RSM optimization. Having verified the simulation results, the layout of proposed VCO circuit is drawn in Fig 6. The layout area including the pads is 565 μm×665 μm. Table 6 shows the performance comparison between proposed VCO and some reported VCOs [7-8,14-17].

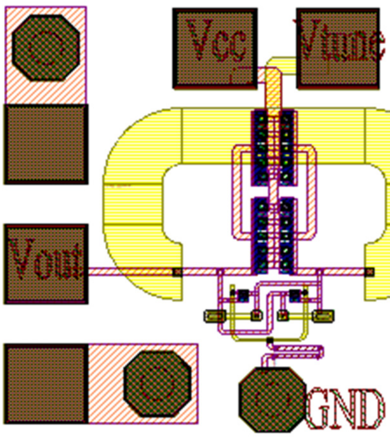


Fig 6. Layout of the VCO circuit

Table 6. Performance comparison with some reported VCOs

Ref	Process	f_c GHz	PN dBc/Hz	TR %	P_{vco} mW	FOM dBc/Hz
[7]	SiGe BiCMOS	17	-116	15	45	-184
[8]	CMOS	20.1	-103.8	32	4.9	-186.3
[14]	GaAs HBT	11.14	-130	20.5	725	-180.6
[15]	GaAs HBT	23.89	-104.6	8.6	60	-176.5
[16]	GaAs HBT	19.9	-116	3.1	90	-182.5
[17]	GaAs HBT	9.2	-136	14.1	665	-175.8
*	GaAs HBT	14.05	-105.5	28.6	20.75	-184.4
**	GaAs HBT	13.49	-110.6	28.2	18.05	-189.6

*This work before RSM ** This work

5. Conclusion

The paper presents a differential cross-coupled Colpitts VCO based on GaAs HBT, the differential cross-coupled structure and the Colpitts structure make VCO have lower noise and excellent performance. To achieve more excellent performance, the RSM is applied to optimize the parameters of the VCO circuit. The regression models of response values (center frequency, phase noise, tuning range) are established by RSM. Through analysis of variance, the center frequency, phase noise and tuning range regression models are accuracy, moreover, through significant analysis of impact factors and their interaction, the regression model equations can be reorganized owing to remove insignificant factors, which makes the regression model equations simpler and more precise.

RSM is a good method to promote the performance of the VCO circuit. Compared with traditional methods, such as improving circuit structure or device process, it seeks the best combination of circuit parameters by establishing the response surface equations of performance indicators to circuit parameters based on device itself. In addition, this method omits the complex simulation process and saves time in circuit design. The results after RSM optimization show that, the performance of the VCO circuit is significantly improved. The FOM of 1μm GaAs HBT VCO has been increased from 184.4 dBc/Hz to 189.6 dBc/Hz, which verifies the effectiveness of RSM.

Conflict of Interest Disclosure

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H. Lee, S. Jang, and Y. Chen, “Low phase noise buffe-reused BiCMOS oscillator,” Microw Opt Technol Lett, vol. 63, no. 7, pp. 1881-1885, Jul. 2021, doi: 10.1002/mop.32867.

[2] L. Pantoli, S. Arena, and T. Cavanna, “Enhancing performance of a InGaP/GaAs VCO by means of a switching architecture,” Electron. Lett., vol. 54, no. 11, pp. 695-696, May 2018, doi: 10.1049/ el. 2018.0965.

[3] J. Zhang et al., “A Ku-band wide-tuning-range high-output-power VCO in InGaP/GaAs HBT technology,” J. Semicond., vol. 36, no. 6, p. 065010, Jun. 2015, doi: 10.1088/1674-4926/36/6/ 065010.

[4] J.-Y. Han, Y. Jiang, G.-L. Guo, and X. Cheng, “An evolution of Colpitts VCO for simultaneous optimization of phase noise and FoM in GaAs technologies,” Analog Integr. Circuits Process., vol. 105, no. 3, pp. 441-457, Dec. 2020, doi: 10.1007/s10470-020-01725-7.

[5] X. Xia, F. Chen, X. Cheng, J. Han, and X. Luo, “A GaAs Colpitts VCO Using gm -Boosting and Collector-Emitter Cross-Coupling Techniques,” IEEE Trans. Circuits Syst. II, vol. 67, no. 12, pp. 2873-2877, Dec. 2020, doi: 10.1109/TCSII.2020.2995957.

[6] X. Cheng, F.-J. Chen, X.-L. Xia, J.-A. Han, X.-H. Luo, and Z.-C. Zhao, “A Modified Darlington-Based Class-C VCO With Simultaneous Optimization of Phase Noise/FoM in GaAs Technology,” IEEE Microw. Wireless Compon. Lett., vol. 30, no. 5, pp. 500-503, May 2020, doi: 10.1109/LMWC.2020.2983845.

[7] S. Veni, P. Andreani, M. Caruso, M. Tiebout, and A. Bevilacqua, “Analysis and Design of a 17-GHz All-npn Push-Pull Class-C VCO,” IEEE J. Solid-State Circuits, vol. 55, no. 9, pp. 2345-2355, Sep. 2020, doi: 10.1109/JSSC.2020.2991512.

[8] Z. Zhang, L. Liu, N. Qi, J. Liu, and N. Wu, “A 17.6-to-24.3 GHz -193.3 dB figure-of-merit LC voltage-controlled oscillator using layout floorplan optimization technique for Q-factor enhancement,” Jpn. J. Appl. Phys., vol. 59, no. SG, p. SGGL05, Apr. 2020, doi: 10.35848/1347-4065 /ab709c.

[9] G. K. Sharma, A. K. Johar, T. B. Kumar, and D. Boolchandani, “Effectiveness of Taguchi and ANOVA in design of differential ring oscillator,” Analog Integr Circ Sig Process, vol. 104, no. 3, pp. 331-341, Sep. 2020, doi: 10.1007/s10470-020-01671-4.

[10] Z. Chen, Y. Xu, C. Wang, Z. Wen, Y. Wu, and R. Xu, “A Large-Signal Statistical Model and Yield Estimation of GaN HEMTs Based on Response Surface Methodology,” IEEE Microw. Wireless Compon. Lett., vol. 26, no. 9, pp. 690-692, Sep. 2016, doi: 10.1109/LMWC.2016.2597196.

[11] P. Hansdah, S. Kumar, and N. R. Mandre, “Performance optimization of dewatering of coal fine tailings using Box–Behnken design,” Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 40, no. 1, pp. 75-80, Jan. 2018, doi: 10.1080/15567036.2017.1405112.

[12] J. kumar and T. Soota, “Multi-response optimization of machining parameter for Zircaloy by response surface methodology and grey relation analysis,” Materials Today: Proceedings, vol. 21, pp. 1544-1550, 2020, doi: 10.1016/j.matpr.2019.11.084.

[13] A. Zhang and J. Gao, “A new method for determination of PAD capacitances for GaAs HBTs based on scalable small signal equivalent circuit model,” Solid-State Electronics, vol. 150, pp. 45-50, Dec. 2018, doi: 10.1016/j.sse.2018.10.005.

[14] C. Florian, S. D’Angelo, D. Resca, and F. Scappaviva, “A chip set of low phase noise MMIC VCOs at C, X and Ku band in InGaP-GaAs HBT technology for satellite telecommunications,” in 2017 IEEE MTT-S International Microwave Symposium (IMS), Honololu, HI, USA, Jun. 2017, pp. 1148-1151. doi: 10.1109/MWSYM.2017.8058802.

[15] T. Yan, Y.-M. Zhang, H.-L. Lu, Y.-M. Zhang, and Y. Wu, “A K-band low phase noise and wide tuning range LC VCO,” in 2014 12th IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT), Guilin, China, Oct. 2014, pp. 1-3. doi: 10.1109/ICSICT.2014.7021604.

[16] Y. Peng, H.-L. Lu, Y.-M. Zhang, and Y.-M. Zhang, “A K-band Low Phase Noise GaAs HBT vco,” in 2012 11th IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT), Xi'an, China, Oct. 2012, pp. 1-3, doi: 10.1109/ICSICT.2012.6466692.

[17] D. Kuylenstierna, S. Lai, Mingquan Bao, and H. Zirath, “Design of Low Phase-Noise Oscillators and Wideband VCOs in InGaP HBT Technology,” IEEE Trans. Microwave Theory Techn., vol. 60, no. 11, pp. 3420-3430, Nov. 2012, doi: 10.1109/TMTT.2012.2216893.