A 40 GHz MODIFIED-COLPITTS VOLTAGE CONTROLLED OSCILLATOR WITH INCREASED TUNING RANGE

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ABSTRACT

A 40 GHz modified-Colpitts voltage controlled oscillator (VCO) is presented that offers wider tuning range than the basic Colpitts structure with comparable phase noise performance. The modification entails the addition of a negative-resistance to compensate for the low-Q of the micro-strip lines used as the inductive element. Simulations show a 15 % increase in tuning range for the modified Colpitts VCO, a significant improvement over that of the basic structure.

1. INTRODUCTION

Integrated VCOs in the 40 GHz and above frequency ranges have recently been reported in the literature. These are typically LC oscillators comprised of a resonant tank and active devices, either MOS or bipolar [1][2]. Although bipolar has been the preferred active device for RF circuits, LC oscillators in CMOS technology are being developed that boast of low cost and low power consumption [2]. The inductive element, physically implemented as planar spirals or micro-strip lines in the available metal layers, has poor quality factor due to inherent limitations of the process technology. At frequencies above 40 GHz, micro-strip lines offer advantages over the spiral inductor in terms of accuracy of modeling and optimized quality factor [1]. However, the achievable Q value of micro-strip lines is still low, thus limiting the tuning range and adversely affecting phase noise performance of the oscillator.

In this paper, we modify the well-known basic Colpitts topology with the addition of a negative-resistance that compensates for the low-Q of the micro-strip lines used as the inductive element. We study the result of this modification from tuning range and phase noise viewpoints. A basic Colpitts VCO and the modified-Colpitts VCO are designed in a 125-GHz f_T SiGe HBT technology. The micro-strip lines are implemented in metal layers 5 and 6. The VCOs operate under a supply voltage of 3.3V.

This paper is organized as follows. In the following section, the requisite background and the motivation for modifying the basic-Colpitts structure are discussed. The circuit implementation and simulation results for the two VCOs are presented next. Finally, a comparison of the two architectures is made.

2. BACKGROUND

2.1 Basic Colpitts Circuit

The basic Colpitts oscillator is shown in Fig. 1. Routine analysis of the circuit gives the oscillation criterion and frequency of oscillation when the criterion is precisely met. Using a parallel loss model for the inductor, the following characteristic polynomial is obtained

$$s^3 + s^2\left(\frac{LG_p(C_L + C_\pi)}{LC_LC_\pi}\right) + s\left(\frac{C_L + C_\pi + g_mG_pL}{LC_LC_\pi}\right) + \frac{g_m}{LC_LC_\pi} = 0 \quad (1)$$

where G_p models inductor loss. We know that a system with the following characteristic polynomial

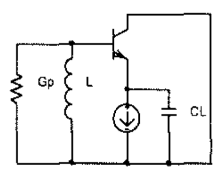

Fig. 1 Basic Colpitts Circuit

$$s^3 + a_2s^2 + a_1s + a_0 = 0 \quad (2)$$

(a_0, a_1, a_2 are positive) will oscillate at

$$\omega_o = \sqrt{a_1} = \sqrt{\frac{a_0}{a_2}} \quad (3)$$

if

$$a_0 > a_1a_2 \quad (4)$$

The oscillation criterion for the basic Colpitts structure is then

$$g_m > \frac{G_p(C_L + C_\pi)(C_L + C_\pi + g_mG_pL)}{C_LC_\pi} \quad (5)$$

The inductor Q is defined as

$$Q = \frac{1}{\omega_o LG_p} \quad (6)$$

From (5) and (6) it follows that the oscillation criterion is

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$$g_m > \frac{C_L \omega_T}{\left(\frac{Q^2 \omega_T^2 C_L L}{1+1/Q^2}\right)^{1/3} - 1} \qquad (7)$$

where ω_T, the BJT cut-off frequency is defined as

$$\omega_T \cong \frac{g_m}{C_\pi} \qquad (8)$$

From (1) and (3) the following expression for ω_o at the start of oscillation (under equality condition in (5) or (7)), is obtained:

$$\omega_0 = \sqrt{\frac{C_L + C_\pi + g_m G_p L}{L C_L C_\pi}} = \sqrt{\frac{g_m}{L G_p (C_L + C_\pi)}} \qquad (9)$$

From (7), it is observed that in a given process and for a given biasing current, inductance and load capacitance, the Q of the inductor determines the range of frequencies at which the circuit will oscillate, a wider range being attainable with higher Q. It follows from (6) that this range can be extended by reducing the 'effective' G_p across the inductor.

2.2 Modified Colpitts Circuit

Fig. 2 illustrates the concept of boosting the inductor-Q by partially compensating for its losses.

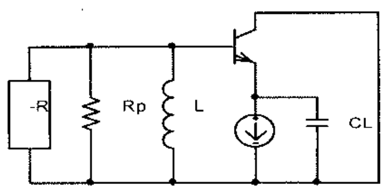

Fig. 2 Modified Colpitts Circuit

For this circuit, it can be seen that by making $|-R| \rightarrow R_p$, the Q of the inductor can be made very large. The negative resistance can be achieved using cross-coupled BJTs [3]. The micro-strip lines used in this work, have a Q of about 4 at a frequency of 40 GHz and an inductance of 280 pH. The Q-enhancement technique is implemented in a Colpitts-type VCO that uses micro-strip lines as the inductive element. The design of differential Colpitts VCOs with and with out negative-resistance is described in Sections 3 and 4 respectively. The tuning range and the phase noise performance of the two VCOs are compared in order to understand the effect of negative resistance.

3. COLPITTS VCO DESIGN

3.1 Circuit Implementation

A simplified schematic of the VCO circuit based on basic Colpitts topology is shown in Fig. 3. The VCO core uses differential version of the circuit in Fig. 1, similar to [1]; the inductor between the two bases is formed as micro-strip lines. Physically they are implemented with the top-most metal layers of the process. The value of the inductance chosen was 280pH, which had a Q of 4 at 40 GHz.

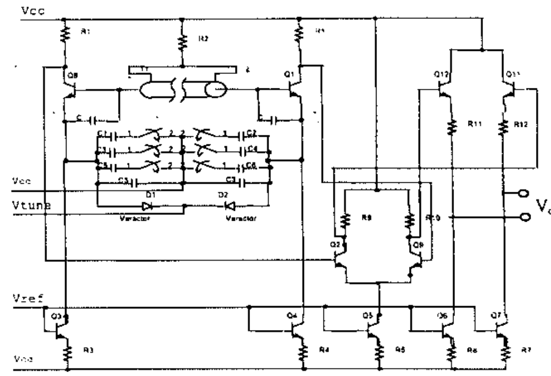

Fig. 3 Schematic of differential Colpitts VCO

Field-solver was used to obtain a transmission-line model for the micro-strip lines, an element of which is shown in Fig. 4. Cascade of these elements is used to achieve desired inductance. The minimum possible value of the inductance was chosen for the particular design to achieve maximum Q.

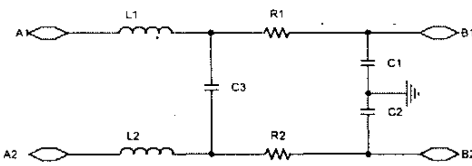

Fig. 4 An element of the transmission line model

The resonant tank consists of the inductor, fixed capacitors, varactor diodes and switched-capacitor arrays. After an optimum value of the inductance has been chosen, the fixed-capacitances were selected such that the center oscillation frequency, as given by (10), is 40 GHz.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \qquad (10)$$

In the above equation, C represents the total tank capacitance which includes the fixed capacitances, the parasitic capacitances of the BJT (e.g. C_π), varactor diode capacitance (C_v), switched-array capacitance (C_c) and the micro-strip line parasitic capacitance (C_T). Frequency tuning is possible by adjusting C_v and C_c using external voltage. The varactor diodes enable fine-tuning determined by the equation of the form:

$$\Delta C \geq 2C \frac{f_{\max} - f_{\min}}{0.5(f_{\max} + f_{\min})} \qquad (11)$$

ΔC is the fraction C that must be variable to tune between f_{max} and f_{min}.

The resistor in the micro-strip line tap sets the dc bias at the bases of the transistors and provides coupling to generate out-of-phase signals. Buffer and level-shifter isolate the VCO from the output load while maintaining appropriate dc levels in the circuit. The current sources are implemented with BJTs Q_3, Q_4, Q_5, Q_6 and Q_7 together with the series connected resistors R_3, R_4, R_5, R_6, and R_7. The tail currents can be adjusted by changing the resistor values.

3.2 Simulation Results

Simulations were performed on the VCO using the vendor supplied Spectre models. Gummel-Poon BJT models were used. The parameters that were adjusted to meet requirements are the emitter length of the BJT (width is fixed), the number of anodes and the anode width of the varactor diode. Accordingly, emitter area = 10.16μm x 0.2μm was used for the transistors in the VCO core, buffer, level-shifter and the switches. The emitter areas for the current source transistor were set according to the tail current requirements.

Fig. 5 shows the frequency-tuning characteristic of the VCO as a function of the control voltage. Combined adjustments of C_v and

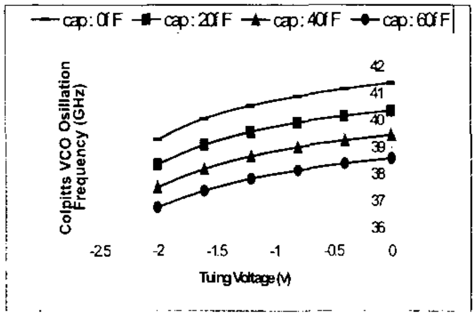

Fig. 5 Tuning characteristic at different coupling capacitances

C_c, gave oscillation frequencies between 36.7 GHz and 41.4 GHz. The total tuning range is 11.7 %. The simulations were also performed over three process corners (SLOW, NOM and FAST) and over a wide temperature range (-20° C to 120° C). The tuning range for which the VCO was designed made it possible to restore the frequency to near 40 GHz, when caused to drift due to process and temperature variations.

The phase noise of the VCO was simulated using Spectre *pss* and *pnoise* analyses. Ten output harmonics and five maximum sidebands were chosen. The beat period is first determined from transient analysis. At 5 MHz offset from the carrier, the phase noise is −96 dBc/Hz. The phase noise plot is shown in Fig. 10.

The final layout of the VCO core, buffer and level shifter stages is shown in Fig. 6. Micro-strip lines are laid out in Metal 6 over a layer of Metal 5.

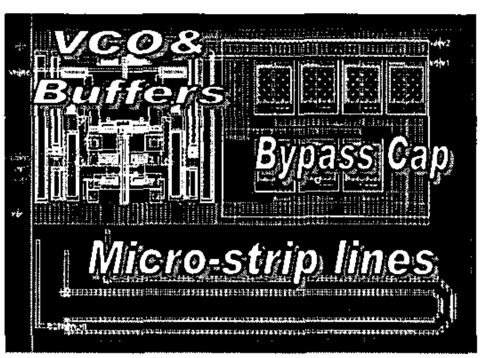

Fig. 6 Layout of Colpitts VCO

4. MODIFIED COLPITTS VCO DESIGN

4.1 Circuit Implementation

The overall circuit implementation is depicted in Fig. 7. The value of the inductance chosen was 590pH with a Q of 1.4 at 40GHz. As discussed earlier, the optimal inductance was chosen based on the tranmission line model.

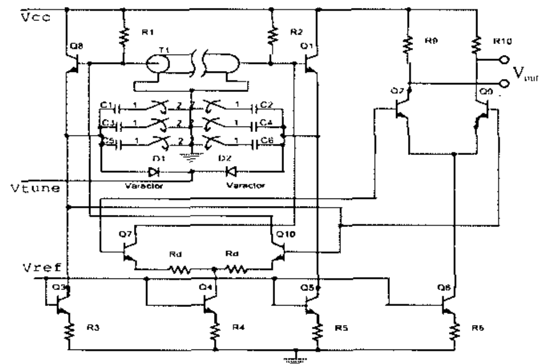

Fig. 7 Schematic of modified Colpitts VCO

The negative resistance is implemented with two bipolar junction transistors Q_7 and Q_{10}, as shown in Fig. 7. The magnitude of resistance, |-R| of the cross-coupled pair can be increased by decreasing the resistors R_d. Its value is adjusted to compensate the losses in the resonant network. BJTs with large emitter areas were used in the core to achieve high loop-gain to start with. The buffer is used to isolate the load from the VCO core. The bias current of the buffer and the resistors R_9 and R_{10} can be adjusted to get the required output swing. The tail currents can be adjusted by changing the resistors connected in series with transistors Q_3, Q_4, Q_5 and Q_6. The switched capacitor array and the varactor diodes provide coarse and fine frequency tuning.

4.2 Simulation Results

The capacitors array was designed to have 4 steps: 0, 40f F, 70f F and 120f F. The oscillation frequency and its corresponding tuning voltage adjustment are shown in Table 1. Fig. 8 is the plot of frequency vs. V_{tune} with different C_c values. From the data in Table 1, it can be seen that the adjustable range is narrower, given a higher Cc value. The adjustable range is between 2.1% and 10.4%. This can be easily explained. The adjustment percentage ε is

$$\varepsilon = \frac{\Delta C_T}{C_c + C_v + C_T} \tag{12}$$

For a given ΔC_T, if C_c increases, ε decreases. The total tuning range is 38.3 GHz - 49.6 GHz, which is 28.3 %. The phase noise was simulated under the same conditions as stated in Section 3. It is shown in Fig. 10. The phase noise at 5 MHz offset from the carrier is −91 dBc/Hz.

The final layout is shown in Fig. 9.

Table 1 Nominal oscillation frequencies and tuning voltage adjustment

C_c	**Nominal Freq.(GHz)**	Adjustment (%)
0	47	10.4
40	43	5.6
70	41	3
120	38.75	2.1

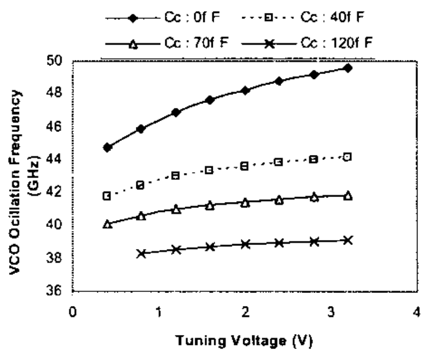

Fig. 8 Frequency Tuning Characteristic

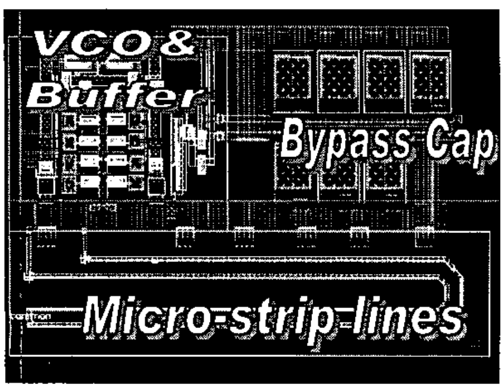

Fig. 9 Layout of Modified Colpitts VCO

5. PHASE NOISE AND TUNING RANGE COMPARISON

Fig. 10 shows the phase noise plots for the two VCOs, obtained at a fundamental frequency of 41 GHz.

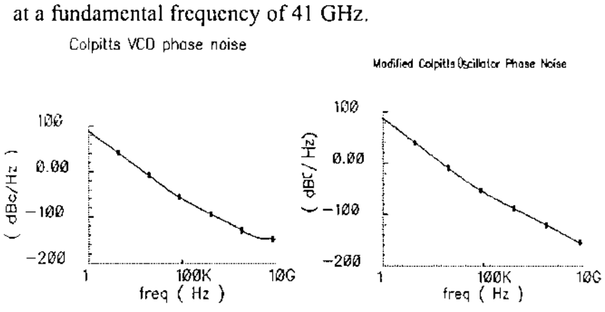

Fig 10 Phase noise of the VCOs

Table 2 summarizes the performance of the VCOs. The figure of merit (FOM) proposed in [4] has been used for the comparison of phase noise performance. It is observed that the addition of negative resistance to the basic Colpitts structure increases the tuning range by about 15 %. This quite reasonably demonstrates the concept of partially compensating inductor losses and increasing its Q thereby meeting the oscillation criterion at wide range of frequencies.

Table 2 Summary of performance measures of VCOs

	Basic Colpitts	Modified Colpitts
Supply voltage	3.3 V	3.3 V
Tuning range	36.7 – 41.4GHz	38.3 – 49.6GHz
Tuning voltage	1.3 – 3.3 V	0.4 – 3.3 V
Power dissipation	83 mW	66 mW
Phase noise at 5 MHz offset	-96 dBc/Hz	-91 dBc/Hz
FOM = – phase noise – 10log (power)	106.8 dBF	102.8 dBF

6. CONCLUSION

A modified Colpitts-type voltage controlled oscillator was introduced that has an increased tuning range compared to that of the basic Colpitts VCO. A 15 % increase in tuning range was obtained at a fundamental frequency of 40GHz by the addition of a negative-resistance in shunt with the inductive element. This improvement comes with no significant degradation in phase noise.

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7. REFERENCES

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