Design of low phase noise InGaP/GaAs HBT-based differential Colpitts VCOs for interference cancellation system

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This paper presents design, fabrication and characterization of two differential Colpitts voltage controlled oscillator (VCOs) - cross-coupled VCO (CC-VCO) and double cross-coupled VCO (DC-VCO) - in InGaP/GaAs HBT technology. Their main parameters like the oscillation frequency, output power and phase noise performance are measured and compared with other recently published studies. In the cores of two VCOs, two switching transistors are introduced to steer the core bias current to save power. An LC tank with higher inductor quality factor \(Q\) is used to generate oscillation frequency. The differential CC-VCO exhibited a superior phase noise characteristics of -130.12 dBc/Hz at 1 MHz from the carrier frequency (1.566 GHz) when supplied with a control voltage of 0 volt. In the same way, the differential DC-VCO achieved -134.58 dBc/Hz at 1 MHz from the carrier frequency (1.630 GHz) with the same control voltage. Two pairs of on-chip base collector (BC) diodes are used in the tank circuit to increase the VCO tuning range. It is concluded that the faster switching action of InGaP/GaAs HBT transistors exhibited the excellent phase noise characteristics.

Keywords: Differential VCO, InGaP/GaAs HBT VCO, MMIC VCO, Voltage controlled oscillator, Differential Colpitts VCO, Low phase noise VCO, Colpitts oscillator

The proposed differential Colpitts VCOs are designed using InGaP/GaAs HBT process for the down converter block of an adaptive feedback interference cancellation system (AF-ICS) application\(^1\). The AF-ICS system cancels the feedback signal from the transmitting antenna by generating anti-phase, same amplitude and same time delay in a ‘transmit and receive’ system of the wireless repeater system. The configurations of two VCOs are introduced in this study, one is a cross coupled (CC-VCO) and the other is double cross coupled (DC-VCO). Both are designed differentially in Colpitts structure. A Colpitts voltage controlled oscillator is widely used in wireless communication system using various technologies due to its good cyclostationary properties and potentially lower phase noise characteristics. Wang et al.\(^2\) reported that bipolar transistors have better switching properties when implemented in Colpitts structure. In comparison with other oscillator configurations, the Colpitts oscillator has fairly good frequency stability, and easy tunability, and can be used for a wide range of frequencies.

The designed VCOs used InGaP/GaAs HBT process which produces further phase noise suppression due to the use of a ledge located between the base metal and emitter. The ledge also reduces intrinsic semiconductor noise. High linearity transistors, HL_F2\(\times2\times20\) (number of emitter fingers, width and length in micrometer respectively) and base-collector (BC) diodes, BC_35\(\times40\) (width and length in micrometer respectively). This high linearity process has a cut-off frequency \((f_T)\) of 50 GHz and a maximum oscillation frequency \((f_{MAX})\) of 80 GHz.

Circuit Designs and Layouts

In this work, two VCO topologies, differential cross-coupled Colpitts VCO (CC-VCO) and differential double cross-coupled Colpitts (DC-VCO) are demonstrated and achieved good VCO performances. The bias circuit and buffer circuit are designed as shown in Fig. 1 in which transistor \(T_{C0}\) is diode-connected to lower the current and it provides somehow temperature compensation also. In order to lower the further current, the emitter of transistor \(T_{C0}\) is connected with the resistor, \(R_b\). Identical transistors, \(T_{C1}\) and \(T_{C2}\) are used to get unity gain and transistor \(T_{C1}\) is diode-connected where collector-base voltage forces to maintain the same voltage as in the collector\(^3\). Therefore, transistors \(T_{C1}\) and \(T_{C2}\) act as a current mirror circuit in which amount of current at the collector of \(T_{C1}\) and \(T_{C2}\) thereby having the same amount of current at the collector of the \(T_{C3}\) and \(T_{C4}\).

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The four emitter degeneration resistors $R_{e1}$, $R_{e2}$, $R_{e3}$ and $R_{e4}$ are used to improve the noise and the matching performances. The emitter follower output buffer circuits ($T_5$ and $T_6$) are added on both sides of the VCOs core output.

In Fig. 2, the base of the transistors, $T_1$ and $T_3$ are directly connected to collector of $T_4$, and in the same way, the base of $T_2$ and $T_4$ are connected to the collector of the $T_3$ and thus made cross-coupled to have a differential configuration. These transistors are base-biased in the base-emitter junction using optimized value of resistors in both sides. Transistors $T_1$ and $T_2$ act as switches to control the transistors $T_3$ and $T_4$. Therefore, it can reduce the DC power in the core of the VCO (since VCO core is consist of $T_3$, $T_4$, $C_1$ and $C_2$). But in Fig. 3, transistors $T_1$ and $T_2$ made cross-coupled and $T_3$ and $T_4$ are also the same, hence the name double cross-coupled (DC-VCO). The designed Colpitts VCOs consist of asymmetric tank structure, VCO core, output buffer amplifiers and bias network. The energy loss in the active device is usually a strong function of its voltage and current waveforms. The energy transfer efficiency can be improved by proper timing of the voltage and current. And also the energy loss in the LC tank is provided by the transconductance of the active circuit. These switching transistors $T_1$ and $T_2$ in DC-VCO reduce the current consumption in the VCO core by switching current alternately and it can help to reduce DC power in the core. These transistors also guarantee the start up condition by enhancing the small signal loop gain due to use of negative resistance. In both designs, LC tank is used and the inductance value is optimized to achieve superior phase noise. The tank energy should be maximized that leads to a maximization of the tank inductance. The tank circuit is designed for tank amplitude comparable with the breakdown voltage of the chosen active device. The ratio of feedback capacitors ($C_1$ and $C_2$) gives a great impact on selecting frequency.

The voltage control part is composed of two pairs of BC-diodes (which are integrated in the same chip) with an LC tank structure to achieve wide tuning range. In order to improve the phase noise characteristics, the quality factor, $Q$ of the tank circuit
is very important since it determines the major phase
noise suppression of the VCO. Therefore, \( Q \) factor of
inductor used in LC tank of each configuration is 12.8
at 1.566 and 12.4 at 1.630 GHz (Fig. 4) respectively.
These inductors have low series resistance which are
good for maintaining VCOs performance. After
layout performance of cross-coupled (CC-VCO) and
double cross-coupled (DC-VCOs) VCOs, these VCOs
were implemented with commercially available
6-inch InGaP/GaAs HBT process. The fabricated
CC-VCO and DC-VCO are shown in Figs 5 and 6
respectively with the size of \( 1.07 \times 0.9 \) mm\(^2\) and
\( 0.9 \times 0.9 \) mm\(^2\).

Measurement Results
The VCOs were measured using Agilent’s
spectrum analyzer (E4440A) after mounting the chips
on PCB test board and connecting the necessary
wire-bondings. Figure 7 shows the output spectrum
and phase noise characteristics of cross-coupled VCO
(CC-VCO). The CC-VCO produced excellent output
power of -5.3 dBm. It can be tuned within 168 MHz
with a control voltage of 0 to 3.3 V. It has superior
phase noise of -105.3 dBc/Hz and -130.12 dBc/Hz at
100 kHz and 1 MHz offset frequencies respectively
from the carrier frequency of 1.566 GHz. The double
cross-coupled VCO (DC-VCO) shows the output
spectrum with a low phase noise of -122.38 dBc/Hz
and -134.58 at 100 kHz and 1 MHz offsets
respectively from the carrier frequency 1.630 GHz as
shown in Fig. 8 and it generates output power of
-3.91 dBm. The DC-VCO has tuning range of 218
MHz when supplying control voltage of 0 to 4.2 V.
Figure 9 shows the variation of output power and
oscillation frequency as a function of control voltage
of cross-coupled VCO (CC-VCO). Figure 10 shows
the variation of output power and oscillation
frequency as a function of control voltage of
DC-VCO.

The figure-of-merit (FoM) is also another
important parameter used in evaluating the phase
noise performance of the VCO and it confirms the
quality of spectral purity. It is useful in comparing the performance of oscillators with different parameter values. The widely used Leeson’s formula can be used for calculating the FoM calculation:

\[
FoM = L(\Delta f_m) - 20\log \left( \frac{f_0}{f_m} \right) + 10\log \left( \frac{P_{dc}}{1\text{mW}} \right),
\]

where \( L(\Delta f_m) \) is the phase noise spectral density, \( P_{dc} \), is the DC power dissipation of the VCO core, \( f_o \), is the oscillation frequency and \( f_m \) is offset frequency. Eq. (1) describes the maximum suppression of phase noise in the VCOs. The calculated value of FoM for CC-VCO is around -182 dBc/Hz with dissipated power of 16.65 mW and in the same way, for the DC-VCO is -187 dBc/Hz with dissipated power of 13.2 mW. Comparatively, DC-VCO achieved better FoM characteristics than CC-VCO. The performance of designed VCOs is summarized in Table 1. The DC-VCO exhibited better VCO performance than CC-VCO due to faster switching action and relaxed oscillation condition. Table 2 shows the comparison

![Fig. 7 — Phase noise characteristics of cross-coupled VCO](image1)

![Fig. 8 — Phase noise characteristics of double cross-coupled VCO](image2)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>CC-VCO</th>
<th>Measurements results</th>
</tr>
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<tbody>
<tr>
<td>Supply voltage</td>
<td>V</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Total current</td>
<td>mA</td>
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<td>15</td>
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<tr>
<td>Osc. frequency</td>
<td>GHz</td>
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<td>1.630</td>
</tr>
<tr>
<td>Phase noise</td>
<td>dBc/Hz</td>
<td>-105.3@106 kHz -130.12@1 MHz</td>
<td>-122.38@106 kHz -134.58@1MHz</td>
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<tr>
<td>Output power</td>
<td>dBm</td>
<td>-5.3</td>
<td>-3.91</td>
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<tr>
<td>Tuning range</td>
<td>MHz</td>
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<td>218</td>
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<tr>
<td>2nd Harmonics</td>
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<td>Chie size</td>
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of phase noise and figure-of-merits (FoM) characteristics of differential VCOs in InGaP/GaAs HBT Technology with other recently published results. The present study shows good VCO characteristics.

Conclusions

Two VCOs were fabricated and characterized for ICS application using InGaP/GaAs HBT Technology. The cross CC-VCO achieved low phase noise of -130.3 dBc/Hz at 1 MHz offset from the carrier frequency 1.566 GHz and the DC-VCO achieved excellent phase noise of -134.58 dBc/Hz at 1 MHz offset from the carrier frequency 1.630 GHz. Optimized feedback capacitors \(C_1\) and \(C_2\) ratio were used to improve desired output wave form. The DC-VCO exhibited better characteristics when compared with the first one due to faster switching action and relaxation start-up state. These two VCOs achieved good output power and are quite comparable to the VCOs designed with the same technology as indicated in the Table 2. The designed VCOs have significant impact on practical application in not only ICS but also in other wireless systems.

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References


Table 2—Comparison of the designed MMIC VCOs with other published studies

<table>
<thead>
<tr>
<th>References</th>
<th>(P_{out}) (dBm)</th>
<th>Freq. (GHz)</th>
<th>PN@1MHz (dBc/Hz)</th>
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<tbody>
<tr>
<td>[2] 0.35 BiCMOS</td>
<td>-</td>
<td>2.8</td>
<td>-123</td>
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<td>[7] InGaP/GaAs HBT</td>
<td>-10.25</td>
<td>1.721</td>
<td>-133.9</td>
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<td>[8] 0.35 CMOS</td>
<td>-</td>
<td>1.96</td>
<td>-129</td>
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<td>[9] InGaP/GaAs HBT</td>
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<td>-130.12</td>
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<tr>
<td>Present work (DC-VCO)</td>
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<td>-134.58</td>
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