A 220 MHz Low PhaseNoise Colpitts Oscillator

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Invited paper

***Abstract*—This paper presents the design of a VCO using Colpitts topology. The VCO is designed to work at 220 MHz as part of the Frequency Generating Unit (FGU). The circuit has been realized by discrete level circuits. The frequency range is between 217 MHz and 222 Mhz. The low phase noise of -122 dBc/Hz at 20 kHz offset frequency was achieved by the varactor tuned Colpitts oscillator. Both simulation and measurements demonstrate the low noise performance.**

I. INTRODUCTION

In typical wireless communication systems, both receiving and transmitting parts use Voltage-Controlled Oscillator (VCO) in the frequency synthesizer to generate the local oscillator (LO) signals for the mixers. The phase noise of the VCOs affects both the received and transmitted spectrum noise levels.

The increasing demands for the professional radios bands have pushed to the 220 MHz band. The 220 MHz band contains the frequency range between 217MHz and 222 MHz, which expands the limited capacity of VHF and UHF bands. Motorola Solutions Inc is developing a new professional digital 2-way radio system for the 220 MHz band, as a part of the MotoTRBO series radios. We hereby introduce the Colpitts oscillator as LO circuit for the Tx frequency synthesizer.

As shown in Fig 1, the Colpitts oscillator [1] has a resonance tank made of two capacitors and one inductor. The feedback is taken from the divider of two capacitors.

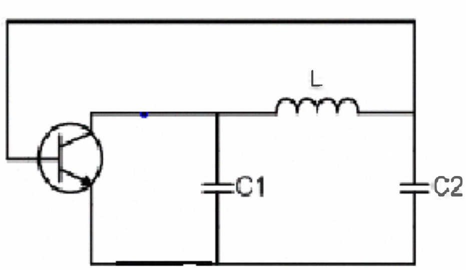

Figure 1. Closed loop Colpitts VCO architecture

Section II is about the circuit design of the Colpitts VCO and the discussion of the performances including the phase noise and stability. Section III presents the measurements of the designed circuits. Section IV gives a final conclusion.

II. THE DESIGN OF THE VCO AND DISCUSSION

A simple Colpitts Oscillator is shown in Figure 1. It consists of a bipolar junction transistor (BJT) and an LC tank to feedback the signal. The fundamental oscillation frequency is given in equation (1) below:

$$f = \frac{1}{2\pi\sqrt{L\frac{C1C2}{C1+C2}}} \qquad (1)$$

The phase noise from the VCO can corrupt the signal from the mixer. The phase noise [2, 4, 6] from the signal path of the oscillator can be expressed by the Leeson's equation (2) below:

$$\begin{aligned} SBNR &= 10\log\left\{\left(\frac{FkT}{2P_{avs}}\right)\left[1+\left(\frac{f_o}{2f_mQ_L}\right)^2\right]\right\} \\ &= 10\log 0.5 + 10\log kT + 10\log F - 10\log P_{avs} + 10\log\left[1+\left(\frac{f_o}{2f_mQ_L}\right)^2\right] \\ &= -3(dB) - 174(dBc/Hz) + NF(dB) - P_{avs}(dBm) + 20\log\left(\frac{f_o}{2f_mQ_L}\right) \end{aligned} \qquad (2)$$

The first four terms are phase noise floor. The 2nd term of -174 dBc/Hz is the thermal noise floor, and NF is the noise figure of the transistor. In the last term, f_o is the carrier frequency and f_m is the offset from the carrier frequency .The single side band noise ratio (SBNR) expression in equation (2) shows clearly that increasing loaded quality factor Q improves the phase noise.

The phase noise from the control voltage can be expressed in equation (3) below.

$$L(f) = 20\log\left(\frac{Kv\,Vn}{2fn}\right) \qquad (3)$$

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The K_v is the tuning sensitivity, and V_n is the amplitude of the input noise. The phase noise improves as the tuning sensitivity decreases

Figure 2 shows the schematic of the Colpitts VCO we designed. Based on the equations (2) and (3), the oscillator with low phase noise can be achieved by high tank quality factor Q and low tuning sensitivity Kv. The 2 varactors CR1 and CR2 have a back-to-back topology in order to reduce the RF voltage across each varactor and also reduce the harmonic distortion. The L and C form the main tank and determine the fundamental frequency of the oscillator. The varactors are coupled to the main tank through the varactor coupling capacitor Cvc. The Q value can be increased by splitting the coupling capacitor Cvc, therefore a better phase noise could be achieved .The LC tank energy is also coupled to the transistor via the tank coupling capacitor Ctc. The feedback loop is completed by the emitter feedback resistor Re, and it increases the transistor input impedance and improves the SBNR. The emitter choke Le provides high impedance to reduce loading effect of the emitter resistor.

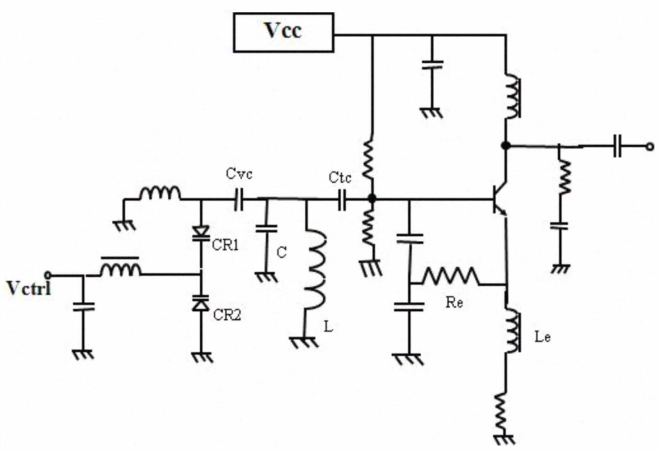

Figure 2. Schematic of the Colpitts VCO

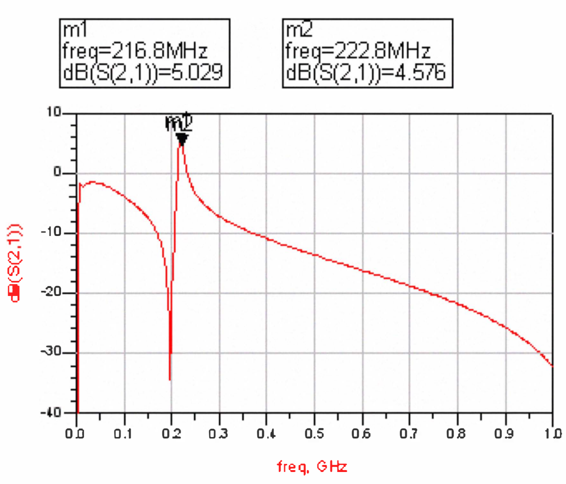

Figure 3 (a) gain of the open loop oscillator

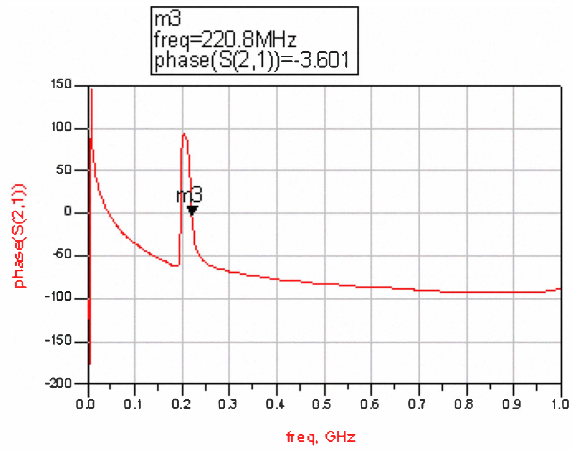

Figure 3(b) phase of the open loop oscillator

In order to verify the stability of the VCO at 220 MHz, an open loop analysis was done by ADS simulation. The components' models contain the parasitic effects and their accuracy can be proved in the comparison with experimental results.The feedback loop was opened at the emitter resistor. The gain and phase diagrams in Figure 3 suggest the VCO oscillate stably at 220 MHz, since the loop has a positive gain only at the design frequency and also a zero degree phase with negative slope.

The VCO startup margin is estimated by the formula derived by Randall and Hock [3] in equation (4). The gain margin calculated turns out to be very good. Therefore the open loop analysis proves the stability of the VCO at 220 MHz and gain margin that's enough to start up oscillation.

$$G = \frac{S_{21} - S_{12}}{1 - S_{11}S_{22} + S_{12}S_{21} - 2S_{12}} \qquad (4)$$

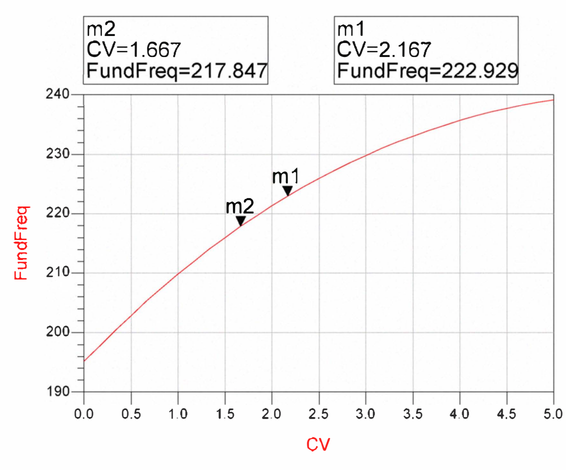

Figure 4 Control voltage Cv for the VCO

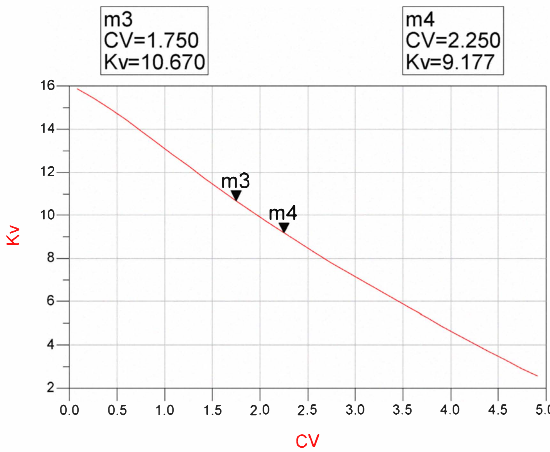

Figure 5 Tuning sensitivity of the VCO

The simulated control voltage Cv and tuning sensitivity Kv under different control voltage are shown in Figure 4 and Figure 5. The desired voltage range for the design frequency range of 5 MHz is from 1.6 V to 2.1 V, and the Kv is around 10 MHz/V. There's enough control voltage margin to tolerate the components' variation, parasitic effects and shields that covers the VCO.

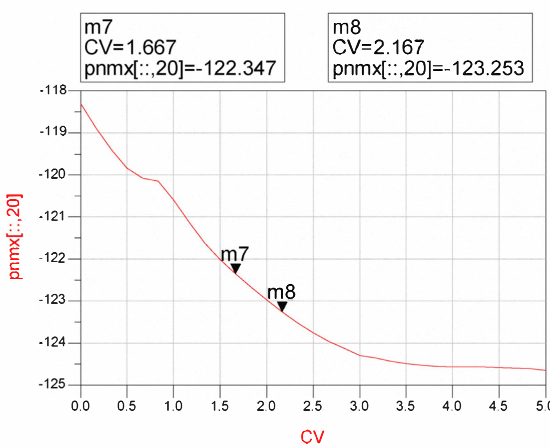

Figure 6 Phase noise at 20 KHz offset

The simulation of the single side band noise ratio (SBNR) at the offset of 20 KHz under all the control voltage range is presented in Figure 6. We can see the SBNR is all below -122 dBc/Hz within the desired voltage range.

The RF voltages on the common terminal of the varactors are shown in Figure 7 in time domain, with curves corresponding from 0V to 5V control voltage. The voltage on the varactors is always above -0.6 V, so the varactors are always reverse biased.

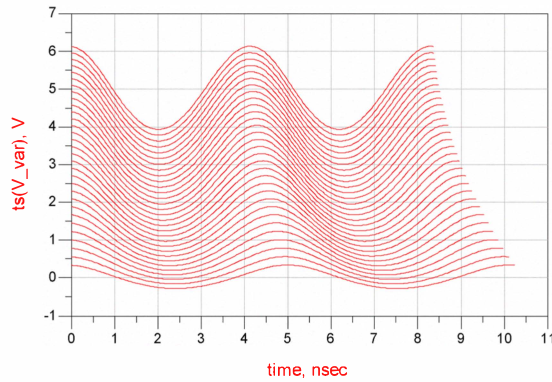

Figure 7. Simulated voltage on the varactor in time domain

III. EXPERIMENTAL RESULTS

The oscillator has been realized on the PCB with discrete components. Verification is done on the open loop VCO without external frequency synthesizer. The measurements were done with Agilent 4352B signal source analyzer [5].

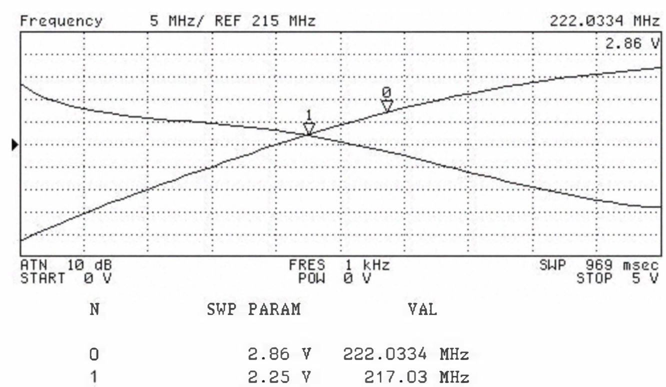

Figure 8 Kv and control voltage curve for the VCO

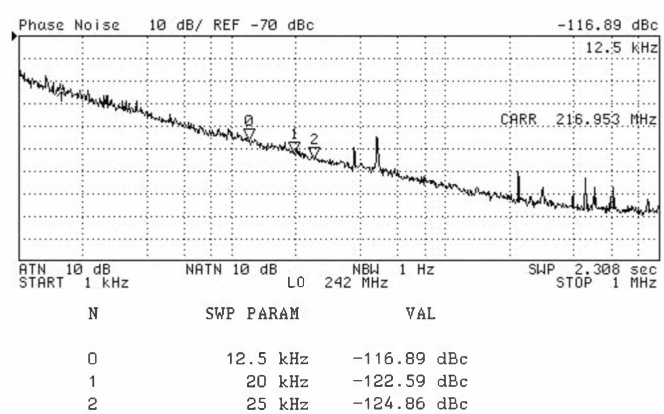

Figure 9 (a) measured SBNR of the VCO at 217 MHz

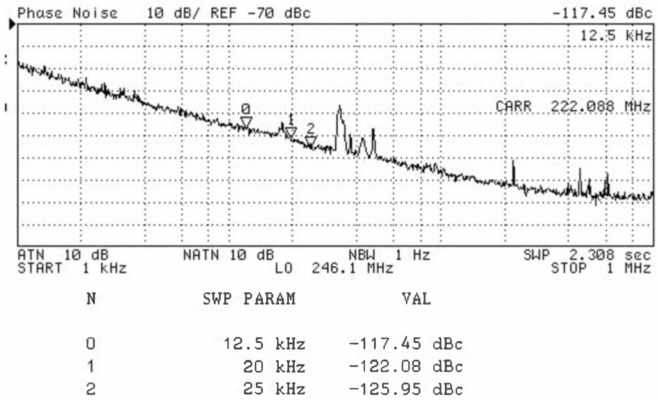

Figure 9 (b) measured SBNR of the VCO at 222 MHz

The control voltage (Cv) and tuning sensitivity curve are measured for the VCO system as shown in Figure 8. The increasing curve is for the frequency, and the voltage range is between 2.25 V to 2.86 V for the 217 MHz to 222 MHz range. The tuning sensitivity varied between 7.3 MHz/V to 8.8 MHz/V. The measured single side band noise ratio at 217 MHz and 222 MHz is presented in Figure 9 (a) and Figure 9 (b). The SBNR at offset of 20 KHz is below -122 dBc/Hz, based on the graphs.

The comparison between simulations and measurements is made in the Table 1. The measured results show good agreement with the simulation and suggest the accuracy of our components models with parasitics.

Parameters	Simulations	Measurements
Frequency range	217~ 222 MHz	217 ~222 MHz
SBNR - 12.5 kHz	-118.5 dBc/Hz	-116.9 dBc/Hz
SBNR - 20 kHz	-122.4 dBc/Hz	-122.1 dBc/Hz
SBNR - 25 kHz	-124.3 dBc/Hz	-124.9 dBc/Hz
Tuning sensitivity	9.2~10.7 MHz/V	7.3~8.8 MHz/V

Table 1. summarized simulation and measurements.

IV. CONCLUSION

A VCO architecture for the 220 MHz professional 2-way radio has been proposed and fabricated. The Colpitts topology oscillator was used to achieve the low phase noise. The theory to reduce the phase noise for the VCO has been discussed. Control voltage range, tuning sensitivity and SBNR are both simulated and measured, and they turn out to be in good agreement.

REFERENCES

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[4] T. H. Lee and A. Hajimiri, "Oscillator Phase Noise: A Tutorial", IEEE Journal Of Solid-State Circuits, Vol. 35, No. 3, March 2000

[5] Agilent 4352B service manual

[6] A. Hajimiri, et al., *The Design of Low Noise Oscillators*, Kluwer Academic Publishers, 1999.