HIGH POWER VARACTORLESS VOLTAGE CONTROLLED OSCILLATOR (HPV^{2}CO) DESIGN

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ABSTRACT

This paper presents a new technique for designing a Voltage Controlled Oscillator (VCO) based on a novel architecture by avoiding the usage of a varactor, or a capacitive tuning element which enables high power VCO output. With conventional designs, high power is not possible due to rectification occurring in the varactor diode. The High Power Varactorless VCO (HPV^{2}CO) eliminates the need of several pre-power amplifier stages in conventional telemetry products. Utilizing this technology allows for a single stage transmitter thereby resulting in more compact designs.

INTRODUCTION

Emhiser Research, Ltd. designs and manufactures a complete line of cutting-edge airborne and ground-based telemetry equipment specifically for demanding military applications. The search for innovative solutions to overcome design constraints prompted Emhiser Research to design and develop a unique discrete VCO, paving the way for the realization of single-stage compact high-power transmitters.

Indirect frequency synthesis techniques based on the combination of a VCO and a phase comparator in a phase-locked loop system has been preferred to generate programmable RF frequencies in RF transceiver applications [1]. The basic operation of a VCO in conventional frequency synthesizers is to vary the frequency continuously as a function of a DC-shifted time varying voltage applied to its tuning port. The conventional LC-VCO architecture consists of a voltage dependent capacitive element known as a varactor diode, which is a controllable tuning element. The varactor is AC coupled to the oscillator's active element through other elements of the resonant tank circuit. The capacitance of the varactor can be varied by changing the applied reverse-biased voltage hence it changes the resonant frequency. Since the varactor is a voltage controlled device, it responds to any level of AC signals applied across it. If the peak AC voltage across the varactor surpasses the DC bias voltage, especially at the low tuning voltage, the varactor starts functioning in forward bias, resulting in partial rectification. This issue causes a change in the level of DC bias voltage that results in a distortion in the oscillator operation as shifting the frequency, increasing the losses and degradation in phase noise performance. To overcome the rectification problem, the output power of the VCO needs to be held constant and limited with Automatic Gain Control (AGC) mechanisms [2].

Power-limited VCOs require subsequent pre-amplifier/amplifier stages, as well as inter-stage filters and isolators, to achieve the desired power level at the output of the transmitters. HPV^{2}CO uses a novel design topology without a varactor, or a capacitive tuning element to achieve high power and removes the limitations of the conventional VCOs.

HPV^{2}CO DESIGN

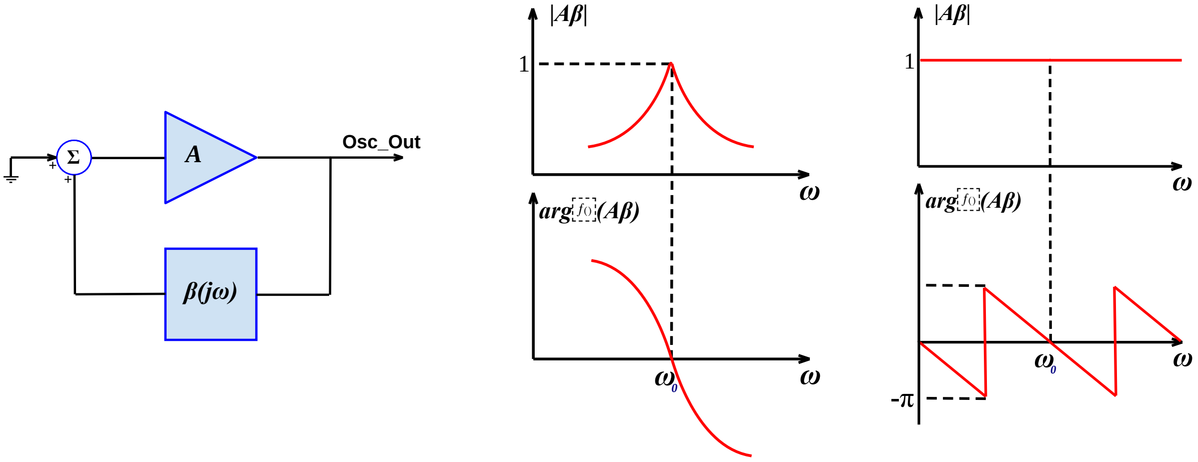
Fundamentals of the Oscillator

The oscillator is a self-sustaining circuit that can generate a continuous periodic waveform at a single or tunable precise frequency without an input signal. A basic feedback oscillator consists of an amplifier with a specified gain and a regenerative feedback network that determines the frequency of the closed loop form [3]. The amplitude and phase conditions of the steady-state oscillating circuit are defined by the Barkhausen criteria given in equations (1, 2).

$$|A\beta(j\omega)| = 1 \tag{1}$$

$$\arg A\beta(j\omega) = 0 \tag{2}$$

In order to satisfy the sustainable oscillation, the total phase shift around the closed loop must be 0 degrees or any integer multiple of 360 degrees, and the loop gain must be equal to 1.



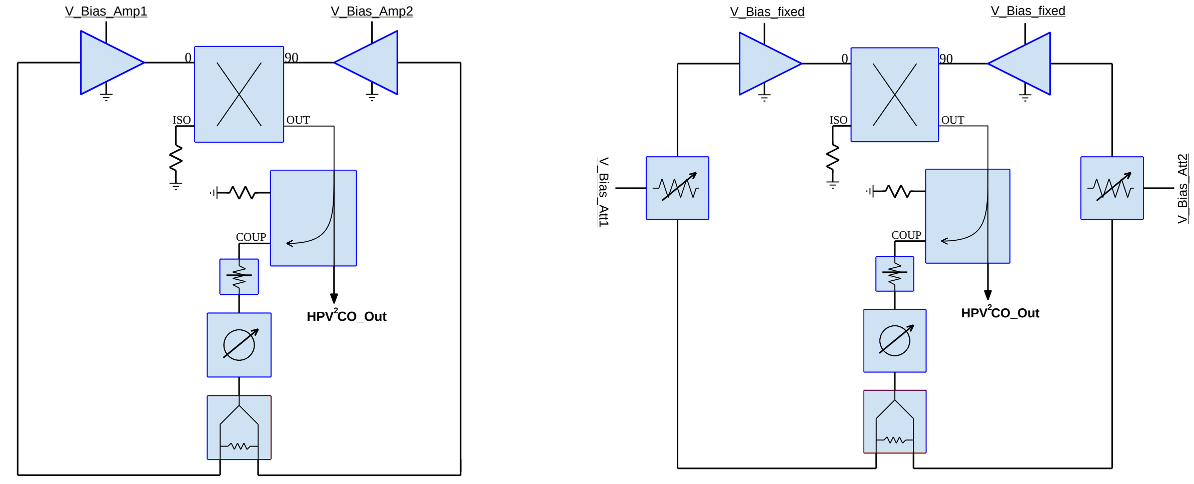
i) ii) iii)

Figure 1. Basic Topology of the Feedback Oscillator

The angular characteristics of the resonator or the delay line in the feedback path determine the oscillation frequency. Using the advantage of positive feedback, the output power of the amplifier increases until the nonlinearity of the amplifier limits the loop gain to unity. Systematically controlling the phase in the feedback path varies the oscillation frequency and ensures a constant oscillation power. On the basis of the feedback loop, frequency can be tunable if an adequate phase control is achieved.

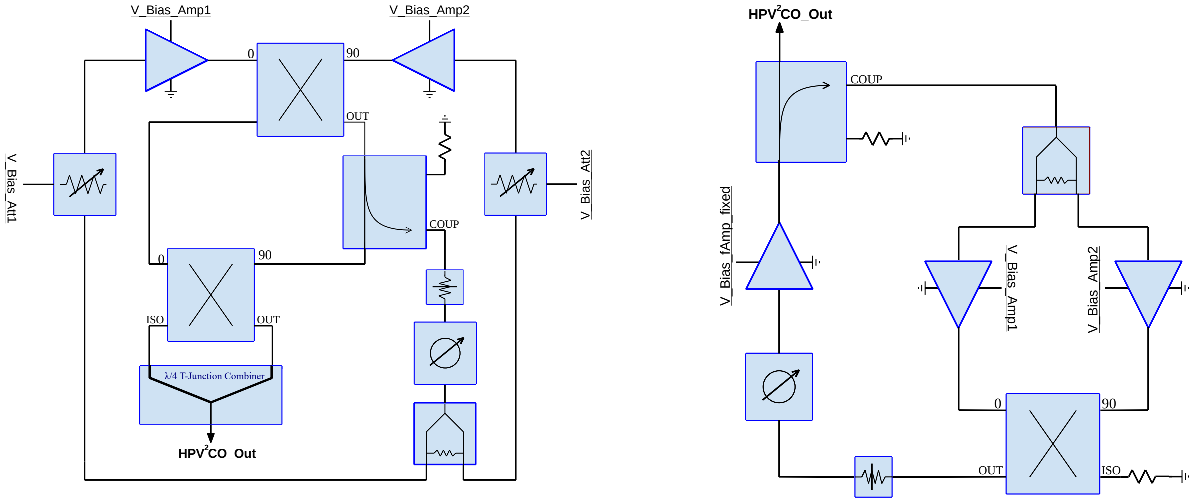
HPV^{2}CO System Design

HPV^{2}CO design is based on the control of the phase in the loop structure which is essentially comprised of identical amplifiers, a quadrature hybrid combiner, and a fixed delay line. In the fundamental HPV^{2}CO design, the identical RF amplifiers are combined using a 90° hybrid coupler with the through/coupled port is sampled with a directional coupler. A fixed phase shift is added to the coupled signal and a fixed attenuation is applied according to the loop power budget before feeding the signal back to the input of each amplifier with equal power and phase division. The oscillator output is provided from the through port of the directional coupler. The block diagram of the primary system design is shown in Figure 2i.



i) Config. 1 HPV^{2}CO with bias controlled amplifiers

ii) Config. 2 HPV^{2}CO with voltage variable RF attenuators



iii) Config. 3 HPV^{2}CO Power Recovery

iv) Config. 4 Efficient HPV^{2}CO

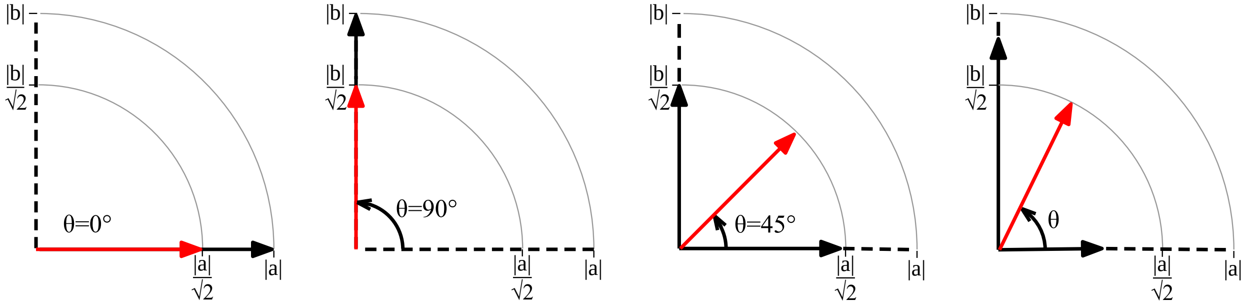
Figure 2. HPV^{2}CO Configurations

The identical amplifiers are expected to have similar phase and gain response with respect to the frequency under the same environmental conditions. Setting the bias conditions of each amplifier by bias voltage variation gives a scalable power output. Combining two amplifiers with controllable bias conditions using a quadrature hybrid inserts a phase change to the loop and thus provides frequency varied oscillation as long as the Barkhausen criteria is met.

The idea let us come up with several design concepts based on how the input of the hybrid is controlled. In the main configuration, the change of the power at the hybrid input is done by varying the amplifier bias (V_Bias_Amp1 and V_Bias_Amp2). The second configuration is achieved by changing the input power level of the amplifier. This concept can be applied by varying the bias of the voltage variable RF attenuators (V_Bias_Att1 and V_Bias_Att2). In this configuration, the bias voltages of the amplifiers are fixed as shown in Figure 2.ii. In the third configuration, due to the power loss in the quadrature hybrid combiner, a power recovery subsystem is added to the configuration. The third configuration provides an efficient solution for temperature sensitive applications. The fourth configuration promises to have minimum power loss and a controllable high power option by providing high loop gain. In this design, another amplifier as a final stage is added in the loop and the final stage is biased by a fixed voltage. A highly coupled directional coupler can be used to reduce the insertion loss. The frequency can be varied as in Config.1 and Config.2. In all configurations, single oscillator tuning voltages can be provided using a control circuit that has a non-inverting OpAmp with a fixed reference voltage.

HPV^{2}CO Inherent Phase Control

In order to present a mathematical perspective to analyze the design, the theory of the branchline type quadrature waveguide coupler is considered. Quadrature hybrids are 3dB, four port directional couplers having a 90 degree phase difference between its output ports [4]. According to its scattering matrix, if the inputs of the quadrature hybrid are $a\angle 90°$ and $b\angle 90°$, the through and the coupled outputs are given as $1/\sqrt{2}(a\angle 0° + b\angle -90°)$, $1/\sqrt{2}(a\angle -90° + b\angle 0°)$ respectively. If the two inputs are in phase, the product of vector combination of different amplitude levels is shown in Figure 3.



i) $|b| = 0$ ii) $|a| = 0$ iii) $|a| = |b|$ iv) $\forall\ |a|, |b|$

Figure 3. Phase Variation in Quadrature Hybrid Combiner

The phase variation can be acquired by varying the input power level of the hybrid from minimum to its maximum range. The conditions are summarized in the below equation:

$$\theta(\vec{a},\vec{b}) = \begin{cases} 0^\circ & , \quad if\ |b| = 0 \\ 90^\circ & , \quad if\ |a| = 0 \\ 45^\circ & , \quad if\ |a| = |b| \\ [0^\circ, 90^\circ] & \quad \forall\ |a|, |b| \end{cases} \tag{3}$$

The circuit can be tuned to oscillate at its center frequency through equally biased amplifiers and a fixed delay line. The circuit oscillates at the desired frequency by continuously introducing a phase shift θ to the feedback network that is satisfied by the new Barkhausen phase condition as defined in Equation (4).

$$\arg A\beta(j\omega) + (\theta - \frac{\pi}{4}) = 0 \tag{4}$$

Maximum Tuning Range of HPV^{2}CO

The maximum tuning range of the oscillator is a function of the total phase introduced to the feedback network. For tuning the oscillator to the edge frequencies in the band at ideal phase response, either one of the amplifiers is biased with the minimum bias voltage or shut down and the other supplies full power with the maximum bias voltage (Fig.3.i and Fig.3.ii). For pulling the VCO to the center frequency, the amplifiers shall be biased with an equal power level that is 3dB below the saturated power (P1dB) as in Fig.3.iii. The power that gets in the combiner should be arranged to cover 90 degrees phase range while supplying a stable output power. Table 1 shows the power levels that need to be supplied to the inputs of the combiner. 3dB power is sacrificed for pulling the oscillation frequency to get the most bandwidth.

Table 1. Phase/Frequency Control by Amplifier Ouput Power Variation

Phase (θ)	**Input-1 rel. P1dB (dB)**	**Input-2 rel. P1dB (dB)**	**Freq.**
0°	off	0	f_{min}
15°	-11.7	-0.35	
30°	-6	-1.25	
45°	-3	-3	f_c
60°	-1.25	-6	
75°	-0.35	-11.7	
90°	0	off	f_{max}

In order to get a stable oscillation, the amplifier or the attenuator bias should be configured according to the relative saturated power of the amplifier. For instance, to get 30 degree phase angle, the amplifiers should be biased to supply ‘PBdb-6’ dBm and ‘P1dB-1.25’ dBm power levels at the combiner inputs with equal phase. The calculation to find the reference power level is based on the vector summation of the input signals. The phase change of the transistor is assumed to be stable over the intended frequency range.

The maximum tuning range of the HPV^{2}CO, its bandwidth, is controllable within 90 degrees phase variation as long as the Barkhausen condition is met. The fixed delay line in the feedback path determines the center frequency when the amplifiers are biased equally. Thus, the group delay of the delay line and the passive components are also other significant terms that define the bandwidth. The total group delay is the measure of the transit time of the signal through the loop as a function of the frequency. The group delay of the passive components is assumed to be constant within the frequency range. For a non-dispersive system, the group delay is defined as:

$$\tau = \tau_{dl} + \tau_f \tag{5}$$

$$\tau_{dl} = -\frac{1}{2\pi}\frac{d\theta}{df} \tag{6}$$

The delay parameter τ_f defines the fixed delay of the passive RF components, and τ_{dl} stands for the controllable group delay in which θ accounts for the total integrated phase shift. The delay line of the HPV^{2}CO is assumed to have a uniform transmission line of length l without any discontinuities. In this condition, the group delay is directly related to the length and the permittivity of the dielectric material within the transmission line, that is,

$$\tau_{dl} = l\frac{\sqrt{\epsilon}}{c} \tag{7}$$

If the delay introduced by the passive components, except for the total transmission line, is assumed to be 0, the formula of the bandwidth becomes

$$\nabla f \cong \frac{c\nabla\theta}{2\pi\sum l\sqrt{\epsilon}} \tag{8}$$

The controllable bandwidth of the HPV^{2}CO is dependent on the total phase shift and the total electric length of the loop.

HPV^{2}CO Phase Noise

Phase noise is one of the most critical terms to specify for an oscillator which is known as the short term random phase fluctuation of the oscillator and described as one sided spectral density of phase fluctuations per unit bandwidth. The phase noise of the HPV^{2}CO behaves similar to the delay-line oscillator given in [5]. The quality factor of the transmission line and additional group delays of the circuit components are the important factors that are effective on the determination of the phase noise characteristics. The way of the tuning and the narrowband circuit components gives an inherent selectivity to the HPV^{2}CO, and thus; it stops the fast phase fluctuations. In addition to the selectivity, the utilization of a band pass filter with flat group delay helps to ensure the phase and gain conditions will be met in the predetermined frequency range. As the phase noise improves, the bandwidth of the HPV^{2}CO decreases.

HPV^{2}CO General Design Requirements

The design requirements are identified along with the commentary:

a. The HPV^{2}CO shall be designed with COTS and discrete SMD components according to the configurations described in previous chapters.

b. The HPV^{2}CO frequency range shall be in IEEE UHF, L, S bands.

c. LNA’s or gain blocks with minimum matching components are desirable for the selection of the transistor. The output RF power of the HPV^{2}CO is targeted to be the range of 27-38 dBm. The maximum output power of the VCOs in the market is in the range of 8-15dBm. For the Config. 2, the linearity of the voltage variable attenuator is critical as the selection of the transistor in Config. 1 to achieve more constant tuning sensitivity.

d. The passive circuit components shall have minimum phase and amplitude unbalance.

e. Amplifiers and the passive components shall provide a sufficient loop gain to sustain the oscillation. The open loop gain is considered to be over 1. Thus, the total insertion loss shall be lower than the gain of the amplifier or total gain of the loop in case the Config.4 is used.

f. The total transmission phase of the amplifiers, the passive components, and the delay line shall have sufficient linear phase response with regard to the frequency in the intended bandwidth.

g. The oscillation center frequency shall be set by a tunable fixed printed transmission (delay) line.

HPV^{2}CO TEST RESULTS

The proof-of-concept is demonstrated in all systematical configurations shown in Fig.2. The measured critical VCO parameters are given in Table 2.

Table 2. Functional Test Results

Prototype	**HPV^{2}CO-001**	**HPV^{2}CO-002**	**HPV^{2}CO-003**	**HPV^{2}CO-004**
Configuration	**1 & 2**	**1**	**3**	**4**
Center Frequency (MHz)	900	1475	2250	2350
Bandwidth	>10%	>6%	>4%	>3%
Output Power (dBm)	29	27.6	29	38.2
Power flatness (dB)	±0.5	±0.7	±0.5	±0.1
Tuning Voltage (V)	[3.5 - 11.5]	[3 - 12]	[2 - 12]	[2 - 10]
Tuning Sensitivity (MHz/V)	[6 - 12]	[8 - 24]	[4 -15]	[3 - 9]
Phase Noise @100kHz dBc/Hz	<-90	<-90	<-90	<-85
Current (A) Typ.	0.25A @12V	0.3A @12V	0.3A @12V	0.7A @23V
Harmonics 2nd (dBc)	<-15	<-20	<-20	<-50

The VCO frequency pushing test, in other words measuring the sensitivity of the VCO with respect to the voltage supply, is not applicable for HPV^{2}CO concepts. A non-ideal load connected directly to the HPV^{2}CO output may pull the HPV^{2}CO frequency out of specification due to the poor isolation of the quadrature hybrid combiner. Hence, an RF isolator is always preferred at the front end.

Temperature and vibration tests were performed in accordance with MIL-STD-810G. The HPV^{2}CO successfully passed the related tests.

DISCUSSIONS

Tuning Linearity: The linearity of the power output of the amplifier according to the bias voltage is the key parameter that is determinative on tuning sensitivity. Due to the positive feedback, the amplifier is kept in saturation to sustain the oscillation. Thus, the tuning range is limited by the behavior of the nonlinear amplifier. In order to have a more linear frequency tuning, the amplifier is selected from any type of RF transistors that have linear biasing features.

Phase Compensation: Many designs assume that the transmission phase shifts of identical amplifiers are equal. In practice, amplifiers cannot avoid having variations in their transmission phase just like their output power, even if they are from the same lot and have the same design characteristics [6, 7]. The phase variations cause power loss and distortion on HPV^{2}CO sensitivity. Additionally, biasing the amplifier from the minimum voltage to the maximum voltage adds phase shift which limits the bandwidth and may worsen the power flatness of the HPV^{2}CO. A phase compensation circuitry may be needed in each branch of the feedback loop.

Harmonic Control: The loop reaches the stationary condition when the large signal gain saturation stabilizes the amplifier as the gain gets close to 1. Running the amplifier in compression by increasing the input power of the amplifier pushes the excess power to the harmonics. Thus, it is desirable to keep the total feedback insertion loss value close to the amplifier gain.

Subharmonics: The VCO may oscillate at subharmonics according to the loop gain outside of the intended band. A BPF with flat group delay is needed to suppress the subharmonic/harmonic oscillations. The insertion of a BPF to the feedback loop may improve the phase noise and help to stabilize the gain across the limited BW. A selector filter like a Bessel type ensures the phase and gain conditions are met in the predetermined frequency range.

Power Recovery: Half of the output power is dissipated on the isolated terminal of the quadrature hybrid combiner in Config. 1 and 2. This power loss may cause a heat management problem for a high power output and it will affect the stability of the gain. A power recovery mechanism is developed as in Config. 3 to improve the power efficiency. Initial results show that the power is recoverable by over 2dB. It also improves the power flatness of the output.

Insertion Loss: It is inevitable to have an output power loss due to the insertion loss added on the through port of the directional coupler. Theoretically, 5 dB and 10 dB couplers have minimum 1.65 dB and 0.46 dB insertion losses respectively on the main line. Reducing the main line loss is preferable by using a high coupling rate directional coupler; however the sustainable loop gain cannot be provided if the gain of the amplifier is lower than the total insertion loss.

Efficient HPV^{2}CO: Config. 4 provides a solution for achieving a high gain in the loop. The insertion loss can be compensated by using a third amplifier coupled in the loop. The configuration 4 shows more efficient performance according to the power efficiency and the power flatness.

CONCLUSION

In this paper, we have proposed a novel VCO architecture named High Power Varactorless Voltage Controlled Oscillator (HPV^2CO) to overcome the limitations of conventional VCO designs that have limited output power due to the characteristics of the varactor diode. The HPV^2CO is presented with alternative design configurations, and theoretical baselines and experimental test results. The HPV^2CO that does not include a varactor diode, or a capacitive tuning element has the capability to provide 20 dB more power with a similar phase noise performance compared to the conventional VCOs in the market.

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