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A Linear Wide Band Voltage Control Oscillator Based On Negative Resistance Active Device

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Abstract

Losses in tank circuit is one of the major problem in design of oscillators. This paper describes the analysis and design of a novel Negative Resistance Based Linear wide band Voltage Control Oscillator. In contrast with the feedback oscillators, that use two ports amplifying device, the Voltage Control Oscillator topology uses only one port devices with negative resistance to cancels the resistance loss of the circuit creating a resonator with no damping, generating oscillations at its resonant frequency. This configuration can be tuned to various center frequencies within the operating range of 1.56 to 1.96 GHz. In order to affirm the design, of the high frequency voltage oscillator. The voltage-controlled oscillator architecture, VCO requirement, mathematical modeling, Amplifier design, resonant circuit design and design challenges are included. Result of the output are well discussed.

Keywords: Voltage Control Oscillator (VCO), Negative Resistance, Phase Noise, Harmonics distortion, Open-Loop Gain, Frequency Pushing, Load Pulling, Barkhausen criterion.

1 Introduction

Voltage controlled oscillators are electronic circuits designed to produce a periodic sinusoidal signal whose frequency is dependent on the voltage applied at the input Chattopadhyay, D. (2016). The voltage-controlled oscillators (VCOs) are widely used in modern communication and instrumentation systems Thomas L. Floyd (2015). Most of modern *LC* oscillators use BJTs or MOS transistors as active devices. Voltage controlled oscillators are electronic circuits designed to produce a periodic sinusoidal signal whose frequency is dependent on the voltage applied at the input (Metha, V.K and Metha R., 2006*)*. The desired frequencies can range from several hundreds of megahertz to several gigahertz. Ideally speaking, low input tuning voltage, phase noise, output power, high frequency stability, and tuning range, is expected from our final design of VCO R. Ludwig, G. Bogdanov, (2012). However, fulfilling all these requirements tend to be conflicting in selection of components for the device, as several factors are to be considered in selecting both active and passive components for the VCO. Basic oscillator design specifications often require a given output power into a specified load at the design frequency. In contrast with the feedback oscillators that use a two-port amplifying element, negative resistance oscillators use only one port devices with negative resistance. These oscillators tend to be used at high frequencies, even at microwave range and above Chattopadhyay, D. (2016). The drive level and bias current set the fundamental output current and the oscillation frequency is set by the resonator components U.Rohde(2005). Instances where VCOs find use are in radio frequency signal jammer, digital clock generators, system synchronizers, frequency synthesizers, and most importantly in modern communication systems where tunable frequency ranges for local oscillators are necessary for wireless transmission Wayne Storr, (2014).

As the electronics industry is always seeking for accurate and cheaper frequency sources that can be integrated in the increasing demand of front-end systems, this seminar aims to develop a design that has wideband linear tuning while being inexpensive compared to a comparable VCO (Malcolm D. Stewart. 2003). In this section, a general review of oscillator design concepts is presented in order to provide the necessary background information on this work. To begin, basic oscillator concepts and several of its categories are introduced. Following, voltage-controlled oscillator theory and a few of its configurations are analyzed. Finally, essential design steps and parameters of a general VCO are introduced.

1.1 Basic Oscillator Circuit Fundamental

Oscillator are electronic device that generate a continuous harmonic output waveform with a defined frequency. It oscillation frequency depend on the constant of the device. Oscillator can produce both sine wave and non-sine wave output (square wave, triangular wave). In this report we shall focus on the sinusoidal output wave oscillator. Sinusoidal oscillation is based on principle of ***positive feedback***, in which portion of the amplifier circuit is feedback through the feedback network to the tank circuit, to serve as an input to the amplifier in order to reinforce the oscillation. They mainly find use in converting DC input voltage to alternating one. Such oscillators are widely used in electronics devices such as TV sets and radio transmitters.

1.1.1 Basic Oscillator Circuit

A simple oscillator circuit consist of two essential elements which are explained below.

i. **Tank circuit:** It consist of inductor coil (L) in parallel with capacitor (C). The frequency of oscillation of the oscillator depends on the values of this elements.

ii. **Amplifier:** The amplifier circuit is may be discrete transistor amplifier or basically an Operational amplifier. They receive the D.C power from the battery and amplify the thermal noise from the resistor to feedback the tank circuit, for input to the amplifier back.

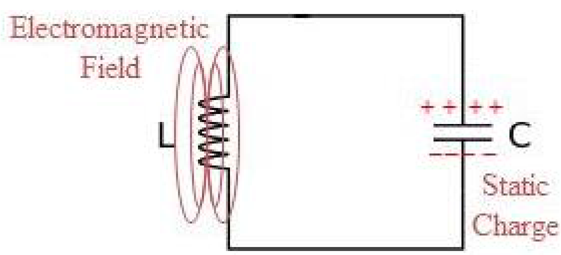

Fig 1.0:*Basic Oscillator Tank Circuit*

In the circuit above, assuming that the circuit is supplied only initially with energy; all this energy is used to charge the capacitor. The charged capacitor discharges its electric energy into an inductor, the charges across the inductor builds up a magnetic field around it. The field built due to the discharging of the capacitor start collapsing immediately after the capacitor finish discharging. This causes an opposite current due to Back E.M.F to start flowing from the inductor to the capacitor to start charging it again for the process to continue. LC oscillators, not necessarily in their basic tank circuit form, are often used in the generation of radio frequency signals with applications in signal generators, radio transmitters, and local oscillators in radio receivers.

2 Related work

As stated previously in this paper, voltage-controlled oscillators (VCOs) allow the user to control the frequency of the output signal by varying a bias voltage. The theoretical basis of which is introduced throughout this section for better explanation on design of the device. VCOs are crucial in frequency translation of RF signals, due to the wide variety of possible signal frequencies. They are majorly used in mobile phones, wireless routers, radios, test equipment and GPS navigation systems. Although they can be found in many different applications, their function of interest is in RF communication systems most importantly in signal jamming device.

Similar to a basic oscillator, the measured VCO output signal is ideally a pure sinusoidal waveform in the time domain as shown below, while in the frequency domain it would represent an ideal impulse (delta function) located at the signal's oscillation frequency (Fosc).

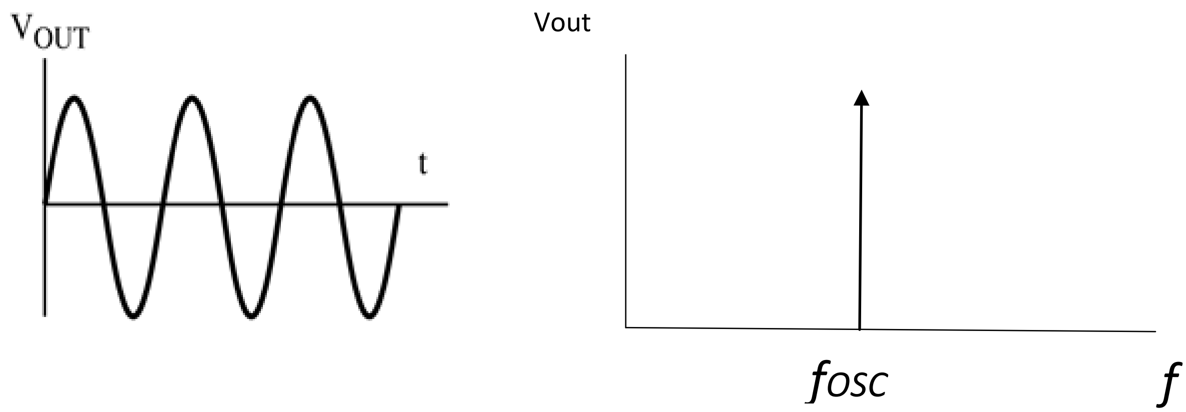

***Fig 2.0:** Ideal Output Waveform of VCO in time domain and frequency domain*

The distinguishing feature of a VCO is its capability of varying the output frequency based on a variable tuning voltage VT. Between the tuning voltage and the output oscillation frequency a linear relationship exists in the ideal case of a VCO.

Voltage control oscillator types: Voltage control oscillators can be classified as follow:

i. Relaxation VCO
ii. Linear VCO

Relaxation Oscillator**:** Are mostly used in Integrated Circuits (IC).

Linear VCO***:*** This is the type of VCO that uses an oscillator, that generates a sinusoidal waveform. The energy consequently decays with the amplitude of oscillation. To compensate for the loss of this oscillator, an amplifier is used over a uniform waveform during a period of time. The resonance frequency is controlled usually by a varactor, a diode that has a variable capacitance. The linear oscillators have several advantages over the relaxation oscillators. They are more frequency stable with respect to temperature and have a better accuracy for the frequency control since the frequency is controlled by the tank circuit. The figure below shows different types of oscillators and the frequency phase noise relationship.

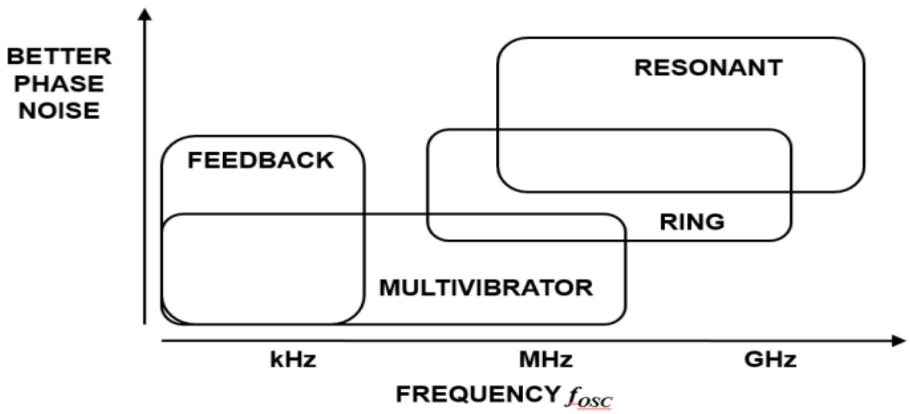

Fig 2.1:*Types Oscillators with their Phase Noise Relationship*

2.1 Voltage control configurations

The Colpitts, Hartley, and Clapp are the most common configurations of voltage control oscillator. Over years the Colpitts configuration has been most widely used oscillator in RF applications. The Clapp oscillator is one of several types of LC circuit build from a transistor and a positive feedback using the combination of an inductance with a capacitor to determine the frequency. Although there are similarities between the Colpitts configuration and Clapp configuration. The only main difference between the Colpitts and Clapp oscillator is that the feedback for the Colpitt device is taken from a voltage divider made of two capacitors in series across the inductor.

2.1.1 Colpitt Configuration

One basic type of VCO topology is the Colpitt configuration, named after it inventor. It uses LC tank circuit as feedback to produces the necessary phase shift, and to also act as resonant filter to pass the desire frequency of oscillation. There are 3 types of BJT Colpitts VCOs. Common-Collector, Common-Emitter and Common-Base. The most used is Common-Collector configuration where the output is often taken from the collector terminal, simply acting as a buffer for the oscillator connection at the base-emitter terminals. They are majorly use for high frequency wide range oscillation.

2.2.2 Clapp Configuration

A Clapp circuit is often preferred over a Colpitts circuit for constructing a variable frequency oscillator. In a Colpitts oscillator, the voltage divider contains the variable capacitors. This causes the feedback voltage to be variable as well, sometimes making the Colpitts circuit less likely to achieve oscillation over a portion of the desired frequency range. This problem is avoided in the Clapp circuit by using fixed capacitors in the voltage divider and a variable capacitor in series with the inductor

2.3 Varactor Diode

The varactor diode also known as variable capacitor is one of the important component of voltage control oscillator, as it majorly use to vary the frequency of oscillation for the VCO due to it good biasing characteristics. The distinguishing characteristic of a varactor diode is that when this element is forward biased, the depletion region decreases which allows current flow. However, when reverse biased, the depletion region increases which prevents currents flow. The PN junction and symbol of varactor diode is shown below.

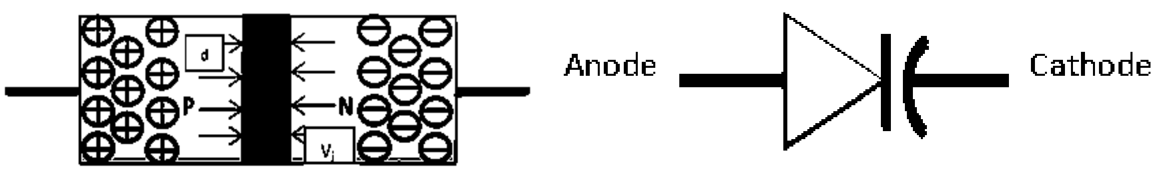

Fig 2.2:*P-N Junction and Symbol of Varactor Diode*

3 Methodology

This section will be focusing on the process by which the **VCO (Voltage Controlled Oscillator)** oscillator's topology and devices were chosen, based on performance requirements, components types and DC power requirements. Since amplifier is an element of oscillator, this section started with the design of a wideband amplifier to be used in the oscillator circuit. The oscillator configuration topology that is used is colpitt with the feedback element consisting of a varactor diode for turning. The advantage of this type of tank circuit configuration is that with less self and mutual inductance in the tank circuit, frequency stability is improved along with a simpler design.

3.1 The Design VCO Requirement

To design a wide band (800MHz-1.5GHz) voltage control oscillator for an RF application that would have the following specifications.

i. The VCO must exhibit a low **Phase Noise** in order to meet the Sensitivity, Adjacent Channel and Blocking requirements. High **Pushing** (change of the oscillation frequency with supply voltage) can cause Phase Noise degradation due to increased sensitivity to the power supply noise.
ii. The VCO should exhibit 2nd harmonic levels on the order of -40 dB
iii. The oscillator excess open-loop gain (which is necessary for initial oscillator build-up) should be minimized in order to prevent amplitude fluctuations from being converted into significant frequency fluctuations.
iv. The VCO should exhibit Monotonic tuning characteristic (having a single frequency at every tuning voltage)
v. Linear Tuning range (Good Tuning Sensitivity).
vi. Should be able to maintain tuning flatness (Flat output power).
vii. Fast Response

3.2 VCO Amplifier Design

Considering the Class, A amplifier circuit diagram given below. The design biasing equation would be calculated to determine the operating point of the transistor amplifier. In order to determine the values of components for the amplifier and it ***Open Loop Gain***.

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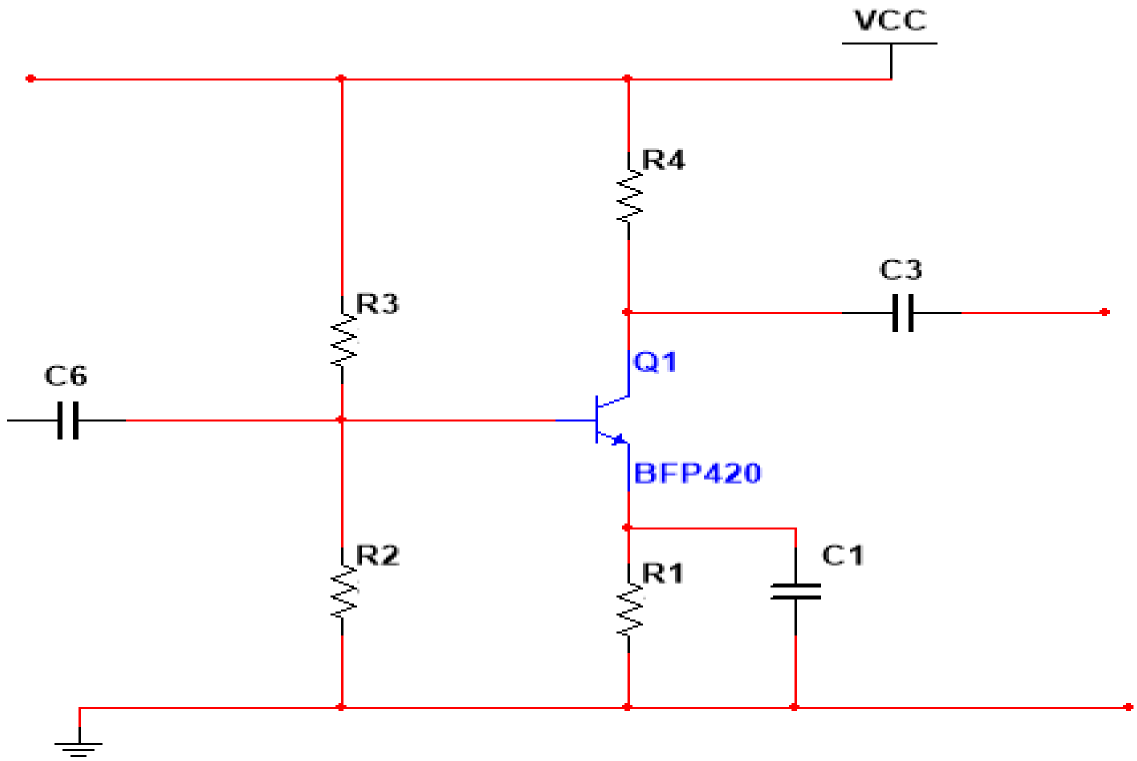

Fig 3.0:*The VCO amplifier Circuit Diagram*

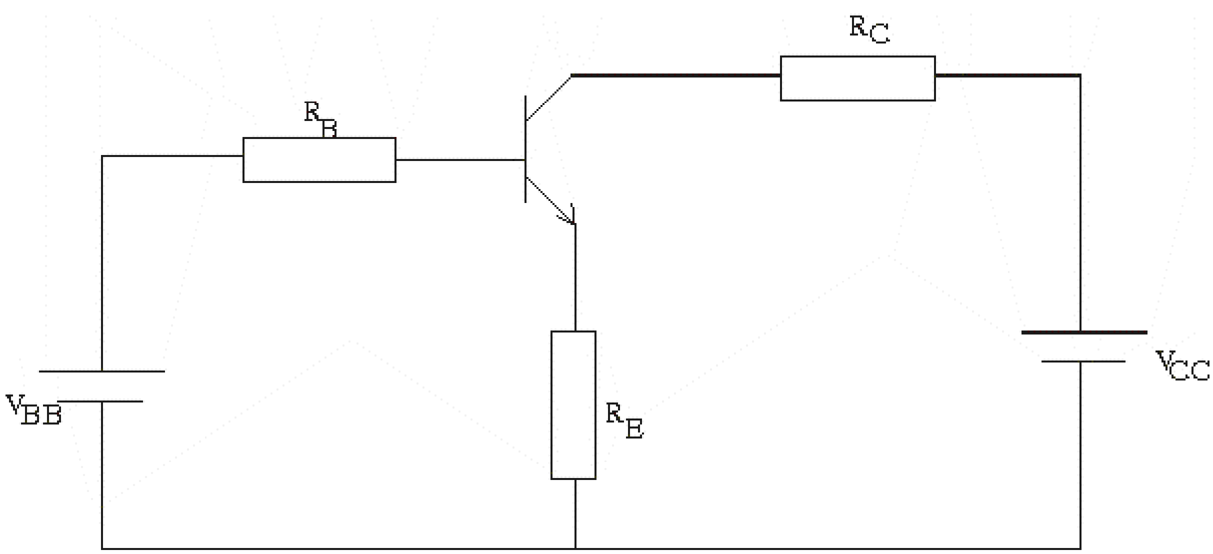

Fig 3.1:*DC Equivalent Circuit of the Amplifier*

Biasing Method : We developed the transistor characteristics. The operating point (Q point) was found to be V_{CE} = 4.5V and I_C= 2.6mA. Voltage divider bias technique is employed. The circuit of figure above is considered and following calculations were made.

3.2.1 Design Equations

Applying Kirchhoff's law to the output and input side of the D.C. equivalent circuit of figure 1 we have

$V_{CC} = I_C R_C + V_{CE} + I_E R_E$ (1)

$V_{BB} = I_B R_B + V_{BE} + I_E R_E$ (2)

For thermal stability of the amplifier.

$R_B \leq 0.3\beta R_E$ (3)

and

$R_E = 0.2R_C$ (4)

$R_B = \frac{R2*R3}{(R2+R3)}$ (5)

From the operating point let V_{CC} = 9v, V_{CE} = 4.5v, I_B = 40μA, I_C = 2.6mA and V_{BE} = 0.71V

$\beta = \frac{IC}{IB}$ = 2.6mA/40μA = 65 (6)

$I_E = I_B + I_C$=40μA+2.6mA= 2.64mA (7)

$R_B = 0.3\beta R_E = 0.3 * 65 * 287.7 = 5610.15\Omega$

Substituting the values above and considering the stability condition in the equation (1) and (2)

Solving for equation (1) becomes

$R_E = \frac{9-4.5}{(5*0.0026)+2.64*10^{-3}} = 287.7\Omega$ (8)

Solving for equation (2) becomes

$V_{BB} = (0.3 * 65 * 287.7 * 40 * 10^{-6}) + 0.71 + (2.64 * 10^{-3} * 287.7)$=1.694V (9)

Calculating for R_C

$R_C = R_E$ x 5 = 1438.6 Ω (10)

Considering (3), we choose R2 and R3 to be 8.25kΩ and 30kΩ respectively.

Calculating the Coupling Capacitors C2 and C3

The low-frequency cut-off for each coupling capacitor is given by

$f_{min} = \frac{1}{2\pi CZ}$

The Z in the above equation is the resistance seen by the capacitance C

Calculating the Total Impedance (Z) from the Hybrid network

Z= [(Zin (base)+(1+ β) R_E)]//R2//R3= 4363.5 Ω (11)

Zin(base)= $\beta\frac{25mV}{Ic}$ =65*10=650 Ω (12)

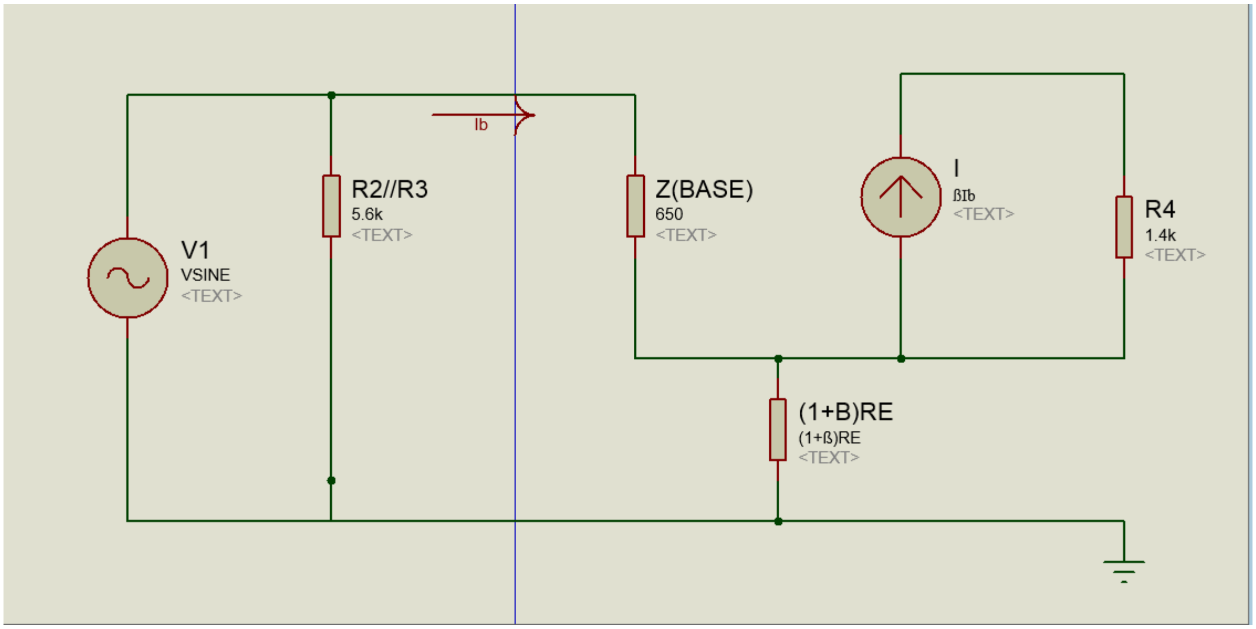

Fig 3.2:*Hybrid Equivalent Network of the Amplifier Circuit*

N.B: At Low frequency the capacitance of the bypass capacitor would be high making it to be acting as open circuit.

Calculating the Gain (Av) from the Hybrid network

$$\text{Av(min)}= \frac{Vo}{Vs} = \frac{-(\beta)\ (R2//R3)*R4}{[(\text{Zin (base)}+(1+\beta)RE)+(R2//R3)]*[\text{Zin (base)}+(1+\beta)\ RE//(R2//R3)]} \quad (13)$$

Approximated formula gives: $-\frac{Rc}{RE} = \frac{1438.6}{287.7} = -5$

Substituting the values of parameters in the above Av= -4.76

Taking 1MHz as our low-frequency cut-off.

$C_6 = \frac{1}{2\pi*1000000*4363.3} = 364pF$

C_3 =110pf

3.3 Resonant Circuit Design

For the oscillator, we need a resonator. The schematic diagram of the designed VCO is as shown in figure below. The resonating circuit is made up of two center tapped capacitors and one inductor connected in series for colpitt oscillation. The series combination of the varactor diode and C4 form one of the center tapped capacitor. The resonant frequency is given by the formula.

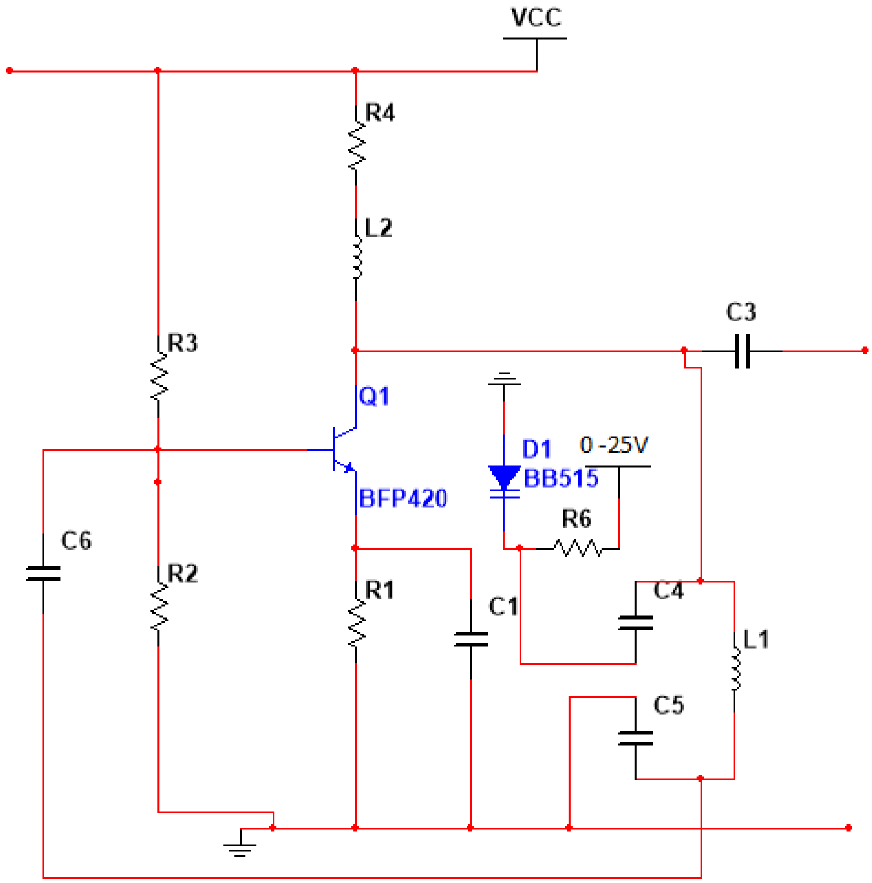

Fig 3.3:Schematic 0f the Design VCO

For Oscillation to occur the ***Barkhausen criterion*** must be met.

Mv*Av≥1

Where:

Mv=Feedback Open Gain

Av= Open Loop Gain of Amplifier

Thus, the Mv= $\frac{C4}{C5}$ = 1/5   thus C_5=C4*5

$f_r = \frac{1}{2\pi\sqrt{LC}}$ where $C = \frac{C4*C5}{C4+C5}$

Choosing f_r = 900MHz and L=5nH

From this we can get the value of C4 and C5

3.4 Voltage Control Oscillator Design Challenges

In general, there are several challenges in choosing components and parameters for VCO circuit as most of the discuss challenges affect the operation of the VCO operation. Considering the selection of transistor amplifier. The gain would extend over all frequencies where the signal needs to be amplified. The higher we aim in the frequencies spectrum, the more difficult it gets to achieve a pure amplified signal in the output. Other challenges are discussed below.

Injection Locking**:** Injection locking can be shown that when a signal of sufficient amplitude and sufficiently small frequency error is impressed on a free-running oscillator. Over time, the free-running oscillator changes its frequency to that of the impressed signal with a corresponding change in its signal phase and amplitude. Normally, injection locking is a very undesirable situation, but it has been used to advantage on occasion such as in narrowband bit synchronizers.

Nonlinear Effects in VCOs**:** Oscillator circuit nonlinearities cause low-frequency noise components to be up-converted and to appear as noise sidebands on the VCO output. Second-order nonlinear distortion determines the degree of noise contamination of the oscillator output for instance. Therefore, second-order distortion in the oscillator should be minimized. The degree to which any oscillator accomplishes this goal can be judged based on the second harmonic output level of the oscillator.

Load Pulling**:** VCO load pulling refers to the change in oscillator frequency that occurs when the oscillator load impedance is changed. If this impedance change is dynamic in nature, load pulling of the oscillator leads to direct frequency modulation of the oscillator. Obviously, if the VCO is contained within a phase-locked loop and the frequency of modulation lies within the closed-loop bandwidth, unwanted interactions can result.

Frequency Pushing**:** VCO frequency pushing is the technical term applied to the oscillator frequency perturbations that result from small changes in the oscillator's supply voltage(s). These perturbations can result from a number of factors including changes in device capacitance values caused by modified reverse biased junction capacitances, changes in the oscillator self-limiting signal mechanism, and changes in the sustaining stage gain. Oscillator frequency pushing can lead to substantial phase noise degradation because any power supply noise directly can lead to frequency modulation of the oscillator.

Varactor Diode Nonlinear Effects**:** One of the main nonlinear VCO elements, particularly in wideband VCOs, is the varactor diode. The potentially large voltage swing across the varactor(s) leads to departures in the frequency tuning curve from nominal and up-conversion of low-frequency noise components that contribute to VCO phase noise sidebands.

Discussion

After all the phases of this work, considering the designed high frequency voltage controlled oscillator, the VCO can be used in the construction of high signal jammer and other RF application for reliable and fast data transmission because of its frequency range of about 690MHz.This wide range also makes it very fit for microwave application such as surveillance and very versatile for many purposes especially when it is used in conjunction with either frequency divider or multiplier circuits as the case may be. The smoothness of the VCO waveforms throughout its tuning range indicated the absence of jitter noise and thus makes it a very good item for accurate timing of electronic communication activities.

Conclusion

In conclusion this project elaborates in detail, the design of wide band high frequency voltage control oscillator VCO and design a wide band VCO using colpitt oscillator configuration which operates in 800MHz to 1.5GHz range. In view of the recommendation that was followed, it shows that the circuit has a bandwidth of 690MHz with a quality tuning flatness. Its wide frequency range, smooth waveform and positive turning slope throughout its turning range are excellent features of this design that make it applicable in making a very high RF jammer.

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