Exstrom Laboratories LLC
P.O. Box 7651
Longmont, Colorado 80501
http://www.exstrom.com

Using Varactors

by
Stefan Hollos, Richard Hollos (Exstrom Laboratories LLC, stefan@exstrom.com, richard@exstrom.com)

Introduction

The word varactor comes from the term ”variable reactor”. It can be used to refer to any electronic component whose reactance can be varied, usually electronically. This includes nonlinear inductors, where the inductance is controlled by a current, and nonlinear capacitors, where the capacitance is controlled by a voltage. The term varactor however, is most commonly used today to refer to a variable capacitance diode. These diodes may also go by the names: varicap, tuning diode, and voltage variable capacitor. In this article we will use the term varactor to refer to these diodes exclusively.

Varactors can be found in most modern radios and RF circuits. They are the solid state answer to the mechanical variable capacitor found in older radios. They take up much less space, are less expensive, and they can be integrated. Since the capacitance of a varactor can be controlled electronically, automatic circuit tuning becomes practical.

A varactor is simply a diode in which the P and N regions are doped in such a manner that the capacitance that normally forms near the PN junction can be precisely controlled by a reverse bias voltage. There is an inverse relationship between the capacitance of a varactor and the applied voltage: a small reverse bias gives a big capacitance, and a large reverse bias gives a small capacitance. Figure 1 shows the schematic symbol for a varactor.

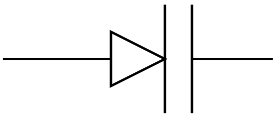

Figure 1: Schematic symbol for a varactor

In this article we will describe how varactors work, and show how the capacitance changes as a function of the bias voltage. We will discuss the varactors circuit model and show how to bias a varactor. We will talk about the distortion that can be caused by varactors and how it can be minimized. Finally we will show a few applications of varactors.

How Do They Work

To understand how varactors work it will be helpful to start with a quick review of capacitors and the concept of capacitance. We can define a capacitor as any two terminal device that stores energy in an electric field. The electric field is created by two spatially separated regions of opposite electric charge between which no appreciable current can flow. The amount of charge, Q, stored in either of the regions, will be some function of the voltage, V, applied across the terminals of the device: charge = Q(V). A capacitor's capacitance, C, is then defined as the ratio of the charge to the applied voltage: C = Q(V)/V.

To analyze the behavior of a capacitor in a circuit we need a relationship between the current and voltage across it. The current, I, is equal to the time rate of change of the stored charge. This relationship can be expressed as follows:

$$I = \frac{dQ}{dt} = \frac{dQ}{dV}.\frac{dV}{dt} = C(V)\frac{dV}{dt} \tag{1}$$

Where C(V) = dQ/dV is called the incremental capacitance. It is the incremental capacitance that is important in AC circuit design. It is possible to have a capacitor with a small capacitance but a large incremental capacitance.

In most cases in circuit design we deal with linear or nearly linear capacitors where the charge is directly proportional to the applied voltage: $\mathrm{Q} = \mathrm{C_0V}$, where $\mathrm{C_0}$ = constant. In this case the incremental capacitance is equal to the capacitance, $\mathrm{C(V) = dQ/dV = C_0}$, and is independent of the voltage. There are devices however where the stored charge is a nonlinear function of the voltage. The incremental capacitance will then be a function of the voltage. One such device, is the varactor.

The charge in a varactor is stored in the depletion region that forms at the PN junction of a semiconductor diode. To understand what this means lets first review a few basic facts about these diodes. A P type semiconductor is doped with impurity atoms called acceptors that lack an electron needed to complete bonds with neighboring atoms. An N type semiconductor is doped with impurity atoms called donors that have an extra electron, not needed in bonds with neighboring atoms. Note that, even though the impurities are said to either lack an electron or have an extra electron, the two semiconductor types are electrically neutral i.e. they have no net charge. This not true however at the PN junction of a diode. Here the extra electrons from the donor atoms on the N side of the junction diffuse across the junction and attach themselves to the acceptor atoms on the P side. In the process, the acceptor atoms, near the junction, acquire a net negative charge while the donor atoms, left behind by the electrons, acquire a net positive charge. The build up of charge at the junction creates an electric field that eventually stops the diffusion of more electrons across the junction. These two oppositely charged regions on either side of the junction together form what is called the depletion region (see figure 2).

The name derives from the fact that the region is depleted of free charge carriers. No appreciable current can therefore flow across the junction. You can see then that the depletion region, according to our previous definition, constitutes a capacitor.

Capacitance as a Function of Bias Voltage

The width of the depletion region can be changed by applying a voltage across the diode. Applying a positive voltage to the N side of the diode and a negative voltage to the P side will cause the width of the depletion region to increase. This is called a reverse bias. The opposite voltage polarity

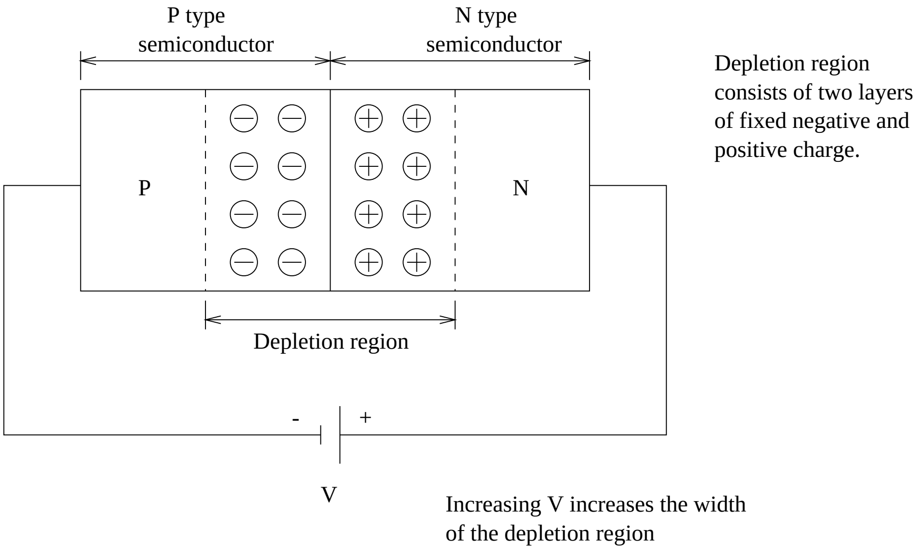

Figure 2: Depletion region of a diode

will cause the width of the depletion region to shrink and is called forward bias. We will limit our discussion to the reverse bias case since this is the way varactors are almost always used. The width of the depletion region will in general be some nonlinear function of the applied voltage. The exact functional form will depend on the density of impurity atoms on the two sides of the junction. Three common density profiles used are: graded, abrupt, and hyperabrupt (see figure 3).

In a graded junction the density of impurity atoms increases linearly as you move away from the junction. In an abrupt junction there is an approximately constant density of donor and acceptor atoms on the two sides of the junction. In a hyperabrupt junction the density decreases as you move away from the junction. Given the density profiles, finding the width of the depletion region as a function of the applied voltage is actually a straight forward electrostatics problem. We will skip the details of solving the problem however and just note that once we have the width as a function of voltage we can get the total charge on either side of the depletion region by a simple integration. Now we have the charge as a function of voltage, Q(V). This is really all that is needed to characterize a capacitor. From this we can get expressions for the incremental capacitance $C(V) = dQ/dV$. Leaving out the details of the derivation [1,2], the expressions for the different doping

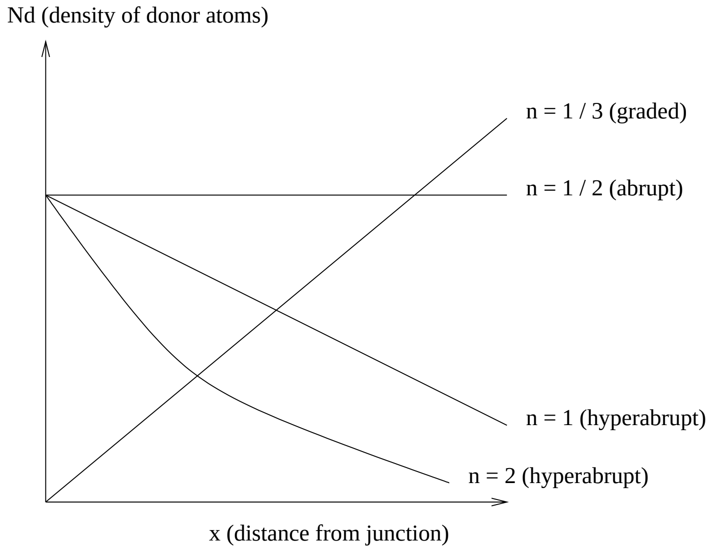

Figure 3: Common impurity density profiles for varactors

profiles all have the following form:

$$C(V) = \frac{C_0}{(1 + V/V_0)^n} \tag{2}$$

V_0 is the junction potential with no bias voltage applied and is usually in the range of .5 to .7 volts. You will not find the value of V_0 on a datasheet but you can easily determine it by measuring the voltage drop across the diode when it is conducting under forward bias. C_0 is the capacitance with zero bias voltage. The exponent n will depend on the doping profile:

- n = 1/3 for a graded junction
- n = 1/2 for an abrupt junction
- n = 1 to 2 for a hyperabrupt junction

V is the applied voltage and is positive for reverse bias and negative for forward bias. Equation (2) does apply for forward bias voltages but only up to about $V = V_0/2$. It is possible to derive an expression for C_0 but in practice the value of C_0 usually has to be determined experimentally. The value of n for an abrupt junction varactor will be close to 1/2 but the exact value for a particular varactor has to be determined empirically. For a hyperabrupt varactor the value of n can range from 1 to 2 and the exact value must once again be determined experimentally. The value n = 2 for a hyperabrupt varactor can be useful when the device is used as part of an LC resonant circuit in a voltage controlled oscillator (VCO) since the oscillation frequency will then be a linear function of the voltage V - we will say more about this later. Most manufacturers do not provide values for C_0 and n. Usually only a graph of C(V) is given from which you can determine C_0 and n. Figure 4 shows how the capacitance varies as a function of voltage for the different junction types.

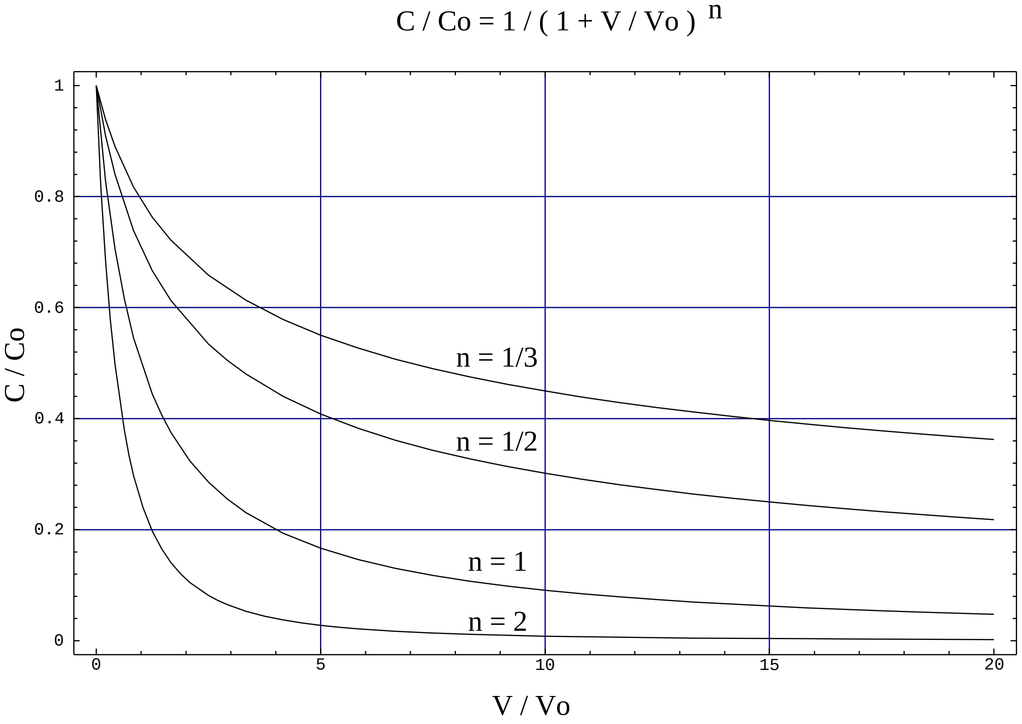

Figure 4: Capacitance as a function of voltage for the different junction types

Parallel Plate Capacitor Analogy

It is possible to draw an analogy between a varactor and a parallel plate capacitor [3]. A parallel plate capacitor (see figure 5) consists of two parallel conducting plates of area A, separated by a slab of dielectric material of thickness d.

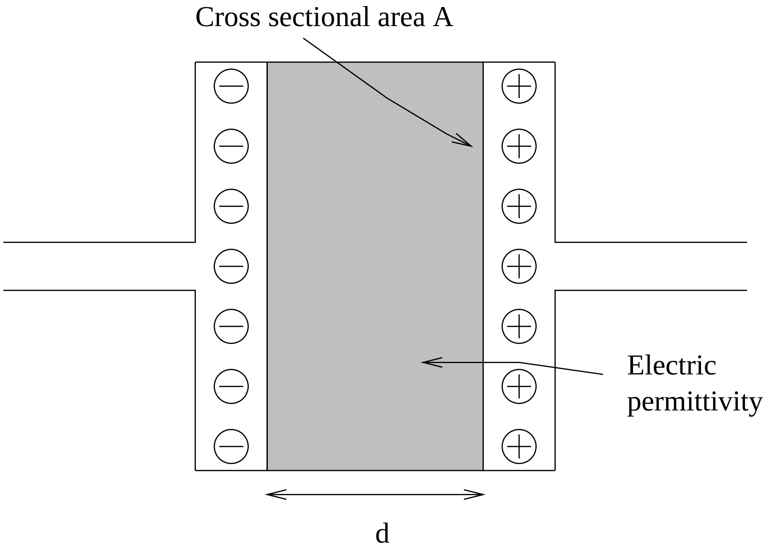

Figure 5: Parallel plate capacitor

If ϵ is the electric permittivity of the material then the capacitance is:

$$C = \frac{\epsilon A}{d} \tag{3}$$

The capacitance is a constant, independent of voltage applied across the plates.

The expression for the capacitance of a varactor can also be written in this form. In the case of a varactor, "ϵ" will be the electric permittivity of the semiconductor, usually silicon or germanium, "A" will be the cross sectional area of the diode, and "d" will be the width of the depletion region. The width of the depletion region is a function of the voltage $d(V) = d_0(1 + V/V_0)^n$. The varactor capacitance can then be written as:

$$C(V) = \frac{\epsilon A}{d(V)} \tag{4}$$

which is similar in form to equation (3). Keep in mind though that this is an incremental capacitance and is a function of the applied voltage, while equation (3) is the actual capacitance and is independent of the voltage.

Datasheets

Varactor datasheets normally specify the capacitance at one or more bias voltages. Another parameter on datasheets is called the tuning or capacitance ratio. This is just the ratio of the capacitance at two specified voltages. For example the MV2115 datasheet [4] lists the tuning ratio as, $C_2/C_{30} = 3.0$, which means that the capacitance at 2 volts bias is 3 times the capacitance at 30 volts bias. Other commonly listed parameters are the reverse breakdown voltage and the reverse leakage current. Like any diode, the reverse bias on a varactor can only be increased so far before it begins to conduct heavily and it no longer acts like a capacitor. Even with a reverse bias below the breakdown voltage, there will be some current through the capacitor. This is called the reverse leakage current and is usually specified at a particular voltage. From this parameter you can get an idea of size of the resistance that is in parallel with the junction capacitance in the varactor circuit model which we discuss below.

Another important parameter on datasheets is the Q. While varactors can replace variable mechanical capacitors in most circumstances, an important difference between the two is the lower Q of the varactor. The Q, also known as quality factor or figure of merit, is equal to the ratio of the energy stored (imaginary part of the impedance) to the energy dissipated (real part of the impedance) in a component. If the component is intended for use as a reactance or energy storage element then the higher the Q is, the better. The Q of an ideal capacitor is equal to infinity. The way in which energy is lost in a varactor and an expression for the Q will be shown below when we discuss the circuit model. On a datasheet the Q is usually always listed at the frequency and reverse bias for which it is a maximum. If you use the device at another frequency or bias you can expect a lower Q.

Circuit Model

The high frequency circuit model for a varactor is shown in figure 6.

L_s is the lead inductance and C_c is the package capacitance. These components of the model only become significant at very high frequencies and we will ignore them in the following discussion. The model we will analyze then is shown in figure 7 [1].

C_j is of course the junction capacitance which varies with applied voltage according to equation (2). The series resistance, R_s, is due to the resistance

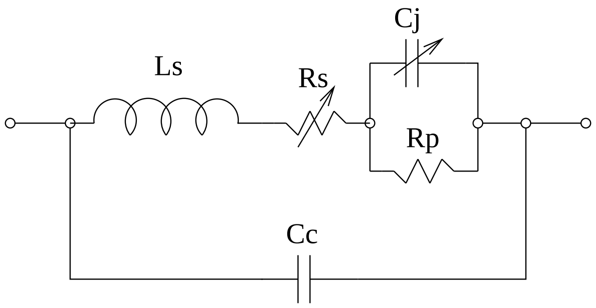

Figure 6: High frequency circuit model for a varactor

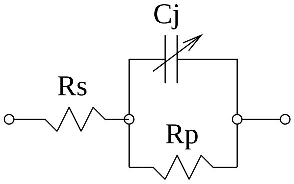

Figure 7: Low frequency model for a varactor

of the semiconductor material of which the diode is made as well as any lead and contact resistance. Only that part of the diode which is not part of the depletion region contributes to this resistance. This means that R$_s$ will be a function of the bias voltage. As the reverse bias is increased, the depletion region gets larger and R$_s$ gets smaller and vice versa. The parallel resistance R$_p$ represents the reverse leakage current. It will in general also vary somewhat with the applied voltage - becoming smaller very rapidly near the reverse breakdown voltage. For most cases though you can assume that it is constant. Using the circuit model shown in figure 7, the normalized impedance is:

$$\frac{Z}{R_s} = \frac{B + 1 + x^2 - jBx}{1 + x^2} \tag{5}$$

where, B = R$_p$ / R$_s$, and x = ω R$_p$ C$_j$. From the equation you can see that both the resistive (real) and reactive (imaginary) parts of the impedance are frequency dependent. The effective resistance reaches a maximum of R$_s$ + R$_p$ in the low frequency limit (x = 0), and a minimum of R$_s$ in the high frequency limit (x = infinity). The effective capacitive reactance goes to zero in both the low and high frequency limits and it has a maximum at, x = 1, or f = $\frac{1}{2\pi R_p C_j}$. The Q is given by:

$$Q = \frac{Bx}{B + 1 + x^2} \tag{6}$$

The Q has a maximum value of $\frac{B}{2\sqrt{B+1}}$ at x = $\sqrt{B+1}$ or f = $\frac{\sqrt{B+1}}{2\pi R_p C_j}$.

The circuit model discussed above can also be applied to any fixed or mechanical capacitor. The series resistance for a varactor however is typically higher than for a mechanical capacitor. This gives the varactor a lower Q than a mechanical capacitor, resulting in less gain when using the varactor in a resonant tank LC circuit and poorer frequency selectivity.

Biasing, Distortion, and Q

The basic circuit for using a varactor is shown in figure 8.

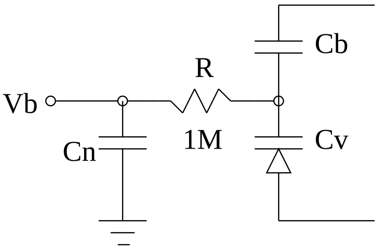

Figure 8: Basic circuit for using a varactor

The capacitor C_b blocks the DC bias voltage preventing it from affecting the rest of the circuit. It is in series with the varactor, therefore it would reduce the effective capacitance of the varactor unless it is made much larger than the varactor capacitance. The capacitor C_n and the 1M resistor help to isolate the RF and bias circuits. The 1M resistor also prevents destruction of the varactor if the bias voltage becomes larger than the varactor's reverse breakdown voltage.

The capacitance of the varactor is a function of the total voltage across it. This means that not only the bias voltage but also the level of the RF signal itself will determine the capacitance. To prevent the RF signal from modulating the capacitance, it should be kept much lower than the bias voltage. A good rule to use is to keep it less than 15 percent of the bias voltage [1]. For example, if you have a bias voltage of 2 volts, the RF signal level should be less than 300 millivolts. Using an RF signal larger than this will make the varactor behave as a nonlinear capacitance, which means that it will generate harmonics of the RF signal and thus cause distortion.

If distortion is a problem, putting the varactors in a back to back configuration will allow RF signals to be much larger before distortion begins. Figure 9 shows the basic circuit for reducing distortion.

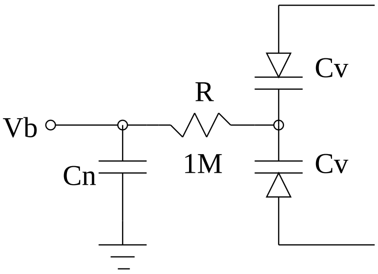

Figure 9: Basic circuit for reducing distortion, but provides only 1/2 the capacitance of a single varactor

This circuit works because when the RF signal level is rising, the total voltage across one varactor is increasing which reduces its capacitance, while the total voltage across the other varactor is decreasing which increases its capacitance. The net effect is less capacitance modulation and therefore less distortion. This circuit, though, only provides 1/2 the capacitance of a single varactor. If you need to keep distortion down and also keep the full capacitance of a single varactor, then you could use the circuit of figure 10 which consists of two pairs of back to back diodes.

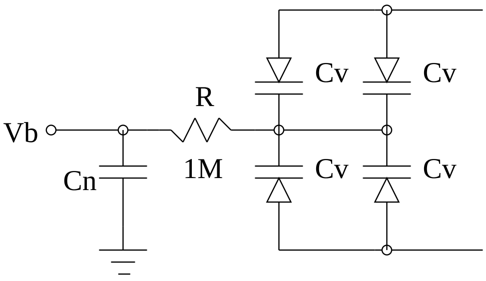

Figure 10: Reducing distortion and providing the capacitance of one varactor

Applications

Varactors are found in most modern televisions, radios, cordless phones, cell phones, and other wireless communications devices. Their most common use in these devices is in frequency selective or resonant circuits. The varactor can be combined with either an inductor or a crystal to create a resonant circuit. In some cases the varactor is part of an integrated circuit with the inductor or crystal connected to it externally. In an LC resonant circuit the varactor is put either in series or in parallel with an inductor. In the series configuration the impedance goes to a minimum at the resonant frequency and in the parallel configuration the impedance goes to a maximum at resonance. In either case the resonant frequency is:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{7}$$

LC resonant circuits are found in: voltage controlled oscillators (VCO), tuned amplifiers, and tunable bandpass filters.

In a VCO the control voltage is usually used to bias the varactor in an LC circuit. The resonant frequency of the LC combination then determines the oscillation frequency. Figure 11 is an example of a VCO, this one based on a Colpitts oscillator.

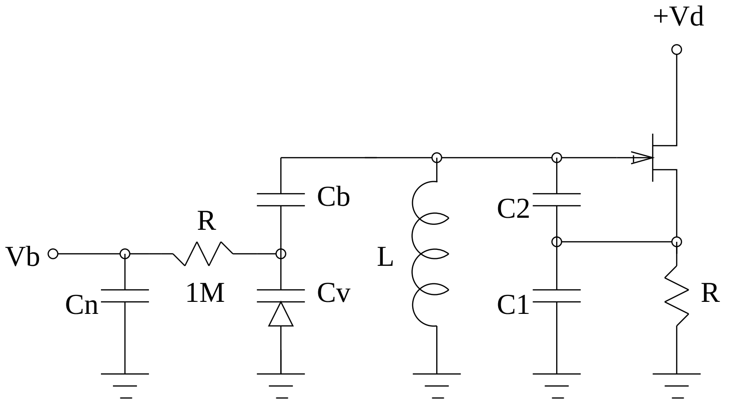

Figure 11: VCO based on a Colpitts oscillator

The frequency of oscillation for this circuit is given by equation (7) where C is the combined equivalent capacitance of the DC blocking capacitor C_b in series with the varactor capacitance C_v. If C_b is much larger than C_v then C will be approximately equal to just C_v. Since the capacitance of C_v depends on the bias voltage V_b, the oscillation frequency is voltage controlled.

In some cases its nice to make the oscillation frequency a linear function of the voltage. You can do this by using a hyperabrupt varactor with exponent n = 2 (see equation 2). The capacitance then becomes:

$$C = C_v = C_0(1 + V/V_0)^{-2} \tag{8}$$

Substituting this into the equation for the oscillation frequency gives:

$$f = \frac{1 + V/V_0}{2\pi\sqrt{LC_0}} \tag{9}$$

which is a linear function of the voltage V. A VCO with linear tuning can be used to create a frequency modulated signal. In this case V is composed of a signal added to a DC bias voltage which determines the center frequency.

A parallel LC resonant circuit containing a varactor can also be used in a tuned amplifier. Figure 12 shows an example of such an amplifier.

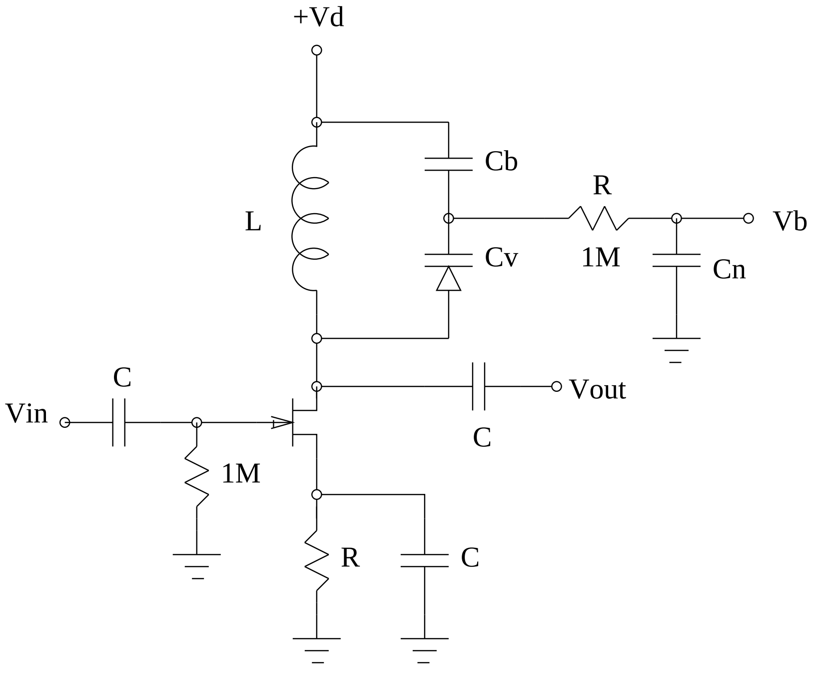

Figure 12: A tuned RF amplifier

The LC combination takes the place of the drain resistor in a common source amplifier. The LC impedance is high only near the resonant frequency so only signals near that frequency are amplified. By varying the bias voltage you can tune the amplifier to different frequencies. Using a micro-controller and a digital to analog converter you can set the varactor bias to tune the amplifier to preset frequencies.

One of the more exotic uses of a varactor, which takes advantage of its nonlinear characteristics, is in a parametric amplifier. Implementing a good parametric amplifier with a varactor can be tricky however, and we will not go into the details here. The following is just a general description of the concept from which you can hopefully see how a varactor might be used.

In a parametric or reactance amplifier, the value of a circuit parameter - capacitance or inductance - is modulated at twice the signal frequency. In its simplest form, if the modulation is in just the right phase with respect to the signal, energy will be pumped into the signal and amplification will occur. A familiar example of this phenomenon is a child on a swing. The child lowers and raises his center of gravity twice during each complete swing, thereby transferring energy into the swinging motion. In the electrical case consider an oscillating LC circuit (assume no resistance) with a parallel plate capacitor in which the plate separation can be changed. If the capacitor plates are pulled apart when the charge on the plates reaches a maximum, the capacitance is decreased, and the voltage as well as as the energy of the capacitor is increased. If they are pushed back together again when there is no charge on the plates, the capacitance increases again but there is no change in the energy. There is then a net flow of energy into the circuit and the oscillation amplitude will increase.

In spite of the shortcomings of lower Q than variable mechanical capacitors, varactors are indispensable in modern radio frequency devices because of the ease with which their capacitance can be changed and because their much smaller size is perfect for portable devices. If you have an interest in making RF devices, getting to know varactors is well worth your time.

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Biographical Info

Stefan Hollos and Richard Hollos design nuclear magnetic resonance (NMR) spectrometers and magnetometers at the company they founded, Exstrom Laboratories LLC. They each have degrees in both physics and electrical engineering. Stefan is like the professor on Gilligan's Island, who can make a radio with a coconut and a few scraps of wire. Richard is more like Gilligan, the essential human element in the realization of the professor's ideas.

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Manufacturers

- Advanced Semiconductor, Inc. http://www.advancedsemiconductor.com/ 7525 Ethel Ave. North Hollywood, CA 91605 1-800-423-2354
- Alpha Industries http://www.alphaind.com/ 20 Sylvan Rd. Woburn, MA 01801 781-935-5150
- API Electronics http://www.api-electronics.com/ 375 Rabro Drive Hauppauge, NY 11788 1-800-627-0218
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