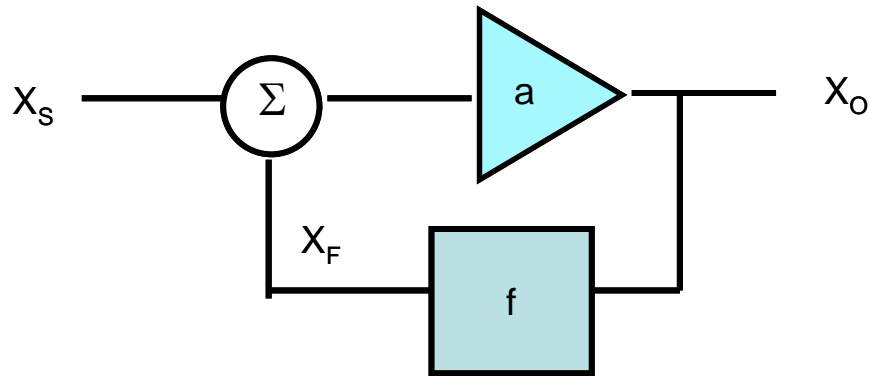# Oscillators

1. Introduction
    What makes an oscillator?
2. Types of oscillators
    Fixed frequency or voltage controlled oscillator
    LC resonator
    Ring Oscillator
    Crystal resonator
    Relaxation/Multivibrator/RC oscillators
3. Design of oscillators
    Frequency control, stability
    Amplitude limits
    Buffered output – isolation
    Bias circuits
    Voltage control
    Phase noise

Oscillator Basics

A feedback amplifier: with positive feedback. Gain with feedback is

$$a_F = \frac{a}{1-af} = \frac{X_o}{X_S}$$

What conditions are needed for oscillation?

$$|af| = 1 \qquad\qquad \angle af = 0$$

This is called the *Barkhausen criterion.*

Of: If the oscillation is to be sustained with Xs = 0, no input, then

$$X_o = aX_F = afX_o$$
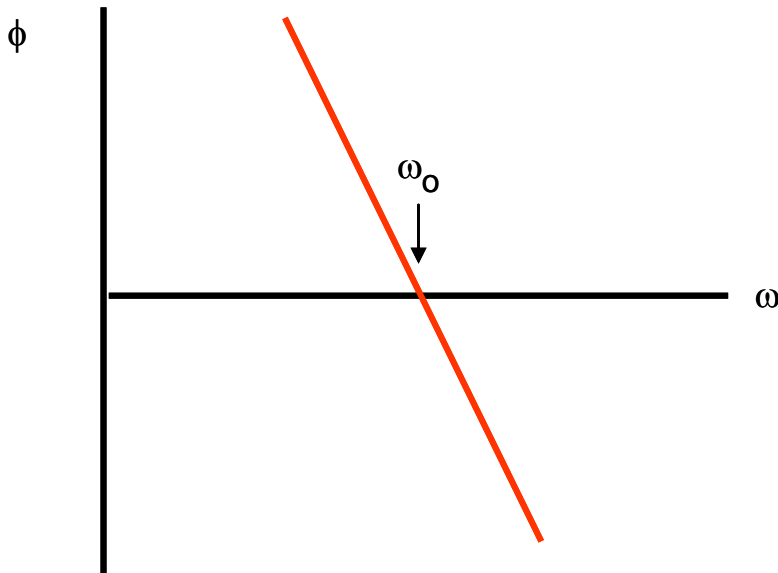$$X_F = fX_o$$

Amplitude is controlled by the magnitude |af|
Frequency is controlled by the phase of af.

Typically, the feedback block is frequency dependent – a resonator or filter or phase shift network.

Considering a resonant circuit like a parallel RLC, the phase slope

$$\frac{d\phi}{d\omega}$$

will set the frequency.

You can see that a change in phase dϕ will result in a change in frequency dω.

A large phase slope produces less frequency variation for a given dϕ.
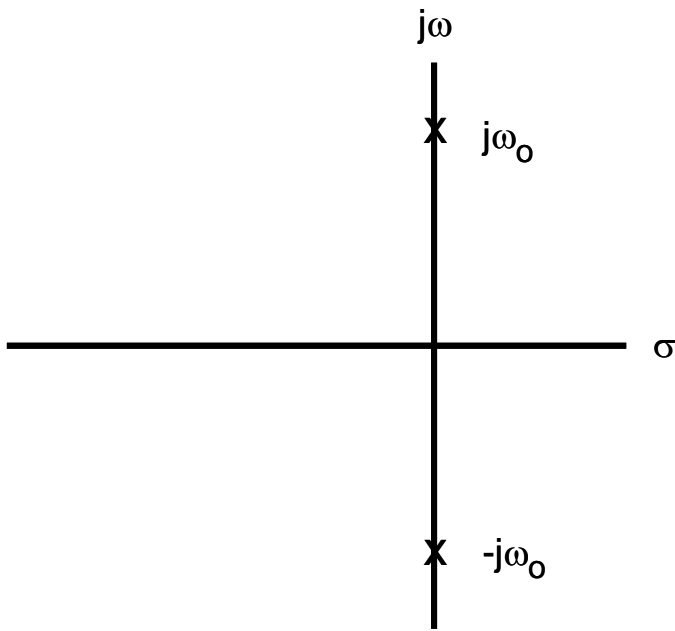
What would cause a dϕ?

A second way to study the operation of oscillators is to evaluate the characteristic equation: the roots of which are the circuit poles.

$$1 - a(s)f(s) = 0$$

For sustained oscillations at ω_o, we need roots on the $j\omega$ axis at $s = +/- j\omega_o$. This would be the case with a factor $(s^2 + \omega_o{}^2)$.

The inverse Laplace transform gives the solution: $\sin(\omega_o t)$ *or* $\cos(\omega_o t)$
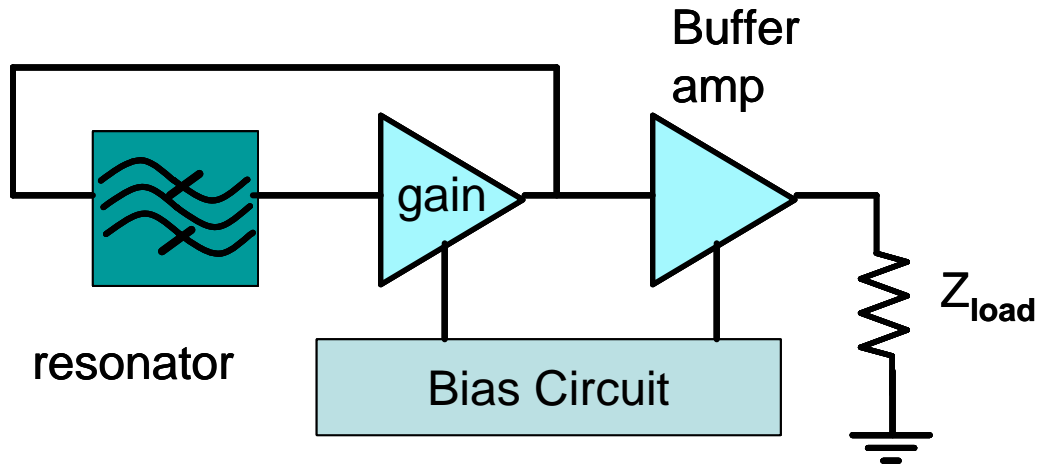An undamped sinusoid.

LC Oscillators

Utilize an LC tank circuit as a resonator to control frequency.
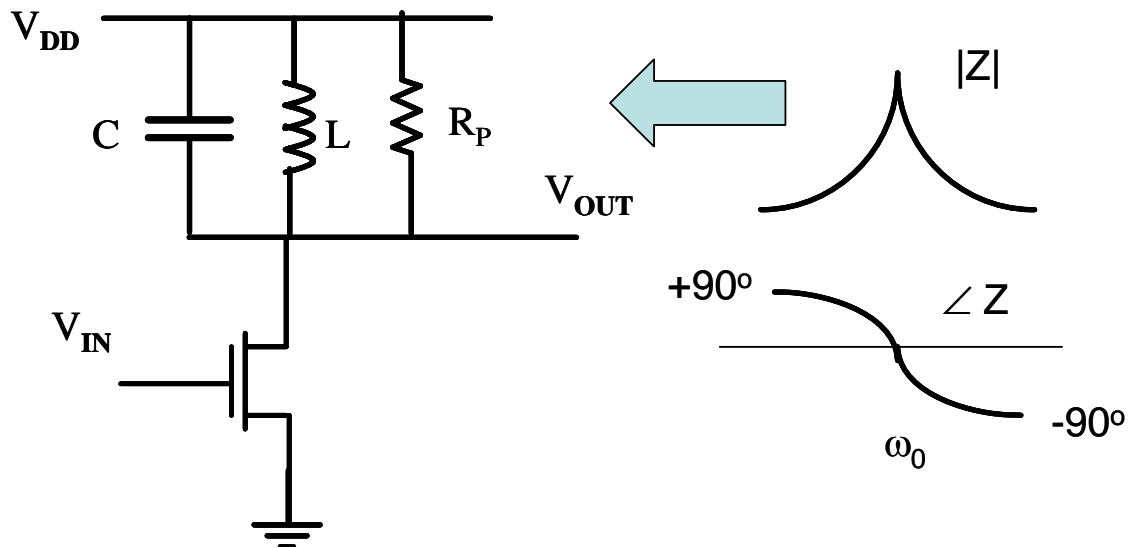   High Q resonator provides good stability, low phase noise
      The frequency can be adjusted by voltage if desired, by using varactor diodes in
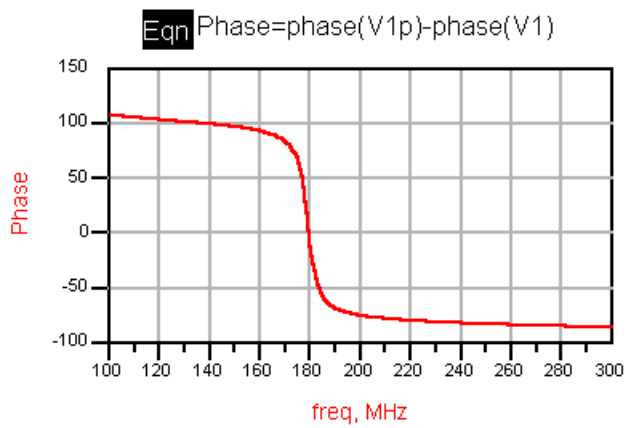   the resonator.
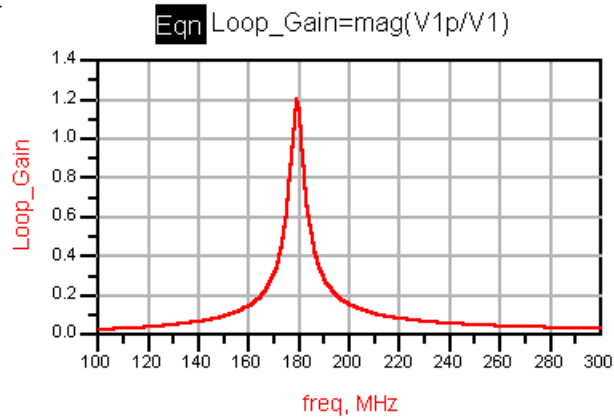

For oscillation to begin, open loop gain $A\beta \geq 1$ and $\angle A\beta = 0$.

Circuit #1:

Consider this tuned amplifier:

Load: The impedance of the resonator peaks (= Rp)and the phase is 0° at ω_0. The
susceptances of the L and C cancel at resonance.

Eqn Loop_Gain=mag(V1p/V1)

Eqn Phase=phase(V1p)-phase(V1)

We represent the MOSFET with its simplest small signal model.

$$g_m \, v_{gs} \qquad R_P$$
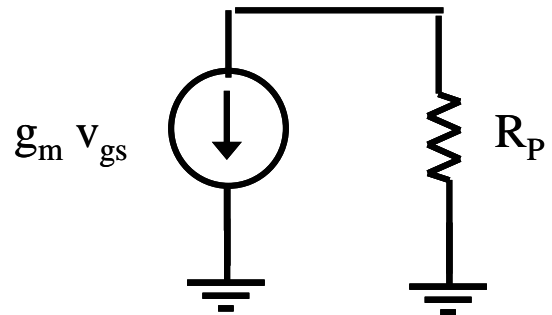
The small signal gain is given by:

$$Vout = - g_m \, R_P \, v_{gs}$$

Notice the inversion between input and output. This produces a 180 degree phase shift for the stage, an inverter.

The large signal output will be a sine wave with a DC component equal to V_{DD}. Since there is very little DC voltage drop across the inductor, the average value of the output over one period must be equal to V_{DD}. The signal is out of phase with the input.

The maximum AC output voltage amplitude will be limited by either clipping (<u>voltage limiting</u>)

$$Vout = V_{DD} - V_{Dsat}$$

or by <u>current limiting</u>

$$Vout = I_{Dmax} R_P$$

The two mechanisms have very different behavior. With <u>voltage limiting</u>, the output voltage begins to resemble a square wave. The odd-order harmonic distortion will increase. If the circuit is intended to provide good linear amplification or good spectral purity, this scenario is to be avoided.

With <u>current limiting</u>, the signal amplitude can be adjusted so that it never reaches clipping. It swings above and below V_{DD} without distorting. Always build the oscillator so that it current limits.
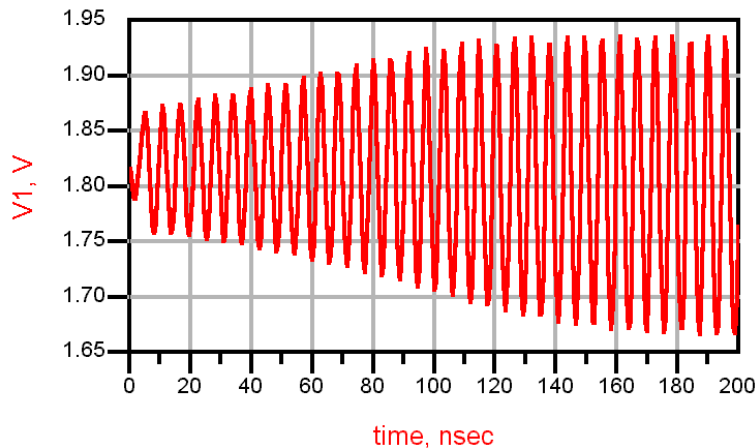
Circuit #2:

The tuned amplifier can form the core of an oscillator. We need to add feedback and one more inversion.
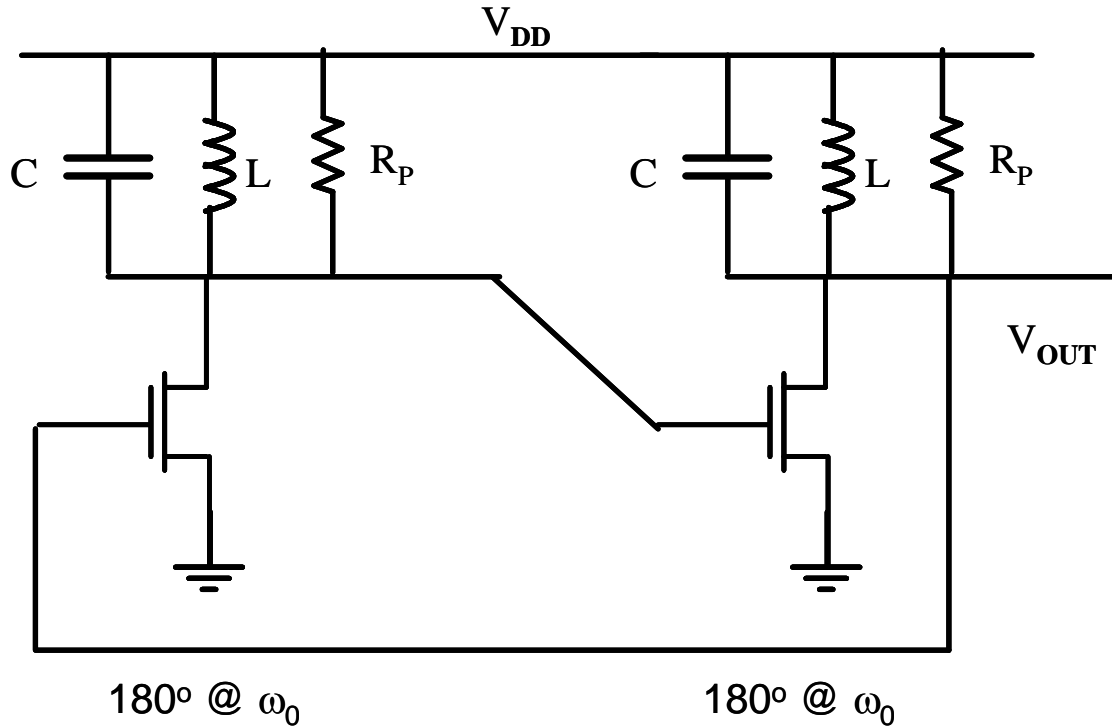
If $(g_m R_P)^2 \geq 1$, this circuit will oscillate. It can only oscillate at ω_0, because only at that frequency will we have a total phase shift of 0°.

The oscillations will begin when the noise inherent in the transistors is amplified around the loop. The strength of the oscillations will build exponentially with time. The small signal analysis doesn't provide a limit to this growth. Obviously, this is wrong. The amplitude will reach a limit either by voltage or current. The example below is current limiting.

This circuit is also known as the "Cross-coupled Oscillator". We can redraw it to look like this:
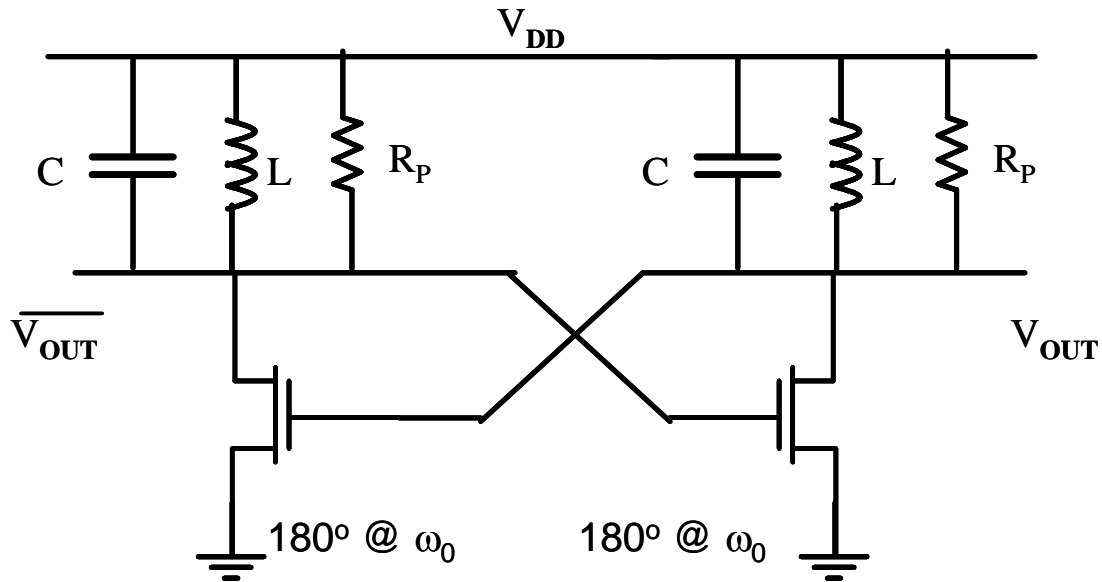
This representation emphasizes the differential topology. The two outputs are 180 degrees out of phase. This can be very useful for many applications – driving a Gilbert cell mixer, for example. It has one major shortcoming, however.

Problem: <u>amplitude control</u>   **Vout = $I_D R_P$**

Vout can be controlled by adjusting the widths of the active devices. This sets the maximum current that the device is capable of providing at a given V_{GS} since $I_D \alpha (V_{GS} - V_T)$ for a deep submicron MOSFET.

BUT,

Vout also will depend on V_{DD}, because the average $V_{GS} = V_{DD}$ in this circuit.

That means that it may not always be possible to avoid voltage limiting. If the device width is reduced too far, there may not be sufficient gain for a reliable startup.

Circuit #3:

One popular solution to achieve better amplitude control is to break the ground connection, connect the sources, and bias the cross-coupled pair with a current source.
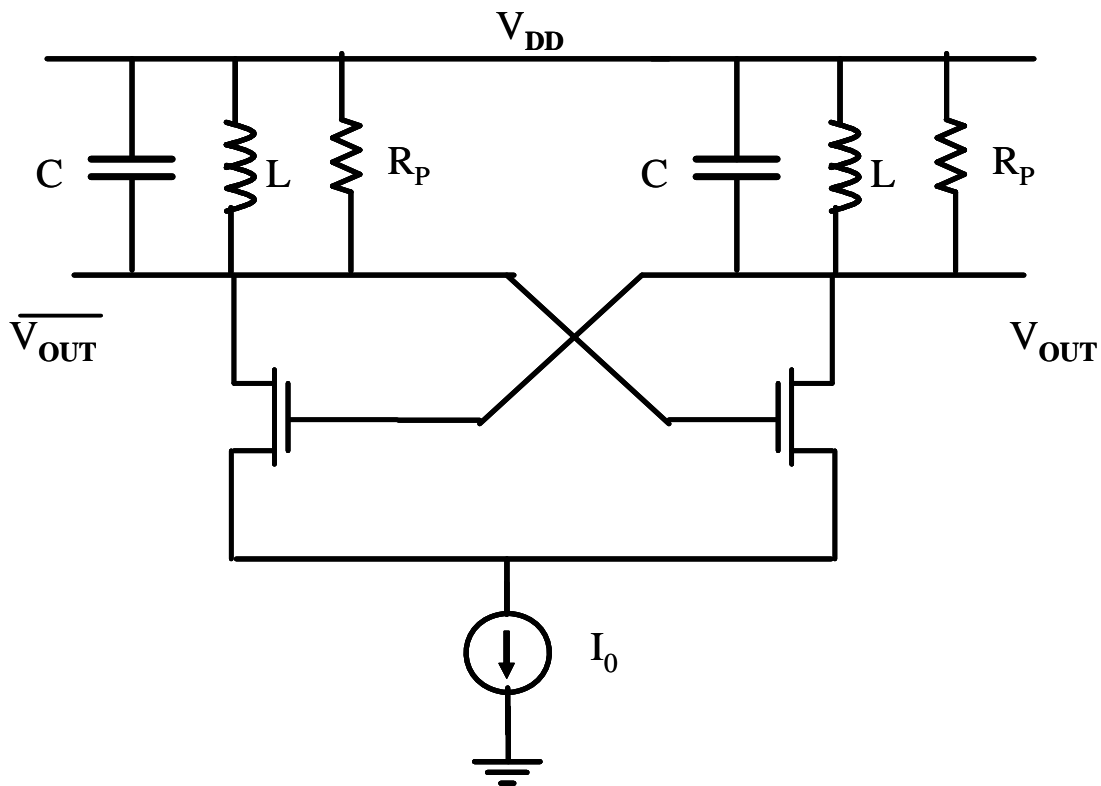
Now, the amplitude is controlled by I_0. All of this current is steered between either the left or right side of the diff pair. Thus, the amplitude of the output will be $I_0 R_P$. This is not perfect, because no transistor current source is ideal. The current will vary slightly with changes in V_{DD}, but it is much more stable than circuit #2. Also, the drain-substrate capacitances of the MOSFET vary with V_{DD} causing some frequency shift. Yet, it is much better for most applications than Circuit #2.

The only drawback for this design comes from the current source noise. The channel noise of the device adds to the total noise of the amplifier, so the phase noise of this current-biased design is somewhat worse than that of circuit #2.

Circuit #4: Colpitts Oscillator
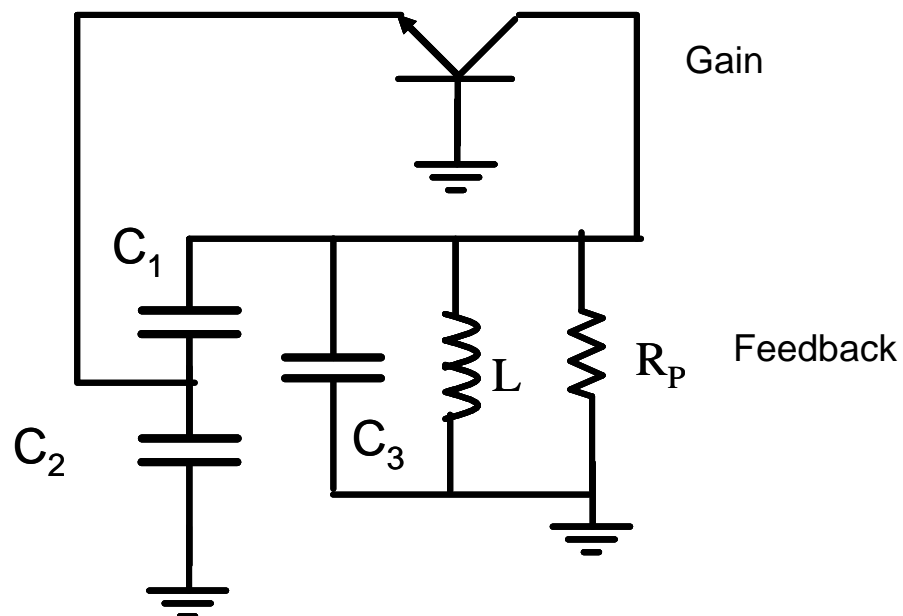
In this configuration the active device is in a common base configuration. The open loop gain will be set by the gm of the device, by Rp and the capacitive divider. The frequency of oscillation is determined by the resonator as in the previous examples.

To analyze the open loop gain, let's open the loop
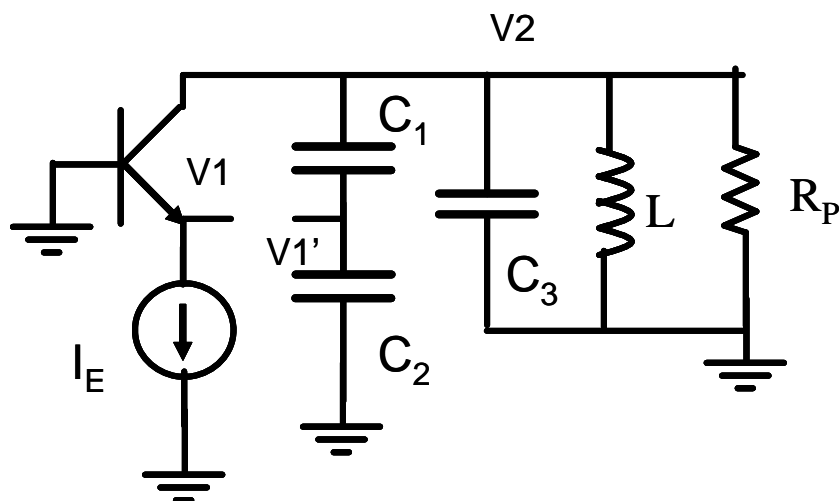
An oscillator example: Common Base Colpitts.

This oscillator uses an LC resonator to set the oscillation frequency and a capacitive divider to establish the loop gain. The collector voltage is in phase with the input for a common base configuration. The goal is to determine the conditions where the open loop gain = 1 considering the voltage gain of the amplifier AL, and the feedback factor 1/N The loading effects of the device and the unloaded Q of the resonator must be considered in the analysis.

ap_npn_2N5179_19930601
Q1
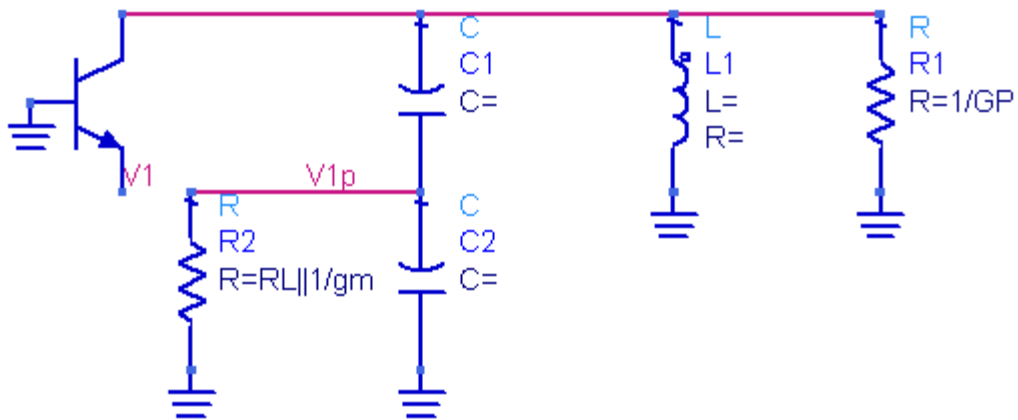
Here is a partial schematic – without biasing details. The C1 C2 divider sets the feedback ratio. The loop is broken between V1 and V1p.

Assume 1/gm << RL. Then, the loading effect of the device input impedance, 1/gm, is transformed up by the tapped C network to N^2/gm. This is combined with GP due to the unloaded Q of the resonator.
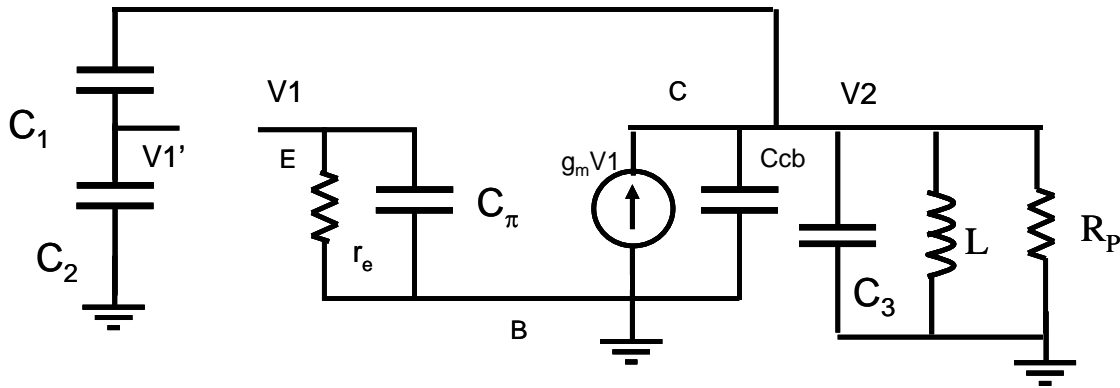
$$A = \frac{g_m}{G_P + g_m / N^2}$$

$$\beta = \frac{C_1}{C_1 + C_2} = \frac{1}{N}$$

Then the open loop gain is given by:

$$A_{OL} = \frac{V_1^{'}}{V_1} = \left(\frac{g_m}{G_P + g_m / N^2} \right) \frac{1}{N}$$

Setting $A_{OL}=1$ and solving for N, we get: $N = \dfrac{g_m}{2G_P A_{OL}} \pm \dfrac{1}{2}\sqrt{\left(\dfrac{g_m}{G_P A_{OL}}\right)^2 - \dfrac{4g_m}{G_P}}$

This is bias dependent because gm = I_C/V_T.

We also need to consider the effects of the device capacitors on the frequency.

- Note that Cp is in parallel with C2.

- Also, Ccb is in parallel with C3 and C_T where

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

and capacitor C3 might represent the varactor diode or tuning capacitance.

How do you find the device capacitances? The data sheet will give you Ccb and the f_T. From f_T, you will find $C\pi$.

$$f_T = \frac{g_m}{2\pi(C_\pi + C_{cb})}$$

Thus, subtract $C\pi$ from C2 and Ccb from C_T.

For startup, we should choose an open loop gain greater than 1. Choose 3 for example. Select Ibias and determine gm. Evaluating the equation for N at an open loop voltage gain of 3, we obtain two answers. The larger N value limits loop gain by the tapped C ratio. The smaller N limits by the loading of the tank with N^2/gm.

One further consideration is the phase shift caused by the parallel combination of C2 and re (= 1/gm). There will be a slight phase shift that will move the total phase around the loop off the peak of the resonator.

- Not desirable: resonator has maximum phase slope at ω_o.

- The effect is minimized by making C2 large and re large: $\dfrac{1}{\omega_o C_2} << r_e$

- Or, you can add resistance in series.
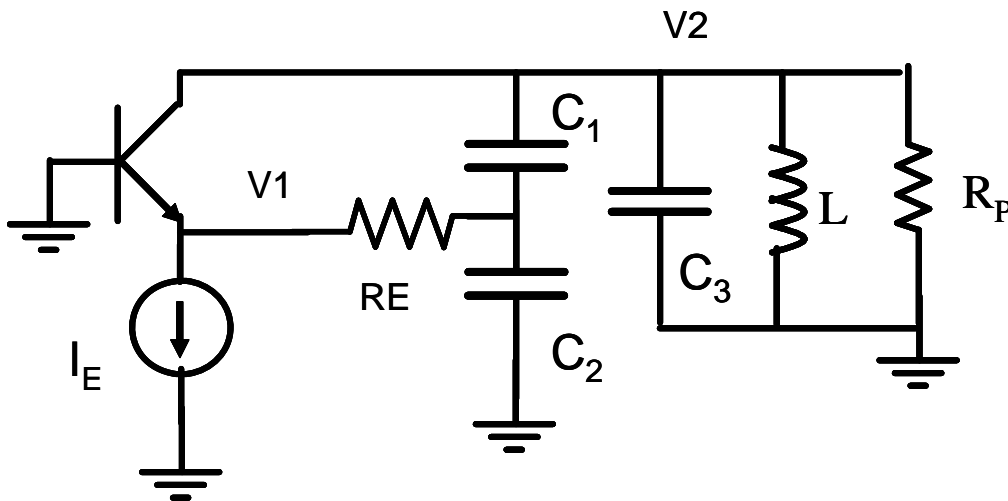
RE can help reduce the phase shift by making $\quad re + RE >> \omega C_2$

This will also reduce the loop gain.

Oscillator simulation methods:
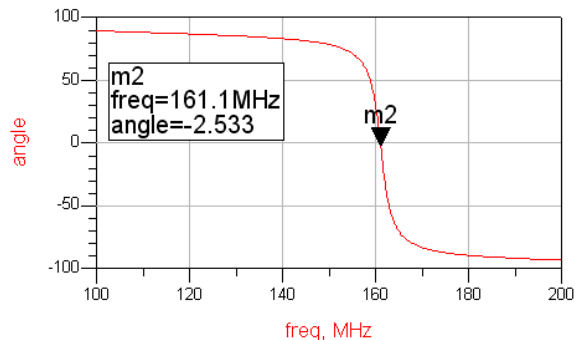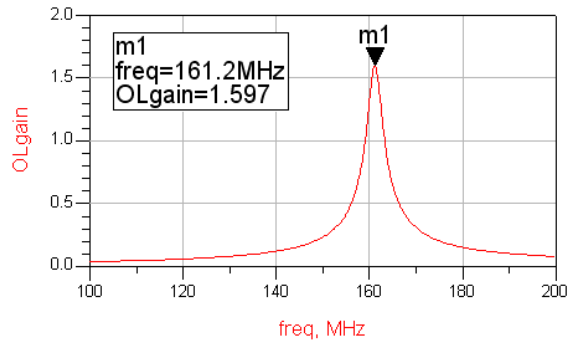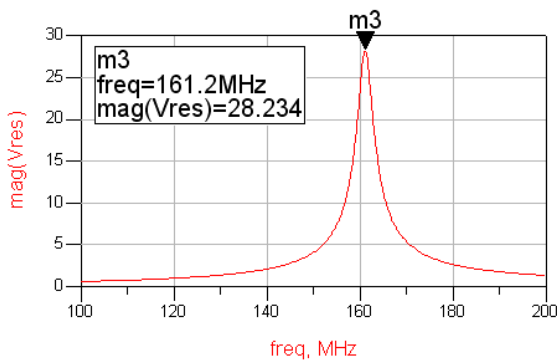
Biasing and Bypassing

In order to simulate the open loop gain and the oscillator closed loop response, we first need to bias the transistor. The choice of collector current is arbitrary but the amplitude will grow in proportion to I_C. So, you need to choose V_{CC} and the base bias voltage to avoid voltage limiting due to forward biasing of the base-collector junction. In the example shown here, $I_C = 0.5$ mA. The base voltage source $= V_{CC}/2$. Since the base current in the device is quite low, about 10 uA, there is no need to dump a lot of current into the base bias resistive divider. Also, RF bypass capacitors should be appropriately chosen for the frequency in use. In this case, 165 MHz. A 1nF capacitor has roughly 1 ohm capacitive reactance at this frequency. Choosing much larger capacitors runs the risk of encouraging low frequency parasitic oscillations. Where V_{CC} enters the board, however, a larger capacitor, typically tantalum or electrolytic, is appropriate to provide a charge reservoir on the PC board and to provide low frequency isolation from the power source.

AC simulation of open loop. AC is a linearized simulation, so the result is independent of the choice of Vac. If you look at the ratio of V1p to V1, you find a gain of approximately 1.6 at the gain peak 161 MHz. Perhaps the frequency is off slightly due to Ccb being larger than expected.

R1[0]	RL[0]	gm[0]
50.000	1000.000	0.019

Eqn OLgain=mag(Vep)/mag(V1)

Eqn angle=phase(Vep)-phase(V1)

m3
freq=161.2MHz
mag(Vres)=28.234

m1
freq=161.2MHz
OLgain=1.597

m2
freq=161.1MHz
angle=-2.533

Note that the peak OL gain simulated is less than the analysis predicted; 1.6 vs. 3. Replacing the device with a Voltage controlled Current source (VCCS), the simulations

and analysis agreed exactly. Evidently, our simplified small signal model of the BJT, which does not include Rbb, is not good enough to get exact agreement.

Transient analysis of oscillator.

This is used for a closed loop analysis of the oscillator. Starting the simulation requires that an impulse be delivered to the resonator. Otherwise, the oscillator will not start in simulation. A pulsed current source is ideal in that it defaults to an open circuit when inactive. Make sure the period of the pulse is longer than the simulation time. Otherwise you will get multiple impulses making for a confusing output signal!
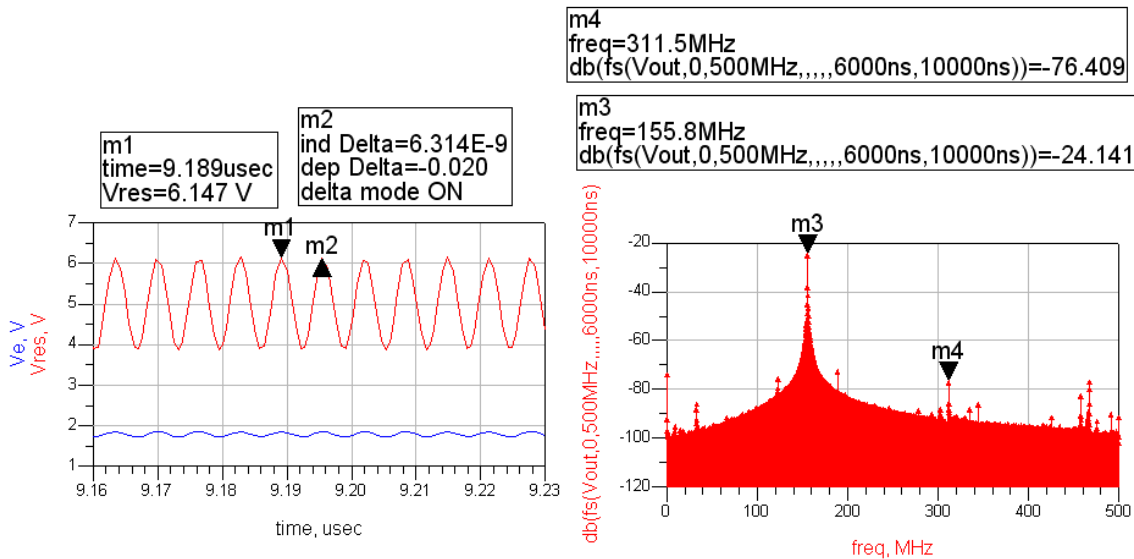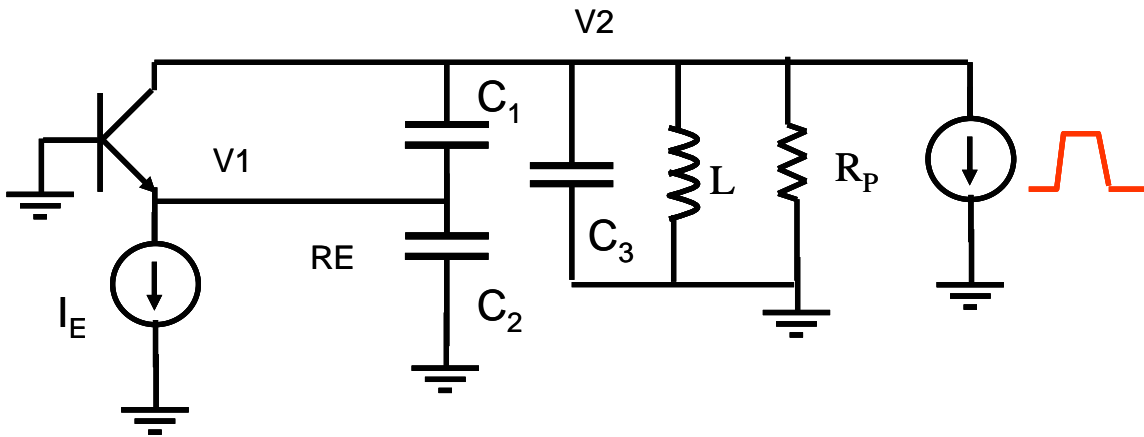
We see that the oscillator has reached a limiting amplitude of 1.147V. Note that the oscillator is current limiting, not voltage limiting because V_{CB} = Vres – Ve never drops below 2V. The resonator amplitude seems to be predicted by Vres = $I_C*(RP||N^2/gm)$, off

by a factor of 2 from Lee's predictions[1]. This may be explained by the rather low bias current which is not driving the device strongly into cutoff.

The frequency spectrum was made using the fs function in ADS. The syntax is:

```
y = fs(x{, fstart, fstop, numfreqs, dim, windowType, windowConst,
tstart, tstop, interpOrder, transformMethod})
```

I used fs(Vout,0,500MHz,,,,,6us,10us)

This windows the fft to the end of the transient simulation data, thus avoiding the crazy startup stuff which would give misleading spectral information
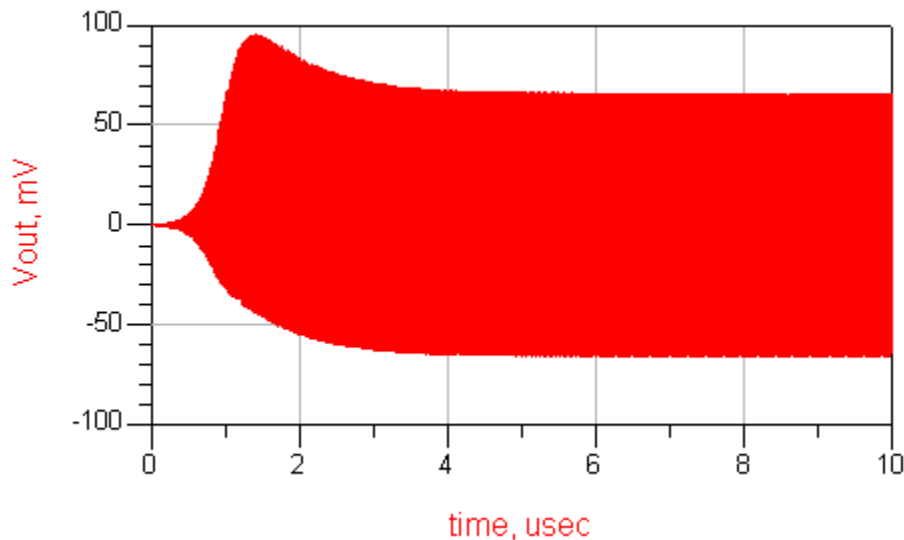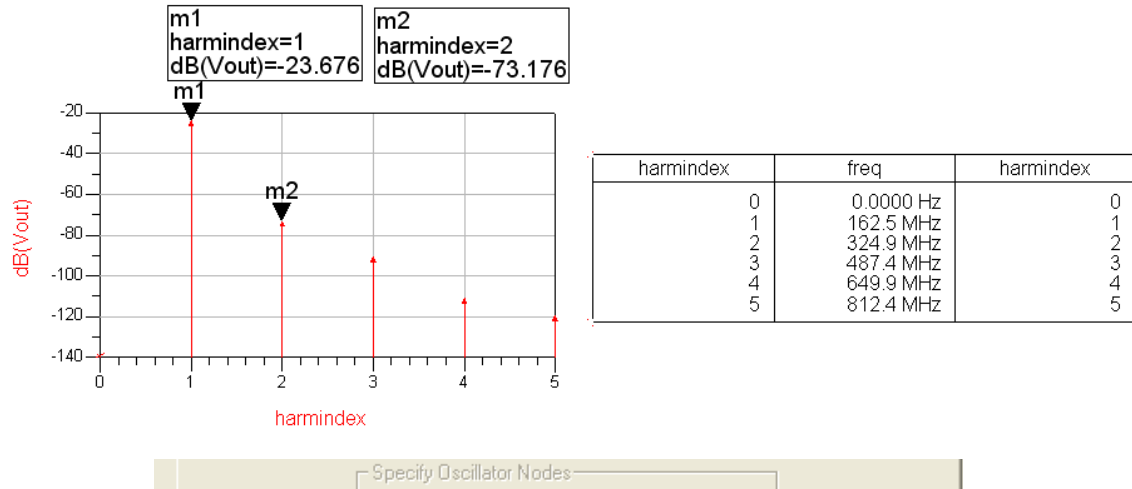

Harmonic balance simulation can also be used for closed-loop oscillator analysis. HB has be advantage that it calculates the steady-state solution directly and is relatively fast compared with transient analysis (when it converges). To simulate an oscillator, the ADS OscPort must be inserted into the signal path. The arrow must point in the right direction.

It is important to give HB a starting frequency that is close to what you expect to be the frequency of oscillation. Specify sufficient harmonics so that harmonic distortion can be calculated at the desired integer multiples of the fundamental frequency.

---

[1] T. Lee, The Design of CMOS Radio-Frequency Integrated Circuits, Second ed., Cambridge, 2004.

The harmonic balance controller must be activated for oscillator analysis in order to recognize the OscPort.

m1	m2
harmindex=1	harmindex=2
dB(Vout)=-23.676	dB(Vout)=-73.176

harmindex	freq	harmindex
0	0.0000 Hz	0
1	162.5 MHz	1
2	324.9 MHz	2
3	487.4 MHz	3
4	649.9 MHz	4
5	812.4 MHz	5

Specify Oscillator Nodes

The spectral output from HB for the example oscillator is shown above. Harmindex represents the harmonic frequency.

The output from a HB oscillator simulation can be either a frequency spectrum or a time domain representation of any voltage or current in the circuit. You can see that the spectral representation is much cleaner than the FFT generated one from Transient simulation. This is because HB calculates only the harmonic frequencies.

The time domain is generated using the ts function. This is an inverse Fourier Transform or something similar that is used to convert the harmonic frequency amplitudes and phases into a time domain sequence.
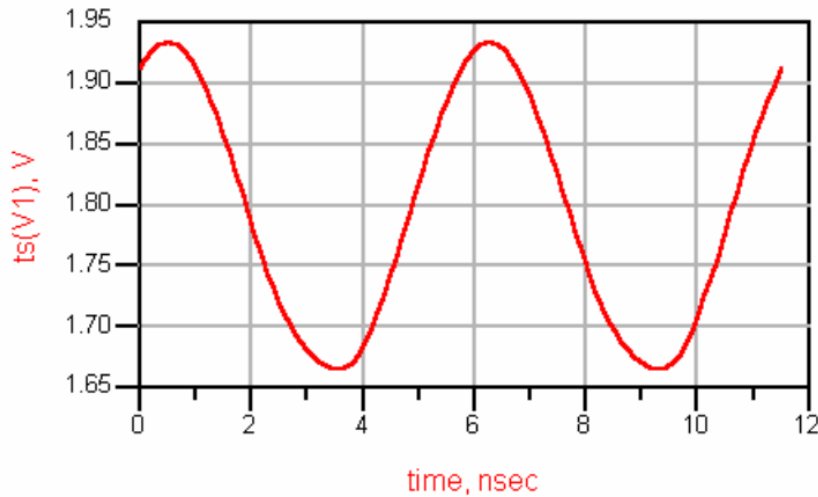
OscPort (Grounded Oscillator Port)
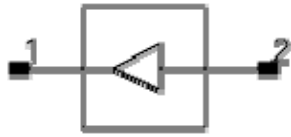
Symbol

Available in ADS and RFDE

Parameters

V = initial guess at fundamental voltage

Z = initial value for Z_0, in ohms (default: 1.1 ohms)

NumOctaves = number of octaves to search (default: 2)

Steps = number of steps per search octave (default: 10)

FundIndex = fundamental number for oscillator (default: 1)

Harm = harmonic or fundamental for oscillator (default: 1)

MaxLoopGainStep = maximum arc length continuation step size during loop-gain search

Notes/Equations

1. This is a special device used for an oscillator analysis. Do not use more than one oscillator port in a circuit.

2. NumOctaves specifies the total number of octaves over which the oscillator search is done. Half of the octaves are below the initial frequency and half are above. For example, if NumOctaves is 2, then the frequency search goes from Freq/2 to Freq×2. Steps sets the number of frequency points per octave that are used in the search. For a high-Q oscillator, a large number of steps might be required.

3. If fundamental voltage V is not specified, the simulator first performs a small-signal AC analysis to determine the actual frequency and oscillation voltage.

    If V is specified, it represents an initial guess at the fundamental oscillator voltage at the point where the OscPort is inserted. The initial guess for V should be as close to the actual value as possible. An inaccurate value increases the simulation time and might prevent convergence. If it is not known, don't specify it.

4. Provided the circuit produces at least one complex conjugate pole pair in the right-half-plane over the frequency range tested, the analysis will determine the oscillation waveform and amplitude. Proper probe placement and impedance can reduce the analysis time significantly and help ensure accurate oscillator analysis results. To reduce the probability of a failed analysis, place the probe and set the initial impedance in a manner consistent with the following guidelines:

Feedback Oscillators (such as Colpitts)

- o Insert probe at a point in the feedback loop where the signal is contained to a single path.
- o Point the arrow of the probe in the direction of positive gain around the loop.
- o Insert probe at a point in the feedback loop where source impedance is much smaller than load impedance (at least a factor of 10; a factor of 100 or more is preferable).
- o Point the arrow of the probe at the high impedance (load) node.
- o Set the initial probe impedance (Z_0) to a value approximately half-way between the source and load impedances presented by the circuit at the point of insertion.

To minimize the analysis time, set the probe impedance to a factor of 10 below the load impedance, and a factor of 10 above the source impedance (provided the source and load impedances are sufficiently far apart). Doing this effectively reduces to zero the dependence of the small signal loop gain on Z_0.

Negative Resistance Oscillators

- o Insert probe between a negative and positive impedance in the circuit. There should be no other signal paths between these two parts of the circuit. Typically, the probe is inserted between the resonator and the effective negative resistance.
- o You can point the arrow of the probe at either the negative impedance node or the positive impedance node.
- o Set the initial probe impedance to any reasonable value. To minimize the analysis time, it should be at least a factor of two higher or lower than the magnitude of the passive load impedance.

The frequency is specified on the harmonic balance analysis component. The value for Z is chosen based on impedance levels in the circuit and the degree of non-linearity in the circuit. Do not use either 1 or 0 for Z as this will cause convergence problems.
If the oscillator analysis fails, and this test indicates that the circuit should oscillate, the failure may be due to the fact that the circuit is too nonlinear. This problem can sometimes be solved by trying different impedance values of OscPort (determined by the Z attribute). Lower impedance values usually seem to work better. Also try reversing the OscPort direction.
Another approach is to try to get the oscillator to oscillate at some nicer parameter value and then to sweep the parameter value to the desired value. The parameter may be bias, self-bias impedance, some gain controlling value,

or another factor. In short, anything that will make the oscillator more linear, yet still let it oscillate.

FundIndex is used for selecting which fundamental tone is considered the unknown frequency during oscillator analysis.

The FundIndex default is 1, which means that Freq[1] on the Harmonic Balance controller is the unknown frequency. This should be changed only if a larger multi-tone system is simulated, such as an oscillator and mixer. In this case, the user may want Freq[1] to be a known driven source and Freq[2] to be the unknown frequency used by the oscillator; for this, set FundIndex=2. For the best harmonic balance solution, the frequency that causes the most nonlinearity should be Freq[1].

Harm is used to make a circuit oscillator on a harmonic of the fundamental frequency rather than directly on the fundamental. For example, the circuit may consist of a 2GHz oscillator followed by a divide-by-two circuit. In this case, the harmonic balance analysis would be set up with Freq[1]=1 GHz, and OscPort2 would have Harm=2. (Note that successful simulation of an oscillator and divider will most likely require that transient-assisted harmonic balance be used.)

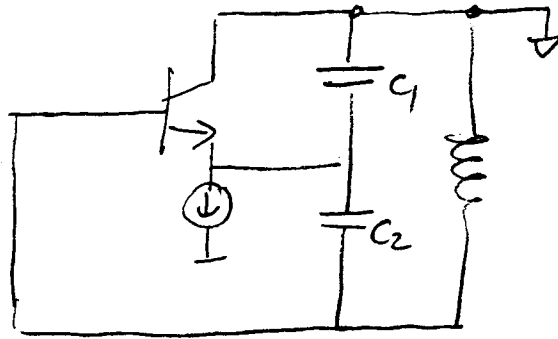Phase noise: Read T.Lee 18-1 to 18-3
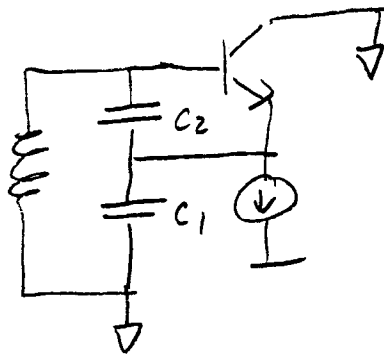
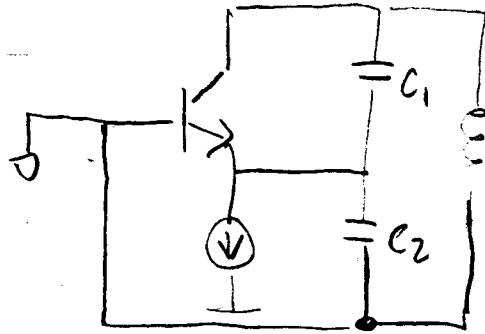# other permutations of the Colpitts

CB
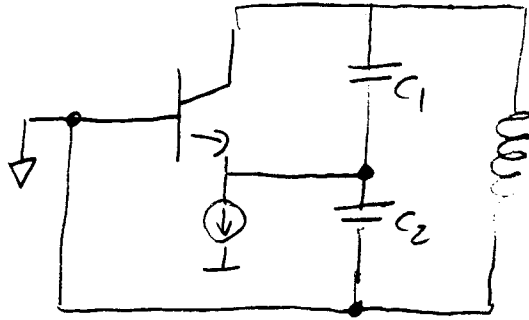
move common ground to collector

CC

this is often drawn like this:
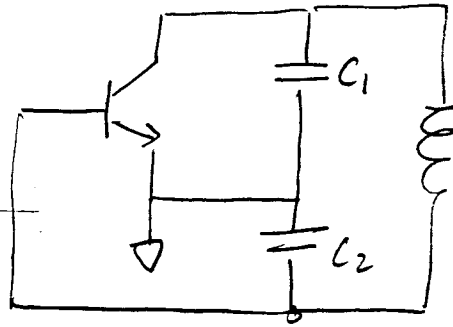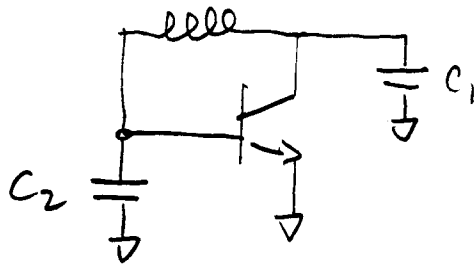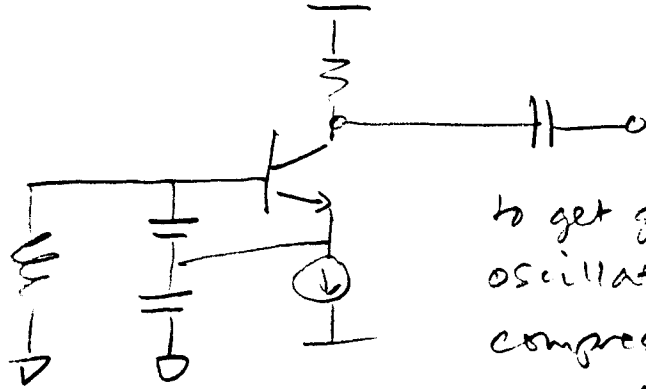

same thing

CB

move common to emitter

CE

this is often drawn like this:
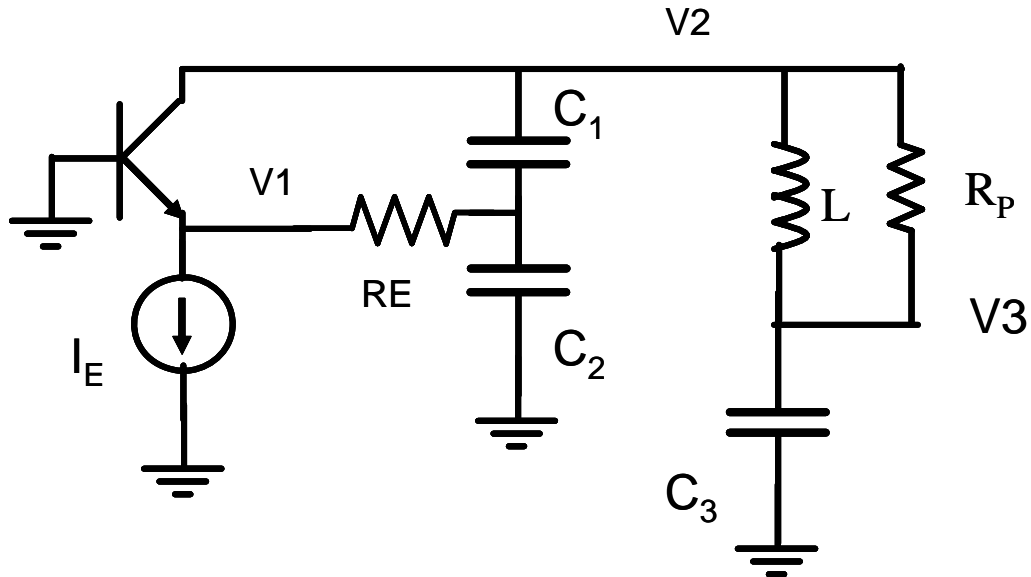

CE

Common. Collector output coupling.

to get good spectral purity,
oscillator must be lightly
compressed. Otherwise drain
current will be nonsinusoid.

Clapp Oscillator

This is a modification of the Colpitts.

The resonator is modified by adding a capacitor C3 in series with the inductor L. Since this branch of the circuit should remain inductive, L must be increased from its Colpitts value.

This provides several benefits:

1. R_P of the inductor will be higher. Consider the series equivalent circuit of the inductor below.

The inductor unloaded Q is $\quad$ $Qu = \omega L/Rs$

The parallel equivalent resistance $\quad$ $R_P = Rs\ Qu^2 = (\omega L)^2/Rs$

As the inductance value is increased, L and Rs both increase at the same rate. But, RP increases with the square of L. This means that the voltage swing $2I_CR_P$ (for the same current) can be increased with larger L. This is desirable for increasing the stored energy in the tank and reducing phase noise.

2. There are now 3 capacitors in series. The voltage at node V3 is stepped up from V2, also storing more energy in the resonator.

3. If C3 is smaller than the series combination of C1 and C2, it can be used to tune the frequency of the oscillator over a relatively wide range.