LECTURE 130 – VOLTAGE-CONTROLLED OSCILLATORS
(READING: [4,6,9])

Objective

The objective of this presentation is examine and characterize the types of voltage-controlled oscillators compatible with both discrete and integrated technologies.

Outline

- Characterization of VCO's
- Oscillators
  - RC
  - LC
  - Relaxation oscillators
  - Ring oscillators
  - Direct digital synthesis (DDS)
- Varactors
- Summary

CHARACTERIZATION OF VOLTAGE-CONTROLLED OSCILLATORS

Introduction to Voltage-Controlled Oscillators

What is an oscillator?

An oscillator is a circuit capable of maintaining electric oscillations.

An oscillator is a periodic function, i.e. $f(x) = f(x+nk)$ for all x and for all integers, n, and k is a constant.

All oscillators use positive feedback of one form or another.

Classification of oscillators:

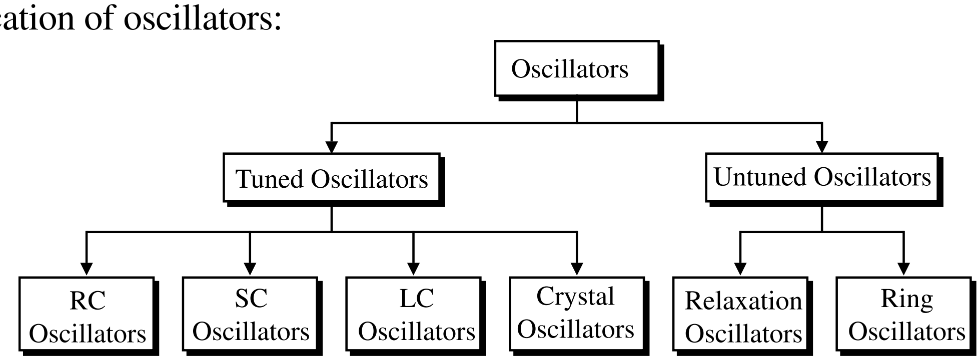


Fig. Osc-01

What are tuned oscillators?

A tuned oscillator uses a frequency-selective or tuned-circuit in the feedback path and is generally sinusoidal.

An untuned or oscillator uses nonlinear feedback and is generally non-sinusoidal

Types of Oscillators

Ring Oscillator:

Cascade of inverters

$$\text{Frequency of oscillation} = \frac{1}{\Sigma \text{ of stage delays}}$$

Controlled by current or power supply

Higher power

LC Oscillator:

$$\text{Frequency of oscillation} = \frac{1}{\sqrt{LC}}$$

Controlled by voltage dependent capacitance (varactor)

Medium power

Relaxation Oscillator:

Frequency determined by circuit time constants

Controlled by current

Medium power

RC Oscillators:

Don't require inductors

Operate at lower frequencies (1-100MHz)

Characteristics of Oscillators

- Frequency of oscillation
- Frequency tuning range as a function of the controlling variable (either voltage or current)
- Frequency stability – phase noise and jitter
- Amplitude stability (adjustable?)
- Purity (harmonics)

Linear Feedback Oscillator System

Simplified block diagram:

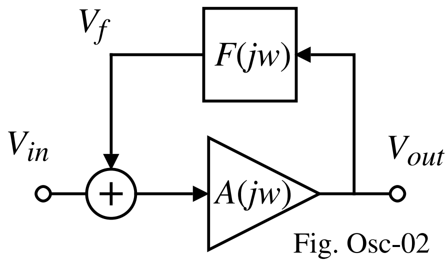


Fig. Osc-02

The loop gain of this diagram is,

$$LG(j\omega) = A(j\omega)F(j\omega)$$

When the loop gain is equal to 1, oscillation occurs.

$$Re[LG(j\omega)] + Im[LG(j\omega)] = 1 + j0$$

The frequency of oscillation is found from,

$$Im[LG(j\omega)] = 0$$

and the gain necessary for oscillation is found from,

$$Re[LG(j\omega)] = 1$$

Linear Oscillator Amplitude Stabilization

What determines the amplitude of the oscillator? Good question.

$A(j\omega)$ and/or $F(j\omega)$ must have an output-input characteristic that looks like an *s* shape.

For small amplitudes, the magnitude of the loop gain is greater than one and the oscillation grows.

As the amplitude grows, the effective gain decreases and stabilizes at just the right amplitude to give an effective loop gain of unity.

Illustration:

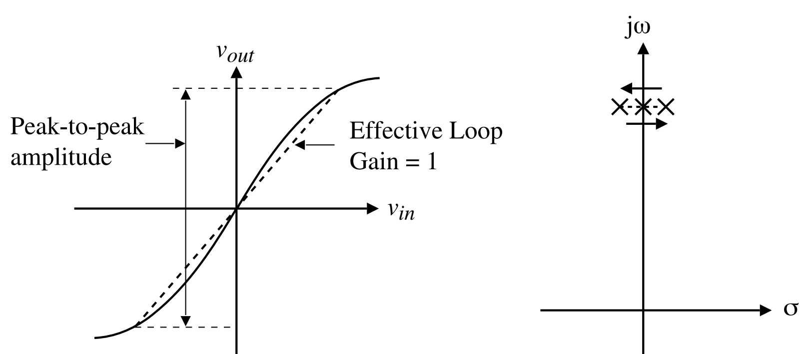
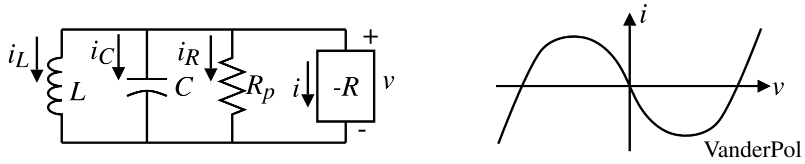


Fig. Osc-03

Pole Locations as a function of amplitude

Van der Pol Equations for Oscillators

Basic RLC oscillator and negative resistance circuit:



$$i_L + i_C + i_R + i = 0 \quad \text{and} \quad i = f(v) = -a_1 v + a_3 v^3$$

$$v_L = L\frac{di_L}{dt} \rightarrow \frac{di_L}{dt} = \frac{v}{L} \qquad \frac{di}{dv} = -a_1 + 3a_3v^2$$

$$i_C = C\frac{dv}{dt} \rightarrow \frac{di_C}{dt} = C\frac{d^2v}{dt^2} \qquad \left.\frac{di}{dv}\right|_{v=0} = -a_1 = -\frac{1}{R_n}$$

$$i_R = \frac{v}{R_p} \rightarrow \frac{di_{R_p}}{dt} = \frac{1}{R_p}\frac{dv}{dt} \qquad \frac{di}{dt} = -a_1\frac{dv}{dt} + 3a_3v^2\frac{dv}{dt}$$

$$\frac{di_L}{dt} + \frac{di_C}{dt} + \frac{di_{R_p}}{dt} + \frac{di}{dt} = 0 \rightarrow \frac{v_L}{L} + C\frac{d^2v}{dt^2} + \frac{1}{R_p}\frac{dv}{dt} + \left[-a_1\frac{dv}{dt} + 3a_3v^2\frac{dv}{dt}\right] = 0$$

$$C\frac{d^2v}{dt^2} + \left[\frac{1}{R_p} - a_1 + 3a_3v^2\right]\frac{dv}{dt} + \frac{v}{L} = 0$$

$$\frac{d^2v}{dt^2} + \left[\frac{1}{CR_p} - \frac{a_1}{C} + \frac{3a_3v^2}{C}\right]\frac{dv}{dt} + \frac{v}{LC} = 0$$

Van der Pol Equations

At start up, v is very small so that $3a_3v^2 \approx 0$

$$\therefore \quad s^2V(s) + \left(\frac{\frac{1}{R_p} - a_1}{C}\right)sV(s) + \frac{V(s)}{LC} = 0 \quad \rightarrow \quad s^2 + ms + \frac{1}{LC} = 0$$

$$\text{Poles} = -0.5m \pm 0.5\sqrt{m^2 - \frac{4}{LC}} = -0.5m \pm j0.5\sqrt{\frac{4}{LC} - m^2}$$

For $j\omega$ axis poles, $m = 0$.

In steady-state, the following relationship must hold.

$$m = \left[\frac{1}{CR_p} - \frac{a_1}{C} + \frac{3a_3v^2}{C}\right] = 0$$

We see that the amplitude of oscillation ($\omega_{osc} = \frac{1}{\sqrt{LC}}$) will be,

$$V = \sqrt{\frac{a_1 - \frac{1}{R_p}}{3a_3}} = \sqrt{\frac{\frac{1}{R_n} - \frac{1}{R_p}}{3a_3}}$$

For $V = 1\text{V}$, $\frac{1}{R_n} = \frac{1}{R_p} - 3a_3$

Open-Loop Concept of an Oscillator

Basic closed-loop oscillator:

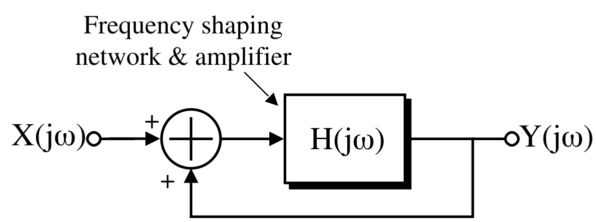


Fig. 12.4-5

Oscillator oscillates when $H(j\omega) = 1+j0$

Open-loop Q:

The open-loop Q is a measure of how much the closed loop system opposes variations in the oscillation frequency. The higher the Q, the lower the phase noise.

Definitions of Q:

1.) $Q = \dfrac{\omega_o}{\Delta\omega}$ where ω_o is the frequency of oscillation.

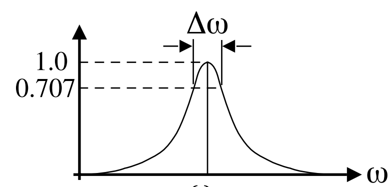


Fig. 12.4-6

2.) $Q = \dfrac{2\pi\cdot\text{Energy Stored}}{\text{Energy Dissipated per Cycle}}$

3.) $Q = \dfrac{\omega_o}{2}\dfrac{d}{d\omega}\left(\text{Arg}[H(j\omega)]\right)$

Voltage Controlled Oscillators - Tuning

A voltage controlled oscillator (VCO) is an oscillator whose frequency can be varied by a voltage (or current).

In local oscillator applications, the VCO frequency must be able to be varied over the Rx or Tx range (quickly).

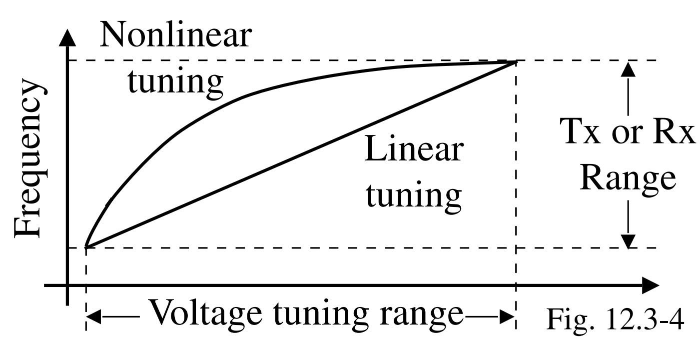


Fig. 12.3-4

Tuning variables:

- Capacitance (varactor)
- Current
- Power supply

Speed of tuning will be determined by the bandwidth of the phase lock loop.

OSCILLATORS

RC Oscillators - Wien-Bridge Oscillator

Circuit:

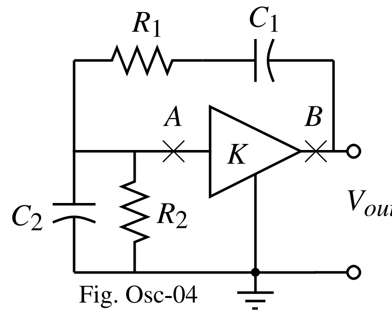


Fig. Osc-04

Open-Loop Gain:

For simplicity, let $R_1 = R_2 = R$ and $C_1 = C_2 = C$.

$$\therefore \qquad LG(s) = \frac{K\frac{s}{RC}}{s^2 + \frac{3}{RC}s + \frac{1}{(RC)^2}} \rightarrow LG(j\omega) = \frac{K\frac{j\omega}{RC}}{\frac{1}{(RC)^2} - \omega^2 + \frac{3}{RC}j\omega}$$

Equating the loop gain to 1+j0 gives

$$\frac{K\frac{j\omega_o}{RC}}{\frac{1}{(RC)^2} - \omega_o{}^2 + \frac{3}{RC}j\omega_o} = 1 + \mathrm{j}0$$

The only way this equation can be satisfied is if $\omega_o{}^2 = \frac{1}{RC}$ and $K = 3$.

Wien-Bridge Oscillator – Continued

How do you realize the amplifier of $K = 3$?

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

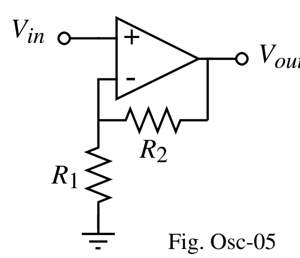


Fig. Osc-05

How does the amplitude stabilize?

- Thermistor (a resistor whose resistance decreases with increasing temperature)
- Nonlinear transfer function

Example:

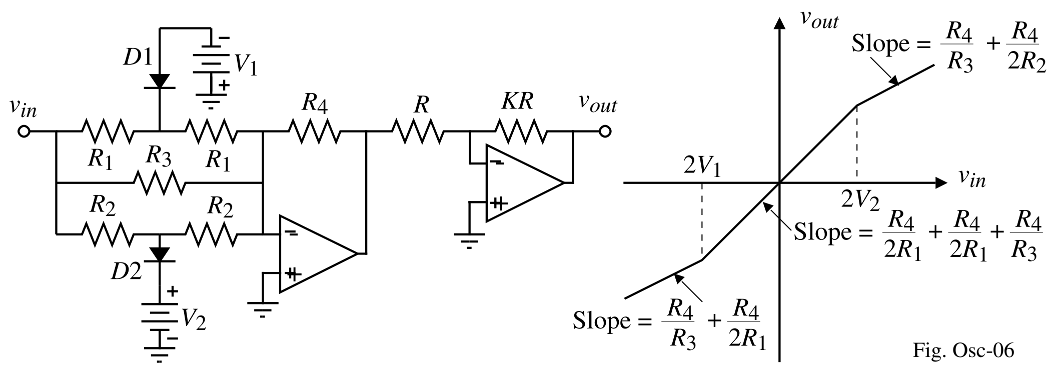


Fig. Osc-06

Other RC Oscillators

RC Phase-Shift Oscillator:

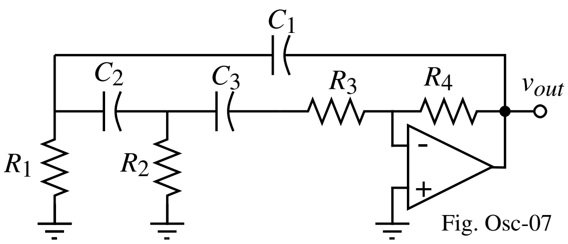


Fig. Osc-07

If $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$, then

$$LG(j\omega) = \frac{(R_4R_3)(j\omega RC)(\omega RC)^2}{[1\text{-}6(\omega RC)^2] + j\omega RC\,[5\text{ -}(\omega RC)^2]}$$

$$\therefore \qquad \omega_{osc} = \frac{1}{\sqrt{6}\,RC} \quad \text{and} \quad K = \frac{R_4}{R_3} = 29$$

Quadrature Oscillator:

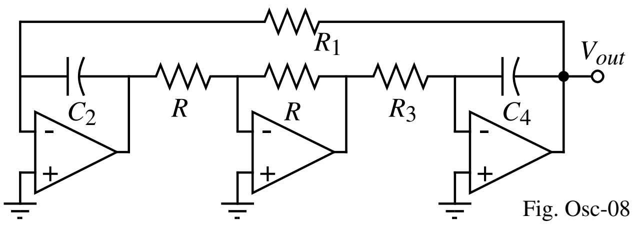


Fig. Osc-08

$$LG(j\omega) = \frac{-1}{(j\omega)^2 R_1C_2R_3C_4}$$

$$\therefore \qquad \omega_{osc} = \frac{1}{\sqrt{R_1C_2R_3C_4}}$$

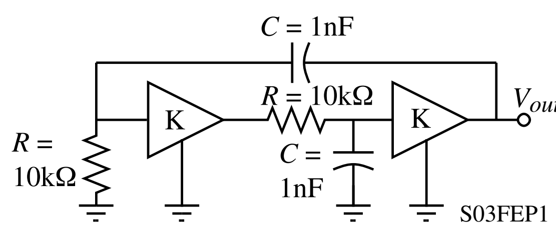
Other RC oscillators: Twin-tee RC oscillator, Sallen-Key bandpass filter with $Q = \infty$, Infinite gain, bandpass filter with $Q = \infty$

How do you tune the RC oscillator?

Must vary either R or C or both.

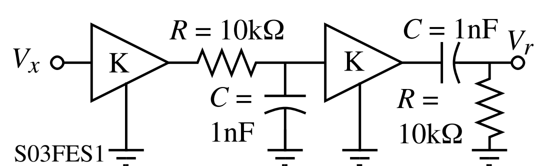
Example

The circuit shown is a *RC* oscillator. Find the frequency of oscillation in Hertz and the voltage gain, *K*, of the voltage amplifiers necessary for oscillation. The voltage amplifiers have infinite input resistance and zero output resistance.



Solution

The loop gain can be found from the schematic shown:



$$T(s) = \frac{V_r}{V_x} = K^2\left(\frac{1}{sRC+1}\right)\left(\frac{sRC}{sRC+1}\right)$$

$$= \frac{K^2 sRC}{s^2R^2C^2 + 2sRC + 1} \;\rightarrow\; T(j\omega) = \frac{K^2 j\omega RC}{1\text{-}\omega^2R^2C^2 + j\omega\,2RC} = 1 + j0$$

We see from this equation that for oscillation to occur, the following conditions must be satisfied:

$$1\text{-}\omega^2R^2C^2 = 0 \qquad \text{and} \qquad K^2 = 2$$

or

$$\omega_{osc} = \frac{1}{RC} = \frac{1}{10^4 \cdot 10^{-9}} = 10^5 \text{ radians/sec.} \;\rightarrow\; f_{osc} = \underline{\underline{15.9\text{kHz}}} \text{ and } K = \sqrt{2} = \underline{\underline{1.414}}$$

Gm-C Oscillators

Same the quadrature oscillator only implemented in a more IC friendly manner.

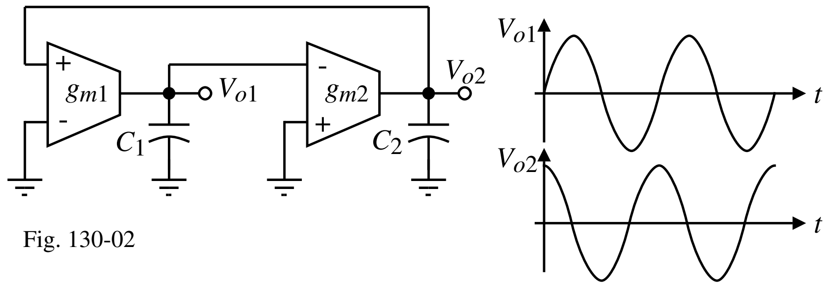


Fig. 130-02

$$\text{Open Loop Gain} = L(s) = \left(\frac{g_{m1}}{sC_1}\right)\left(\frac{-g_{m2}}{sC_2}\right) = \frac{-g_{m1}g_{m2}}{s^2C_1C_2}$$

Letting $s = j\omega$ and setting $L(j\omega) = 1$ gives,

$$\omega_{osc} = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} = \frac{g_{m1}}{C_1} = \frac{g_{m2}}{C_2} \qquad \text{if} \quad g_{m1} = g_{m2} \text{ and } C_1 = C_2$$

This circuit is much easier to tune. If the transconductors are MOS transistors, then

$$g_m = \sqrt{\frac{2K'I_DW}{L}}$$

Varying the bias current will vary g_m and tune the frequency.

Switched Capacitor Oscillators

Concept

Theoretically, the R's of any RC oscillator can be replaced by switches and capacitors to create an SC oscillator.

Quadrature SC Oscillator

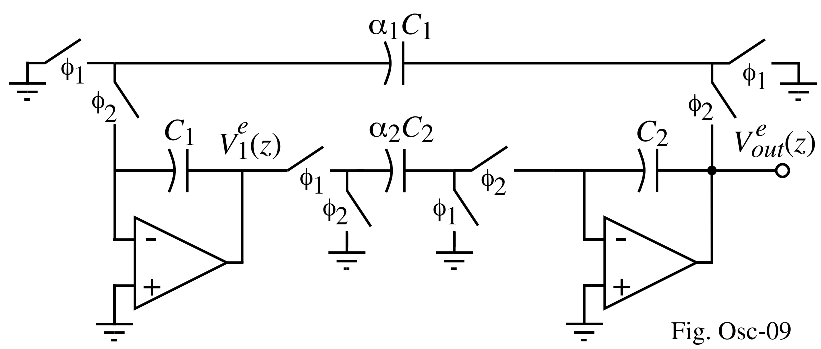


Fig. Osc-09

$$\omega_{osc} = \sqrt{\frac{\alpha_1\alpha_2}{T^2}} = \sqrt{\alpha_1\alpha_2}\, f_{clock} \qquad \text{(really a frequency translator)}$$

The output is a sinusoid at frequency of $\sqrt{\alpha_1\alpha_2}\, f_{clock}$.

LC Oscillator

All LC oscillators require feedback for oscillation to occur.

1.) Hartley or Colpitts oscillators

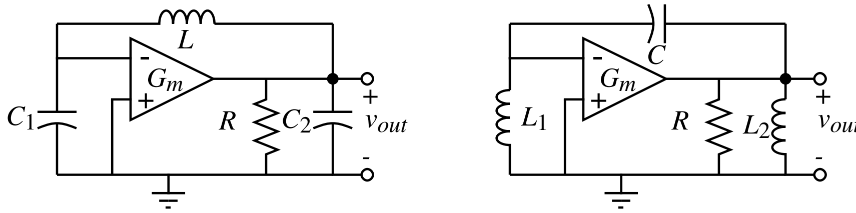


Fig. 12.4-9

$$\omega_o = \frac{1}{\sqrt{L\left(\frac{C_1C_2}{C_1+C_2}\right)}} \text{ and } \frac{C_2}{C_1} = g_mR \qquad \omega_o = \frac{1}{\sqrt{(L_1+L_2)C}} \text{ and } \frac{L_2}{L_1} = g_mR$$

2.) Negative resistance LC tank

$$\omega_o = \frac{1}{\sqrt{LC}}$$

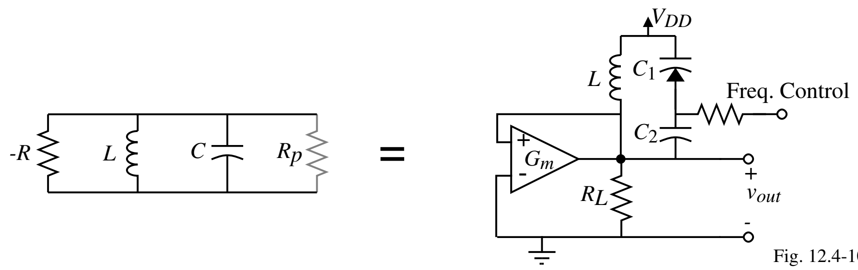
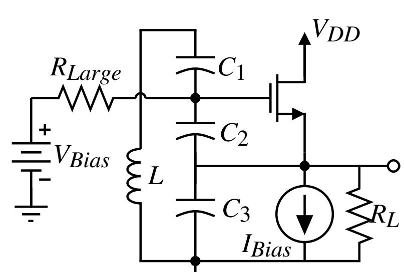


Fig. 12.4-10

Example – Clapp LC Oscillator

A Clapp oscillator which is a version of the Colpitt's oscillator is shown. Find an expression for the frequency of oscillation and the value of g_mR_L necessary for oscillation. Assume that the output resistance of the FET, r_{ds}, and R_{Large} can be neglected (approach infinity).



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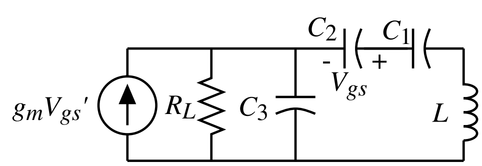
Solution

The small-signal model for this problem is shown below.



F02FES5

The loop gain will be defined as V_{gs}/V_{gs}'. Therefore,

$$V_{gs} = \frac{-g_mV_{gs}' \, R_L||(1/sC_3)}{R_L||(1/sC_3) + \frac{1}{sC_1} + \frac{1}{sC_2} + sL}\left(\frac{1}{sC_2}\right)$$

$$= \frac{-g_mV_{gs}' \frac{R_L(1/sC_3)}{R_L+(1/sC_3)}\frac{1}{sC_2}}{\frac{R_L(1/sC_3)}{R_L+(1/sC_3)} + \frac{1}{sC_1} + \frac{1}{sC_2} + sL}$$

$$T(s) = \frac{V_{gs}}{V_{gs}'} = \frac{\frac{-g_m R_L}{sR_LC_3+1}\frac{1}{sC_2}}{\frac{R_L}{sR_LC_3+1} + \frac{1}{sC_1} + \frac{1}{sC_2} + sL} = \frac{\frac{-g_m R_L}{sC_2}}{R_L + (sR_LC_3+1)\left(\frac{1}{sC_1} + \frac{1}{sC_2} + sL\right)}$$

Example – Continued

$$T(s) = \frac{-g_m R_L}{sC_2R_L + (sR_LC_3+1)(s^2LC_2 + \frac{C_2}{C_1} + 1)}$$

$$T(s) = \frac{-g_m R_L}{sC_2R_L + s^3R_LC_3LC_2 + sR_L\frac{C_2C_3}{C_1} + sC_3R_L + s^2LC_2 + \frac{C_2}{C_1} + 1}$$

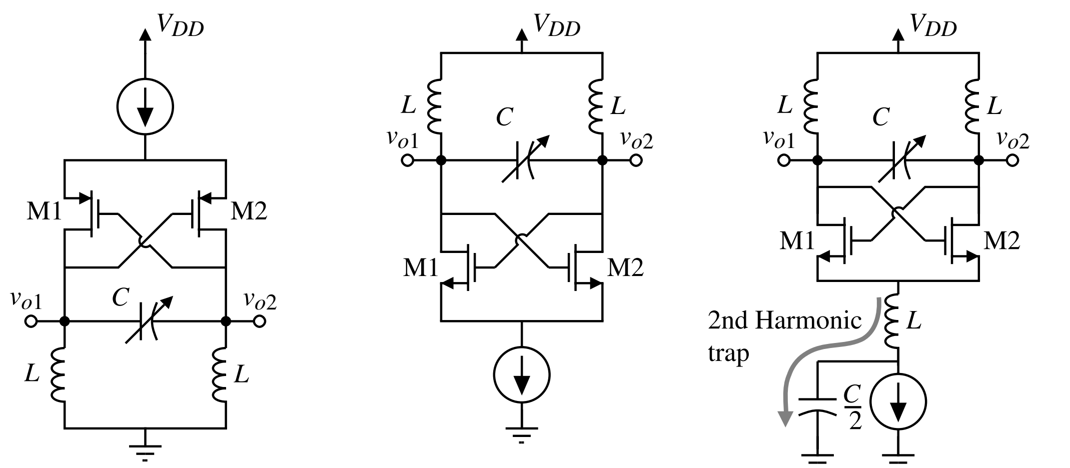
$$T(j\omega) = \frac{-g_m R_L}{[1+\frac{C_2}{C_1} - \omega^2LC_2] + j\omega[R_L(C_2+C_3) + R_L\frac{C_2C_3}{C_1} - \omega^2R_LC_3LC_2]} = 1 + j0$$

$$\therefore \quad C_2 + C_3 + \frac{C_2C_3}{C_1} = \omega_{osc}^2C_3LC_2 \quad \rightarrow \quad \boxed{\omega_{osc} = \sqrt{\frac{1}{L}\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)}}$$

Also, $$g_m R_L = \omega_{osc}^2LC_2 - 1 - \frac{C_2}{C_1} = C_2\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) - \frac{C_2}{C_1} - 1 = \frac{C_2}{C_3} \quad \rightarrow \quad \boxed{g_m R_L = \frac{C_2}{C_3}}$$

LC Oscillators

Circuits:



PMOS LC Oscillator NMOS LC Oscillator Improved NMOS LC Oscillator

Fig. 12.4-10A

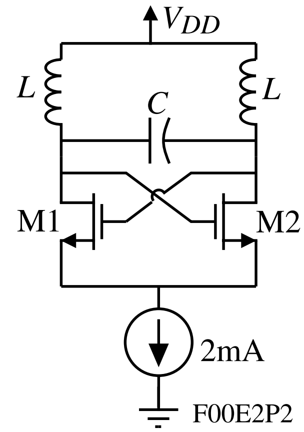
Conditions for oscillation:

$$H(s) = \left[\frac{\frac{g_m}{C}s}{s^2 + \frac{s}{RC} + \frac{1}{LC}}\right]^2 \Rightarrow H(j\omega) = \left[\frac{\frac{g_m}{C}j\omega}{-\omega^2 + \frac{j\omega}{RC} + \frac{1}{LC}}\right]^2 = 1+j0 \Rightarrow \omega_{osc}^2 = \frac{1}{LC} \;\&\; \frac{g_m}{C} = 1$$

Output swing of the improved circuit is twice that of the other circuits plus the second harmonic is removed.

Example – LC Oscillator

An LC oscillator is shown. The value of the inductors, L, are 5nH and the capacitor, C, is 2.5pF. If the Q of each inductor is 5, find (a.) the value of negative resistance that should be available from the cross-coupled, source-coupled pair (M1 and M2) for oscillation and (b.) design the W/L ratios of M1 and M2 to realize this negative resistance (if you can't find the negative resistance of part (a.) assume that the desired negative resistance is -100Ω).



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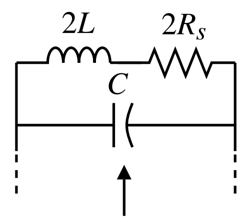
Solution

(a.) The equivalent circuit seen by the negative resistance circuit is:



F00E2S2A

The frequency of oscillation is given as $1/\sqrt{2LC}$ or $\omega_o = 2\pi \mathrm{x} 10^9$ radians/sec.

Therefore the series resistance, R_s, is found as

$$R_s = \frac{\omega L}{Q} = \frac{2\pi \mathrm{x}10^9 \cdot 5\mathrm{x}10^{-9}}{5} = 2\pi\ \Omega$$

Converting the series impedance of $2L$ and $2R_s$ into a parallel impedance gives,

$$Y = \frac{1}{2R_s + j\omega 2L} = \frac{0.5}{R_s + j\omega L} \cdot \frac{R_s - j\omega L}{R_s - j\omega L} = \frac{0.5R_s}{R_s^2 + \omega^2 L^2} - j\frac{0.5\omega L_s}{R_s^2 - \omega^2 L^2}$$

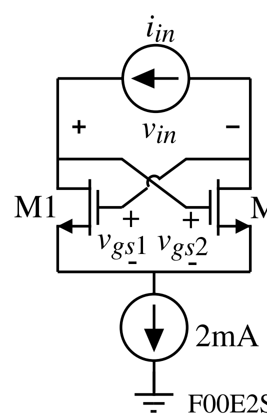
LC Oscillator Example - Continued

The reciprocal of the conductance is the parallel resistance, R_p, given as

$$R_p = \frac{R_s^2 + \omega^2 L^2}{0.5R_s} = \frac{4\pi^2 + 4\pi^2 \cdot 25}{\pi} = 4\pi(26) = 326.7\Omega$$

$\therefore$ $\underline{\underline{R_{neg} = -104\pi\ \Omega = -326.7\Omega}}$

(b.) The negative resistance seen by the RLC circuit is found as follows.



F00E2S2B

$$i_{in} = g_{m1}v_{gs1} = -\,g_{m2}v_{gs2}$$

$$\therefore \quad R_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{gs2} - v_{gs1}}{i_{in}} = \frac{-1}{g_{m2}} - \frac{1}{g_{m1}} = \frac{-2}{g_m}$$

Assuming the 2mA splits evenly between M1 and M2 for the negative resistance calculation gives,

Thus, $g_m = g_{m1} = g_{m2} = \sqrt{2 \cdot 2\mathrm{mA} \cdot 110\mathrm{x}10^{-6}\,(W/L)} = \dfrac{\sqrt{W/L}}{1508} = \dfrac{2}{104\pi}$

$$\therefore \quad W/L = \left(\frac{1508}{52\pi}\right)^2 = 841 \quad \Rightarrow \quad \underline{\underline{W/L = 841}}$$

LC Oscillator

VCO with PMOS pair:

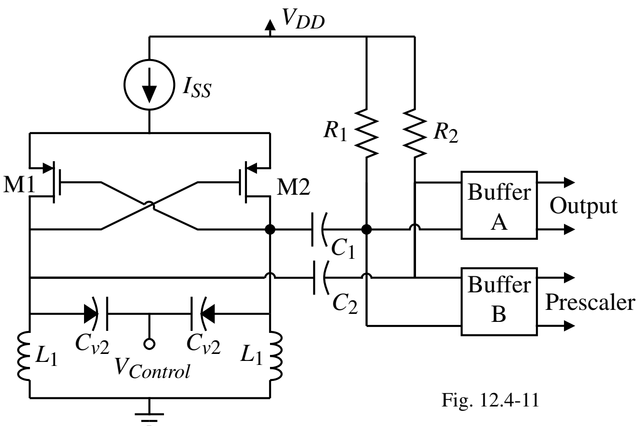


Fig. 12.4-11

Design:

- Inductors - $L_1 = L_2 = 7.1$nH, $Q = 8.5$ at 910MHz (Metal 3 with spacing of 2.1µm and width of 16.1µm and 5 turns)
- R_1, C_1 and R_2, C_2 form ac coupling filters
- Buffers A and B isolate the VCO from the next stages to avoid the pulling effect of the center frequency due to injection from the external load or the prescaler fed by the VCO. Buffer A provides a matched 50Ω output impedance and buffer B drives the large capacitance of the prescaler.
- $I_{SS} = 1.5$mA

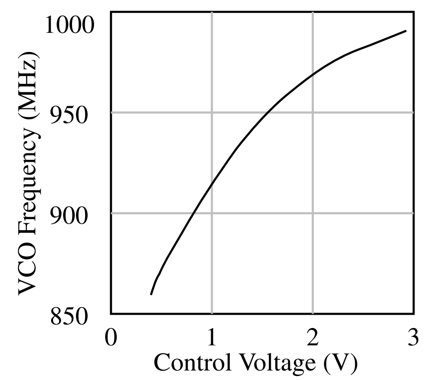


Fig. 12.4-12

Relaxation Oscillators

Circuit:

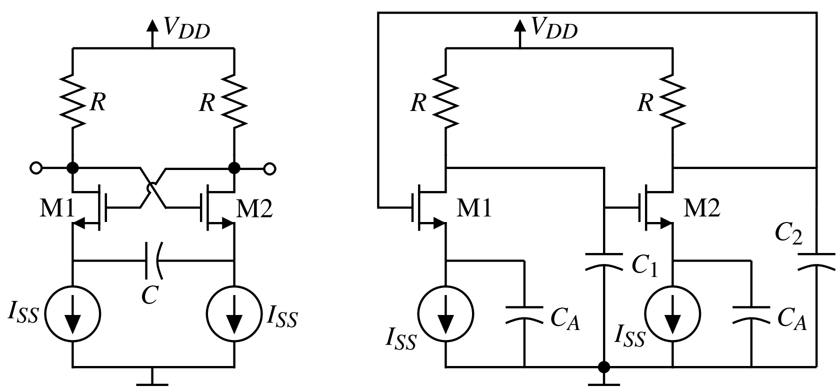


Fig. 12.4-13

Open Loop:

Assume that C in the closed loop circuit is really two $2C$ capacitors in series and ground the midpoint to obtain the open-loop circuit. C_1 and C_2 are capacitances to ground from the drains of M1 and M2.

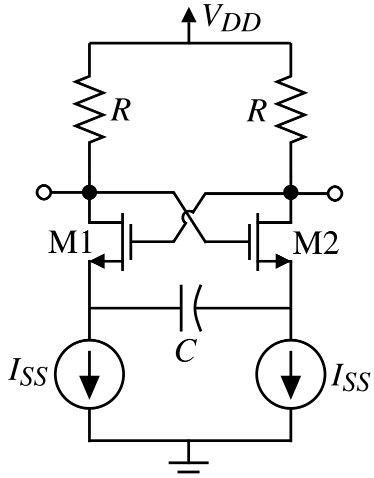
$$H(s) = \left[\frac{-g_m R C_A s}{(g_m + C_A s)(R C_D s + 1)}\right]^2$$

where g_m = transconductance of each transistor and $C_D = C_1 = C_2$.

It can be shown that,

$$\omega_o = \frac{g_m}{R C_A C_D} \quad \text{and} \quad Q = 4\left(1 - \frac{C_D}{C_A}\right)\frac{C_D}{C_A} \Rightarrow Q_{max} = 1 \;\Rightarrow\; S_{o\theta}(f_m) = \frac{1}{4}\left(\frac{f_o}{f_m}\right)^2 S_\theta(f_m)$$

Relaxation Oscillator - Experimental Results



W/L = 100µm/0.5µm

g_m = 1/84µS

R = 275Ω

C = 0.6pF

I_{SS} = 3mA

Fig. 12.4-14

f_o = 920 MHz

Phase noise = -105 dBc/Hz for f_m = 1MHz and -115dBc/Hz for f_m = 5MHz

Ring Oscillator VCO

Three-stage ring oscillator:

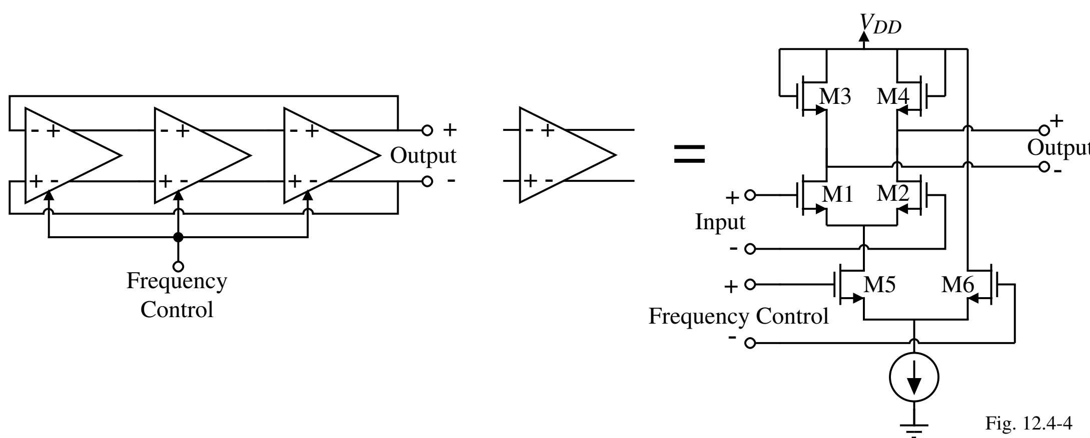
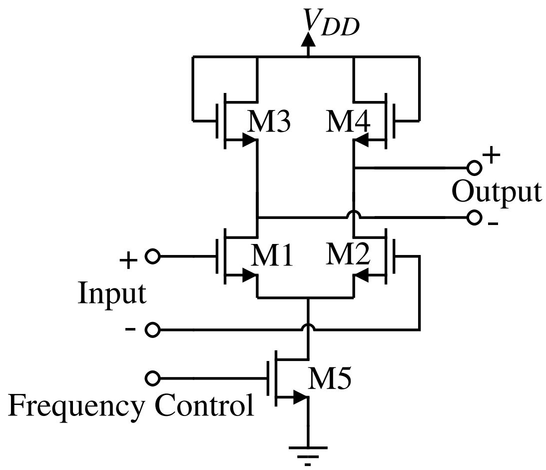


Fig. 12.4-4

Comparison of a Three-Stage and Four-Stage Ring Oscillator:

Characteristic	3-Stage Ring Oscillator	4-Stage Ring Oscillator
Min. Required Gain	2	$\sqrt{2}$
Noise Shaping Function	$\frac{1}{27}\left(\frac{f_o}{f_m}\right)^2$	$\frac{1}{16}\left(\frac{f_o}{f_m}\right)^2$
Open-Loop Q	$0.75\sqrt{2}$	$\sqrt{2}$
Power Dissipation	1.8mW	3.6mW

Ring Oscillator - Experimental Results



M1 and M2: W/L = 97µm/0.5µm
g_m = 1/214µS

M3 and M4: W/L = 13.4µm/0.5µm
g_m = 1/630µS

M5: W/L = 13.4µm/0.5µm
I_D = 790µA
g_m = 1/530µS

Fig. 12.4-8

f_o = 2.2GHz

Phase noise at 1MHz = -99.2 dBc/Hz

General Comments:

Phase noise is proportional to power dissipation

Wide tuning range (2 to 1)

Poor phase noise performance

Direct Digital Frequency Synthesizer - DDFS

A sinusoid is digitized and stored in a ROM. These stored values are applied to a DAC at regular time intervals by a reference clock. The frequency is increased by taking fewer , but further separated samples from the ROM look-up table.

Block Diagram:

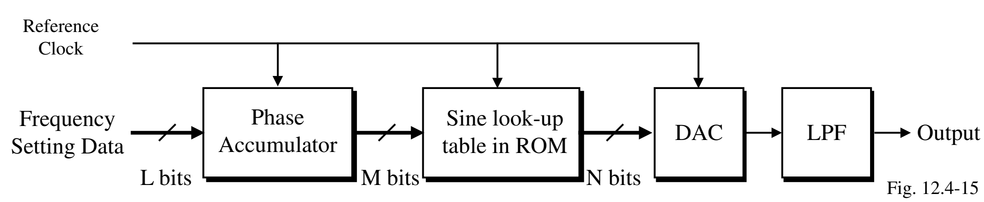


Fig. 12.4-15

Operation:

1.) Phase accumulator adds the frequency setting data to the previous contents once every clock cycle. The most significant bits of the results are used to address the ROM look-up table.

2.) The address decoding circuitry of the ROM selects the corresponding N bit sample and feeds it to the DAC.

3.) The DAC converts this digital data to an analog signal.

4.) The analog signal is passed through the low-pass filter to smooth the waveform and remove out-of-band high frequency noise from the signal.

Advantages:

- Very high frequency resolution ($f_{clock}/2^N$)
- Fast switching time

Disadvantages:

- High power consumption
- Restricted to low frequencies

Quadrature VCO's

Polyphase Oscillator:

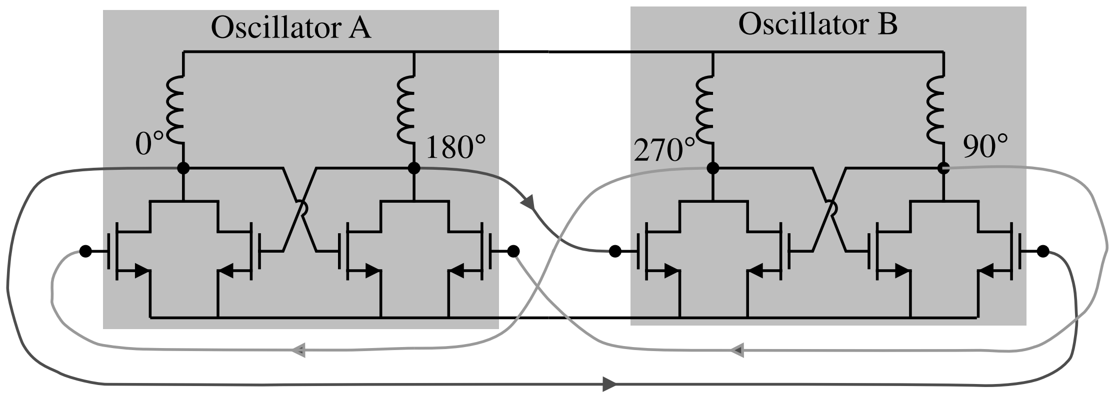


Fig. 12.5-14

- Two cross-coupled oscillators synchronize in exact quadrature
- Phase inaccuracy insensitive to mismatch in resonators
- Large amplitudes available, balanced oscillation available to drive mixer FETs

Performance:

830 MHz

Unwanted sideband -46 dB below wanted sideband

Leakage 49 dB below wanted sideband

Quadrature Oscillators

Frequency Division Approach:

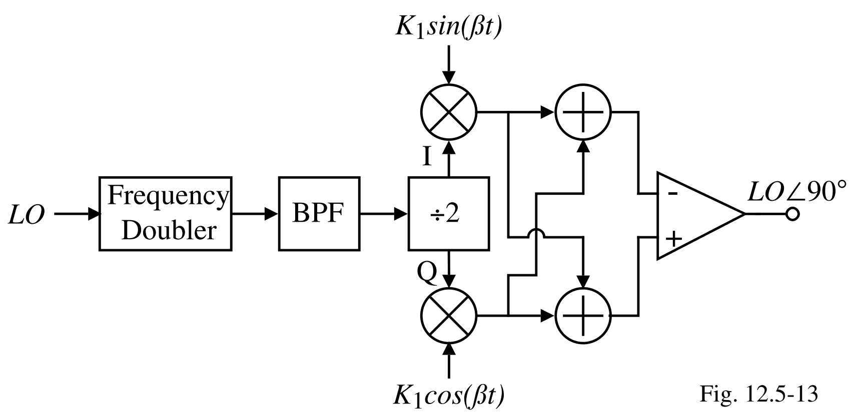


Fig. 12.5-13

Comments:

- Start with a single phase local oscillator at twice the desired frequency
- Divide by 2 is done by positive and negative edge triggered flip-flops
- Phase accuracy depends on timing skews between the flip-flop channels (typically 1-2°)

VARACTORS – VARIABLE CAPACITORS

One of the components that can be used to vary the frequency is the capacitor.

Types of Capacitors Considered

- pn junction capacitors
- Standard MOS capacitors
- Accumulation mode MOS capacitors
- Poly-poly capacitors
- Metal-metal capacitors

Characterization of Capacitors

Assume C is the desired capacitance:

1.) Dissipation (quality factor) of a capacitor is

$$Q = \omega C R_p$$

where R_p is the equivalent resistance in parallel with the capacitor, C.

2.) C_{max}/C_{min} ratio is the ratio of the largest value of capacitance to the smallest when the capacitor is used as a variable capacitor.

3.) Variation of capacitance with the control voltage.

4.) Parasitic capacitors from both terminal of the desired capacitor to ac ground.

Desirable Characteristics of Varactors

1.) A high quality factor

2.) A control voltage range compatible with supply voltage

3.) Good tunability over the available control voltage range

4.) Small silicon area (reduces cost)

5.) Reasonably uniform capacitance variation over the available control voltage range

6.) A high C_{max}/C_{min} ratio

Some References for Further Information

1.) P. Andreani and S. Mattisson, “On the Use of MOS Varactors in RF VCO’s,” *IEEE J. of Solid-State Circuits*, vol. 35, no. 6, June 2000, pp. 905-910.

2.) A-S Porret, T. Melly, C. Enz, and E. Vittoz, “Design of High-Q Varactors for Low-Power Wireless Applications Using a Standard CMOS Process,” *IEEE J. of Solid-State Circuits*, vol. 35, no. 3, March 2000, pp. 337-345.

3.) E. Pedersen, “RF CMOS Varactors for 2GHz Applications,” *Analog Integrated Circuits and Signal Processing*, vol. 26, pp. 27-36, Jan. 2001

Digitally Varied Capacitances

In a digital process, high-quality capacitors are very difficult to achieve. A high-quality variable capacitor is even more difficult to realize.

Therefore, digitally controlled capacitances are becoming more popular.

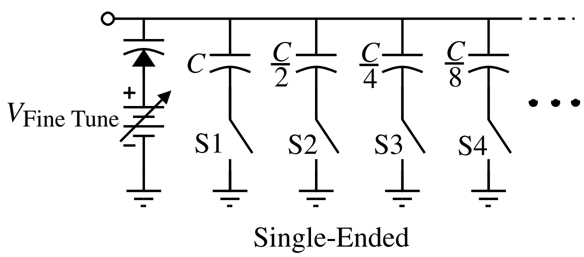
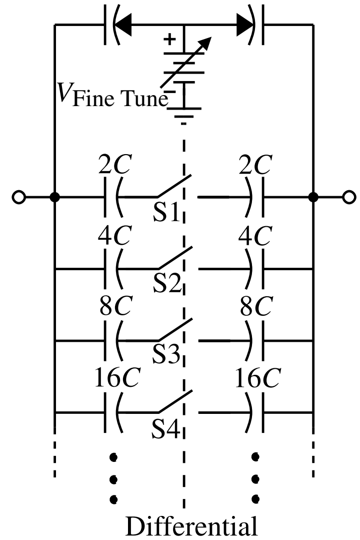


Fig. 3.1-44



Concerns:

- Switch parasitics
- Switch ON resistance (will lower Q)

K_{vo} of Digitally Tuned *VCOs*

The value of the VCO gain constant can be made smaller which is desirable in many applications of the VCO.

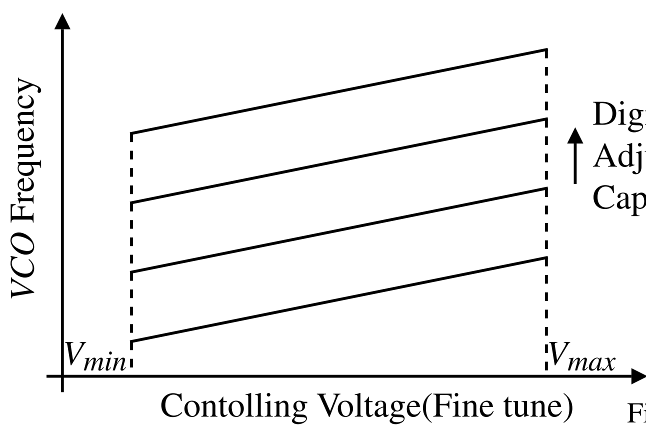


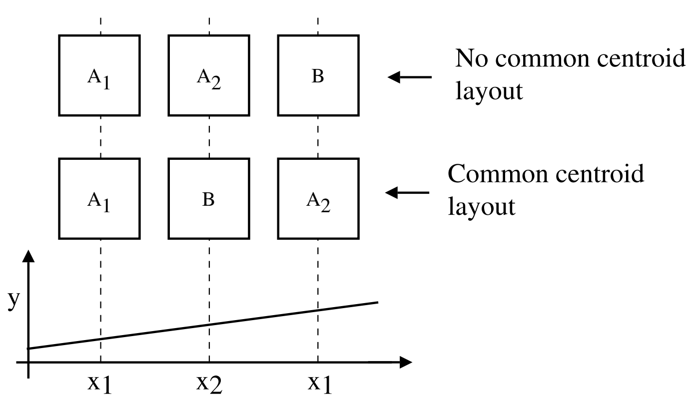
Fig. 3.1-45

Capacitor Errors

1.) Oxide gradients
2.) Edge effects
3.) Parasitics
4.) Voltage dependence
5.) Temperature dependence

Capacitor Errors - Oxide Gradients

Error due to a variation in oxide thickness across the wafer.



Only good for one-dimensional errors.

An alternate approach is to layout numerous repetitions and connect them randomly to achieve a statistical error balanced over the entire area of interest.

A	B	C	A	B	C	A	B	C
C	A	B	C	A	B	C	A	B
B	C	A	B	C	A	B	C	A

0.2% matching of poly resistors was achieved using an array of 50 unit resistors.

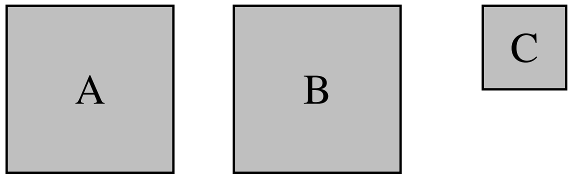
Capacitor Errors - Edge Effects

There will always be a randomness on the definition of the edge.

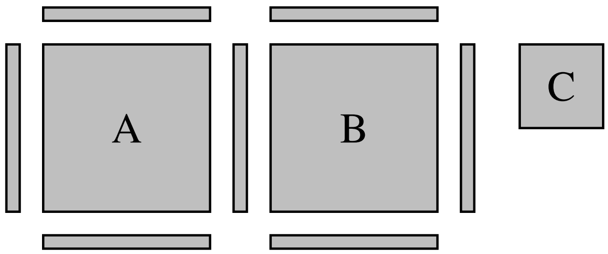
However, etching can be influenced by the presence of adjacent structures.

For example,

Matching of A and B are disturbed by the presence of C.



Improved matching achieve by matching the surroundings of A and B.



Capacitor Errors - Area/Periphery Ratio

The best match between two structures occurs when their area-to-periphery ratios are identical.

Let $C'_1 = C_1 \pm \Delta C_1$ and $C'_2 = C_2 \pm \Delta C_2$

where

C' = the actual capacitance

C = the desired capacitance (which is proportional to *area*)

ΔC = edge uncertainty (which is proportional to the *periphery*)

Solve for the ratio of C'_2/C'_1,

$$\frac{C'_2}{C'_1} = \frac{C_2 \pm \Delta C_2}{C_1 \pm \Delta C_1} = \frac{C_2}{C_1}\left(\frac{1 \pm \frac{\Delta C_2}{C_2}}{1 \pm \frac{\Delta C_1}{C_1}}\right) \approx \frac{C_2}{C_1}\left(1 \pm \frac{\Delta C_2}{C_2}\right)\left(1 \mp \frac{\Delta C_1}{C_1}\right) \approx \frac{C_2}{C_1}\left(1 \pm \frac{\Delta C_2}{C_2} \mp \frac{\Delta C_1}{C_1}\right)$$

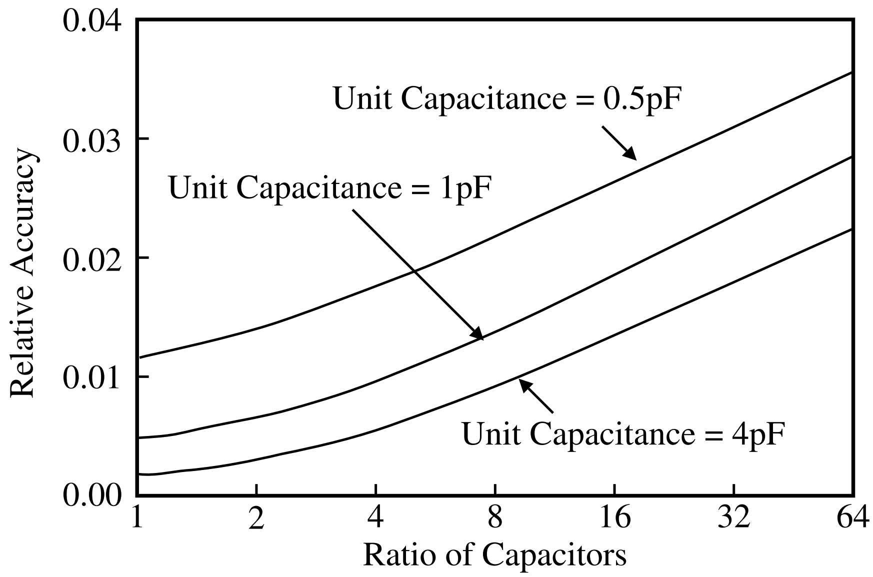
If $\frac{\Delta C_2}{C_2} = \frac{\Delta C_1}{C_1}$, then $\boxed{\frac{C'_2}{C'_1} = \frac{C_2}{C_1}}$

Therefore, the best matching results are obtained when the area/periphery ratio of C_2 is equal to the area/periphery ratio of C_1.

Capacitor Errors - Relative Accuracy

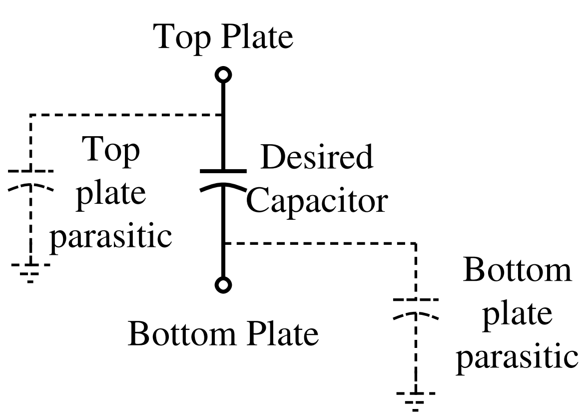
Capacitor relative accuracy is proportional to the area of the capacitors and inversely proportional to the difference in values between the two capacitors.

For example,



Capacitor Errors - Parasitics

Parasitics are normally from the top and bottom plate to ac ground which is typically the substrate.

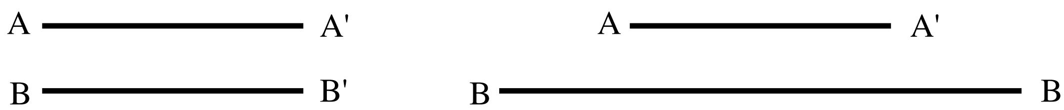


Top plate parasitic is 0.01 to 0.001 of $C_{desired}$

Bottom plate parasitic is 0.05 to 0.2 $C_{desired}$

Other Considerations on Capacitor Accuracy

Decreasing Sensitivity to Edge Variation:



Sensitive to edge variation in both upper andlower plates

Sensitive to edge varation in upper plate only.

Fig. 2.6-13

A structure that minimizes the ratio of perimeter to area (circle is best).

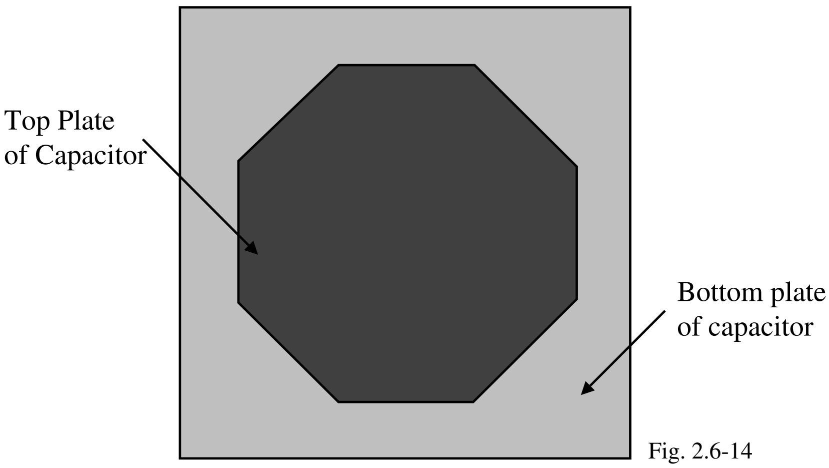


Fig. 2.6-14

Definition of Temperature and Voltage Coefficients

In general a variable y which is a function of x, $y = f(x)$, can be expressed as a Taylor series,

$$y(x = x_0) \approx y(x_0) + a_1(x- x_0) + a_2(x- x_0)^2 + a_1(x- x_0)^3 + \cdots$$

where the coefficients, a_i, are defined as,

$$a_1 = \frac{df(x)}{dx}\bigg|_{x=x_0},\ a_2 = \frac{1}{2}\frac{d^2f(x)}{dx^2}\bigg|_{x=x_0},\ \ldots.$$

The coefficients, a_i, are called the first-order, second-order, …. temperature or voltage coefficients depending on whether x is temperature or voltage.

Generally, only the first-order coefficients are of interest.

In the characterization of temperature dependence, it is common practice to use a term called *fractional temperature coefficient*, TC_F, which is defined as,

$$TC_F(T{=}T_0) = \frac{1}{f(T{=}T_0)}\frac{df(T)}{dT}\bigg|_{T=T_0} \text{ parts per million/°C (ppm/°C)}$$

or more simply,

$$TC_F = \frac{1}{f(T)}\frac{df(T)}{dT} \text{ parts per million/°C (ppm/°C)}$$

A similar definition holds for fractional voltage coefficient.

Capacitor Errors - Temperature and Voltage Dependence

Polysilicon-Oxide-Semiconductor Capacitors

Absolute accuracy ≈ ±10%

Relative accuracy ≈ ±0.2%

Temperature coefficient ≈ +25 ppm/C°

Voltage coefficient ≈ -50ppm/V

Polysilicon-Oxide-Polysilicon Capacitors

Absolute accuracy ≈ ±10%

Relative accuracy ≈ ±0.2%

Temperature coefficient ≈ +25 ppm/C°

Voltage coefficient ≈ -20ppm/V

Accuracies depend upon the size of the capacitors.

SUMMARY

- Characterization of VCO's
  - Frequency,
  - Frequency tuning range
  - Frequency stability
  - Amplitude stability
  - Spectral purity
- Oscillators
  - RC
  - LC
  - Relaxation oscillators
  - Ring oscillators
  - Direct digital synthesis (DDS)
- Varactors

  Used to vary the frequency of RC and LC oscillators