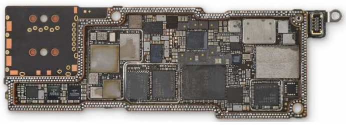
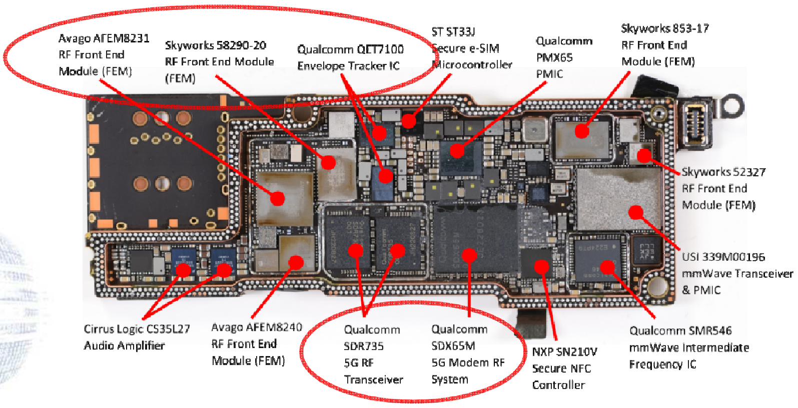
Lecture 2: Oscillators

Prof. Mohammed Hawa
Electrical Engineering Department
The University of Jordan

ICs in Modern Phones & Devices

High-Density PCB





Avago AFEM8231
RF Front End
Module (FEM)

Skyworks 58290-20
RF Front End Module
(FEM)

Qualcomm QET7100
Envelope Tracker IC

ST ST33J
Secure e-SIM
Microcontroller

Qualcomm
PMX65
PMIC

Skyworks 853-17
RF Front End
Module (FEM)

Skyworks 52327
RF Front End
Module (FEM)

USI 339M00196
mmWave Transceiver
& PMIC

Cirrus Logic CS35L27
Audio Amplifier

Avago AFEM8240
RF Front End
Module (FEM)

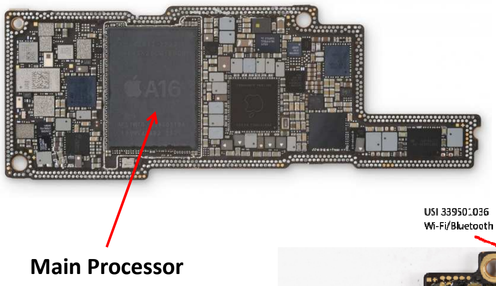
Qualcomm
SDR735
5G RF
Transceiver

Qualcomm
SDX65M
5G Modem RF
System

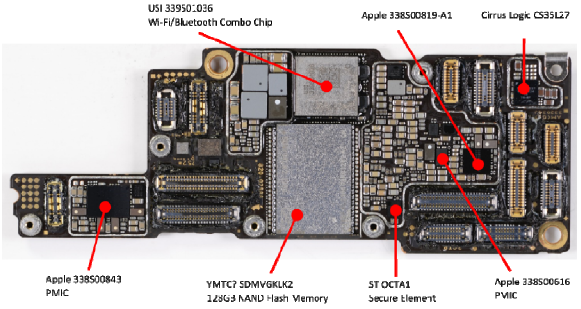
NXP SN210V
Secure NFC
Controller

Qualcomm SMR546
mmWave Intermediate
Frequency IC

Printed Circuit Board (PCB)



Main Processor



USI 339S01036
Wi-Fi/Bluetooth Combo Chip

Apple 338S00819-A1

Cirrus Logic CS35L27

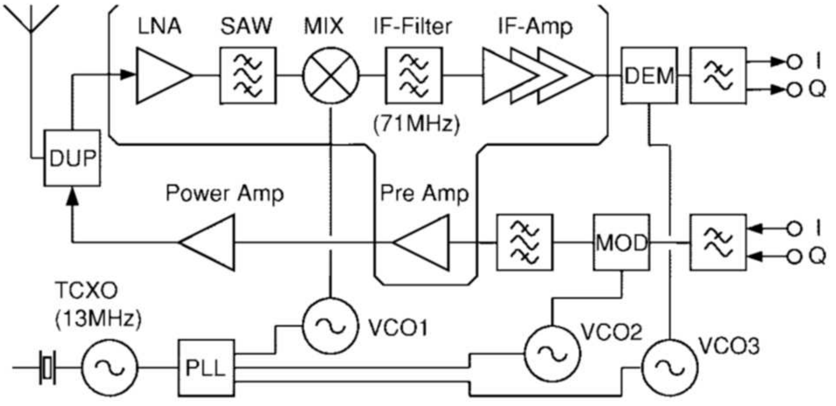
Apple 338S00843
PMIC

YMTC? SDMVGKLK2
128GB NAND Flash Memory

ST OCTA1
Secure Element

Apple 338S00616
PMIC

RF Solid State Modules



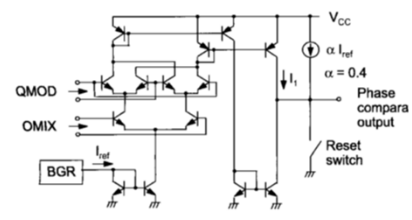


Fig. 8. Phase comparator.

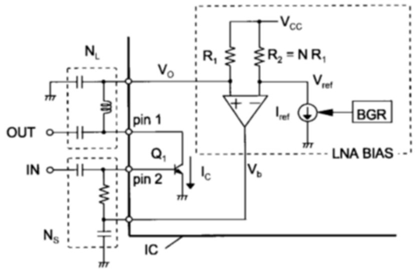


Fig. 9. LNA and active bias.

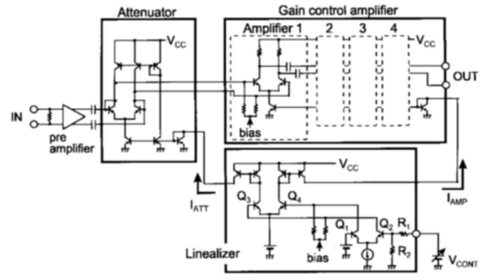
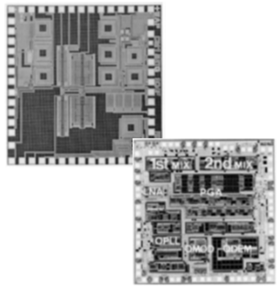


Fig. 10. PGA.



Oscillator

- An oscillator generates periodic signal (e.g., sinusoidal signal, square wave, sawtooth, etc).
- No input required (no external excitation), just a DC power supply (for biasing, energy).
- Sometimes oscillators are named based on output signal frequency:
  - *Low-frequency oscillator* (LFO) generate frequencies below 20 Hz, say to feed audio synthesizers.
  - *Audio oscillator* produces frequencies in the audio/music range, 20 Hz to 20 kHz.
  - *Radio Frequency (RF) oscillator* or *Microwave oscillator* produces signals in the range of 100 kHz and higher.

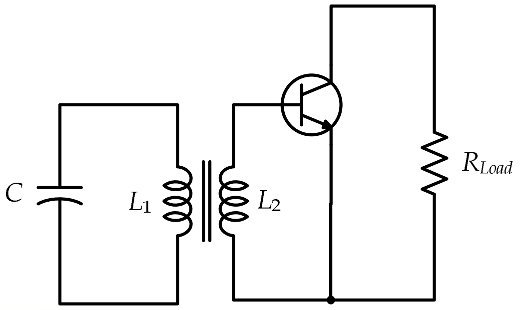
Oscillator Classification

- **Linear** or **harmonic oscillator**: output is sinusoidal (or almost-sinusoidal) signal.
- Most common type in communication systems (produce carrier).
- Use amplifier (e.g., transistor or operational amplifier) with positive feedback through frequency-selective filter.
- **Nonlinear** or **relaxation oscillator**: output is non-sinusoidal periodic signal, (e.g., square, sawtooth, triangle wave, etc).
- Use energy-storage element (mainly capacitor, rarely inductor) plus a switching device (Latch, Schmitt trigger, etc) connected in feedback loop.
- Switching device charges/discharges energy-storage element, (e.g., causing capacitor voltage to increase/decrease periodically).
- Square-waves used as digital clocks. Triangle or sawtooth waves are used as sweep signals (oscilloscopes, TV, etc), etc.

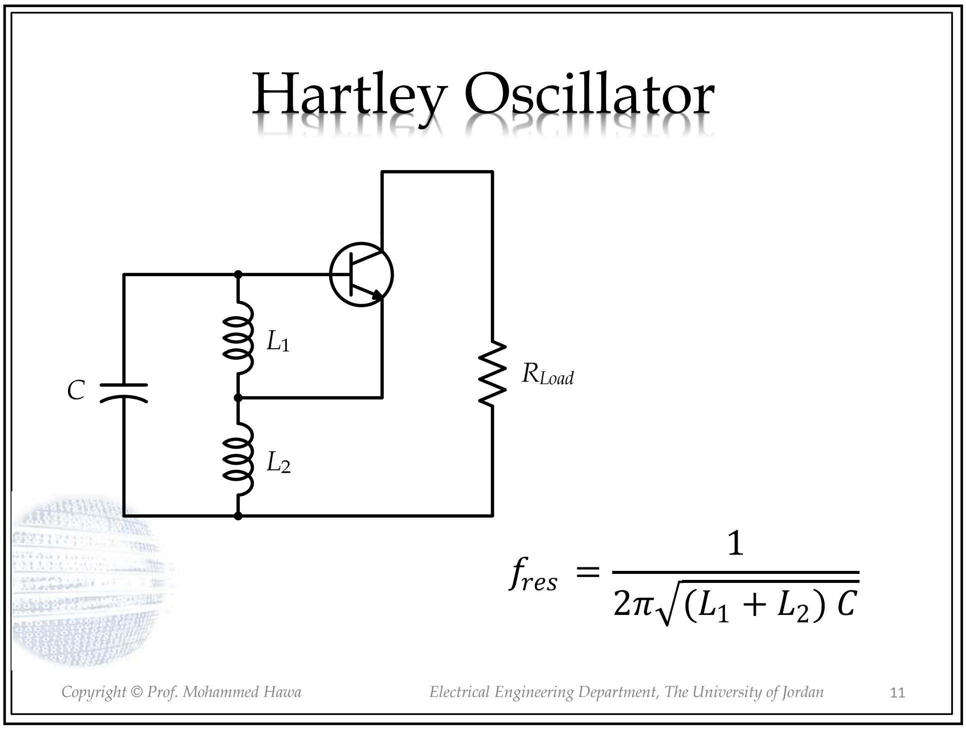
Oscillator Implementations

- Harmonic oscillator implementations:
  - Armstrong oscillator
  - Hartley oscillator
  - Colpitts oscillator*
  - Clapp oscillator*
  - Pierce oscillator*
  - Phase-shift oscillator
  - Wien-Bridge oscillator … *and many more*
- Relaxation oscillator implementations:
  - Multivibrator (e.g., the popular NE555 timer IC)
  - Ring oscillator
  - Comparator-based oscillator
  - Schmitt trigger oscillator … *and many more*

Armstrong Oscillator

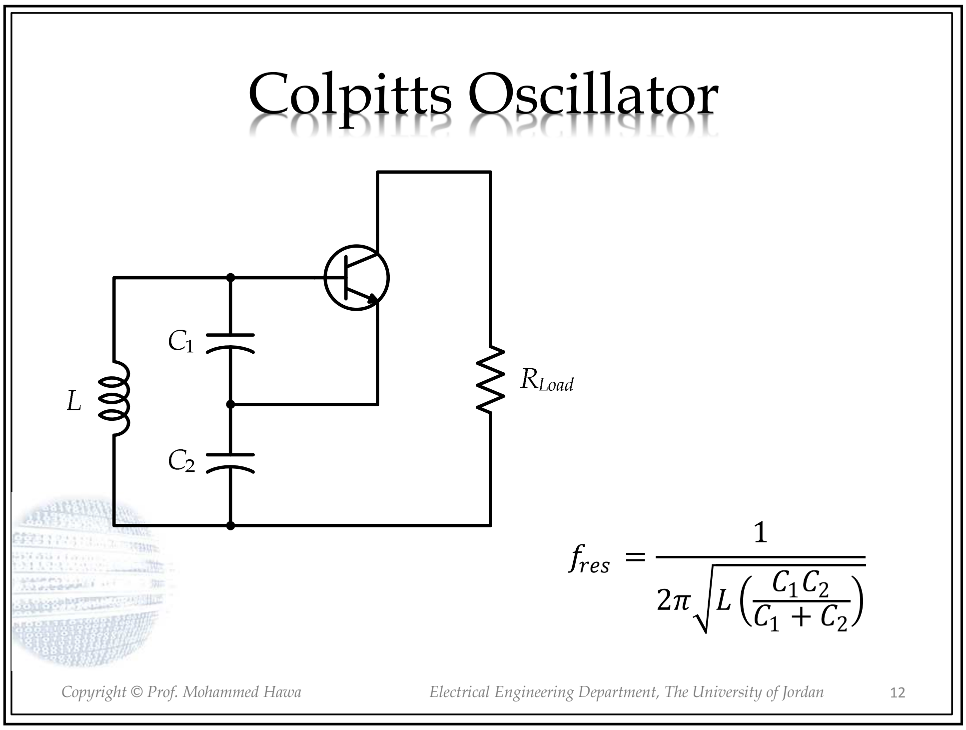


$$f_{res} = \frac{1}{2\pi\sqrt{L_1 C}}$$



Hartley Oscillator

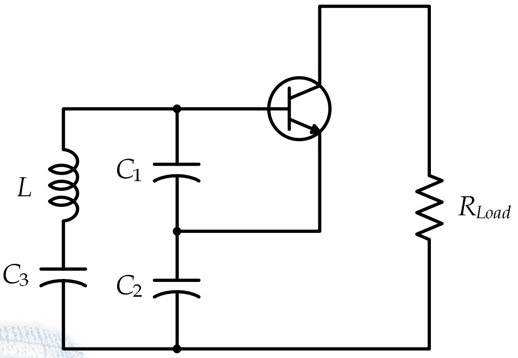
$$f_{res} = \frac{1}{2\pi\sqrt{(L_1 + L_2)\,C}}$$



Colpitts Oscillator

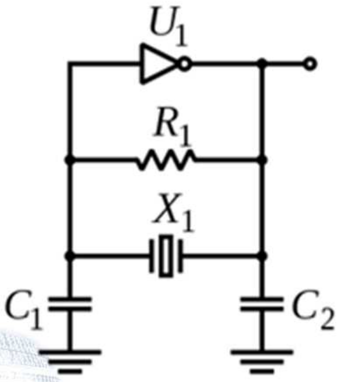
$$f_{res} = \frac{1}{2\pi\sqrt{L\left(\frac{C_1 C_2}{C_1 + C_2}\right)}}$$

Clapp Oscillator

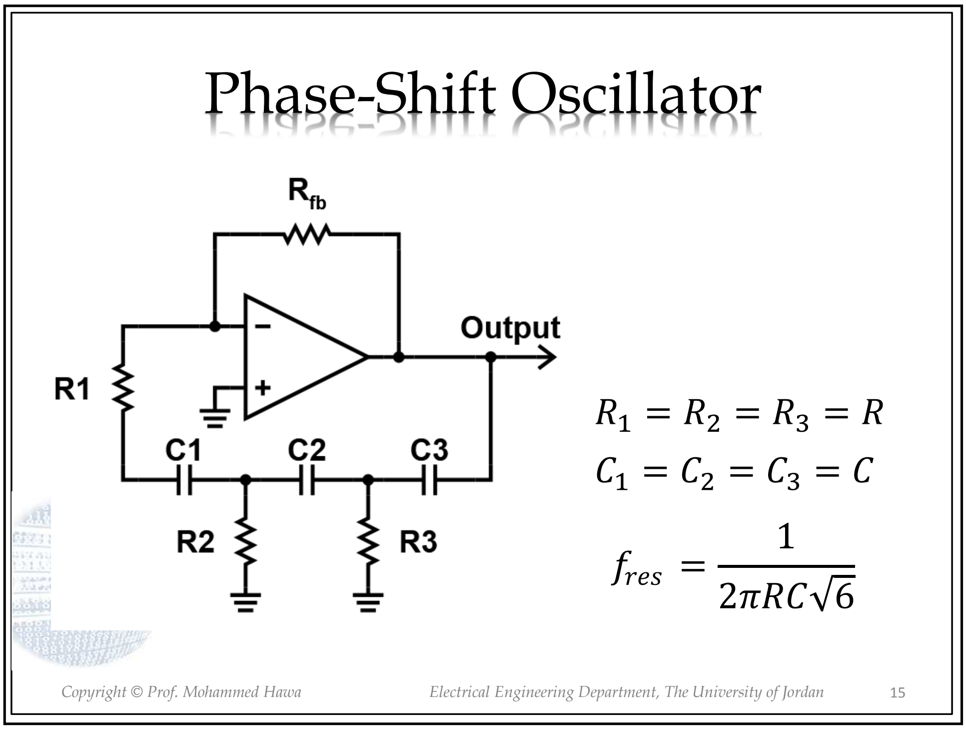


$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{L}\left(\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}\right)}$$

Pierce Oscillator



$$f_{res} = Crystal\ Frequency$$

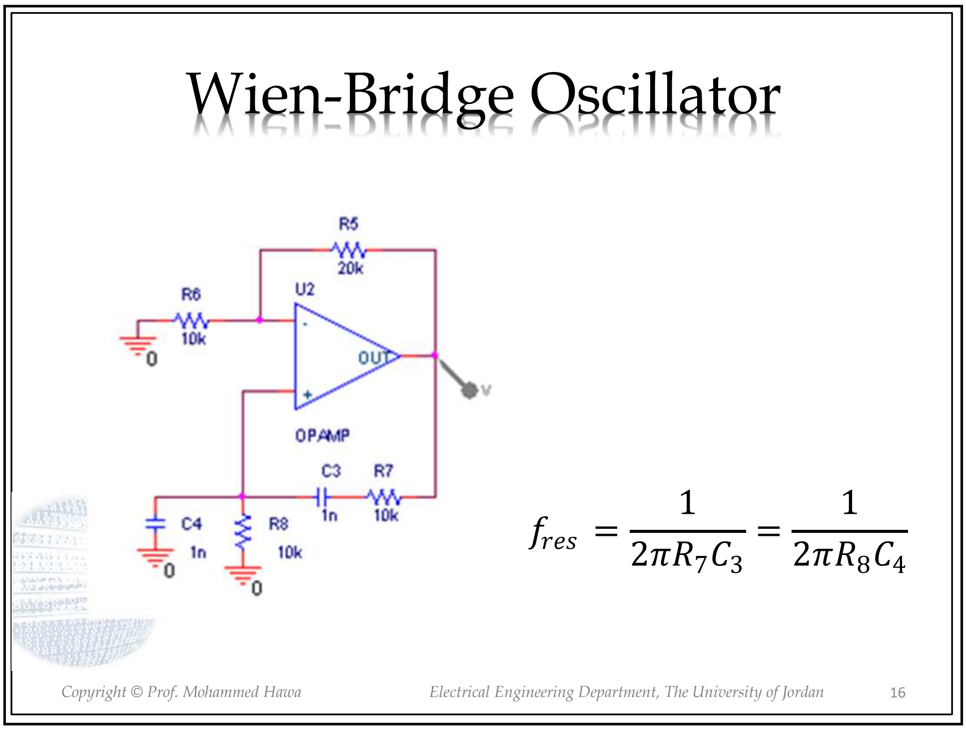


Phase-Shift Oscillator

$$R_1 = R_2 = R_3 = R$$

$$C_1 = C_2 = C_3 = C$$

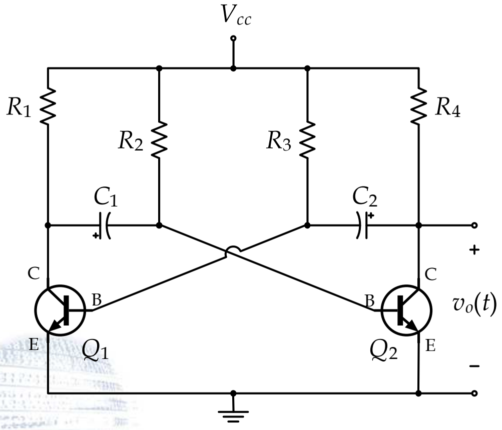
$$f_{res} = \frac{1}{2\pi RC\sqrt{6}}$$



Wien-Bridge Oscillator

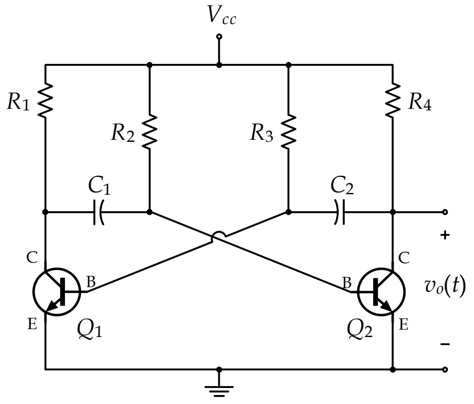
$$f_{res} = \frac{1}{2\pi R_7 C_3} = \frac{1}{2\pi R_8 C_4}$$

Astable Multivibrator



$$f_{res} \approx \frac{1}{\ln(2) \cdot (R_2 C_1 + R_3 C_2)}$$

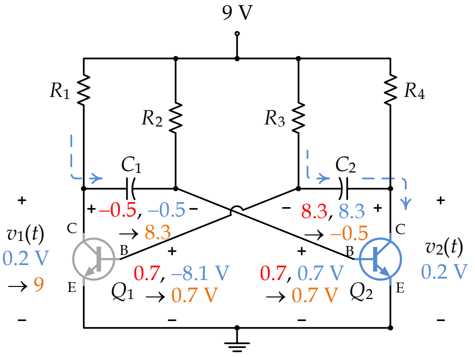
Astable Multivibrator



Capacitors repeatedly charge (output voltage increases to ≈ V_{cc}) then discharge (output voltage drops to ≈ 0.2 V), resulting in periodic signal at $v_o(t)$.

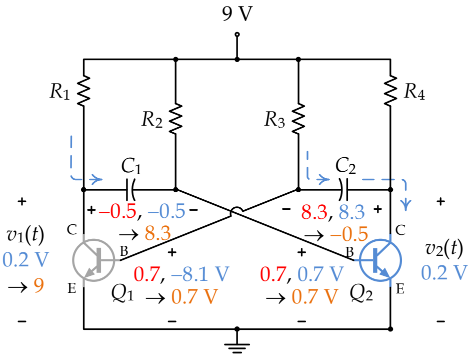
Q2 ON & Q1 OFF

- Q2 just turned **ON** because its V_{be} just built up to 0.7 V.
- Earlier C2 charged to 8.3 V (depending on how long it was charging through R4).
- Q1 now has $V_{be} = -8.3 + 0.2 = -8.1$ V, so Q1 switches **OFF**.
- Q1 is now open circuit, $I_c = 0$.
- C1 charges through R1 (small), so its voltage builds to 8.3 V.
- C2 right plate is connected to $V_{ce(sat)} \approx 0.2$ V, hence C2 discharges through Q2, or we can say C2 charges slowly through R3 (big) to −0.5 V.
- Throughput $v_2(t) \approx 0.2$ V.



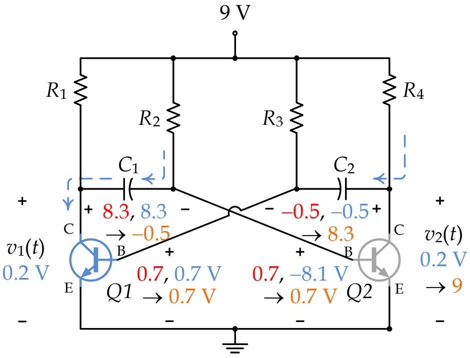
Q2 ON & Q1 OFF

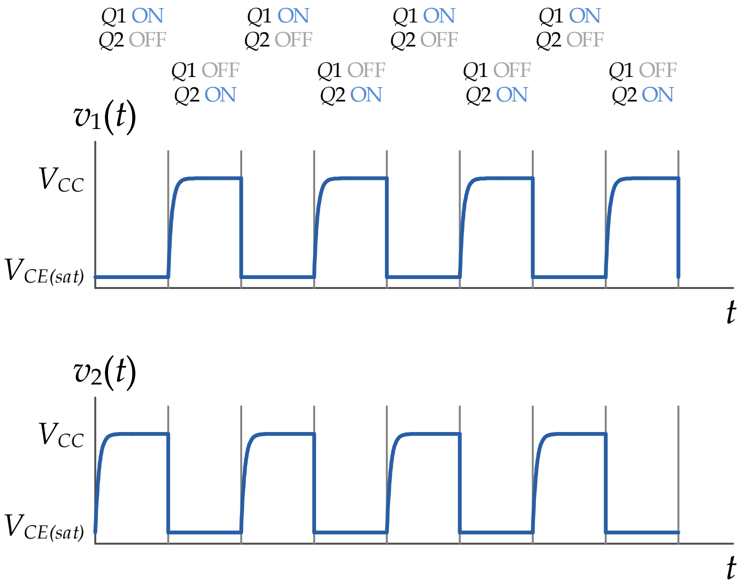
- Notice $v_1(t)$ increases (relatively fast) from 0.2 V to about 9 V (not immediate, but fast enough).
- V_{be} for Q1 builds up slowly from −8.1 V to $V_{be} = -(-0.5) + 0.2 = 0.7$ V
- Once 0.7 V is reached, Q1 switches **ON**.



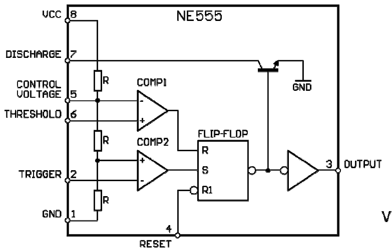
Q1 ON & Q2 OFF

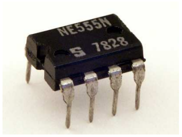
- Q1 just turned **ON**.
- Earlier C1 charged to 8.3 V.
- Q2 now has $V_{be} = -8.3 + 0.2 = -8.1$ V, so Q2 switches **OFF**.
- Q2 is now open circuit, $I_c = 0$.
- C2 charges through R4 (small), so its voltage builds to 8.3 V.
- C1 right plate is connected to $V_{ce(sat)} \approx 0.2$ V, hence C1 discharges through Q1, or we can say C1 charges slowly through R2 (big) to −0.5 V.
- Throughput $v_1(t) \approx 0.2$ V, but $v_2(t)$ increases from 0.2 V to about 9 V.

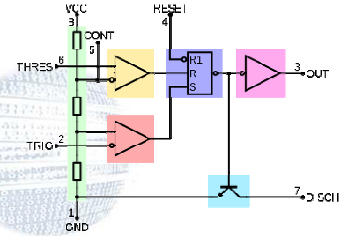


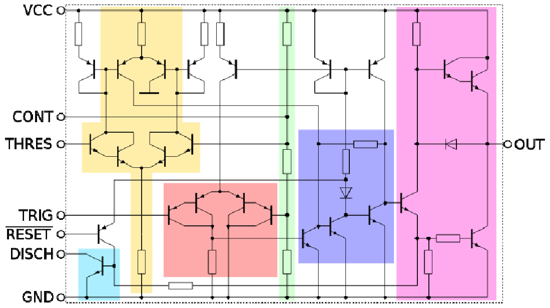


Multivibrator (NE555)

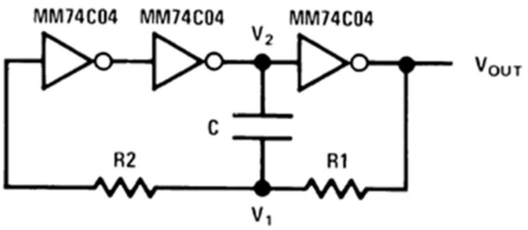






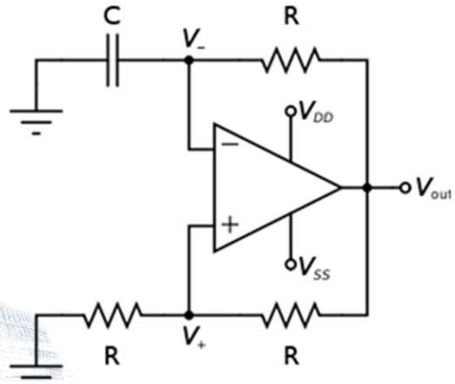


Ring Oscillator



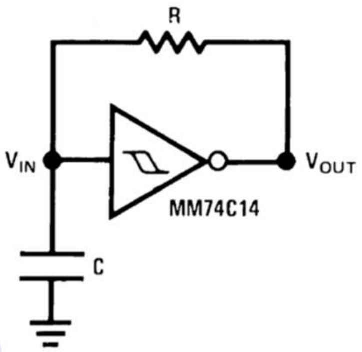
$$f \cong \frac{1}{2\,R1\,C\left(\dfrac{0.405\ R2}{R1 + R2} + 0.693\right)}$$

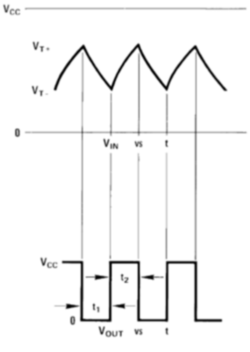
Comparator-based Oscillator



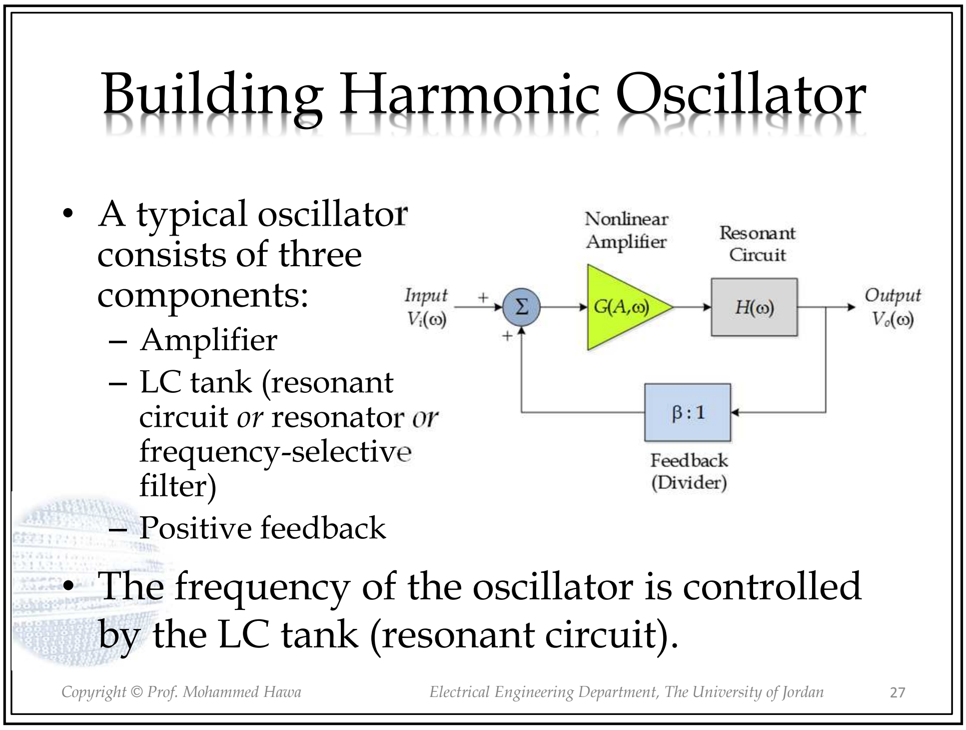
$$f_{res} = \frac{1}{2\ln(3)\,RC}$$

Schmitt Trigger Oscillator



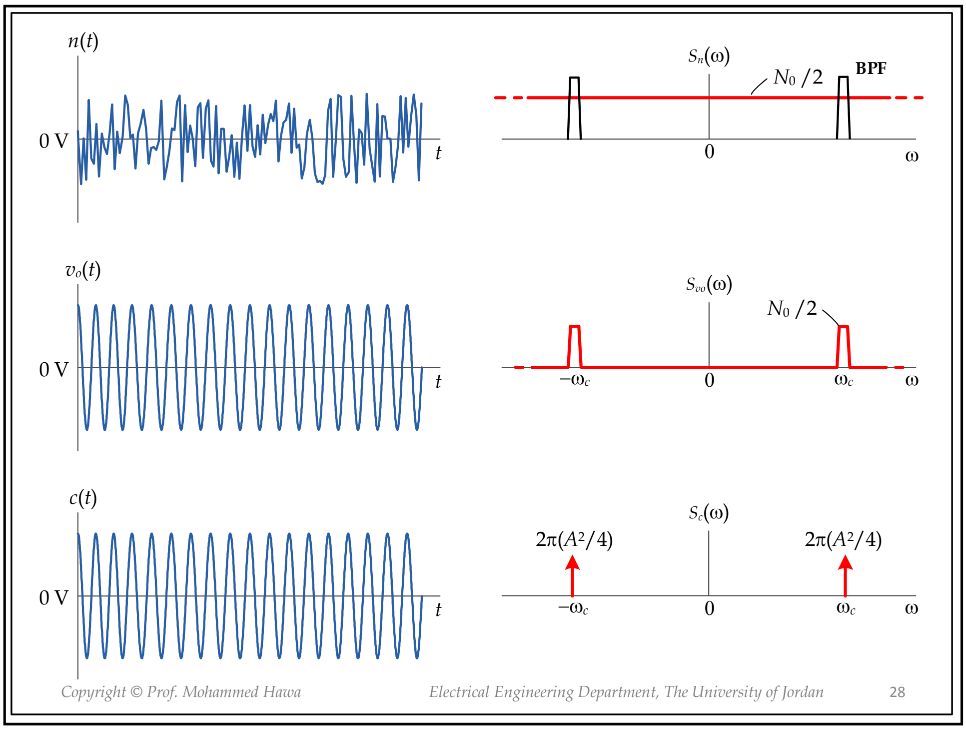


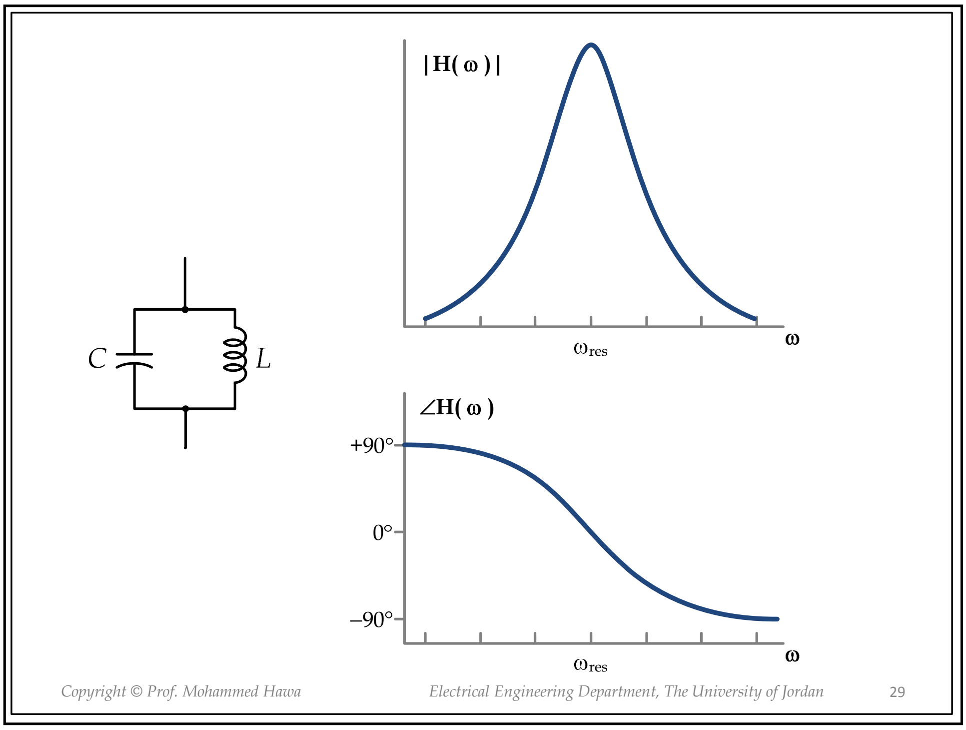
$$f_{res} = \frac{1}{RC\ln\left[\left(\frac{V_{cc}-V_{T-}}{V_{cc}-V_{T+}}\right)\left(\frac{V_{T+}}{V_{T-}}\right)\right]} \approx \frac{1}{1.7\,RC}$$



Building Harmonic Oscillator

- A typical oscillator consists of three components:
  - Amplifier
  - LC tank (resonant circuit *or* resonator *or* frequency-selective filter)
  - Positive feedback
- The frequency of the oscillator is controlled by the LC tank (resonant circuit).





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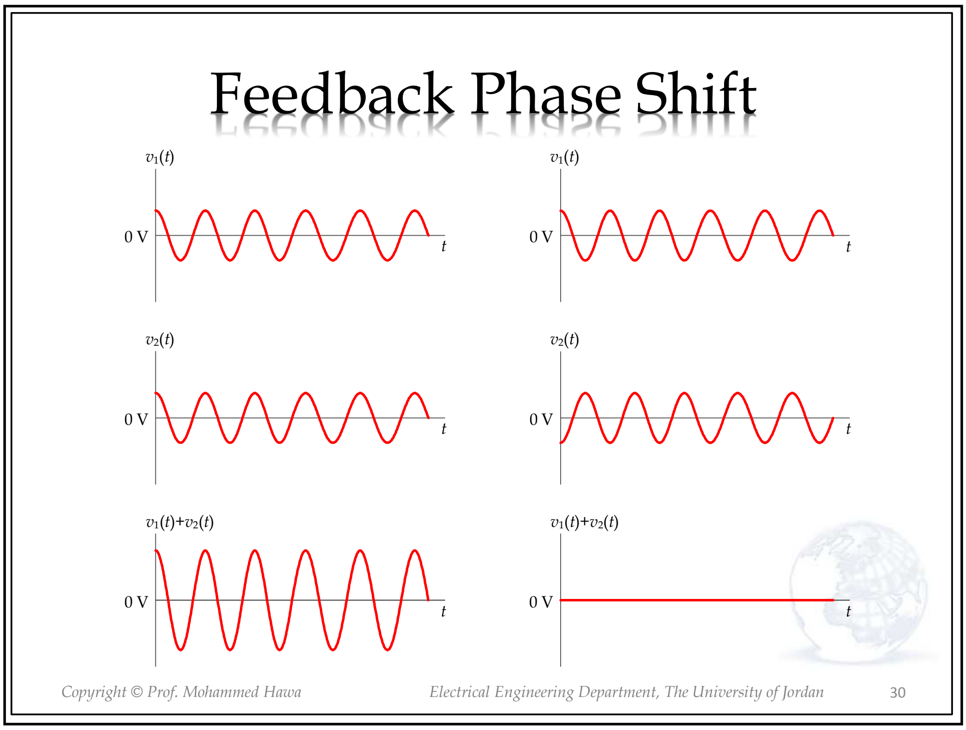

Feedback Phase Shift

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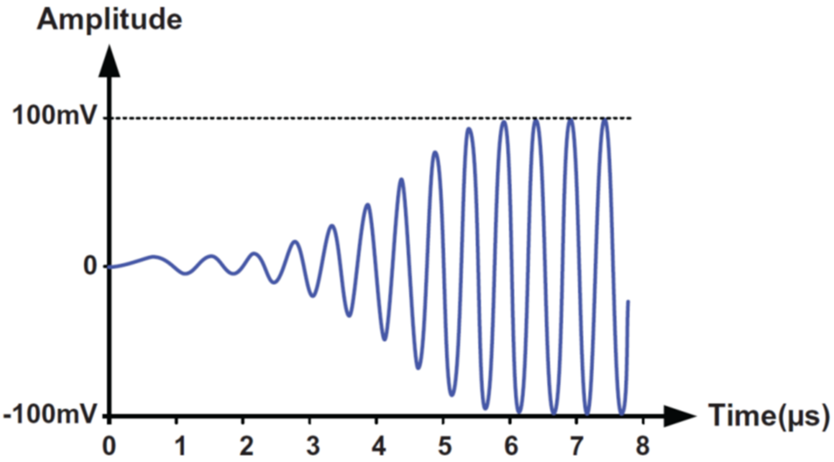
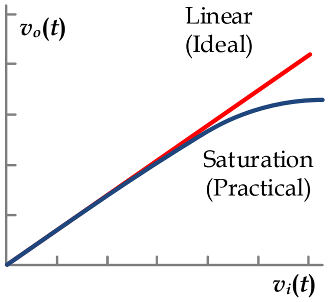
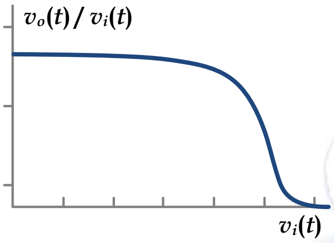
Oscillation Build Up: *Transient*



Non-linear Amplifier

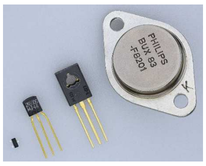




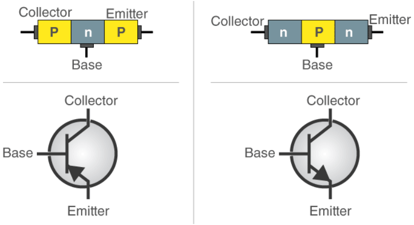
Available Active Elements

- **Triode** *or* Vacuum Tube *or* Thermionic Valve
- Frequency ~4 GHz
- Old hardware

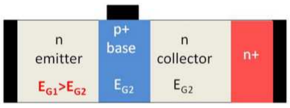
Transistors



- **Bipolar Junction Transistor (BJT)**
- Frequency ~20 GHz
- **Heterojunction Bipolar Transistor (HBT)**
- HBT is BJT that uses differing semiconductor materials for emitter and base to build a heterojunction
- Frequency ~100 GHz

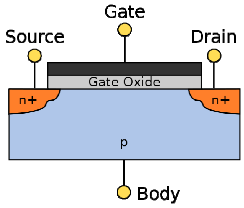


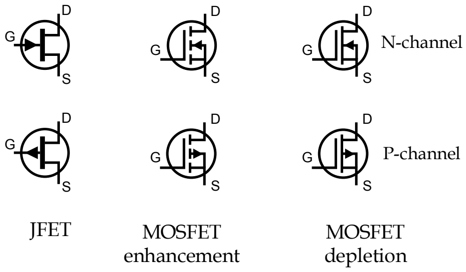
Wide gap Emitter HBT



Field-Effect Transistor (FET)

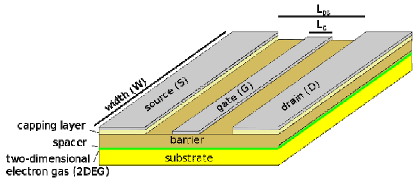
- **Junction-gate FET (JFET)**
- **Metal-Oxide-Semiconductor FET (MOSFET)**
- Frequency ~30 GHz
- **Metal-Epitaxy-Semiconductor Field-Effect Transistor (MESFET)**
- Similar to JFET but with Schottky (metal–semiconductor) junction instead of p–n junction for gate.
- Frequency ~50 GHz

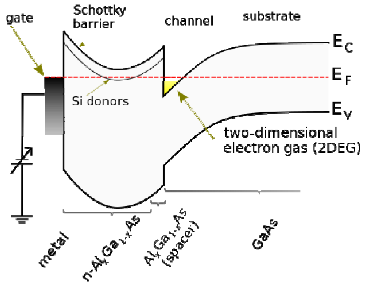




Transistors

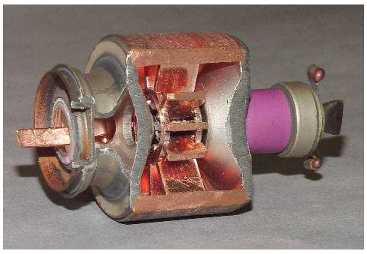
- **High-Electron-Mobility Transistor (HEMT)**
- Similar to FET incorporating a junction between two materials with different band gaps (i.e. a heterojunction)
- Frequency ~600 GHz





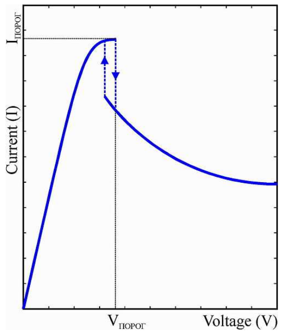
Cavity Magnetron

- **Cavity magnetron** is high-power vacuum tube used in microwave ovens and in linear particle accelerators.
- Generates microwaves using the interaction of a stream of electrons with a magnetic field, while moving past a series of cavity resonators (small, open cavities in a metal block).
- Frequency ~100 GHz



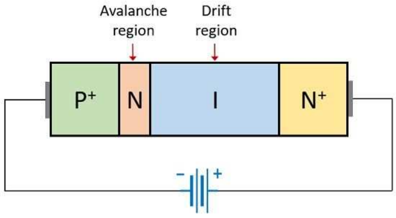
Gunn Diode

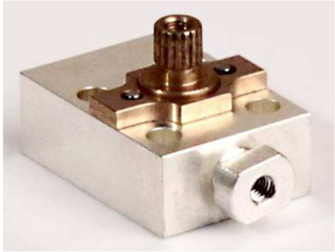
- **Gunn diode** consists of heavily N-doped on each terminal, with thin layer of lightly N-doped material between them.
- Based on "Gunn effect" and provides negative resistance when biased properly.
- Used for oscillators in radar speed guns, microwave relay data link transmitters, etc.
- Frequency ~200 GHz.



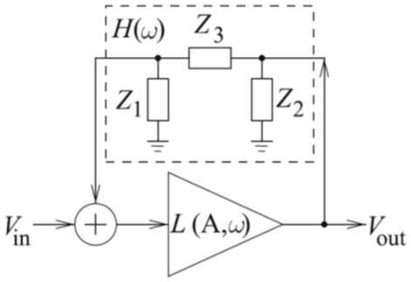
IMPATT Diode

- **IMPATT** (Impact Ionization Avalanche Transit-Time) diode is high-power semiconductor diode.
- Provides negative resistance for oscillators at microwave frequencies.
- Frequency ~350 GHz

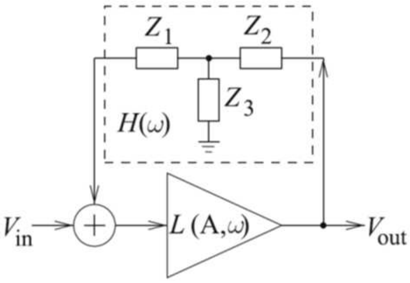




Pi-type *or* T-type Feedback Circuits



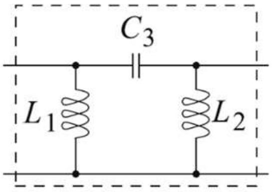
(a) Pi feedback network



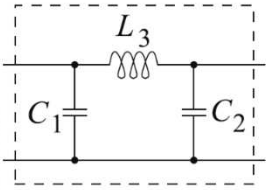
(b) T feedback network

Main Pi-type Networks

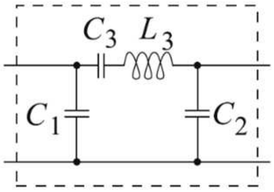
- Main Pi-type networks that are well-suited to amplitude saturation characteristics of FET and BJT active devices, resulting in stable oscillation.



(c) Hartley



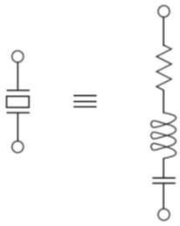
(d) Colpitts

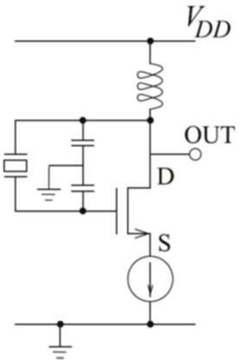


(e) Clapp

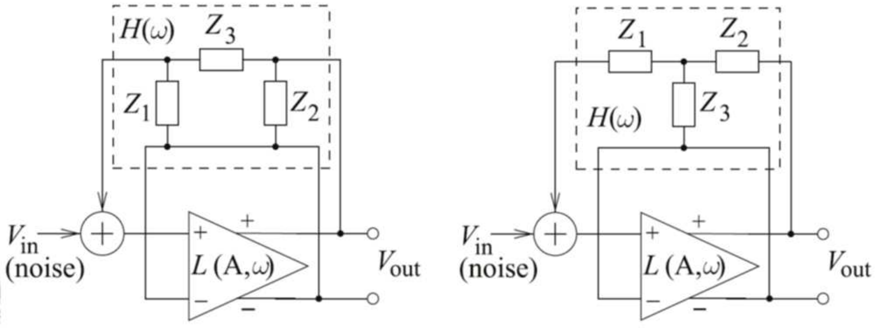
FET Crystal Oscillator

- FET crystal oscillator as a Clapp oscillator
- Piezoelectric crystal equivalent circuit is series RLC.



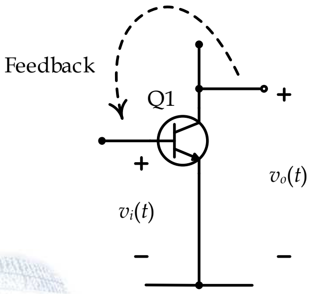


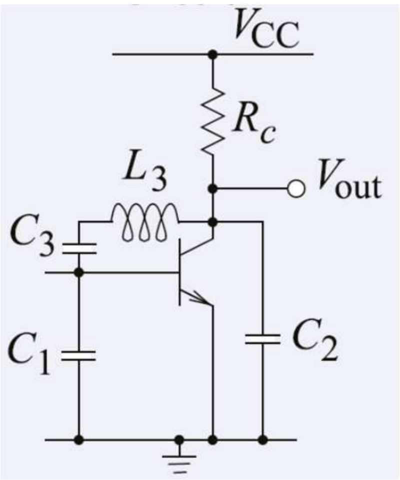
Feedback for Differential Amplifier



(a) Pi feedback network (b) T feedback network

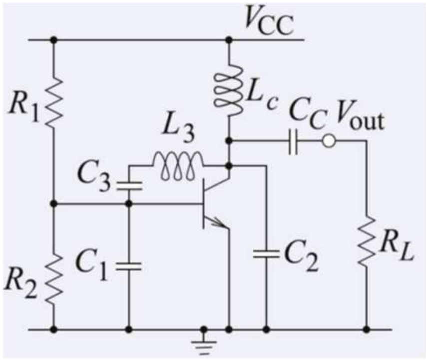
Common-Emitter BJT Clapp



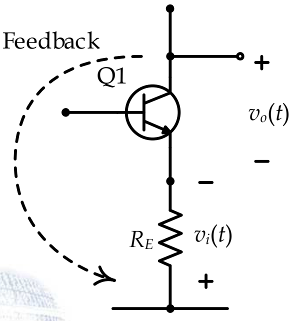


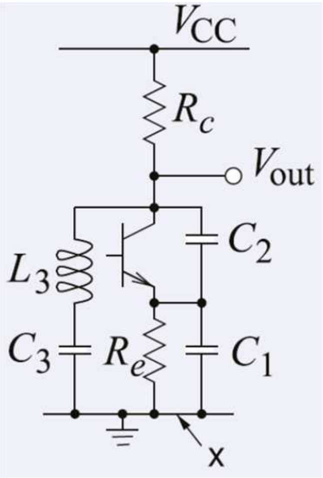
BJT Clapp Oscillator

- Parasitic base-emitter capacitance can be absorbed into C1.
- Parasitic collector-emitter capacitance can be absorbed into C2.
- Parasitic collector-base capacitance cannot be absorbed (so extra care that C_{cb} does not result in instability).



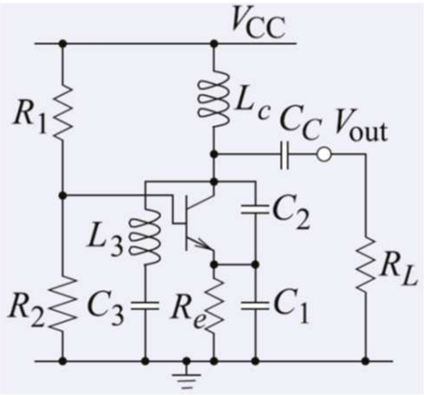
Clapp Other Configuration



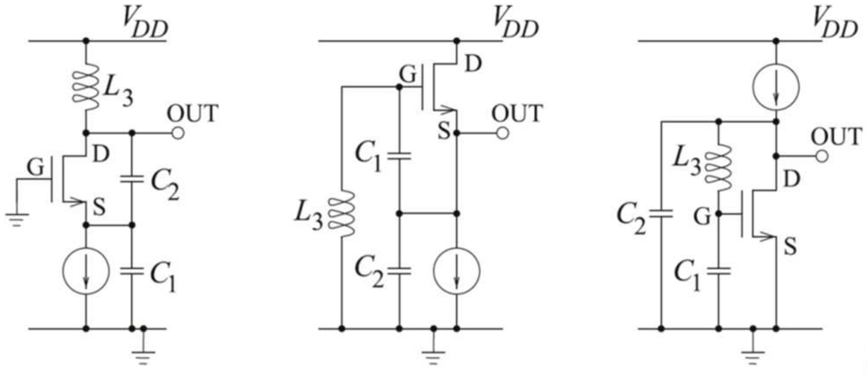


Clapp Oscillator

- Avoid delivering power to R_c, and only deliver it to load R_L using a choke inductor L_c (energy storage, not onsumption)
- Choke is small resistance (almost short circuit) in DC, so applies bias.
- Choke is large resistance (open circuit at RF), directs voltage to R_L and allows large output voltage swing.
- C_c is large coupling capacitor blocks DC, but has small impedance at RF.



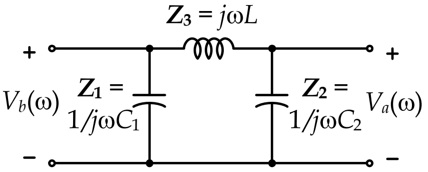
Colpitts FET Oscillators



(a) Common gate (b) Common drain (c) Common source

Colpitts Resonant Frequency

- Assume amplifier input impedance is high (open circuit).
- Assume amplifier output impedance and load are also high (open circuit).
- Apply nodal analysis.



$$\frac{\boldsymbol{V_b}(\omega)}{\boldsymbol{Z_1}(\omega)} + \frac{\boldsymbol{V_b}(\omega) - \boldsymbol{V_a}(\omega)}{\boldsymbol{Z_3}(\omega)} = 0$$

$$\frac{\boldsymbol{V_a}(\omega)}{\boldsymbol{Z_2}(\omega)} + \frac{\boldsymbol{V_a}(\omega) - \boldsymbol{V_b}(\omega)}{\boldsymbol{Z_3}(\omega)} = 0$$

$$\frac{\boldsymbol{V_b}(\omega)}{\boldsymbol{Z_1}(\omega)} + \frac{\boldsymbol{V_b}(\omega) - \boldsymbol{V_a}(\omega)}{\boldsymbol{Z_3}(\omega)} = 0$$

$$\frac{\boldsymbol{V_a}(\omega)}{\boldsymbol{Z_2}(\omega)} + \frac{\boldsymbol{V_a}(\omega) - \boldsymbol{V_b}(\omega)}{\boldsymbol{Z_3}(\omega)} = 0$$

$$\begin{bmatrix} \left(\frac{1}{\boldsymbol{Z_1}} + \frac{1}{\boldsymbol{Z_3}}\right) & -\frac{1}{\boldsymbol{Z_3}} \\ -\frac{1}{\boldsymbol{Z_3}} & \left(\frac{1}{\boldsymbol{Z_2}} + \frac{1}{\boldsymbol{Z_3}}\right) \end{bmatrix} \begin{bmatrix} \boldsymbol{V_b} \\ \boldsymbol{V_a} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$det = \left(\frac{1}{\boldsymbol{Z_1}} + \frac{1}{\boldsymbol{Z_3}}\right)\left(\frac{1}{\boldsymbol{Z_2}} + \frac{1}{\boldsymbol{Z_3}}\right) - \frac{1}{\boldsymbol{Z_3}}\frac{1}{\boldsymbol{Z_3}}$$

Solution

A valid solution is possible if *determinant* of matrix is 0

$$\left(\frac{1}{\boldsymbol{Z_1}}+\frac{1}{\boldsymbol{Z_3}}\right)\left(\frac{1}{\boldsymbol{Z_2}}+\frac{1}{\boldsymbol{Z_3}}\right)-\frac{1}{\boldsymbol{Z_3}}\frac{1}{\boldsymbol{Z_3}}=0$$

$$\frac{1}{\boldsymbol{Z_1Z_2}}+\frac{1}{\boldsymbol{Z_1Z_3}}+\frac{1}{\boldsymbol{Z_2Z_3}}+\frac{1}{\boldsymbol{Z_3^2}}-\frac{1}{\boldsymbol{Z_3^2}}=0$$

$$\frac{1}{\boldsymbol{Z_1Z_2}}+\frac{1}{\boldsymbol{Z_1Z_3}}+\frac{1}{\boldsymbol{Z_2Z_3}}=0$$

$$\frac{1}{\frac{1}{j\omega C_1}\times\frac{1}{j\omega C_2}}+\frac{1}{\frac{1}{j\omega C_1}j\omega L}+\frac{1}{\frac{1}{j\omega C_2}j\omega L}=0$$

Resonant Frequency

$$\frac{1}{\frac{1}{j\omega C_1}\times\frac{1}{j\omega C_2}}+\frac{1}{\frac{1}{j\omega C_1}j\omega L}+\frac{1}{\frac{1}{j\omega C_2}j\omega L}=0$$

$$-\omega^2C_1C_2+\frac{C_1}{L}+\frac{C_2}{L}=0$$

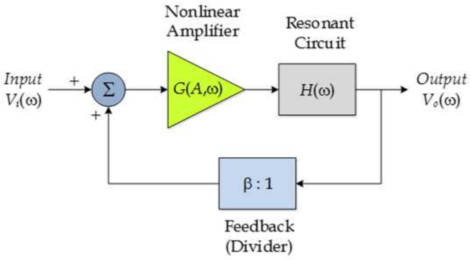
$$\omega^2C_1C_2=\frac{C_1+C_2}{L}$$

$$\omega_{res}=\sqrt{\frac{1}{L}\left(\frac{C_1+C_2}{C_1C_2}\right)}$$

Oscillator Design & Analysis

- **Approach #1: Positive Feedback**
  - Main theory in textbooks and references.
  - Uses circuit analysis and control theory.
  - View oscillator as two-port amplifier (active element) with positive feedback through a linear frequency-selective filter.
- **Approach #2: Negative Resistance/Conductance**
  - Used by several microwave oscillator designers.
  - Sometimes named reflection oscillator configuration.
  - View oscillator as two circuits: one-port (two terminal) negative resistance (or conductance) device (i.e., active device) connected to a one-port resonator network (i.e., tank circuit).

Approach #1: Positive Feedback



$$V_o(\omega) = G(A,\omega)H(\omega)V_i(\omega) + G(A,\omega)H(\omega)V_o(\omega)\beta$$

$$V_o(\omega)(1 - G(A,\omega)H(\omega)\beta) = G(A,\omega)H(\omega)V_i(\omega)$$

$$V_o(\omega) = \frac{G(A,\omega)H(\omega)}{1 - G(A,\omega)H(\omega)\beta}V_i(\omega)$$

$$\frac{V_o(\omega)}{V_i(\omega)} = \frac{G(A,\omega)H(\omega)}{1 - \beta\, G(A,\omega)H(\omega)} = \frac{G(A)H(\omega)}{1 - \beta\, G(A)H(\omega)}$$

Oscillation Criterion

- Amplifier transfer function depends on input amplitude A, with value greater than 1.
- Transfer characteristics of filter depend on frequency ω.
- Input noise (very small ≈ 0) exists when supply is powered ON.
- Oscillations build up when

$$\beta \, G(A)H(\omega) = 1$$

- Known as **Barkhausen criterion**.
- Oscillations build up at resonant frequency f_{res} of LC tank.
- As oscillation amplitude builds, $G(A)$ compresses until denominator is finite but close to zero (oscillations stabilize).

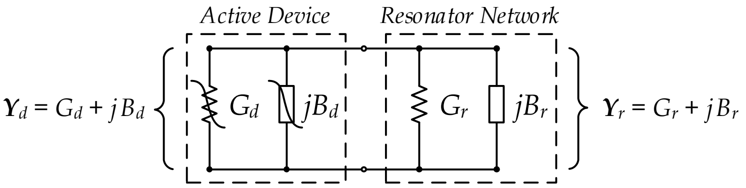
Note

- Barkhausen criterion is a necessary criterion for oscillation, but not sufficient. It does not indicate whether a system is unstable.
- Nyquist criterion is the necessary and sufficient criterion for oscillation in feedback oscillators.
- **Stable oscillation** require careful design. Unstable oscillator generates chaotic signal (rapid amplitude *&* frequency variations).

Design Considerations

- **Stability**: changes of frequency with changes in temperature or changes in component values (tolerances)
- **Signal purity**: avoid extra harmonics (i.e., distortion).
- **Power consumption**: affects battery life for phones or portable devices.
- **Phase noise** produced by the oscillator: undesirable to amplify noise.
- Theory based on two-port with feedback helps in the above design calculations.

Approach #2: Negative Conductance



- Active device d assumed to be negative admittance $\boldsymbol{Y_d}$ (*generates* power).
- Resonator network r is in parallel (shunt) with device, its admittance is positive $\boldsymbol{Y_r}$ (*consumes* power).
- Conductance G is counterpart of Resistance R (S or ℧)
- Susceptance B is counterpart of Reactance X (S or ℧)
- Impedance $\boldsymbol{Z} = R + jX = 1/\boldsymbol{Y} = 1/(G + jB)$

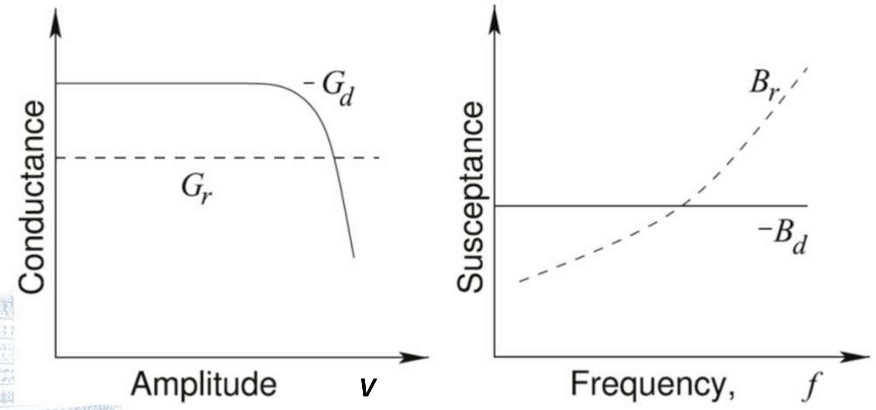
Kurokawa Condition

- Kurokawa condition for stable (single-frequency) oscillation requires

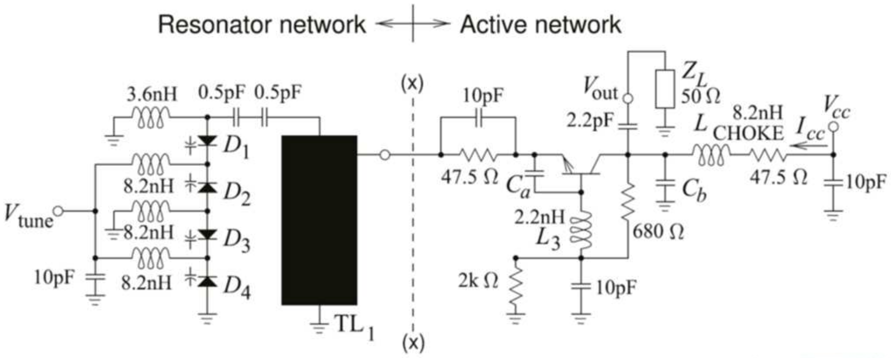
$$\left.\left(\frac{\partial G_d}{\partial V}\frac{\partial B_r}{\partial \omega} - \frac{\partial B_d}{\partial V}\frac{\partial G_r}{\partial \omega}\right)\right|_{V=V_0,\omega=\omega_0} > 0$$

- V_0 is oscillation amplitude at the interface of active and resonator networks, ω_0 is oscillation frequency.
- For fixed-frequency oscillator, resonator network is linear so G_r and B_r are independent of amplitude.
- G_r can be designed to be independent of frequency. However, B_r varies with frequency.
- With careful design, active device G_d can be frequency independent and B_d can be amplitude independent.
- This gives $\left.\left(\frac{\partial G_d}{\partial V}\frac{\partial B_r}{\partial \omega}\right)\right|_{V=V_0,\omega=\omega_0} > 0$

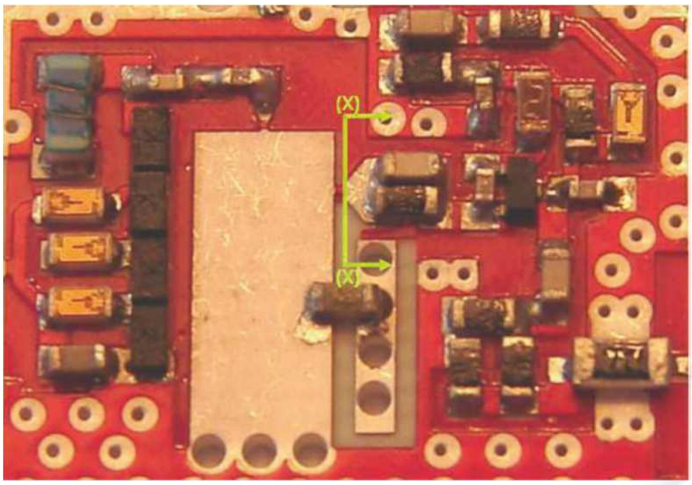
Example



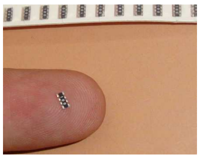
Microwave C-band VCO (4.5 to 5.3 GHz) with TL

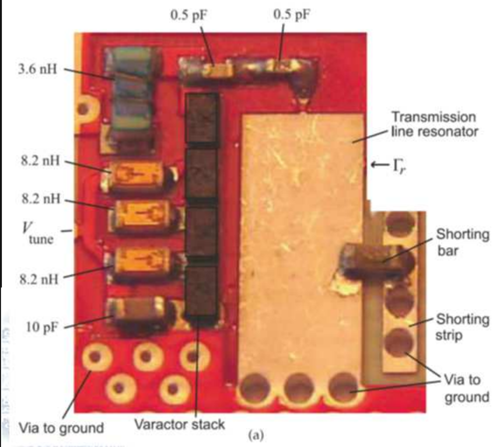


PCB Implementation

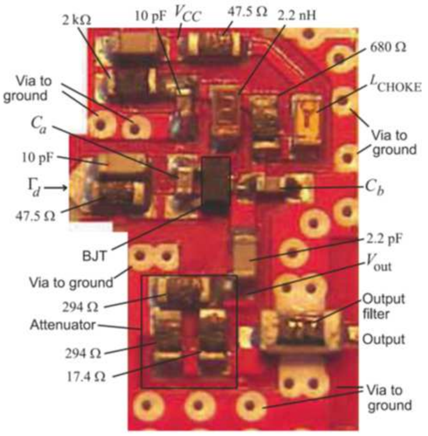


Resonator / Active Device





(a)



(b)