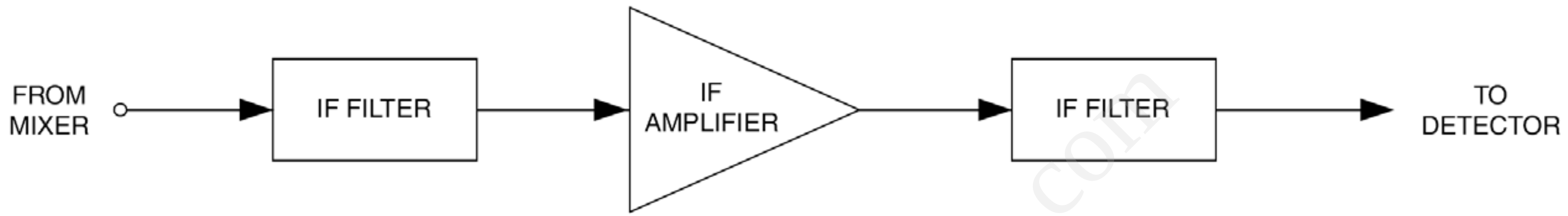
Chapter 5:

IF Amplifiers and Filters

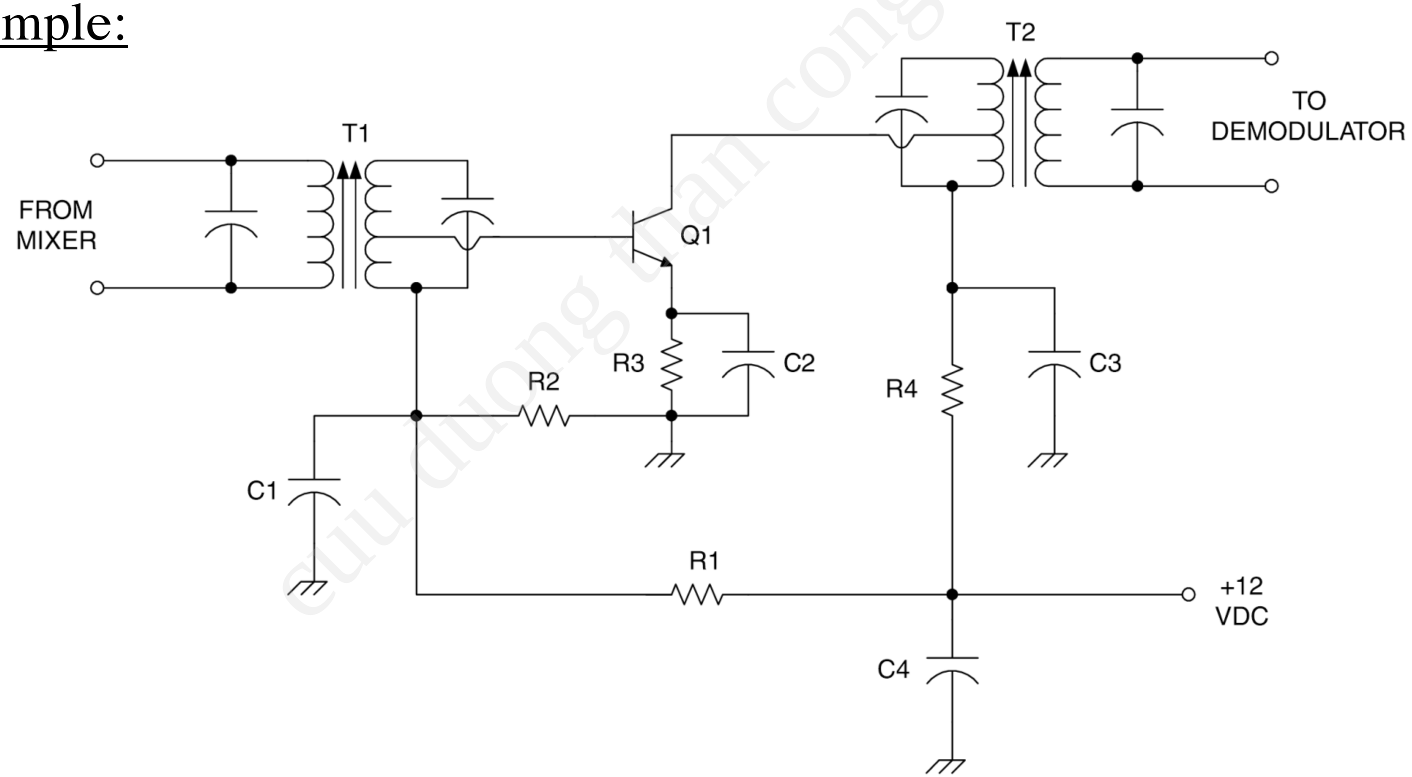
References

[1] J. J. Carr, *RF Components and Circuits*, Newnes, 2002.

IF Amplifier and Filters



Example:

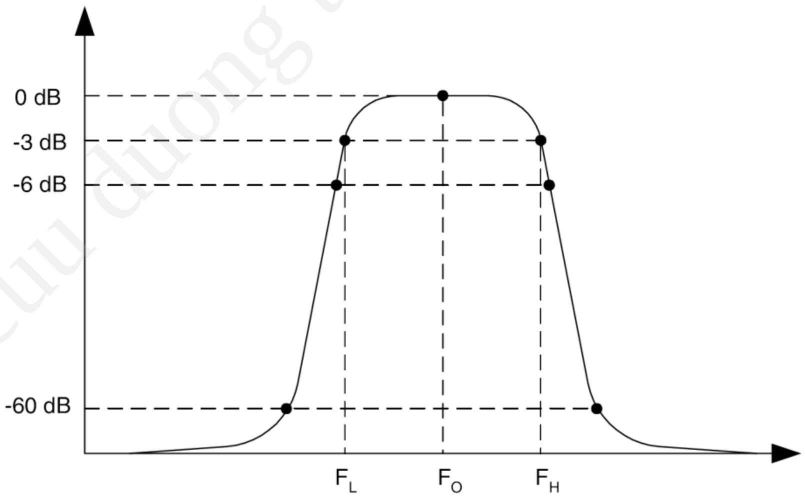


IF Filters: General Filter Theory

- The **bandwidth** of the filter is the bandwidth between the –3 dB points. The *Q* of the filter is the ratio of centre frequency to bandwidth, or:

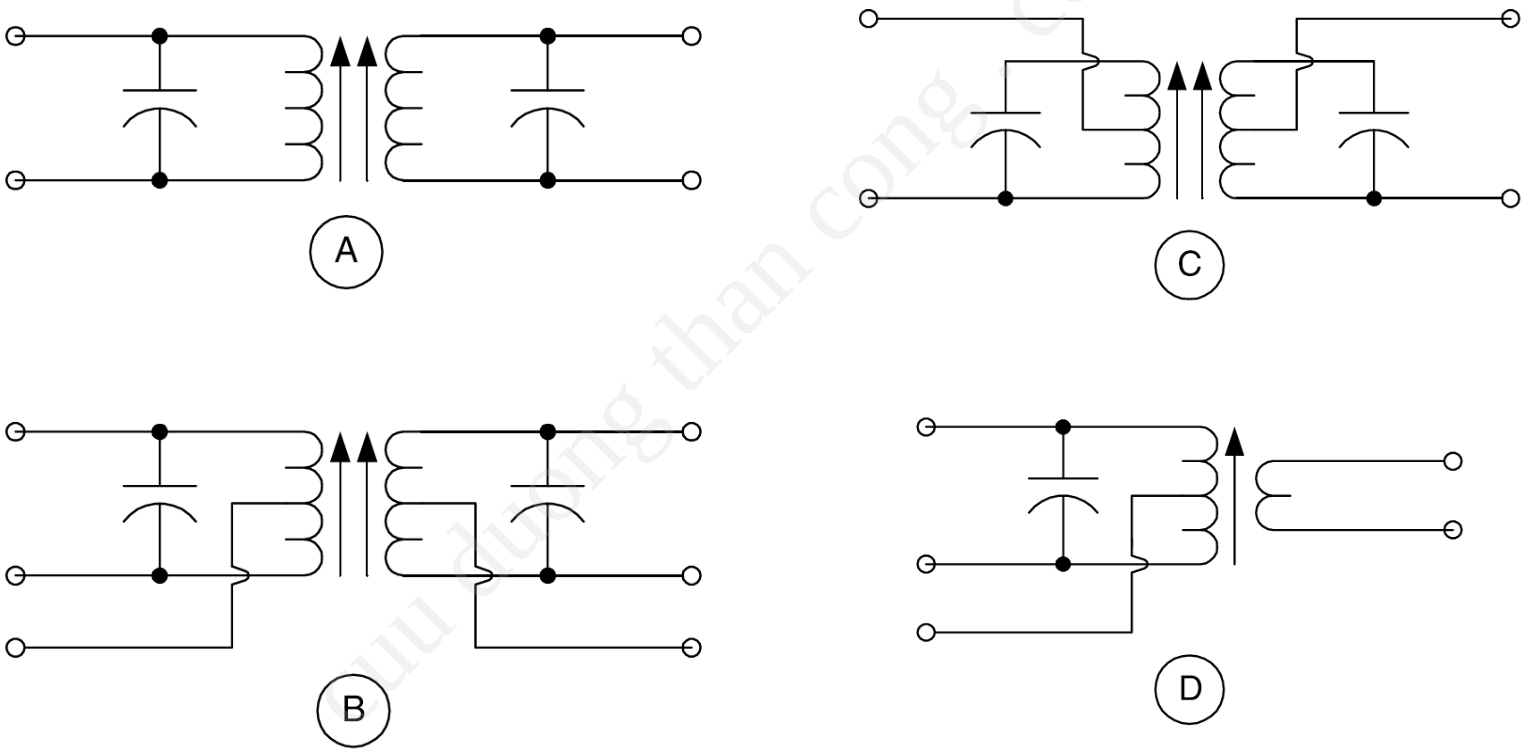
$$Q = \frac{F_O}{B}$$

- The **shape factor** of the filter is defined as the ratio of the –60 dB bandwidth to the –6 dB bandwidth. This is an indication of how well the filter will reject out of band interference. The lower the shape factor the better (shape factors of 1.2:1 are achievable).



L–C IF Filters

- The basic type of filter, and once the most common, is the **L–C filter**, which comes in various types:

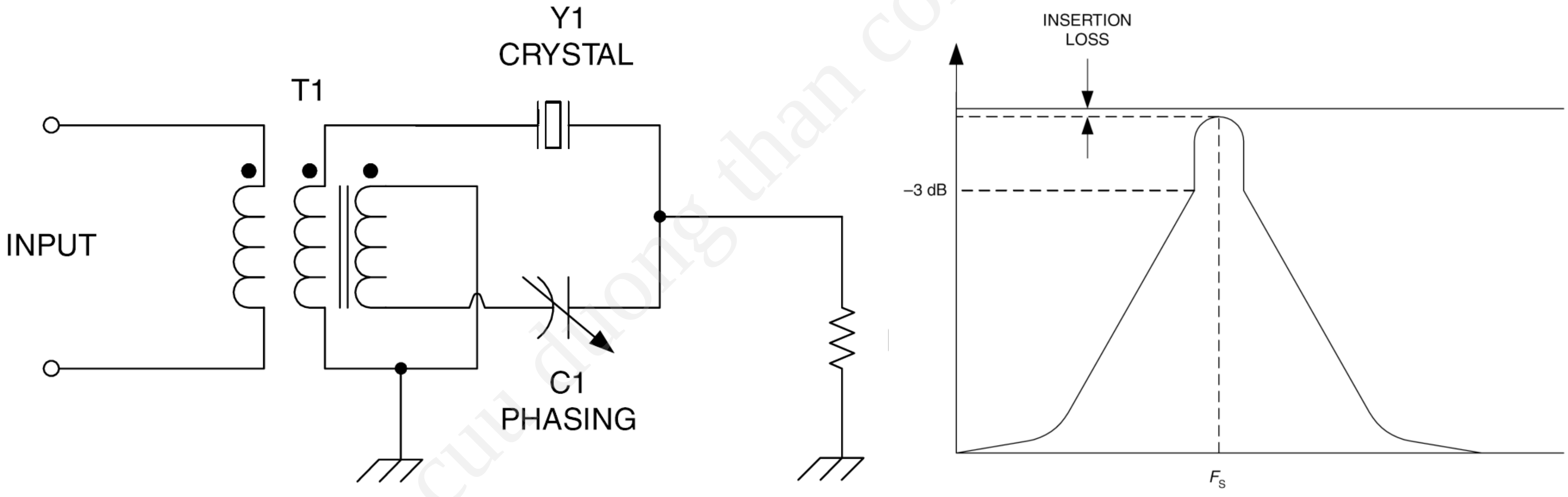


Crystal Filters (1)

- The **quartz piezoelectric crystal resonator** is ideal for IF filtering because it offers high *Q* (narrow bandwidth) and behaves as an L–C circuit. Because of this feature, it can be used for high quality receiver design as well as single sideband (SSB) transmitters (filter type).

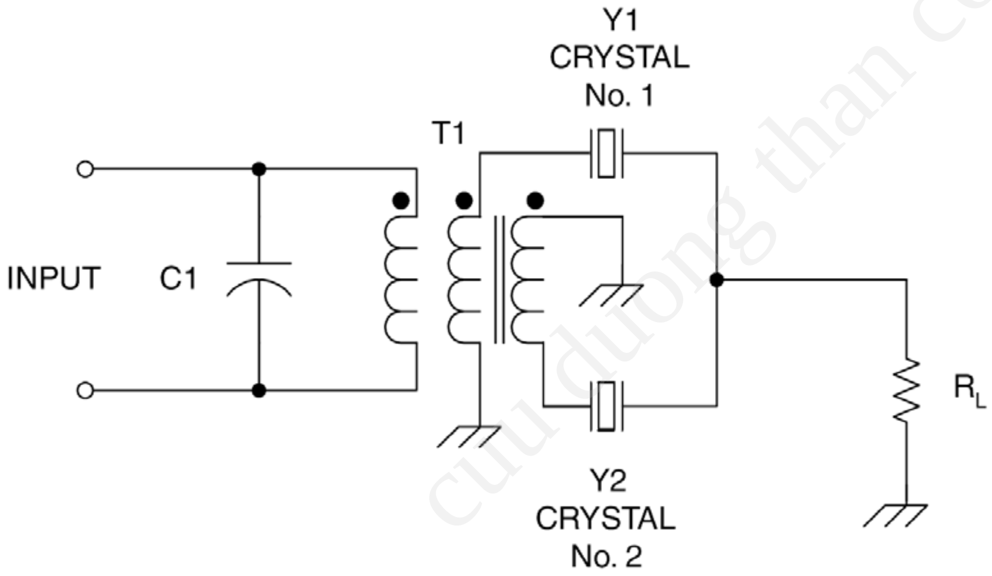
Crystal Filters (2)

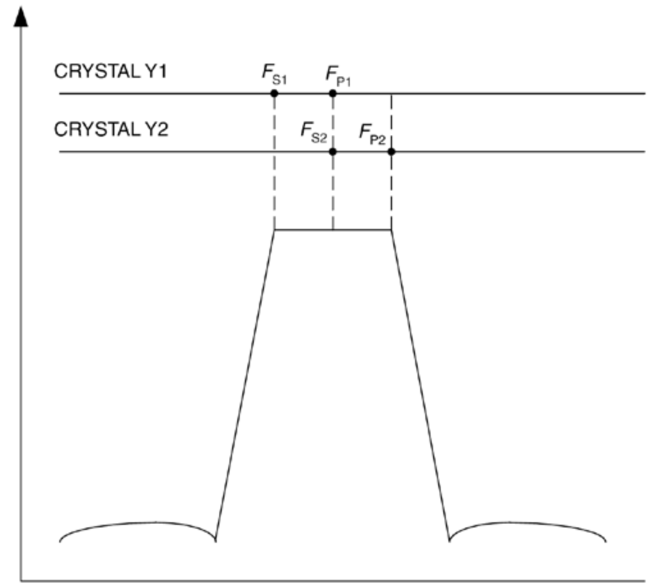
- **<u>Crystal phasing filter</u>**: a simple crystal filter, the figure shows the attenuation graph for this filter. There is a 'crystal phasing' capacitor, adjustable from the front panel, that cancels the parallel capacitance. This cancels the parallel resonance, leaving the series resonance of the crystal.



Crystal Filters (3)

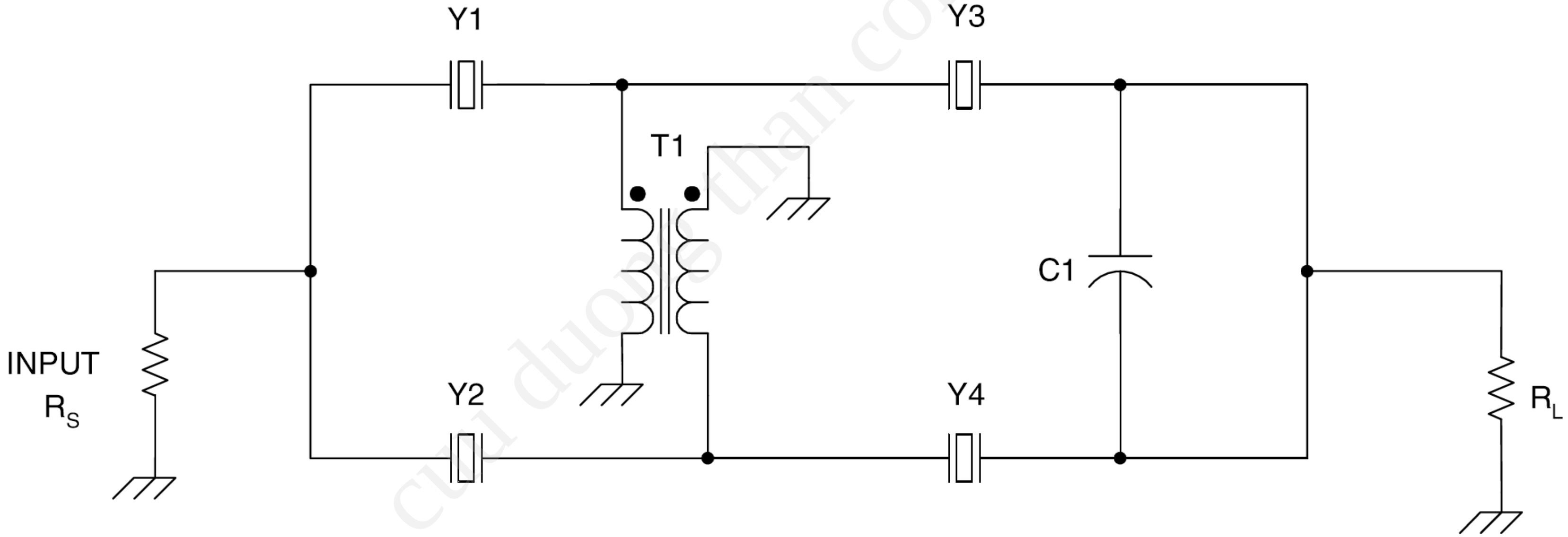
- **<u>Half-lattice crystal filter</u>**: Instead of the phasing capacitor there is a second crystal in the circuit. They have overlapping parallel and series resonance points such that <u>the parallel resonance of crystal no. 1 is the same as the series resonance of crystal no. 2</u>.





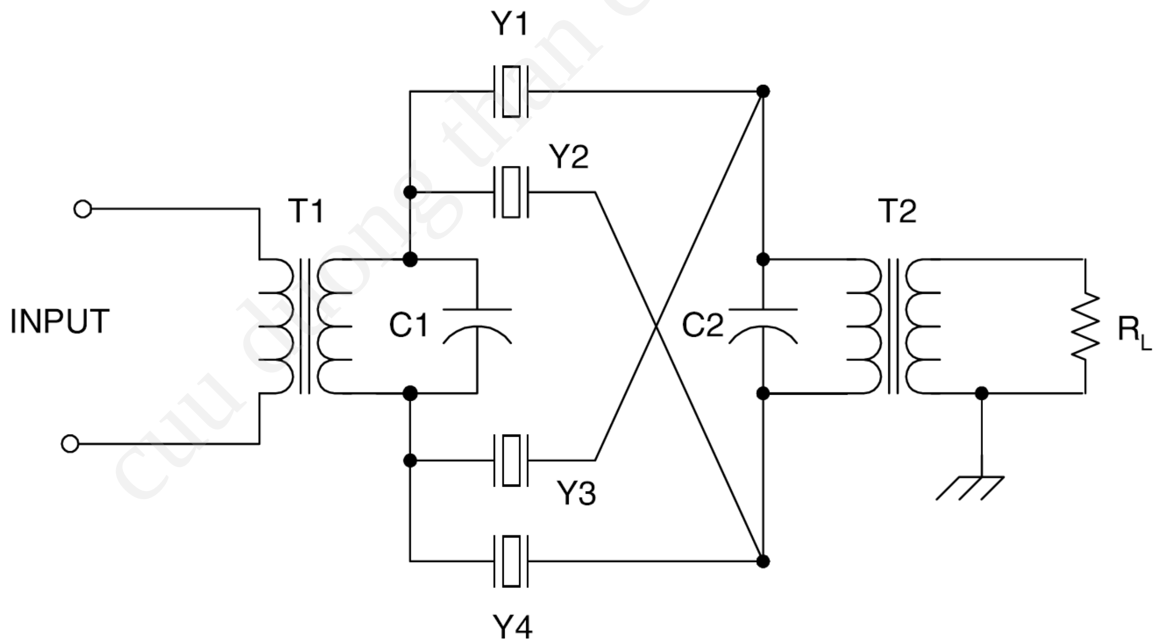
Crystal Filters (4)

- **<u>Cascade half-lattice filter</u>**: The cascade half-lattice filter has increased skirt selectivity and fewer spurious responses compared with the same pass band in the half-lattice type of filter.



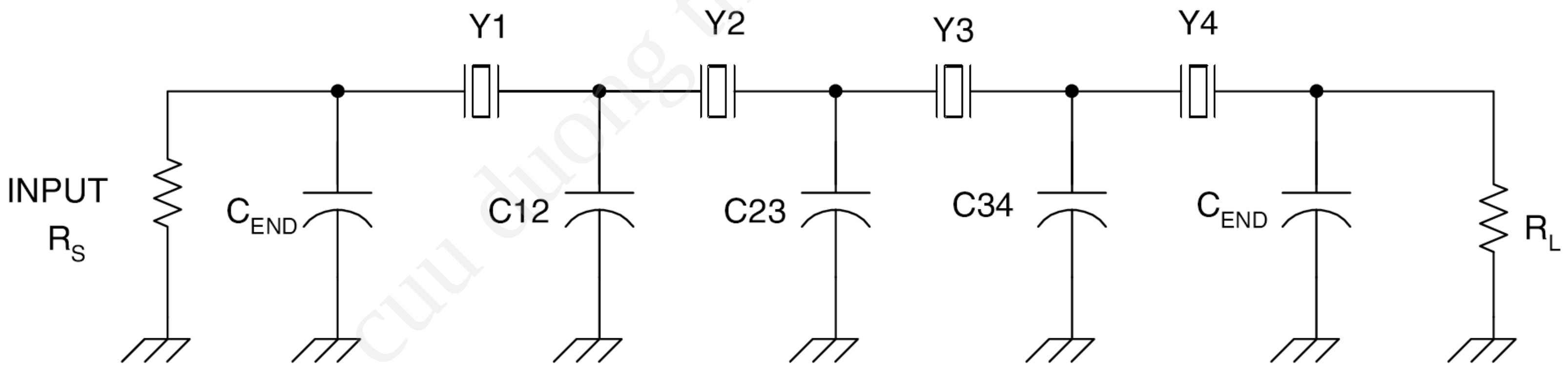
Crystal Filters (5)

- **Full lattice crystal filter** uses four crystals like the cascade half-lattice, but the circuit is built on a different basis than the latter type. It uses two tuned transformers (T1 and T2), with the two pairs of crystals that are cross-connected across the tuned sections of the transformers. Crystals Y1 and Y3 are of one frequency, while Y2 and Y4 are the other frequency in the pair.



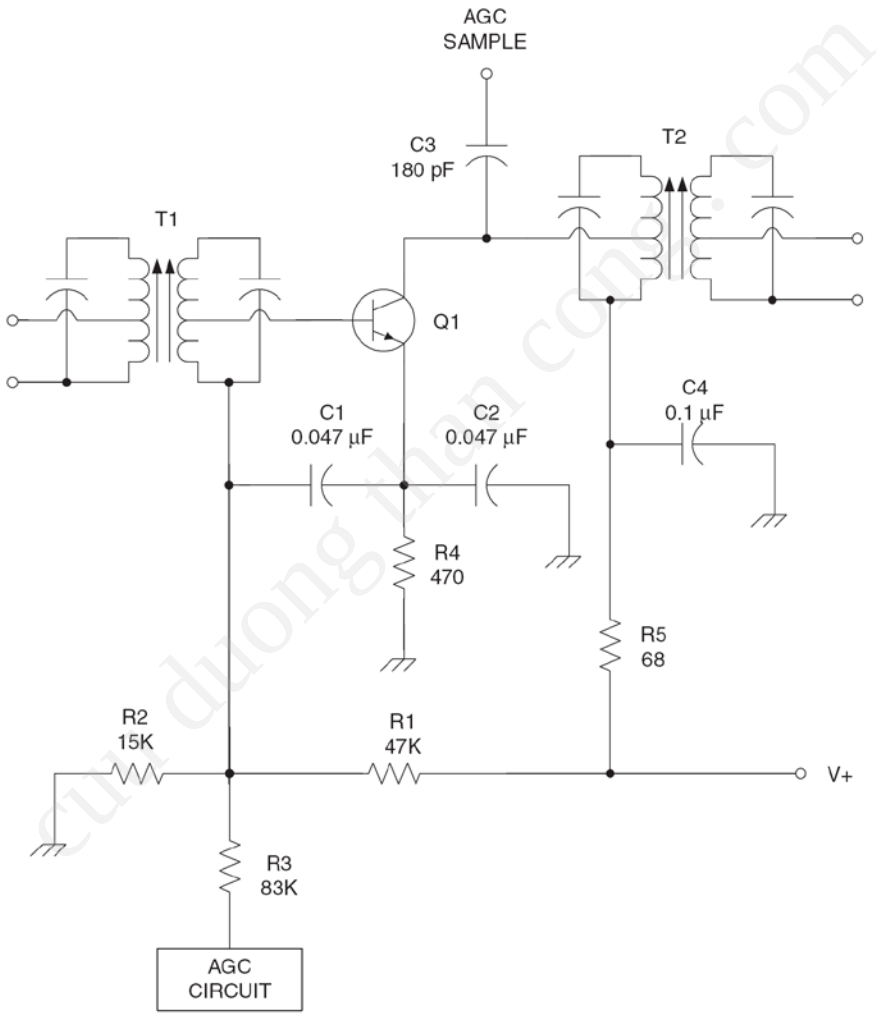
Crystal Filters (6)

- **Crystal ladder filters:** crystal ladder filter. This filter has several advantages over the other types:
  - All crystals are the same frequency (no matching is required).
  - Filters may be constructed using an odd or even number of crystal.
  - Spurious responses are not harmful (especially for filters over four or more sections).
  - Insertion loss is very low.



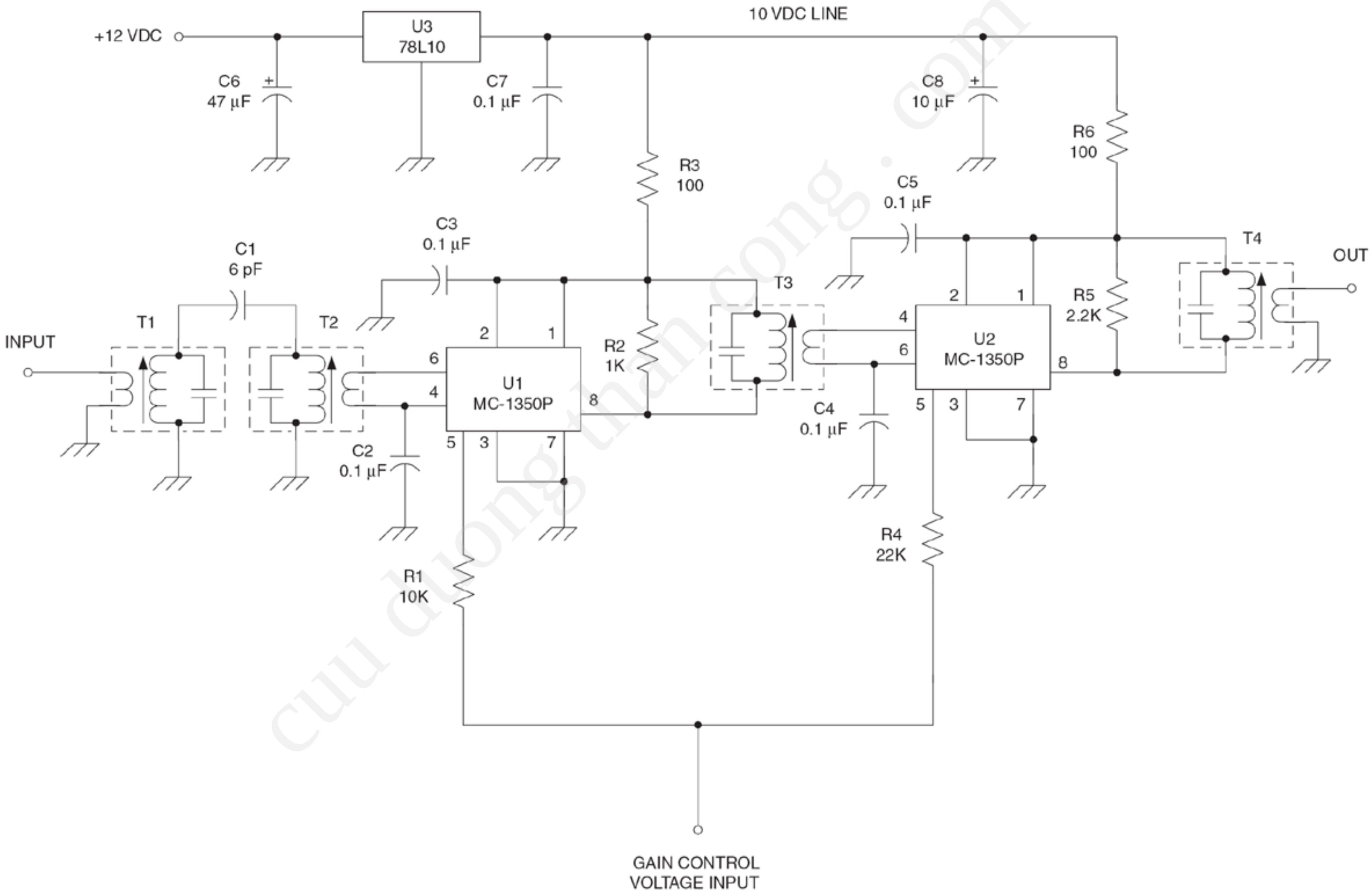
IF Amplifiers (1)

- A simple IF amplifier is shown in below figure:



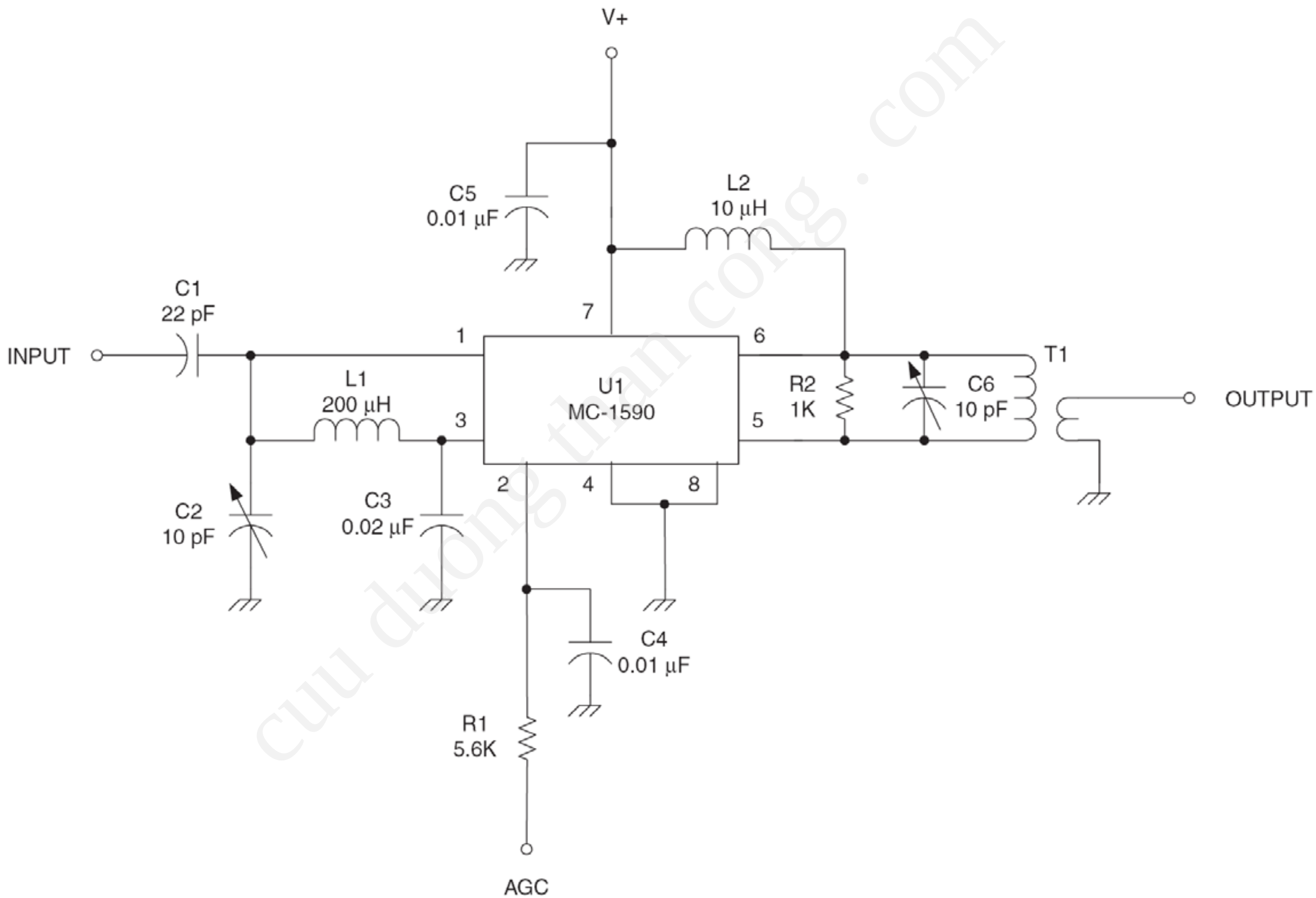
IF Amplifiers (2)

- The IF amplifier in below is based on the popular MC-1350P:

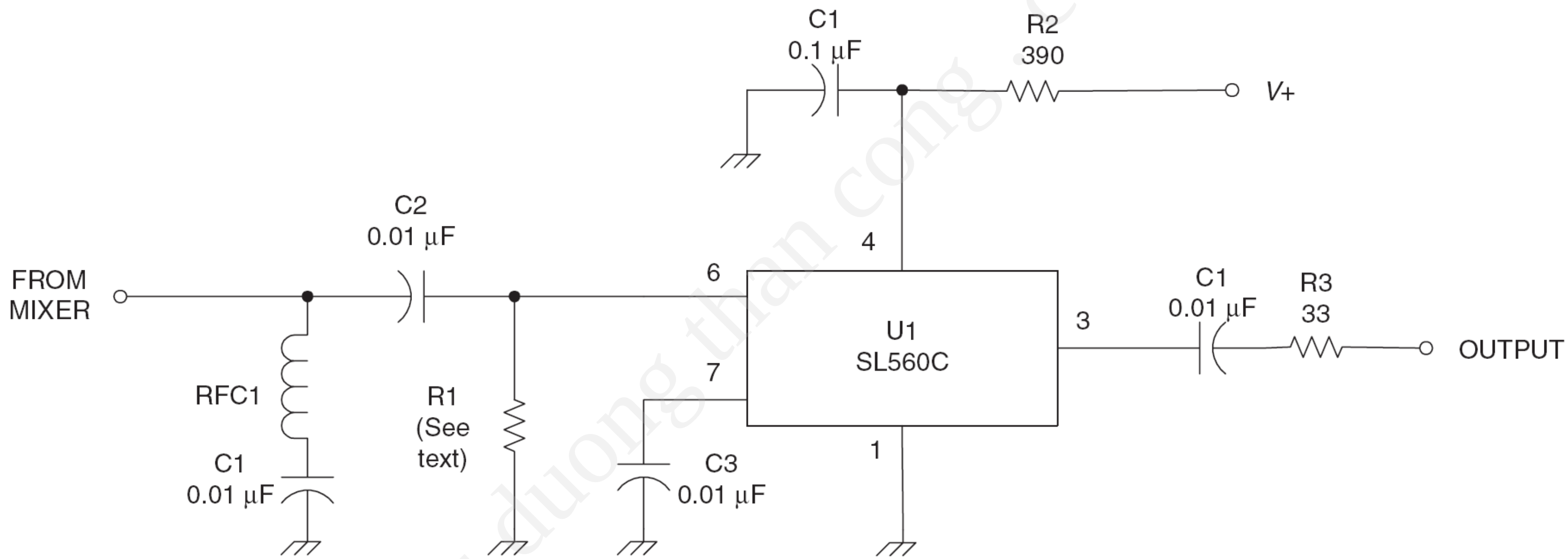


IF Amplifiers (3)

- More IF amplifier ICs (MC-1590, SL560C):



IF Amplifiers (4)



Chapter 6:

RF Oscillator and Frequency Synthesizer

References

[1] J. Rogers, C. Plett, *Radio Frequency Integrated Circuit Design*, Artech House, 2003.

[2] W. A. Davis, K. Agarwal, *Radio Frequency Circuit Design*, John Wiley & Sons, 2001.

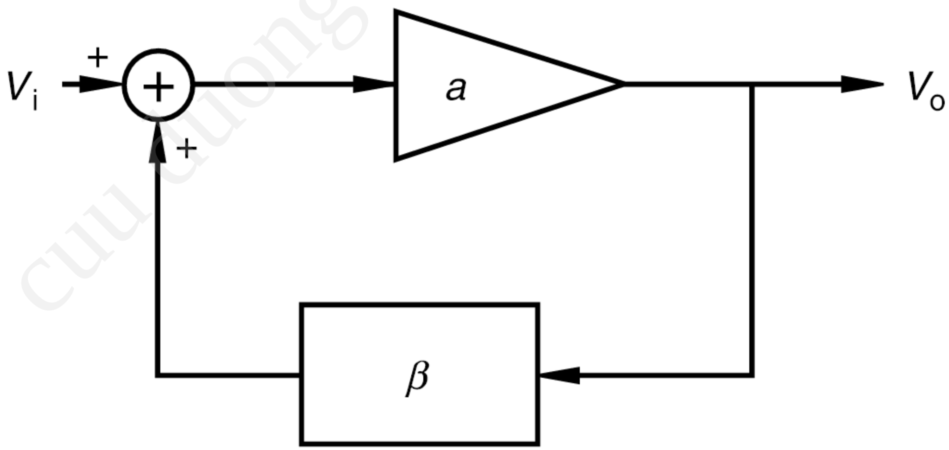
[3] F. Ellinger, *RF Integrated Circuits and Technologies*, Springer Verlag, 2008.

[4] U. L. Rohde, D. P. Newkirk, *RF/Microwave Circuit Design for Wireless Applications*, John Wiley & Sons, 2000.

Oscillator Fundamentals (1)

- An **oscillator** is a circuit that converts energy from a power source (usually a DC power source) to AC energy (periodic output signal). In order to produce a self-sustaining oscillation, there necessarily must be **feedback** from the output to the input, **sufficient gain (amplifier)** to overcome losses in the feedback path, and a **resonator (filter)**.

- The block diagram of an oscillator with positive feedback is shown below. It contains an amplifier with frequency-dependent forward gain $a(\omega)$ and a frequency-dependent feedback network $\beta(\omega)$.



Oscillator Fundamentals (2)

The output voltage is given by:

$$V_o = aV_i + a\beta V_o$$

It gives the closed loop gain as:

$$A = \frac{V_o}{V_i} = \frac{a}{1 - a\beta}$$

For an oscillator, the output V_o is nonzero even if the input signal V_i is zero. This can only possible if the closed loop gain A is infinity. It means:

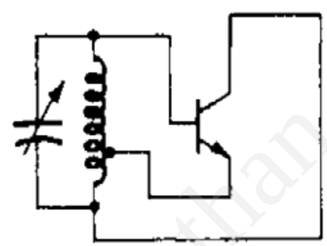
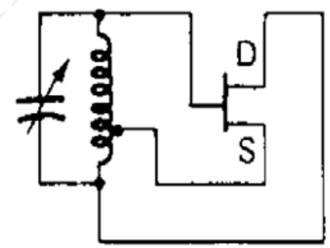
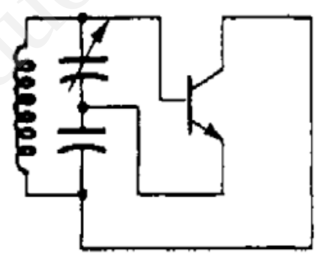
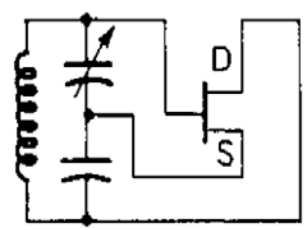
$$a\beta = 1$$

This is called the **Barkhausen criterion** for oscillation and is often described in terms of its magnitude and phase separately. Hence oscillation can occur when

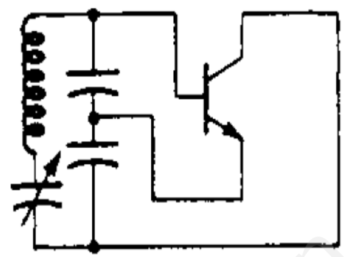
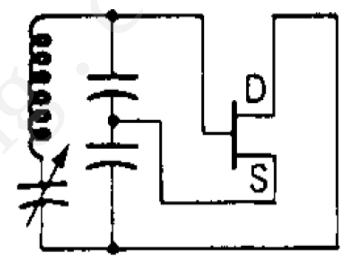
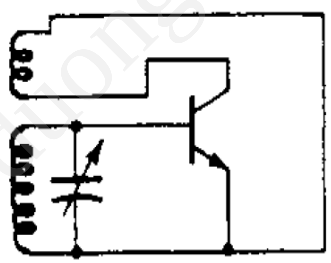
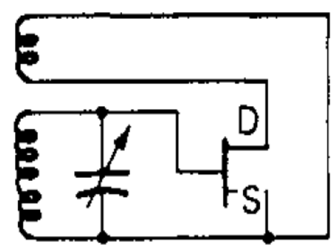
$$|a\beta| = 1 \text{ and } \angle a\beta = 360^\circ$$

Oscillator Fundamentals (3)

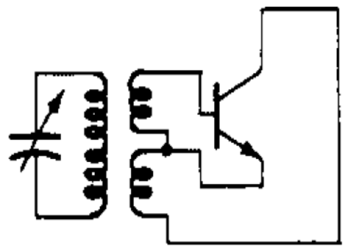
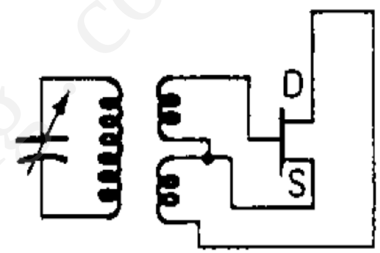
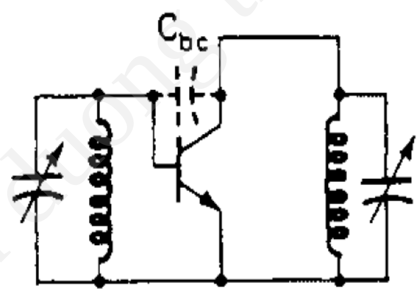
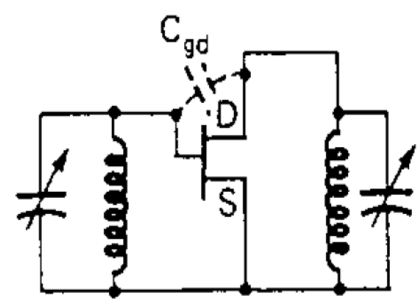
❑ Osillator type: (DC and bias circuit not shown)

Oscillator Type	Bipolar Transistor RF Circuit	FET RF Circuit
Hartley		
Colpitts		

Oscillator Fundamentals (4)

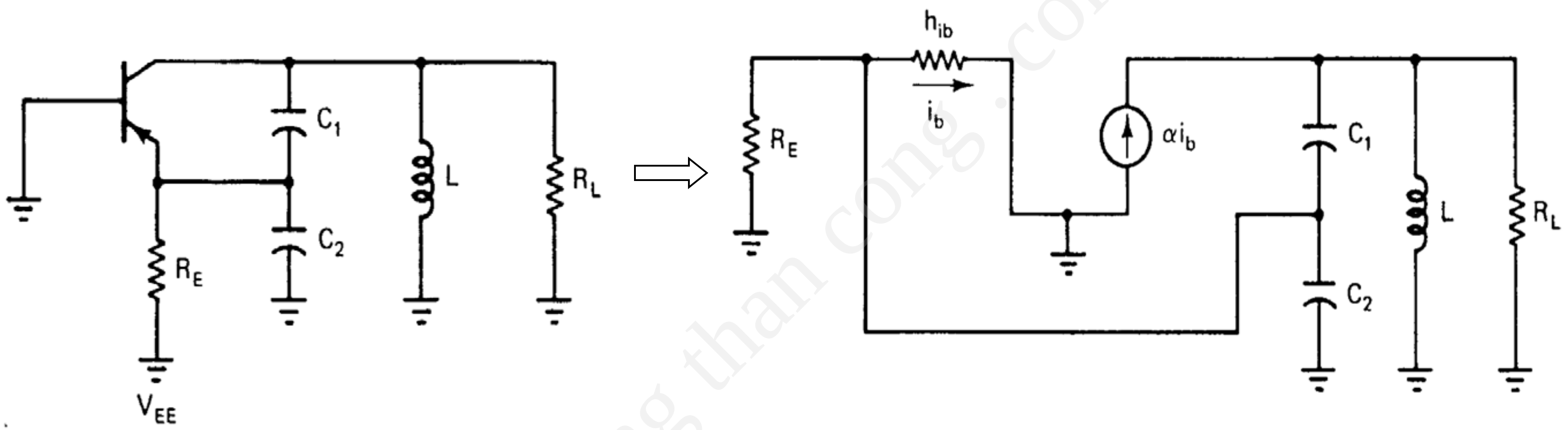
Clapp (Gouriet)		
Transformer Feedback		

Oscillator Fundamentals (5)

Meissner		
Tuned Input/ Tuned Output		

Oscillator Fundamentals (6)

- Example: This example illustrates the design method. The transistor is in CB configuration, then there is no phase inversion for the amplifier.

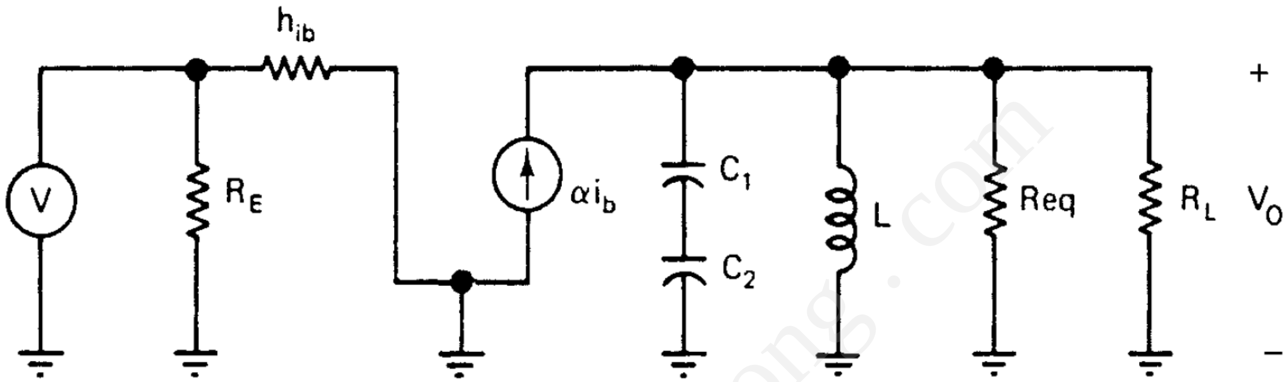


The circuit analysis can be simplified with the assumption:

$$\frac{1}{\omega C_2} \ll R_E \parallel h_{ib} = \frac{R_E h_{ib}}{R_E + h_{ib}}$$

It is also assumed that the quality factor of load impedance is high. Then, the circuit reduces to:

Oscillator Fundamentals (7)



where $V = \dfrac{V_o C_1}{C_1 + C_2}$

and $R_{\mathrm{eq}} = \dfrac{h_{ib} R_E}{h_{ib} + R_E} \left(\dfrac{C_1 + C_2}{C_1} \right)^2$

The forward gain: $a = \dfrac{h_{fb}}{h_{ib}} Z_L = \dfrac{\alpha}{h_{ib}} Z_L$

and the feedback transfer function: $-\beta = \dfrac{C_1}{C_1 + C_2}$

Oscillator Fundamentals (8)

where

$$Y_L = \frac{1}{Z_L} = \frac{1}{j\omega L} + \frac{1}{R_{eq}} + \frac{1}{R_L} + \frac{1}{j\omega C}$$

According to **Barkhausen criterion** for phase**:**

$$\angle a\beta = 360^\circ$$

and in this example β does not depend on frequency, then the phase shift of a or Z_L must be 360^o (or 0^o). This only occurs at the resonant frequency of the circuit:

$$\omega_o = \frac{1}{\sqrt{L[C_1 C_2/(C_1 + C_2)]}}$$

At this frequency:

$$Z_L = \frac{R_{eq} R_L}{R_{eq} + R_L}$$

Oscillator Fundamentals (9)

and

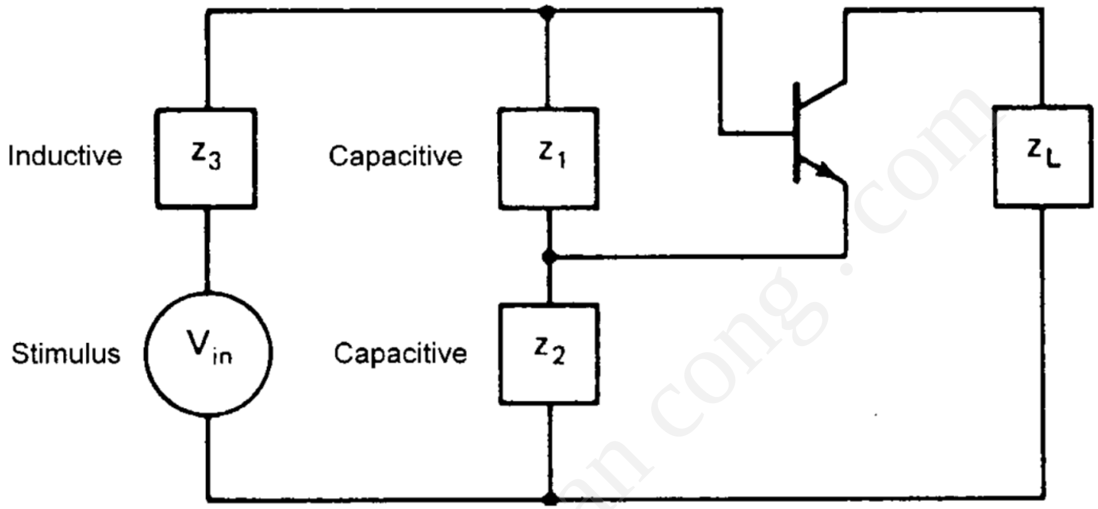
$$a\beta = \frac{h_{fb}}{h_{ib}}\left(\frac{R_{eq}R_L}{R_{eq}+R_L}\right)\frac{C_1}{C_1+C_2}$$

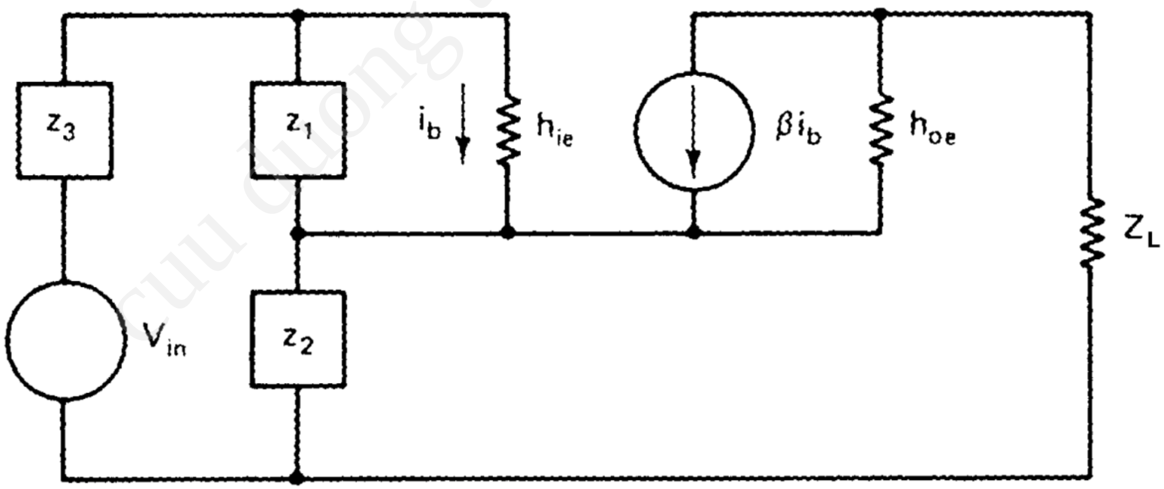
The Barkhausen criterion for magnitude is:

$$a\beta = \frac{\alpha}{h_{ib}}\left(\frac{R_{eq}R_L}{R_{eq}+R_L}\right)\frac{C_1}{C_1+C_2} = 1$$

- **<u>Three-reactance oscillators</u>**: Instead of using block diagram formulation using Barkhausen criterion, a direct analysis based on circuit equations is frequently used (particular for single ended amplifier), as shown in next slide.

Oscillator Fundamentals (10)





Oscillator Fundamentals (11)

Omitting h_{oe}, the loop equations are then:

$$V_{\text{in}} = I_1(Z_3 + Z_1 + Z_2) - I_b Z_1 + h_{fe} I_b Z_2$$

$$0 = -I_1 Z_1 + I_b(h_{ie} + Z_1)$$

For the amplifier to oscillate, the current I_b and I_1 must be nonzero even $V_{\text{in}} = 0$. This is only possible if the system determinant:

$$\Delta = \begin{vmatrix} Z_3 + Z_1 + Z_2 & h_{fe} Z_2 - Z_1 \\ -Z & h_{ie} + Z_1 \end{vmatrix}$$

is equal to 0. That is:

$$(Z_3 + Z_1 + Z_2)(h_{ie} + Z_1) - Z_1^2 + h_{fe} Z_1 Z_2 = 0$$

which reduces to:

$$(Z_1 + Z_2 + Z_3)\, h_{ie} + Z_1 Z_2 h_{fe} + Z_1(Z_2 + Z_3) = 0$$

Oscillator Fundamentals (12)

Assumed that Z_1, Z_2, Z_3 are purely reactive impedance. Since both real and imaginary parts must be zero, then

$$h_{ie}(Z_1 + Z_2 + Z_3) = 0$$

and

$$Z_1[(1 + h_{fe})Z_2 + Z_3] = 0$$

Since h_{fe} is real and possitive, Z_2 and Z_3 must be of <u>opposite sign</u>. That is:

$$(1 + h_{fe})Z_2 = -Z_3$$

Since h_{ie} is nonzero, then

$$Z_1 + Z_2 - (1 + h_{fe})Z_2 = 0$$

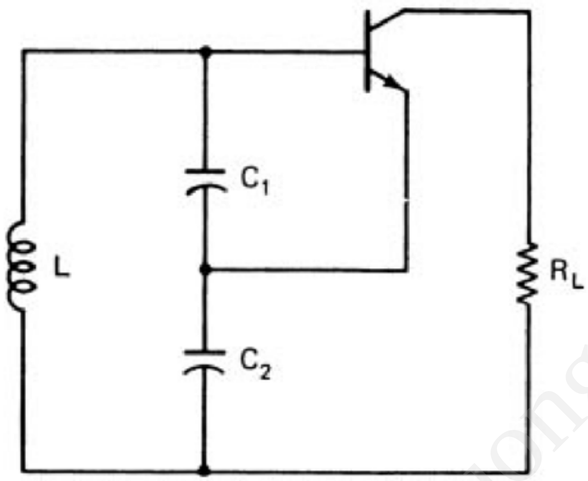
or

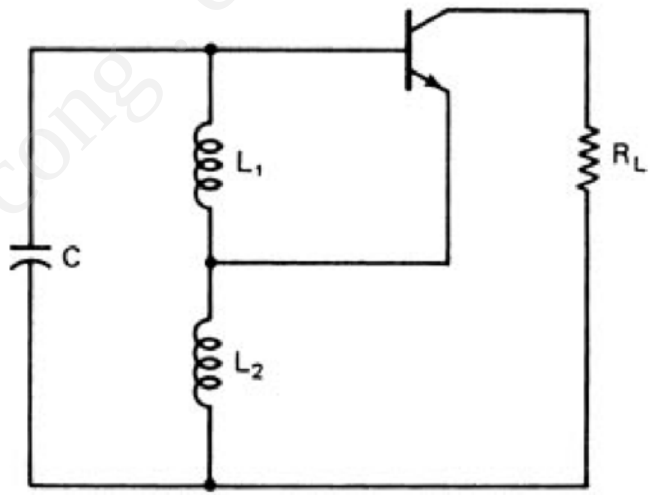
$$Z_1 = h_{fe}Z_2$$

Thus, since h_{fe} is positive, then Z_1 and Z_2 will be <u>reactances of same kind</u>.

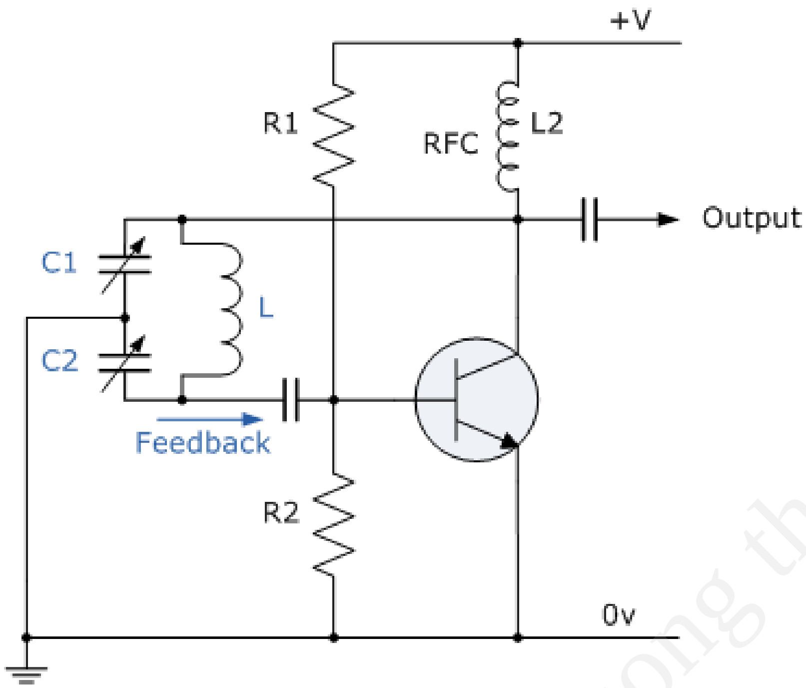
Oscillator Fundamentals (13)

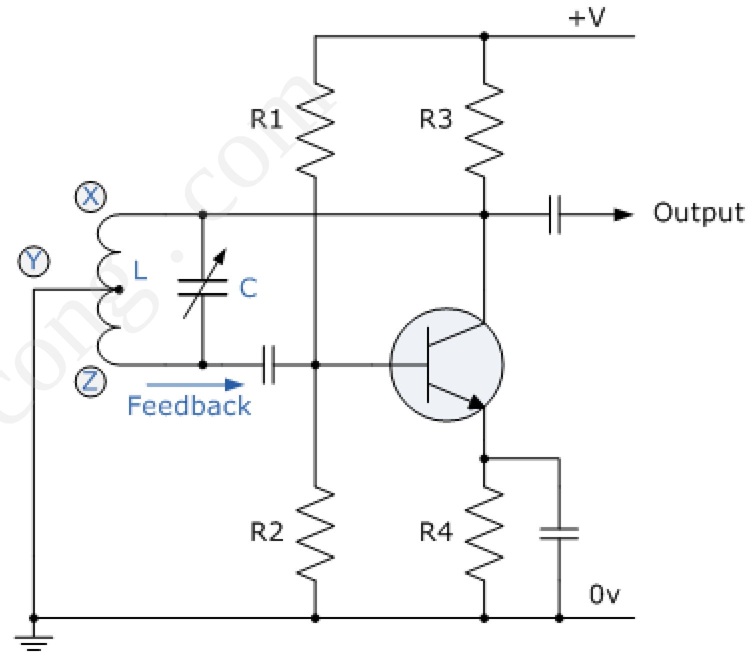
If Z_1 and Z_2 are capacitors, Z_3 is an inductor, then it is referred as Colpitts oscillator. If Z_1 and Z_2 are inductors, Z_3 is a capacitor, then it is referred as Hartley oscillator.





Oscillator Fundamentals (14)





Example of Colpitts circuit (with bias), oscillating frequency:

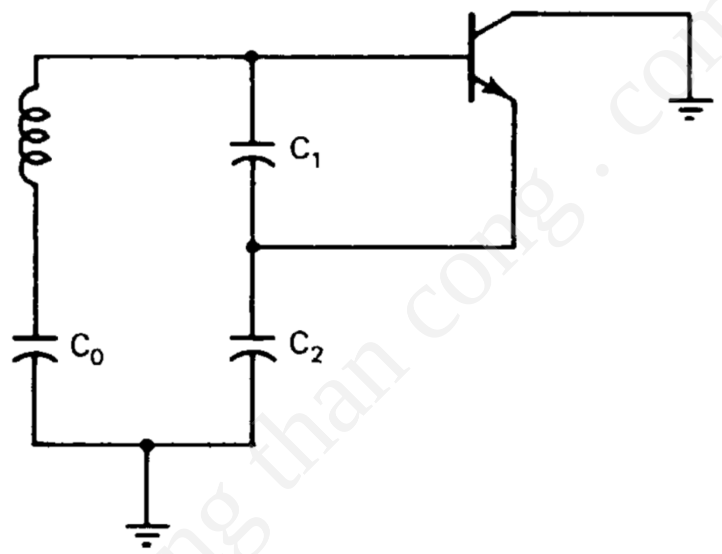
$$f = \frac{1}{2\pi\sqrt{L\frac{C_1 C_2}{C_1 + C_2}}}$$

Example of Hartley circuit (with bias), oscillating frequency:

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

Oscillator Fundamentals (15)

An oscillator known as the Clapp circuit (or Clapp-Gourier circuit):

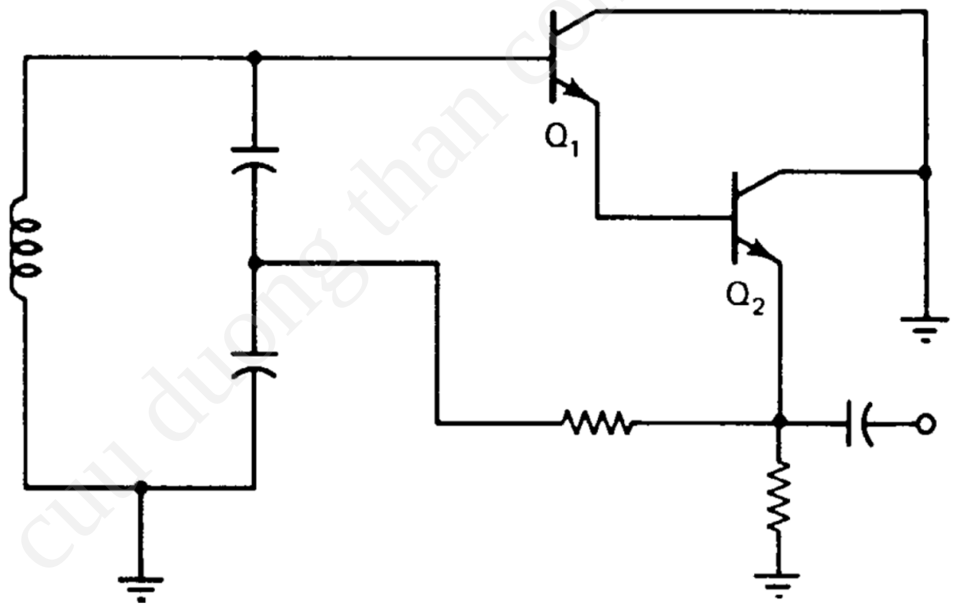


This circuit has practical advantage of being able to provide another degree of design freedom when making C_o much smaller than C_1 and C_2. The C_o can be adjusted for the desired oscillating frequency ω_o, which is determined from:

$$\omega_o L - \frac{1}{\omega_o C_o} - \frac{1}{\omega_o C_1} - \frac{1}{\omega_o C_2} = 0$$

Oscillator Fundamentals (16)

- **<u>Oscillating amplitude stability</u>**: Two methods for amplitude controlling is:
  - Operating the transistor in nonlinear region, and
  - Using second stage for amplitude limitting. For example:



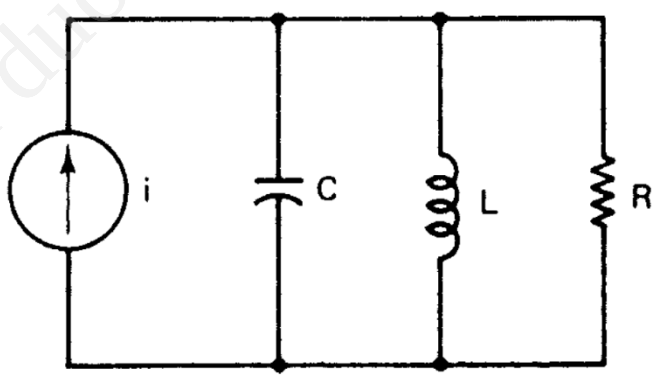
Oscillator Fundamentals (17)

- **Oscillating phase (frequency) stability**:
  - Long-term stability (the oscillating frequency changes over a period of minutes, hours, days, or years) due to components' temperature coefficients or aging rates.
  - Short-term stability is measured in term of seconds. The frequency stability factor SF is defined as

$$S_F = 2Q$$

where

$$\omega_o = \frac{1}{\sqrt{LC}} \quad \text{and} \quad Q = \frac{R}{\omega_o L}$$



Crystal Oscillators (1)

- One of the most important features of an oscillator is its frequency stability, or in other words its ability to provide a constant frequency output under varying conditions. Some of the factors that affect the frequency stability of an oscillator include: temperature, variations in the load and changes in the power supply.

  Frequency stability of the output signal can be improved by the proper selection of the components used for the resonant feedback circuit including the amplifier but there is a limit to the stability that can be obtained from normal LC and RC tank circuits. For very high stability a **quartz crystal** is generally used as the frequency determining device to produce another types of oscillator circuit known generally as **crystal oscillators**.

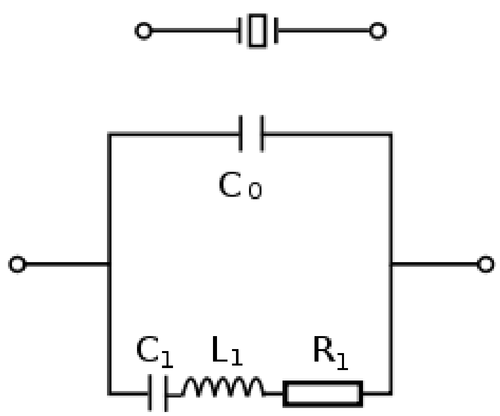
Crystal Oscillators (2)

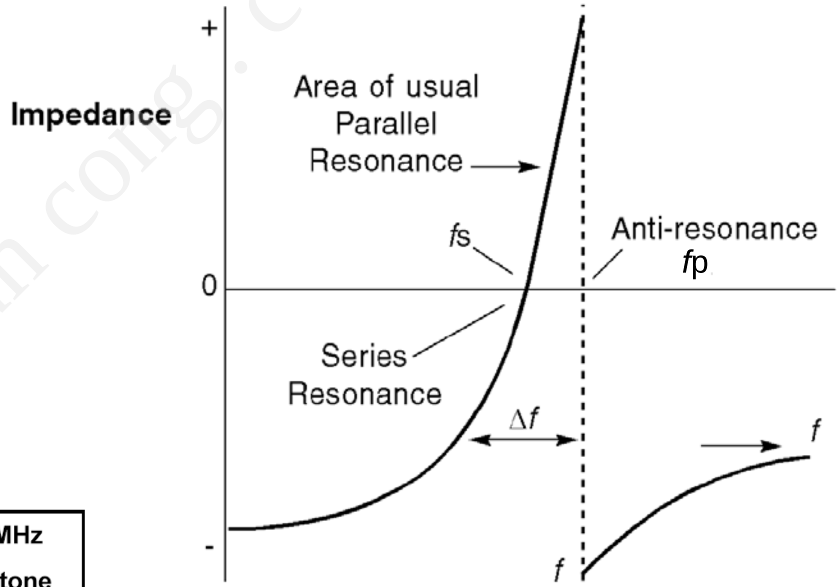
- When a voltage source is applied to a small thin piece of crystal quartz, it begins to change shape producing a characteristic known as the **piezo-electric effect**. This piezo-electric effect is the property of a crystal by which an electrical charge produces a mechanical force by changing the shape of the crystal and vice versa, a mechanical force applied to the crystal produces an electrical charge. Then, piezo-electric devices can be classed as transducer as they convert energy of one kind into energy of another. This piezo-electric effect produces mechanical vibrations or oscillations which are used to replace the LC circuit.

  The quartz crystal used in **crystal oscillators** is a very small, thin piece or wafer of cut quartz with the two parallel surfaces metallized to make the electrical connections. The physical size and thickness of a piece of quartz crystal is tightly controlled since it affects the final frequency of oscillations and is called the crystals "characteristic frequency".

Crystal Oscillators (3)

A mechanically vibrating crystal can be represented by an equivalent electrical circuit consisting of low resistance, large inductance and small capacitance as shown below:





Parameter	32 kHz fundamental	200 kHz fundamental	2 MHz fundamental	30 MHz overtone
R_1	200 kΩ	2 kΩ	100 Ω	20 Ω
L_1	7000H	27H	529 mH	11 mH
C_1	0.003 pF	0.024 pF	0.012 pF	0.0026 pF
C_0	1.7 pF	9 pF	4 pF	6 pF
Q	100k	18k	54k	100k

Crystal Oscillators (4)

The impedance of the equivalent circuit is

$$Z(s) = \left(\frac{1}{s \cdot C_1} + s \cdot L_1 + R_1\right) || \left(\frac{1}{s \cdot C_0}\right)$$

or

$$Z(s) = \frac{s^2 + s\frac{R_1}{L_1} + {\omega_s}^2}{(s \cdot C_0)[s^2 + s\frac{R_1}{L_1} + {\omega_p}^2]}$$

$$\Rightarrow \omega_s = \frac{1}{\sqrt{L_1 \cdot C_1}}, \quad \omega_p = \sqrt{\frac{C_1 + C_0}{L_1 \cdot C_1 \cdot C_0}} = \omega_s \sqrt{1 + \frac{C_1}{C_0}} \approx \omega_s \left(1 + \frac{C_1}{2C_0}\right) \quad (C_0 \gg C_1)$$

where ω_s is series resonant frequency and ω_p is parallel resonant frequency (or anti-resonant frequency). The series and parallel resonant frequencies are very stable and not affected by temperature variations.

At <u>series resonant frequency</u>, the crystal has a <u>low impedance </u>(ideally, zero impedance). At parallel resonant frequency, the crystal has a <u>high impedance.</u>

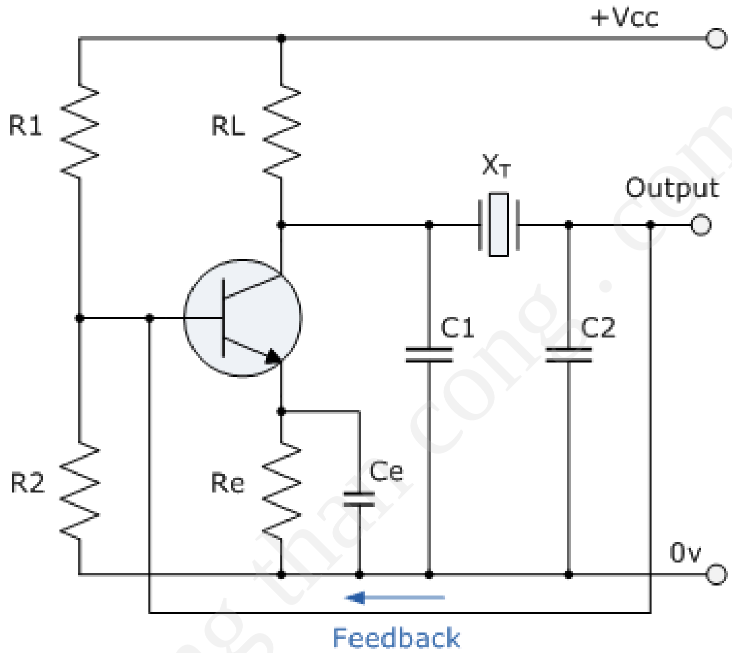
Crystal Oscillators (5)

- A quartz crystal has a resonant frequency similar to that of a electrically tuned tank circuit (LC circuit) but with a much higher Q factor due to its low resistance, with typical frequencies ranging from <u>4kHz to 10MHz</u>.

  In a crystal oscillator circuit the oscillator will oscillate at the crystals <u>fundamental series resonant frequency</u> when a voltage source is applied to it. However, it is also possible to tune a crystal oscillator to any even harmonic of the fundamental frequency, (2nd, 4th, 8th etc.) and these are known generally as **harmonic oscillators** (while **overtone oscillators** vibrate at odd multiples of the fundamental frequency, 3rd, 5th, 11th etc).

- **<u>Colpitts crystal oscillator</u>:** The design of a crystal oscillator is very similar to the design of the Colpitts oscillator, except that the LC circuit has been replaced by a quartz crystal as the example shown below:

Crystal Oscillators (6)



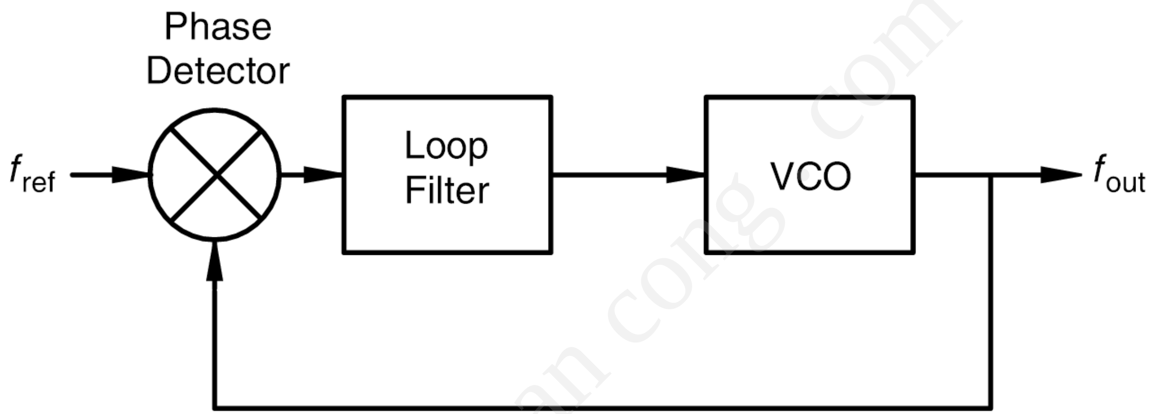
These types of crystal oscillators are designed around the CE amplifier stage of a Colpitts oscillator. The input signal to the base of the transistor is inverted at the transistors output. The output signal at the collector is then taken through a 180^o phase shifting network which includes the crystal operating as an <u>Inductor (parallel resonance area)</u>. The output is also fed back to the input which is "in-phase" with the input providing the necessary positive feedback.

Voltage-Controlled Oscillator (VCO)

- **VCO** is an electronic oscillator specifically designed to be controlled in oscillation frequency by a voltage input. The frequency of oscillation, is varied with an applied DC voltage, while modulating signals may be fed into the VCO to generate frequency modulation (FM), phase modulation (PM), and pulse-width modulation (PWM).

Phase Locked Loop (1)

- Basic **Phase Locked Loop (PLL):**



- **Phase detectors:** If the two input frequencies are exactly the same, the phase detector output is the phase difference between the two inputs. This loop error signal is filtered and used to control the VCO frequency. The two input signals can be represented by sine waves:

$$V_1 = V_a \sin(\omega_1 t + \phi_1)$$

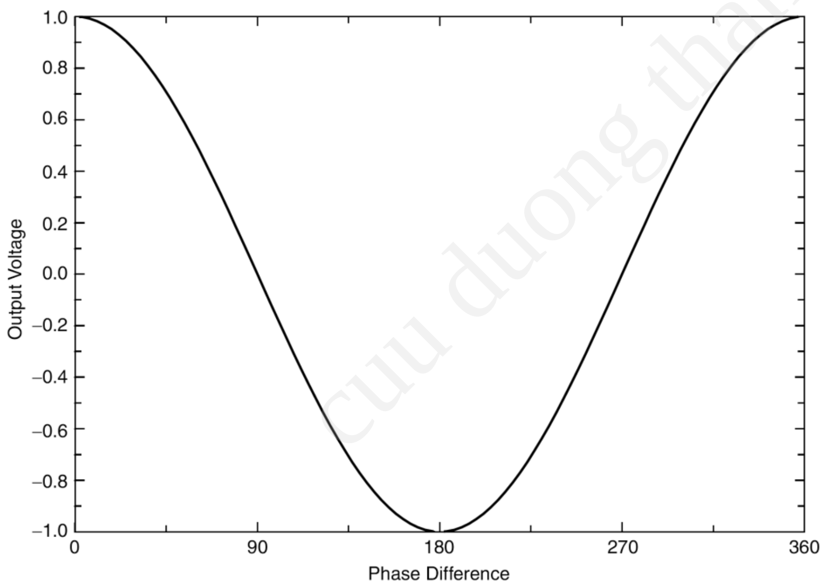
$$V_2 = V_b \sin(\omega_2 t + \phi_2)$$

Phase Locked Loop (2)

The difference frequency term is the error voltage given as:

$$V_e = K_m \cdot V_1 \cdot V_2 = \frac{K_m V_a V_b}{2} \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)]$$

where K_m is a constant describing the conversion loss of the phase detector (or mixer). When the two frequencies are identical, the output voltage is a function of the phase difference, $\Delta\phi = \phi_1 - \phi_2$:

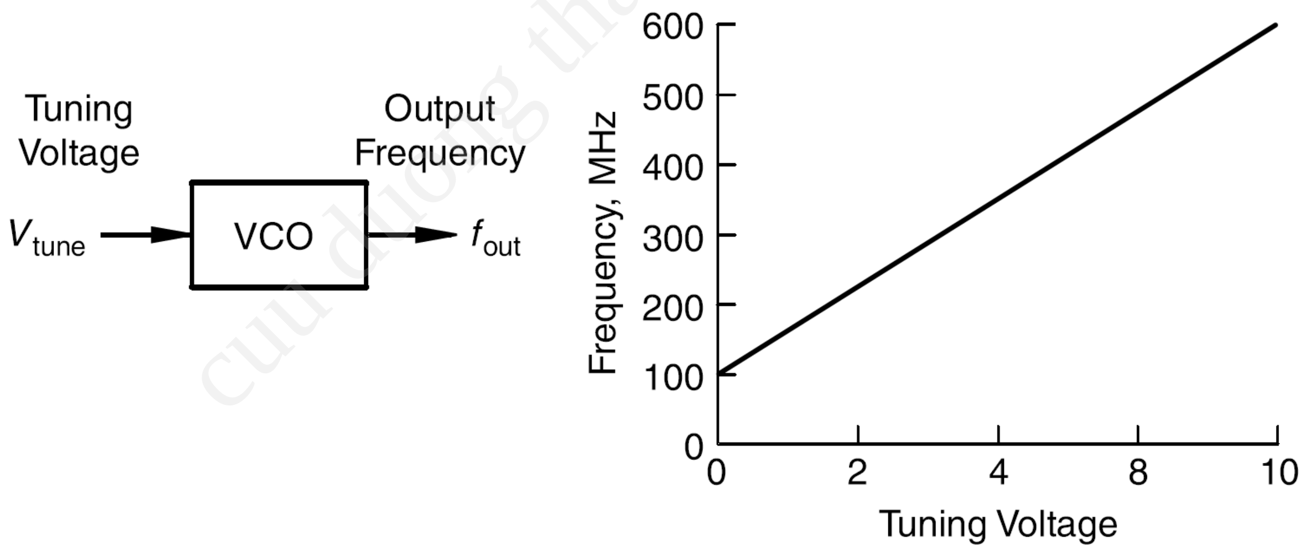


$$V_e = \frac{K_m V_a V_b}{2} \cos(\Delta\phi)$$

Phase Locked Loop (3)

- **<u>Voltage-Controlled Oscillator (VCO)</u>:** The VCO is the control element for a PLL in which its output frequency changes monotonically with the its input tuning voltage. A linear frequency versus tuning voltage is an adequate model for understanding its operation:

$$\omega_{\text{out}} = K_{\text{vco}} \cdot V_{\text{tune}} + \omega_0$$



Phase Locked Loop (4)

In a PLL the ideal VCO output phase may be expressed as:

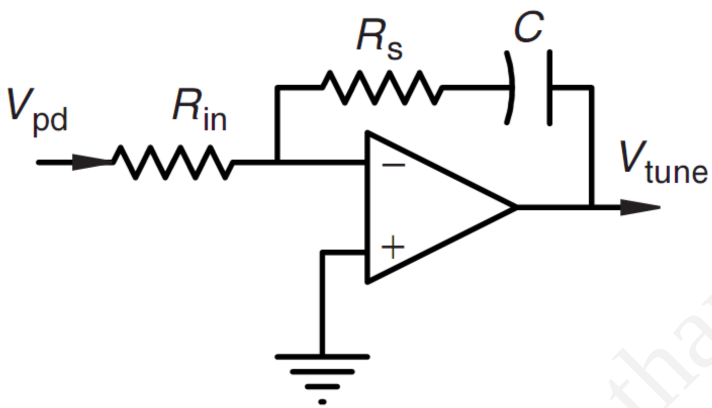
$$\phi(t) = \omega_0 t + \int_0^t K_{\text{vco}} V_{\text{tune}} dt + \phi_0$$

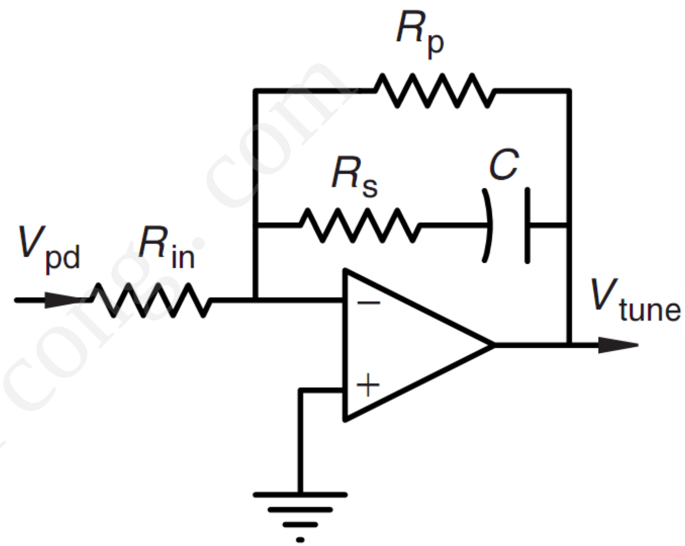
where ω_0 is the free-running VCO frequency when the tuning voltage is zero and K_{vco} is the tuning rate with the unit of rad/s-volt.

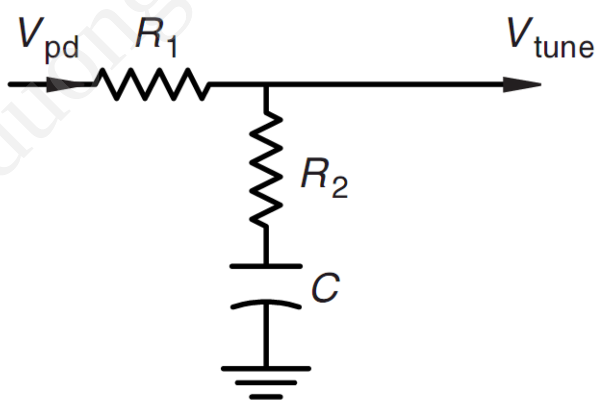
The error voltage from the phase detector first steers the frequency of the VCO to exactly match the reference frequency (f_{ref}), and then holds it there with a constant phase difference.

❑ **Loop Filters:** A loop filter is a low-pass filter circuit that filters the phase detector error voltage with which it controls the VCO frequency. While it can be active or passive, it is usually analog and very simple as shown below:

Phase Locked Loop (5)



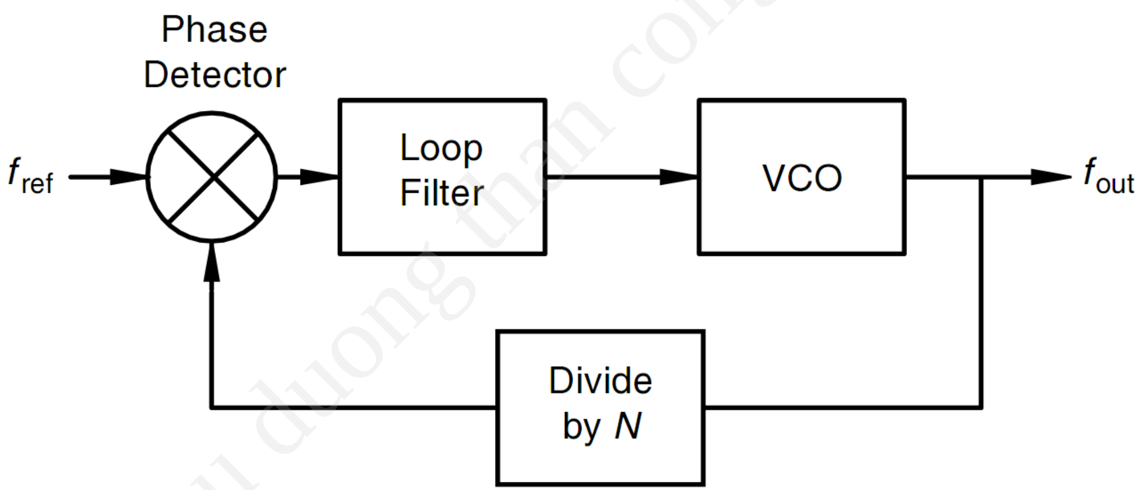




Phase Locked Loop (6)

While the loop filter is a simple circuit, its characteristic is important in determining the final closed loop operation. The wrong design will make the loop unstable causing oscillation or so slow that it is unusable.

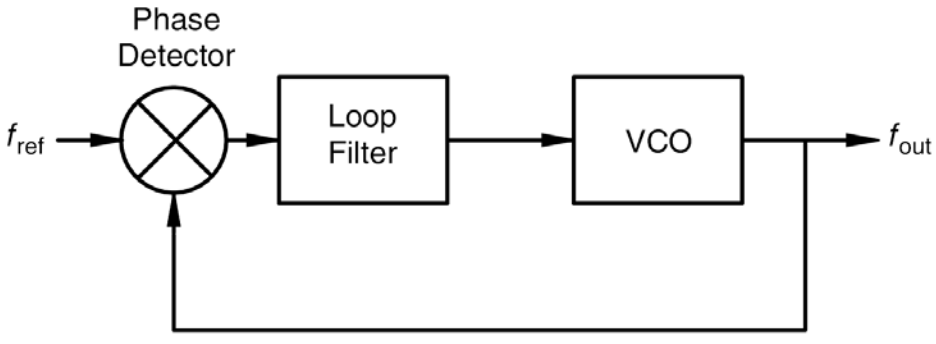
❑ **PLL with frequency divider**:



Frequency dividers: When the output frequency must be a multiple of the input frequency, frequency dividers may be included in a PLL. Most dividers are digital circuits.

Phase Locked Loop (7)

- **<u>Basic principle of operation of a PLL</u>**: With no input signal applied to the system, the error voltage V_e is equal to zero. The VCO operates at the free-running frequency f_o. If an input signal is applied to the system, the phase detector compares the phase and frequency of the input signal with the VCO frequency and generates an error voltage, $V_e(t)$, that is related to the phase and frequency difference between the two signals. This error voltage is then filtered and applied to the control terminal of the VCO. If the input frequency is sufficiently close to f_o, the feedback nature of the PLL causes the VCO to synchronize, or lock, with the incoming signal. <u>Once in lock, the VCO frequency is identical to the input signal</u>, except for a finite phase difference.



Phase Locked Loop (8)

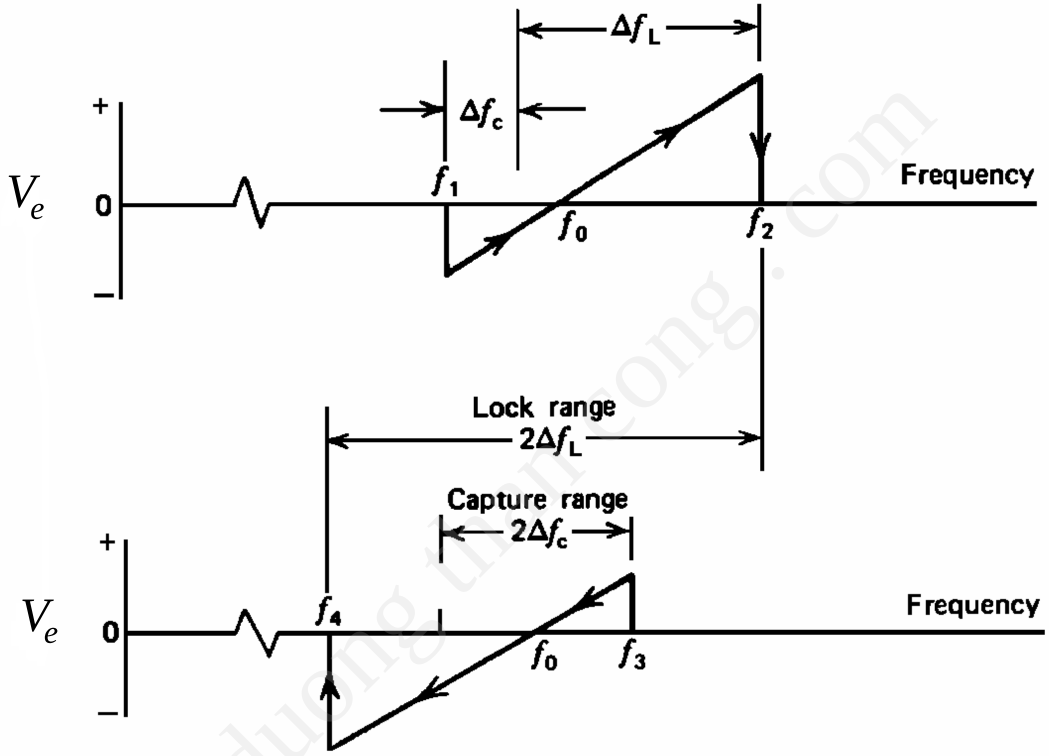
- Two key parameters of a PLL are its **lock range** and **capture range**. They can be defined as follows :

  - **Lock range**: Range of frequencies in the vicinity of free-running frequency f_o, over which the PLL can maintain lock with an input signal. It is also known as the **tracking range** or **holding range**. Lock range increases as the overall gain of the PLL is increased.

  - **Capture range**: Band of frequencies in the vicinity of f_o where the PLL can establish or acquire lock with an input signal. It is also known as the **acquisition range**. It is always smaller than the lock range, and is related to the low-pass filter bandwidth. It decreases as the filter bandwidth is reduced.

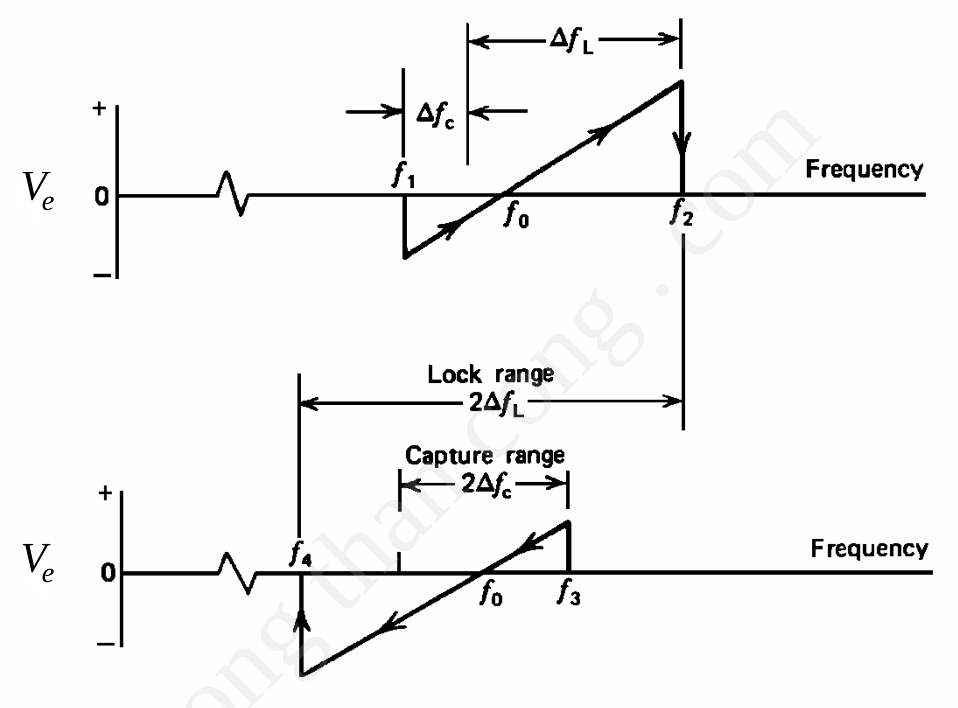
The lock and capture ranges of a PLL can be illustrated with reference to the following figure, which shows the typical frequency-to-voltage characteristics of a PLL. In the figure, the input is assumed to be swept slowly over a broad frequency range. The vertical scale corresponds to the loop-error voltage.

Phase Locked Loop (9)



In the upper part of the above figure, the loop frequency is being gradually increased. The loop does not respond to the signal until it reaches a frequency f_1, corresponding to the lower edge of the capture range. Then, the loop suddenly locks on the input, causing a negative jump of the loop-error voltage.

Phase Locked Loop (10)



Next, V_e varies with frequency with a slope equal to the reciprocal of the VCO voltage-to-frequency conversion gain, and goes through zero as $f = f_o$. The loop tracks the input until the input frequency reaches f_2, corresponding to the upper edge of the lock range. The PLL then loses lock, and the error voltage drops to zero.

Phase Locked Loop (11)

If the input frequency is now swept slowly back, the cycle repeats itself as shown in the lower part of the preceding figure. The loop recaptures the signal at f_3 and traces it down to f_4. The frequency spread between (f_1, f_3) and (f_2, f_4) corresponds to the total capture and lock ranges of the system; that is, $f_3 - f_1$ = capture range and $f_4 - f_2$ = lock range.

The PLL responds only to those input signals sufficiently close to the VCO frequency f_o to fall within the lock or capture range of the system. Its performance characteristics, therefore, offer a high degree of frequency selectivity, with the selectivity characteristics centered about f_o.

If an incoming frequency is far removed from that of the VCO, so that their difference exceeds the pass band of the low-pass filter, it will simply be ignored by the PLL. Thus, the PLL is a frequency-selective circuit.

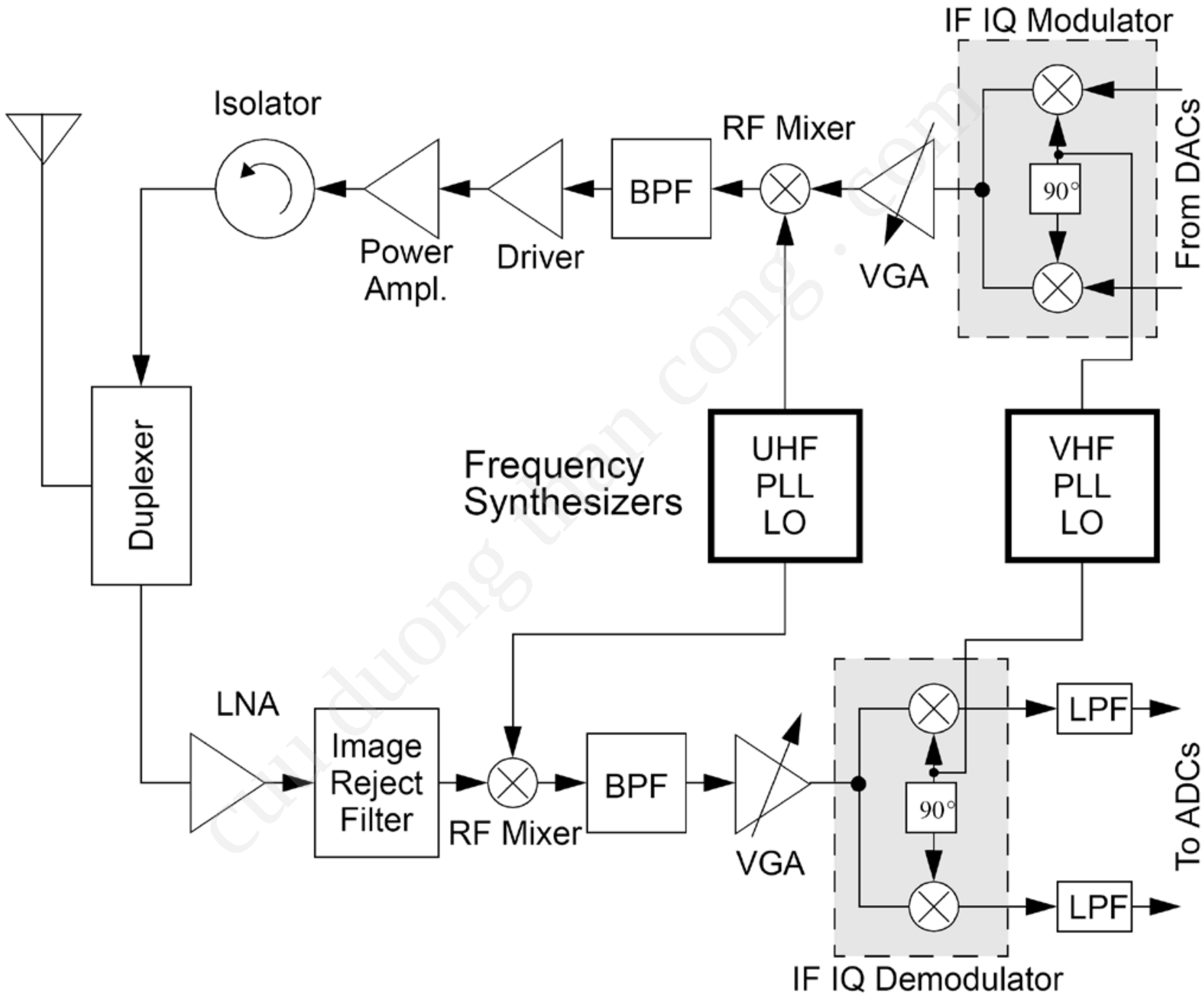
Frequency Synthesizer (1)

- In wireless applications frequency synthesizers provide local oscillators for up and down conversion of modulated signals.

  Any radio based electronics that operates over multiple frequencies, likely incorporates a frequency synthesizer.

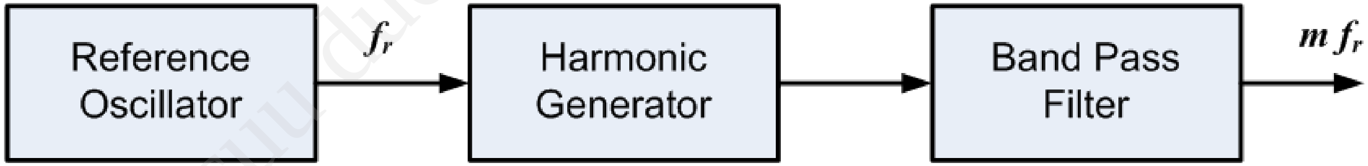
  Example: The transmitter and receiver of a cellular telephony handset is shown below:

Frequency Synthesizer (2)



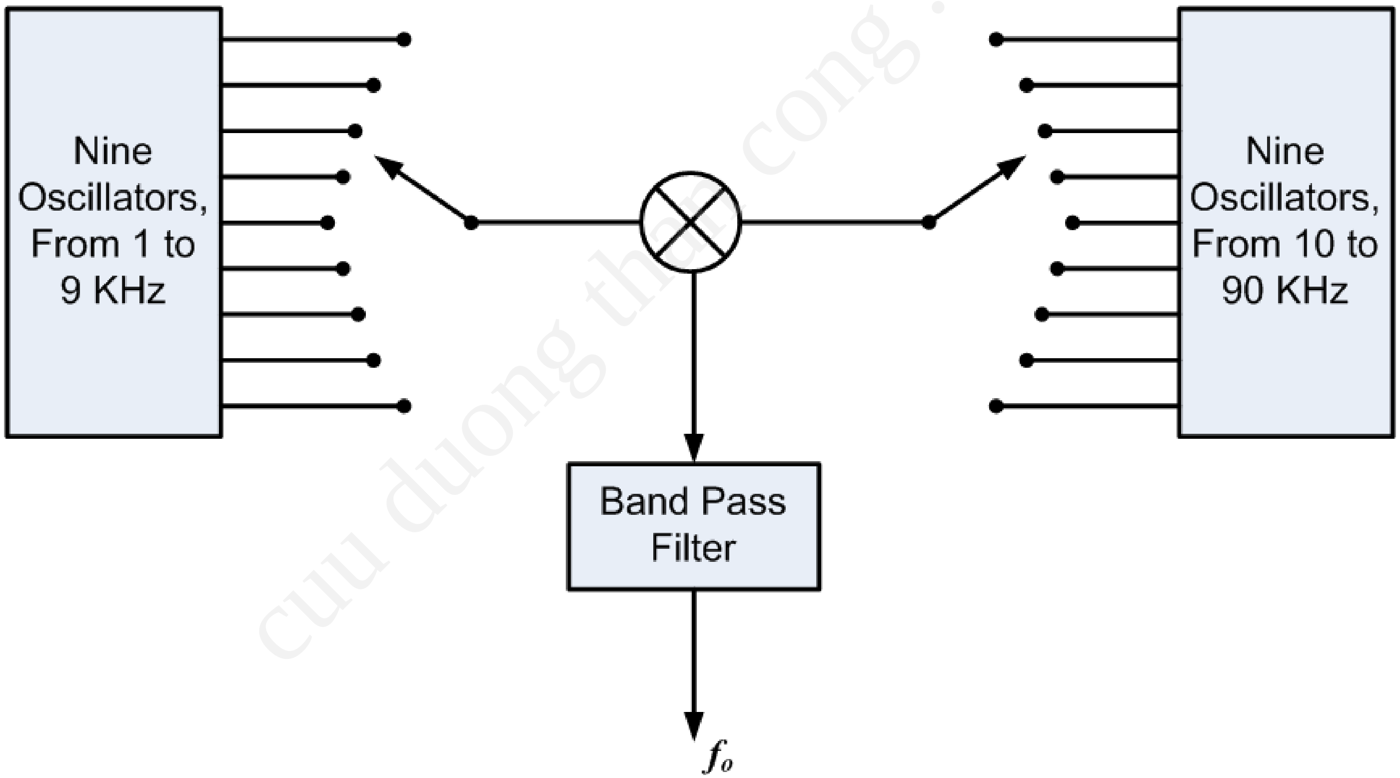
Frequency Synthesizer (3)

- **Direct Frequency Synthesis:**
  - The oldest of the frequency synthesis methods.
  - **Direct frequency synthesis** refers to the generation of few frequencies from one or more reference frequencies by using a combination of harmonic generators, filters, multipliers, dividers, and frequency mixers.
  - One method is shown below. The desired frequency is obtained with a filter tuned to a given output frequency, requiring highly selective filters.



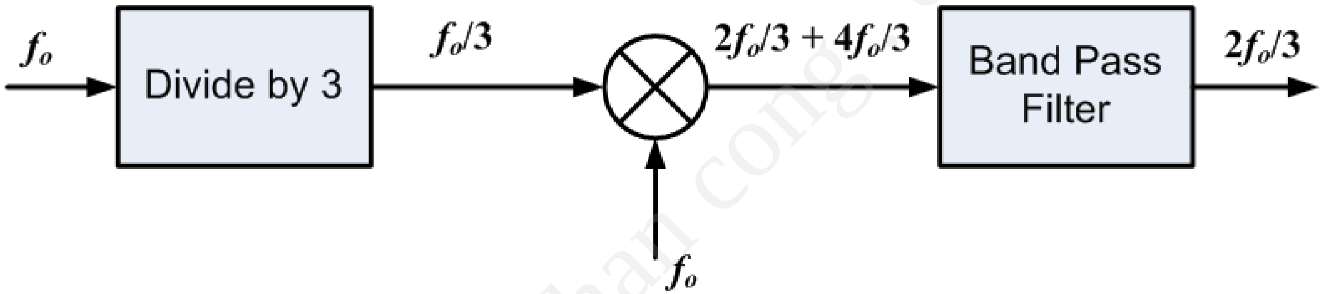
Frequency Synthesizer (4)

- An alternative approach is to use multiple oscillators. Synthesizer shown below generates 99 frequencies from 18 oscillators; BPF selects the higher of the two produced frequencies:



Frequency Synthesizer (5)

- Example of direct synthesis; the new frequency $(2/3)f_o$ is realised from f_o by using a divide-by-3 circuit and a mixer and BPF.

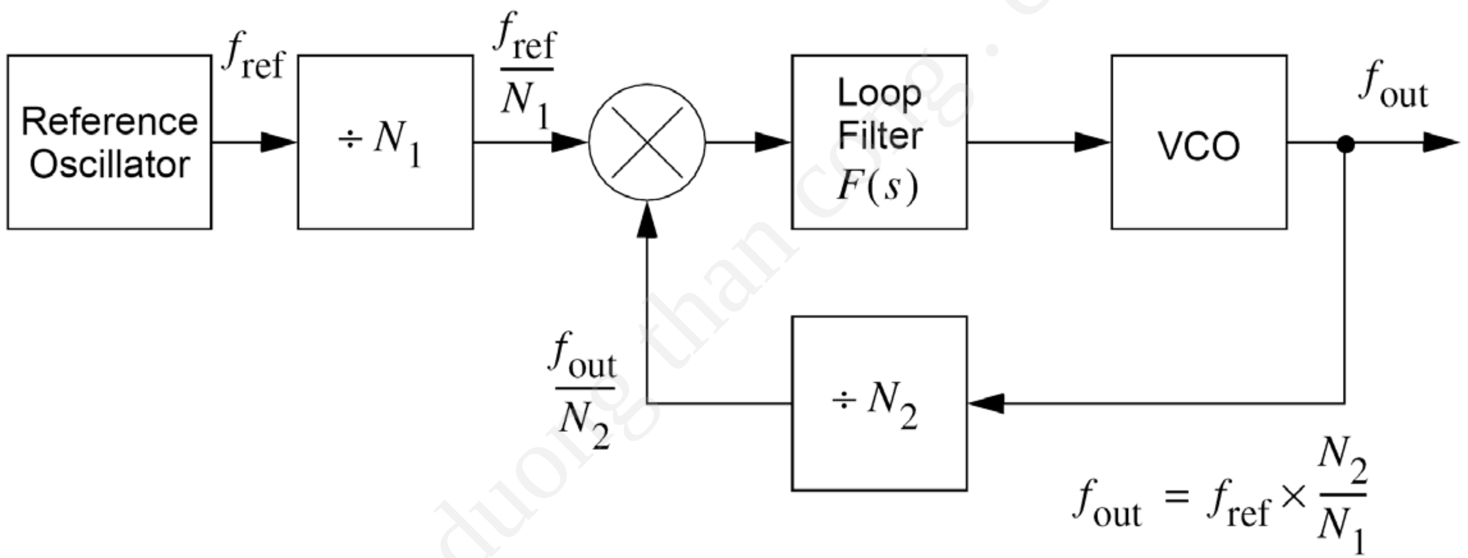


- One of the most critical consideration is that the direct synthesis method requires highly selective filters. This can be reduced with the frequency synthesis method that employs a PLL.

Frequency Synthesizer (6)

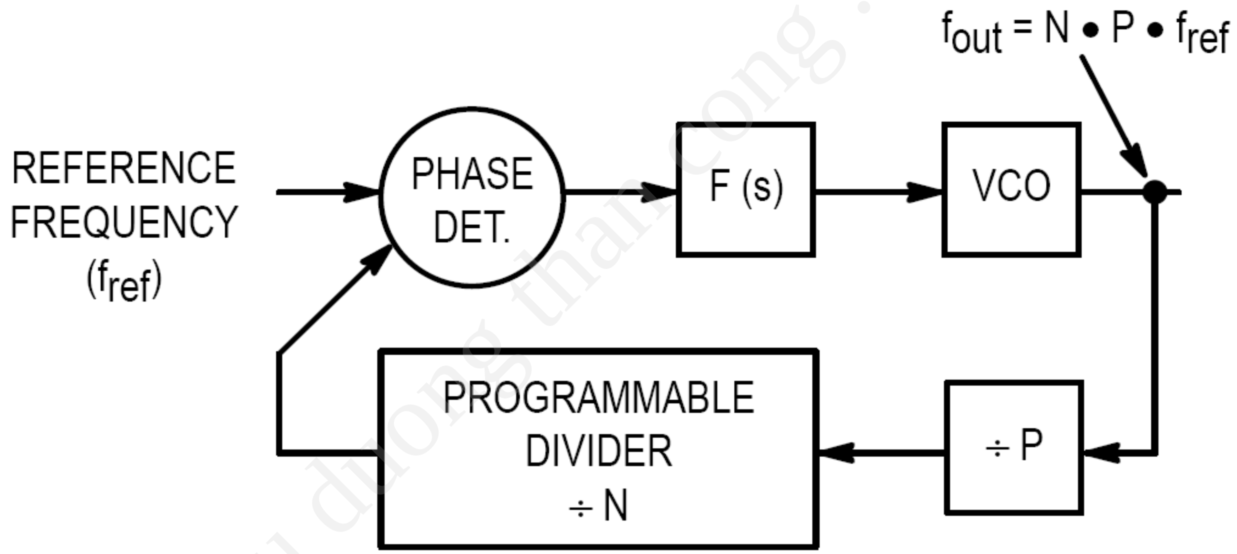
❑ PLL Frequency Synthesis (Indirect Synthesis):

- **A basic PLL synthesizer** is the following:



Frequency Synthesizer (7)

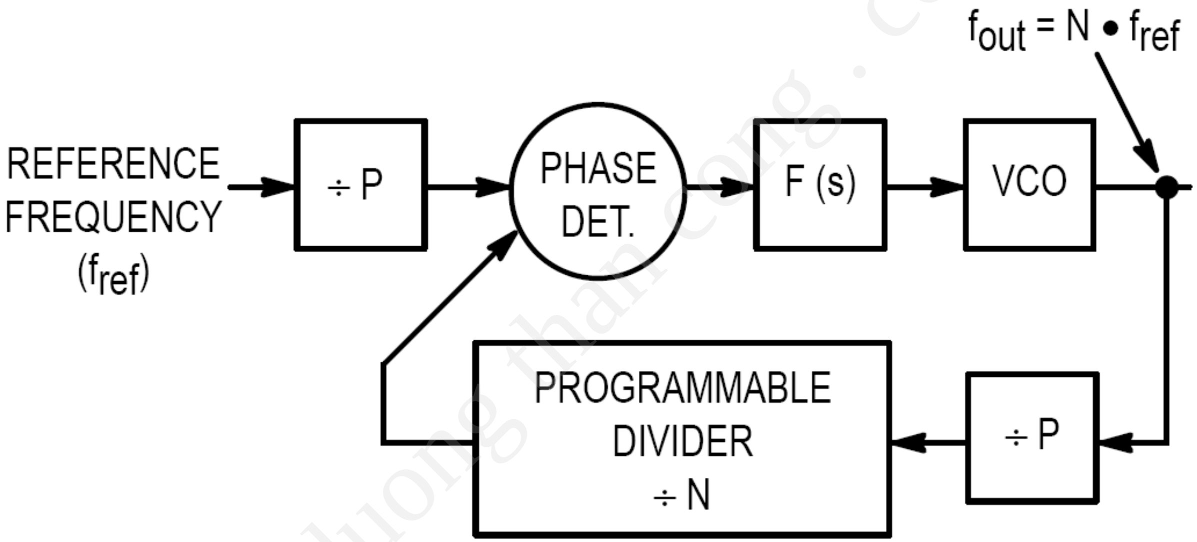
- **Frequency synthesis by Prescaling** (divide by P): using when ouput frequency f_{out} is larger then the maximum clock of the Programmable Divider.



(see additional material)

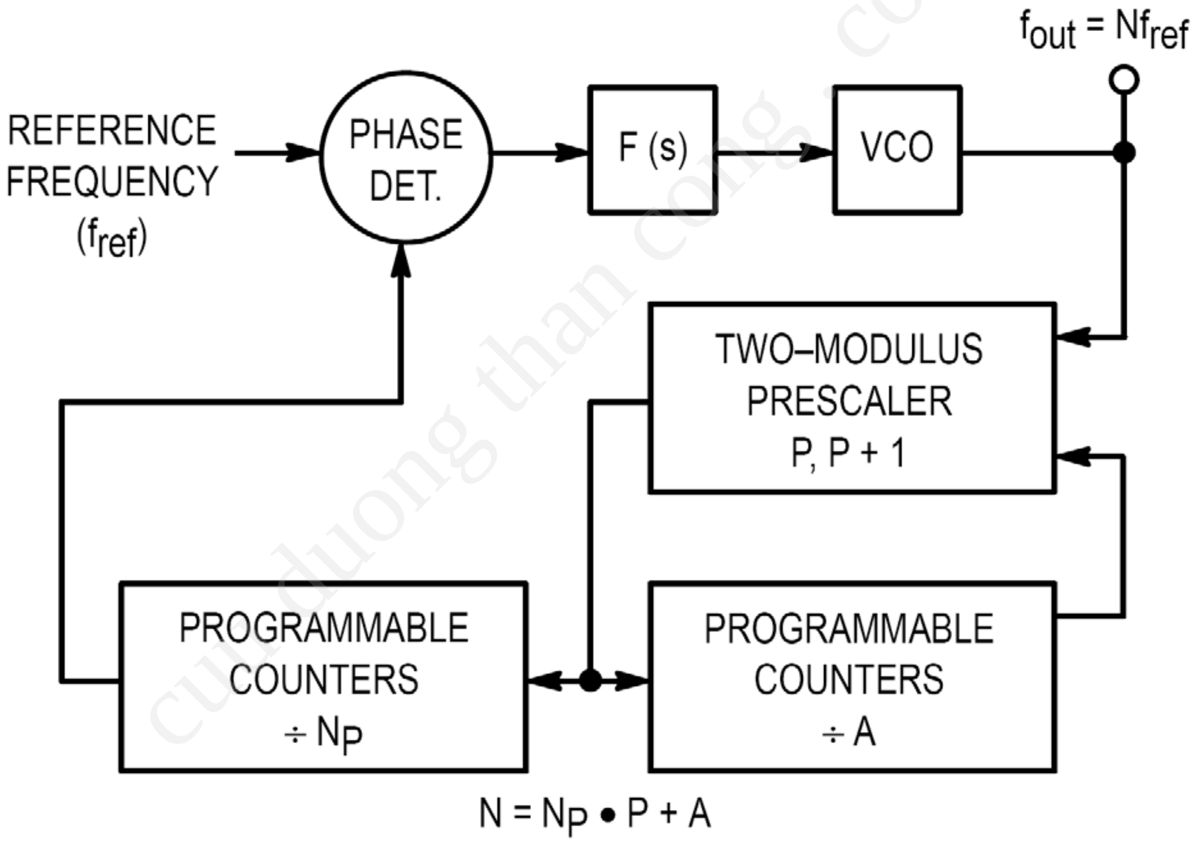
Frequency Synthesizer (8)

or



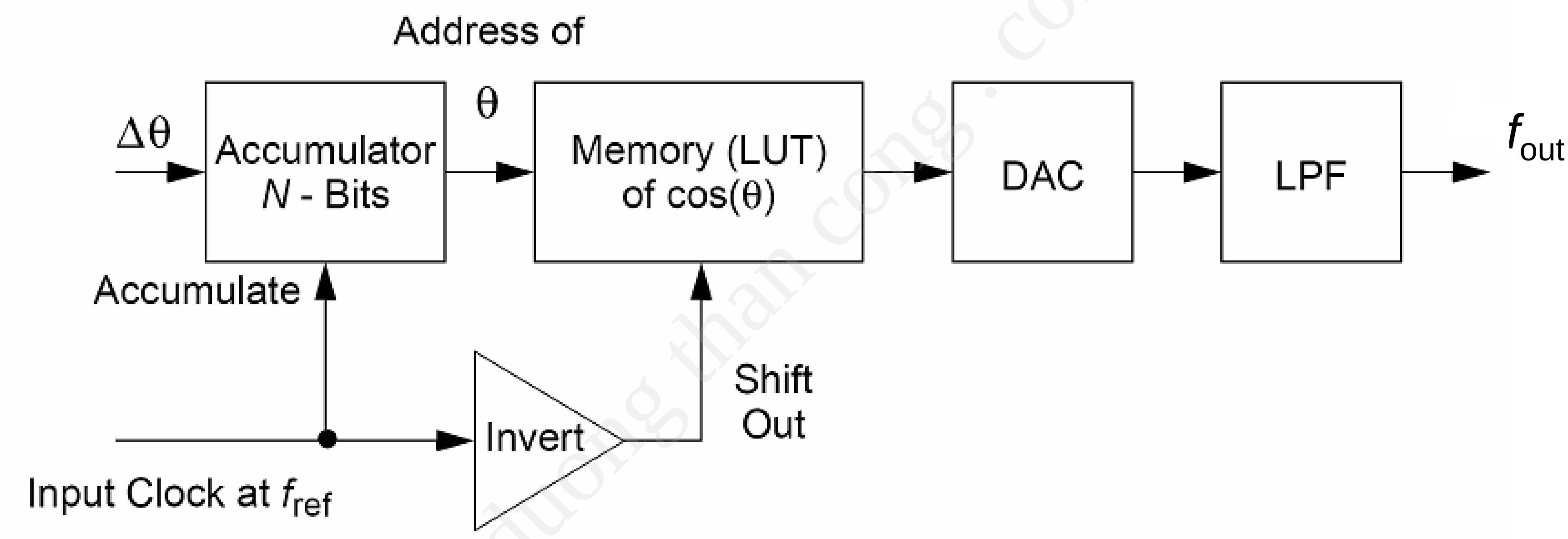
Frequency Synthesizer (9)

- **Frequency synthesis by Two–Modulus Prescaling**: (see additional material)



Frequency Synthesizer (10)

- **<u>Direct Digital Synthesis (DDS):</u>** A <u>digital</u> technique for generating a sine wave from a fixed-frequency clock source:

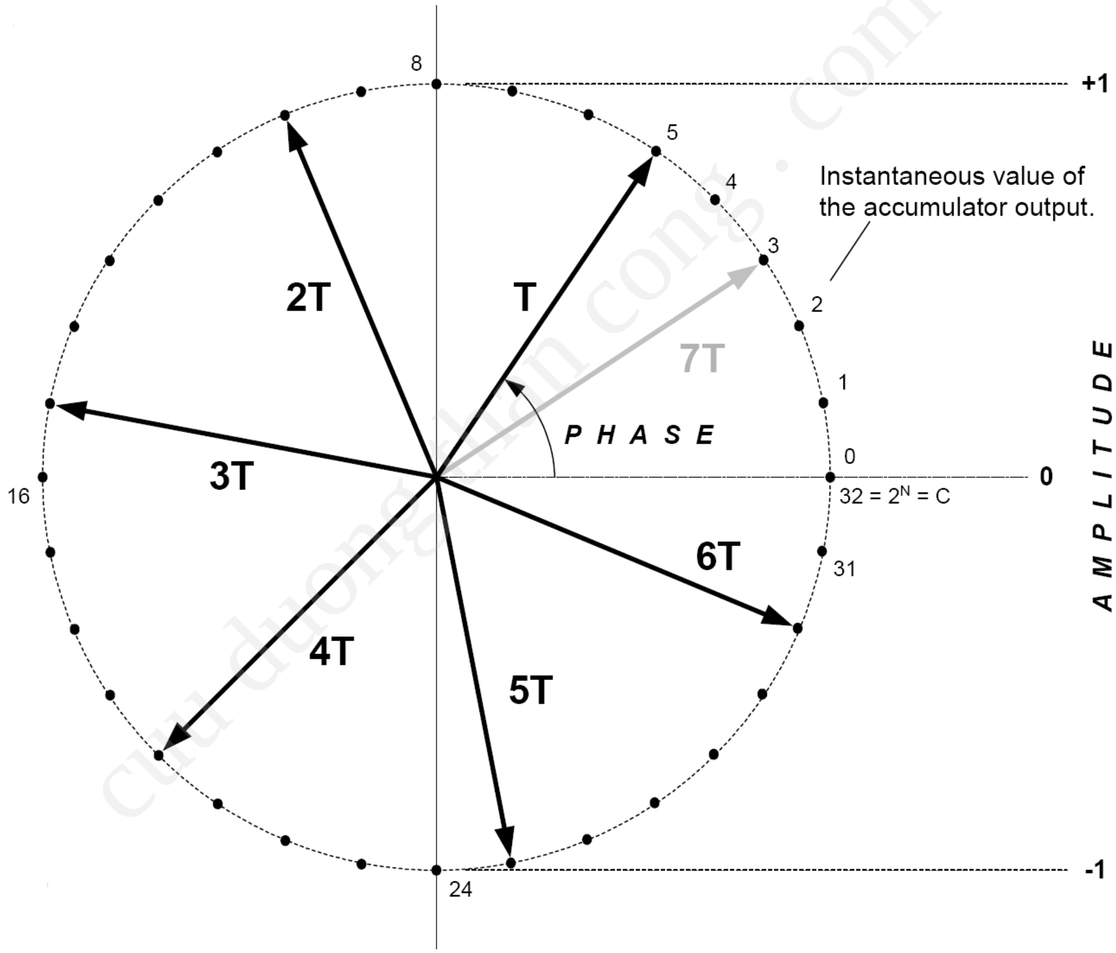


The <u>output frequency</u> is given by: $$f_{\text{out}} = \frac{N_i}{2^N} f_{\text{ref}}$$

where N_i corresponds to the phase step size.

Frequency Synthesizer (11)

The <u>phase wheel</u> concept for DDS:



Frequency Synthesizer (12)

- **<u>Hybrid Methods</u>**: To meet various design goals, combinations of the above method may be employed:
  - Several PLL synthesizers can be combined to create a <u>multi-loop synthesizer</u>.
  - DDS and a PLL can be combined to achieve fine step sizes, yet the wide tuning range of a PLL.

Frequency Synthesizer (13)

Example: Frequency synthesizer with fixed and adjustable outputs.