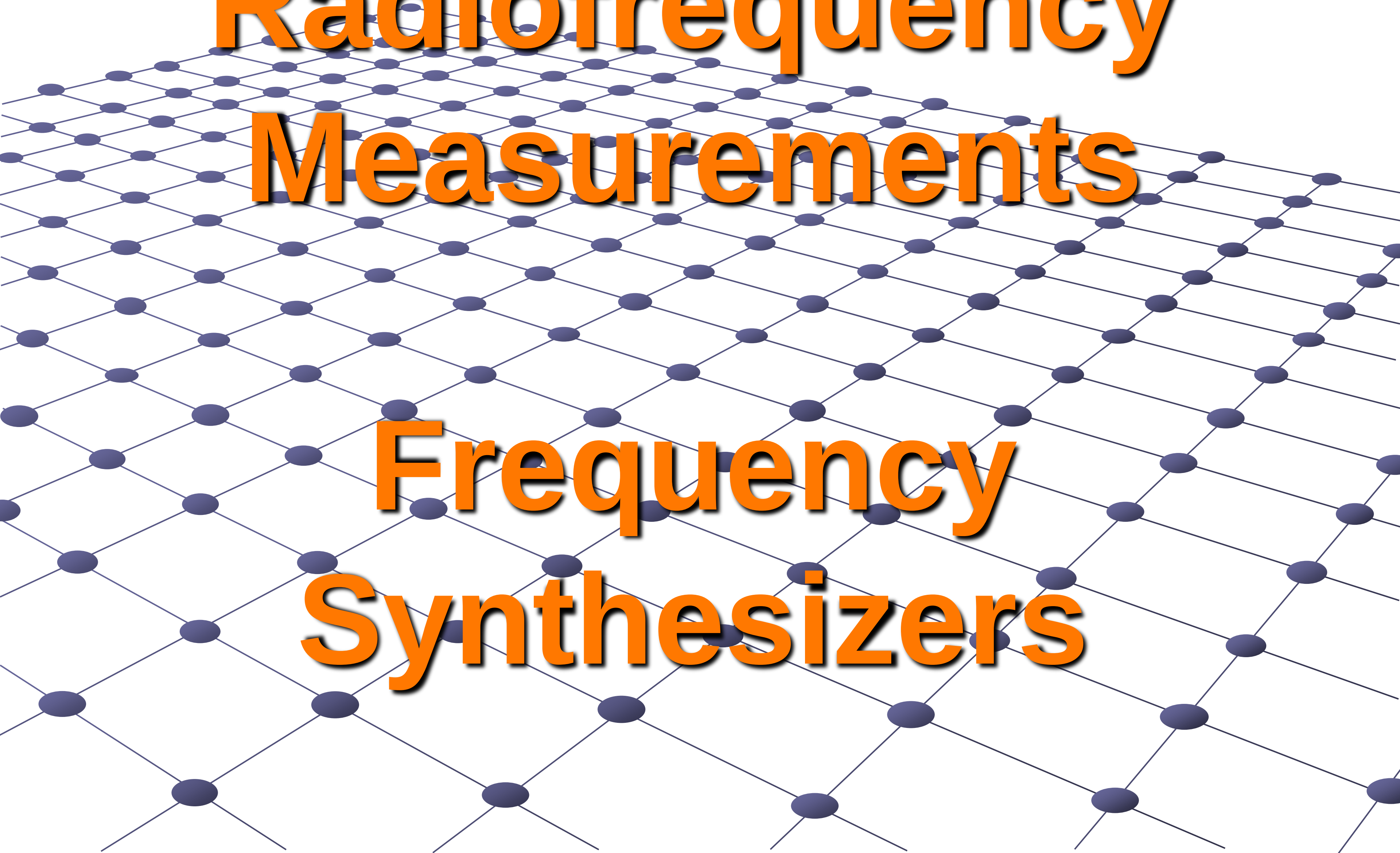
Radiofrequency Measurements

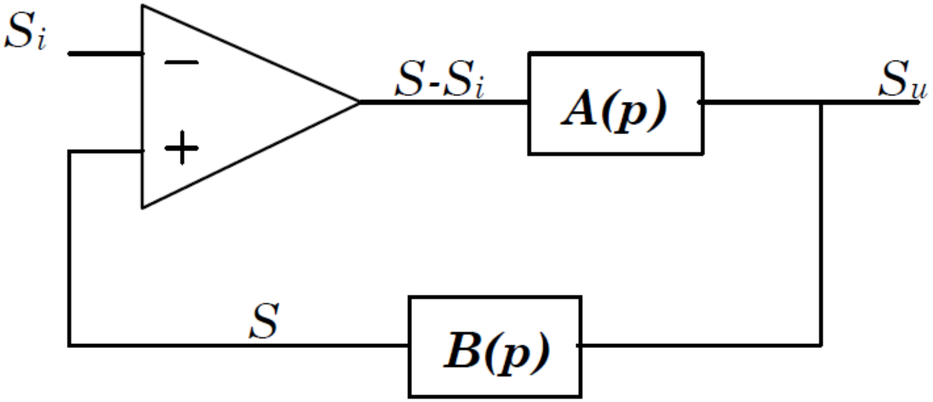
Frequency Synthesizers

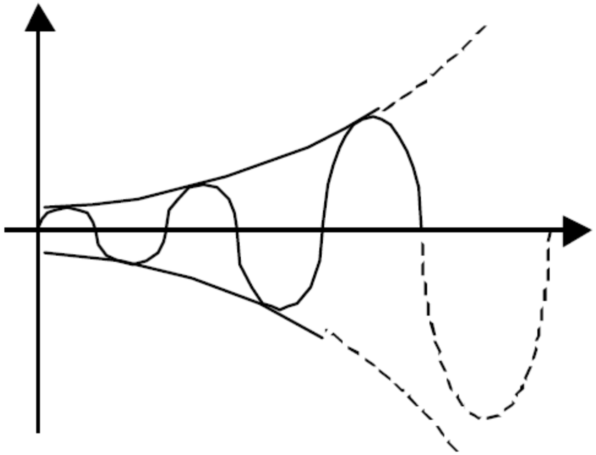


The next slides material is taken from

- AGILENT “**Fundamentals of Quartz Oscillators**”, Application Note 200-2
- AGILENT “**Source Basics**”
- John R. Vig “**Quartz Crystal Resonators and Oscillators For Frequency Control and Timing Applications - A Tutorial**”
- Victor S. Reinhardt “**Frequency and Time Synthesis, A Tutorial**”

Oscillators





Positive feedback

$$A_0 \cdot B(\omega_0) > 1 \quad \Longrightarrow \quad A \cdot B(\omega_0) = 1$$

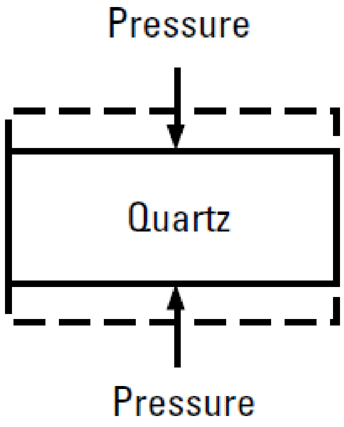
Starting condition

BARKHAUSEN criterion

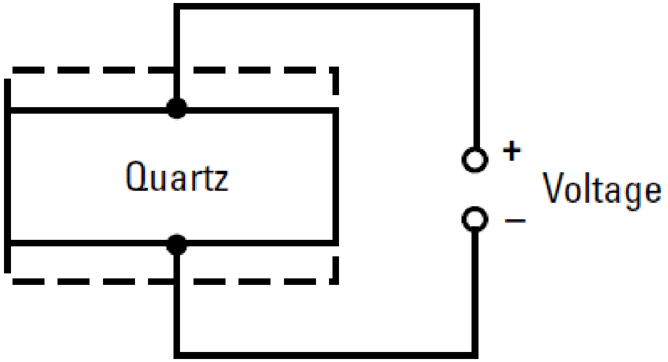
Piezoelectricity

Piezoelectricity is the primary property of a crystal which makes it usable as a resonator. Piezoelectricity is “electric polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it.”

This electric polarization can be produced by strain such as bending, shear, torsion, tension, and compression on a piece of quartz. The electric polarization provides a source of electromotive force (voltage). Additionally, the inverse effect can be created, i.e., a voltage applied across the crystal produces mechanical movement



Applied pressure
generates voltage



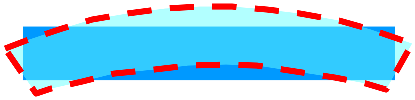
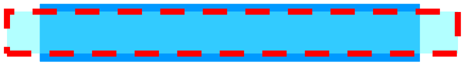
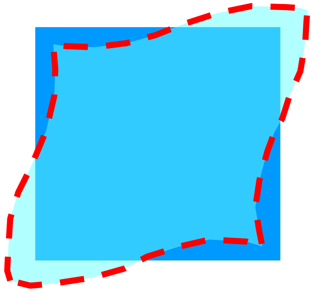
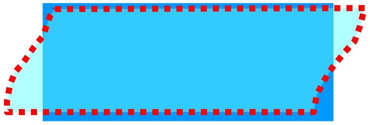
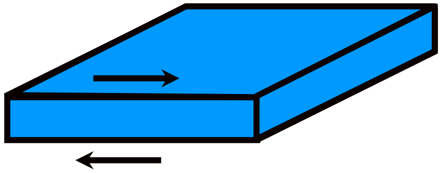
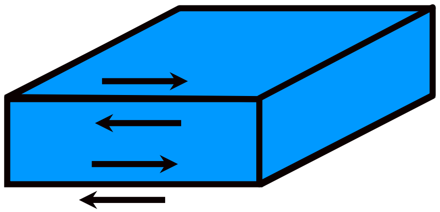
Applied voltage
causes contraction

Why Quartz?

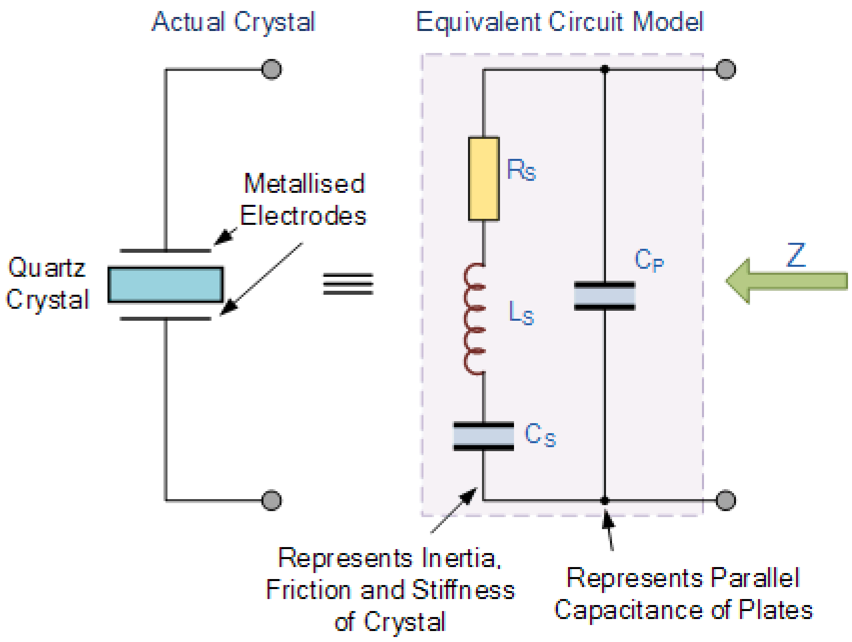
Quartz is the only material known that possesses the following combination of properties:

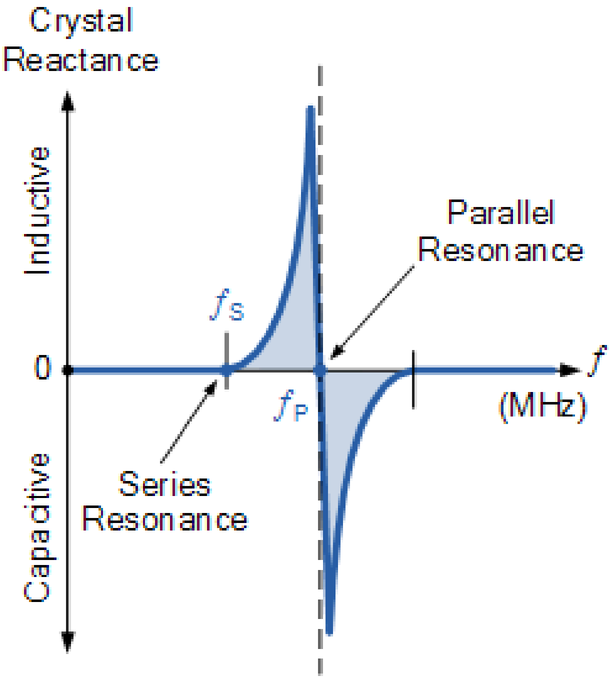
- Piezoelectric ("pressure-electric"; piezein = to press, in Greek)
- Zero temperature coefficient cuts exist
- Stress compensated cut exists
- Low loss (i.e., high Q)
- Easy to process; low solubility in everything, under "normal" conditions, except the fluoride and hot alkali etchants; hard but not brittle
- Abundant in nature; easy to grow in large quantities, at low cost, and with relatively high purity and perfection. Of the man-grown single crystals, quartz, at ~3,000 tons per year, is second only to silicon in quantity grown (3 to 4 times as much Si is grown annually, as of 1997).

Modes of Motion

 Flexure Mode	 Extensional Mode	 Face Shear Mode
 Thickness Shear Mode	 Fundamental Mode Thickness Shear	 Third Overtone Thickness Shear

Crystal Oscillators Model





$$f_S = \frac{1}{2\pi\sqrt{L_S C_S}}$$

$$f_P = \frac{1}{2\pi\sqrt{L_S\left(\frac{C_P C_S}{C_P + C_S}\right)}}$$

Example

A quartz crystal has the following values: Rs = 6.4Ω, Cs = 0.09972pF and Ls = 2.546mH. The capacitance across its terminal, Cp is measured at 28.68pF

The crystals series resonant frequency

$$f_S = \frac{1}{2\pi\sqrt{L_S C_S}} = \frac{1}{2\pi\sqrt{2.546\text{mH} \times 0.09972\text{pF}}}$$

$$f_S = \frac{1}{2\pi\sqrt{0.002546 \times 99.72 \times 10^{-15}}} = 9.987\text{MHz}$$

The crystals parallel resonant frequency,

$$f_P = \frac{1}{2\pi\sqrt{L_S\left(\frac{C_P C_S}{C_P + C_S}\right)}}$$

$$f_P = \frac{1}{2\pi\sqrt{2.546\text{mH}\left(\frac{28.68\text{pF} \times 0.09972\text{pF}}{28.68\text{pF} + 0.09972\text{pF}}\right)}}$$

$$f_P = 10{,}004{,}996\text{Hz or } 10.005\text{MHz}$$

We can see that the difference between ƒs, the crystals fundamental frequency and ƒp is small at about 18kHz (10.005MHz – 9.987MHz). However during this frequency range, the Q-factor (Quality Factor) of the crystal is extremely high because the inductance of the crystal is much higher than its capacitive or resistive values. The Q-factor of our crystal at the series resonance frequency is given as:

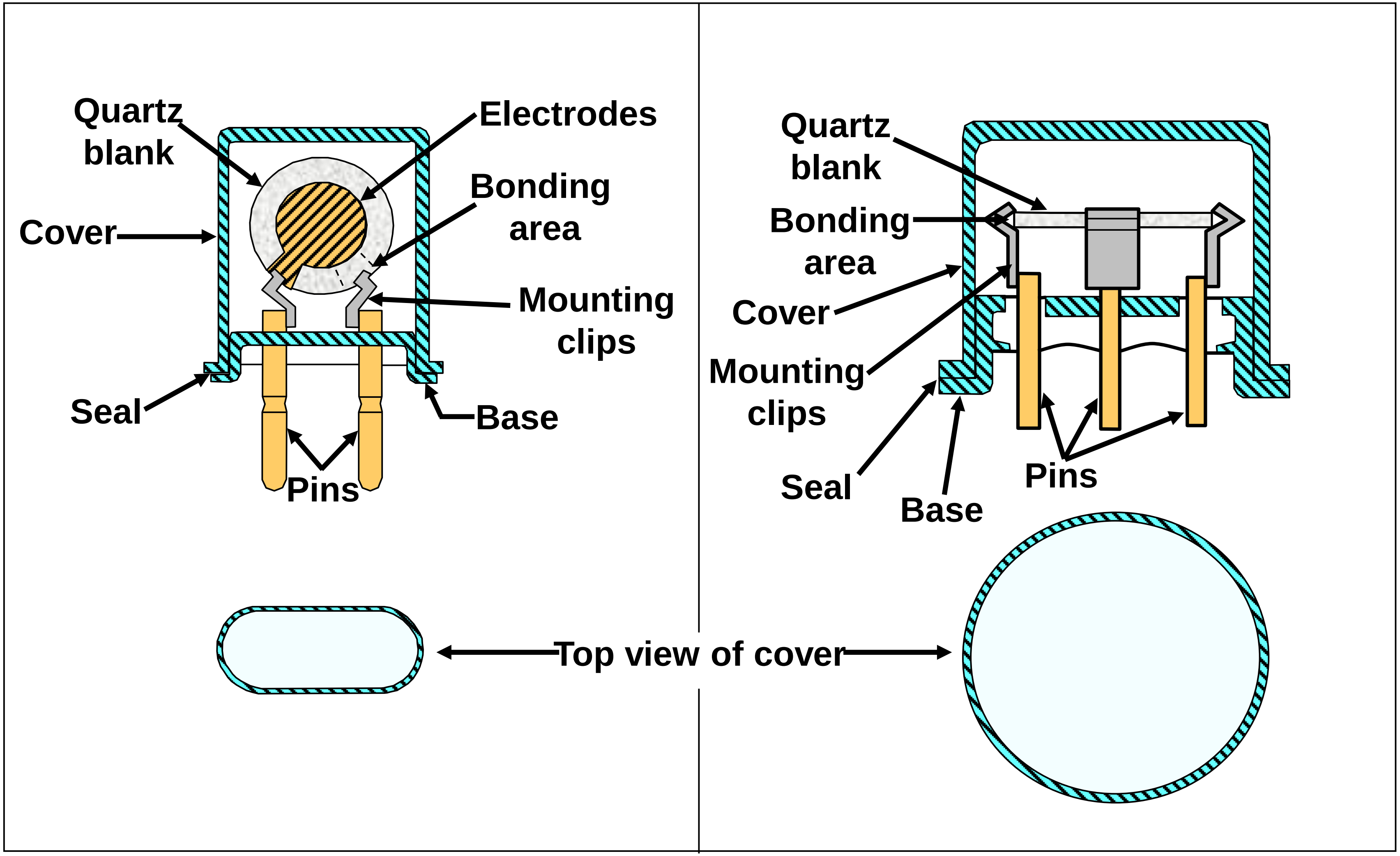
Crystal Oscillators Q-factor

$$Q = \frac{X_L}{R} = \frac{2\pi f L}{R} = \frac{2\pi \times 9.987 \times 10^{6} \times 0.002546}{6.4}$$

$$Q = 24966 \text{ or } 25{,}000$$

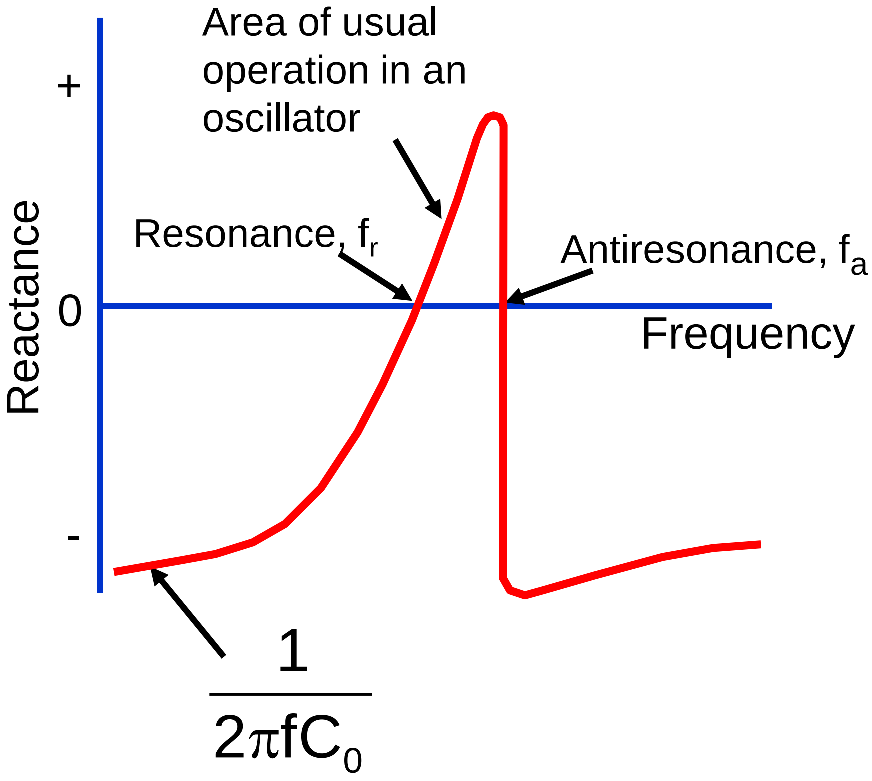
Resonator Packaging

Two-point Mount Package **Three- and Four-point Mount Package**

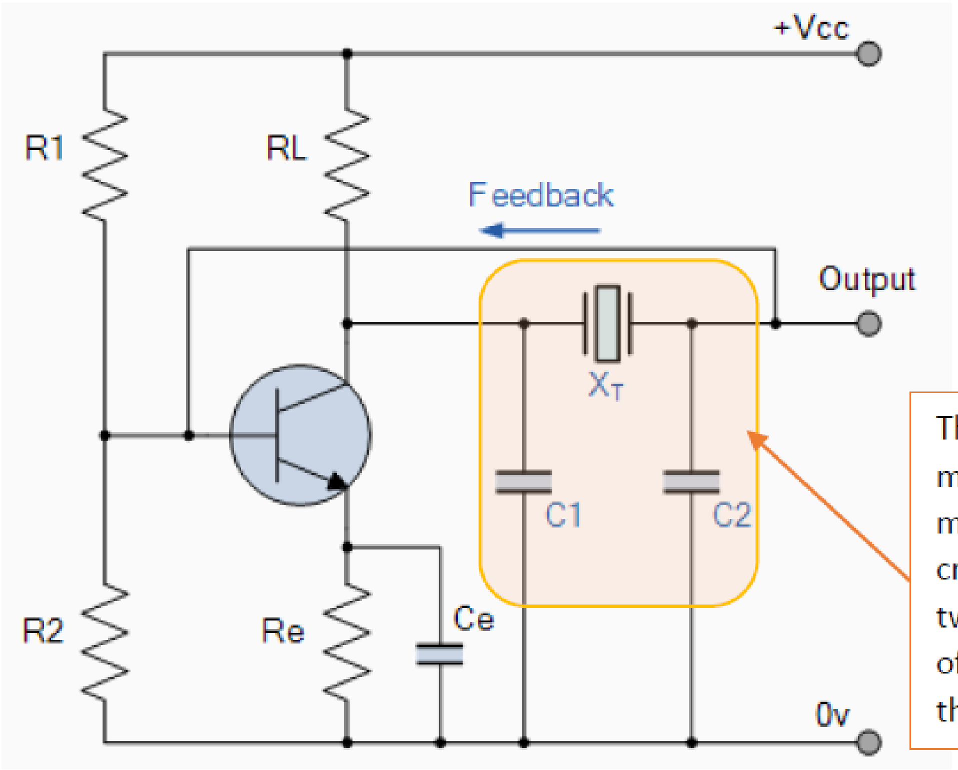


Resonator Reactance vs. Frequency

In the oscillator, it works as an INDUCTOR



Oscillator Example



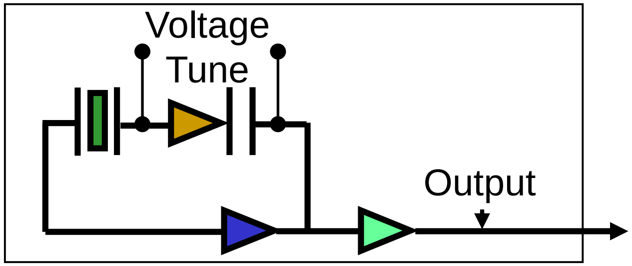
This is the circuitry that must be attached to the microcontroller: a crystal resonator and two capacitors. The rest of the circuit is inside the microcontroller.

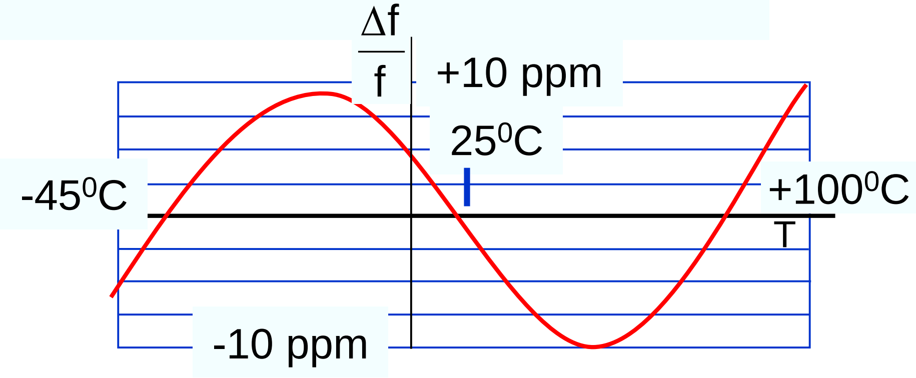
Crystal Oscillator Categories

The three categories, based on the method of dealing with the crystal unit's frequency vs. temperature (f vs. T) characteristic, are:

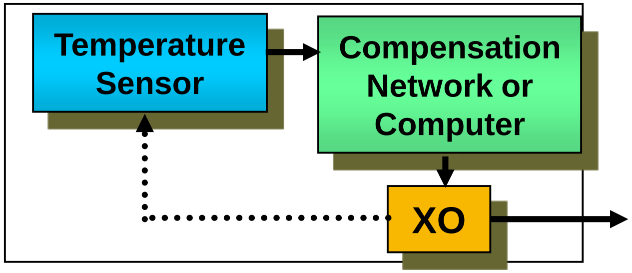
- **XO, crystal oscillator,** does not contain means for reducing the crystal's f vs. T characteristic (also called PXO-packaged crystal oscillator).
- **TCXO, temperature compensated crystal oscillator,** in which, e.g., the output signal from a temperature sensor (e.g., a thermistor) is used to generate a correction voltage that is applied to a variable reactance (e.g., a varactor) in the crystal network. The reactance variations compensate for the crystal's f vs. T characteristic. Analog TCXO's can provide about a 20X improvement over the crystal's f vs. T variation.
- **OCXO, oven controlled crystal oscillator,** in which the crystal and other temperature sensitive components are in a stable oven which is adjusted to the temperature where the crystal's f vs. T has zero slope. OCXO's can provide a >1000X improvement over the crystal's f vs. T variation.

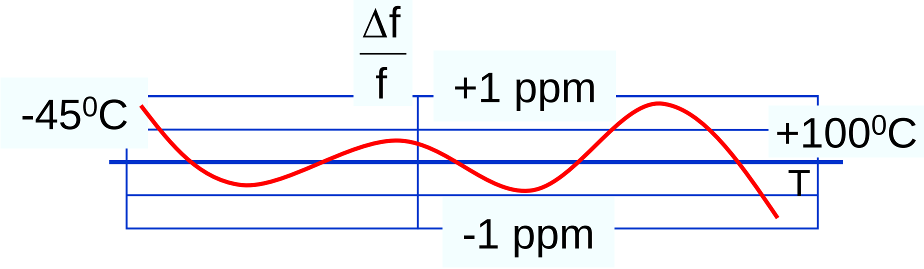
Crystal Oscillator Categories



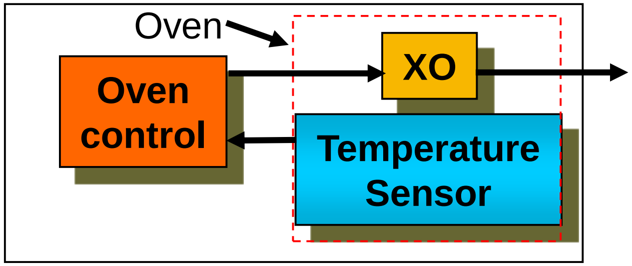


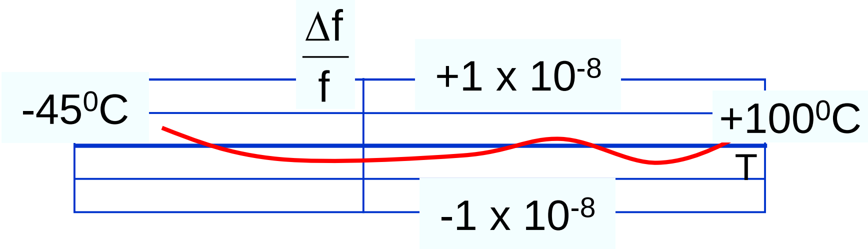
- Crystal Oscillator (XO)





- Temperature Compensated (TCXO)





- Oven Controlled (OCXO)

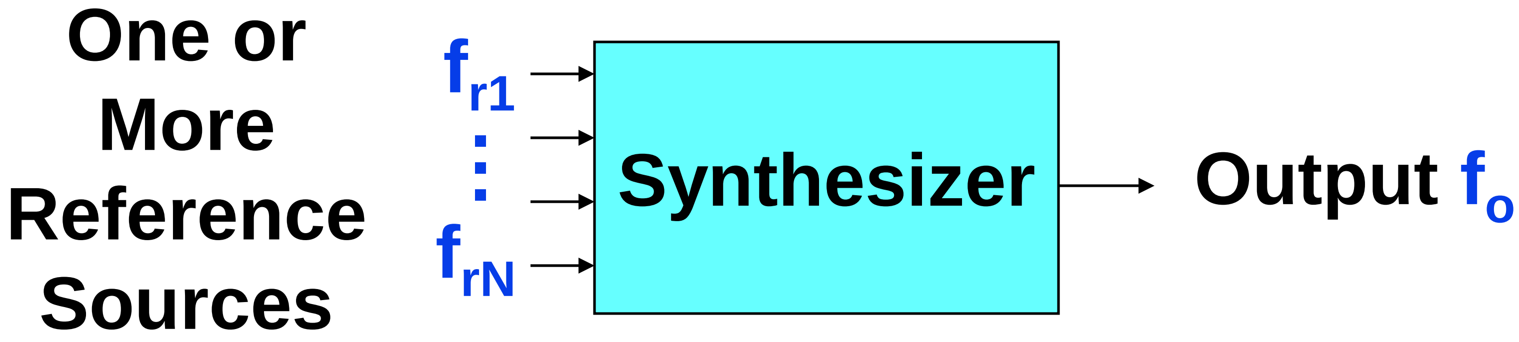
Hierarchy of Oscillators

Oscillator Type*	Accuracy**	Typical Applications
● Crystal oscillator (XO)	10^{-5} to 10^{-4}	Computer timing
● Temperature compensated crystal oscillator (TCXO)	10^{-6}	Frequency control in tactical radios
● Microcomputer compensated crystal oscillator (MCXO)	10^{-8} to 10^{-7}	Spread spectrum system clock
● Oven controlled crystal oscillator (OCXO)	10^{-8} (with 10^{-10} per g option)	Navigation system clock & frequency standard, MTI radar
● Small atomic frequency standard (Rb, RbXO)	10^{-9}	C^3 satellite terminals, bistatic, & multistatic radar
● High performance atomic standard (Cs)	10^{-12} to 10^{-11}	Strategic C^3, EW

* Sizes range from <1cm^3 for clock oscillators to > 30 liters for Cs standards
Costs range from <$1 for clock oscillators to > $50,000 for Cs standards.

** Including environmental effects (e.g., -40°C to +75°C) and one year of aging.

Frequency Synthesizers



One or More Reference Sources

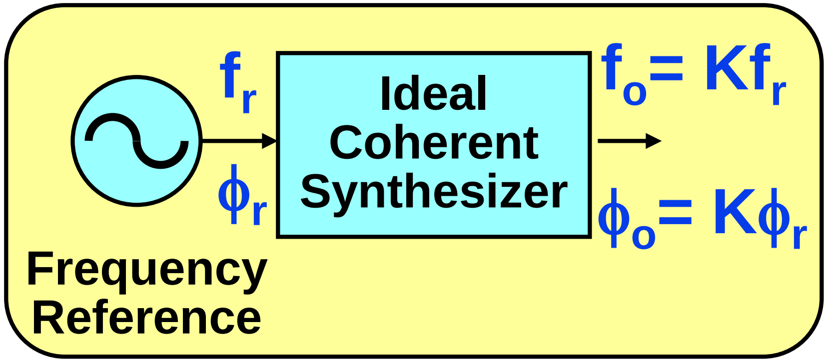
f_{r1} : f_{rN}

Synthesizer

Output f_o

- One or More Input Reference Sources $f_{r1} \ldots f_{rn}$
- Translation to New Frequency f_o
- Phase or Frequency Coherent With References
- Basic Properties
  - Frequency Range
  - Frequency Resolution
  - Switching Rate/Settling Time
  - DC Power, Weight, Cost, etc.
  - Phase/Frequency Stability (Time Domain, Environmental Effects)
  - Spectral Purity (Frequency Domain, Spurs, Noise)

Ideal Coherent Synthesizer



f_r ϕ_r

Ideal Coherent Synthesizer

$f_o = Kf_r$

$\phi_o = K\phi_r$

Frequency Reference

$$y_o = \frac{\delta\omega_o}{\omega_o} = \frac{K\delta\omega_r}{K\omega_r} = \frac{\delta\omega_r}{\omega_r} = y_r$$

$$x_o = \frac{\phi_o}{\omega_o} = \frac{K\phi_r}{K\omega_r} = \frac{\phi_r}{\omega_r} = x_r$$

- **Coherent Frequency Translation by Factor K**
  - **Multiplies the Input Frequency f_r by a Factor K**
  - **Ideal: Doesn’t Add Noise**
- **Input Phase Error ϕ_r Also Multiplied by K**
  - **The Phase Error Integral of the Angular Frequency Error**
- **The y and x of a Reference Oscillator are *Independent of* the *Final* Output *Frequency***

Frequency Synthesizers

Main techniques:

- **Direct Synthesis:**

it uses the 4 operations (+ - x /) on frequency

- **Indirect Synthesis:**

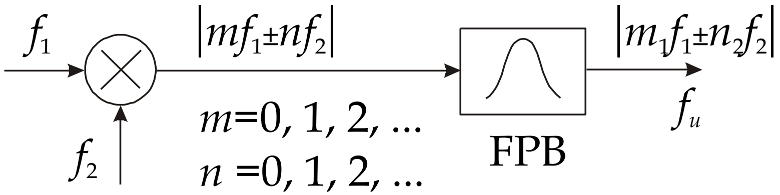
A VCO generates a wave locked in phase to a reference oscillator

- **Digital Synthesis**

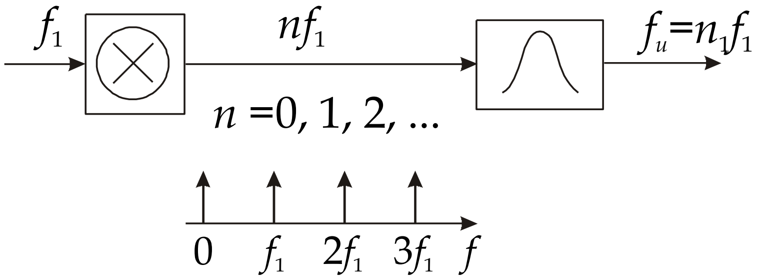
It is based on a DAC, referred to a clock

Direct Synthesis: operations

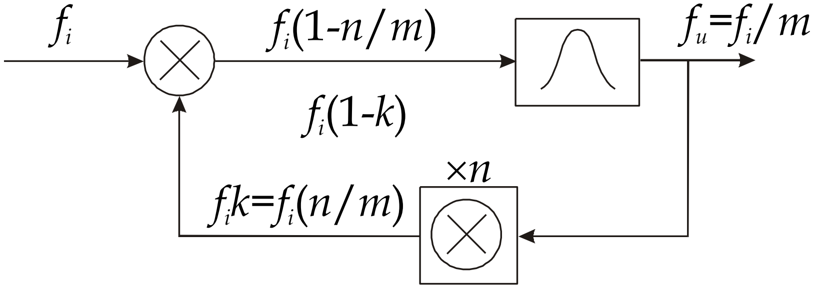
SUM and SUBTRACTION (mixers)



MULTIPLICATION (harmonic generation)

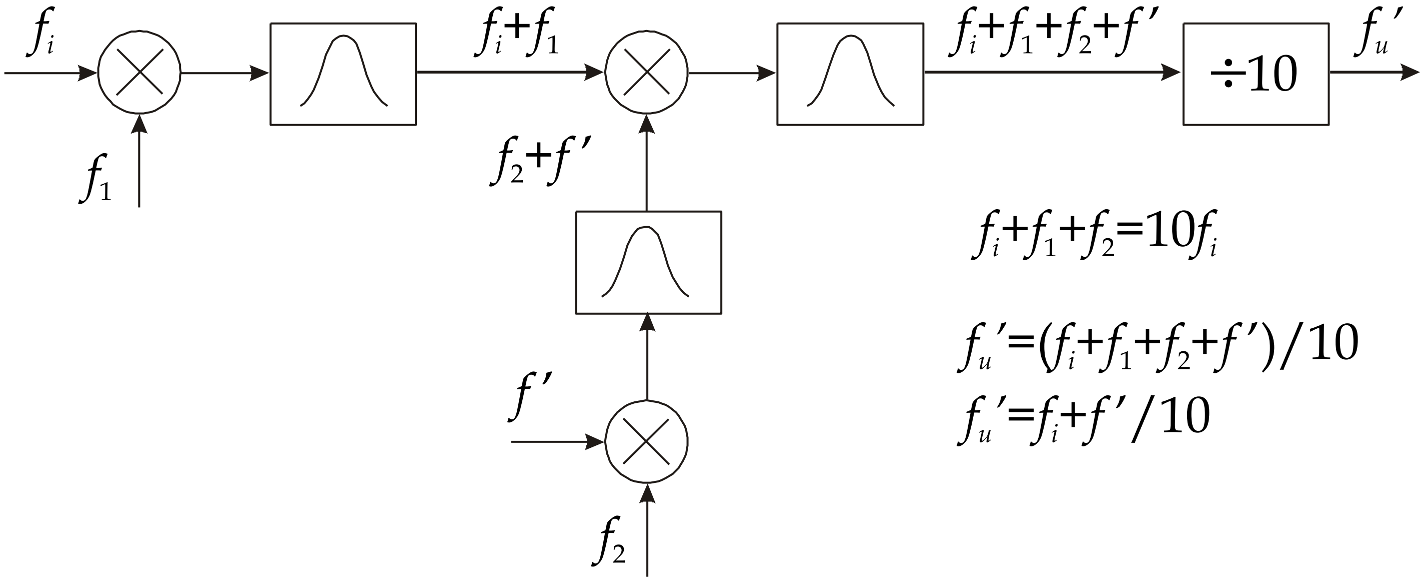


DIVISION (Miller divider or counters)



$f_i(1-n/m)=f_i/m$ se $m-n=1$ $k=n/m<1$

Direct Synthesis: scheme



$$f_i+f_1+f_2=10f_i$$

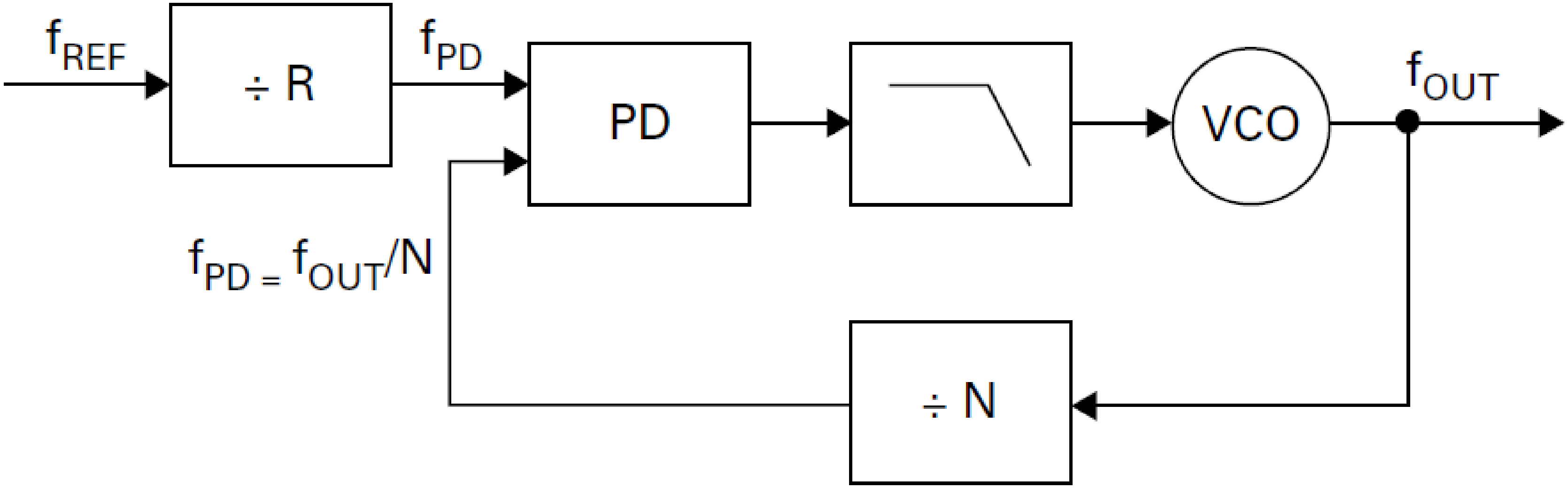
$$f_u'=(f_i+f_1+f_2+f')/10$$

$$f_u'=f_i+f'/10$$

It requires a number of mixers, filters and switches, but the realized output shows almost the same spectral purity of the reference oscillator

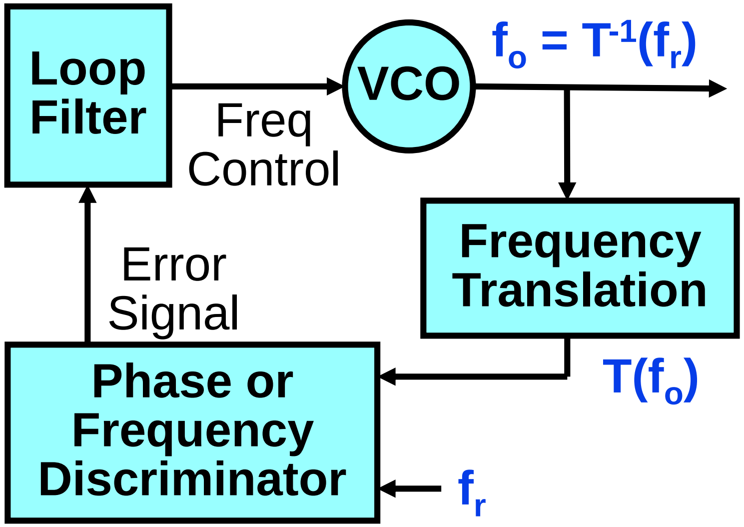
Indirect Synthesis

A Voltage-Controlled-Oscillator (VCO) is locked to a reference oscillator by a Phase-Locked-Loop (PLL)



$$f_{OUT} = \frac{N}{R} f_{REF}$$

Indirect Synthesis



Loop Filter

Freq Control

VCO

$f_o = T^{-1}(f_r)$

Frequency Translation

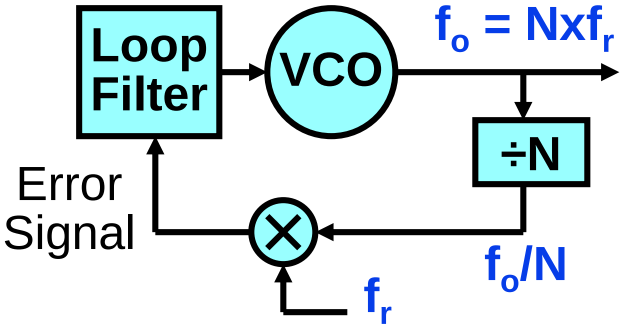
$T(f_o)$

Error Signal

Phase or Frequency Discriminator

f_r

Indirect Synthesis



Loop Filter

VCO

$f_o = N\text{x}f_r$

÷N

Error Signal

f_o/N

f_r

Example: Divider Loop

- **Utilizes Phase or Frequency Locked VCO to Act as:**
- **Operation Inverter**
  - **VCO Output f_o Goes Through Frequency Translation $T(f_o)$**
  - **Phase or Frequency Discriminator Compares f_r to $T(f_o)$ and Generates Error Signal**
  - **Through Loop Filter and VCO Frequency Control, Error Signal Driven to Zero so**

    $$f_r = T(f_o)$$

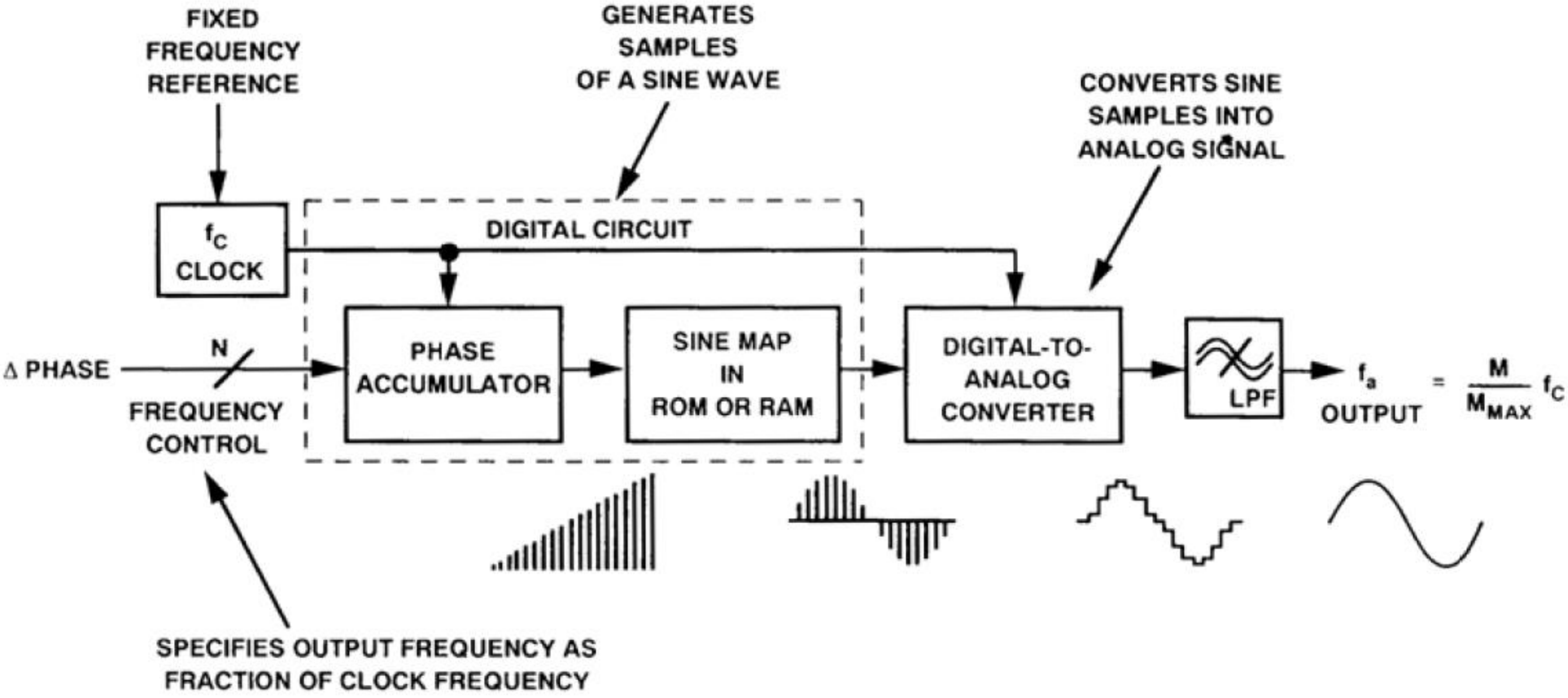
  - **Thus VCO Output is Inverse of T**

    $$f_o = T^{-1}(f_r)$$

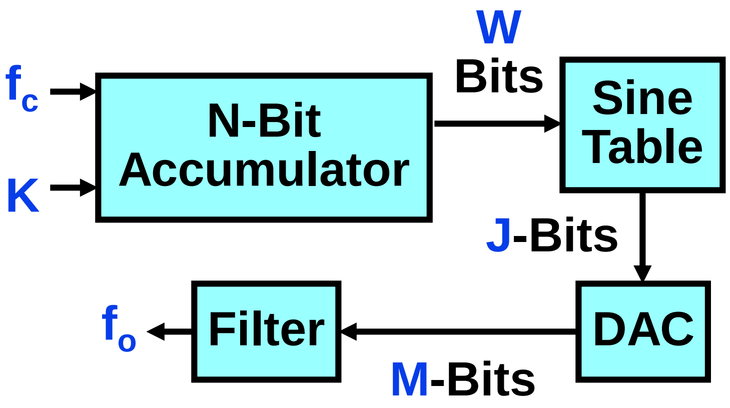
- **Tracking Filter**
  - **Uses Bandwidth Properties of Loop to Filter Reference Signal**

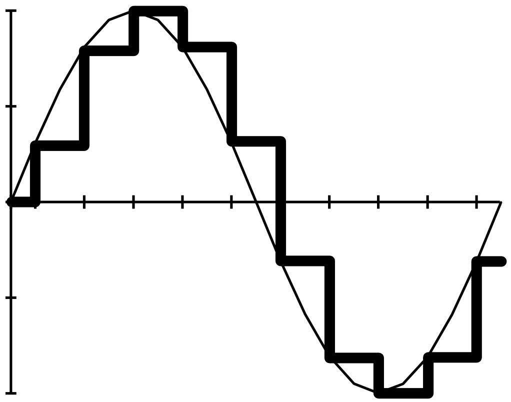
Direct Digital Synthesizers

- **DDSs also called Numerically Controlled Oscillators**
- **Directly Synthesize a Selectable Output Frequency from a Clock Using Digital Techniques**



Sine Output DDS

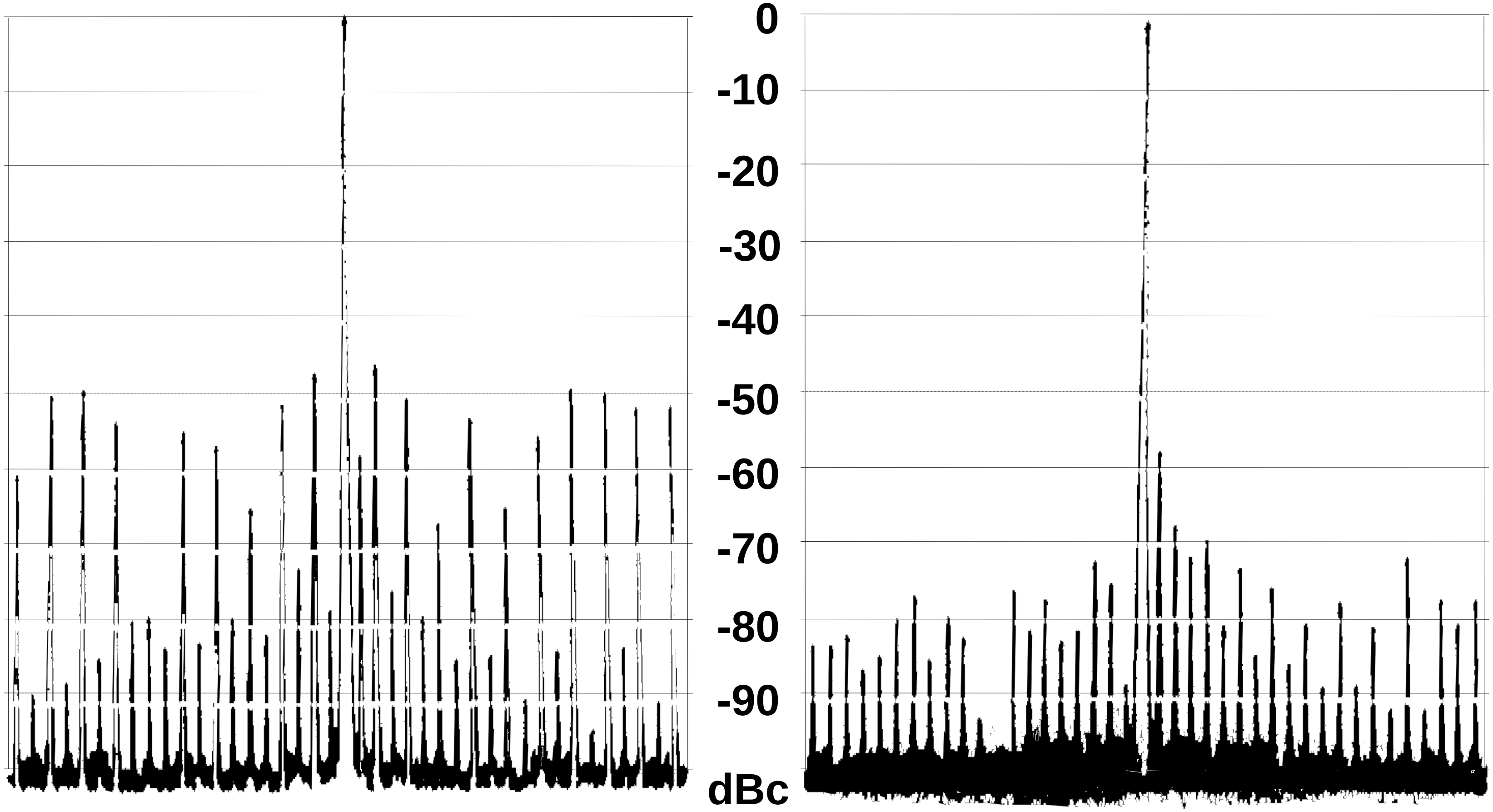




Stepped DDS Output

- **Reduces Spurs by Adding Sine Table and DAC**
  - **N Determines Frequency Resolution**
  - **Argument of Sine Table = W Bits out of N Bit Accumulator**
  - **Sine Table Value = J Bits**
  - **DAC M Bits**
- **Nyquist Theorem: No (In-Band) Spurs if**
  - **Sine Table and DAC Perfect**
  - **$f_o < 0.5 f_c$ (Must LP Filter Output)**
- **Spur Levels**
  - **6 dBc per bit for W & J**
  - **6-8 dBc per bit for M (Use Effective Number of Bits not Actual Bits)**
  - **Worst Case Determines Spurs**

Typical Sine Output DDS Frequency Spectrums

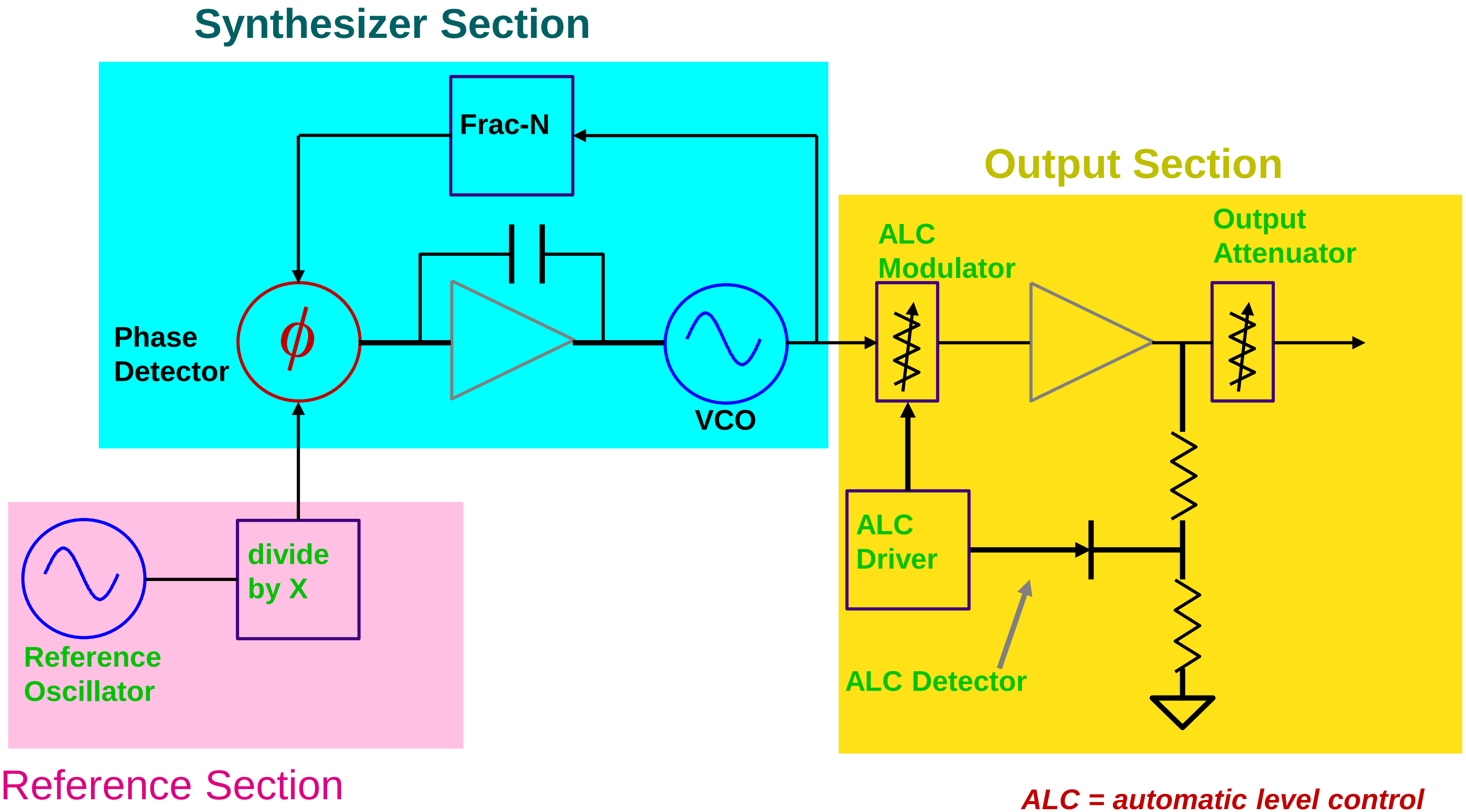


5-Bit DAC

11-Bit DAC

f_o=333.25 kHz f_c=1 MHz Span=10 kHz   RBW=10 Hz

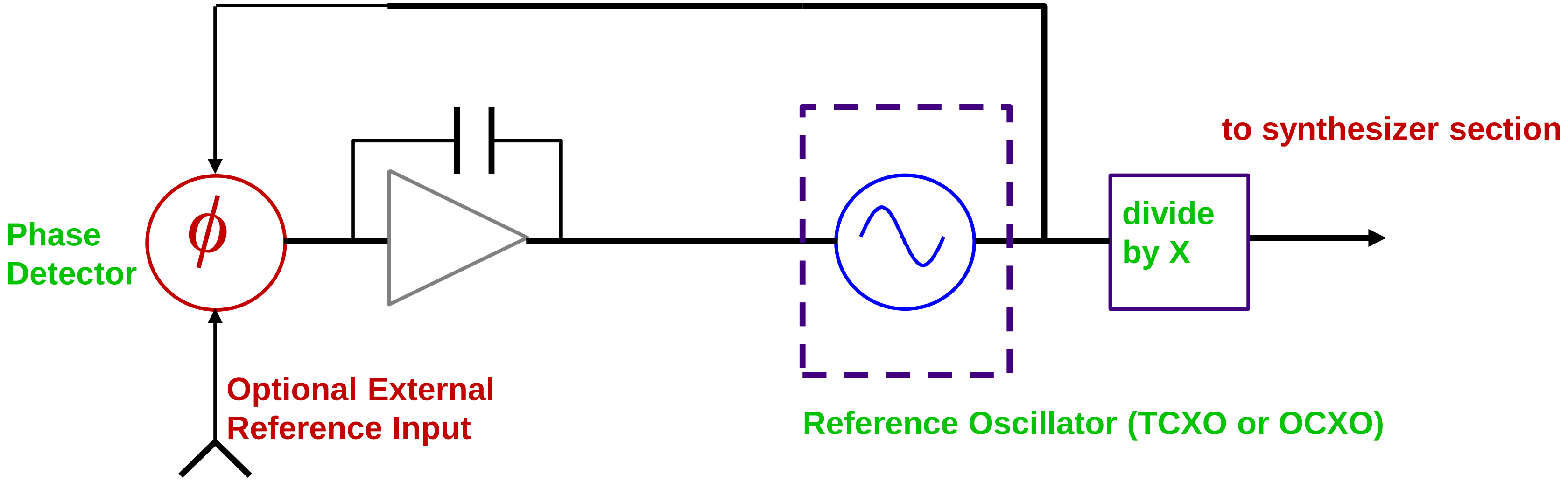
RF CW Block Diagram



ALC = automatic level control

RF CW Block Diagram

Reference Section



Phase Detector

to synthesizer section

divide by X

Optional External Reference Input

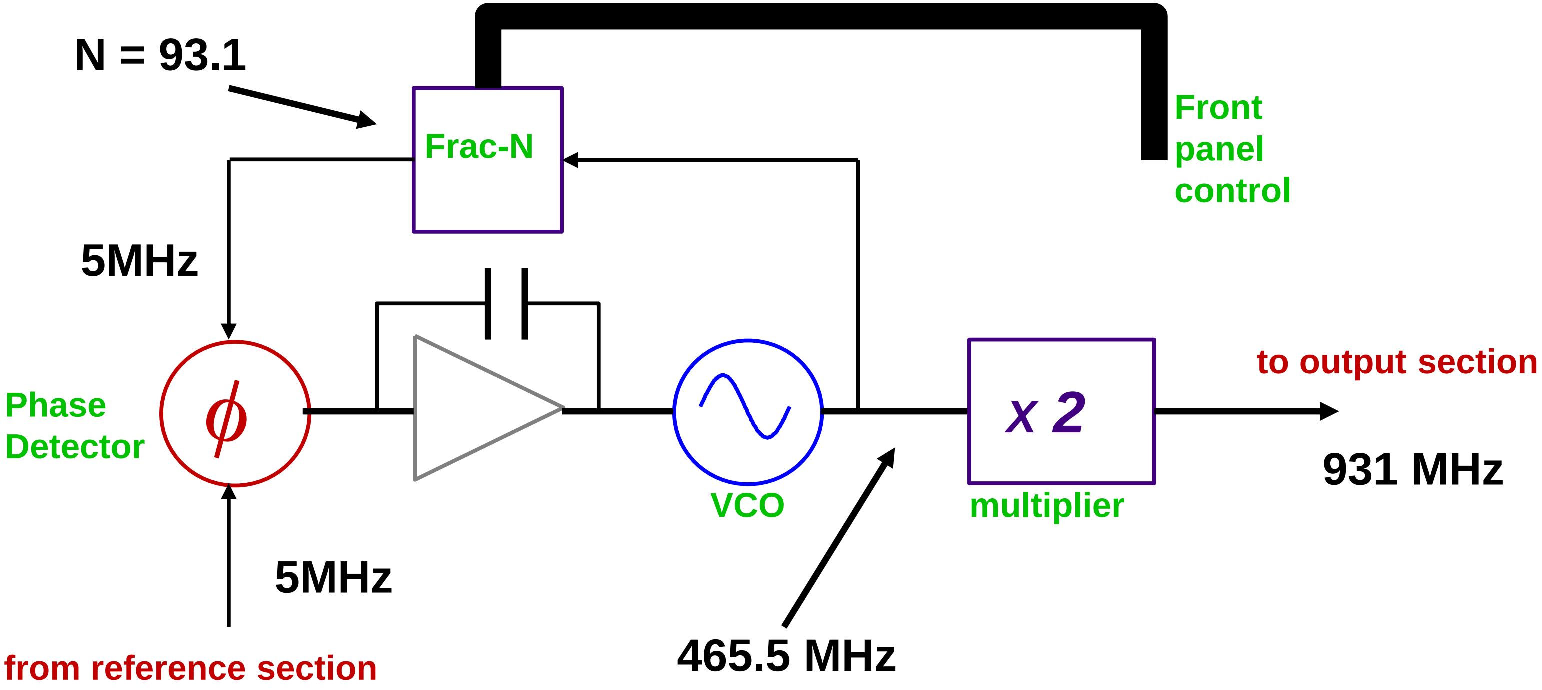
Reference Oscillator (TCXO or OCXO)

	TCXO	**OCXO**
Aging Rate	+/- 2ppm/year	+/- 0.1 ppm /year
Temp.	+/- 1ppm	+/- 0.01 ppm
Line Voltage	+/- 0.5ppm	+/- 0.001 ppm

RF CW Block Diagram

Synthesizer Section

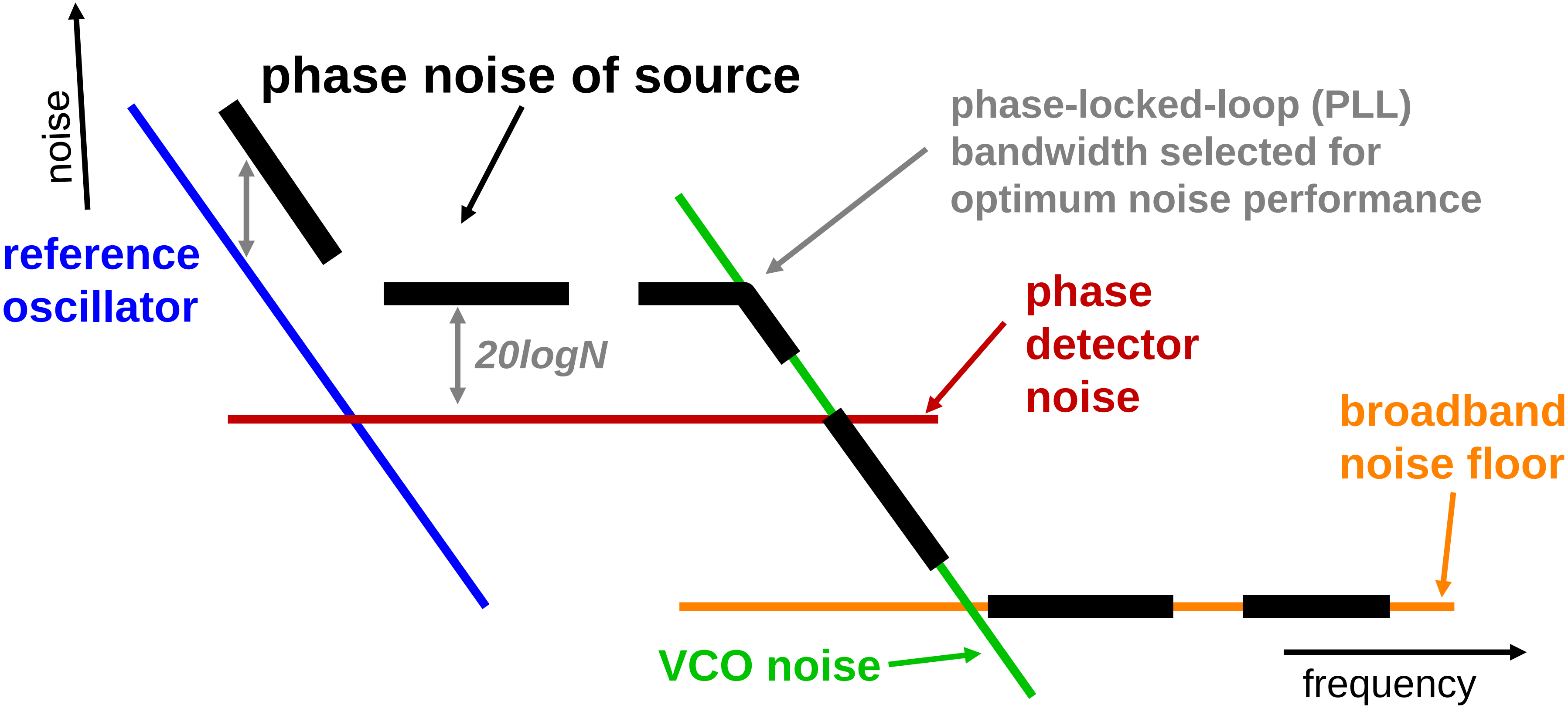
...produces accurate, clean signals



RF CW Block Diagram

Synthesizer Section

PLL / Fractional - N
...suppresses phase noise



noise

phase noise of source

phase-locked-loop (PLL) bandwidth selected for optimum noise performance

reference oscillator

20logN

phase detector noise

broadband noise floor

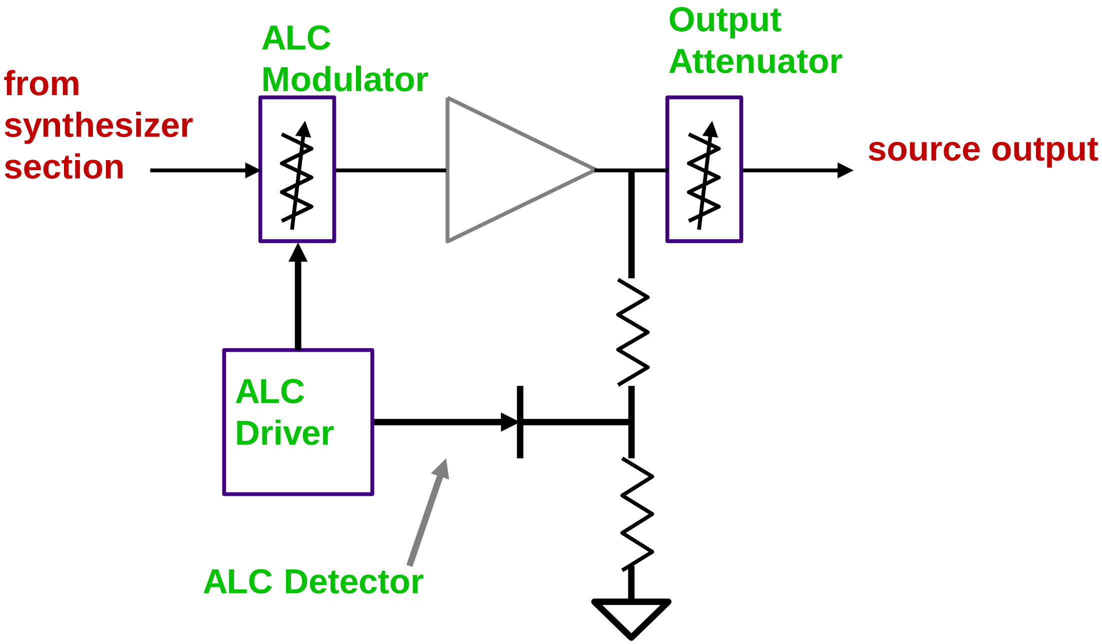
VCO noise

frequency

RF CW Block Diagram

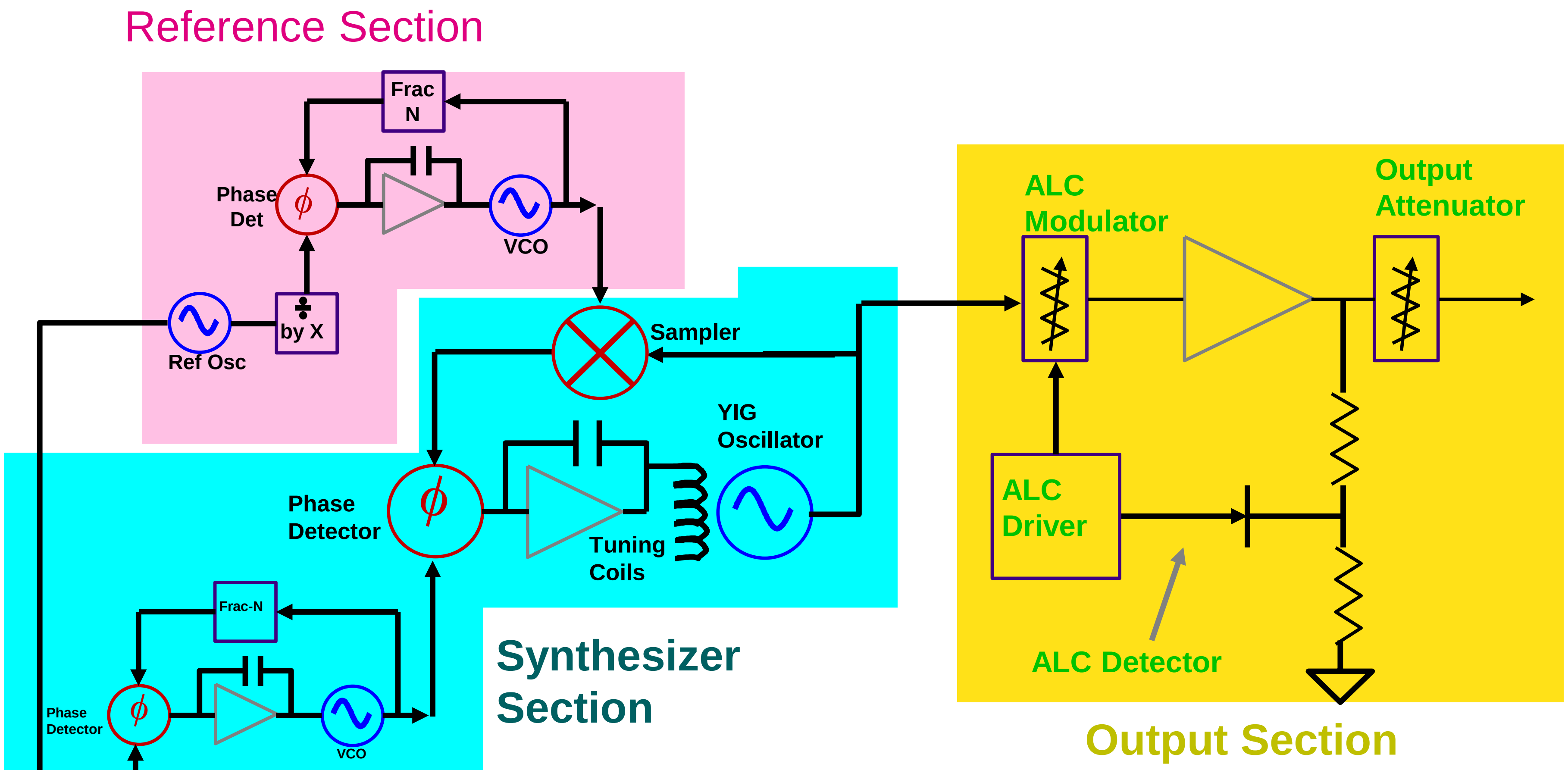
Output Section

- ALC
  - maintains output power by adding/subtracting power as needed
- Output Attenuator
  - mechanical or electronic
  - provides attentuation to achieve wide output range (e.g. -136dBm to +13dBm)



ALC = automatic level control

μWave CW Block Diagram



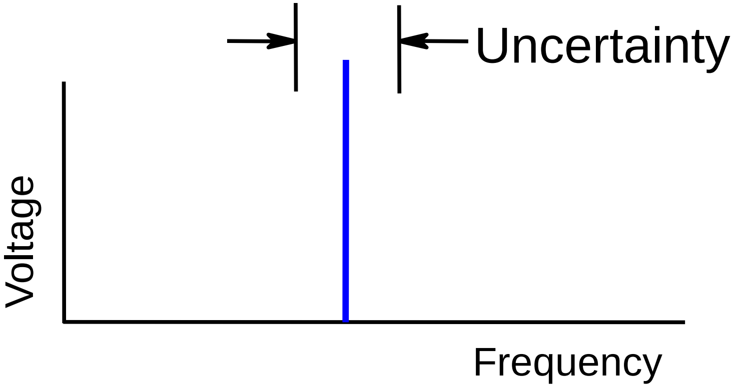
CW Source Specifications

...Frequency

- Range: Range of frequencies covered by the source
- Resolution: Smallest frequency increment.
- Accuracy: How accurately can the source frequency be set.

EXAMPLE

Accuracy = $\pm f_{CW} * \tau_{aging} * \tau_{cal}$



f_{CW} = CW frequency = 1 GHz

τ_{aging} = aging rate = 0.152 ppm/year

τ_{cal} = time since last calibrated = 1 year

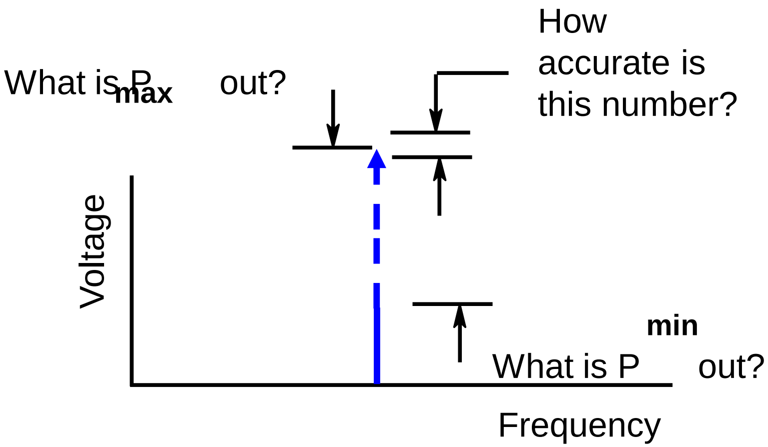
⇒ Accuracy = $\pm$ 152 Hz

CW Source Specifications

...Amplitude

- Range (-136dBm to +13dBm)
- Accuracy (+/- 0.5dB)
- Resolution (0.02dB)
- Switching Speed (25ms)
- Reverse Power Protection

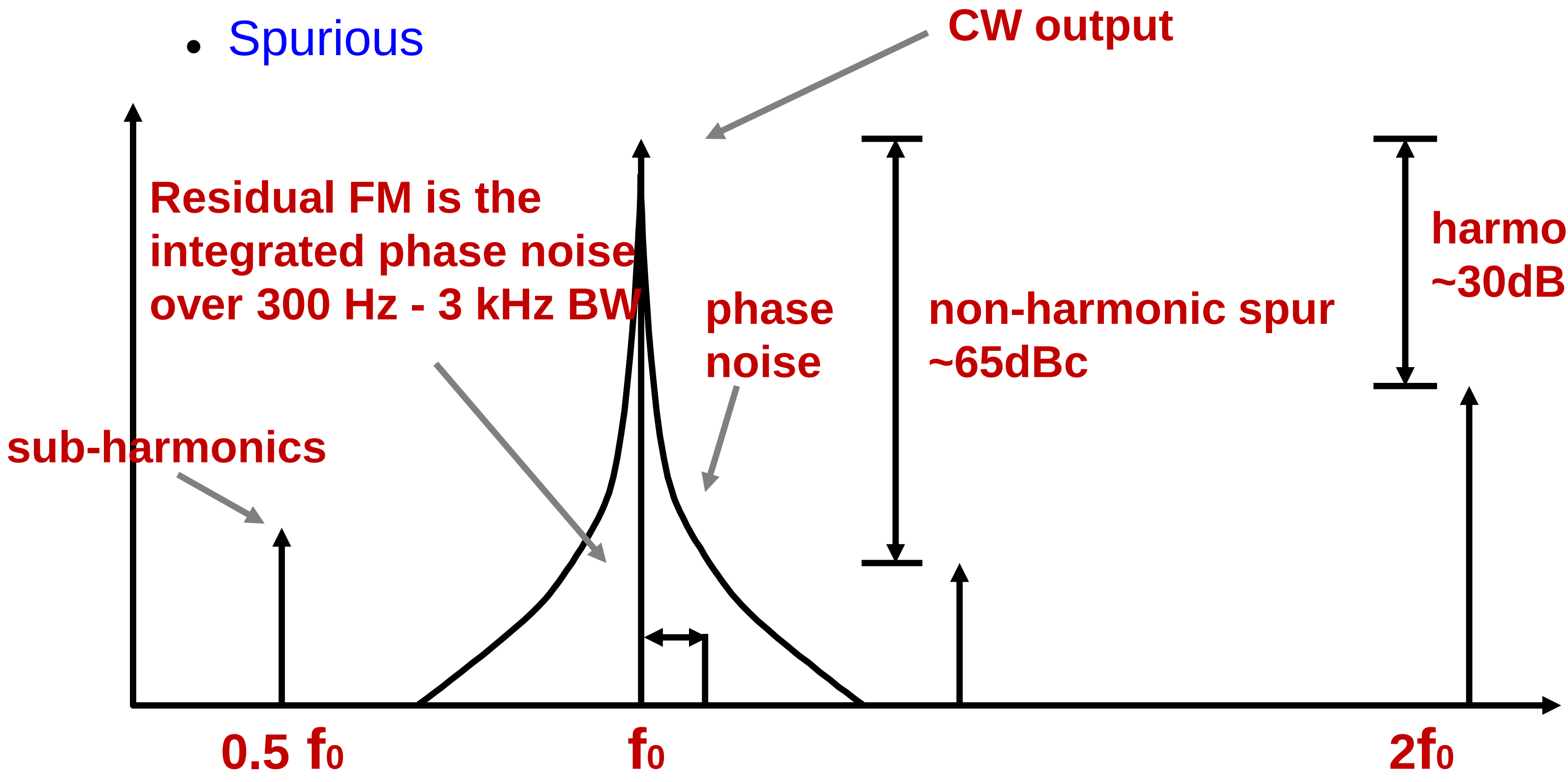
Source protected from accidental transmission from DUT



CW Source Specifications

...Spectral Purity

- Phase Noise
- Residual FM
- Spurious



Agilent Technologies

CW Source Specifications

... Spectral Purity: Phase Noise