EEC 134 A&B

Design of RF & Microwave Systems

Lecture 4: Building Blocks of RF Systems – Oscillators and Synthesizers

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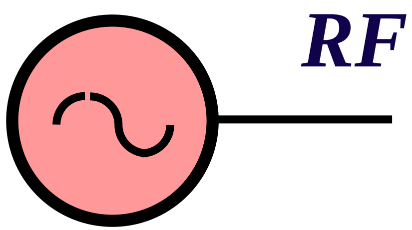
RF Oscillator

- Oscillator
  - RF signal source
  - Converts dc energy into RF



- Oscillator in an RF system

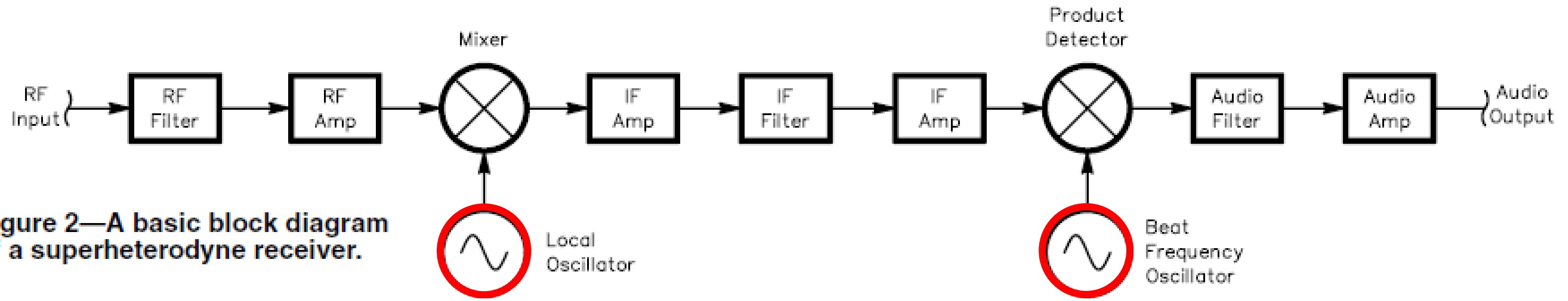


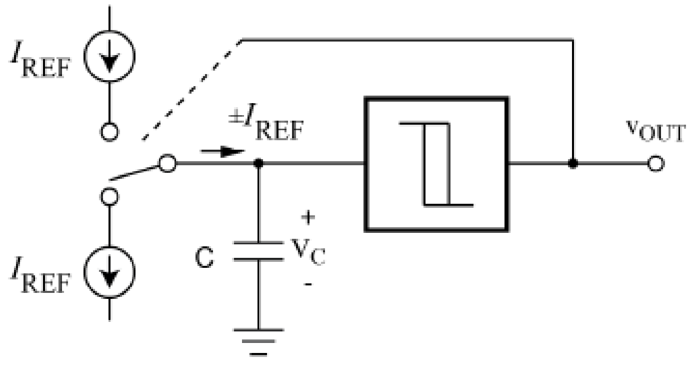
Figure 2—A basic block diagram of a superheterodyne receiver.

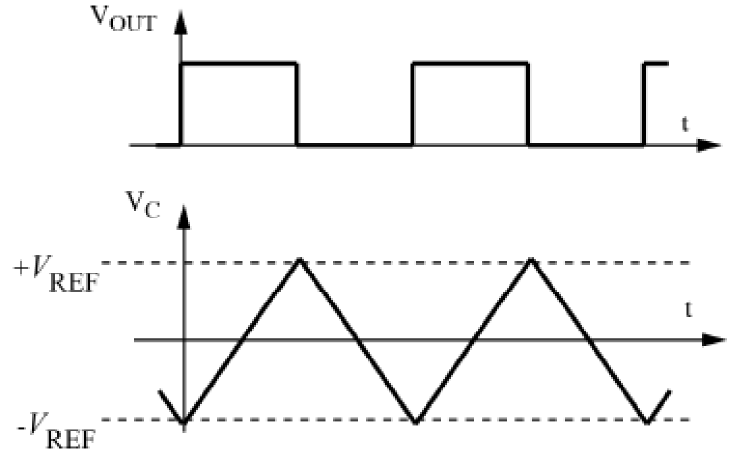
Types of Oscillator Design

- Multi-vibrator
- Ring
- Feedback
- Negative Resistance

Multi-vibrator Oscillator

- One or more current sources charge and discharge an energy storage element whose voltages flips a comparator (usually with hysteresis) to disconnect or connect the current source(s)
- Also called astable or relaxation oscillator
- Amplitude is controlled by the thresholds
- Start-up is guaranteed (will always oscillate)
- Usually used for low frequency (up to a few MHz)





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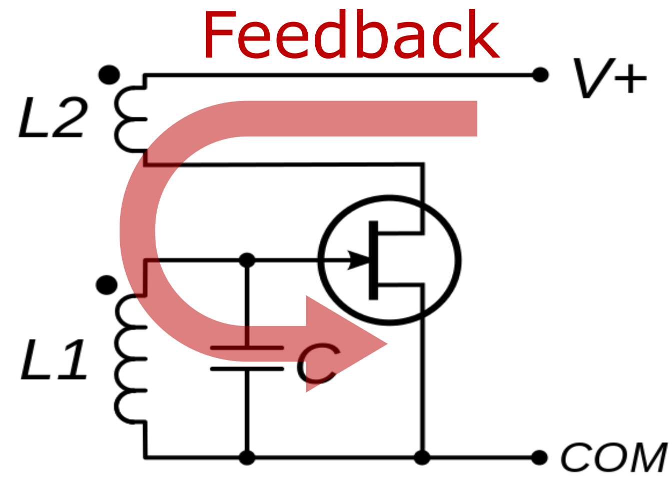
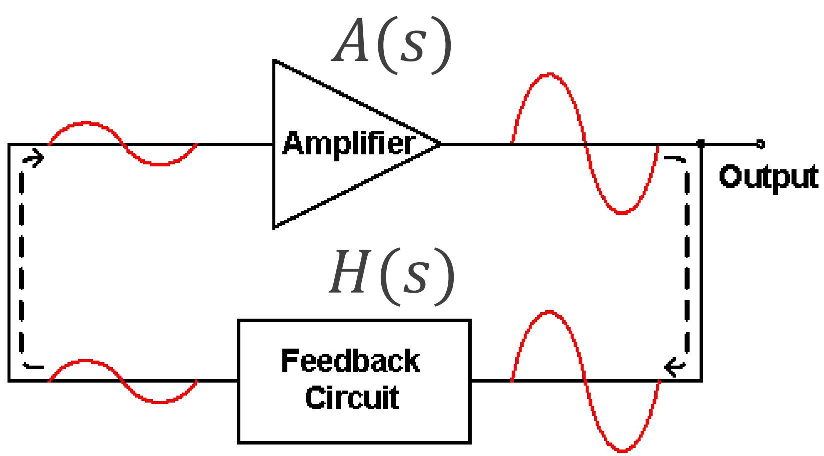
Feedback Oscillator

- While in college, Edwin H. Armstrong observed high frequency oscillation if the output signal of a vacuum tube amplifier is fed back to its input; thus inventing an oscillator which could be used to generate strong signals for radio transmitters
- **Oscillation can be created by introducing positive feedback**

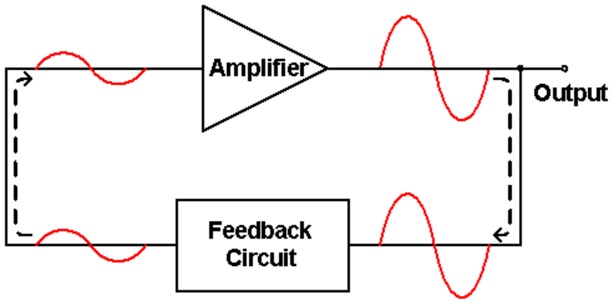




$$\frac{S_0}{S_i}(s) = \frac{A(s)}{1 - A(s)H(s)}$$

Barkhausen Criteria

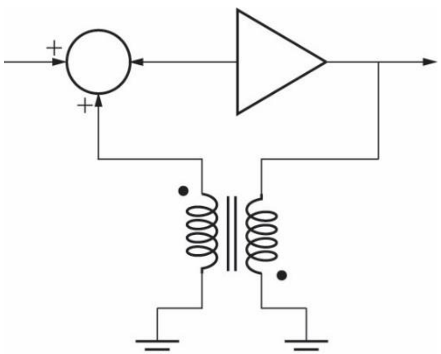
- It states that if $A(s)$ is the gain of the amplifying element in the circuit and $H(s)$ is the transfer function of the feedback path, so HA is the loop gain around the feedback loop of the circuit, the circuit will sustain steady-state oscillations only at frequencies for which:
  - The loop gain is equal to unity in absolute magnitude, that is, $\beta A = 1$, and
  - The phase shift around the loop is zero or an integer multiple of 2π: $\angle HA = 2n\pi, n = 0,1,2,\ldots$
- In an actual oscillator, the HA product will **initially exceed 1** to start the oscillation; As the oscillation grows, the gain compresses to reach the $HA = 1$ steady state.



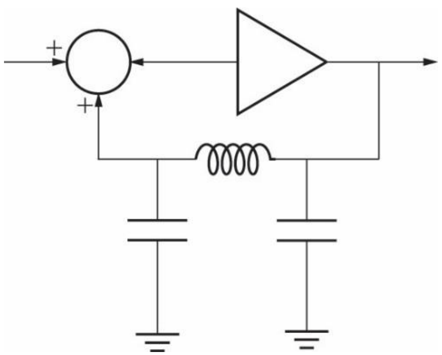
$$\frac{S_0}{S_i}(s) = \frac{A(s)}{1 - A(s)H(s)}$$

Realization of the Feedback Oscillator

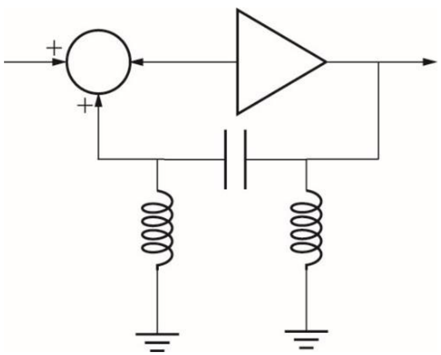
- A frequency selective network is usually used as the feedback network
- Most oscillator designs are based on a few classic structures (templates)



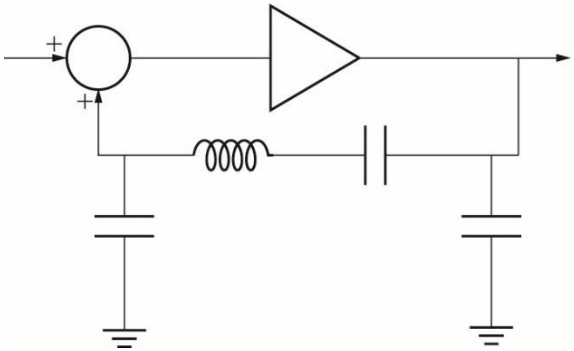
Armstrong oscillator



Colpitts Oscillator



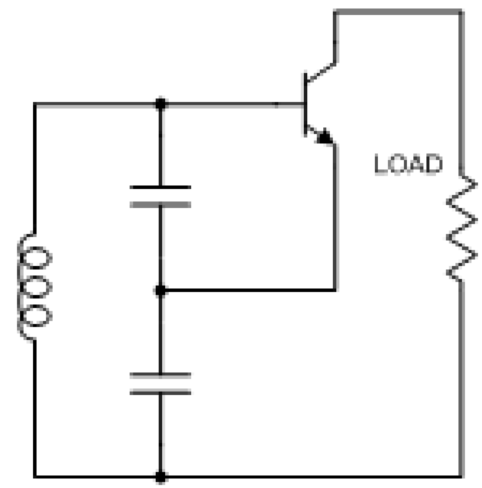
Hartley Oscillator



Clapp Oscillator

Frequency Selective Network

- The frequency selective (feedback) network is usually a bandpass network whose center frequency set the correct frequency
- In general, the higher the Q of the frequency selective network, the more stable the oscillation is.
- The frequency selective network can be made of a variety of resonator structures
  - Simple L-C resonator (Q of 5 ~ 100)
  - Transmission line resonator (Q of 30 ~ 250)
  - Waveguide/Cavity resonator (Q of 300 ~ 5000)
  - Dielectric resonator (Q of 3000 ~ 6000)
  - Crystal resonator (Q of 10,000 ~ 200,000!)



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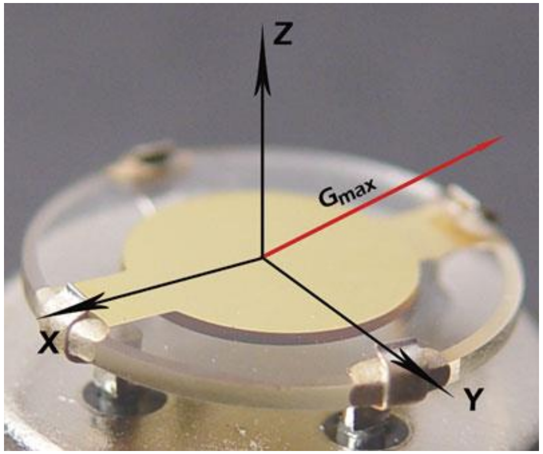
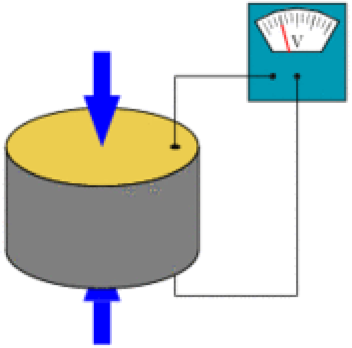
Crystal Oscillators

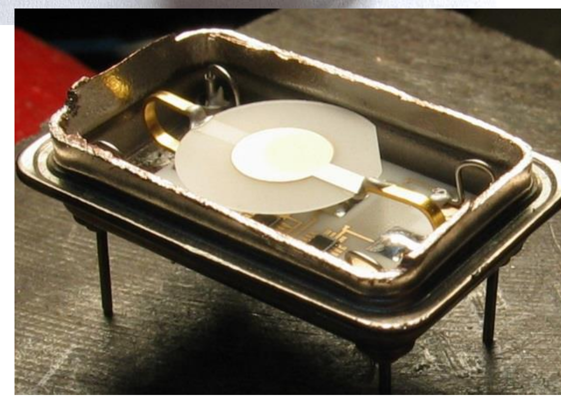
- The "crystal" is a piece of well shaped single crystal piezoelectric material (most commonly quartz) sandwiched between two metal electrodes.
- The piezoelectric effect is a property that some materials exhibit: external applied mechanical stress can induce a voltage potential and vice versa.
- Quartz is a natural piezoelectric material.
- The piezoelectric effect serves as a transduction mechanism, converting electric signals into mechanical vibration and back to electric signal again
- The transduction is the strongest when the crystal oscillates at its natural frequency which is determined by the shape of the crystal

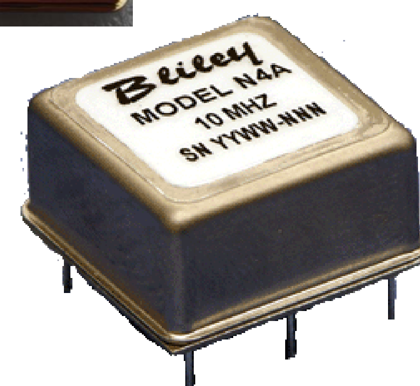




Crystal Oscillators (cont.)

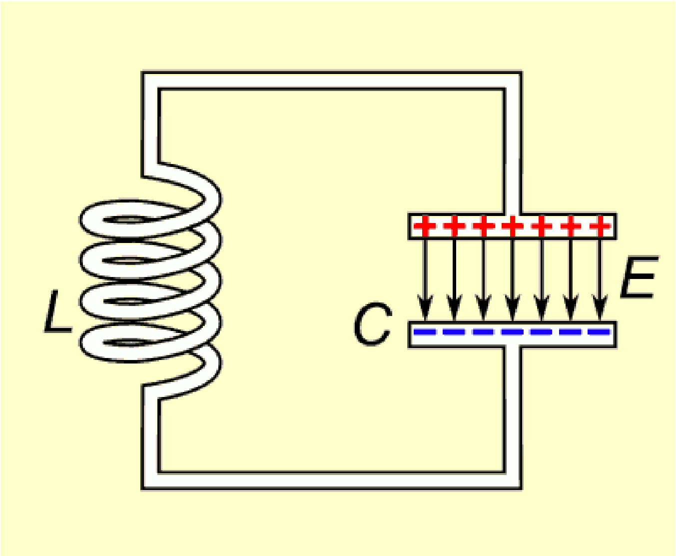
- Because of the extremely high Q, crystal oscillators are often used as very stable frequency sources.
- The frequency of crystal oscillators are in the range of ~10 kHz to ~100 MHz.
  - The frequency is primarily determined by the size and shape of the crystal. The lower frequency is usually bound by the crystal size; the higher end bound by the precision of machining the crystal.
- The frequency of a crystal oscillator (XO) is temperature dependent, which is an undesirable effect.
  - ***Temperature compensated crystal oscillator (TCXO)*** are designed carefully to reduce the temperature dependence
  - ***Oven controlled crystal oscillator (OCXO)*** uses active temperature control to maintain a stable temperature around the crystal for the best stability. Downside is that it burns power and needs start-up (warm-up) time.

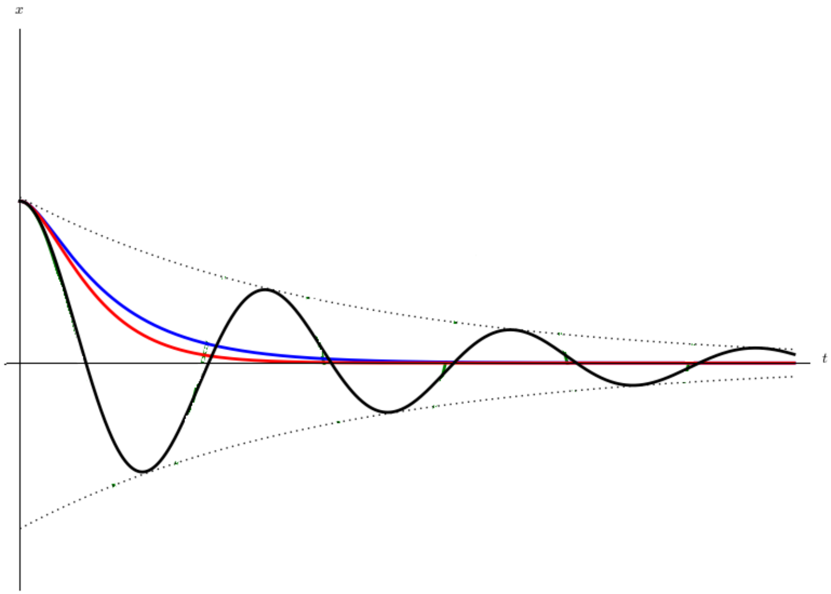




Another Oscillator Design Perspective

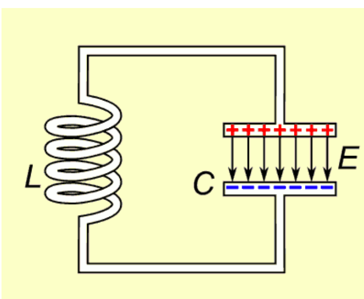
- Let's look at oscillation of voltage/current in a resonant circuit
- The quality factor (Q) determines the damping (loss) of the system
  - The higher the Q, the lower the damping, the longer the oscillation lasts
  - In all practical systems, the oscillation eventually dies down

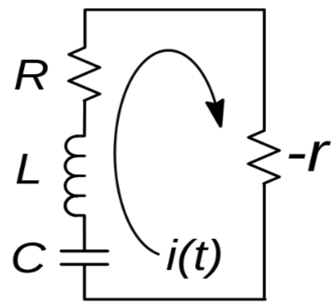


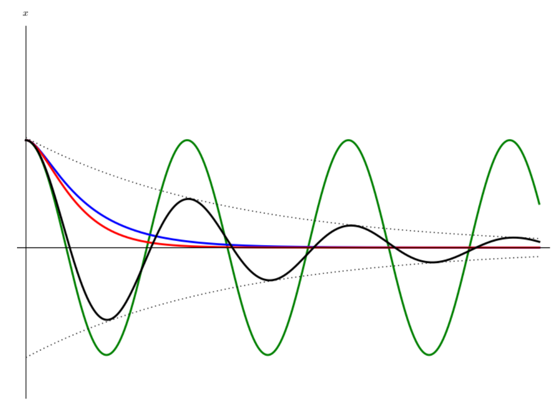


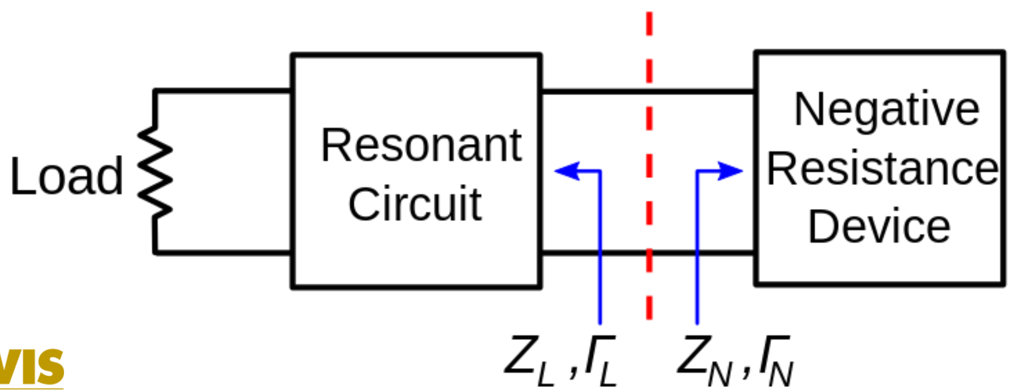
Sustaining the Oscillation – Negative Resistance

- If we can replenish the dissipated energy in a resonator, we could possibly sustain the oscillation
- Adding a “negative resistance” device will do the trick
  - A positive resistance dissipates energy; a negative resistance generates energy



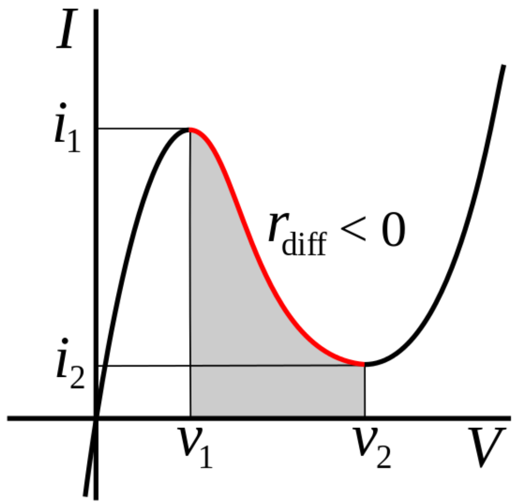


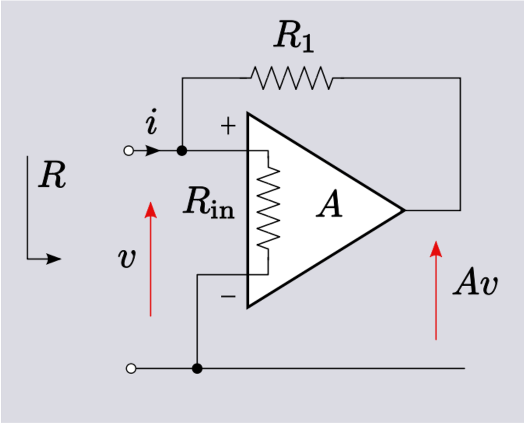




Creating Negative Resistance

- How do we realize negative resistance?
  - I-V curves with negative slope
  - Positive feedback provides effective negative resistance; the idea of a negative resistance oscillator is unified with a feedback oscillator



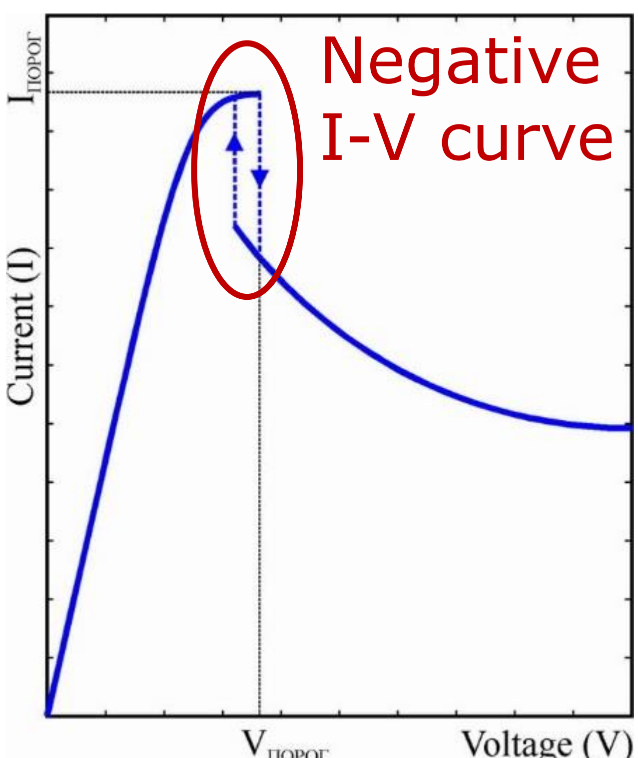


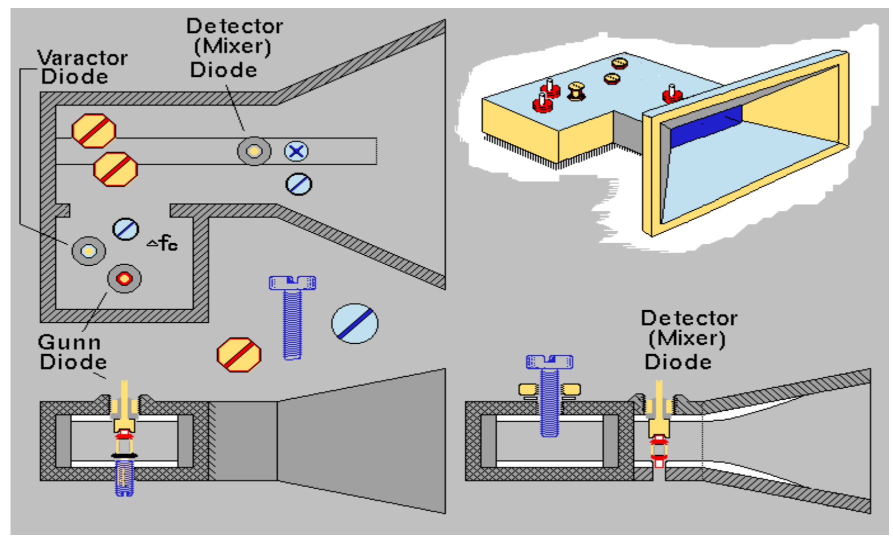
$$i = \frac{v - Av}{R_1} + \frac{v}{R_{\text{in}}}$$

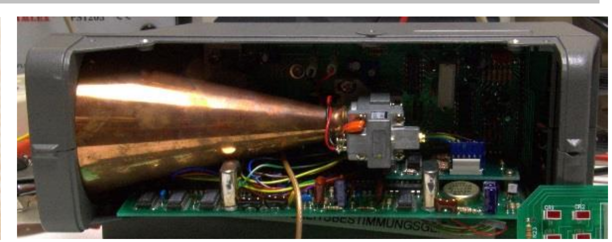
$$R = \frac{v}{i} = \frac{R_1}{1 + R_1/R_{\text{in}} - A}$$

Creating Negative Resistance

- How do we create negative resistance?
  - Some semiconductor devices exhibit negative resistance naturally; the mechanism cannot be described clearly with positive feedback
  - The microwave Gunn diode is a great example
  - Can be placed into a high-Q cavity resonator to generate oscillation







http://en.wikipedia.org/wiki/Gunn_diode

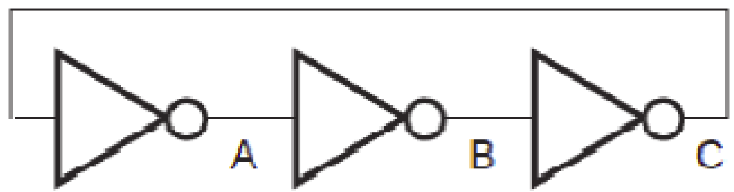
http://www.eevblog.com/forum/projects/gunn-oscillator-doppler-radar-transceiver/

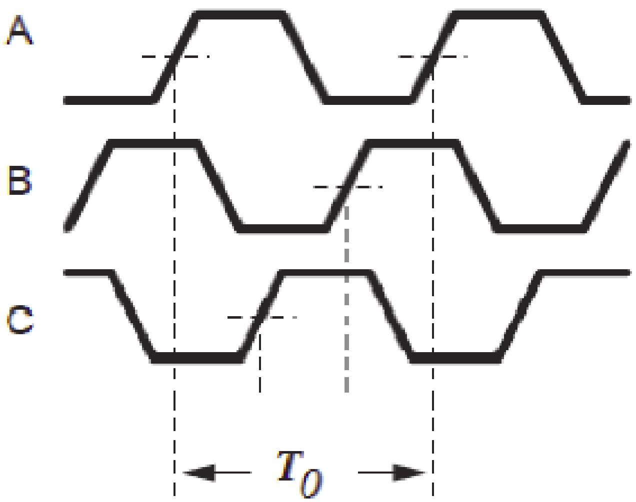
Ring Oscillator

- Frequency is determined by the delay of amplifiers (inverters)

$$f = \frac{1}{N\tau_d}$$

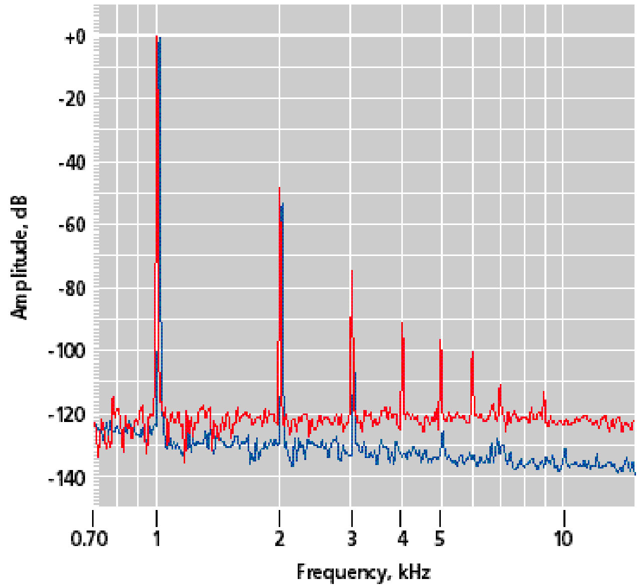
- Guaranteed start up.

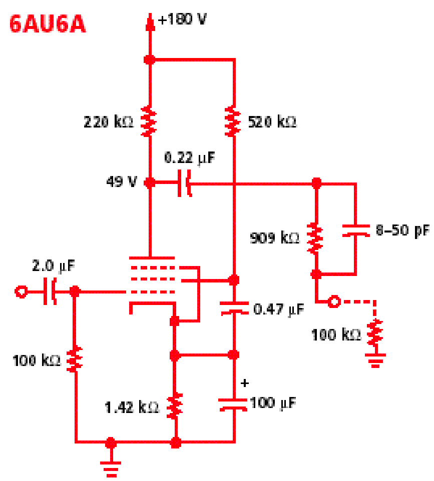


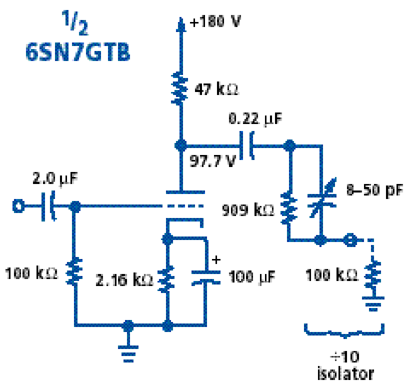


Oscillator Specifications

- Output power
  - Some oscillators have built in buffer/driver amplifiers to improve the output power, obviously at the penalty of high dc power consumption
- Harmonics
  - In reality, the voltage/current waveform in an oscillator is not purely sinusoidal. Some distortion is usually present, resulting in harmonic content in the output spectrum.

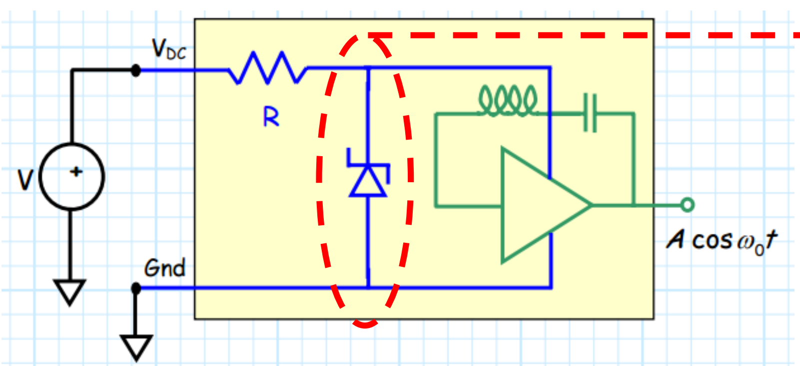






Oscillator Specifications – Pushing

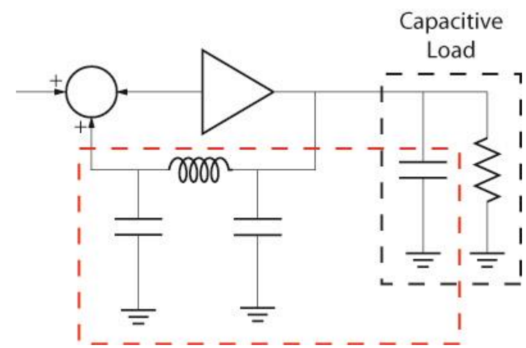
- In practical oscillators, the active circuit characteristics will be influenced by the supply voltage
  - e.g. recall that a transistor's IV characteristics are functions of both gate (base) and drain (collector) voltages
  - Fluctuation in the supply voltages can result in fluctuation in the oscillator output frequency and power
- Oscillator **frequency pulling** is specified as the frequency shift per volt change in the supply voltage: **Hz/V,** or Hz/mV, kHz/mV, MHz/V, or any other variants
- To counteract pushing, some oscillators integrate a voltage regulator/reference

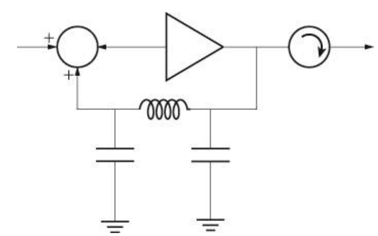


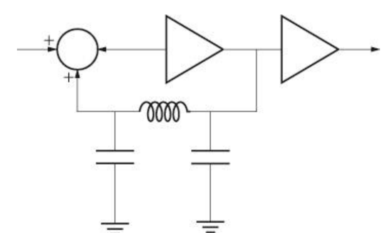
Shunt
voltage reference

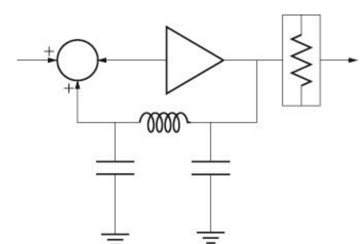
Oscillator Specifications – Pulling

- The load impedance of an oscillator can also affect the oscillator output performance
  - e.g. consider a conceptual Collpitts oscillator shown in the left: the capacitance in the load becomes part of the frequency selective network, which may shift the resonant frequency and the output power of the oscillator. The pulling characteristics in a real oscillator may be much more complex.
  - Because impedance is a complex number, there is not a single quantity to quantify pulling, a typical specification could read “less than 2 MHz at VSWR = 3”; this is usually the worst-case specification.
- To counteract pulling of an oscillator, the output is usually isolated from the load by an isolator/circulator, amplifier, or simply an attenuator.



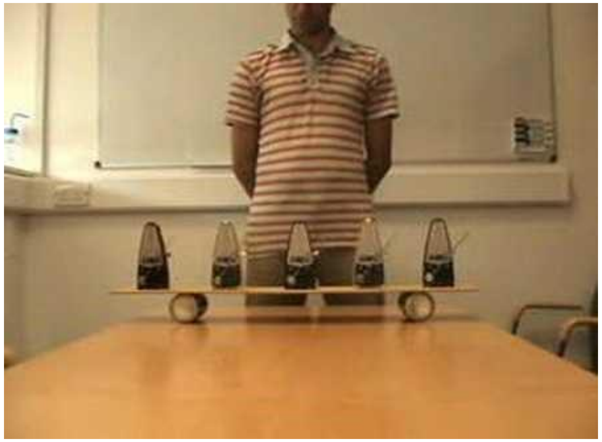




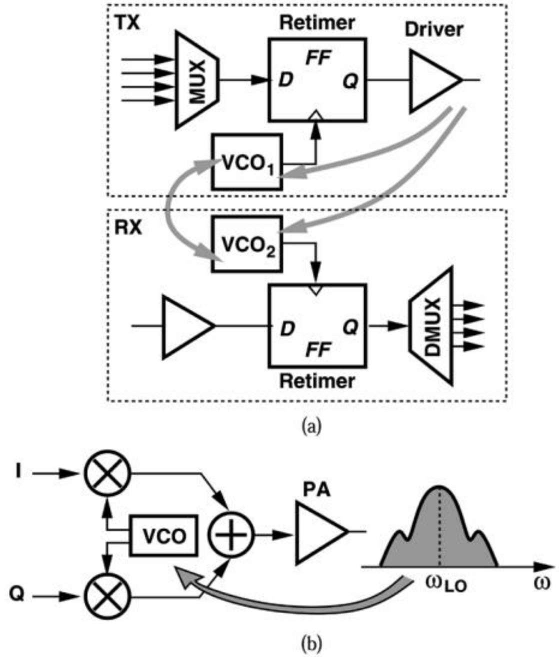


Oscillator Characteristics – Locking

- When oscillators are coupled with each other, they tend to synchronize in phase and frequency
  - Watch a video on mechanical oscillators synchronizing in phase
  - Same phenomena can be observed in electronic oscillators – we call it ***injection locking or pulling*** (when the initial frequency or phase difference is too great to achieve total synchronization)
- Locking can be used to our advantage
  - E.g. clock distribution – locking many oscillators to the same frequency reference
- Unwanted locking can also be detrimental to an RF system



Synchronization of mechanical oscillators

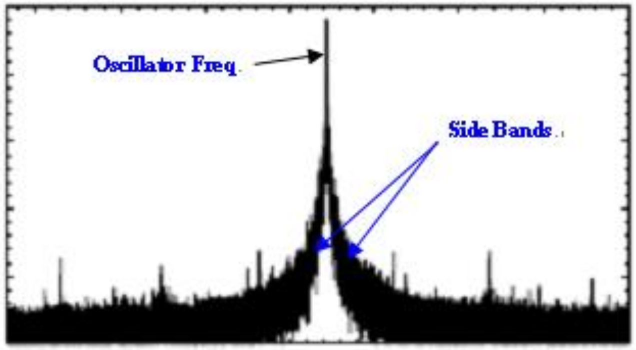


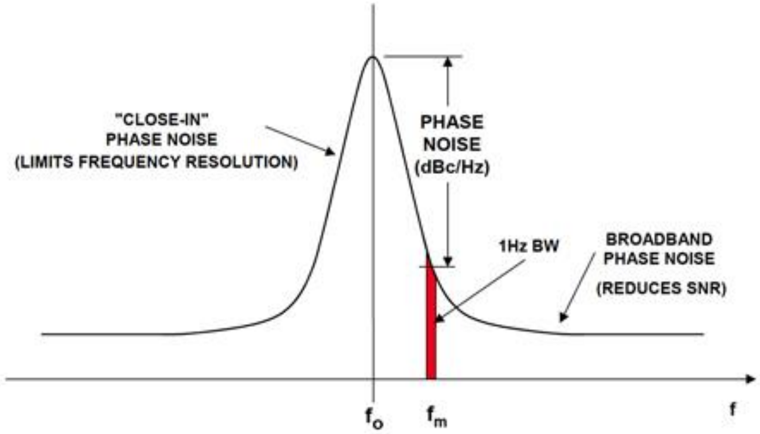
Undesirable Effects of Injection Pulling

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1327738&tag=1

Phase Noise

- Phase noise is a very important system parameter and is worth learning a little more about
- Phase noise results from
  - imperfect frequency selectivity of the feedback network
  - noise sources that modulates the high frequency current/voltage that passes through the active (gain) part of an oscillator
  - Noise (mostly thermal) from loss components in the passive part of the circuit
- Phase noise is usually specified with respect to the carrier power: dBc, in which “c” means carrier. Also, because phase noise shows itself as a continuous spectrum, its power is measured within a certain bandwidth, hence the unit of “dBc/Hz”

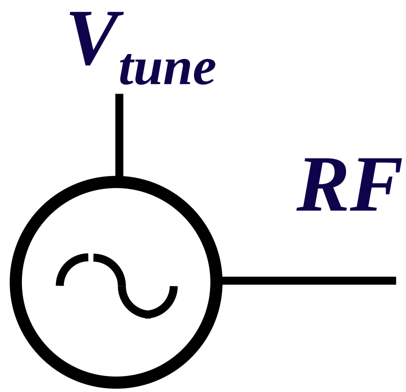


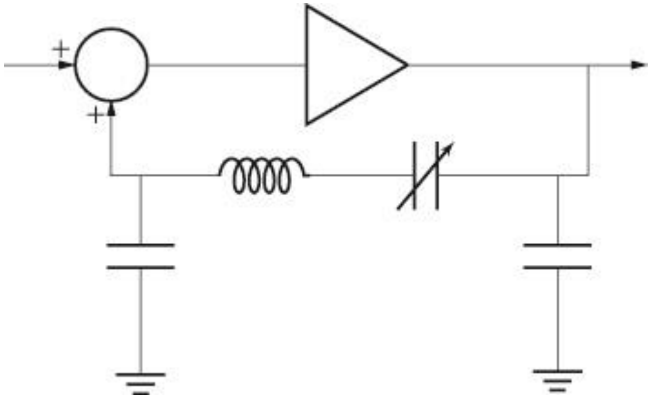


http://www.mti.com.tw/_english/06_center/02center.php?MainID=9&ID=57
http://www.digikey.com/en/articles/techzone/2010/dec/converting-oscillator-phase-noise-to-time-jitter

Voltage Controlled Oscillator (VCO)

- An oscillator whose output frequency can be controlled by a voltage signal
- Usually implemented by tuning the feedback network by a variable capacitor
- Very useful component in any system whose operating frequency needs to change
  - FM radio
  - Frequency sweeping radars
  - Frequency synthesizers
  - Spectrum analyzers
  - Network analyzers





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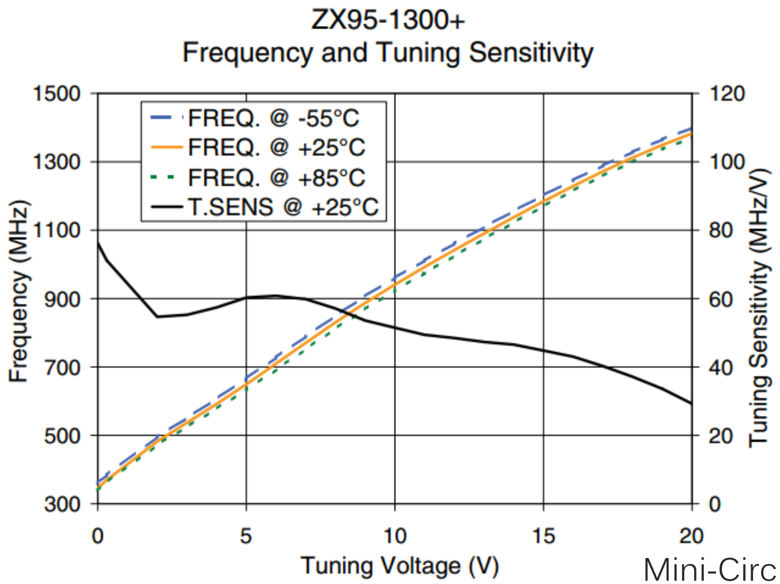
VCO Specifications

- All the specifications for fixed oscillators are still applicable
- Tuning sensitivity: frequency change per volt of tuning voltage change
  - Sometimes referred to as “VCO gain”
  - Specified in Hz/V, or MHz/V
  - A higher sensitivity means that you can cover a large frequency range with small tuning voltage; it also means that the output frequency is more sensitive to the noise in the tuning voltage
- In some applications, particularly frequency modulation (FM) systems, tuning linearity is of particular concern
  - Good linearity ensures good modulation fidelity



Mini-Circuits

Example VCO Datasheet

❖ Mini-Circuits ZX95-1300+

Coaxial

Voltage Controlled Oscillator ZX95-1300+

Wide Band 400 to 1300 MHz

Features
- very wide band frequency
- linear tuning characteristics
- low phase noise
- low pushing
- protected by US patent 6,790,049

Applications
- r & d
- lab
- instrumentation
- wireless communications
- industrial communications
- test equipment

CASE STYLE: GB956

Connectors	Model	Price	Qty.
SMA	ZX95-1300-S+	$49.95 ea.	(1-9)

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Electrical Specifications

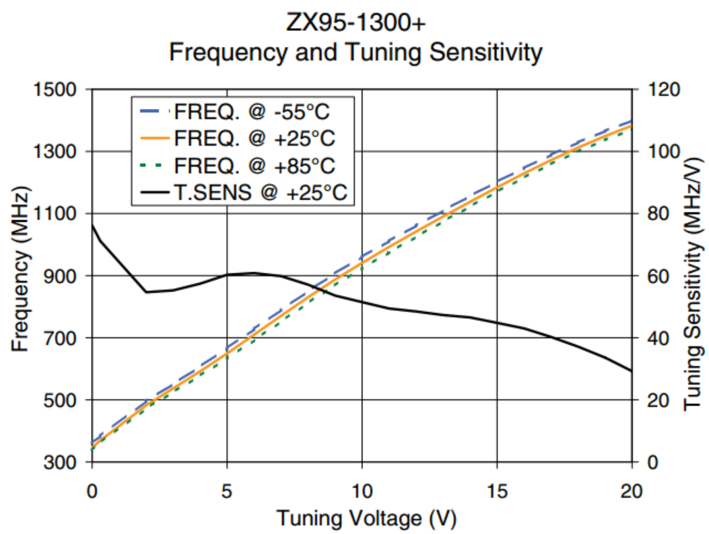
MODEL NO.	FREQ. (MHz)		POWER OUTPUT (dBm)	PHASE NOISE dBc/Hz SSB at offset frequencies,kHz Typ.				TUNING VOLTAGE RANGE (V)		TUNING SENSI-TIVITY (MHz/V)	TUNING PORT CAP (pF)	TUNING 3 dB MODULATION BANDWIDTH (MHz)	NON HARMONIC SPURIOUS (dBc)	HARMONICS (dBc)		PULLING pk-pk @12 dBr (MHz)	PUSHING (MHz/V)	DC OPERATING POWER Vcc (volts)	DC OPERATING POWER Current (mA)
	Min.	Max.	Typ.	1	10	100	1000	Min.	Max.	Typ.	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Typ.		Max.
ZX95-1300+	400	1300	+8	-65	-91	-120	-141	0.3	20	40 - 60	100	30	-90	-12	-	3.5	1.5	5	40

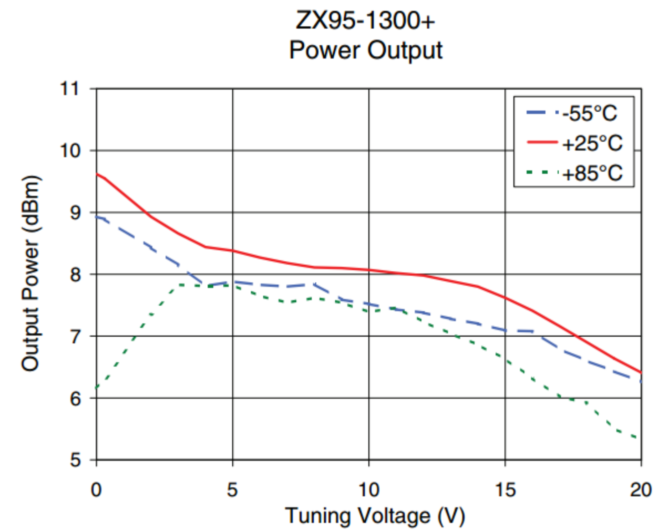
Example VCO Datasheet (cont.)

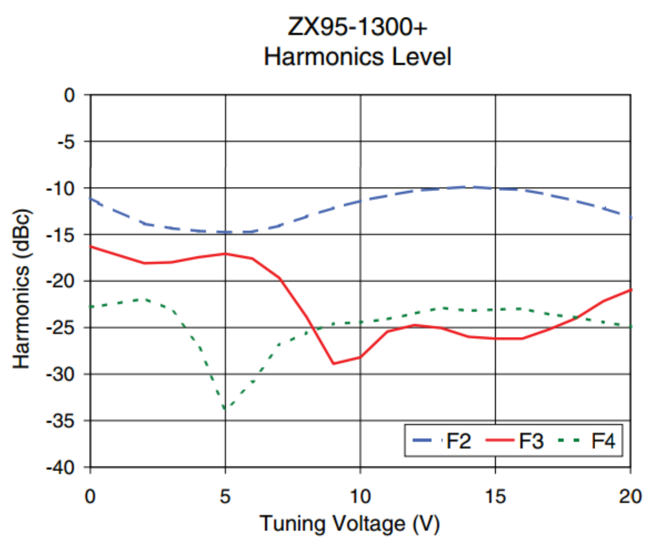
V TUNE	TUNE SENS (MHz/V)	FREQUENCY (MHz)			POWER OUTPUT (dBm)			Icc (mA)	HARMONICS (dBc)			FREQ. PUSH (MHz/V)	FREQ. PULL (MHz)	PHASE NOISE (dBc/Hz) at offsets				FREQ OFFSET (KHz)	PHASE NOISE at 850 MHz (dBc/Hz)
		-55°C	+25°C	+85°C	-55°C	+25°C	+85°C		F2	F3	F4			1kHz	10kHz	100kHz	1MHz		
0.00	76.16	361.3	346.5	339.1	8.93	9.62	6.16	29.90	-11.1	-16.3	-22.8	2.56	0.80	-63.1	-88.0	-118.0	-139.8	1.0	-65.96
0.30	71.15	383.9	369.3	361.9	8.89	9.55	6.29	30.05	-11.6	-16.6	-22.7	2.29	1.02	-63.7	-88.8	-118.3	-139.9	2.0	-73.98
2.00	54.66	496.1	482.1	472.6	8.43	8.93	7.35	30.89	-13.9	-18.1	-21.9	1.28	1.74	-67.4	-92.1	-120.2	-140.9	3.5	-79.77
3.00	55.23	551.2	536.8	524.9	8.15	8.66	7.83	31.31	-14.3	-18.0	-23.1	0.90	1.55	-68.4	-94.0	-120.9	-141.7	6.0	-85.98
4.00	57.41	607.4	592.0	578.0	7.81	8.44	7.81	31.68	-14.6	-17.5	-26.9	0.64	2.24	-68.6	-94.0	-121.4	-142.3	8.5	-88.86
5.00	60.29	666.6	649.4	633.6	7.88	8.38	7.82	31.93	-14.8	-17.1	-33.9	0.90	4.21	-69.8	-92.6	-121.1	-142.2	10.0	-91.08
6.00	60.80	728.1	709.7	692.4	7.83	8.27	7.65	32.09	-14.7	-17.6	-30.8	1.28	4.31	-66.2	-92.8	-120.2	-141.6	20.8	-99.24
7.00	59.84	789.8	770.5	752.5	7.80	8.18	7.54	32.16	-14.1	-19.7	-26.9	1.54	4.21	-64.1	-91.2	-119.8	-141.2	35.5	-106.61
8.00	57.09	849.9	830.3	812.2	7.84	8.11	7.62	32.23	-13.1	-23.8	-25.6	1.66	3.95	-66.2	-91.4	-120.0	-141.4	60.7	-113.68
9.00	53.57	907.2	887.4	869.2	7.59	8.10	7.54	32.30	-12.2	-28.9	-24.6	1.79	2.62	-66.2	-91.2	-120.2	-141.5	86.7	-118.37
10.00	51.46	960.8	941.0	923.3	7.52	8.07	7.39	32.25	-11.4	-28.2	-24.4	1.66	3.67	-65.2	-91.1	-120.0	-141.7	100.0	-119.89
11.00	49.41	1011.6	992.4	975.2	7.43	8.02	7.46	32.19	-10.8	-25.4	-24.1	1.28	4.21	-64.4	-91.6	-120.4	-142.1	148.1	-124.35
12.00	48.45	1061.1	1041.9	1025.2	7.38	7.98	7.23	32.03	-10.3	-24.7	-23.5	1.15	4.22	-66.0	-92.0	-121.0	-142.5	177.0	-126.14
13.00	47.30	1109.2	1090.3	1074.6	7.28	7.89	7.04	31.87	-10.1	-25.1	-22.9	1.15	4.35	-68.2	-92.5	-121.4	-142.8	211.6	-127.85
14.00	46.53	1156.4	1137.6	1122.7	7.20	7.80	6.86	31.69	-9.9	-26.0	-23.2	1.41	3.41	-68.2	-92.6	-122.0	-143.1	302.4	-131.25
15.00	44.80	1202.2	1184.1	1170.0	7.09	7.62	6.63	31.54	-10.1	-26.2	-23.1	1.41	3.85	-66.9	-93.2	-122.5	-143.8	361.5	-132.89
16.00	43.01	1246.3	1228.9	1215.6	7.08	7.41	6.32	31.41	-10.2	-26.2	-23.0	1.54	3.96	-66.7	-94.4	-123.0	-144.4	507.5	-135.86
17.00	40.26	1289.0	1271.9	1258.9	6.79	7.16	6.02	31.34	-10.8	-25.2	-23.6	1.79	2.22	-66.8	-95.2	-123.4	-144.3	606.7	-137.44
18.00	37.12	1328.7	1312.2	1299.6	6.60	6.90	5.92	31.31	-11.4	-24.0	-23.9	1.66	3.77	-69.7	-95.3	-123.8	-144.6	851.6	-140.19
20.00	29.25	1399.2	1382.9	1370.3	6.26	6.41	5.33	31.30	-13.1	-21.0	-24.9	1.54	3.89	-71.6	-96.7	-123.4	-144.3	1000.0	-141.30

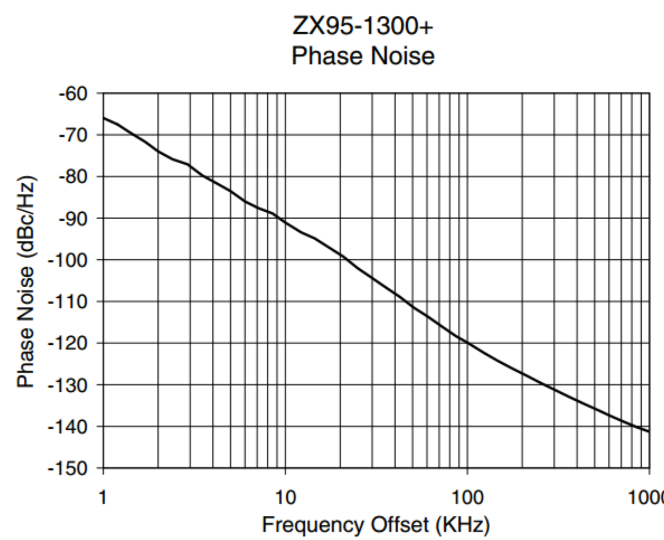
*at 25°C unless mentioned otherwise

Example VCO Datasheet (cont.)









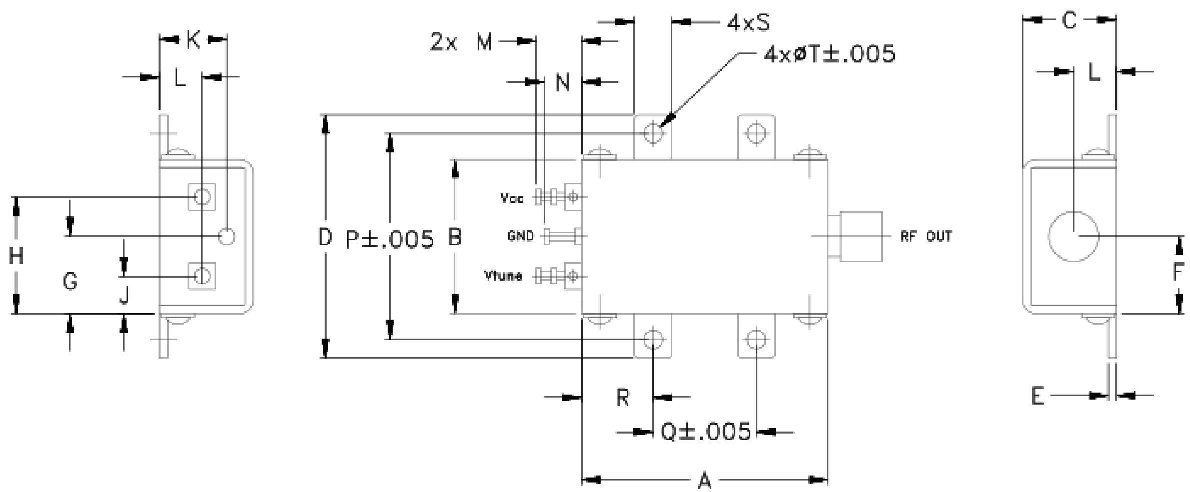
Example VCO Datasheet (cont.)

Maximum Ratings

Operating Temperature	-55°C to 85°C
Storage Temperature	-55°C to 100°C
Absolute Max. Supply Voltage (Vcc)	6V
Absolute Max. Tuning Voltage (Vtune)	22V
All specifications	50 ohm system

Permanent damage may occur if any of these limits are exceeded.

Outline Drawing



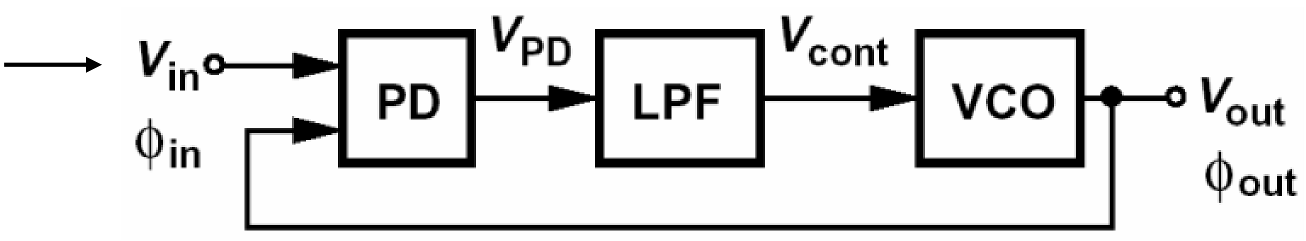
Outline Dimensions (inch / mm)

A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	wt.
1.20	**.75**	**.46**	**1.18**	**.04**	**.38**	**.38**	**.57**	**.18**	**.33**	**.21**	**.22**	**.18**	**1.00**	**.50**	**.35**	**.18**	**.106**	grams
30.48	19.05	11.68	29.97	1.02	9.65	9.65	14.48	4.57	8.38	5.33	5.59	4.57	25.40	12.70	8.89	4.57	2.69	35.0

Phase-Locked-Loop (PLL)

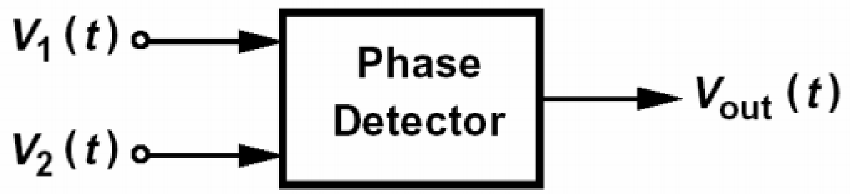
- A feedback loop to achieve very high frequency stability and low phase noise
- Also a very useful technique to accurately track the frequency and phase of the input signal

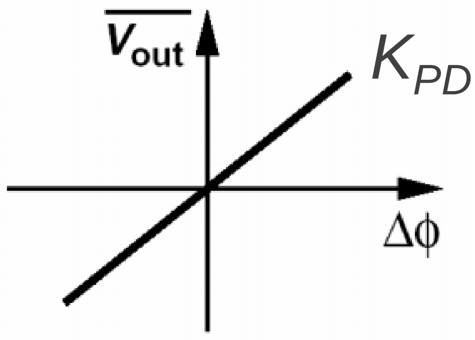
Crystal frequency reference



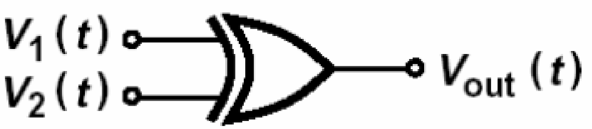
Read more: http://www.analog.com/library/analogDialogue/archives/33-03/phase/index.html

Phase Detector

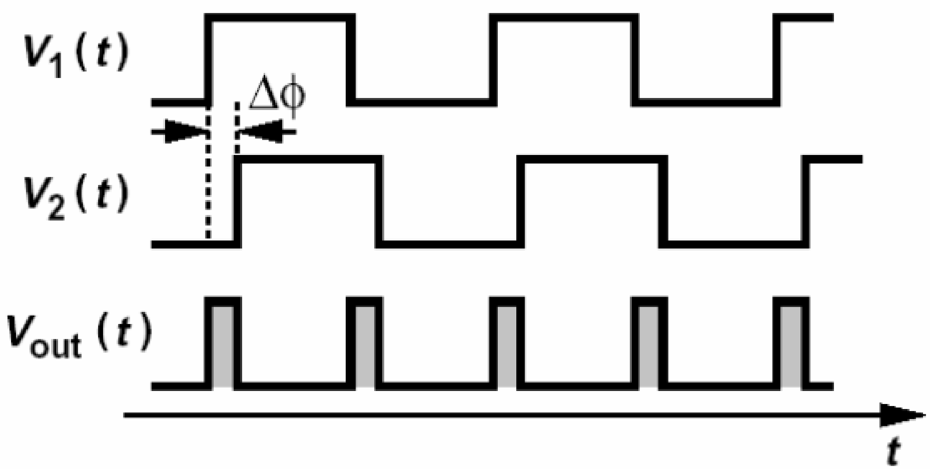




Transfer function

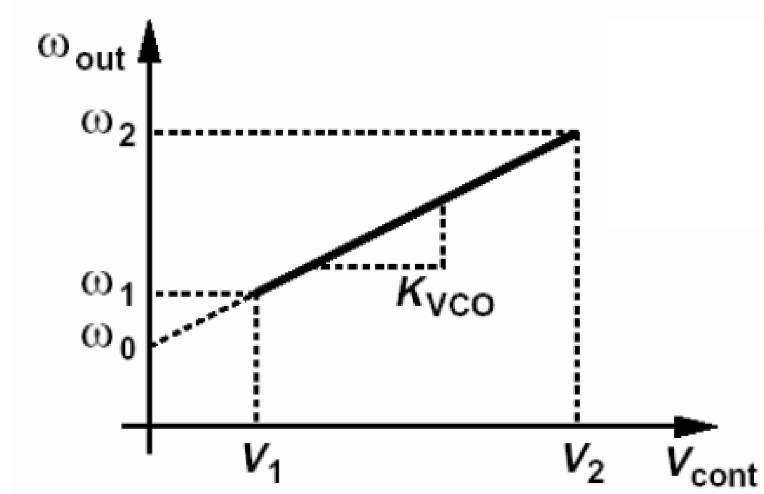


XOR as a simple implementation

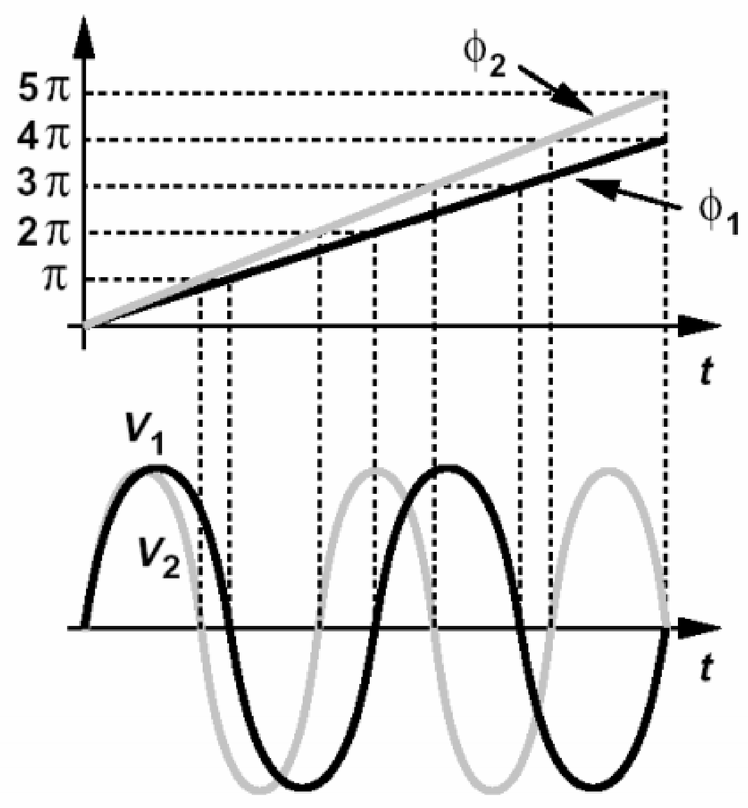


Modeling the VCO

- Assuming that the VCO has a linear tuning characteristics and its sensitivity/gain is K_{VCO}



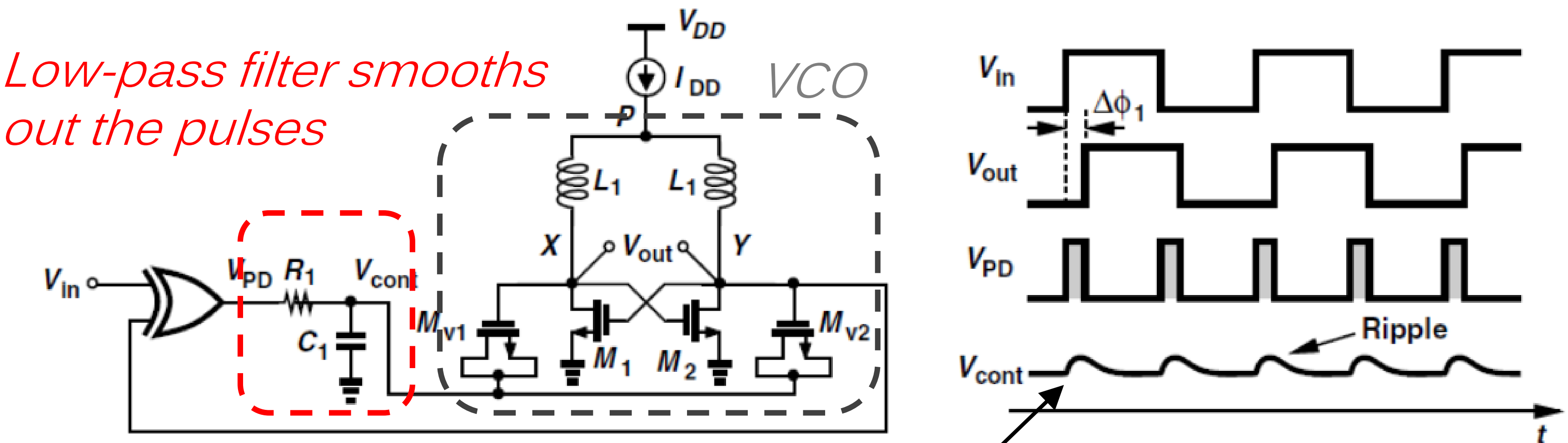
A higher frequency means faster phase progression



$$\omega_{out} = \omega_0 + K_{VCO} V_{TUNE}$$

Example

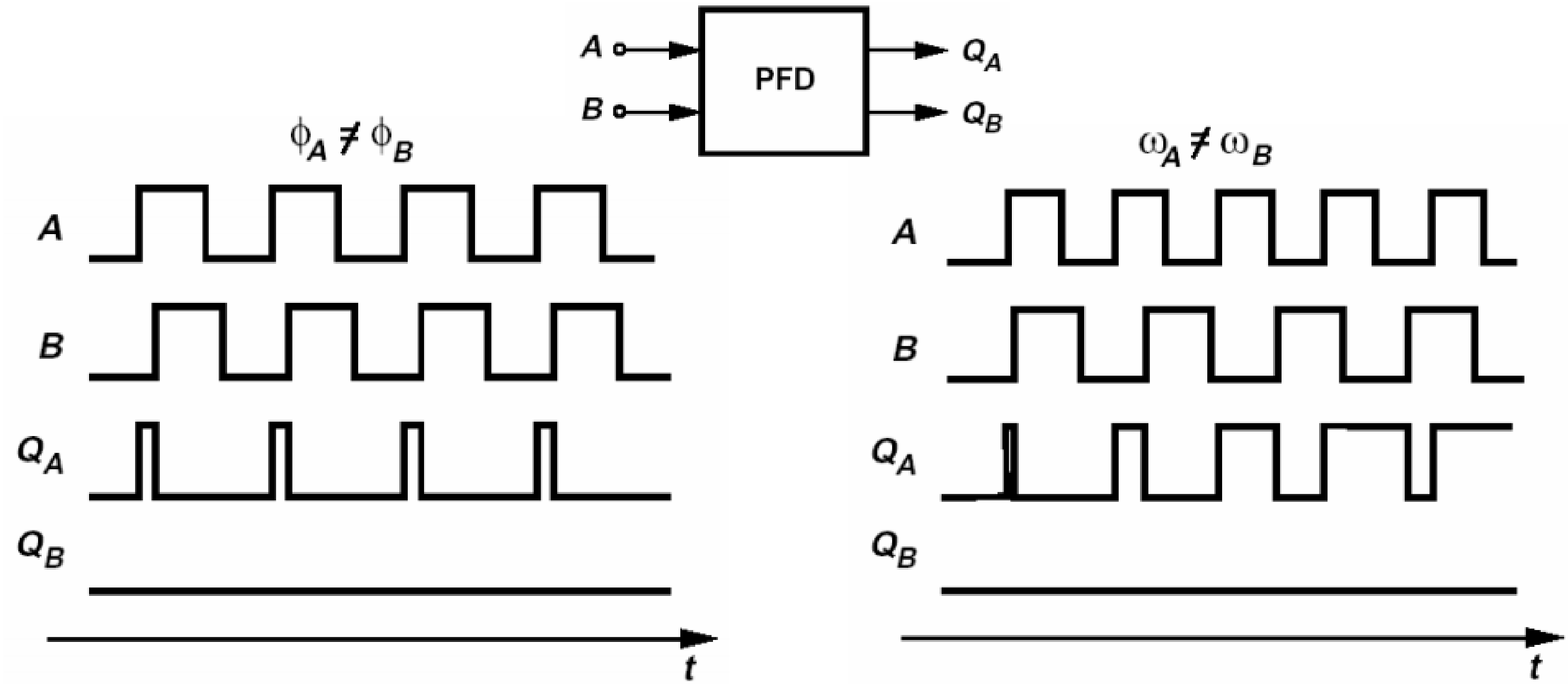
- The PFD allows the use of charge-pump circuits to create the control signal for the VCO



Increase in V_{cont} (V_{TUNE}) bumps up the frequency and therefore the phase progression so that the VCO output phase can catch up with the V_{in} (V_{ref}) phase

Phase/Frequency Detector

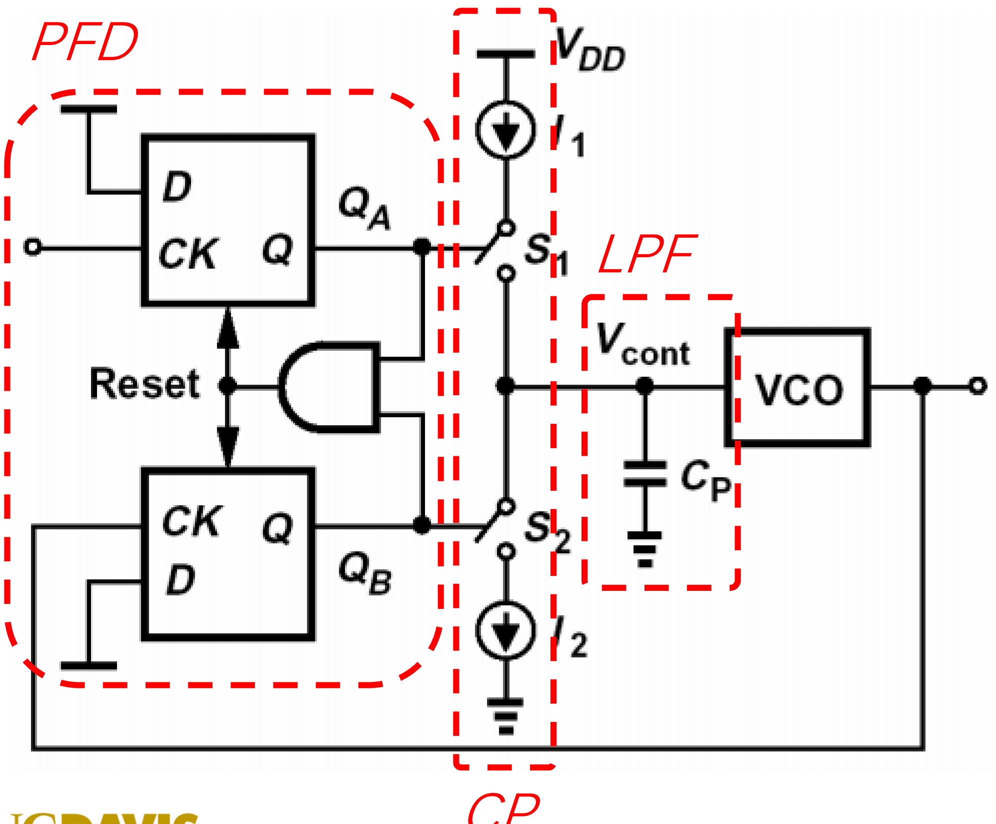
- The phase/frequency detector (PFD) provides the correct output even when the frequencies of the two inputs are different

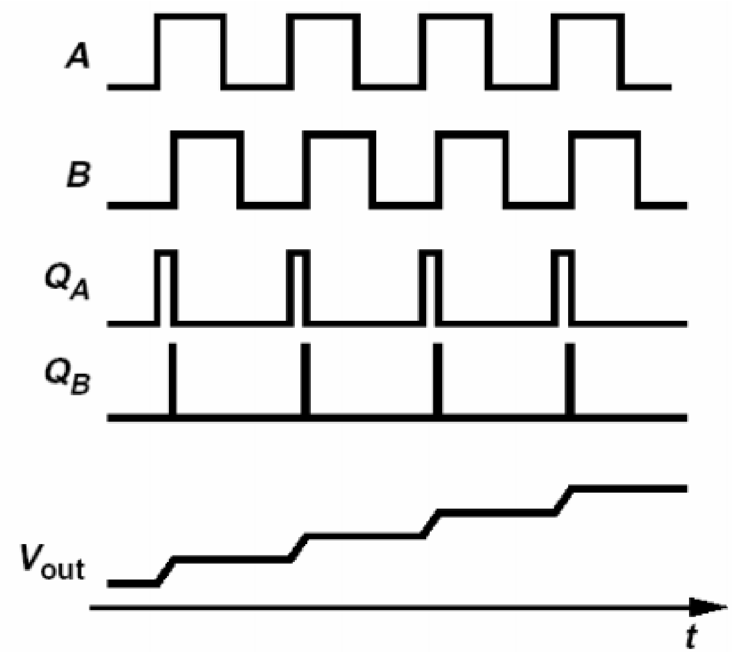


http://www.seas.ucla.edu/brweb/teaching/215C_W2013/PLLs.pdf

PFD+ Charge Pump (CP) in PLL

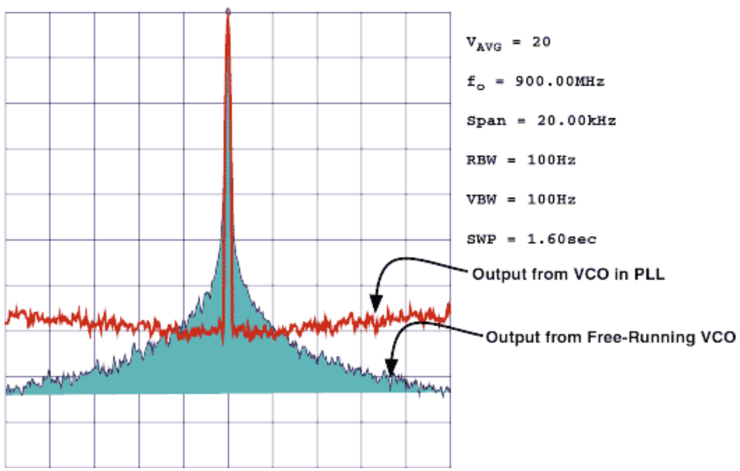
- The charge pump provides the current to drive the subsequent stage in the PLL
- The PLL locks the output signals phase and frequency to the reference: we can now replicate the stability and low phase noise of the reference!

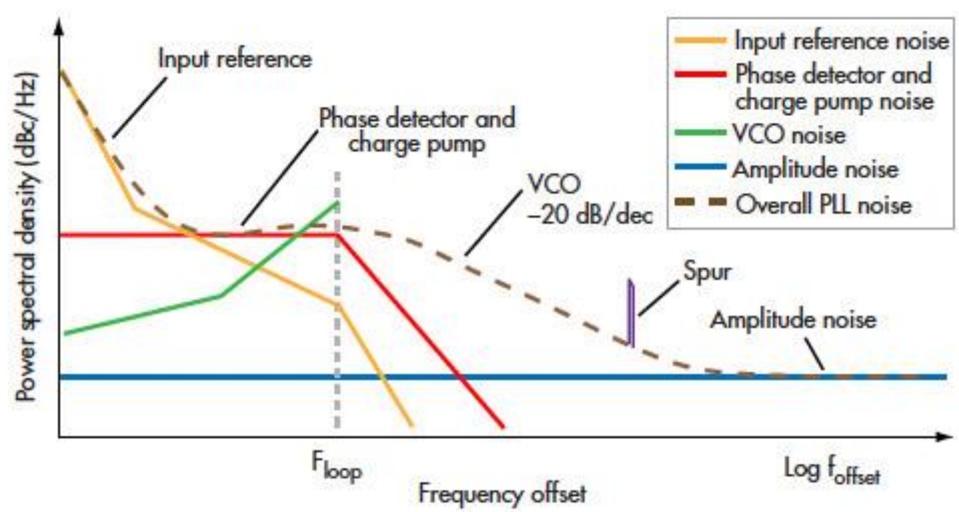




Phase Noise in a PLL

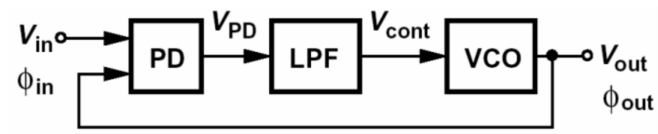
- A PLL is basically a negative feedback look that stabilizes the output signal to the reference.
- The stabilization only takes effect within the loop bandwidth—effectively the bandwidth of the low-pass filter.



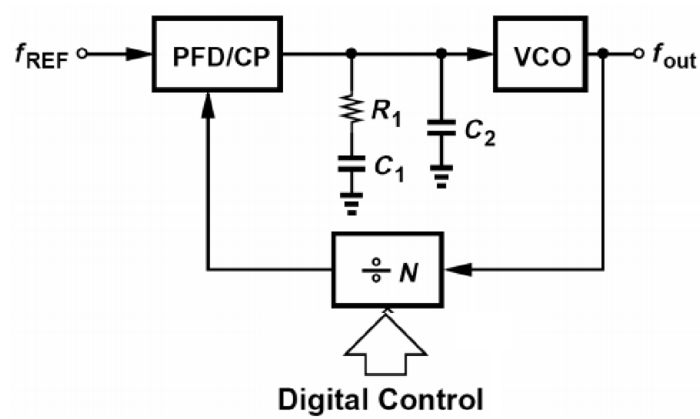


http://www.analog.com/library/analogDialogue/archives/33-05/phase_locked/index.html
http://electronicdesign.com/analog/adc-performance-what-s-jitter-got-do-it

Frequency Synthesis – Integer-N Synthesizer



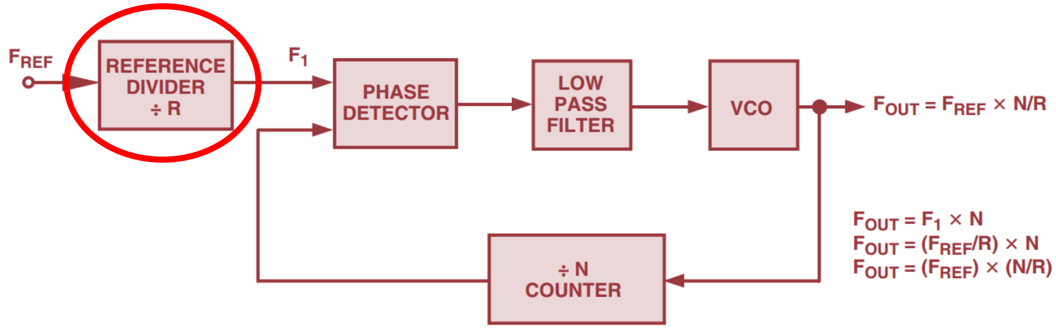
- The basic PLL studied above isn't very useful for frequency synthesis; the output signal frequency is the same as the reference!
- Adding a divide by N block:
  - Output frequency now a multiple of the reference frequency
  - By digitally controlling the divider ratio N we can generate different frequencies
  - Drawback: Output frequency resolution is determined by the reference frequency
  - One penalty paid is the phase noise: **Phase noise grows 6 dB per multiple by 2, or 20 dB per multiple by 10, in frequency**



$$f_{out} = N \times f_{REF}$$

Integer-N Synthesizer – Adding a Reference Counter

- A reference counter can improve frequency resolution



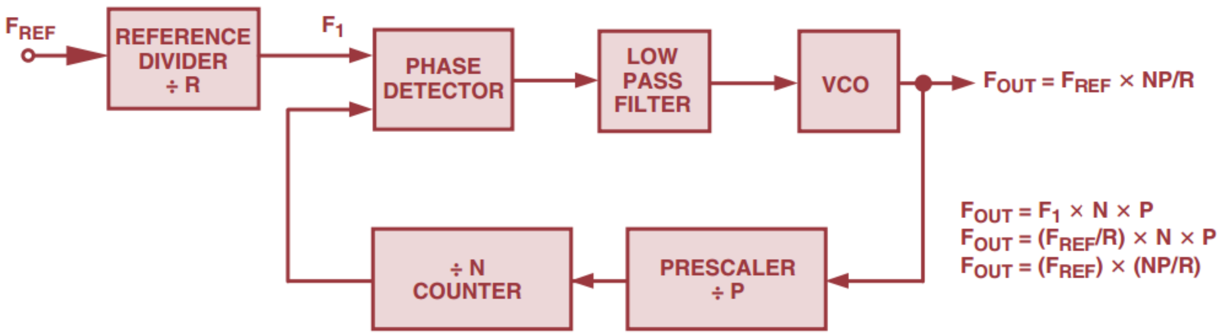
$$f_{out} = \frac{N \times f_{REF}}{R}$$

- Drawback: the reference counter R makes the feedback counter very large!
- Example:
  - Using a 10 MHz reference clock and a reference counter of 1,000, we can achieve frequency resolution of 10 kHz
  - To get an output frequency around 900 MHz, we'd need a N value of 90,000 -> equivalent of a 17-bit counter, difficult to make it working right at high frequency

Mark Curtin and Paul O'Brien, "Phase-Locked Loops for High-Frequency Receivers and Transmitters," Analog Dialogue 33-3, 1999

Integer-N Synthesizer – Prescalar

- Adding a pre-scalar to alleviate the issue: the division is now done in two steps
  - The pre-scalar is a high-frequency component that divide the feedback signal by a **fixed** ratio, e.g. /2, /4, /8, /32, etc
  - Because *P* is fixed, the frequency resolution degrades by *P*! Now we seem be going in circles!
    - Fortunately P is usually much smaller than R, so we still get a net gain
    - And another clever solution exists to solve this issue

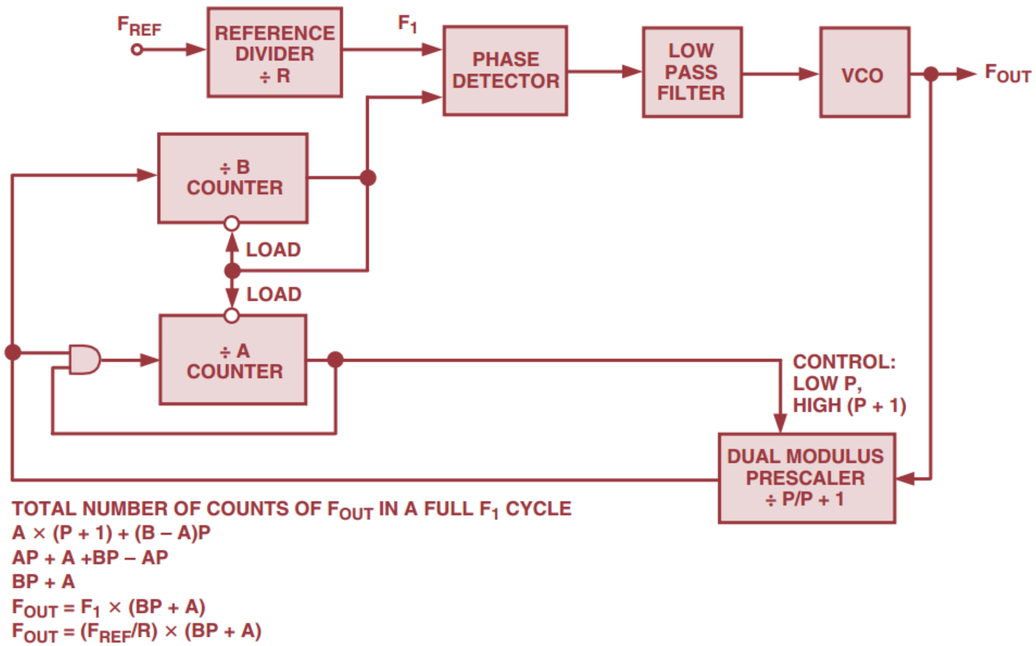


$$f_{out} = \frac{PN \times f_{REF}}{R}$$

Mark Curtin and Paul O'Brien, "Phase-Locked Loops for High-Frequency Receivers and Transmitters," Analog Dialogue 33-3, 1999

Integer-N Synthesizer – Dual Modulus Prescalar

- Counter A and counter B time-outss sequentially to toggle the prescalar value by 1
  - Both A and B can be digitally controlled

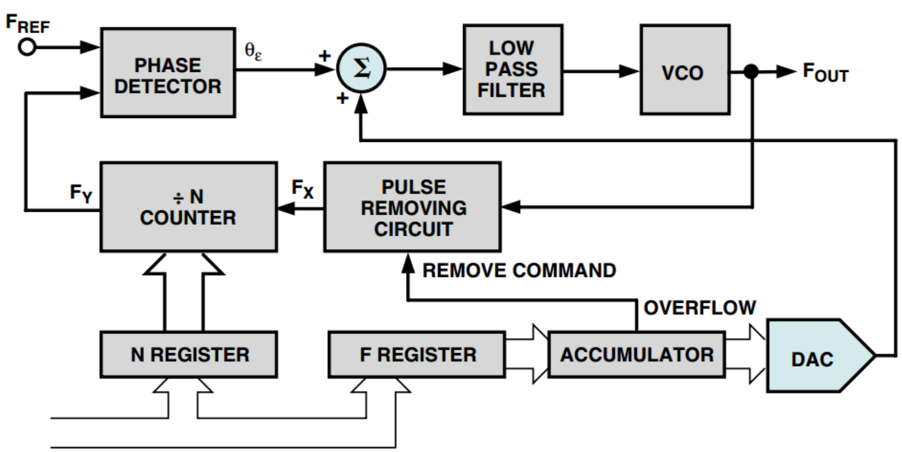


$$f_{out} = \frac{(BP + A) \times f_{REF}}{R}$$

Mark Curtin and Paul O'Brien, "Phase-Locked Loops for High-Frequency Receivers and Transmitters," Analog Dialogue 33-3, 1999

Fractional-N Synthesizer

- Fractional-N synthesizer shifts the modulus of the divider randomly to achieve lower phase noise
- It also achieves greater frequency resolution and faster switching time
- And it's too complicated for this class, so we won't discuss it further.



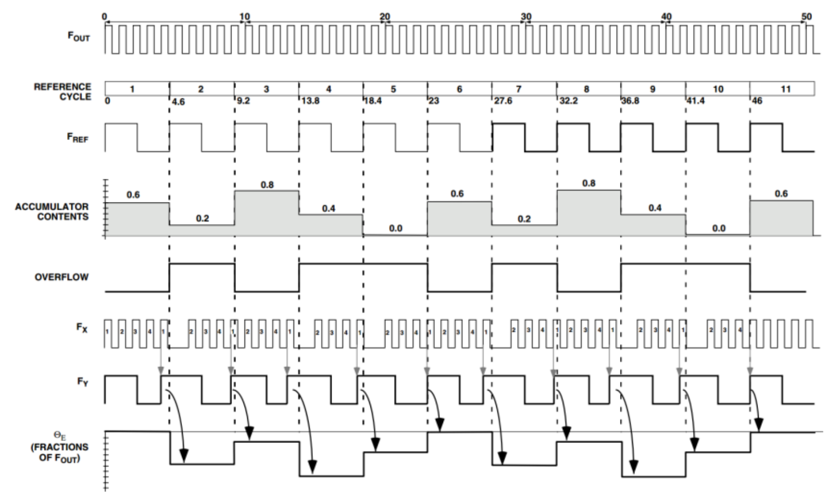


Figure 9. Fractional-N timing.

Mark Curtin and Paul O'Brien, "Phase-Locked Loops for High-Frequency Receivers and Transmitters," Analog Dialogue 33-3, 1999