EEEN3006J

Wireless Systems

Dr. Declan Delaney

(declan.delaney@ucd.ie)

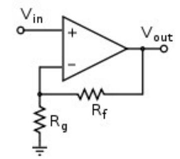
Beijing Dublin International College

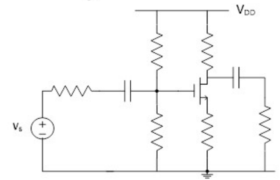
Purpose of the lecture

- In this lecture, we will discuss how to make local oscillators of certain frequency.
- Oscillators are non-linear circuits that take in DC power and output a particular frequency.
- Used in transmitters as:
  - carrier signal into modulator
  - oscillator to drive mixer for up-conversion
- Used in receivers as:
  - local oscillator for mixer for down-conversion
  - local oscillator for demodulation

Purpose of this lecture

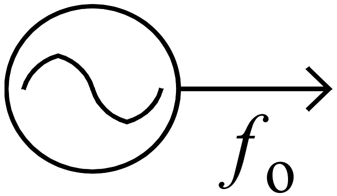
- We usually make them using an amplifier with feedback.
  - The amplifier can be made using
    - Op-amps (Only at lower frequencies), or
    - Transistors

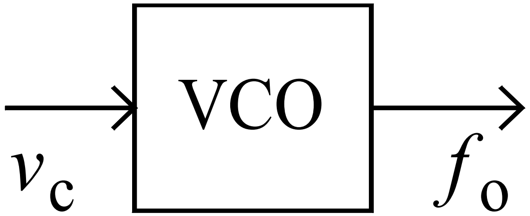




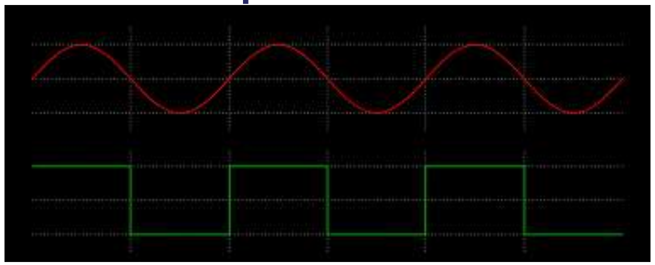
- We usually make them using feedback made up of passive RC or LC circuits.
- Later in the lecture, we will see how to take a very stable low-frequency oscillator and make a tuneable high-frequency oscillator from it.

What makes a good oscillator?



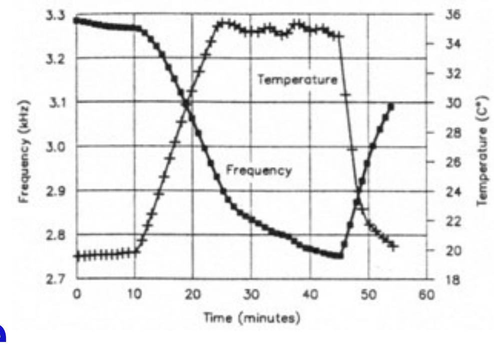


- A periodic signal
  - often sinusoidal signal
  - sometimes a square-wave.



- Frequency may be
  - Fixed value, or
  - controlled by voltage or temperature.
    - VCO = voltage controlled oscillator.

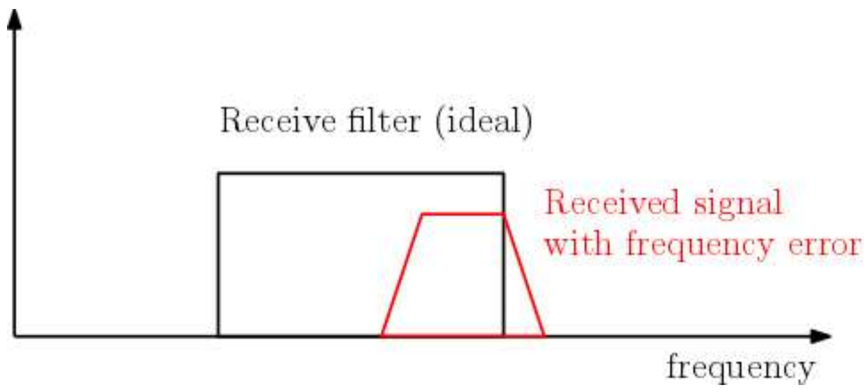
Need: Frequency Stability



Temperature drift in a 7-MHz variable-frequency oscillator. ~10^4 ppm/°C

- Average frequency is accurate
  - over time, and
  - over a reasonable temperature range
- The permitted error ∝ signal bandwidth
  - Easy case: baseband signal, large bandwidth.
  - Difficult case: narrow-band, high-frequency.
- We measure:
  - Error, in parts per million (ppm) or parts per billion (ppb).
  - Variation with temperature; ppm/°C or Hz/°C.
  - Ageing; ppm/year.

- The transmitter needs to transmit at the correct frequency
  - transmit where receiver is expecting signal
  - avoid interference with neighbours
- The receiver needs to shift the frequency of the input signal by the correct amount
  - otherwise wanted signal will not pass through filter.



Datasheet example

MOFH and MOFZ Series / 14 Pin DIP OCXO

- Oven Controlled Oscillator
- 1.0 MHz to 150.0 MHz Available
- 14-pin DIP Package
- -40°C to 85° Available
- ±50ppb to ±500ppb

PART NUMBERING GUIDE:

MOF H 5 S 100 B – Frequency

Output Type
H = HCMOS
Z = Sinewave

Supply Voltage
3 = 3.3 Volt
5 = 5 Volt
12 = 12 Volt

Crystal Cut*
Blank = AT Cut
S = SC Cut

Frequency Stability
050 = ±50ppb
100 = ±100ppb
250 = ±250ppb
500 = ±500ppb

Operating Temperature
A = 0°C to 50°C
B = -10°C to 60°C
C = -20°C to 70°C
D = -30°C to 70°C
E = -30°C to 80°C
F = -40°C to 85°C
G = 0°C to 70°C

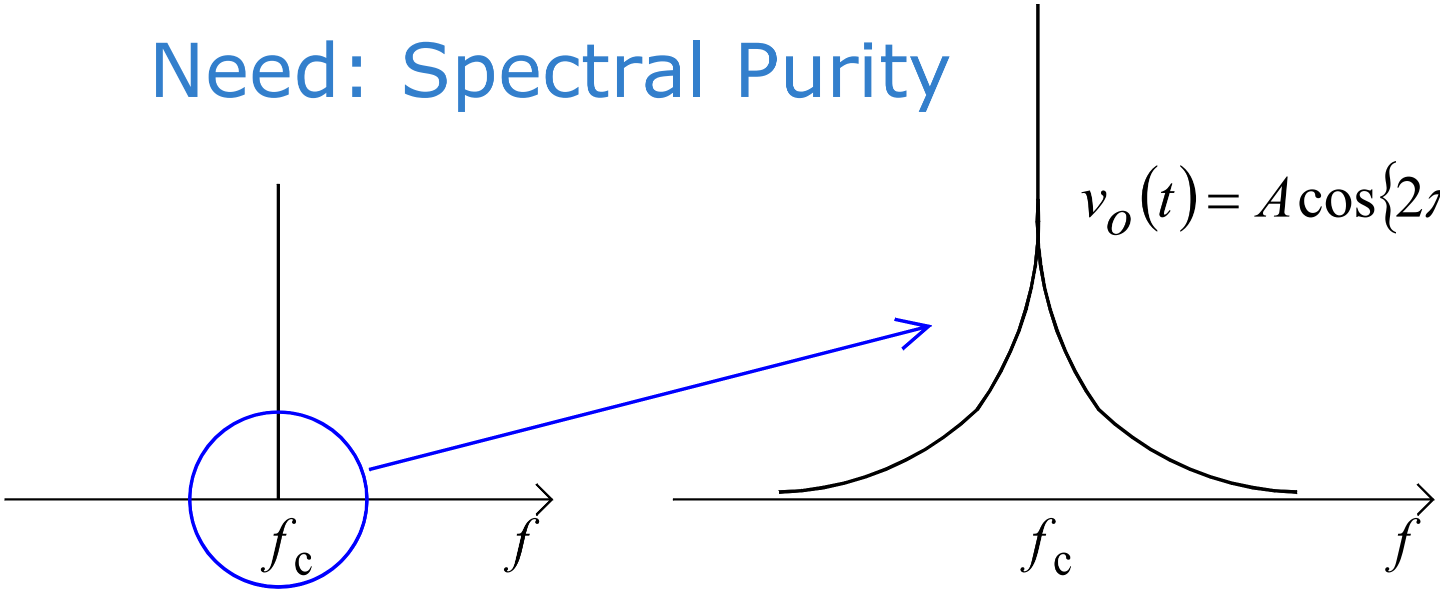
*Specific Stabilites/ Temperatures requires an SC Cut Crystal

ELECTRICAL SPECIFICATIONS:

Frequency Range	1.0 MHz to 150.0MHz		
Frequency Stability	±50ppb to ±500ppb		
Operating Temperature	-40°C to 85°C max*		
* All stabilities not available, please consult MMD for availablity.			
Storage Temperature	-40°C to 95°C		
Output	Sinewave	±3 dBm	50Ω
	HCMOS	10% Vdd max 90% Vdd min	30pF
Supply Voltage (Vdd)	3.3V	5V	12V
Supply Current typ	220mA	200mA	80mA
Supply Current max	550mA	400mA	150mA
Warm-up Time	3min. @ 25°C		
Input Impedance	100K Ohms typical		
Crystal	AT or SC Cut options		
Phase Noise @ 10MHZ	SC	AT	
10 Hz Offset	-100dBc	-92dBc	
100 Hz Offset	-127dBc	-118dBc	
1000 Hz Offset	-140dBc	-135dBc	
Voltage Control 0 to VCC	±3ppm typ	±10ppm typ	
Aging (after 30 days)	±0.5ppm/yr.	±1.5ppm/yr.	

MECHANICAL DETAILS:

Need: Spectral Purity



$$v_o(t) = A\cos\{2\pi f_c t + \phi_n(t)\}$$

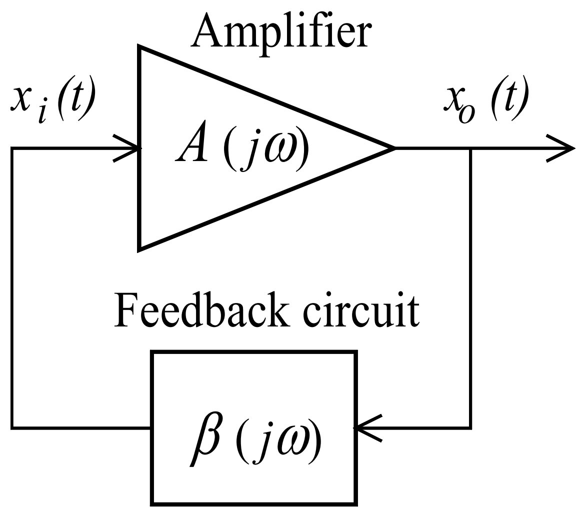
- One line in frequency spectrum
  - no harmonics, no other spurious outputs
- Phase noise = random phase modulation
  - due to random noise in circuit (flicker noise)
  - affects amplitude and phase, but oscillator amplitude control reduces amplitude changes
  - specify power spectral density at some offset
    - e.g. -95 dBc/Hz at 100 kHz
    - dBc = dB relative to carrier (wanted output)

Often Want Frequency Agility

- Frequency adjustable
  - transmitter works over some range of freq.
  - receiver must receive over some range of freq.
- Specify frequency range, step size
  - step size corresponds to channel spacing
- Speed of adjustment
  - frequency-hopping systems - rapid changes
  - generator settles on new frequency quickly
- Conflict with frequency stability
  - oscillator designed for stability usually not adjustable, certainly not quickly

We make oscillators using feedback

- Oscillators: nonlinear circuits convert DC power to AC.
  - Ideally a sinusoid (simpler to design around.)



- Basic idea: amplifier with positive feedback
  - Barkhausen criterion: $A(j\omega)\cdot\beta(j\omega) = 1 + j0$ at some frequency ω.

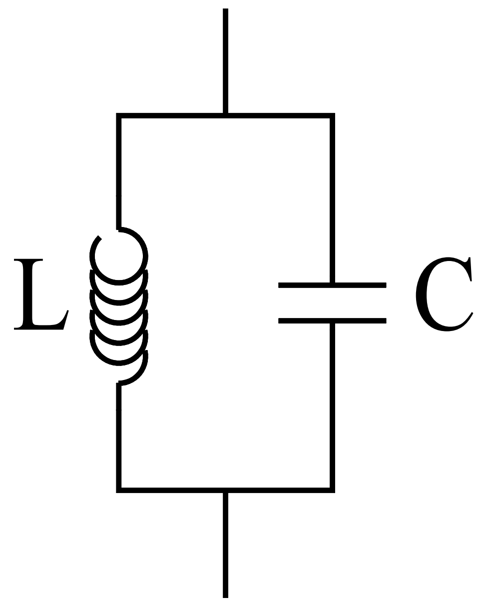
$$x_o = A\,x_i + A\,\beta\,x_0$$

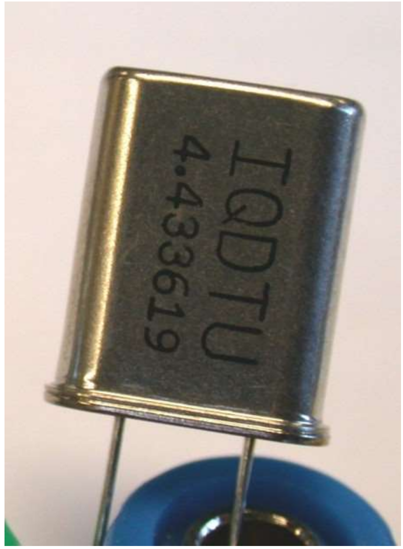
$$x_o = \frac{A}{1 - A\,\beta}\,x_i$$

Barkhausen criterion makes the denominator zero.

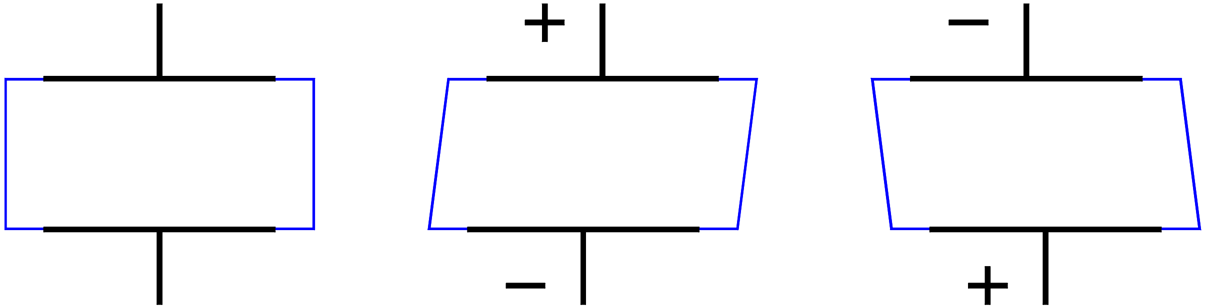
Basic sinusoidal oscillator

- need narrow bandwidth for spectral purity
  - could use L-C resonant circuit (high Q factor)?
  - for narrower bandwidth, use mechanical resonator
- some non-linearity controls amplitude
  - usually in amplifier



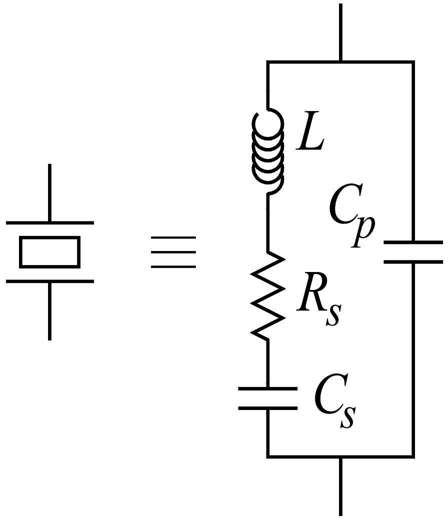


Quartz Crystal Resonator



- Quartz exhibits piezo-electric effect
  - applied voltage causes shape change
  - shape change generates voltage
- Crystal acts as mechanical resonator
  - 2 electrodes, piezo-electric conversions
  - effect is electrical resonator
  - high Q-factor: 10^4 up to 10^6 possible
- Dimensions control resonant frequency
  - up to 100 MHz commonly available

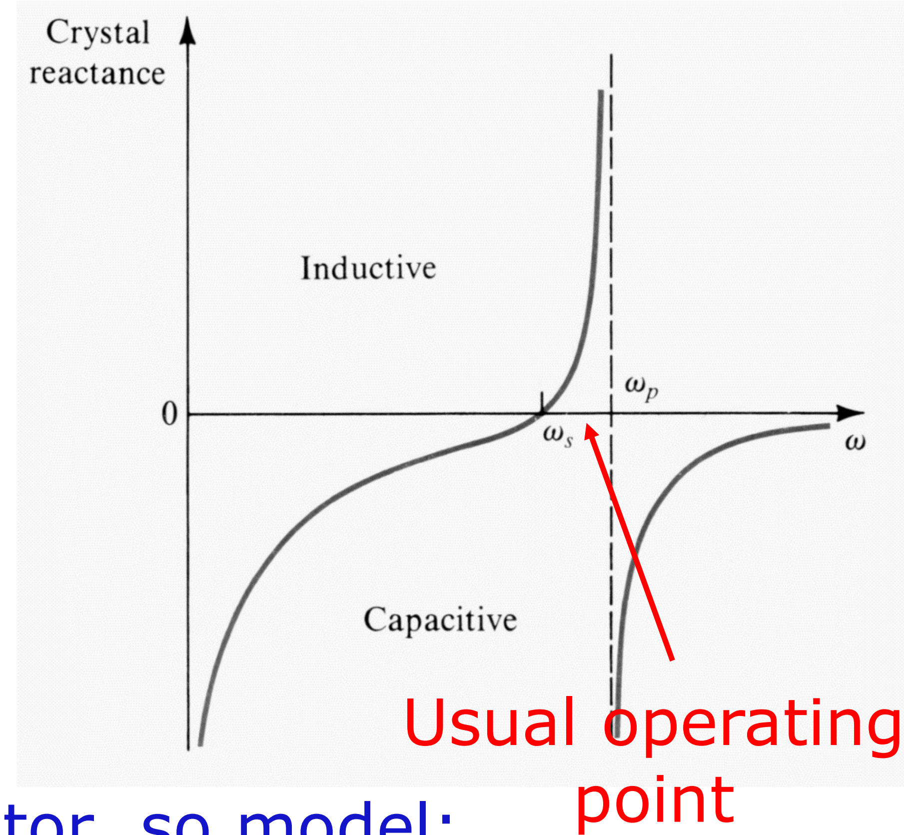
Quartz Resonator



$$\omega_s = \frac{1}{\sqrt{LC_s}}$$

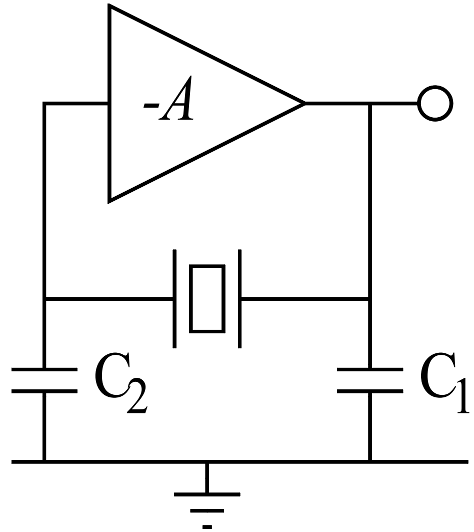
$$\omega_p = \frac{1}{\sqrt{LC'}}$$

$$C' = \frac{C_p C_s}{C_p + C_s}$$



- Mechanical resonator, so model:
  - momentum as large inductance (L, H)
  - elasticity as series capacitance (C_s, fF)
  - Damping and loss as small series resistance R_s
  - also real capacitance between electrodes (pF)
- series and parallel resonances, very close

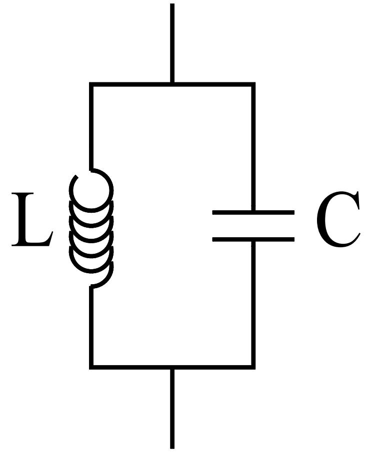
Precision Oscillator



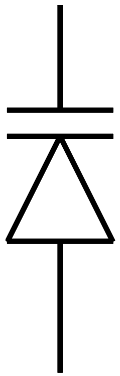
- Want precise frequency, stability, low phase noise
  - use quartz crystal resonator in feedback
    - external capacitors add to parallel capacitance…
    - allow very limited frequency adjustment - ppm
  - for higher precision, place oscillator in oven
    - temperature controlled chamber – TCXO
- Other mechanical resonators possible
  - ceramic resonators
    - similar to quartz, but not as good
  - surface acoustic wave (SAW) resonators
    - vibrations on surface, not in bulk of material

Voltage-Controlled Oscillator

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

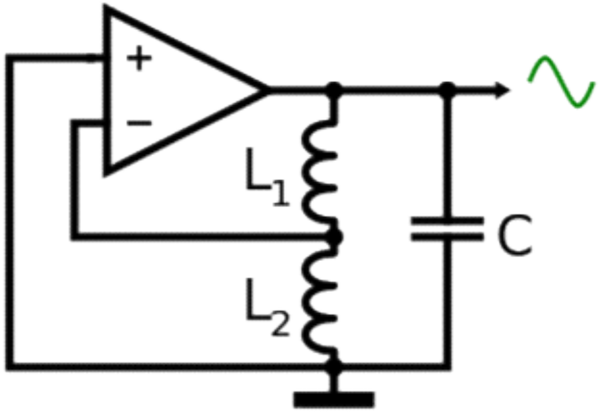


- At RF, usually LC resonant circuit
  - poor precision - Q-factor ~ 10^2
  - (L could be transmission line stub)
- Need electrical adjustment
  - often use capacitance change in diode
  - reverse-biased by control voltage
  - special diodes are optimised for this
  - non-linear relationship



- Easy, quick to change frequency
  - limited range of adjustment
  - difficult to get precise frequency

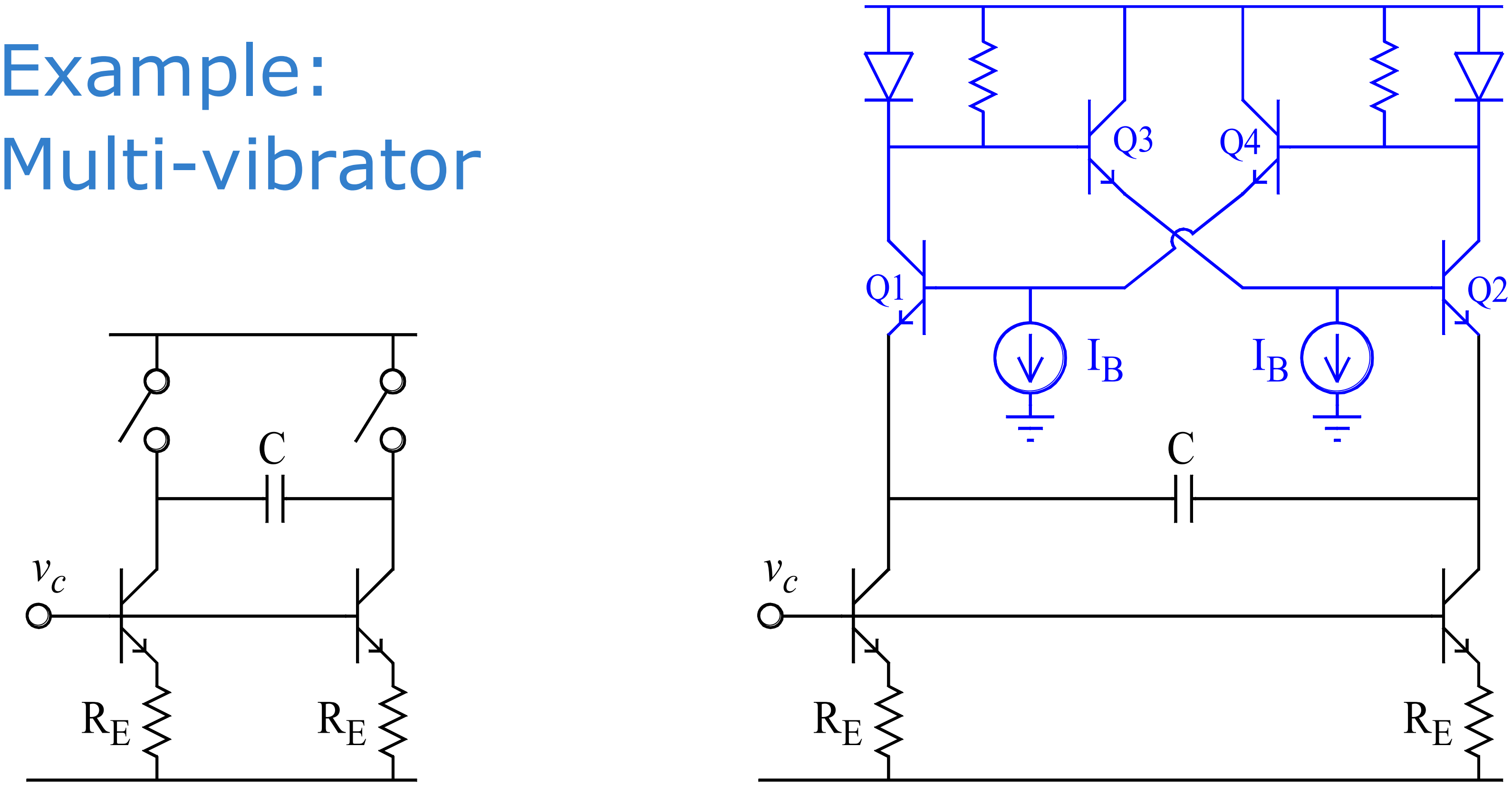
Example: Hartley Oscillator



This diagram shows a variant which uses an op—amp, but transistor-based designs are also common.

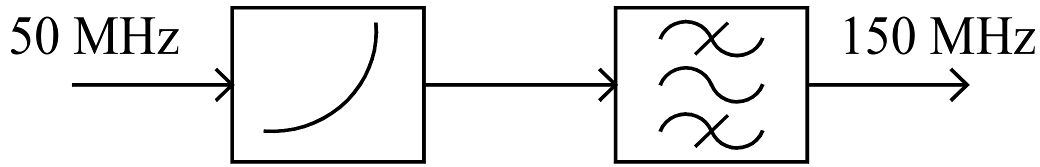
- Basic oscillator uses 2 inductors & 1 capacitor
  - can also use 1 tapped inductor (mutual L)
- Modify for Voltage Controlled Oscillator – replace capacitor with varactor
  - extra capacitor (large) to isolate varactor bias
  - large inductance, “RF choke”, to isolate signal

Example: Multi-vibrator



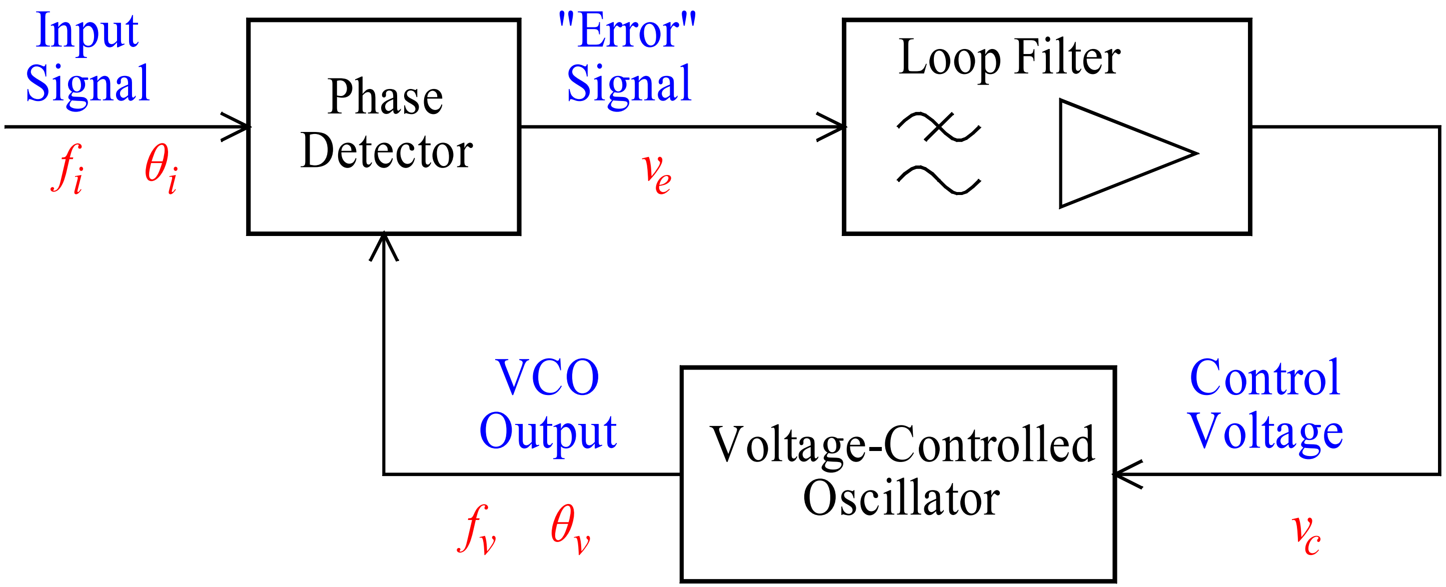
- Capacitor alternately charged & discharged
  - voltage-controlled current sources set freq.
  - switches change charging direction
- More suitable for IC implementation
  - but not at very high frequencies…

Frequency Scaling



- Multiplication
  - use non-linear device to generate harmonics
  - band-pass filter to select required frequency
  - also multiplies phase noise
- Division
  - use flip-flops, counters, etc. to divide by *N*
  - square-wave output (could filter for sine)
  - also divides phase noise
- Addition, subtraction
  - use mixer as seen already (frequency shifting)

Phase-Locked Loop (PLL)

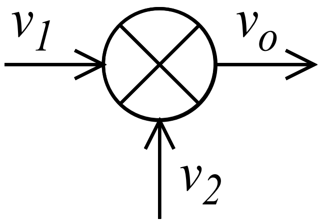


- Feedback control system
  - adjusts frequency of VCO to match input
  - phase detector measures phase difference
  - loop filter provides gain and low-pass filter
    - controls behaviour of the system

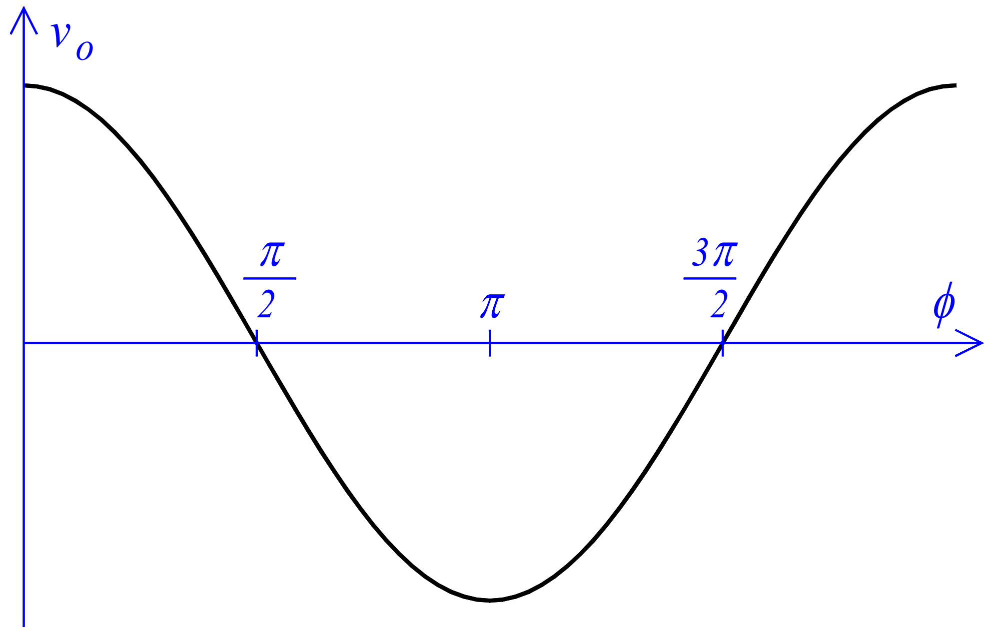
PLL Application Examples

- Noisy or modulated input
  - want VCO to follow average frequency of input
  - use loop filter with narrow bandwidth
  - in communications receiver, extract carrier frequency or clock frequency from signal…
- Frequency Modulation – demodulator
  - get VCO to follow changing input frequency
  - loop filter bandwidth must be wide enough
  - then control voltage $\propto$ modulation…
- Frequency Synthesis
  - input from stable (e.g. crystal) oscillator
  - synchronise VCO with multiple of input freq.
  - get agility of VCO with stability of crystal…

Phase Detector Example 1

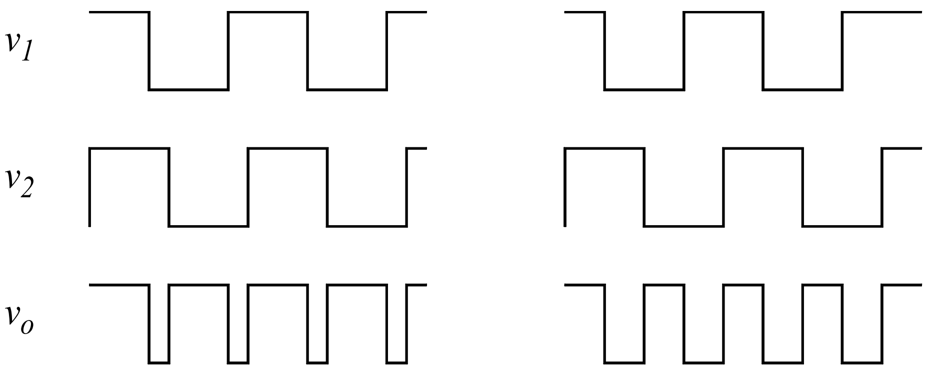


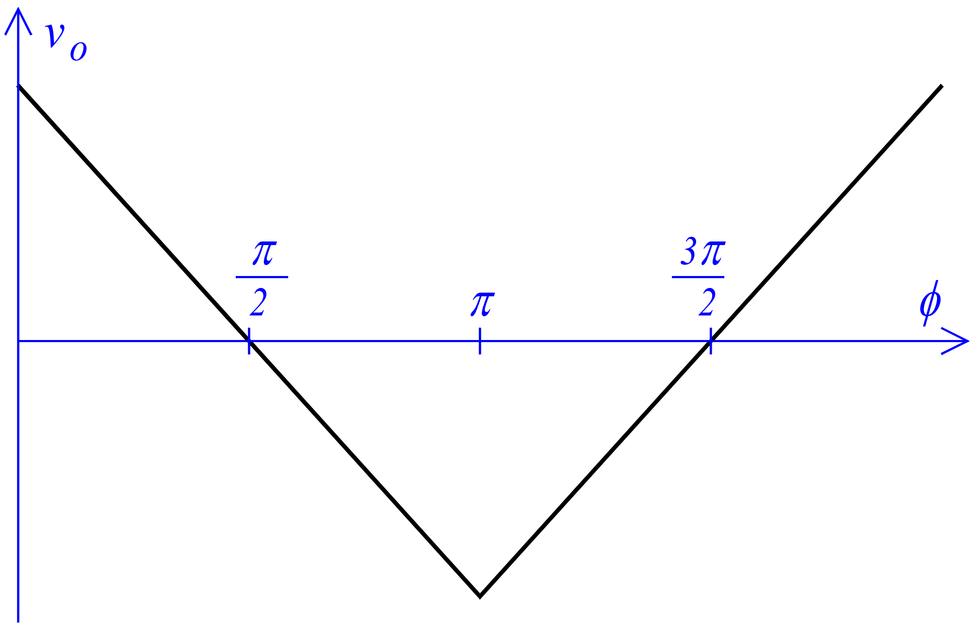
$$v_o(t) = K\, v_1(t) v_2(t)$$



- Ideal Multiplier
  - inputs $v_1(t) = A_1 \sin(\omega_1 t)$ $\quad v_2(t) = A_2 \sin(\omega_2 t + \phi)$
  - $v_o(t) = \mathrm{K}\frac{A_1 A_2}{2}[\cos\{(\omega_2 - \omega_1)t + \phi\} - \cos\{(\omega_2 + \omega_1)t + \phi\}]$
  - high-frequency term removed by loop filter…
- If both frequencies equal (PLL is working properly)
  - effective $\quad v_o(t) = \mathrm{K}\frac{A_1 A_2}{2}[\cos(\phi)]$
  - non-linear relationship phase difference <-> output
    - ~ linear around zero output

Phase Detector Example 2

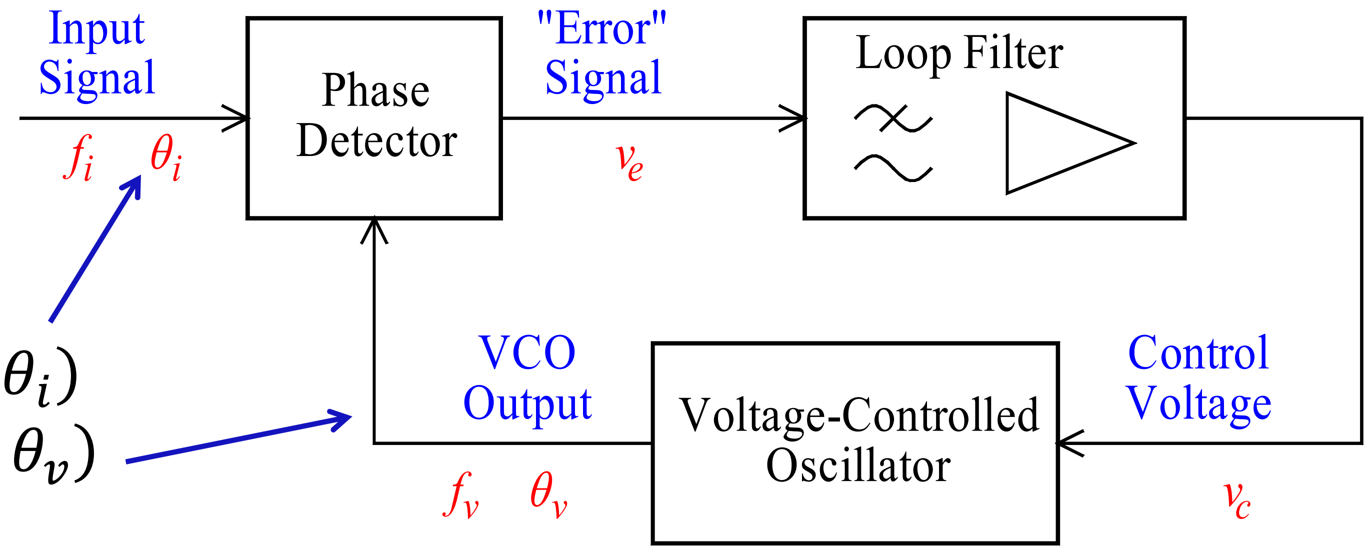




- Multiplier with square-wave signals: ± 1 V
  - exclusive-NOR gate behaves similarly
- For "phase" difference ϕ, average output

  $\overline{v_o} = \frac{K(\pi - |\phi|) - K|\phi|}{\pi} = K\left(1 - \frac{2|\phi|}{\pi}\right)$ assuming same freq.
  - note linear over 180° range
  - periodic in phase difference (as expected)

PLL Operation



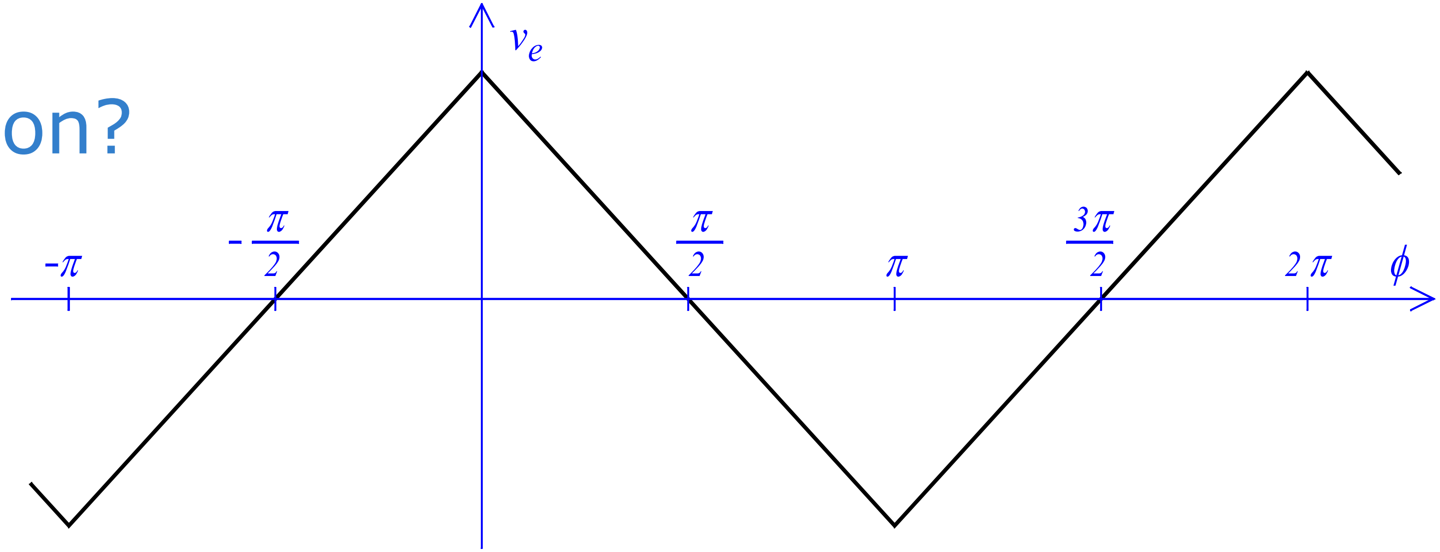
$A_i \cos(2\pi f_0 t + \theta_i)$

$A_v \cos(2\pi f_0 t + \theta_v)$

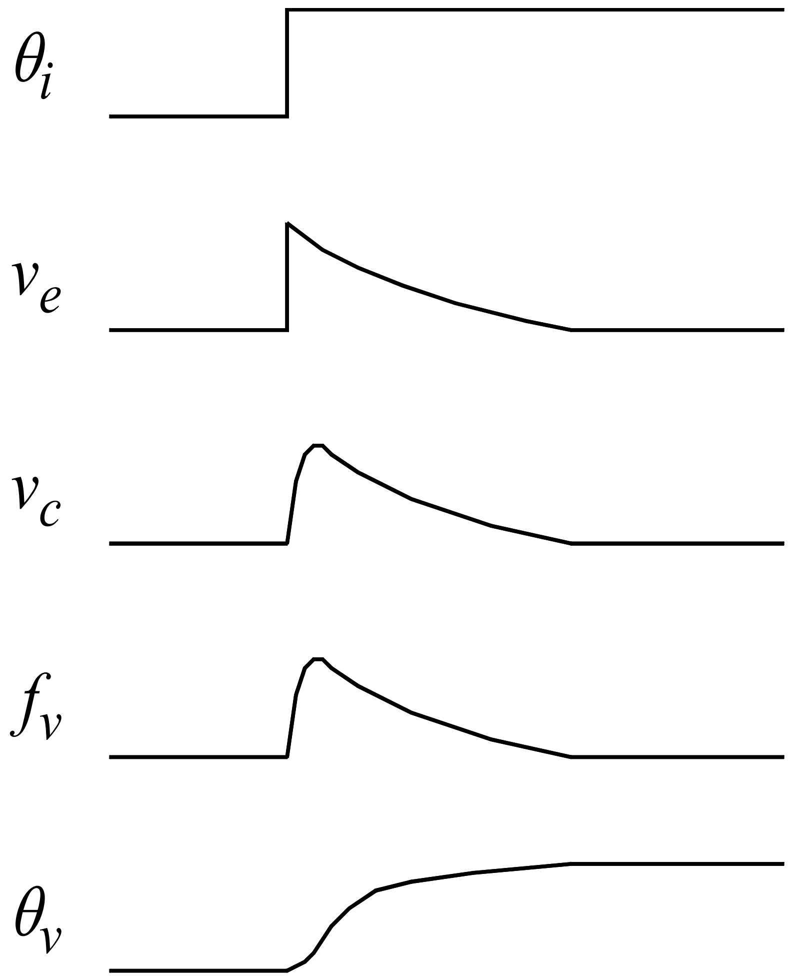
- VCO: $f_v = f_0 + k_f v_c$ $\quad f_v = f_0 + \frac{1}{2\pi}\frac{d\theta_v}{dt}$
  - centre frequency f_0, change proportional to v_c
  - frequency $\propto$ rate of change of phase angle
- In normal operation, loop is “locked”

  $\Rightarrow$ VCO is following frequency of input signal
- If input signal at frequency f_0
  - VCO also at f_0, so $v_c = 0$, so $v_e = 0$
  - so phase difference must be $\pm\frac{\pi}{2}$

Stable Operation?



- Define phase difference $\phi = \theta_i - \theta_v$
- Suppose relative phase of input advances
  - ϕ becomes larger – moving to right on graph
  - what happens to error voltage?
  - what happens to VCO control voltage?
  - what happens to VCO frequency?
  - what happens to VCO phase?
- Which operating point is stable?

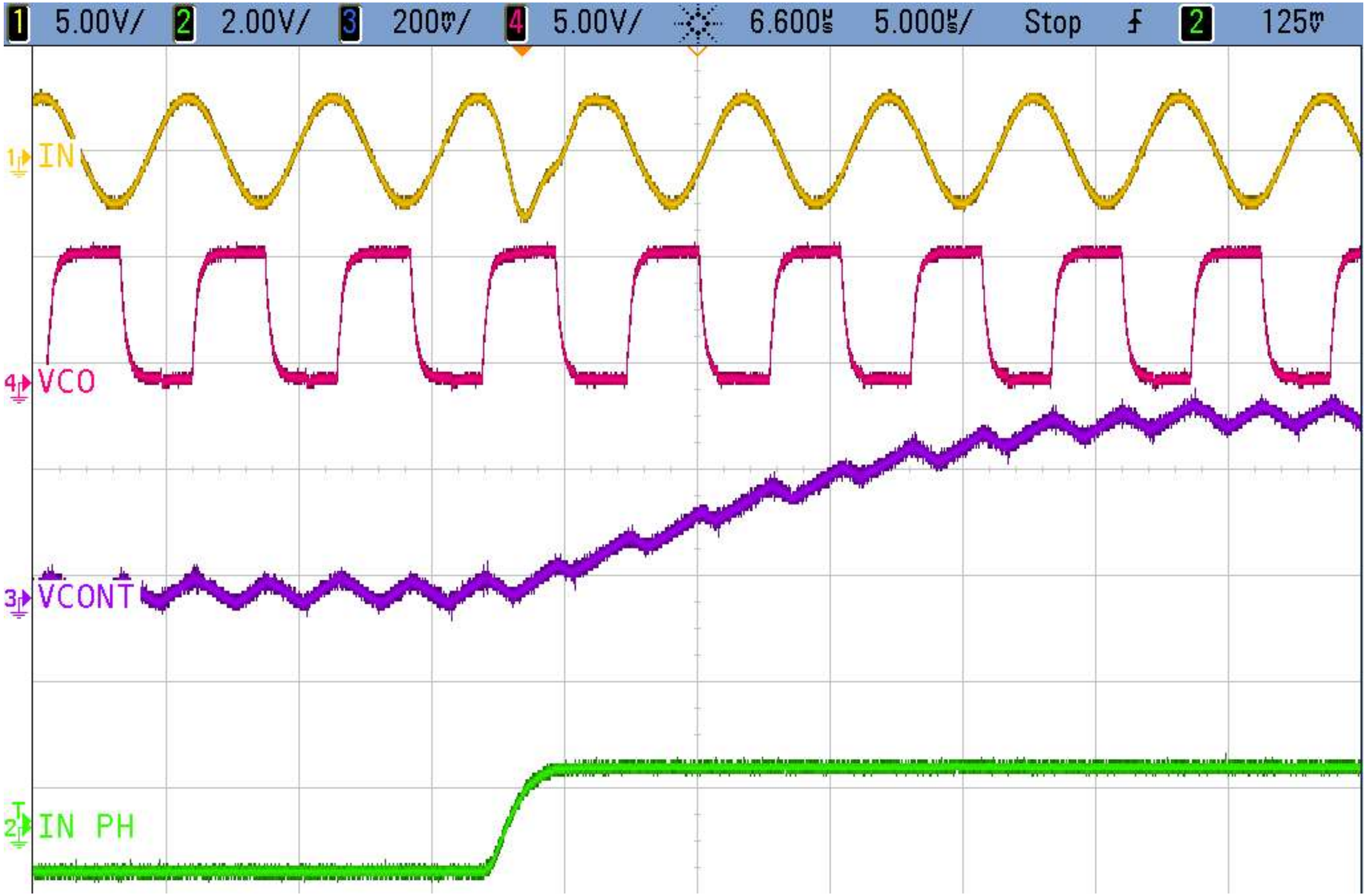


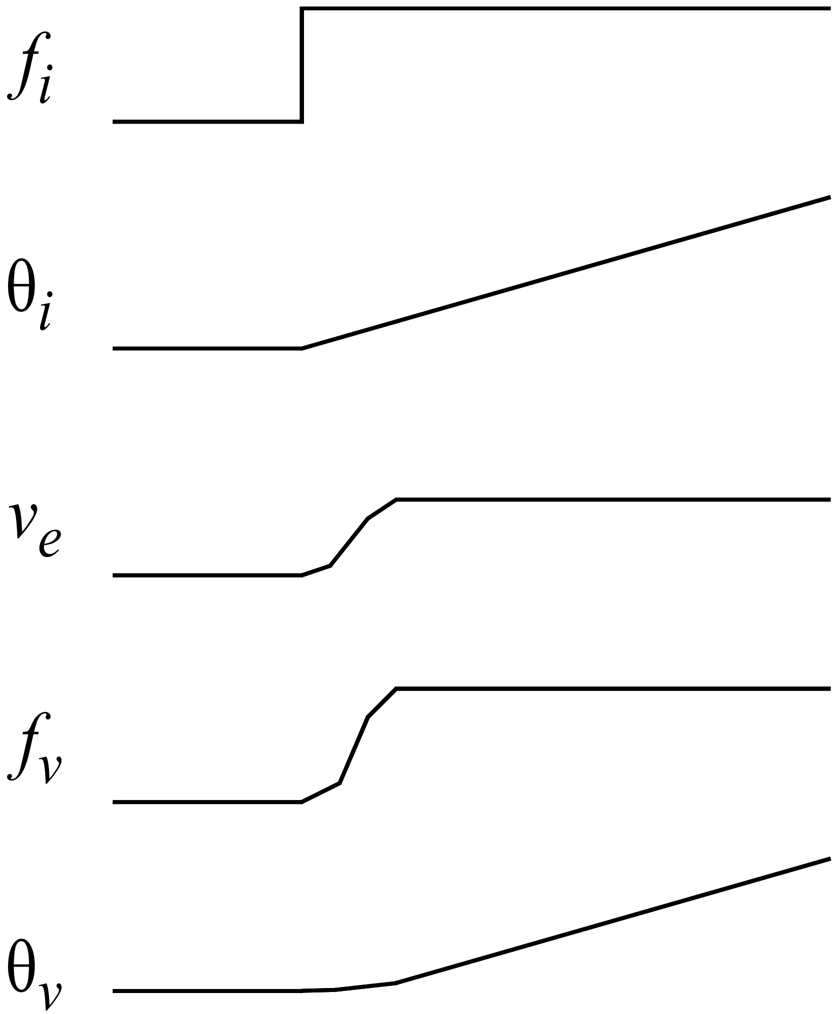
$$\theta_v = \theta_0 + 2\pi \int_0^t f_v \, dt$$

Response to Phase Change

- Step change in θ_i
- $\Rightarrow$ step in v_e
- $\Rightarrow$ v_c starts to rise
  - – low-pass loop filter…
- so f_v follows – VCO
- so phase advances
  - $\Rightarrow$ phase error falls…
- Settles at $v_c = 0$ again
- transient is example
  - depends on loop & filter parameters

Phase Change Example

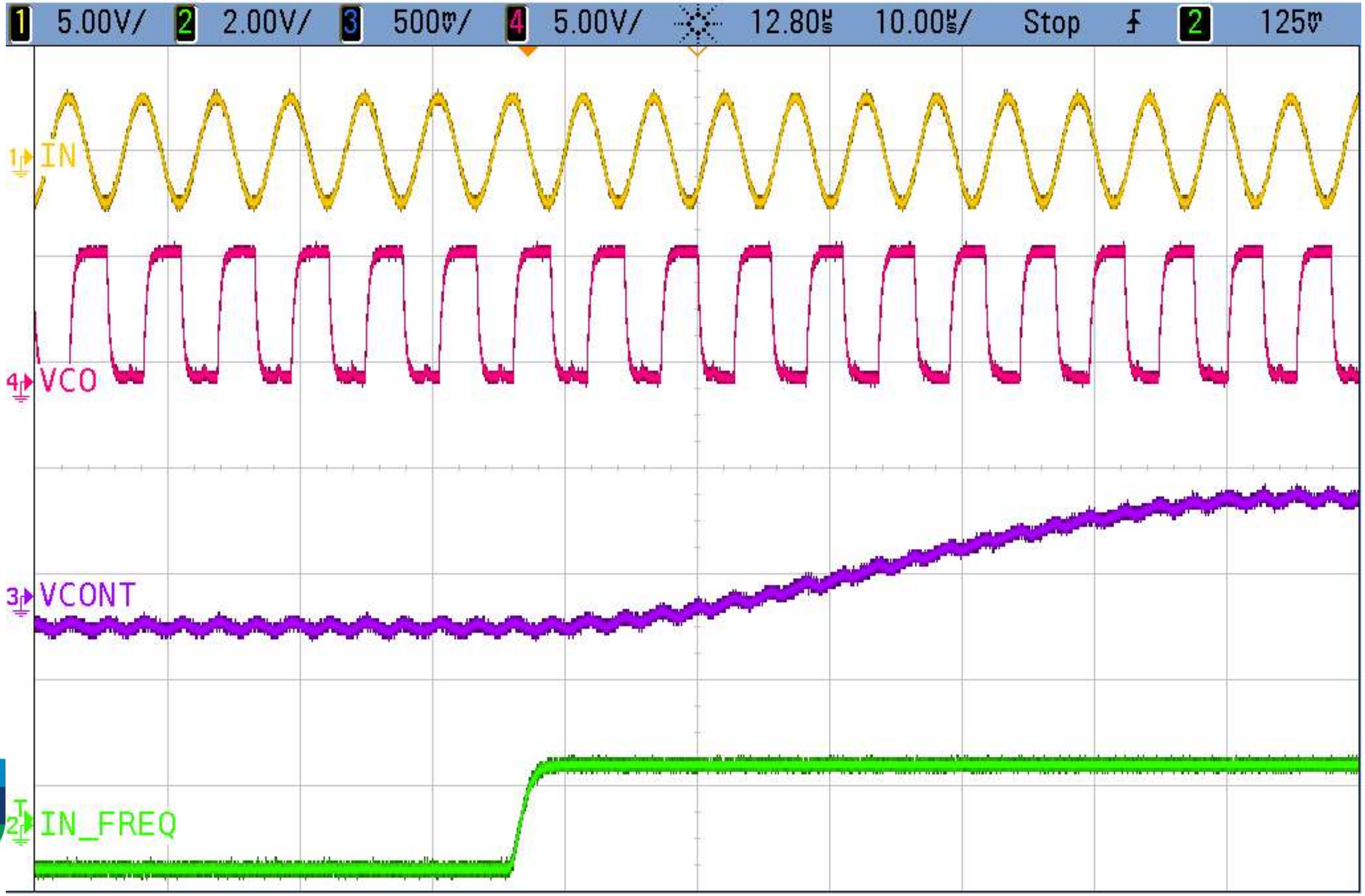




Response to Frequency Change

- Step change in $f_i \longrightarrow f_0 + \Delta f$
  - so θ_i starts to advance
  - v_e increases
  - f_v follows
  - so θ_v advances also
- Settles with $v_c \neq 0$
  - needed to get higher f_v
  - so phase error needed…
- Transient is example

Frequency Change Example



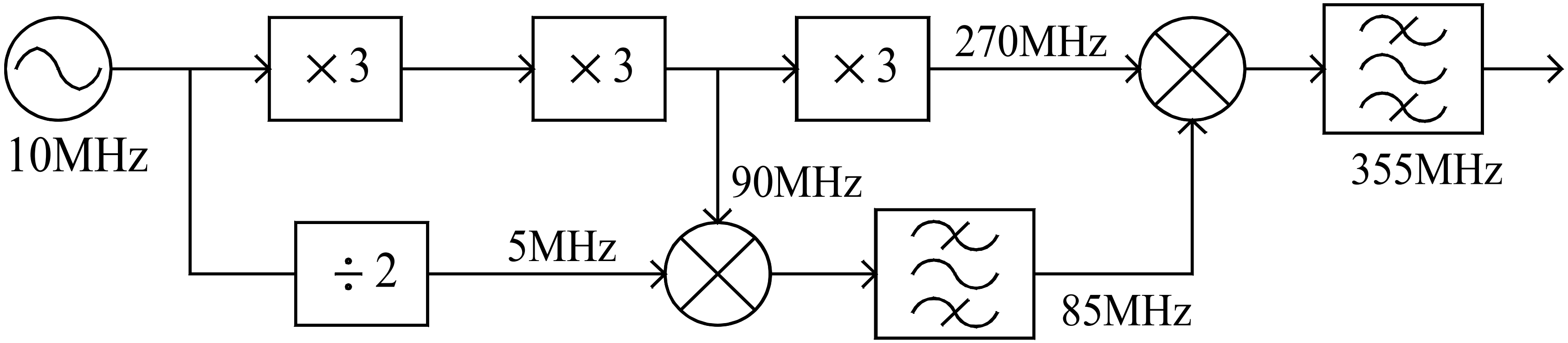
Lock Range

- We define the lock range of PLL as:
  - range of input frequency over which loop can remain locked.
- What determines the lock range?
  - Maybe the limits of the VCO adjustment (if this is small).
  - Otherwise, the limits of the phase detector output
    - multiplied by the gain of the filter, k_a
    - multiplied by the frequency sensitivity of the VCO, k_f.

Capture Range

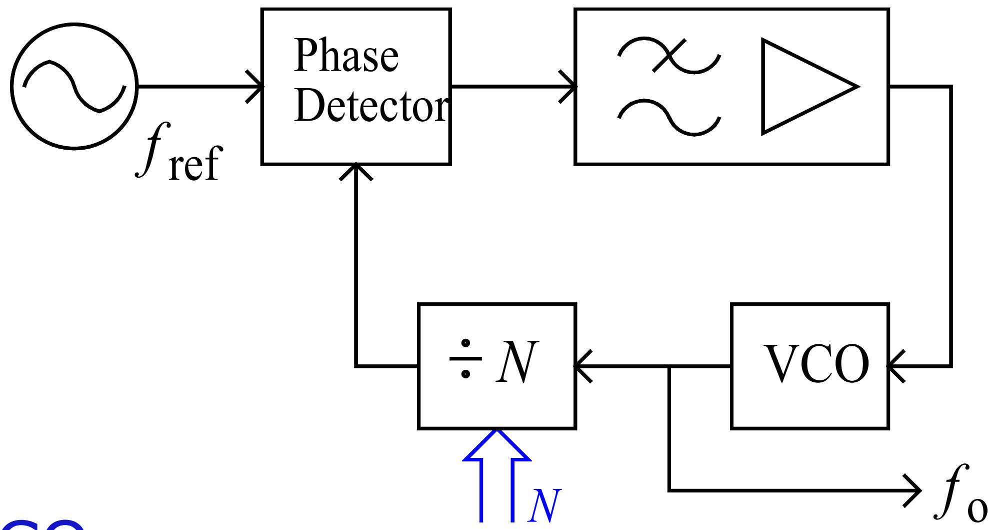
- We define the capture range of the PLL as:
  - The range of input frequencies at which loop can acquire a lock.
  - e.g. if the signal has just been switched on…
- Cannot exceed lock range – usually less
- Depends on bandwidth of loop filter
  - when not locked, phase detector output is at difference frequency
  - must be within bandwidth of loop filter in order to affect VCO frequency
  - with no input, or input far from VCO, VCO runs at centre frequency, f_0

Frequency Synthesis



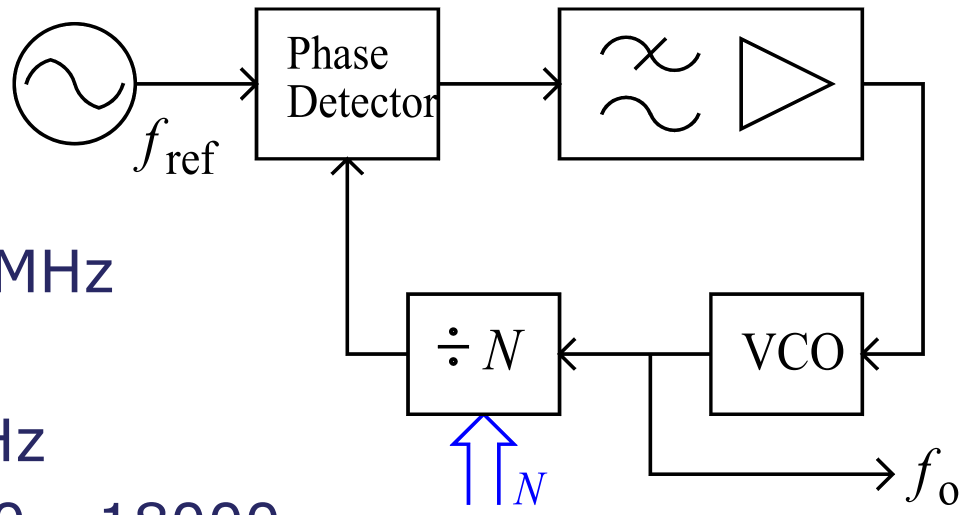
- Generate any one of a discrete set of freq.
  - stability of crystal oscillator
  - agility of VCO
  - usually computer controlled
- Example is original Direct Freq. Synthesis
  - stable crystal oscillator provides input
  - multiply, divide, mix to get desired output
  - switch hardware for adjustable output

Indirect Frequency Synthesis

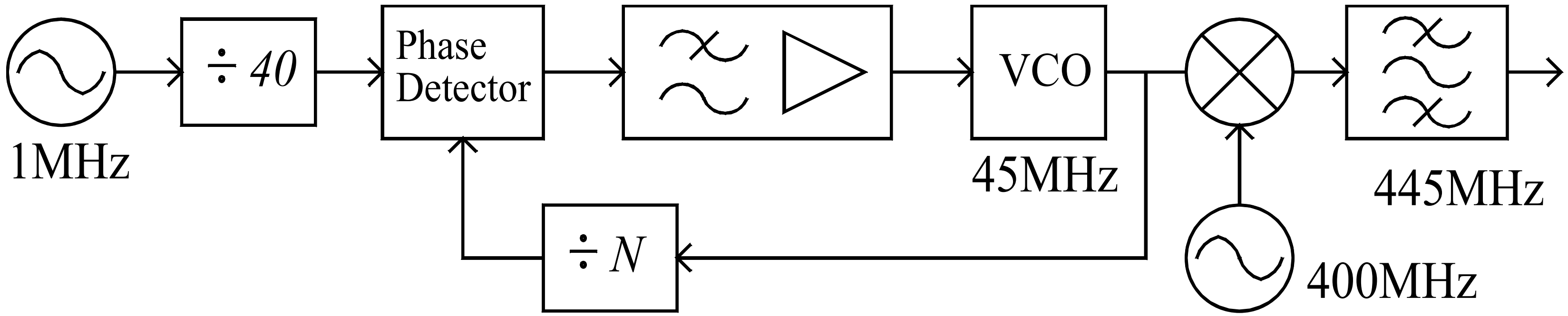


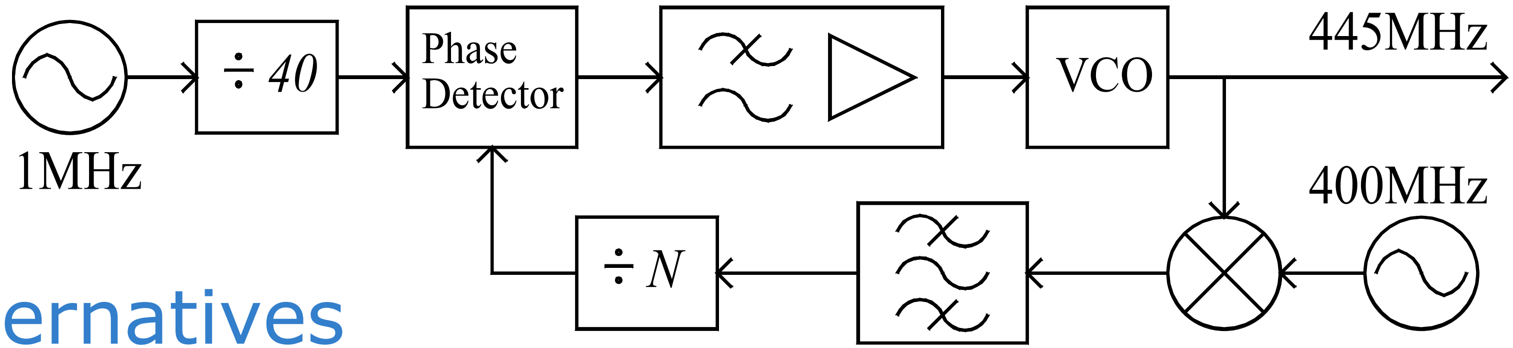
- Output is from VCO
  - use PLL to lock frequency to stable reference
  - if loop locked, inputs to phase detector must be at same frequency, so $f_o = N f_{ref}$
  - reference frequency derived from crystal osc.
  - divider is digital counter, adjustable *N*
  - number-controlled oscillator, step size = f_{ref}
  - small step size at high frequency $\Rightarrow$ large *N*

Problems



- Example:
  - want 440 - 450 MHz
  - steps of 25 kHz
  - need f_{ref} = 25 kHz
  - N in range 17600 - 18000
- Slow response - long settling time
  - phase detector at 25 kHz, narrow loop filter BW
  - VCO control voltage cannot change rapidly
- Phase noise poor
  - close to f_o, get phase noise of reference $\times N$
  - farther out, get phase noise of VCO
    - PLL has no control above loop filter BW
- Hard to build adjustable high-speed divider

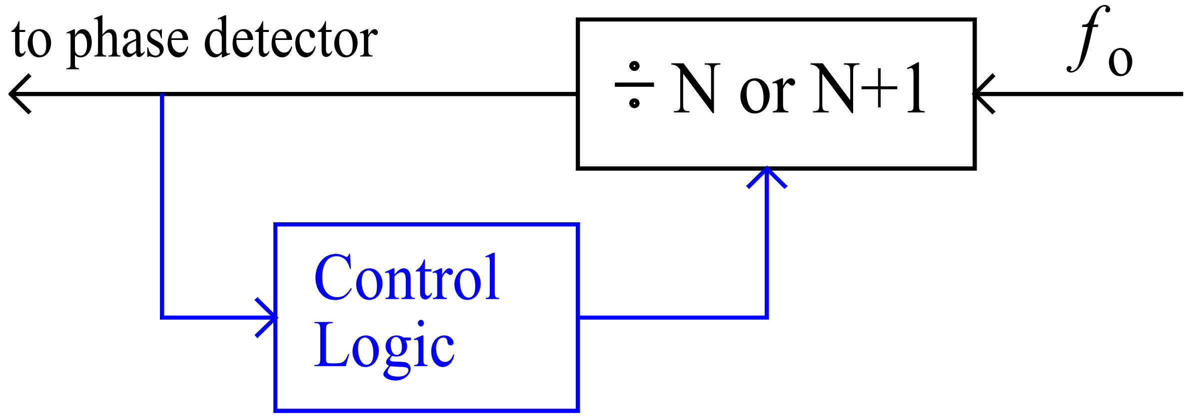




Alternatives

- Combine indirect and direct synthesis
  - PLL used to get range and step size, at low freq.
  - add fixed frequency to get required output
  - or run VCO at output frequency,
  - subtract fixed freq. before input to divider

Fractional-*N* Divider

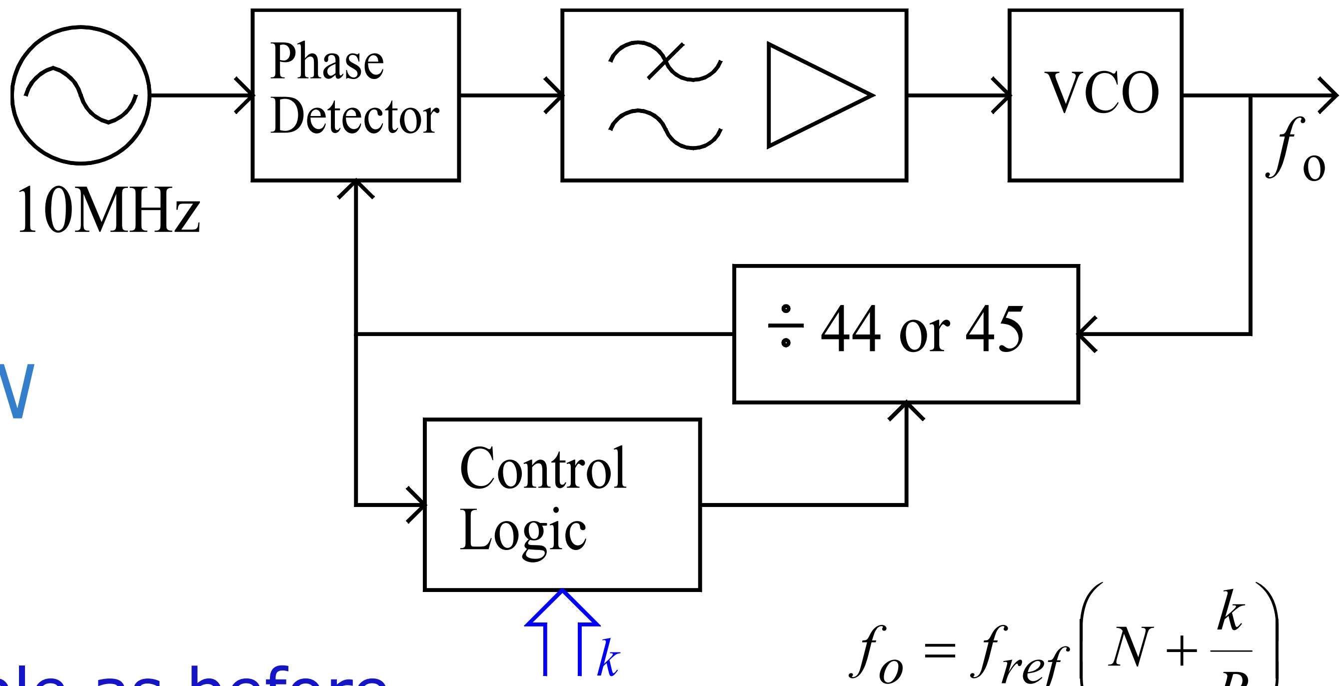


- Modified divider allows non-integer division
  - allows small step size with higher f_{ref}
- High-speed divider, with 2 division ratios
  - *dual-modulus* divider
  - control logic counts output cycles:

    ÷(N+1) for k cycles of each R, then

    ÷N for R-k cycles of each R

    average division ratio = $\dfrac{(N+1)k + N(R-k)}{R} = N + \dfrac{k}{R}$



Fractional-N Synthesis

$$f_o = f_{ref}\left(N + \frac{k}{R}\right)$$

- Example as before
  - want 440 to 450 MHz, 25 kHz steps
  - now use f_{ref} = 10 MHz (for example)
    - allows much larger loop filter BW
  - Choose N to get frequency in required range
    - here N = 44, so minimum output freq. 44 times f_{ref}
  - choose R to get required step size …
  - adjust k to get specific frequency

$$f_o = 440\text{ MHz} + k \times 25\text{ kHz}$$

Problems

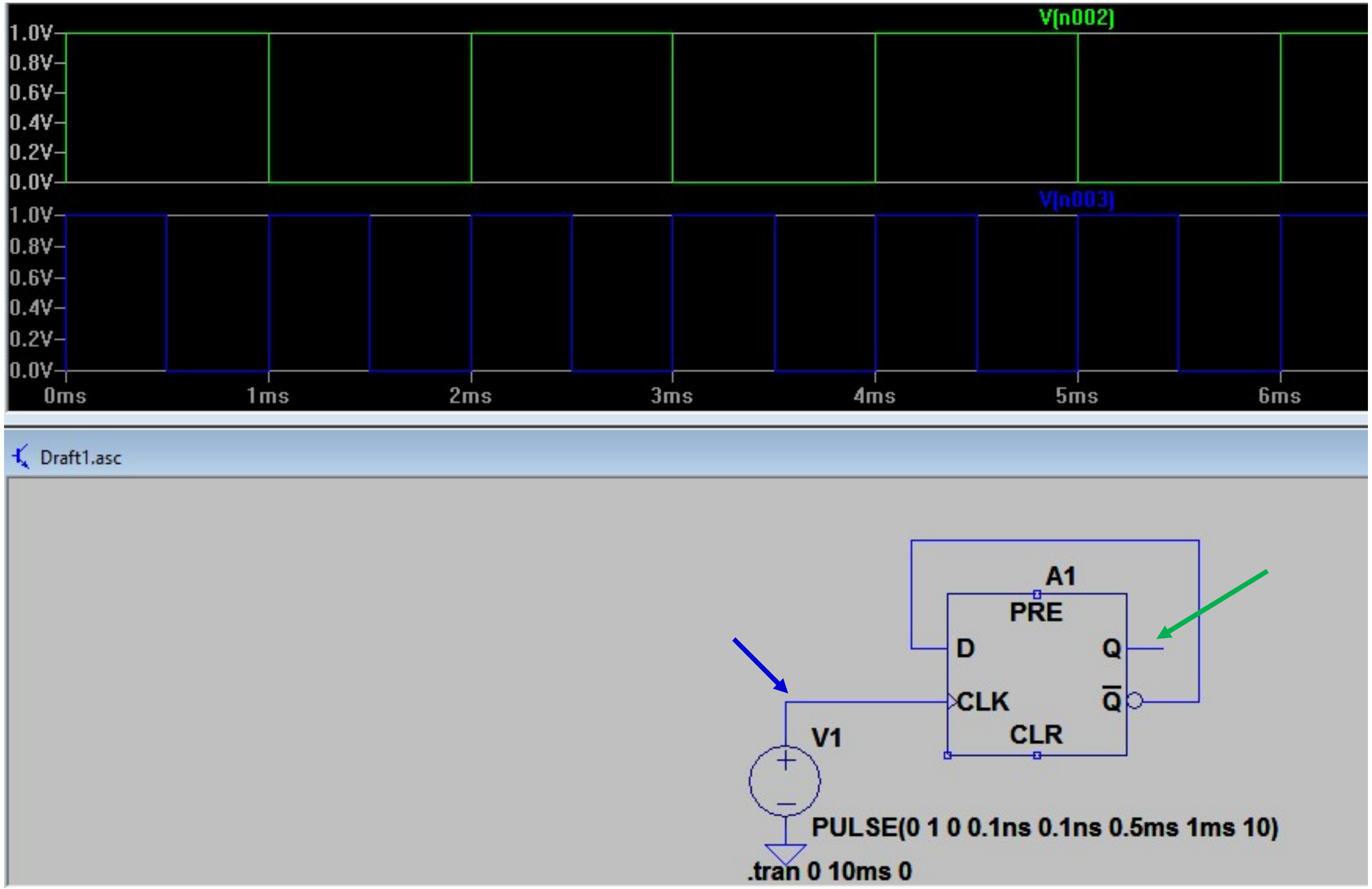
- Spurious components in output
  - note periodic change in division ratio at $\dfrac{f_{ref}}{R}$

  $\Rightarrow$ periodic component in VCO control voltage

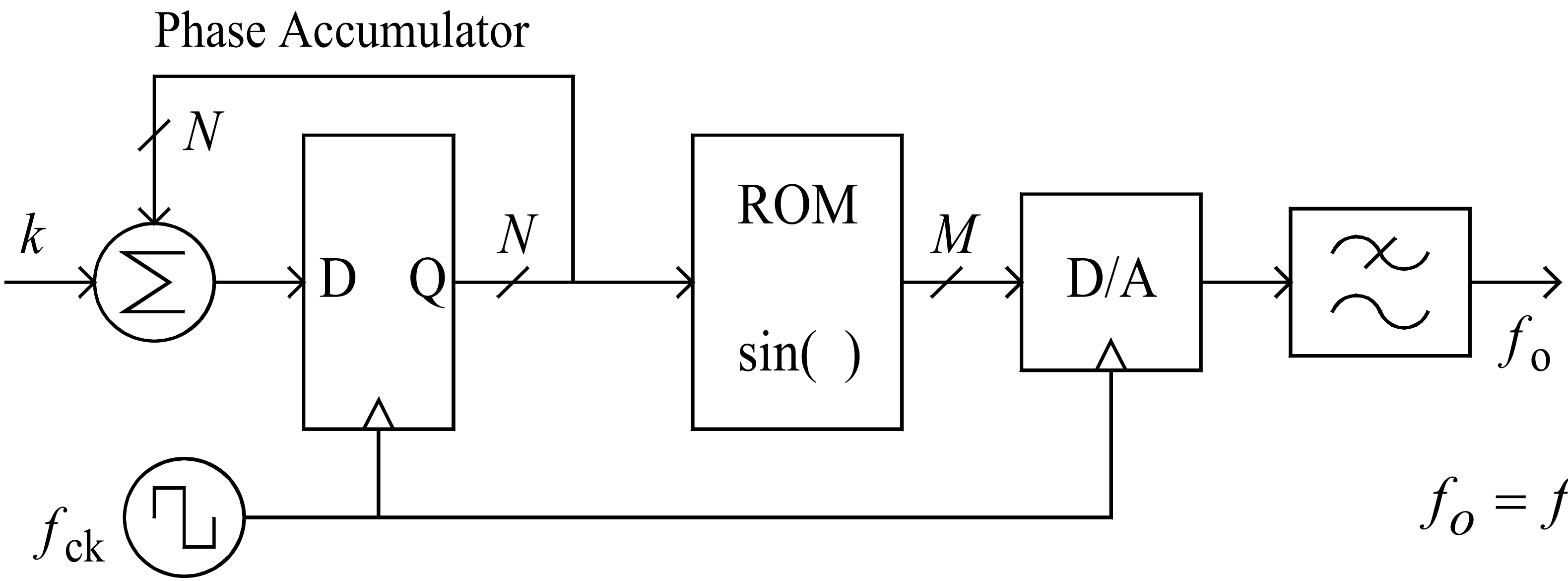
  $\Rightarrow$ periodic frequency modulation of VCO

  $\Rightarrow$ spurious components in output spectrum, at multiples of f_{ref}/R on both sides of f_o .
- Solutions:
  - randomise division adjustment
    - much more complex hardware…
  - add compensating signal to control voltage
    - since error is periodic and predictable…

Double frequency with a d-type flip-flop



Direct Digital Synthesis

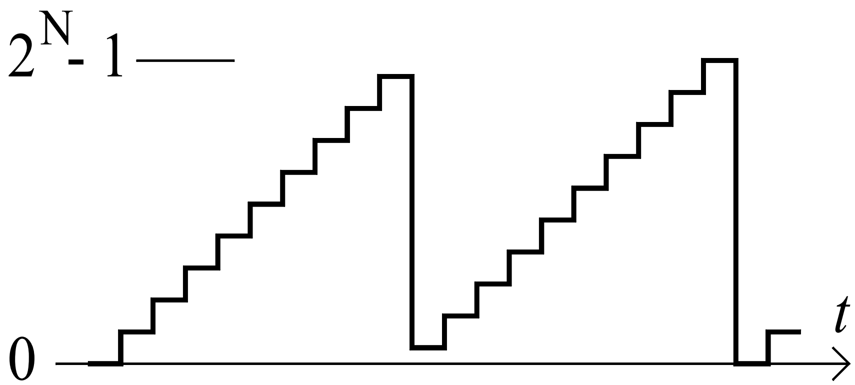


$$f_o = f_{ck} \frac{k}{2^N}$$

- Generate samples of signal digitally
  - add *k* to phase accumulator on each clock
  - so phase value advances at adjustable rate
  - overflows regularly - view as angle, 0 to 2π
  - ROM gives sin( ) of this phase angle
  - apply samples to D/A converter, reconstruct

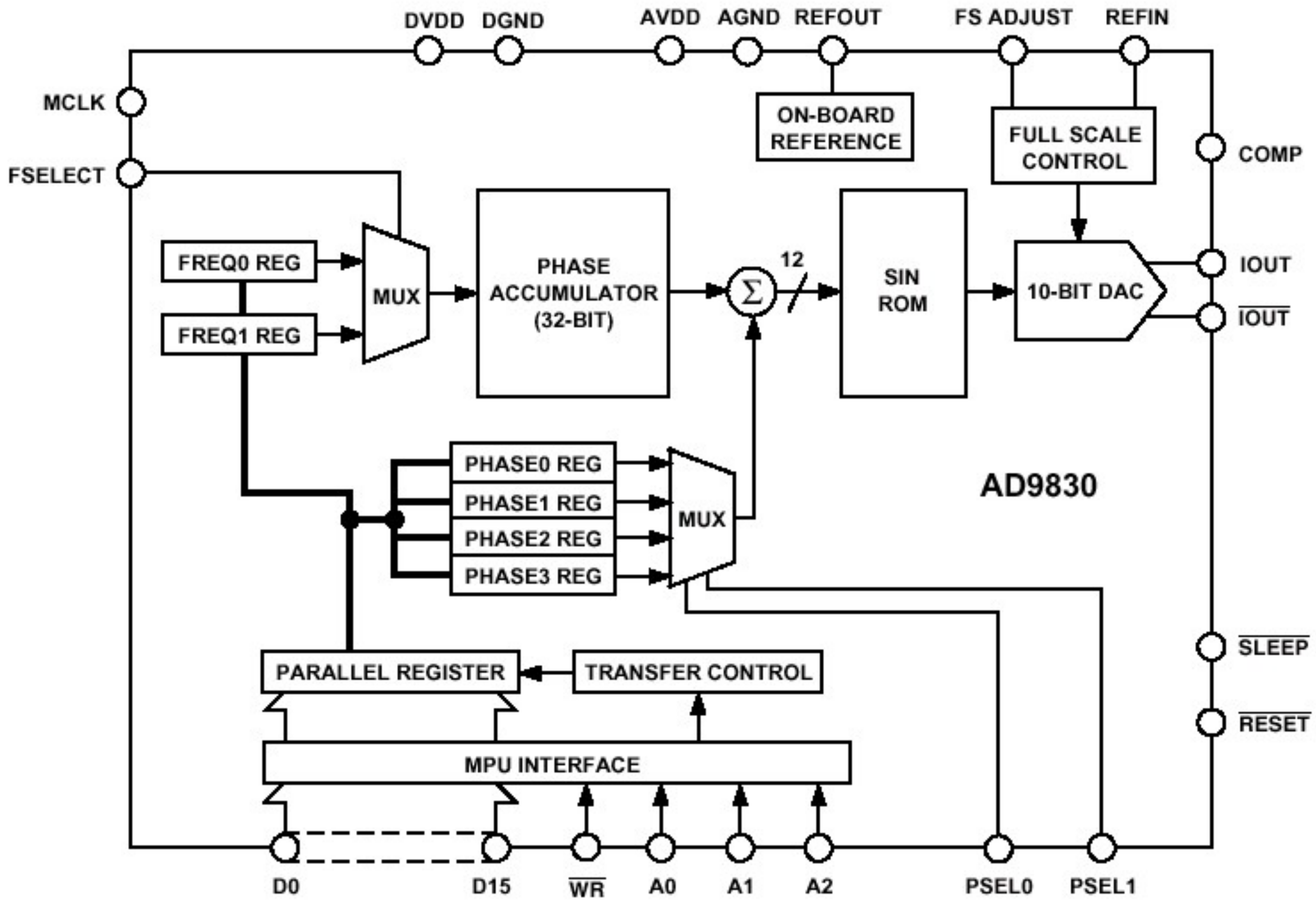
DDS

$$f_o = f_{ck} \frac{k}{2^N}$$



- For large *N*, extremely small frequency steps
  - low phase noise - due to clock jitter
- Many spurious outputs
  - phase has other periodic components
  - in example above, at half output frequency
  - quantisation errors - also periodic
- Output frequency
  - must be much less than clock frequency
  - also limited by speed of D/A converter
- Modulation possible - phase, frequency

Example: AD9830



- 50 MHz max clock, 32-bit phase, 10-bit DAC
- 2 frequencies, 4 phase offsets stored

Example: AD9910

- 1 GHz max clock
  - output up to 400 MHz (with good filter)
- 32-bit phase accumulator, 14-bit DAC
  - freq. resolution ~ 0.23 Hz at 1 GHz clock.

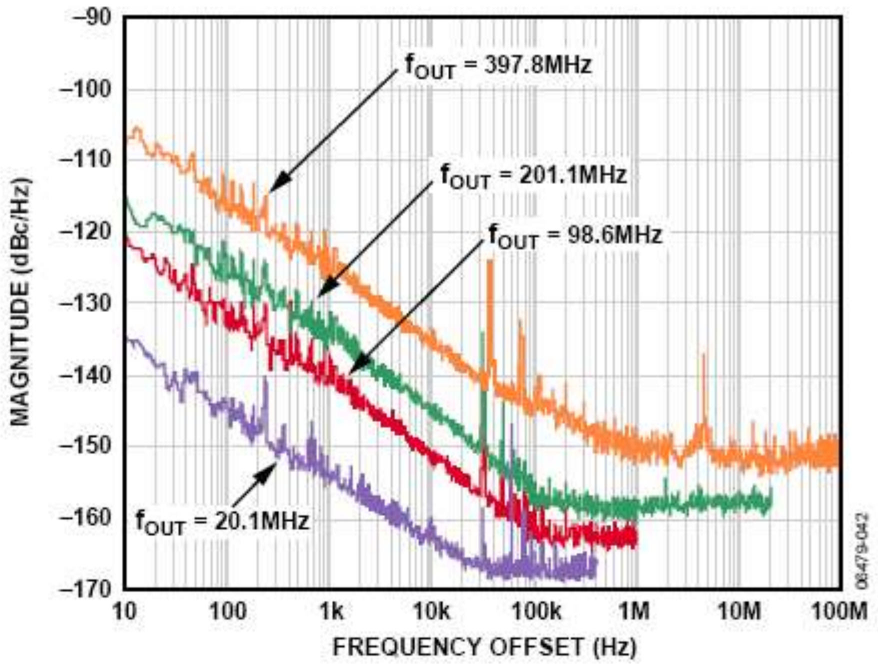


Figure 15. Residual Phase Noise Plot, 1 GHz Operation with PLL Disabled

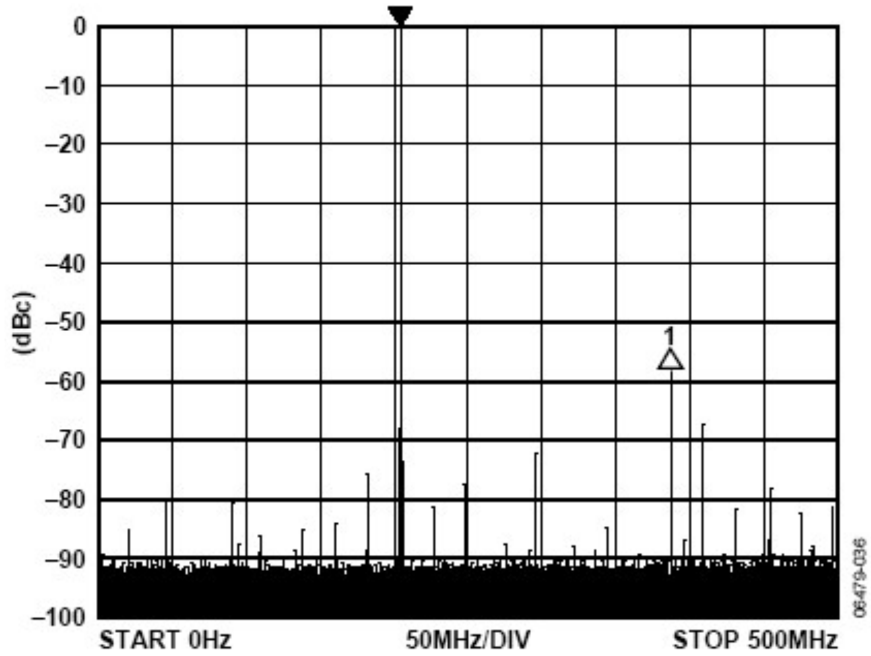


Figure 10. Wideband SFDR at 204 MHz, REFCLK = 1 GHz