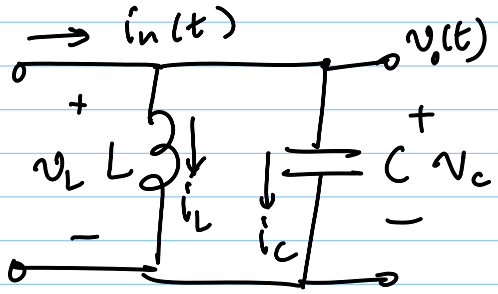
Lecture 32 : VCO Design

ISF



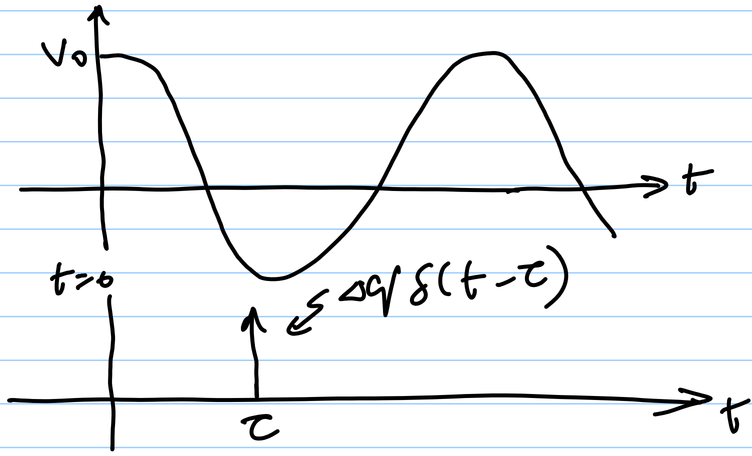
initially, $v_o(t)$ is

$$v_i(t) = V_0 \cos \omega_0 t$$

current pulse @ τ

$\Rightarrow$ $i_n(t) = \Delta q \, \delta(t-\tau)$

* Use superposition because the system is linear



* current pulse of $\Delta q \, \delta(t-\tau)$ $\Rightarrow$ charge of Δq is injected into LC tank

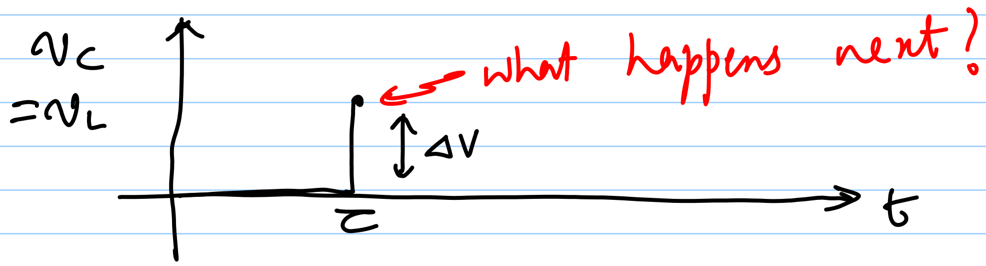
how does current pulse split between L & C?

→ if any portion of $i_n(t)$ pulse flows through L $\Rightarrow$ $v_L = \infty$

→ all of $i_n(t)$ flows through cap. C

$$i_c = C \frac{dv_c}{dt}$$

$\Rightarrow$ v_c experiences a voltage step due to $i_n(t)$

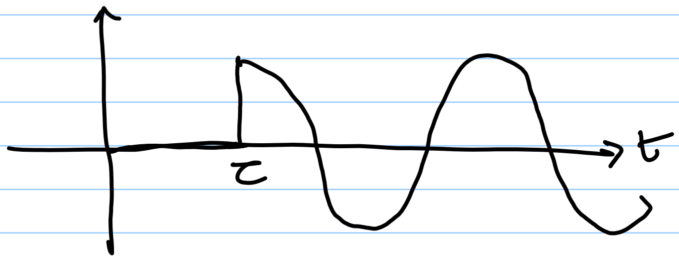


charge $q = \int i_n(t)\,dt = Q_n$

$\Rightarrow \quad \Delta q = C \Delta V \quad \Rightarrow \quad \boxed{\Delta V = \frac{\Delta q}{C}}$

* this initial charge sets up oscillations in the LC system

→ energy sloshes back & forth between L & C



$$v_2(t) = \Delta V \cos\left[w_0(t-\tau)\right]$$

$$v_o(t) = v_1(t) + v_2(t) \quad \{\text{superposition}\}$$

$$= V_0 \cos w_0 t + \Delta V \cos w_0 (t-\tau)$$

$$v_o(t) = V_0 \cos w_0 t + \Delta V \cos w_0 (t-\tau)$$

$$= V_0 \cos w_0 t + (\Delta V \cos w_0 \tau) \cdot \cos w_0 t$$
$$+ (\Delta V \sin w_0 \tau) \cdot \sin w_0 t$$

$$= (V_0 + \Delta V \cos w_0 \tau) \cos w_0 t$$
$$+ (\Delta V \sin w_0 \tau) \cdot \sin w_0 t$$

$$= V \cos(w_0 t + \varphi)$$

$$V = \sqrt{(V_0 + \Delta V \cos w_0 \tau)^2 + (\Delta V \sin w_0 \tau)^2}$$

$$\varphi = \tan^{-1}\left(\frac{\Delta V \sin w_0 \tau}{V_0 + \Delta V \cos w_0 \tau}\right)$$

(i) If $\tau = 0$ $\Rightarrow$ pulse injected @ peak of cosine

$\sin w_0 \tau = 0$, $\cos w_0 \tau = 1$

$\Rightarrow$ $V = (V_0 + \Delta V)$; $\varphi = 0$

$v_0(t) = (V_0 + \Delta V) \cos w_0 t$

$\Rightarrow$ amplitude change, no phase change

(ii) If $\tau = T/4$ $\Rightarrow$ pulse injected @ zero crossing

$\sin w_0 \tau = 1$, $\cos w_0 \tau = 0$

$V = \sqrt{V_0^2 + \Delta V^2}$ $\leftarrow$ ampl. chang

$\varphi = \tan^{-1}\left(\frac{\Delta V}{V_0}\right)$ $\leftarrow$ phase change

(iii) When is φ (phase change) maximum?

φ = max. when $\left.\begin{array}{l}\sin w_0 \tau = 1 \\ \cos w_0 \tau = 0\end{array}\right\} \Rightarrow \tau = T/4$

i.e. pulse injected @ zero-crossing causes max. phase-shift

negative-g_m oscillator (cross-coupled)

* $f_0 = \frac{1}{2\pi\sqrt{LC}}$ ✓

* $V_0 = \frac{2}{\pi} I_T R_p$

$\approx 0.64\, I_T R_p$ ✗

* startup condition

$g_m R_p > 2$ (easier) ✓

Colpitts Osc.

* $f_0 = \frac{1}{2\pi\sqrt{L\left(\frac{C_1 C_2}{C_1+C_2}\right)}}$ ✓

* $V_0 = 2 I_T (1 - 1/n) R_p$

$\frac{1}{n} = \frac{C_2}{C_1+C_2} \sim 0.2$ for best PN

$\Rightarrow V_0 \approx 1.6\, I_T R_p$ ✓

* startup condition

$g_m R_p \left(\frac{1}{n} - \frac{1}{n^2}\right) > 1$

$\Rightarrow g_m R_p (0.2 - 0.04) > 1$

$\Rightarrow g_m R_p > 6.25$ ✗

-ve g_m Osc.

* Tuning range ✓

NMOS - good

PMOS - ok

Compl. - ok

* Good phase noise ✓

(but noise inj. @ zero cross)

* differential ✓

Colpitts Osc.

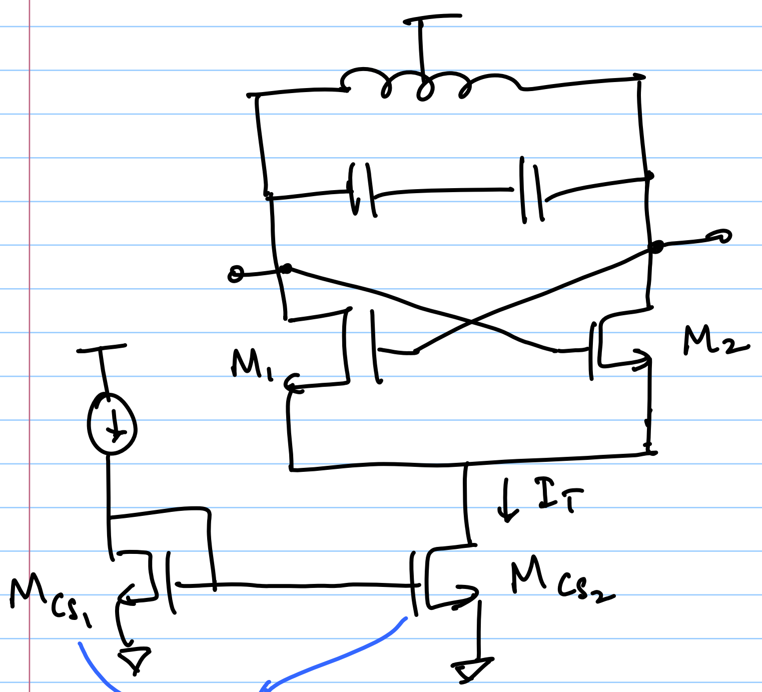
* Tuning Range poor ✗

→ part of cap used to create C_1, C_2 feedback

* Better PN (noise inj. @ voltage peaks) ✓

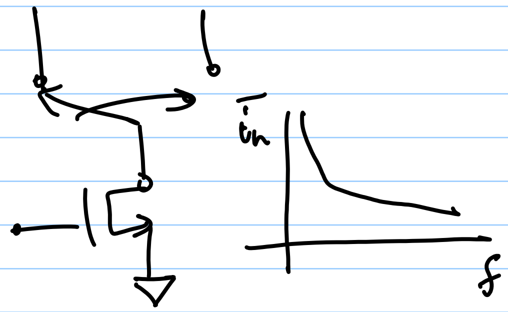
* diffl. form possible ✓

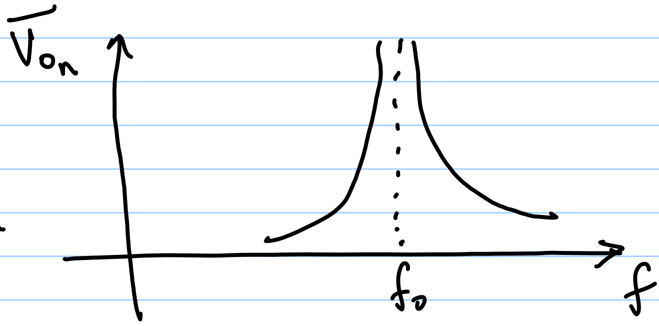
VCO biasing



large W, L ⇒ upto $\frac{1mm}{1\text{-}2\mu m}$ are common

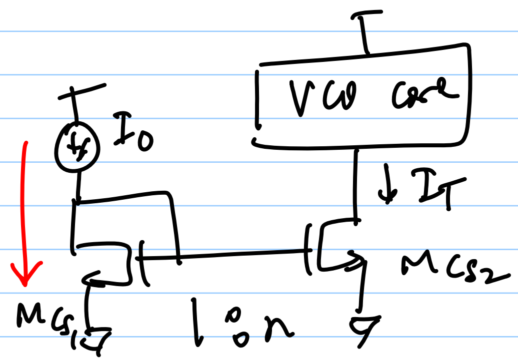
* 1/f noise up conversion
→ tail CS to output
⇒ looks like a mixer





* 1/f noise from both M_{CS_1} & M_{CS_2}
* You may be tempted to have a large CM ratio

wasted power in this leg

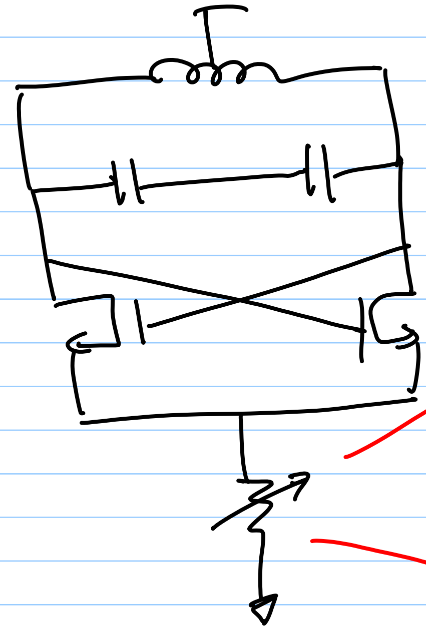


e.g. $I_T = 2mA$
$I_0 = 20\mu A$ (1% of I_T)
$n = 100$
$$\frac{W_{CS_1}}{W_{CS_2}} = \frac{1}{100}$$

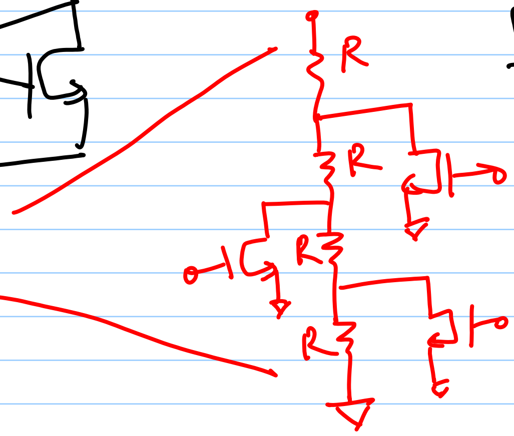
* W_{CS_1} is small ⇒ more 1/f noise
* 1 : n CM ratio ⇒ 1/f noise gets multiplied

⇒ 1/f noise is dominated by M_{CS_1}!

You may be tempted to do this:



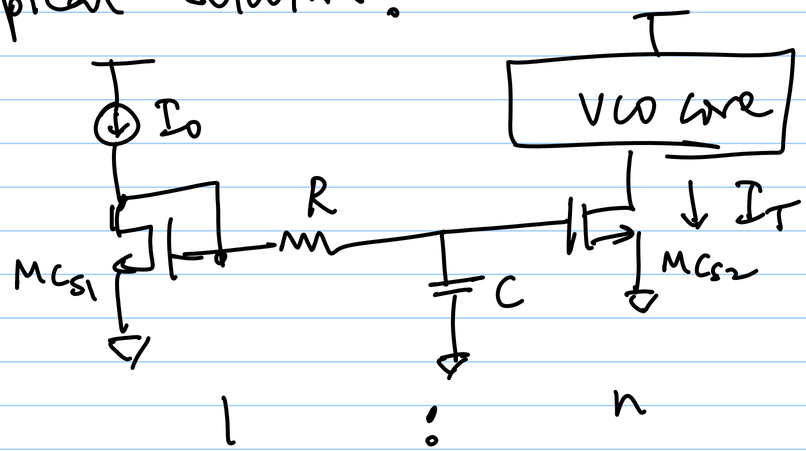
* Bias can still be tuned
* $1/f$ noise from CS absent



Problem: Bias current varies a lot over process

Problem: no rejection of common-mode noise from ground node

typical solution:



* $n = 100$
$\Rightarrow I_0 = 0.01 I_T$
(no wastage of current)

* $1/f$ noise filtered by RC filter!

$$\left.\begin{array}{l} R = 2\,M\Omega \\ C = 400\,pF \end{array}\right\} \quad f_{BW} = \frac{1}{2\pi RC} = 199\ Hz$$

→ low enough so $1/f$ noise does not matter

* Why not choose

$R = 20M\Omega$, $C = 40pF$?

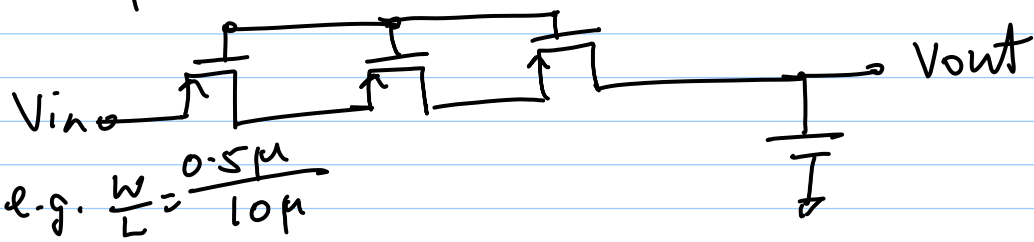
$f_{BW} = 199$ Hz again

→ Remember $\frac{kT}{C}$ noise!

→ you will see a noise hump which may end up at an inconvenient freq.

→ R area starts competing with C area

* Implement R with MOSFET (PMOS!)

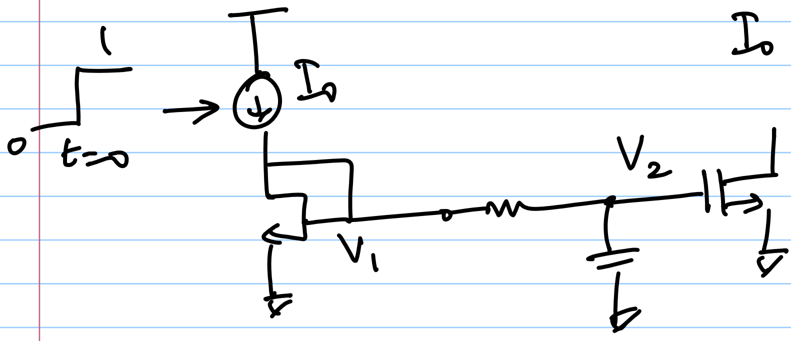


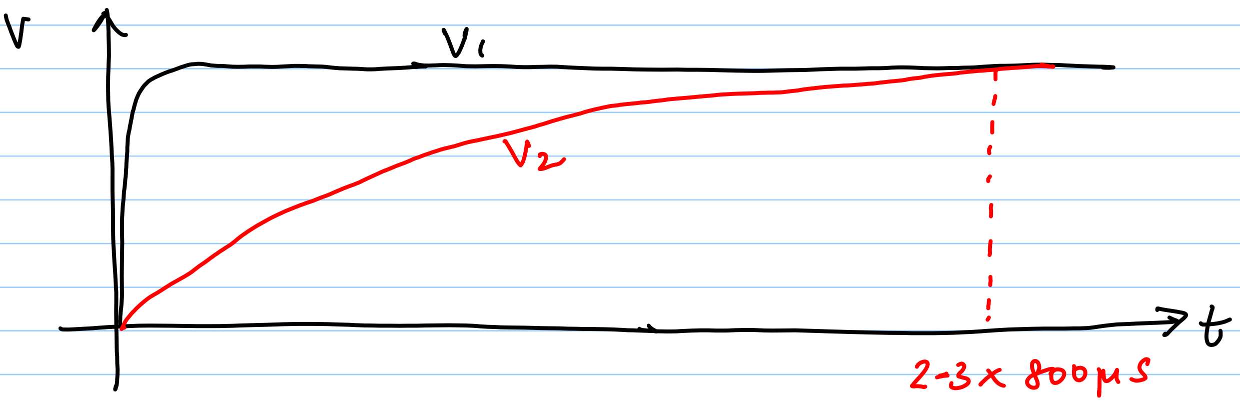
e.g. $\frac{W}{L} = \frac{0.5\mu}{10\mu}$

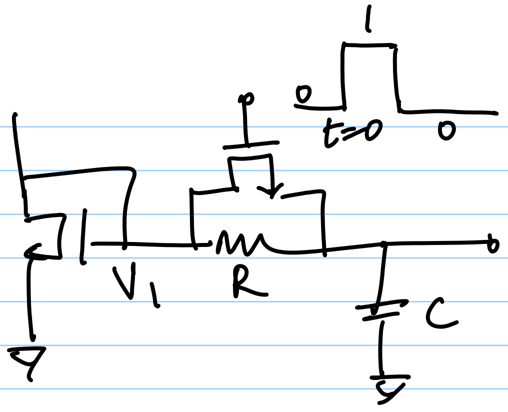
* leads to start-up problem!

$\tau = RC = 800\mu s$! ← very large time constant

I_0 turned ON @ $t=0$

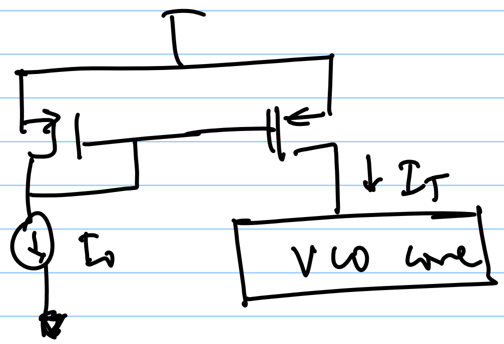






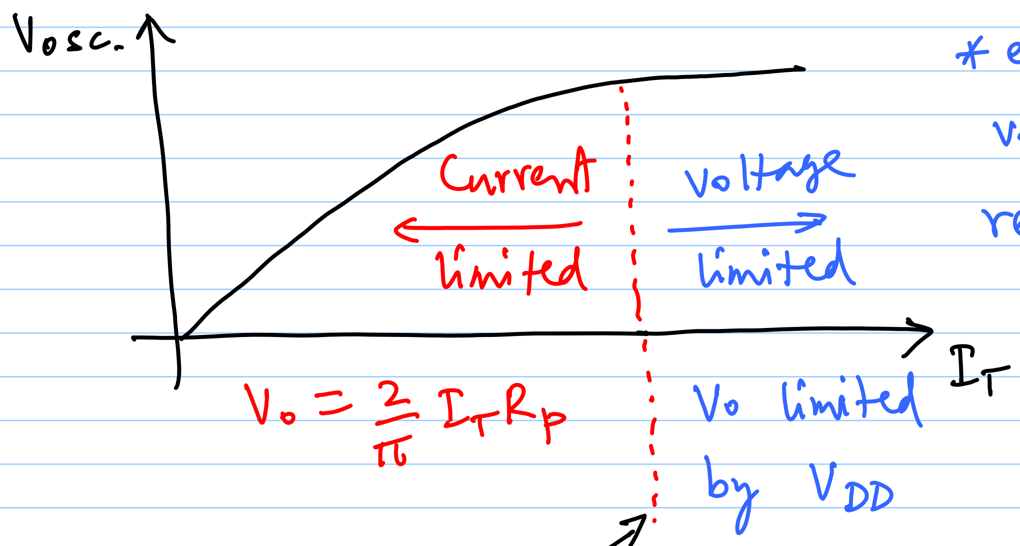
* bypass R till C is charged up (typically in 10-15 μs)
* NMOS switch R matters!
* No need for PMOS here ($V_1 \sim 0.5-0.6V$)

PMOS C-S.



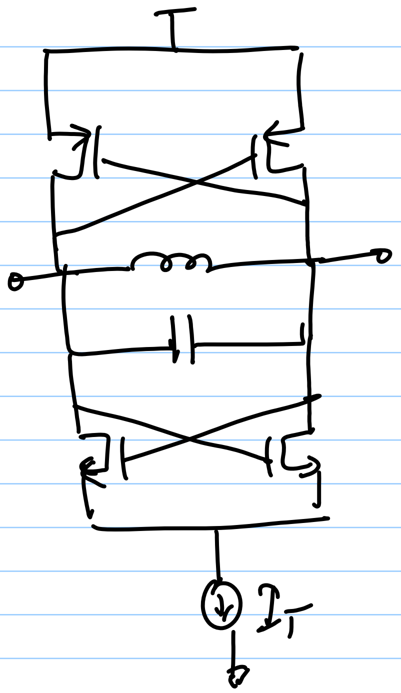
* PMOS may have lower 1/f noise
* But 3x as large for same headroom

VCO - regions of operation



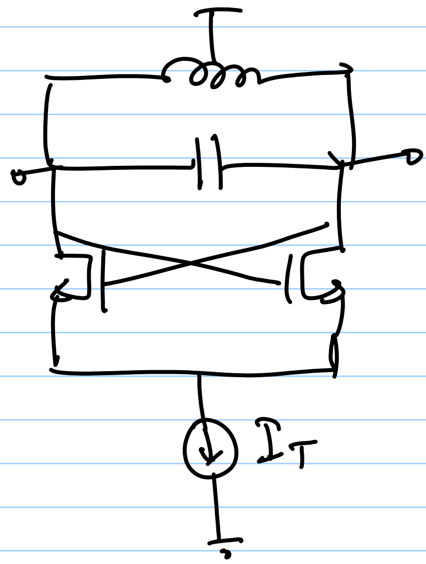
optimum operating point!

* extra power in voltage limited regime goes into
  a) harmonics
  b) noise



→ $V_o = \frac{4}{\pi} I_T R_p$

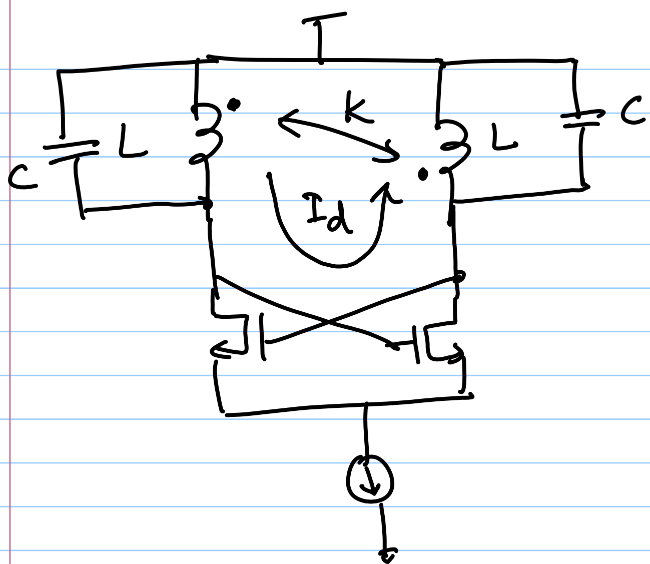
→ $V_{o\,max} \sim V_{DD}$



→ $V_o = \frac{2}{\pi} I_T R_p$

→ V_o can swing above V_{DD}

→ $V_o(max) \sim 2V_{DD}$



I_d = differential current

$k = \frac{M}{\sqrt{L_1 L_2}}$ {coupling factor}

$= \frac{M}{L}$ here

we want max k $(0 \leq k \leq 1)$

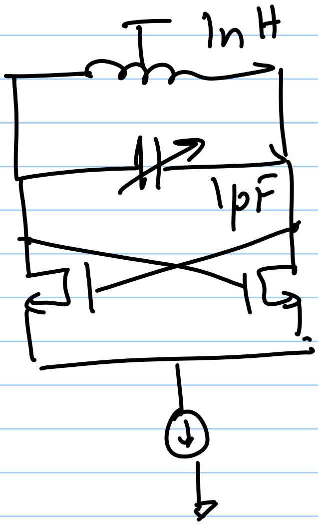
$L_{eff.} = (L + M) = L(1+k)$

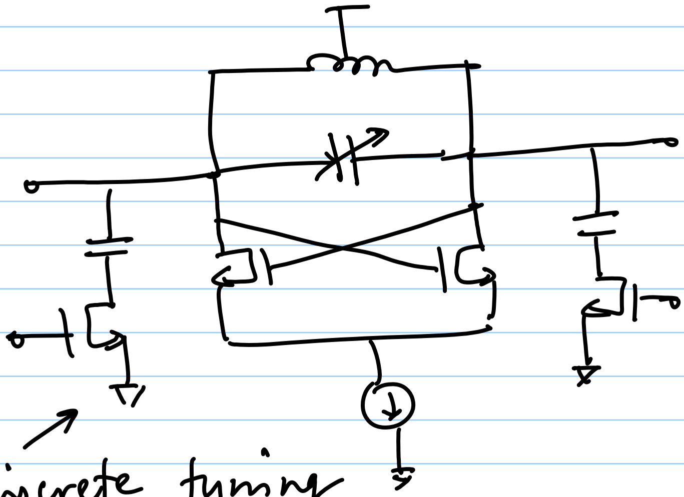
$Q_{eff.} = \frac{\omega_0 L_{eff.}}{r} = \frac{\omega_0 L}{r}(1+k) = Q(1+k)$

series res. of inductor

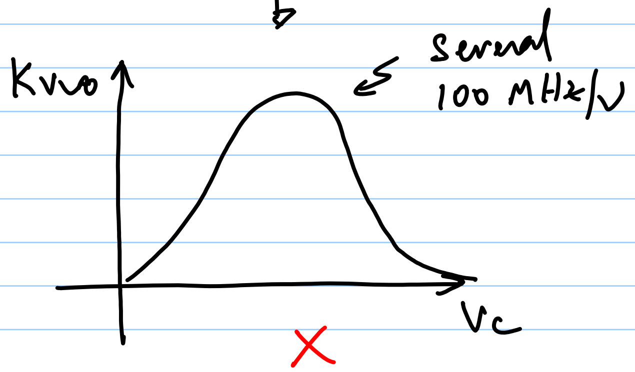
If $Q = 10$, you can almost double it to 20!

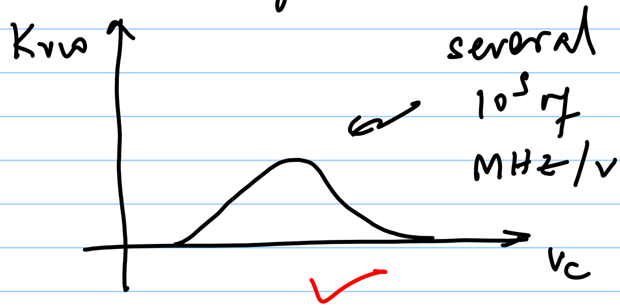
Tuning → continuous (varactor)
→ discrete (cap. bank)



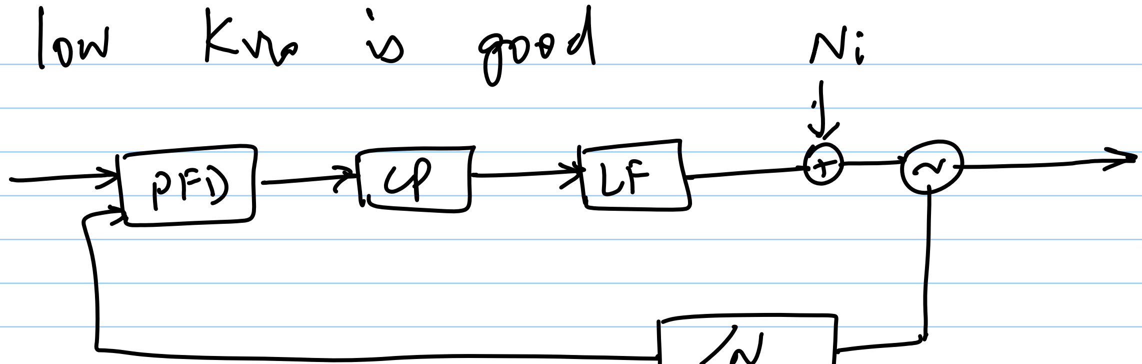


discrete tuning



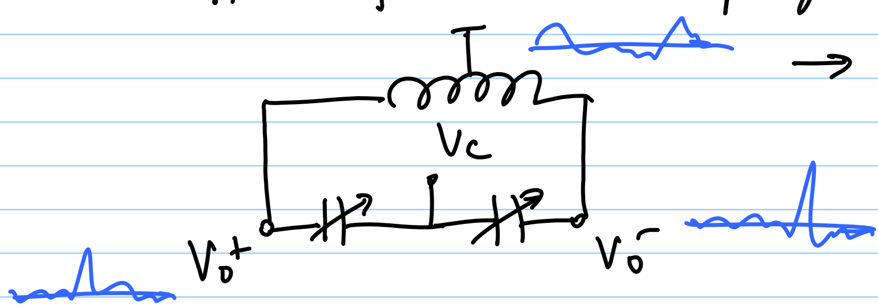


* low Kvco is good



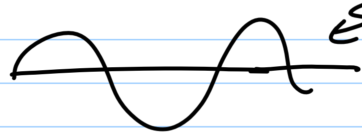
→ noise or spurs coupling @ VCO input do not have a large gain to output

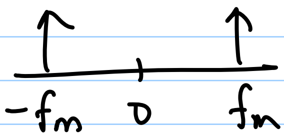
* Effects of noise coupling to A, B

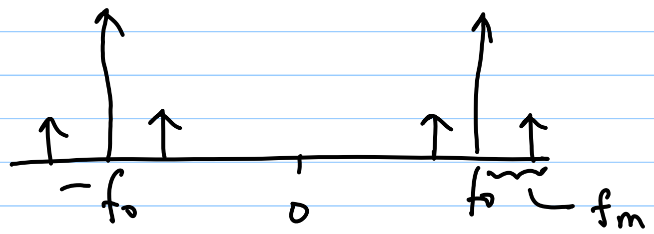


→ Varactor performs AM – PM conversion

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

V_{DD} =  $f_m << f_0$



V_{od} = 

* Need overlap in discrete tuning (PVT variations)