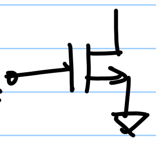
Lecture 22: Linearity & Noise of Gilbert Mixers

Sources of NL

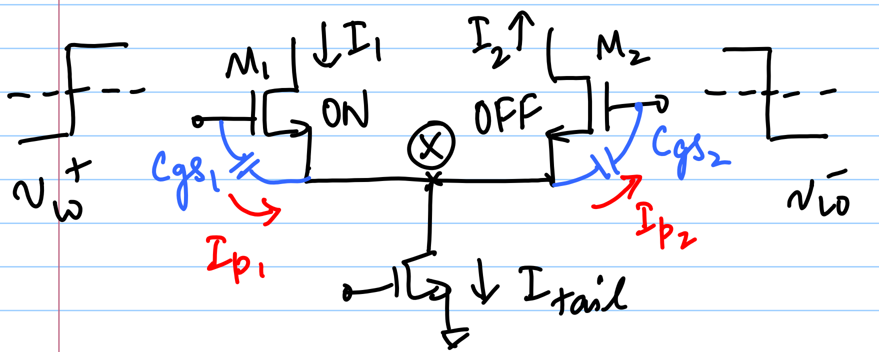
(i) Transconductor Non-linearity

$V_{DC} + v_{RF}$  $\downarrow I_{out} = I_{DC} + g_{m_0} v_{RF} + g_{m_1} v_{RF}^2 + \cdots$

To improve $IIP_3 \Rightarrow \uparrow V_{ov}$

BUT $\Rightarrow g_{m_0} \downarrow \Rightarrow G_c \downarrow \Rightarrow NF \uparrow$

(ii) LO switch Non-linearity



$C_{gs_1} \approx \frac{2}{3} W L C_{ox}$

$C_{gs_2} = W L_D C_{ox}$ (overlap cap)

$C_{gs_1} \neq C_{gs_2} \Rightarrow I_{p_1} \neq I_{p_2}$

KCL @ node X

$I_1 + I_{p_1} = I_{p_2} + I_T + I_2$ ($I_2 \to 0$, M_2 is OFF)

$\Rightarrow I_1 = I_T + (I_{p_2} - I_{p_1})$

$\simeq I_T - I_{p_1} \quad (I_{p_1} \gg I_{p_2})$

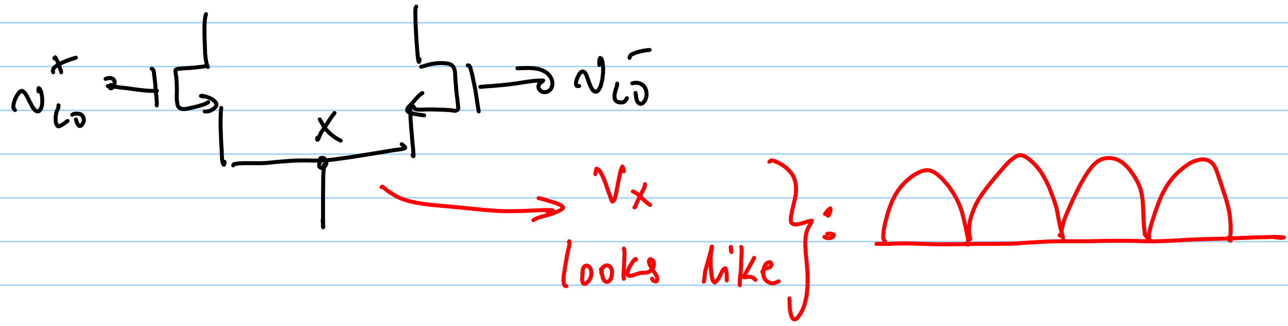
$= I_T - C_{gs_1} \frac{d(V_{LO} - V_x)}{dt}$

displacement current flowing into current source

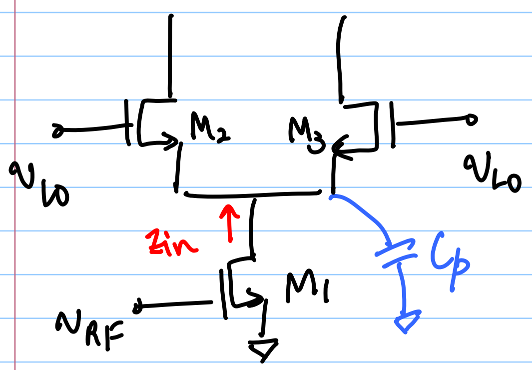
* I_1 is modulated by LO

→ if I_1 becomes small enough, M_1/M_2 may leave saturation ⇒ non-linearity

i.e. sharp LO edges & large v_{LO} make linearity worse (opposite of low-noise requirement – we will see this next class)



LO amplitude & LO switch size



* v_{LO} – large enough for 100 % current switching

* Switching speed depends on v_{LO} : $(V_{GS}-V_T)$ — V_{ov}

faster switching ⟷ lower V_{ov}

↑ $W_{2,3}$ → C_p ↑ ⇒ low-Z path for I_{RF}

↓ I_{DC} → $g_{m_{2,3}}$ ↓ ⇒ Z_{in} ↑ → more I_{RF} through C_p

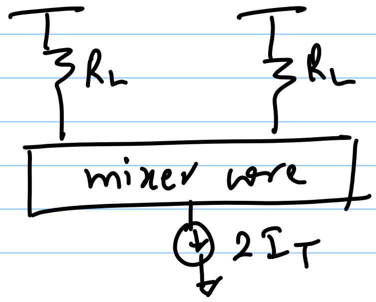
Noise in Gilbert Mixers:

Ref: H. Darabi & A. Abidi, "Noise in RF-CMOS Mixers: A Simple Physical Model", IEEE Journal of Solid-State Circuits, Vol. 35, No. 1, Jan 2000, pp 15-25

1) Load Noise:

a) Resistive load: * $\overline{v_{on,R_L}^2} = 8kTR_L$ {2 resistors}

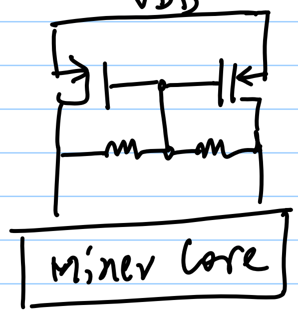
* no 1/f noise (usually)



Issues:

* voltage headroom: $V_{o,CM} = V_{DD} - I_T R_L$
* $G_c \propto R_L$

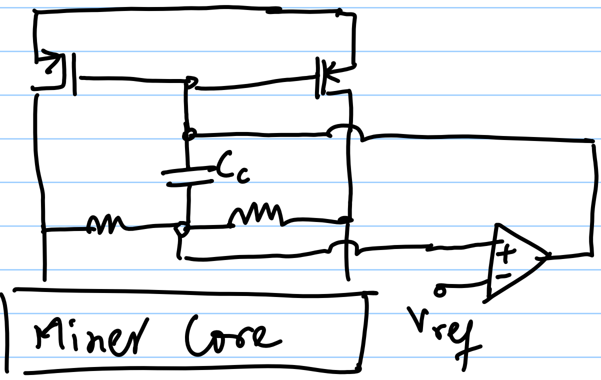
b) PMOS loads



→ $V_{o,CM} = V_{DD} - V_{GS}$

or

CM-feedback



→ $V_{o,CM} \leq V_{DD} - V_{D,SAT}$

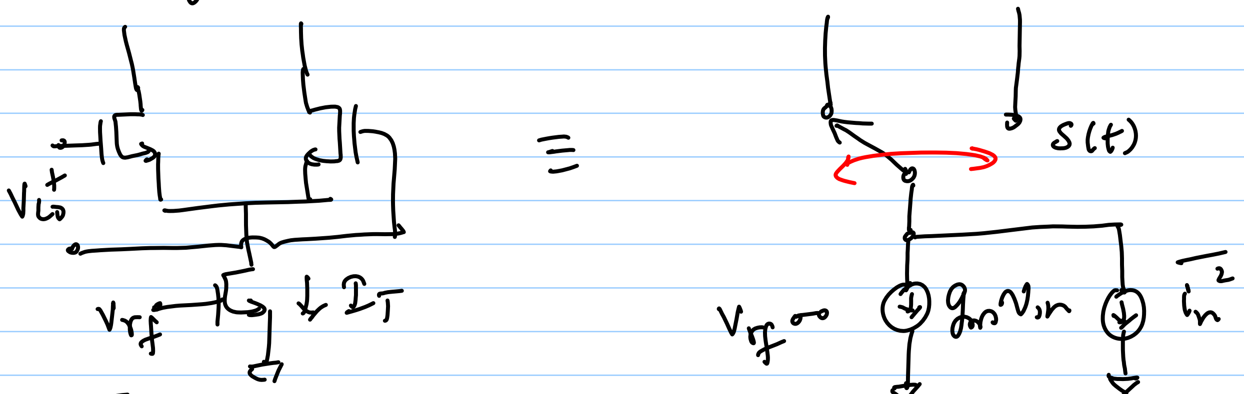
→ best headroom

→ C_c = Miller compensation cap

* Thermal noise of PMOS
* 1/f noise impacts Direct conversion or low-IF Rx (use large PMOSs)

2) Noise from g_m stage

Single-balanced mixer



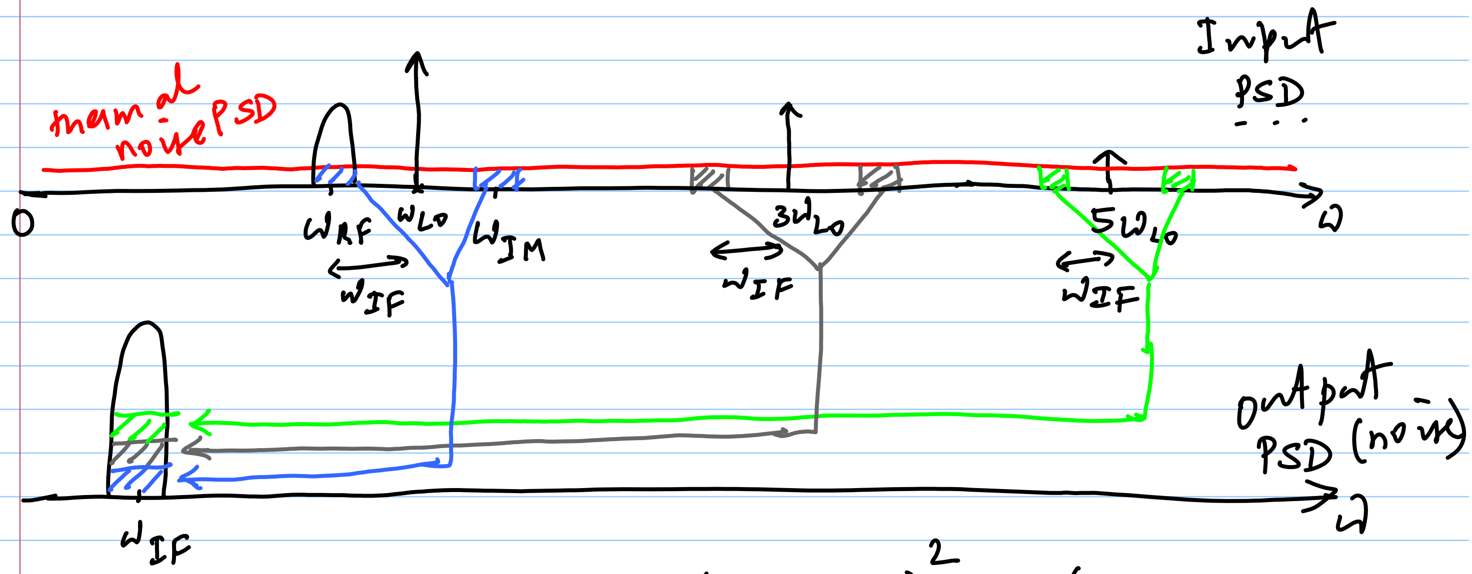
$$\overline{i_n^2} = \overline{i_d^2} + \overline{i_{1/f}^2}$$

* $\overline{i_n^2}$ gets amplitude modulated by $S(t)$

→ noise contribution from frequencies other than around f_{RF}

(a) thermal noise

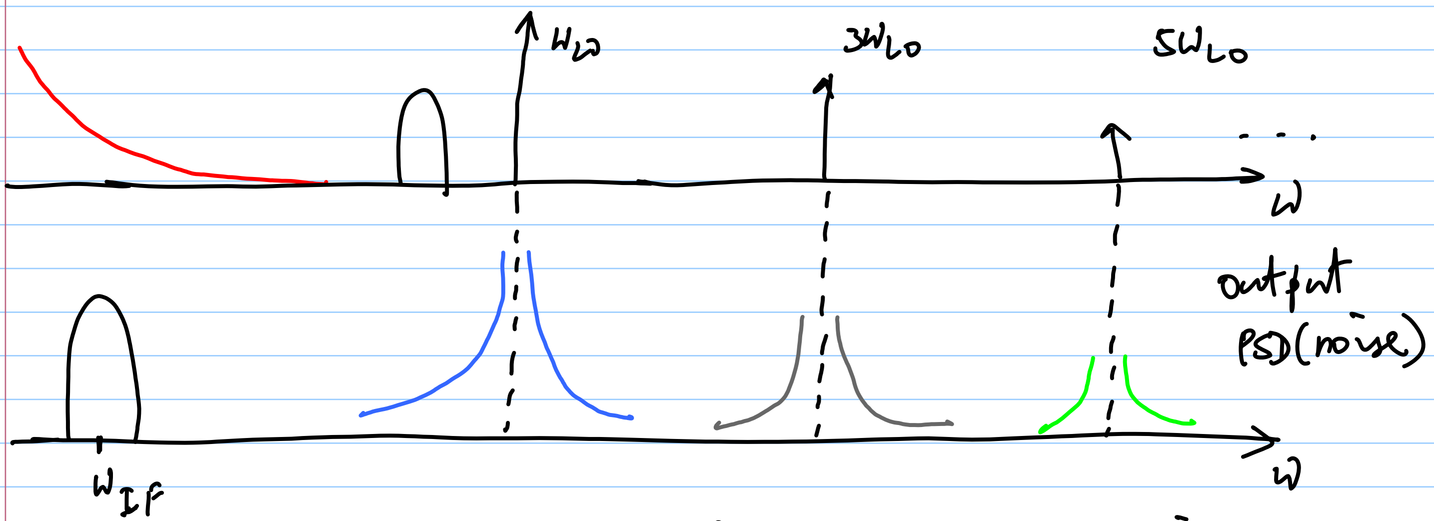
$$S(t) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin(n\omega_{LO} t) \quad , n = \text{odd}$$



$$\frac{\overline{v_{on,gm}^2}}{\Delta f} \simeq \underbrace{\frac{4kT\gamma}{g_m}}_{\text{Input noise PSD}} \times \underbrace{\left(\frac{2}{\pi} g_m R_L\right)^2}_{G_c^2} \times 2 \times \underbrace{\left(1 + \frac{1}{3^2} + \frac{1}{5^2} + \cdots\right)}_{= \pi^2/4}$$

$$\overline{v^2_{on,g_m}} = 4kT\gamma g_m R_L^2$$

b) 1/f noise



Rx mixer : * very little impact from 1/f noise of g_m-stage

* Switching pair mismatch ⇒ some 1/f noise remains @ baseband

Tx mixer : desired signal = ω_{BB}

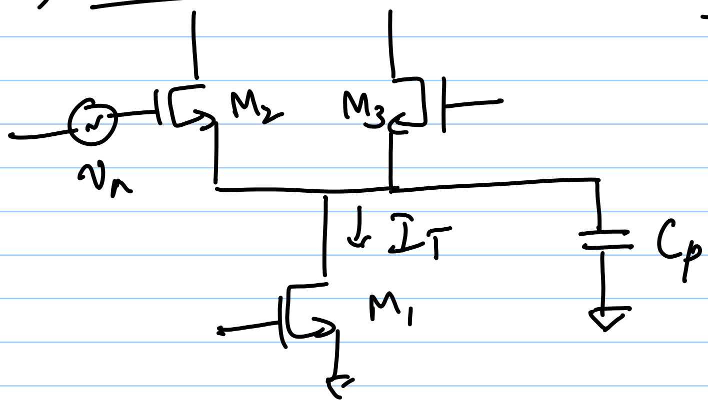
* (1/f noise + BB signal) gets up-converted
* 1/f noise does matter ⇒ design g_m stage with large area

3) Noise from switching pair :

→ more complicated to analyse

→ no noise contribution when current is completely switched (like a cascode)

a) Direct switch noise

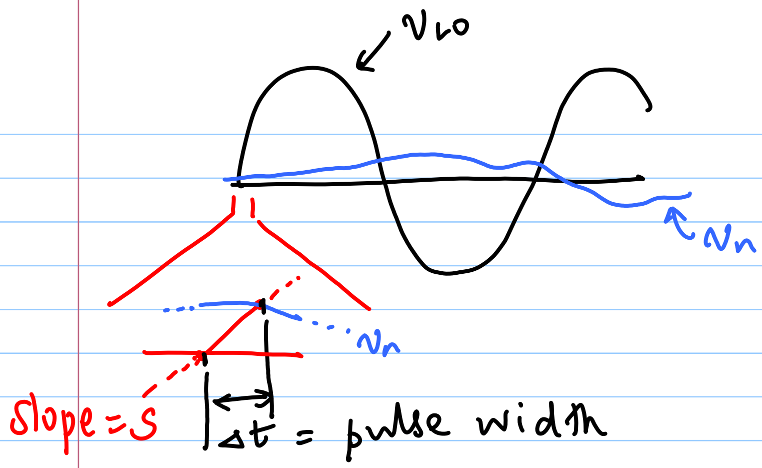


→ If C_p is large, switching devices do contribute noise even when fully on. {Ref. HW3 problem 3}

→ Both devices contribute noise during switching phase

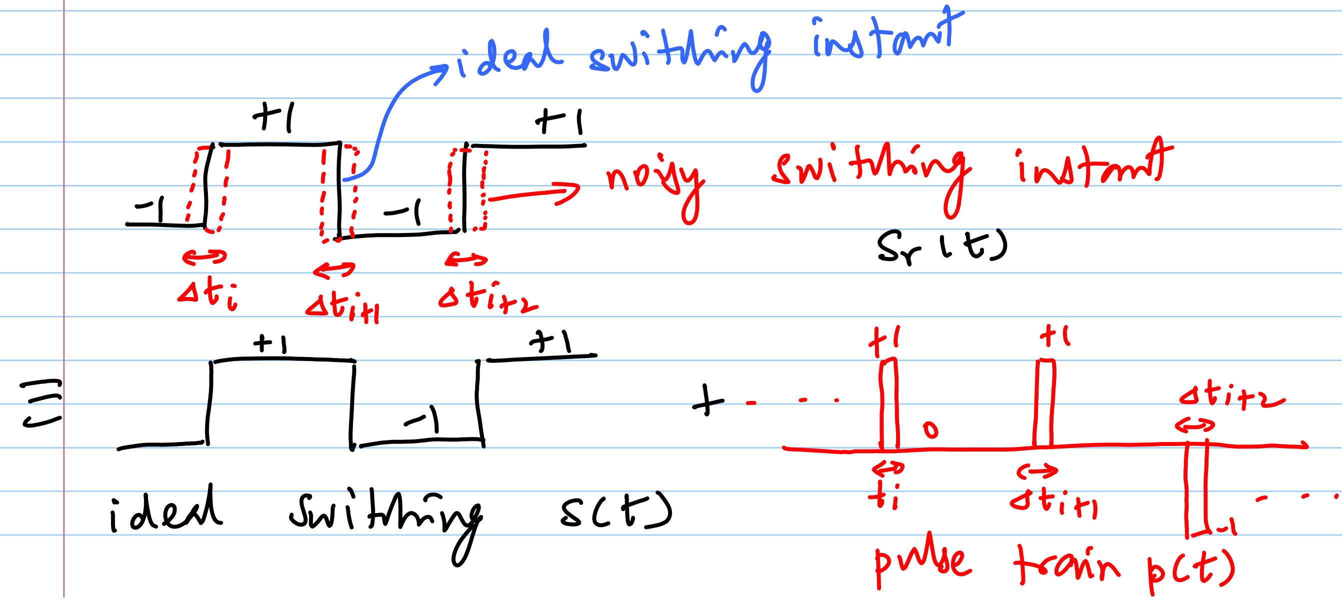
→ $\bar{v}_n$ = single input-referred noise source that captures noise of both switches M_2-M_3

* $\bar{v}_n$ modulates the switching time instant



$$\Delta t = \frac{v_n(t)}{S}$$

S ← slope @ switching instant



$S_r(t) = s(t) + p(t)$

$p(t)$ = pulse train of height $= +1$ or -1

width $\Delta t = \dfrac{v_n(t)}{S}$

rate $= 2\omega_{LO}$

$\bar{i}_{on} \Rightarrow$ pulses of amplitude $2I_T$

average value of output current over one period:

$$\bar{i}_{on} = \frac{2}{T} \times 2I_T \times \Delta t = \frac{2}{T_{LO}} \times 2I_T \times \frac{V_n}{S}$$

$$= 4I_T \cdot \frac{V_n}{S \cdot T_{LO}} \qquad \left\{ T_{LO} = \frac{2\pi}{\omega_{LO}} \right\}$$

$*$ LO signal $= \pm V_{LO} \sin\omega_{LO}t \Rightarrow v_{LOd} = 2V_{LO} \sin\omega_{LO}t$

$\Rightarrow$ slope $= \dfrac{dv_{LOd}}{dt} = 2V_{LO} \cdot \omega_{LO} \cos\omega_{LO}t$

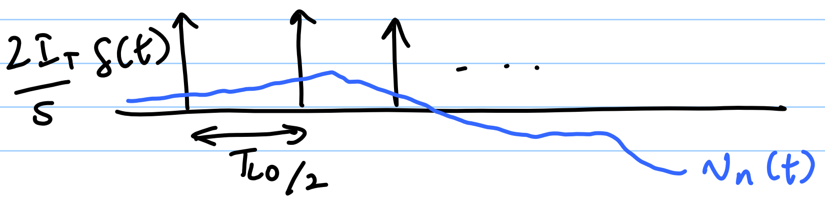
S = slope @ switching time $(t = n\pi/\omega_{LO})$

$= 2V_{LO} \cdot \omega_{LO}$

$\Rightarrow S \cdot T = 2V_{LO}\,\omega_{LO} \cdot T_{LO}$

$= 4\pi V_{LO}$

$\dfrac{\Delta t}{T_{LO}} \ll 1 \Rightarrow$ pulses are approximated by ideal δ-function impulses that sample $v_n(t)$

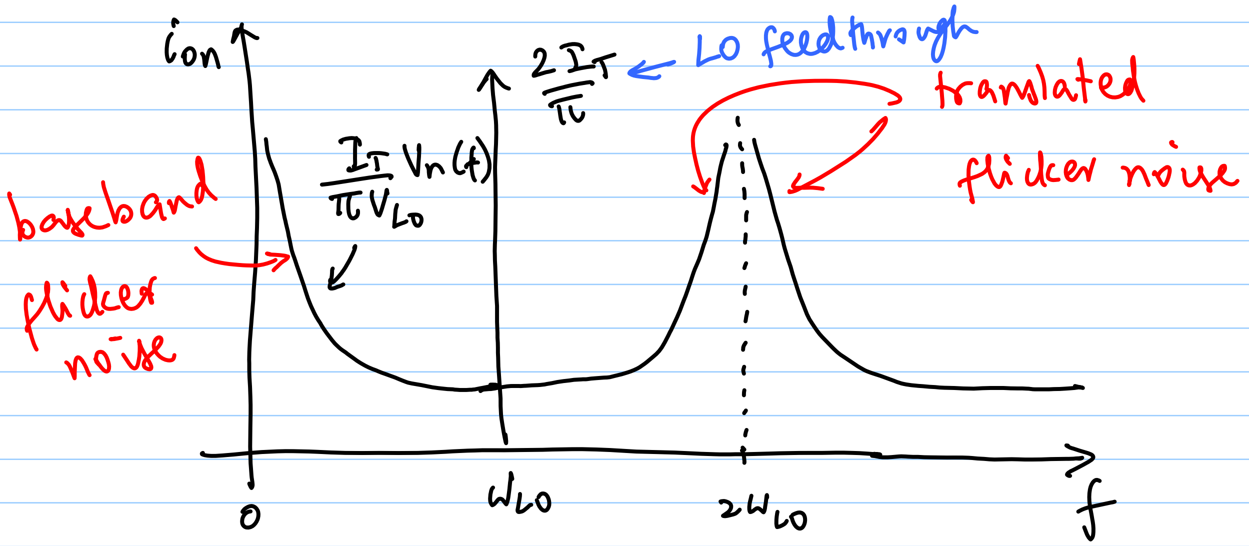


$$i_{on}(f) = \frac{4I}{ST_{LO}} V_n(f)$$

$$= \frac{1}{\pi} \cdot \frac{I_T}{V_{LO}} V_n(f)$$

sampled images appear @ $n \cdot (2f_{LO})$

Flicker noise



U.C. mixer (Tx) → no 1/f noise from switches @ f_{LO}

→ 1/f noise of g_m stage is present