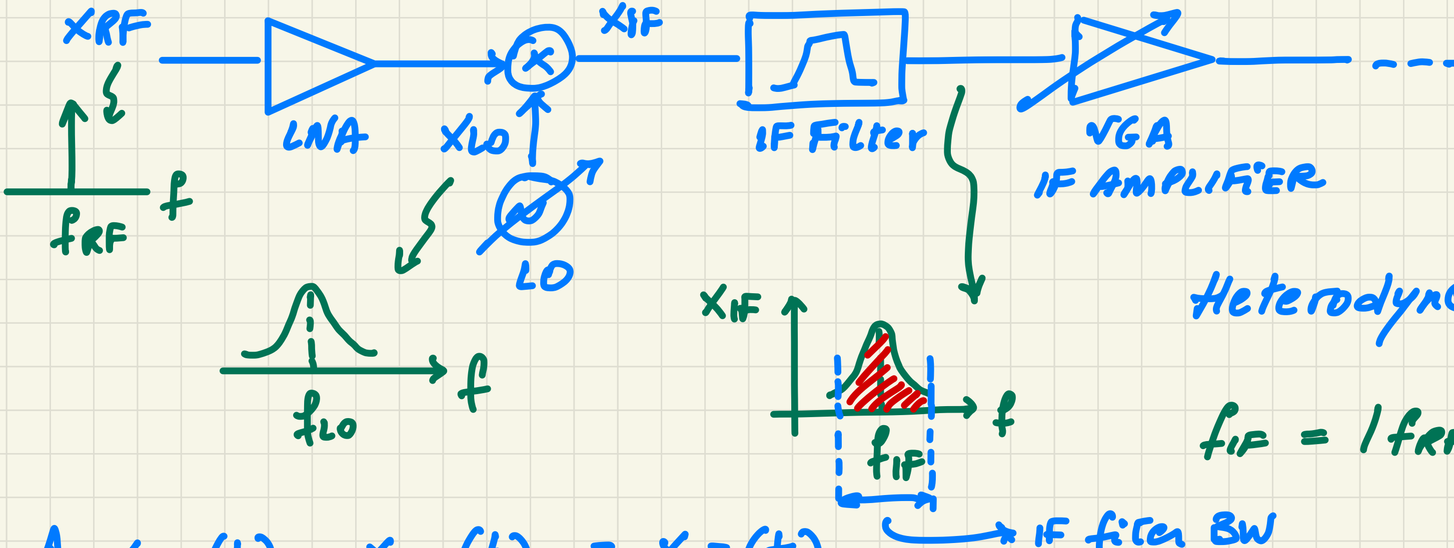
RF Circuit Design

L6

Impact of Phase Noise on RX performance

1. Direct impact



Heterodyne

$$f_{IF} = |f_{RF} - f_{LO}|$$

$$A \cdot x_{RF}(t) \cdot x_{LO}(t) = x_{IF}(t)$$

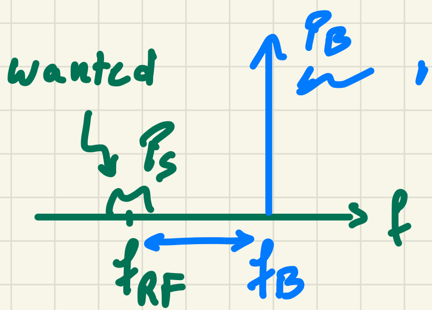
$$\Rightarrow A \cdot X_{RF}(f) * X_{LO}(f) = X_{IF}(f)$$

$$x_{LO}(t) = A_{LO} \cdot \cos[\omega_{LO} t + \varphi_n]$$

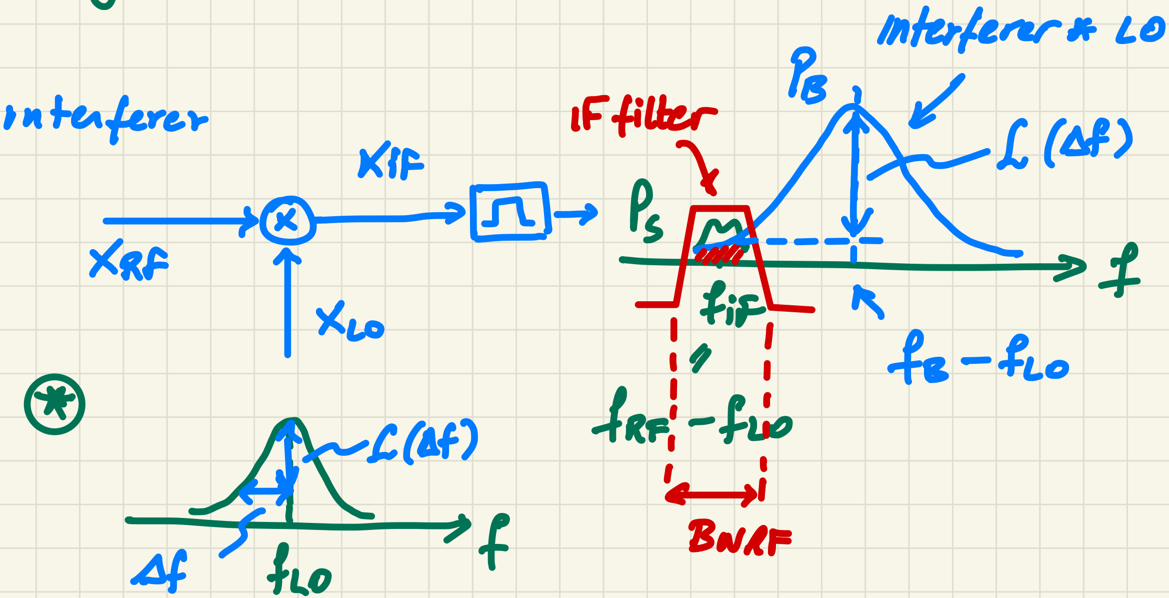
$$SNR \cong \frac{1}{\sigma^2_{\varphi_n}}$$

Phase noise degrades SNR of RX

2. Reciprocal mixing



$\Delta f = f_B - f_{RF}$

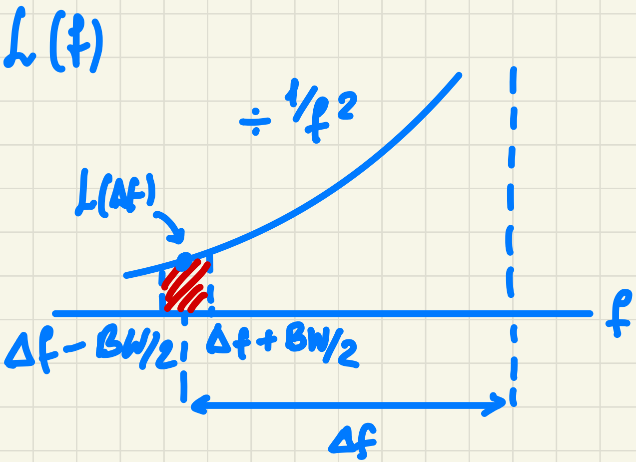


$$\mathcal{L}(\Delta f) \triangleq \frac{P_n(f_{IF}) \text{ in } 1\text{Hz}}{P_B} \quad ; \quad S_n(f_{in}) = \underbrace{\mathcal{L}(\Delta f) \cdot P_B}$$

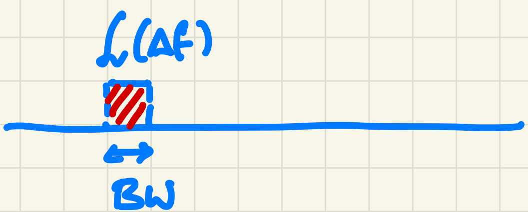
$$SNR = \frac{P_S}{P_n(f_{IF})} \cong \frac{P_S}{\mathcal{L}(\Delta f) \cdot P_B \cdot BW_{RF}} \qquad \Delta f \gg BW_{RF}$$

$$\Rightarrow SNR\big|_{dB} = 10\log_{10} SNR =$$

$$= \underset{(dBm)}{P_S} - \underset{(dBm)}{P_B} - \underset{(dBc/Hz)}{\mathcal{L}(\Delta f)} - 10\cdot\log_{10}(BW_{RF})$$



$$\int_{\Delta f - BW/2}^{\Delta f + BW/2} \mathcal{L}(\Delta f)\, d\Delta f$$



$$\approx \mathcal{L}(\Delta f)\cdot BW$$

ex. GSM

- $P_S = -99$ dBm
- $P_B = -40$ dBm

(out-of-band interf. at 0 dBm attenuated by antenna filter by 40 dB)

$f_{RF} = 2.01$ GHz
$f_B = 2.03$ GHz
$f_{LO} = 2.00$ GHz

$BW_{RF} = 200$ kHz

SNR > 50 dB

$\mathcal{L} = ?$

$$\mathcal{L}(\Delta f) = P_S - P_B - SNR_{dB} - 10\log_{10} BW_{RF} =$$

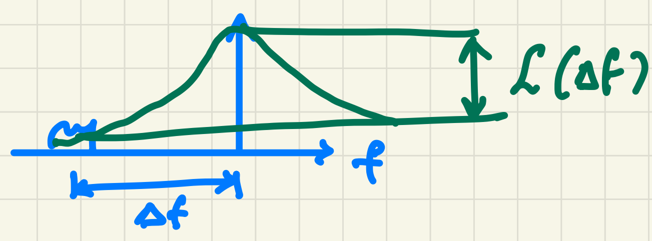
$$= -99 + 40 - 50 - 53 =$$

$$= -162 \text{ dBc/Hz at } 20 \text{ MHz}$$

$$10 \log_{10} BW_{RF} = 10 \log_{10} 2 \cdot 10^5 =$$

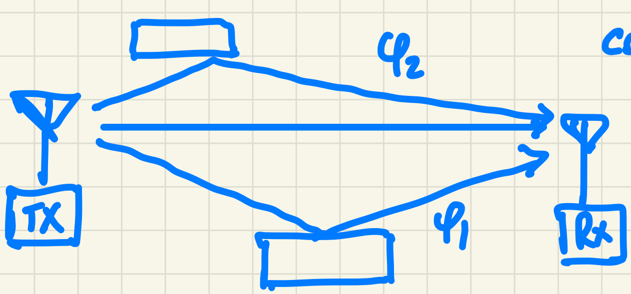
$$= 3 \text{ dB} + 50 \text{ dB} = 53 \text{ dB}$$

$$\Delta f = f_B - f_{RF} = 20 \text{ MHz}$$



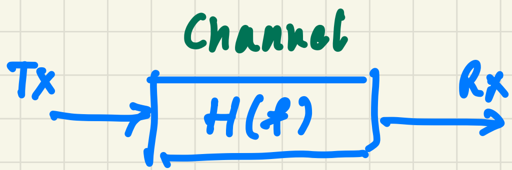
Fading

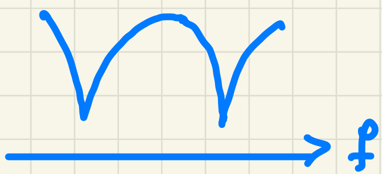
Multipath channel



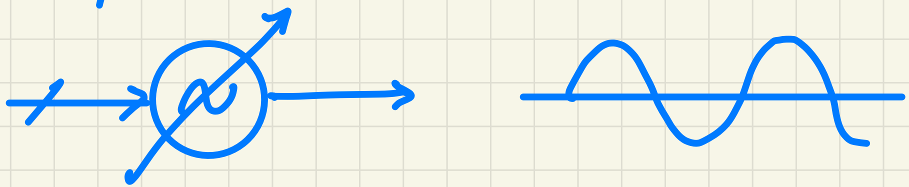
constructive/destructive interference :

$$A \cos \omega t + B \cos(\omega t + \varphi_1) + C \cos(\omega t + \varphi_2)$$





Frequency Synthesizers

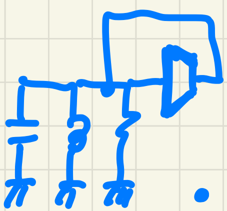
FCW  $f_{LO} \div FCW$

Frequency control word

Specifications:

- Accuracy $\dfrac{\Delta f_{LO}}{f_{LO}}$ (Aging + Drift)

e.g. GSM standard $\Delta f / f = 0.1 \text{ ppm} = 10^{-7}$

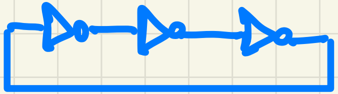


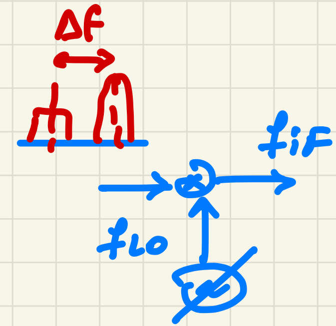
$f \approx 1 \text{ GHz} \Rightarrow \Delta f \approx 10^{9} \cdot 10^{-7} = 100 \text{ Hz}$

- LC oscillators $f = \dfrac{1}{2\pi\sqrt{LC}} \Rightarrow \dfrac{\Delta f}{f} \approx \dfrac{1}{2} \cdot \dfrac{\Delta C}{C} + \dfrac{1}{2} \cdot \dfrac{\Delta L}{L}$

$1 \div 10\%$ $1 \div 10\%$

- RC oscillator $\quad f \div \frac{1}{RC} \Rightarrow \frac{\Delta f}{f} \simeq \frac{\Delta R}{R} + \frac{\Delta C}{C}$





- Resolution : minimum Δf of LO
  - * for channel spacing ~ 100 KHz
  - * for temperature compensation ~ Hz

- Settling time : channel switching time
  - * switch from one freq. to another at each frame
    settling time ~ 100 μs or even ≈ 10 μs
- Spurious content : reciprocal mixing
- Phase Noise

- Pulling sensitivity of ($\frac{\Delta f_0}{\Delta V_{DD}}$) frequency to V_{DD}, to load chang to improve accuracy : master/slave approach

Atomic clock

10^{-9} s/day

$\longrightarrow$ Crystal oscillators (Quartz)

TCXO (temperature compensated crystal oscillator)

- good accuracy

accuracy $\approx$ 100 ppm
aging $\approx$ 0.5 ppm /year
drift $\approx$ 0.5 ppm 0–75°C

- not tunable (fixed frequency)
- low - frequency (1 ÷ 10 MHz)

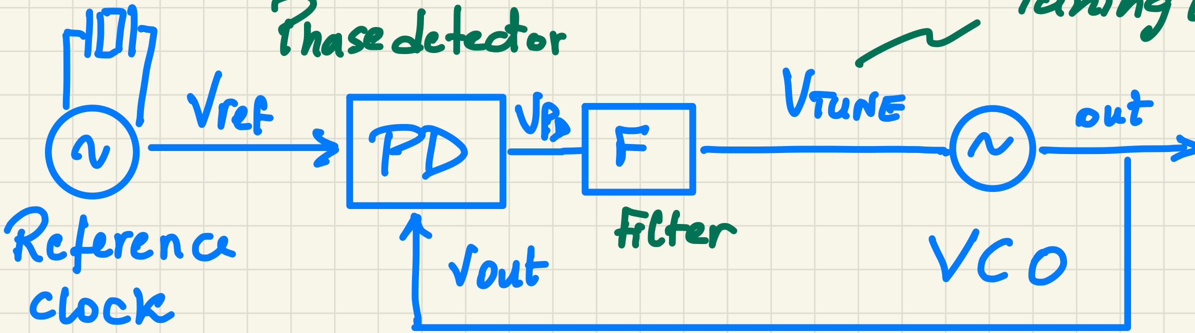
$\longrightarrow$ variable RC / LC oscillators

- poor accuracy
- tunable
- can operate at large frequency 100 GHz+

Phase-locked loop (PLL)

Phase detector

tuning voltage



$\dot{\phi}_\varepsilon = \omega_\varepsilon = 0$

voltage-controlled oscillator

fixed freq. quartz oscillator

Tunable RC/LC oscillator

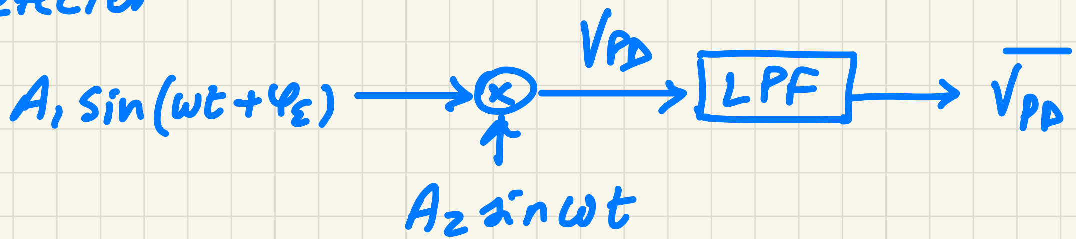
Hyp. linear tuning : $\omega_{out} = \omega_{FR} + K_{VCO} \cdot V_{TUNE}$

ω_{FR}: free-running (angular) frequency

K_{VCO}: tuning sensitivity $[\text{rad/s} / V]$

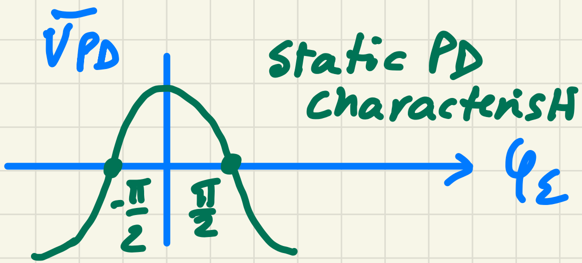
Phase detector

e.g.



$$V_{PD} = \underbrace{-\frac{A_1 A_2}{2} \cos\left(2\omega t + \varphi_\varepsilon\right)}_{\text{fast}} + \underbrace{\frac{A_1 A_2}{2} \cos\left(\varphi_\varepsilon\right)}_{\text{DC}}$$

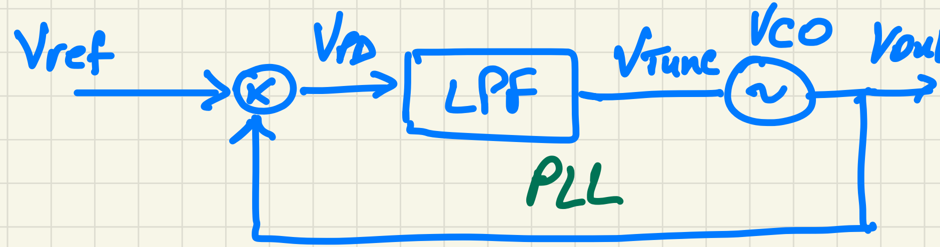
$$\overline{V}_{PD} \propto \frac{A_1 A_2}{2} \cos \varphi_\varepsilon \qquad \text{if } BW_{LPF} \ll 2\omega$$



Static PD characteristic

$\overline{V}_{PD} = 0$ when $\varphi_\varepsilon = \pm \frac{\pi}{2}$

Notation change

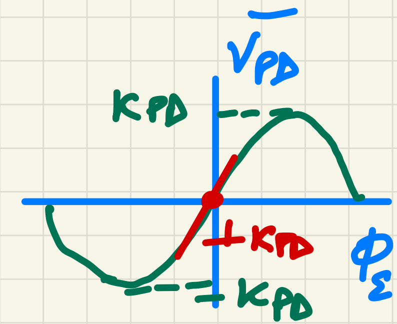


$$V_{ref} = A_r \cdot \sin \Phi_{ref}$$

absolute phase

$$\hookrightarrow (\omega_{ref}\, t + \varphi_{ref})$$

excess phase



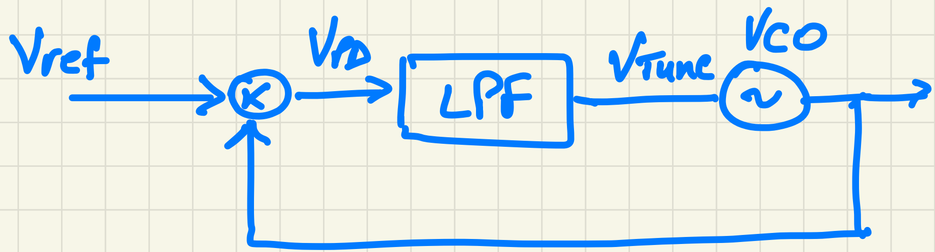
$$V_{out} = A_o \cos \Phi_{out}$$

$$\Rightarrow \overline{V_{PD}} \cong \underbrace{G_c \cdot \frac{A_r \cdot A_o}{2}}_{K_{PD}\ (V)} \cdot \sin\big[\underbrace{\Phi_{ref} - \Phi_{out}}_{\Phi_\varepsilon}\big]$$

K_{PD} (V) PD gain

Φ_ε phase error

$$= K_{PD} \cdot \sin \Phi_\varepsilon$$



$$\dot{\Phi}_\varepsilon = \frac{d\Phi_\varepsilon}{dt}$$

$$\dot{\Phi}_\varepsilon = \dot{\Phi}_{ref} - \dot{\Phi}_{out} =$$

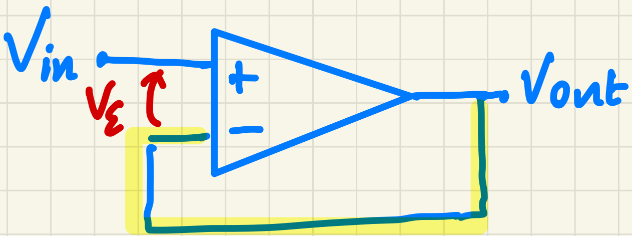
$$= \omega_{ref} - \left(\omega_{FR} + K_{VCO} V_{TUNE}\right) =$$

$$= \underbrace{\omega_{ref} - \omega_{FR}}_{\triangleq \Delta\omega \ (rad/s)} - \underbrace{K_{VCO} \cdot K_{PD}}_{\triangleq K \ \left(\frac{rad}{s}/\cancel{V} \cdot \cancel{V}\right)} \sin\Phi_\varepsilon$$

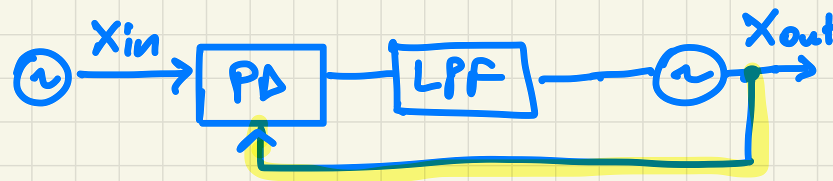
- $\Phi_{ref} = \omega_{ref} \cdot t$
- $\omega_{out} = \omega_{FR} + K_{VCO} V_{TUNE}$
- $\overline{V_{PD}} = K_{PD} \cdot \sin\Phi_\varepsilon$

$$\Rightarrow \boxed{\dot{\Phi}_\varepsilon = \Delta\omega - K \cdot \sin \Phi_\varepsilon}$$

First - order differential eq. $\longrightarrow$ FIRST-ORDER PLL



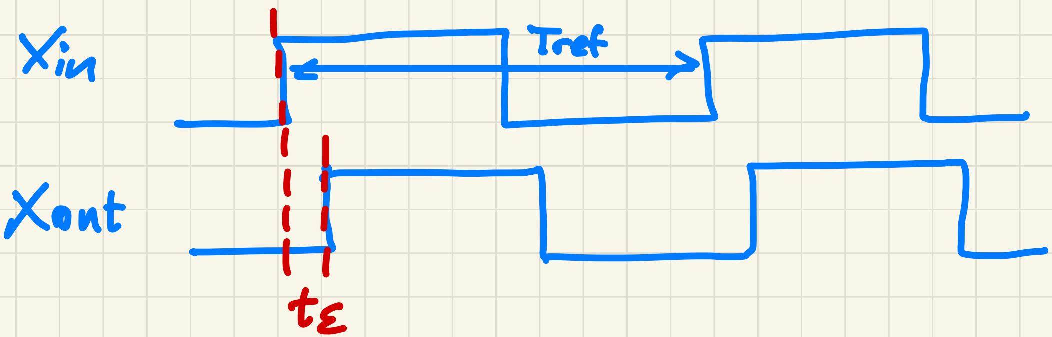
Voltage follower



Phase follower

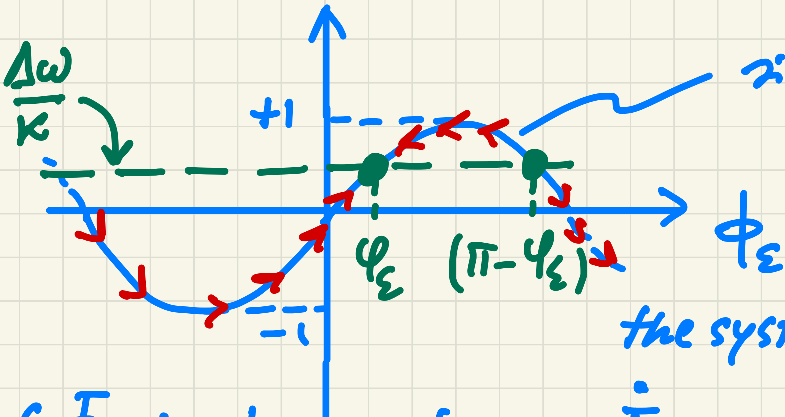
$$\varphi_\varepsilon = \omega_{ref} \cdot t_\varepsilon$$

$$\omega_{ref} = 2\pi / T_{ref}$$



$$\dot{\Phi}_\varepsilon = \Delta\omega - K \cdot \sin \Phi_\varepsilon \qquad \Phi_\varepsilon(t) \text{ unknown}$$

Equilibrium points : $\dot{\Phi}_\varepsilon = 0 \Rightarrow \sin \varphi_\varepsilon = \dfrac{\Delta\omega}{K}$



IF $\left|\dfrac{\Delta\omega}{K}\right| < 1$:

the system has 2 equilibrium points

(Φ_ε is decreasing) $\dot{\Phi}_\varepsilon < 0 \iff \Delta\omega - K \sin\phi_\varepsilon < 0$

$$\sin\phi_\varepsilon > \frac{\Delta\omega}{K}$$

(Φ_ε is increasing) $\dot{\Phi}_\varepsilon > 0 \iff \sin\phi_\varepsilon < \dfrac{\Delta\omega}{K}$

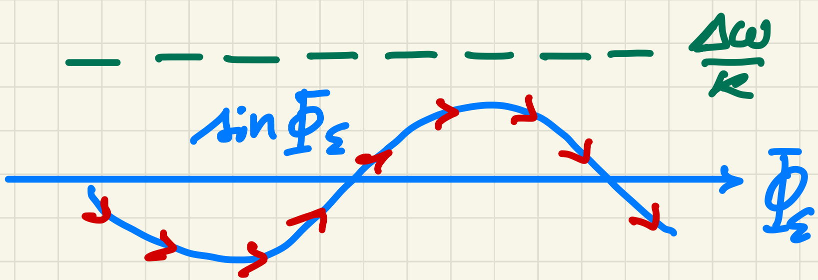
$\Phi_\varepsilon(t) \rightarrow \varphi_\varepsilon = \arcsin\left(\frac{\Delta\omega}{K}\right)$ is STABLE

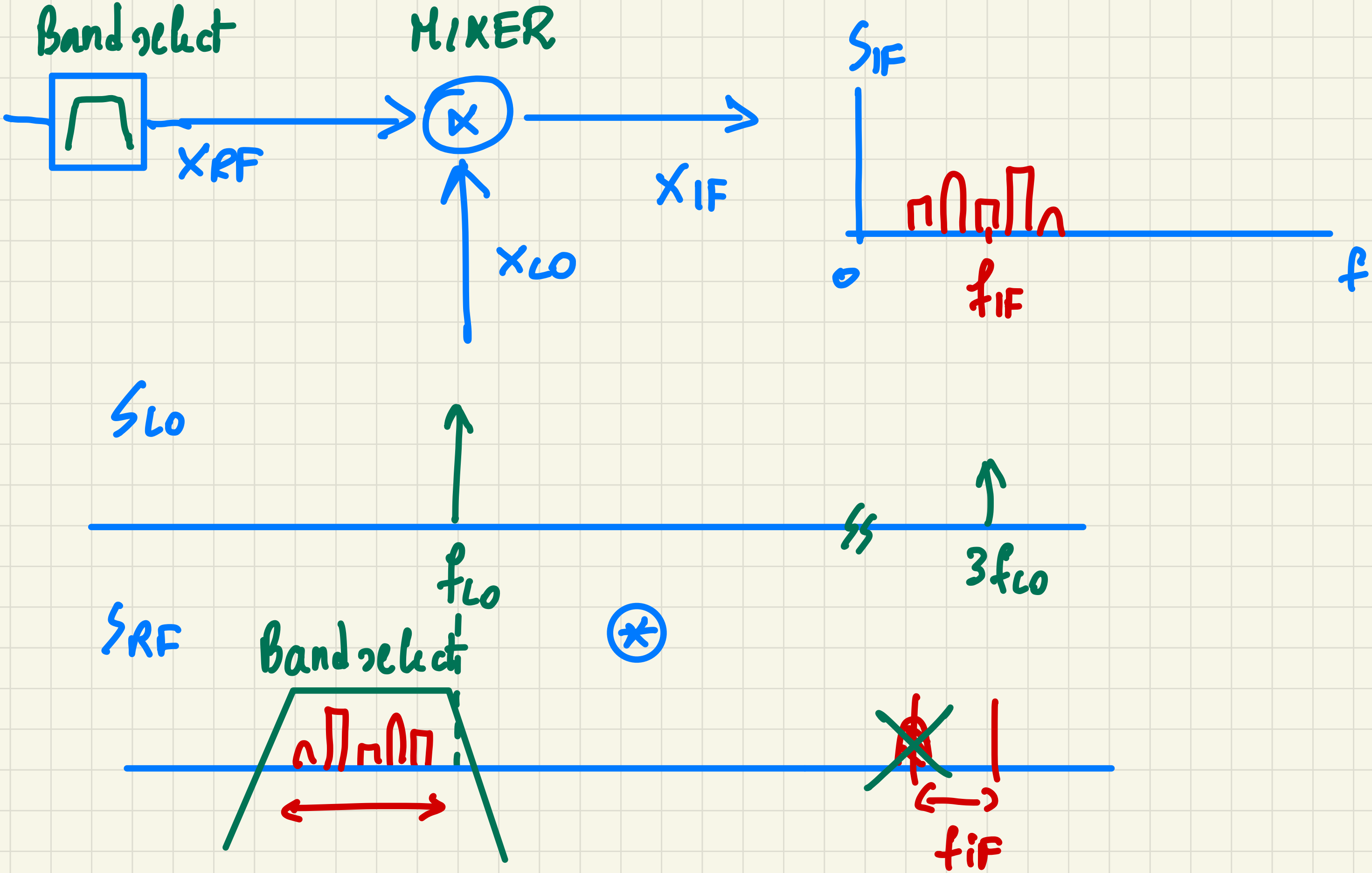
steady-state phase error depends on the frequency offset between ref. and the free-running freq. of the VCO

$(\pi - \varphi_\varepsilon)$ is UNSTABLE eq. point

IF $\left|\frac{\Delta\omega}{K}\right| > 1$: no equilibrium point

$\dot{\Phi}_\varepsilon > 0$




Band select
MIXER
XRF
XIF
XLO
SIF
0
fIF
f
SLO
fLO
3fLO
SRF
Band select
fIF