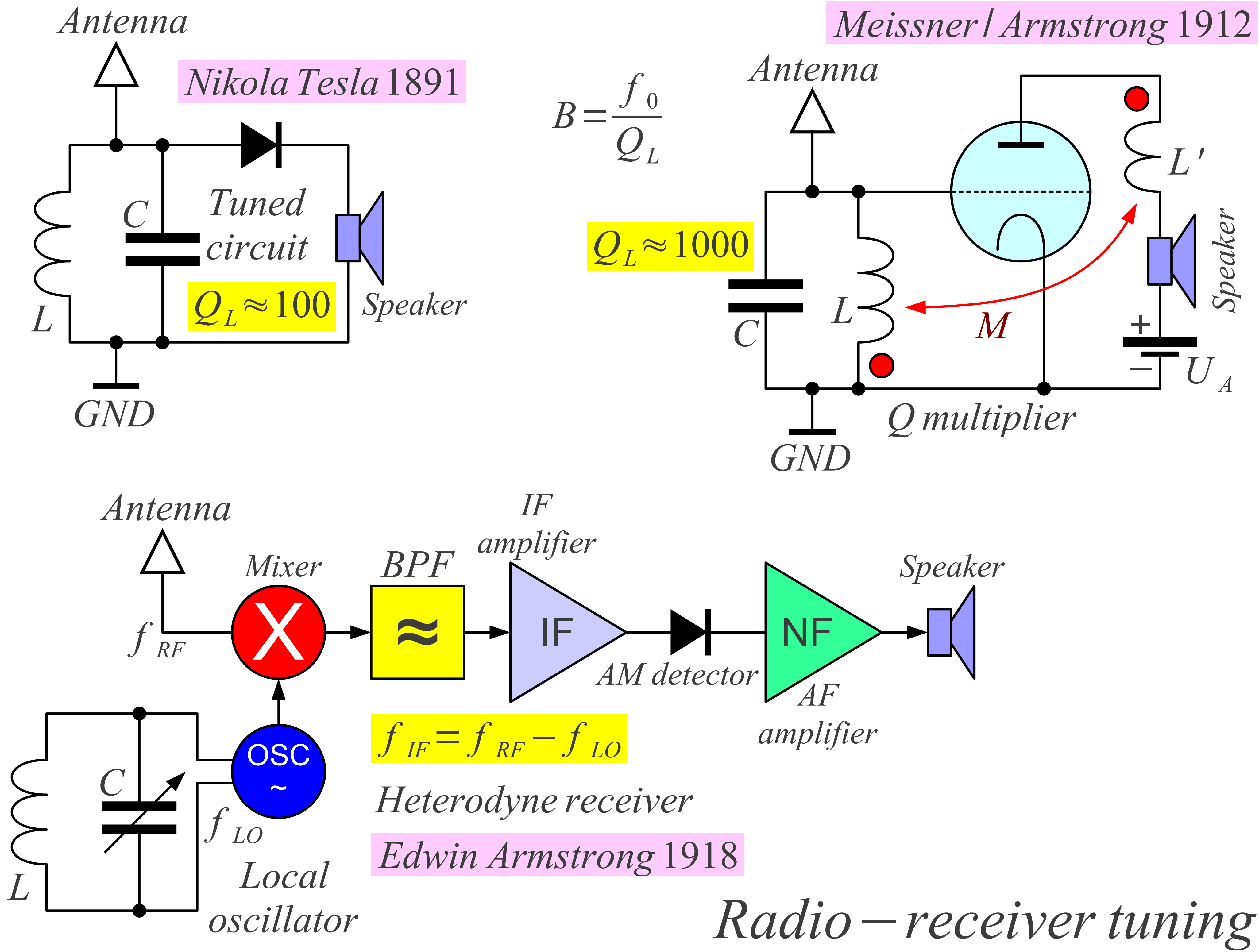
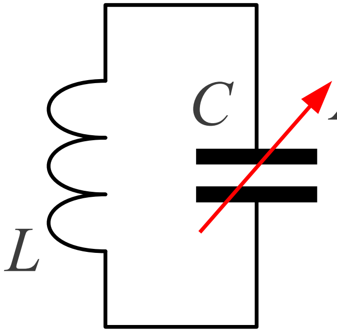
Communication Electronics

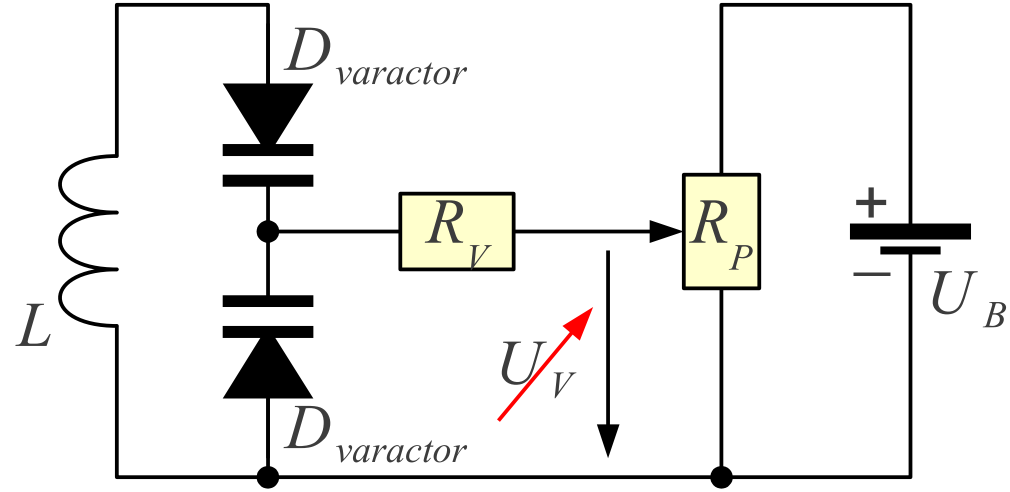
Lecture 15:

Frequency synthesizers


Antenna
Nikola Tesla 1891
C
L
Tuned circuit
$Q_L \approx 100$
Speaker
GND
Meissner / Armstrong 1912
$B = \frac{f_0}{Q_L}$
Antenna
$Q_L \approx 1000$
L'
C
L
M
Speaker
+
–
U_A
GND
Q multiplier
Antenna
Mixer
BPF
IF amplifier
IF
NF
Speaker
f_{RF}
AM detector
AF amplifier
OSC ~
C
L
f_{LO}
Local oscillator
$f_{IF} = f_{RF} - f_{LO}$
Heterodyne receiver
Edwin Armstrong 1918
Radio – receiver tuning



Adjustable (rotating) capacitor

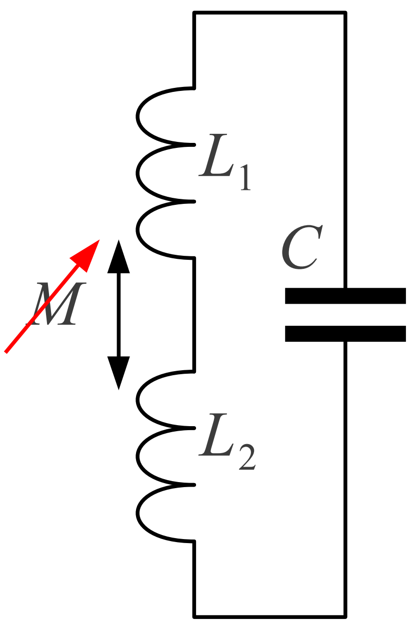


Adjustable varactor voltage

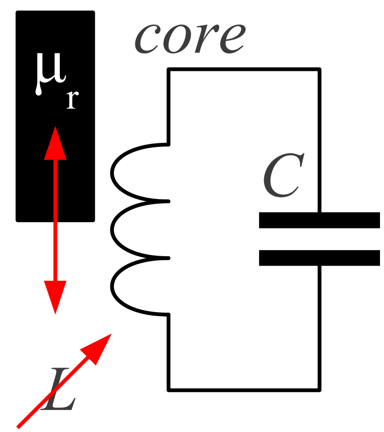
$$f = \frac{1}{2\pi\sqrt{LC}}$$

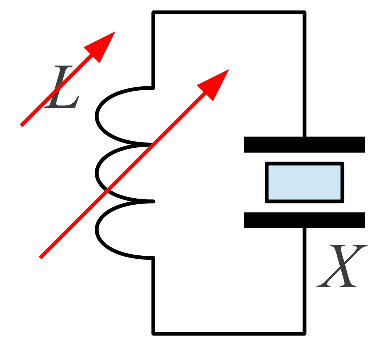
Adjustable magnetic coupling (variometer)

$$L = L_1 + L_2 \pm 2M$$



Adjustable ferromagnetic core



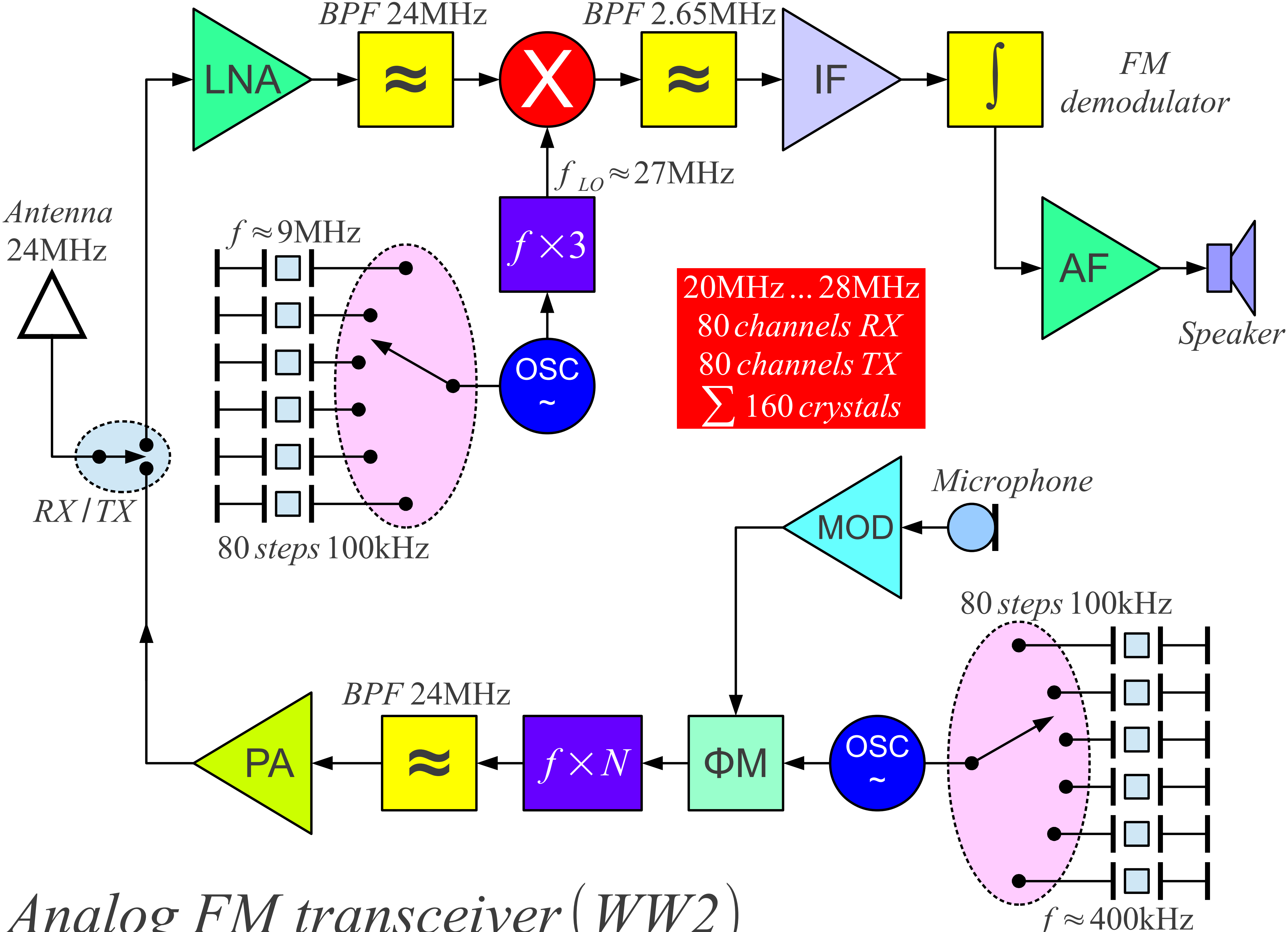


Quartz-crystal tuning

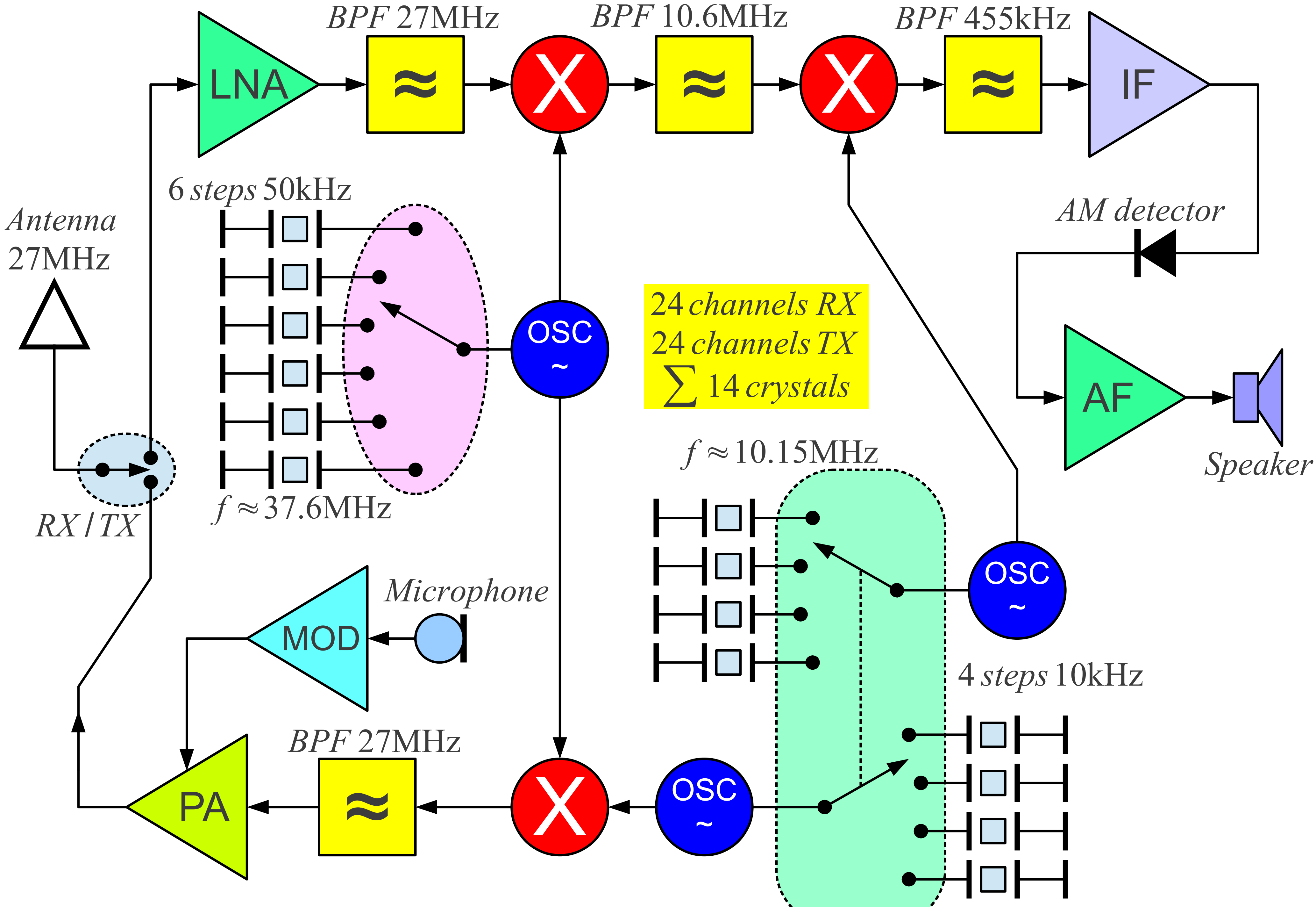
$$\Delta f < 0.1\% f_0$$

Insufficient even for narrowband FM

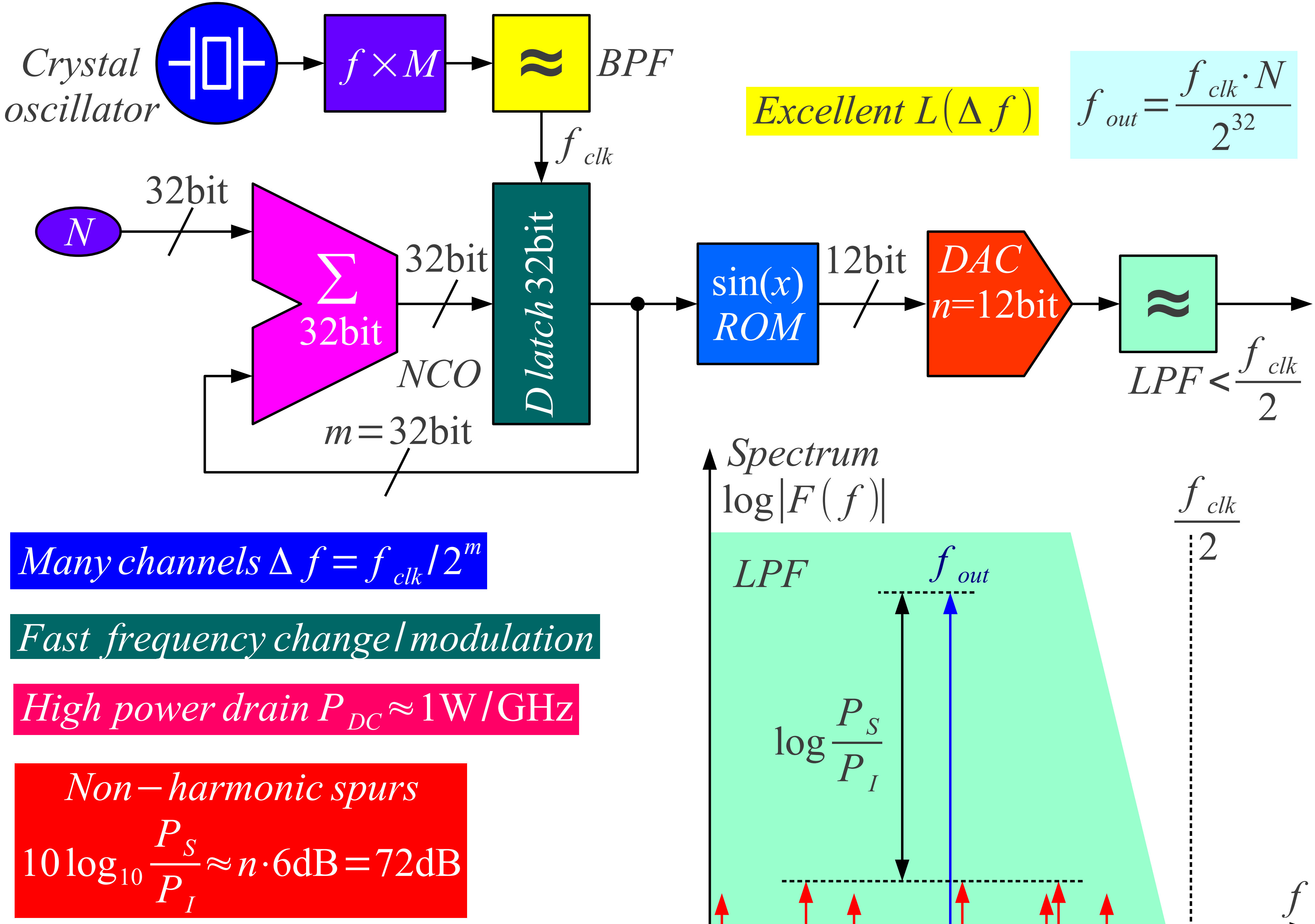
Tuned-circuit frequency adjustment



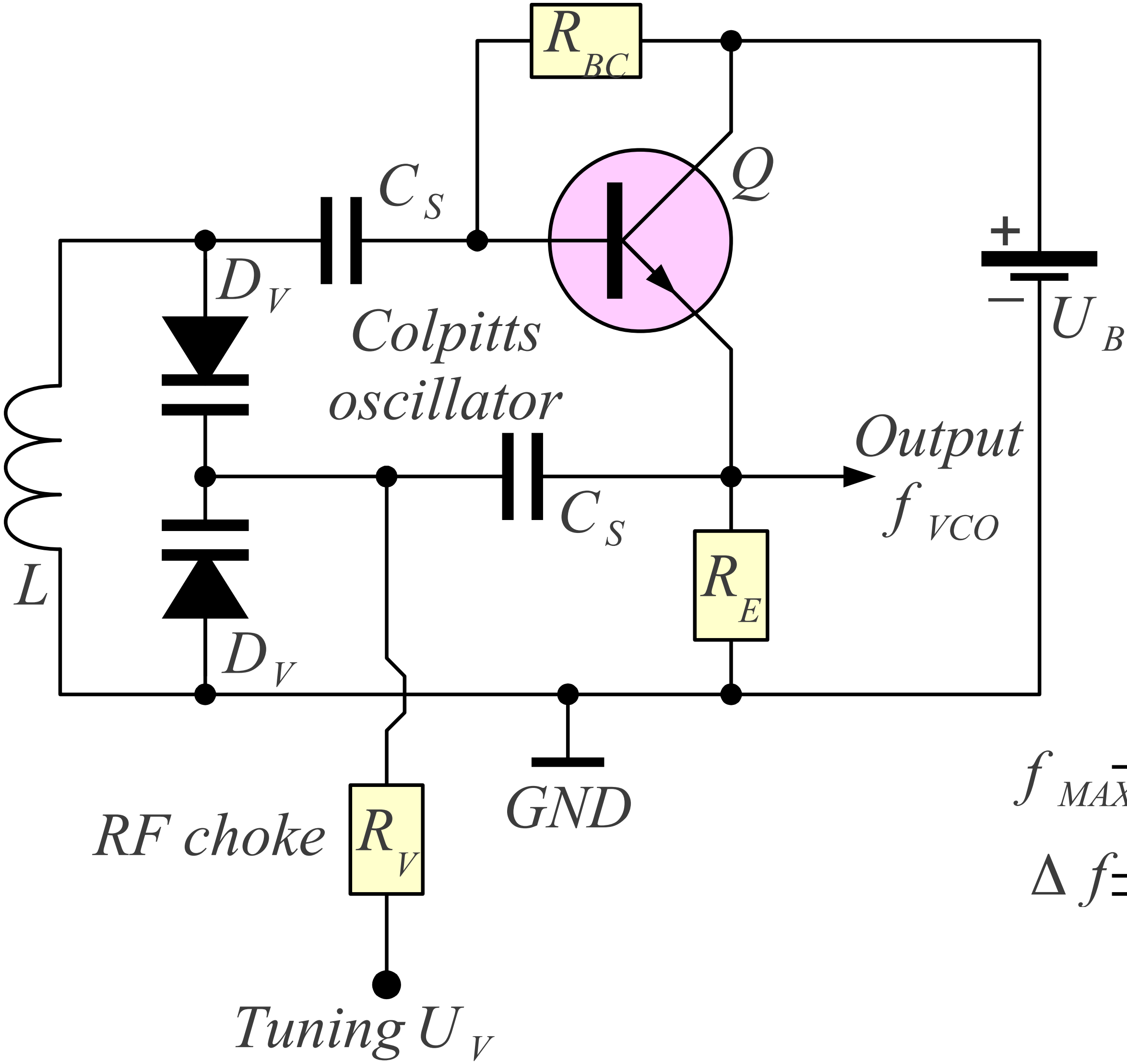
Analog FM transceiver (WW2)



Analog CB transceiver



Direct digital synthesis

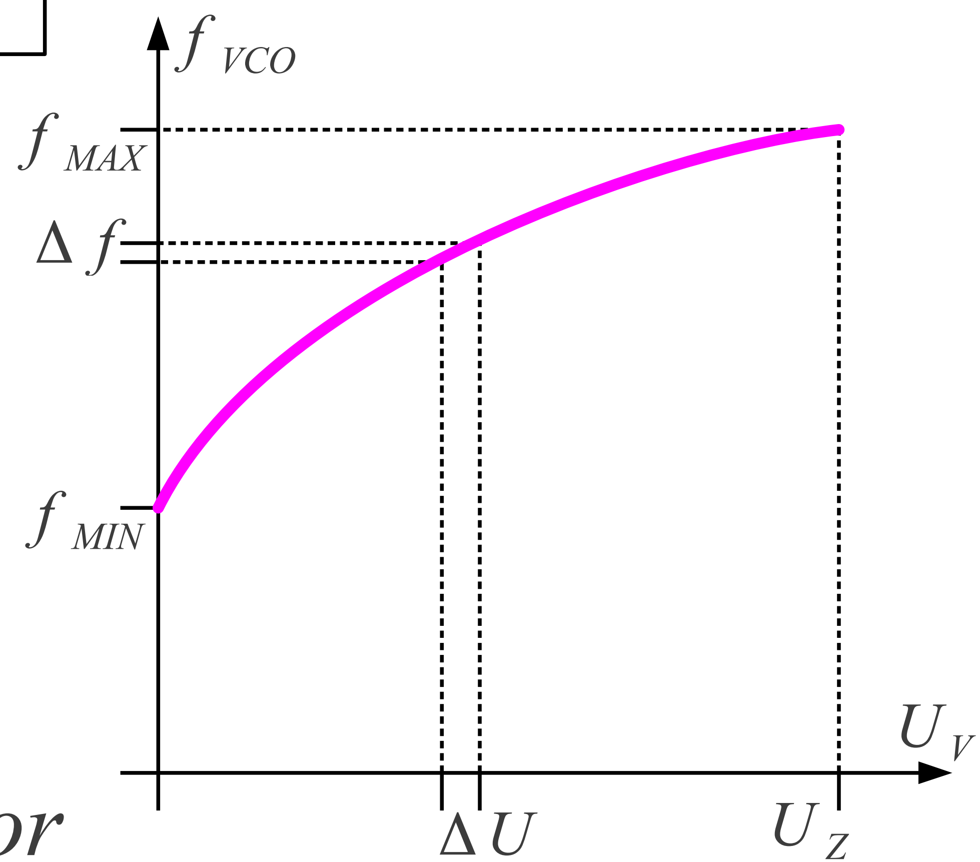


$$K_{VCO}\left[\frac{\text{rd/s}}{\text{V}}\right]=\frac{d\omega}{dU}=2\pi\frac{df}{dU}$$

$$K_{VCO}\left[\frac{\text{Hz}}{\text{V}}\right]=\frac{df}{dU}\approx\frac{\Delta f}{\Delta U}$$

VCO ≡ Voltage − Controlled Oscillator

$$\frac{f_{MAX}}{f_{MIN}}=\left(\frac{C_{MAX}}{C_{MIN}}\right)^{0.5}=\sqrt{\frac{C_{MAX}}{C_{MIN}}}$$

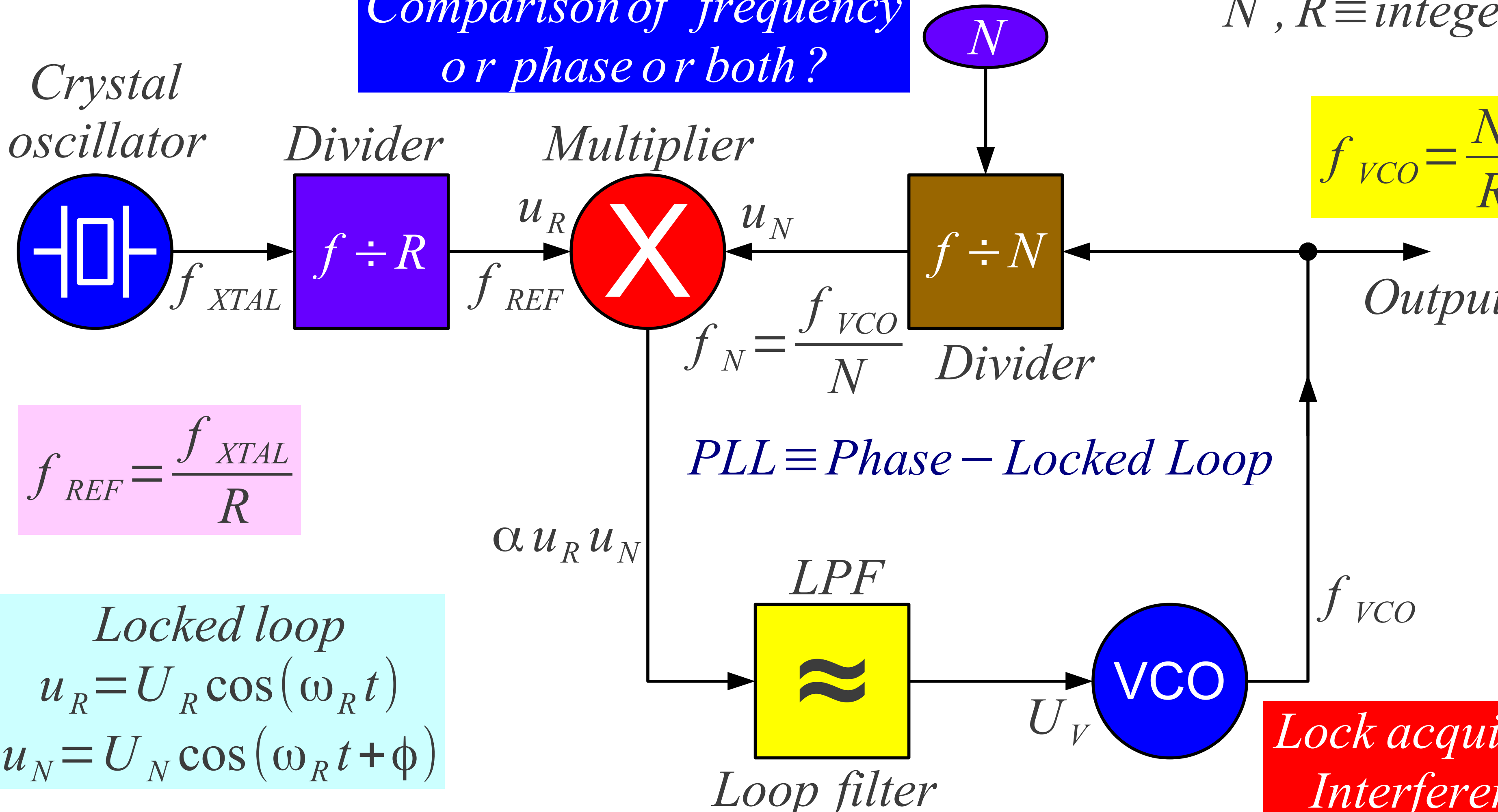


Voltage − controlled oscillator

Phase − locked loop

Comparison of frequency or phase or both?

$N, R \equiv$ integers!



$$f_{VCO} = \frac{N}{R} f_{XTAL}$$

$$f_{REF} = \frac{f_{XTAL}}{R}$$

PLL ≡ Phase − Locked Loop

Locked loop

$$u_R = U_R \cos(\omega_R t)$$

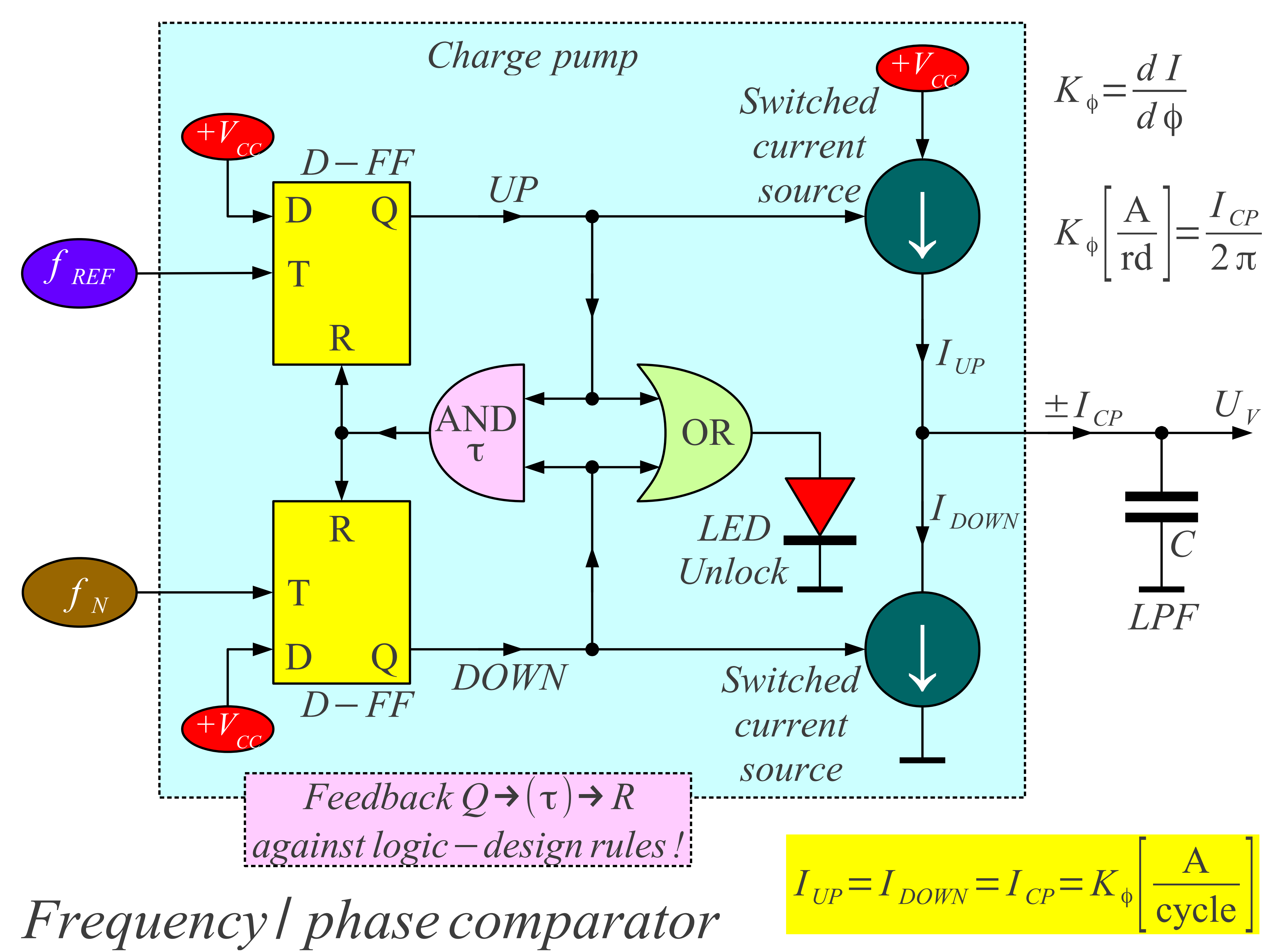
$$u_N = U_N \cos(\omega_R t + \phi)$$

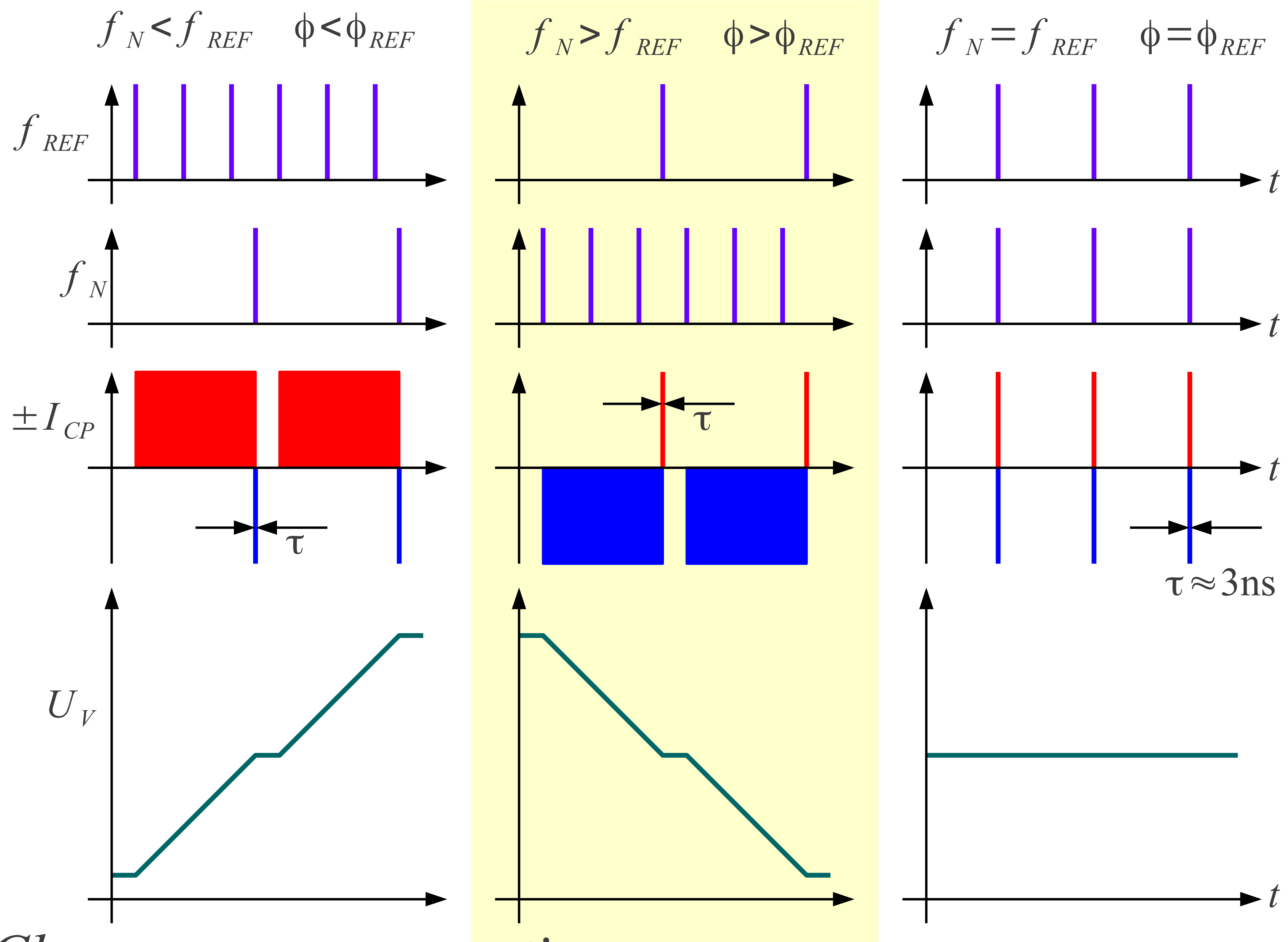
$$\alpha u_R u_N = \alpha \frac{U_R U_N}{2} \cdot \left[\cos(2\omega_R t + \phi) + \cos\phi\right] \rightarrow U_V \approx \alpha \frac{U_R U_N}{2} \cos\phi$$

Interference!

Lock acquisition? Interference & phase noise?

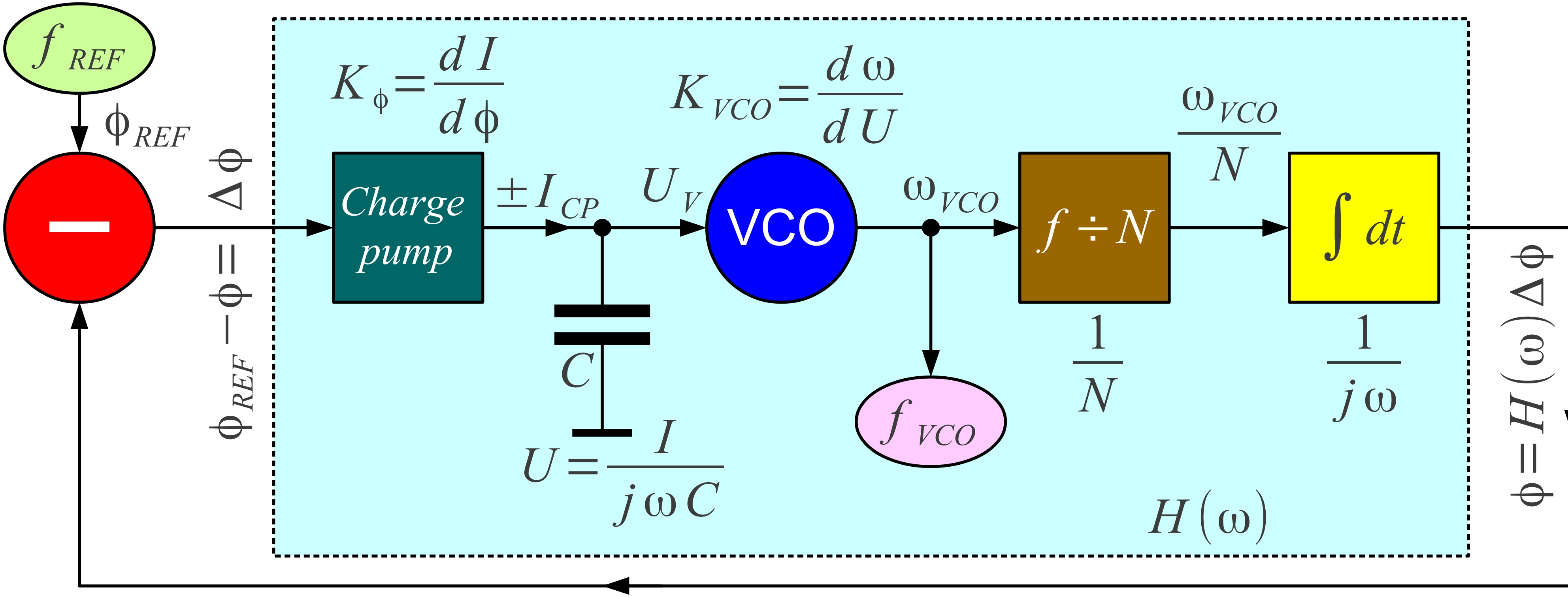
Inexpensive electronics
low power drain
single − chip integration
large choice of N & R


Charge pump
$+V_{CC}$
Switched current source
$K_\phi = \frac{dI}{d\phi}$
$K_\phi \left[\frac{\text{A}}{\text{rd}}\right] = \frac{I_{CP}}{2\pi}$
$D-FF$
D
Q
T
R
UP
f_{REF}
I_{UP}
AND
τ
OR
$\pm I_{CP}$
U_V
R
T
D
Q
f_N
I_{DOWN}
LED Unlock
C
LPF
DOWN
$D-FF$
Switched current source
Feedback $Q \rightarrow (\tau) \rightarrow R$
against logic − design rules !
$I_{UP} = I_{DOWN} = I_{CP} = K_\phi \left[\frac{\text{A}}{\text{cycle}}\right]$
Frequency / phase comparator



Charge – pump operation

Harmonic interference $\phi = A \cdot e^{st} = A \cdot e^{j\omega t}$ (simplified $s = \sigma + j\omega$)

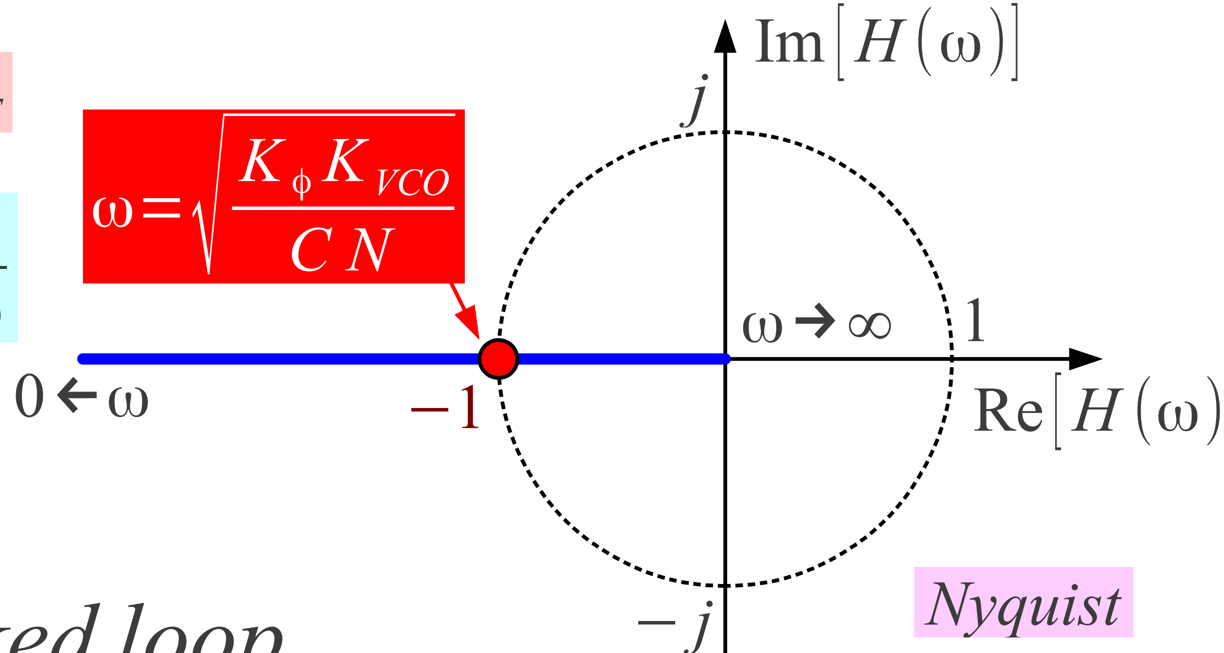


$$\Delta\phi = \frac{\phi_{REF}}{1 + H(\omega)}$$

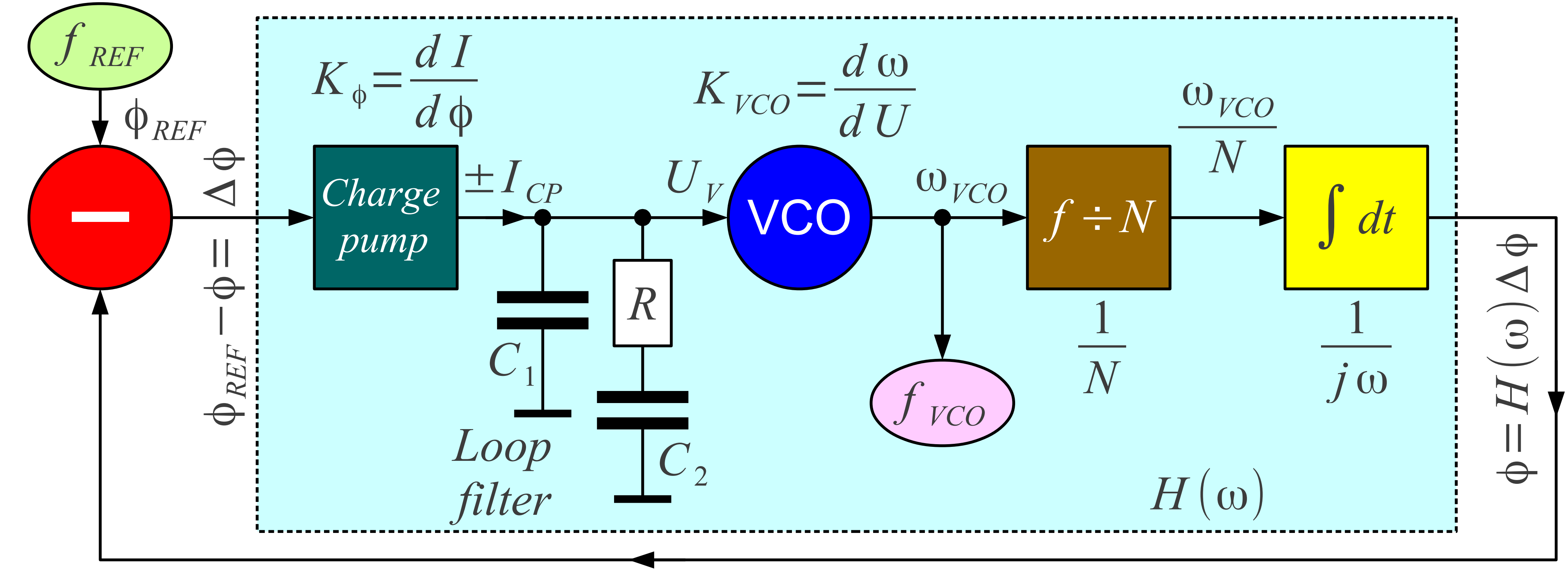
$$\omega \ll 2\pi f_{REF}$$

$$H(\omega) = K_\phi \cdot \frac{1}{j\omega C} \cdot K_{VCO} \cdot \frac{1}{N} \cdot \frac{1}{j\omega}$$

$$H(\omega) = \frac{-K_\phi K_{VCO}}{\omega^2 C N}$$



Unstable phase−locked loop



$$H(\omega)=K_\phi\cdot\frac{1}{j\omega C_1+\dfrac{1}{R+\dfrac{1}{j\omega C_2}}}\cdot K_{VCO}\cdot\frac{1}{N}\cdot\frac{1}{j\omega}$$

$$Zero:\quad \tau_2=RC_2$$

$$H(\omega)=\frac{-K_\phi K_{VCO}}{\omega^2(C_1+C_2)N}\cdot\frac{1+j\omega RC_2}{1+j\omega R\dfrac{C_1C_2}{C_1+C_2}}$$

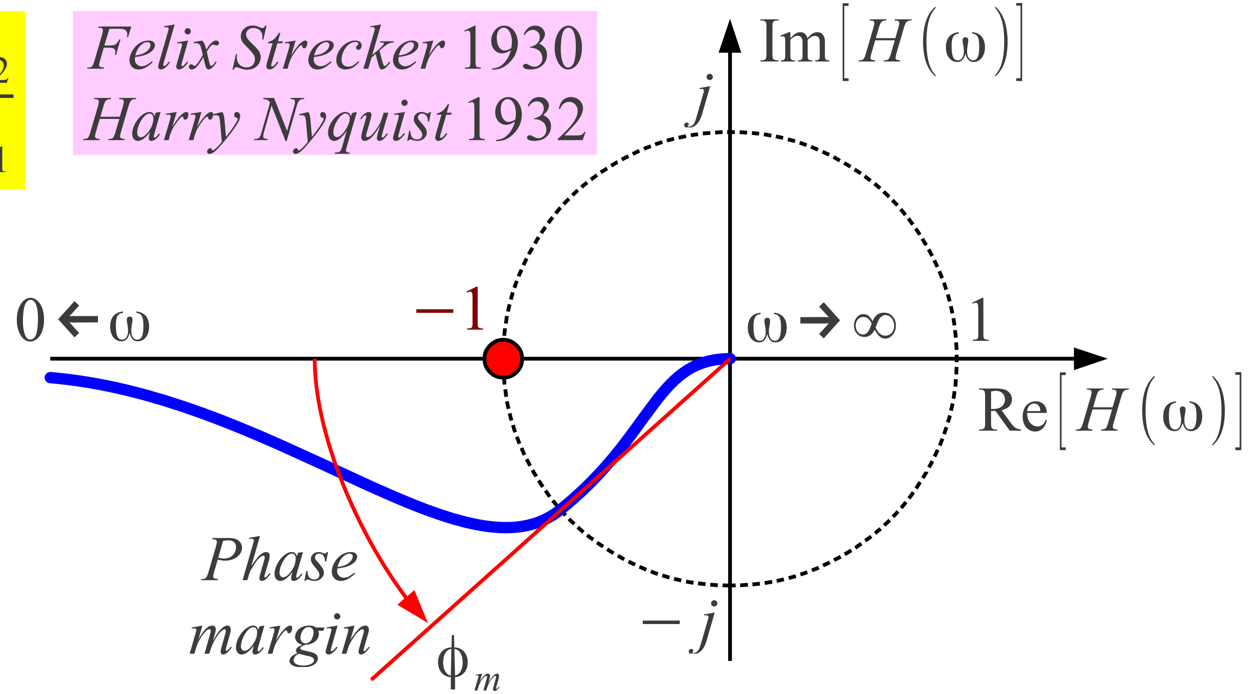
$$H(\omega)=\frac{-K_\phi K_{VCO}}{\omega^2(C_1+C_2)N}\cdot\frac{1+j\omega\tau_2}{1+j\omega\tau_1}$$

$$Pole:\quad \tau_1=R\frac{C_1C_2}{C_1+C_2}$$

Stable phase − locked loop

$$H(\omega)=\frac{-K_{\phi}K_{VCO}}{\omega^2(C_1+C_2)N}\cdot\frac{1+j\omega\tau_2}{1+j\omega\tau_1}$$

Felix Strecker 1930
Harry Nyquist 1932



$$\phi_m=\arctan\frac{\omega(\tau_2-\tau_1)}{1+\omega^2\tau_1\tau_2}$$

Max phase margin:

$$\frac{d\phi_m}{d\omega}=0 \;\rightarrow\; \omega_m=\frac{1}{\sqrt{\tau_1\tau_2}}$$

$$\frac{zero}{pole}\,ratio \equiv m=\frac{\tau_2}{\tau_1} \;\rightarrow\; \sqrt{m}=\omega_m\tau_2=\frac{1}{\omega_m\tau_1} \;\rightarrow\; C_1+C_2=mC_1$$

Unity circle

$$1=|H(\omega_m)|=\frac{K_{\phi}K_{VCO}}{\omega_m^2 m C_1 N}\cdot\sqrt{\frac{1+m}{1+\frac{1}{m}}}=\frac{K_{\phi}K_{VCO}}{\omega_m^2 C_1 N\sqrt{m}}$$

$$C_1=\frac{K_{\phi}K_{VCO}}{\omega_m^2 N\sqrt{m}}$$

$$C_2=(m-1)C_1$$

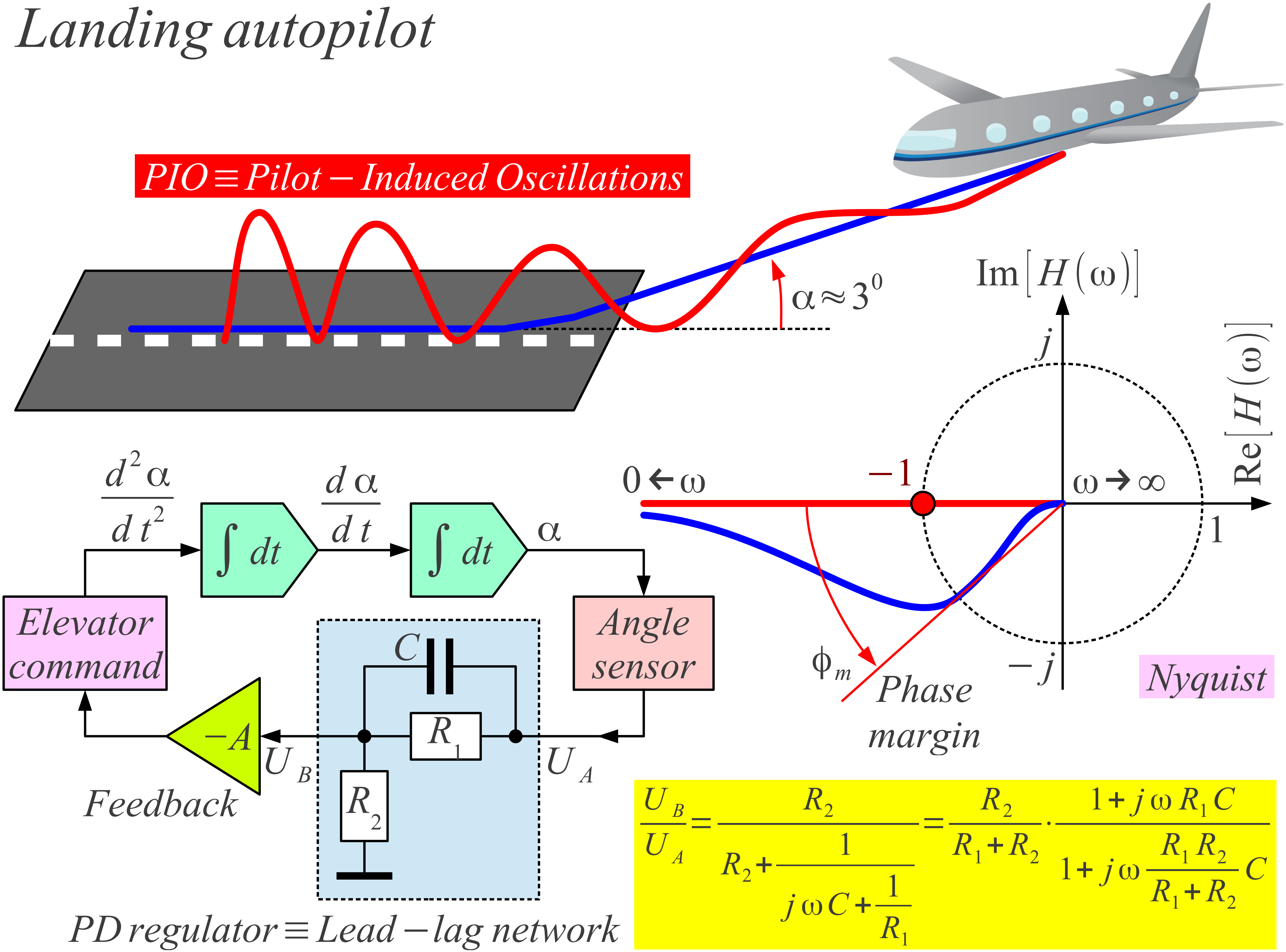
$$R=\frac{\sqrt{m}}{\omega_m C_2}$$

$$\omega_m=\sqrt{\frac{K_{\phi}K_{VCO}}{C_1N\sqrt{m}}}\approx 2\pi B_{loop}$$

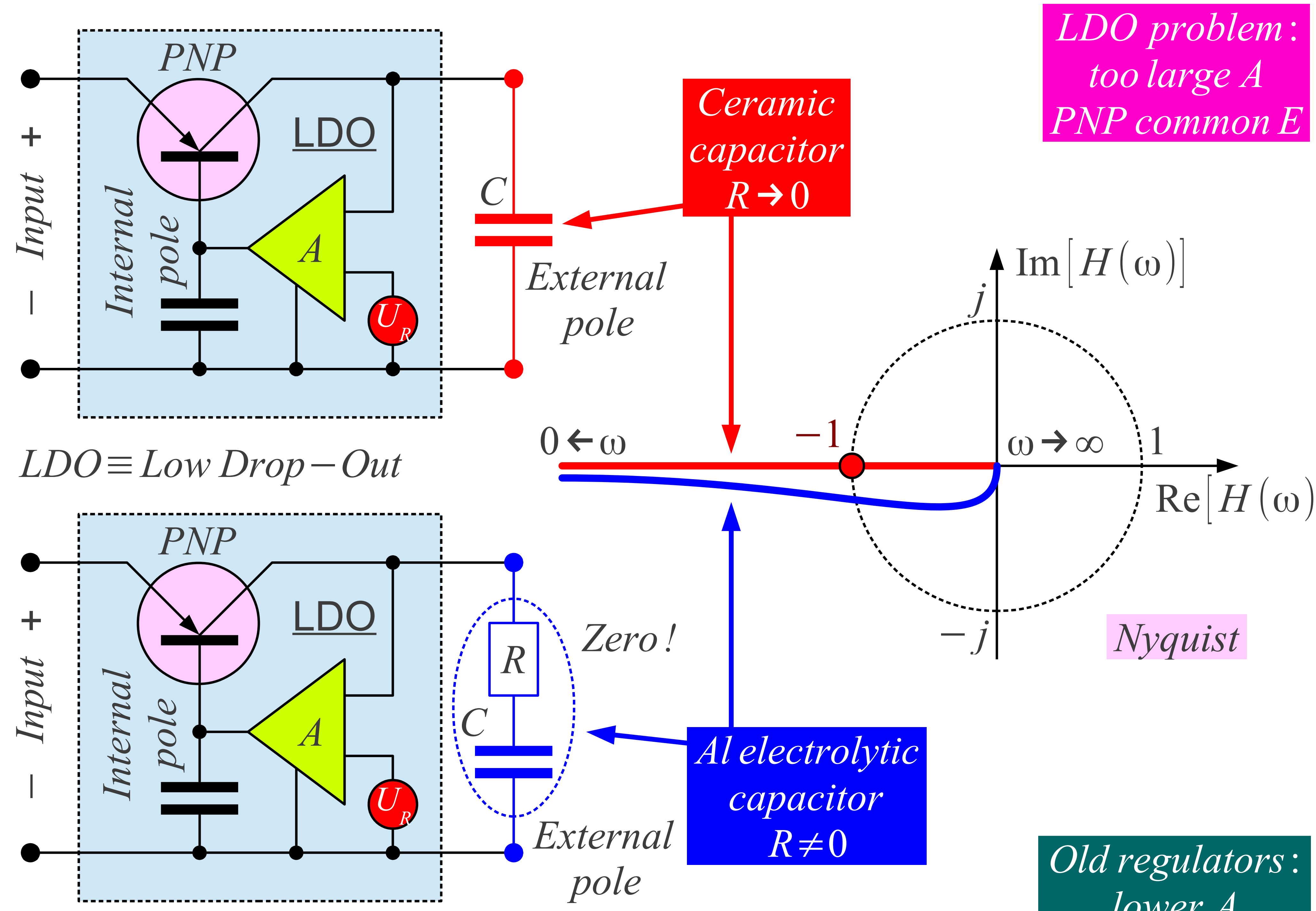
Compatible measurement units! $K_{\phi}K_{VCO}$

Loop − filter calculation

Landing autopilot



$$\frac{U_B}{U_A}=\frac{R_2}{R_2+\dfrac{1}{j\omega C+\dfrac{1}{R_1}}}=\frac{R_2}{R_1+R_2}\cdot\frac{1+j\omega R_1 C}{1+j\omega\dfrac{R_1 R_2}{R_1+R_2}C}$$



Unstable voltage regulator

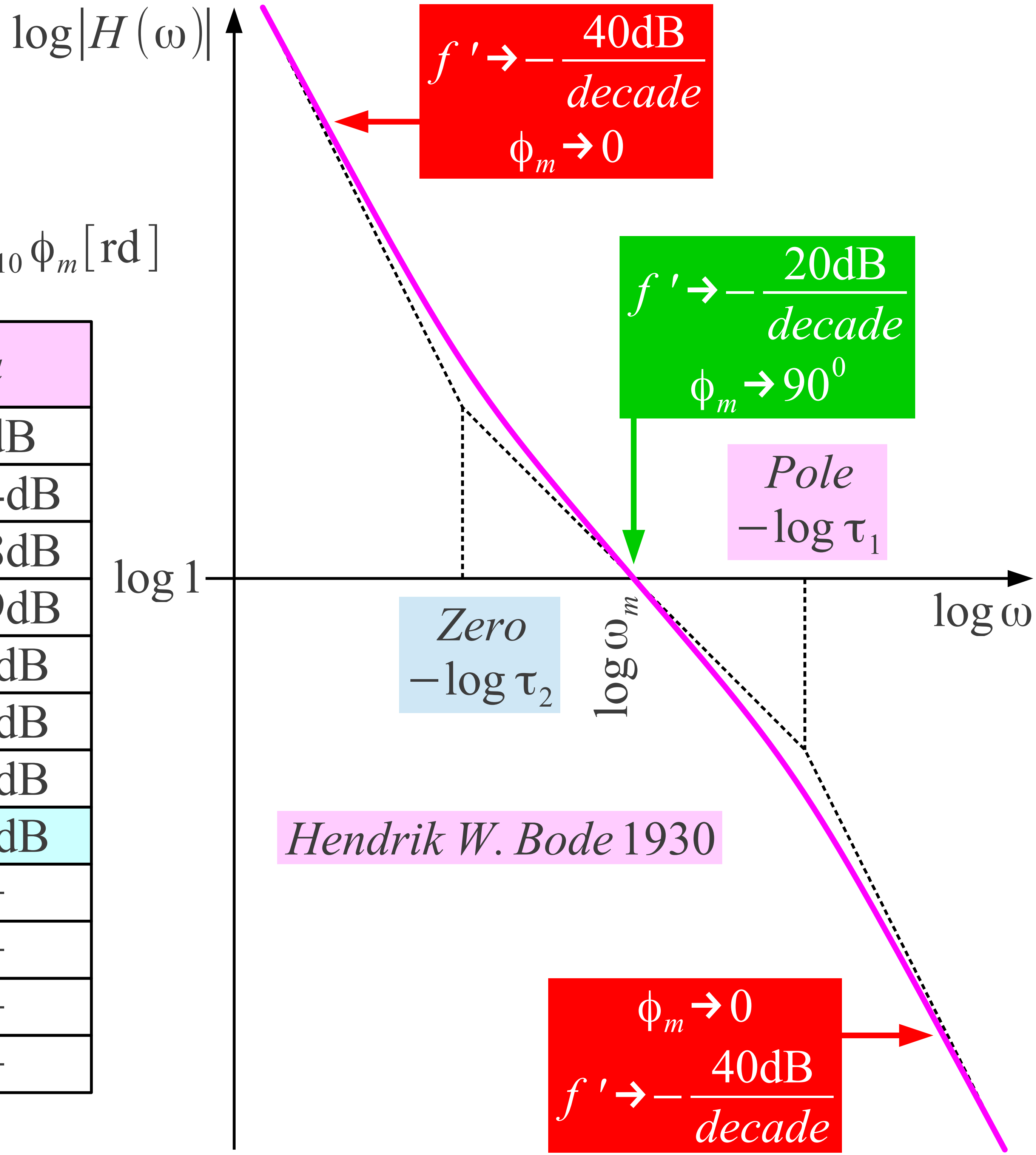
Max phase margin:

$$\phi_m = \arctan\frac{m-1}{2\sqrt{m}}$$

Overshoot: $a_{dB} \approx -20\log_{10}\phi_m[\mathrm{rd}]$

m	C_2/C_1	$\phi_m[^0]$	a
1	0	0^0	∞dB
1.1	0.1	2.73^0	26.4dB
1.2	0.2	5.22^0	20.8dB
1.5	0.5	11.5^0	13.9dB
2	1	19.5^0	9.4dB
3	2	30.0^0	5.6dB
5	4	41.8^0	2.7dB
10	9	54.9^0	0.4dB
20	19	64.8^0	–
50	49	73.9^0	–
100	99	78.6^0	–
200	199	81.9^0	–

Zero / pole ratio



Phase − noise transfer

Max phase margin:

$$\phi_m = \arctan \frac{m-1}{2\sqrt{m}}$$

Overshoot: $a \approx \frac{1}{\phi_m[\mathrm{rd}]}$

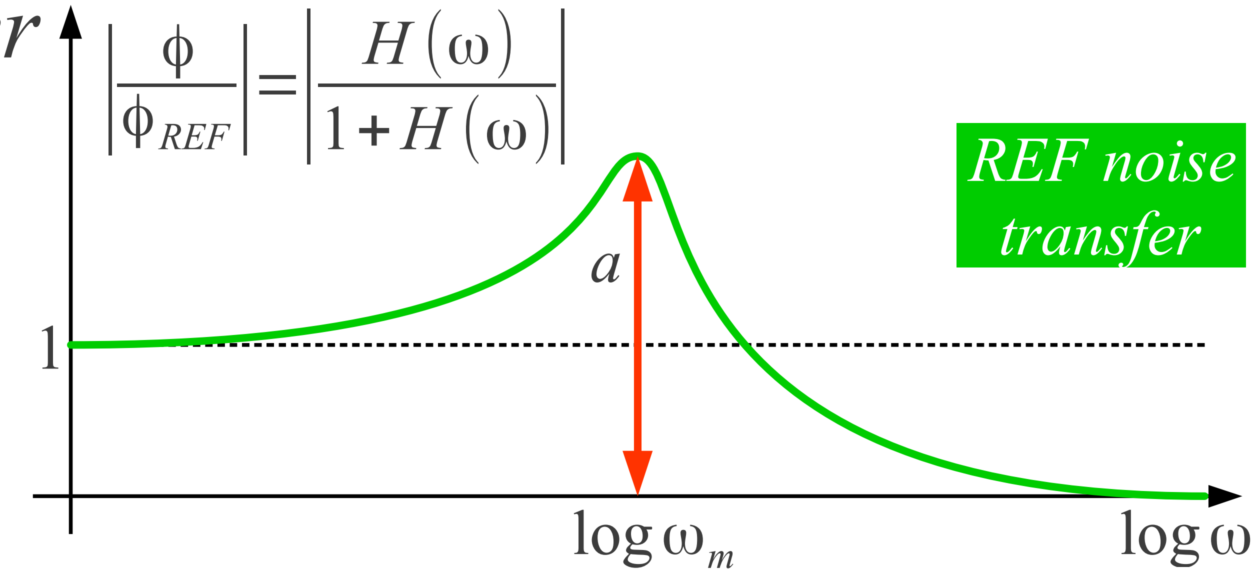
$$a_{\mathrm{dB}} \approx -20 \log_{10} \phi_m[\mathrm{rd}]$$

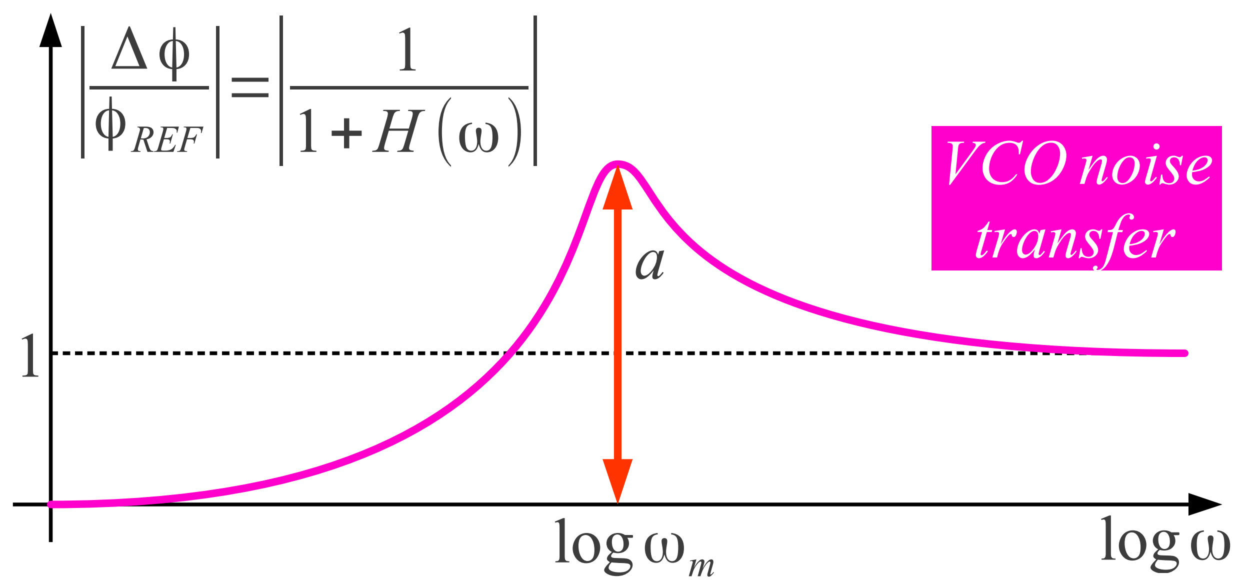
SDH regenerator $a < 0.1\,\mathrm{dB}$

Phase − noise Δf:

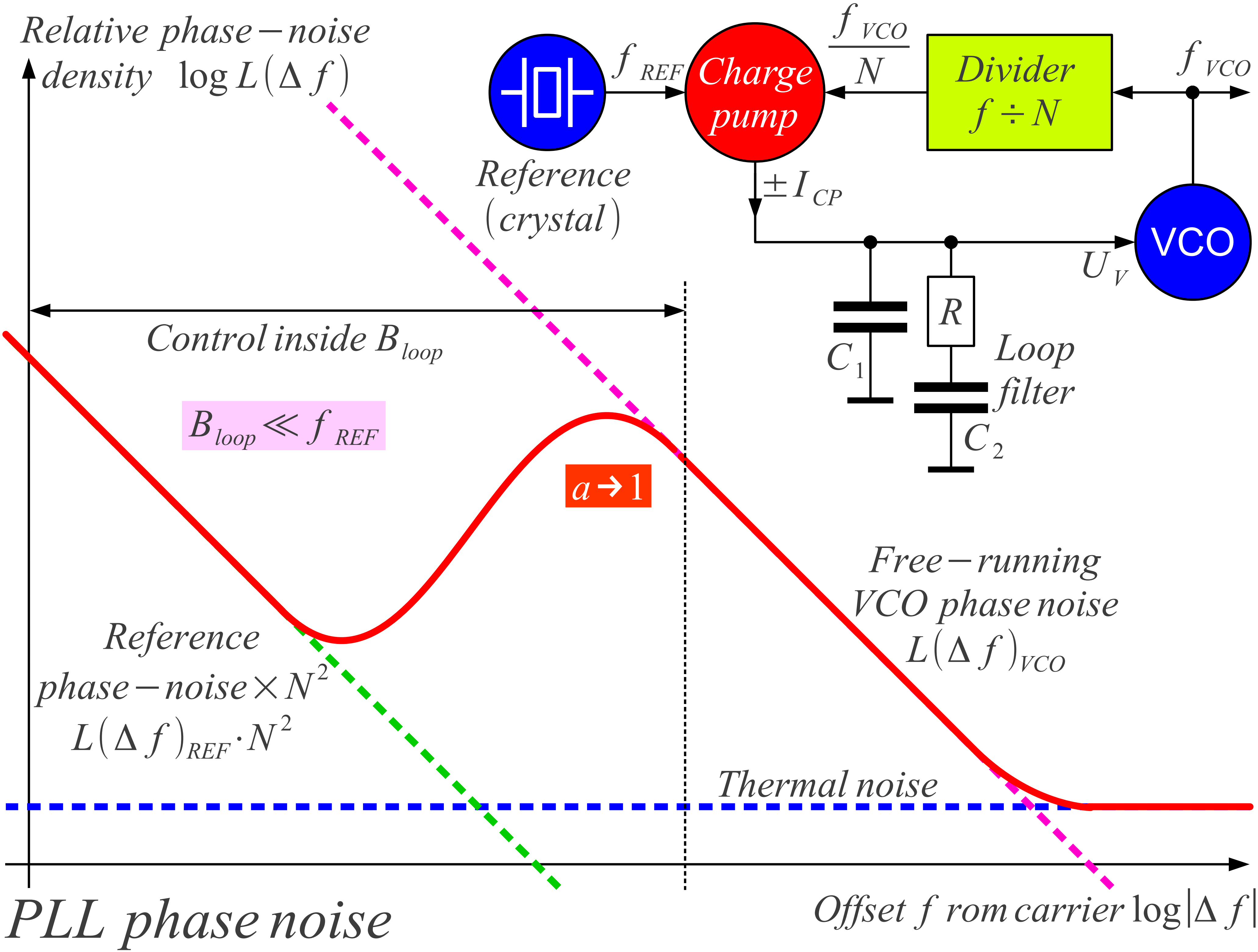
$$\omega \rightarrow 2\pi\Delta f$$

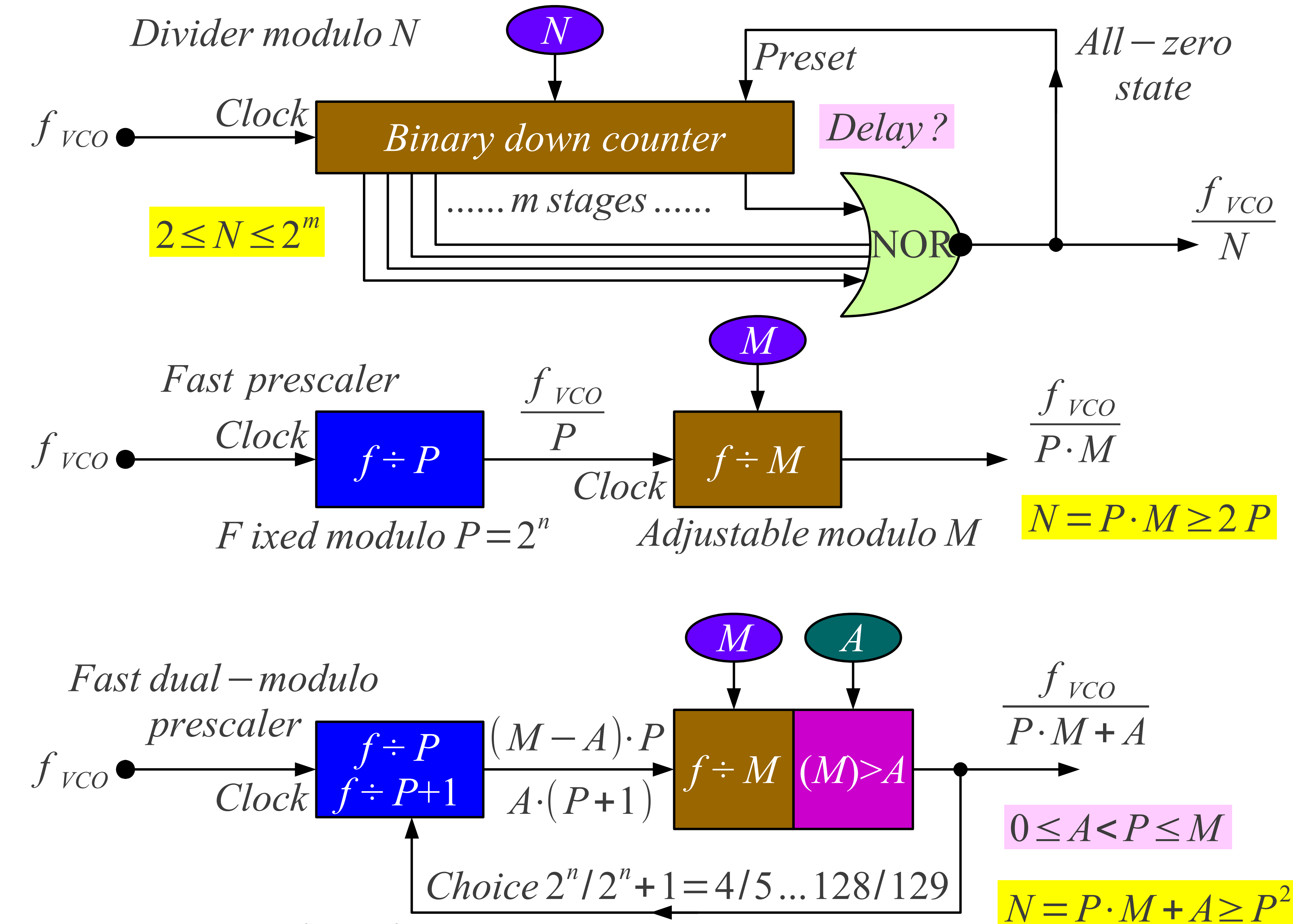
$$H(\omega) \rightarrow H(2\pi\Delta f)$$





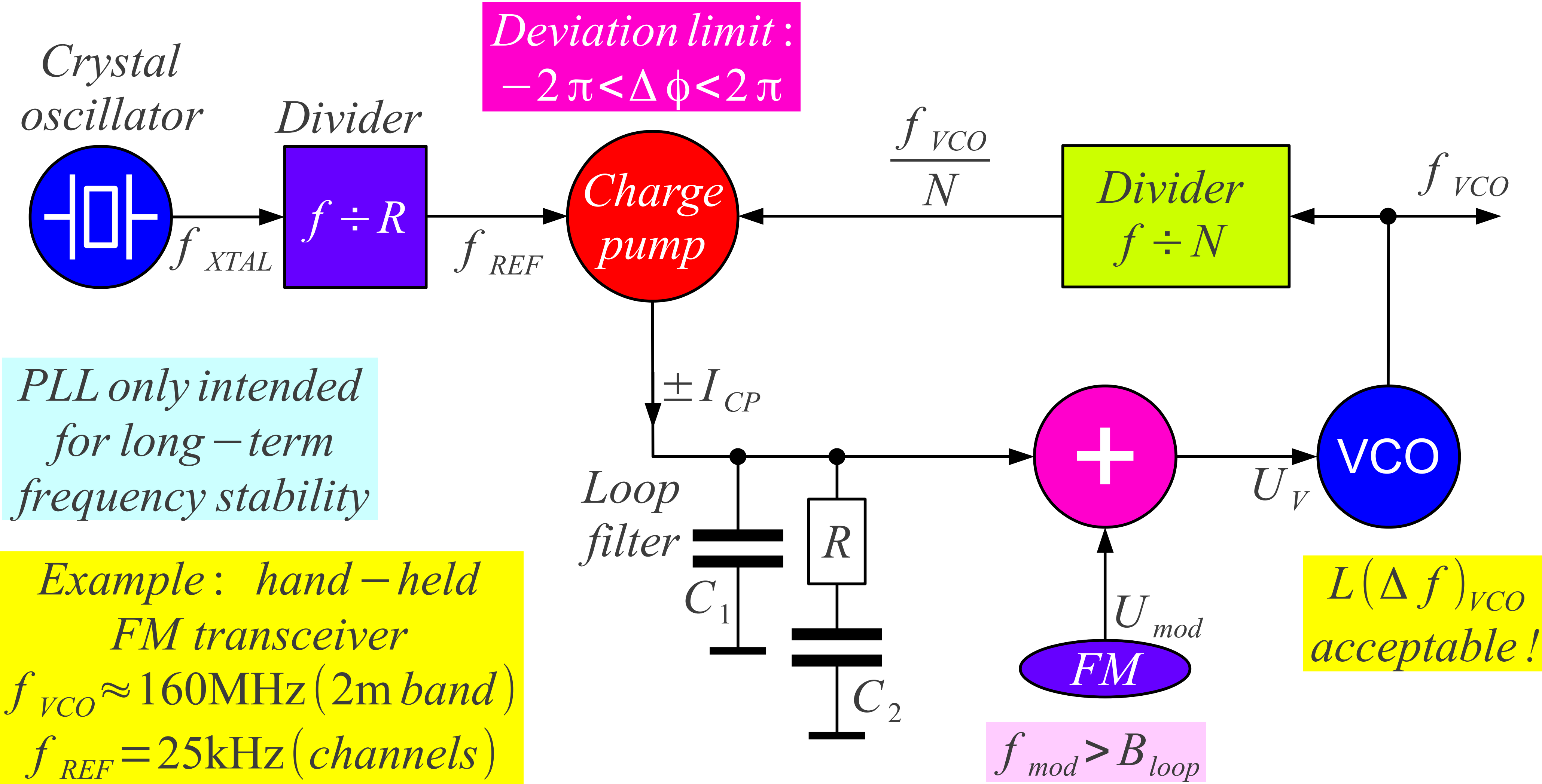
$$L(\Delta f) = L(\Delta f)_{REF} \cdot N^2 \cdot \left|\frac{H(2\pi\Delta f)}{1+H(2\pi\Delta f)}\right|^2 + L(\Delta f)_{VCO} \cdot \left|\frac{1}{1+H(2\pi\Delta f)}\right|^2$$


Relative phase−noise density log L(Δf)
Reference (crystal)
f REF
Charge pump
f VCO / N
Divider f ÷ N
f VCO
±I CP
VCO
U V
C 1
R
C 2
Loop filter
Control inside B loop
B loop ≪ f REF
a→1
Free−running VCO phase noise L(Δf)VCO
Reference phase−noise × N²
L(Δf)REF · N²
Thermal noise
Offset from carrier log|Δf|
PLL phase noise



Frequency dividers

Analog frequency modulation & PLL



Example : hand−held FM transceiver

$f_{VCO} \approx 160\text{MHz}$ (2m *band*)

$f_{REF} = 25\text{kHz}$ (*channels*)

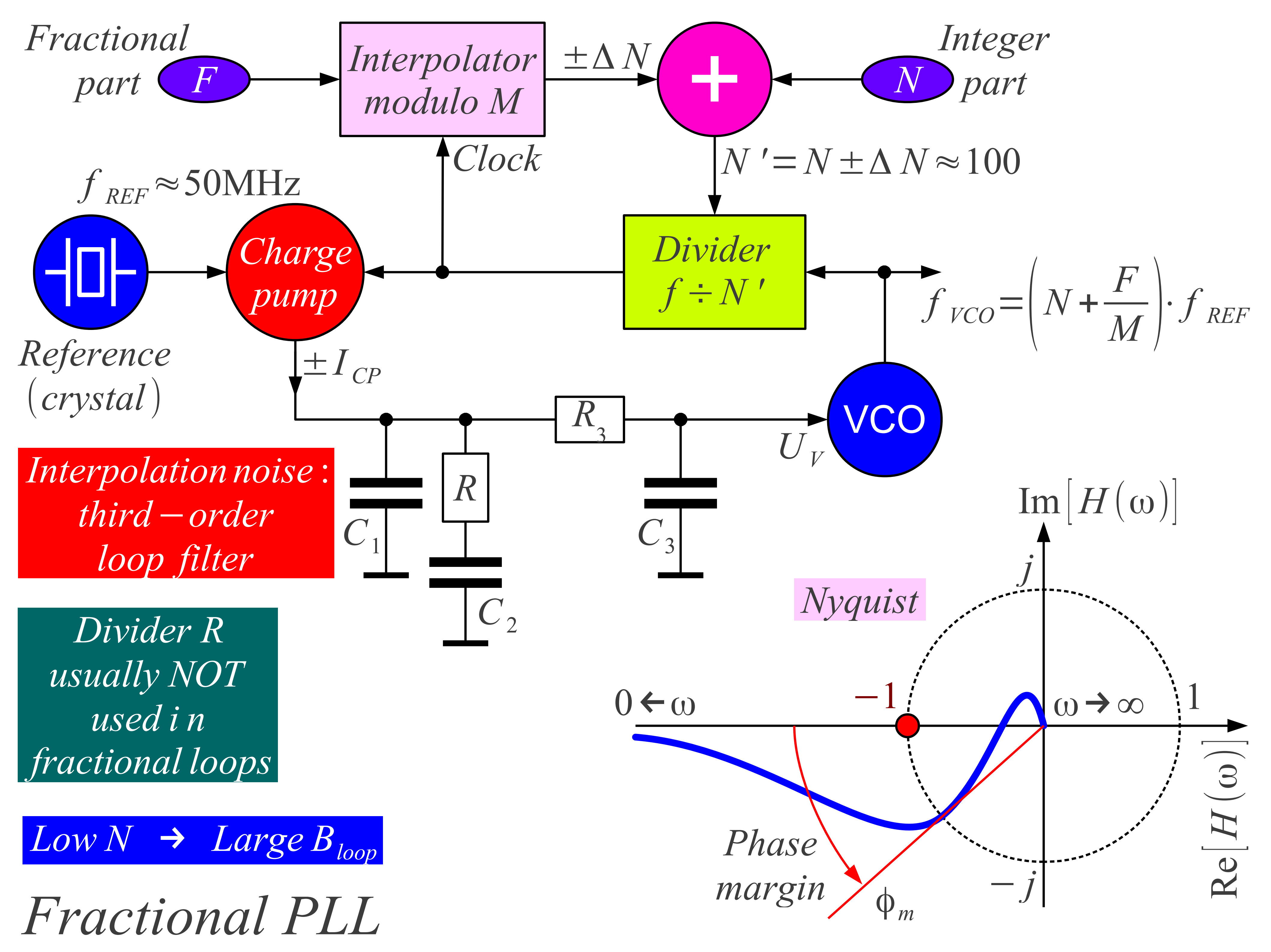
$N \approx 6400$

$B_{loop} \approx 100\text{Hz}$

$300\text{Hz} < f_{mod} < 3\text{kHz}$

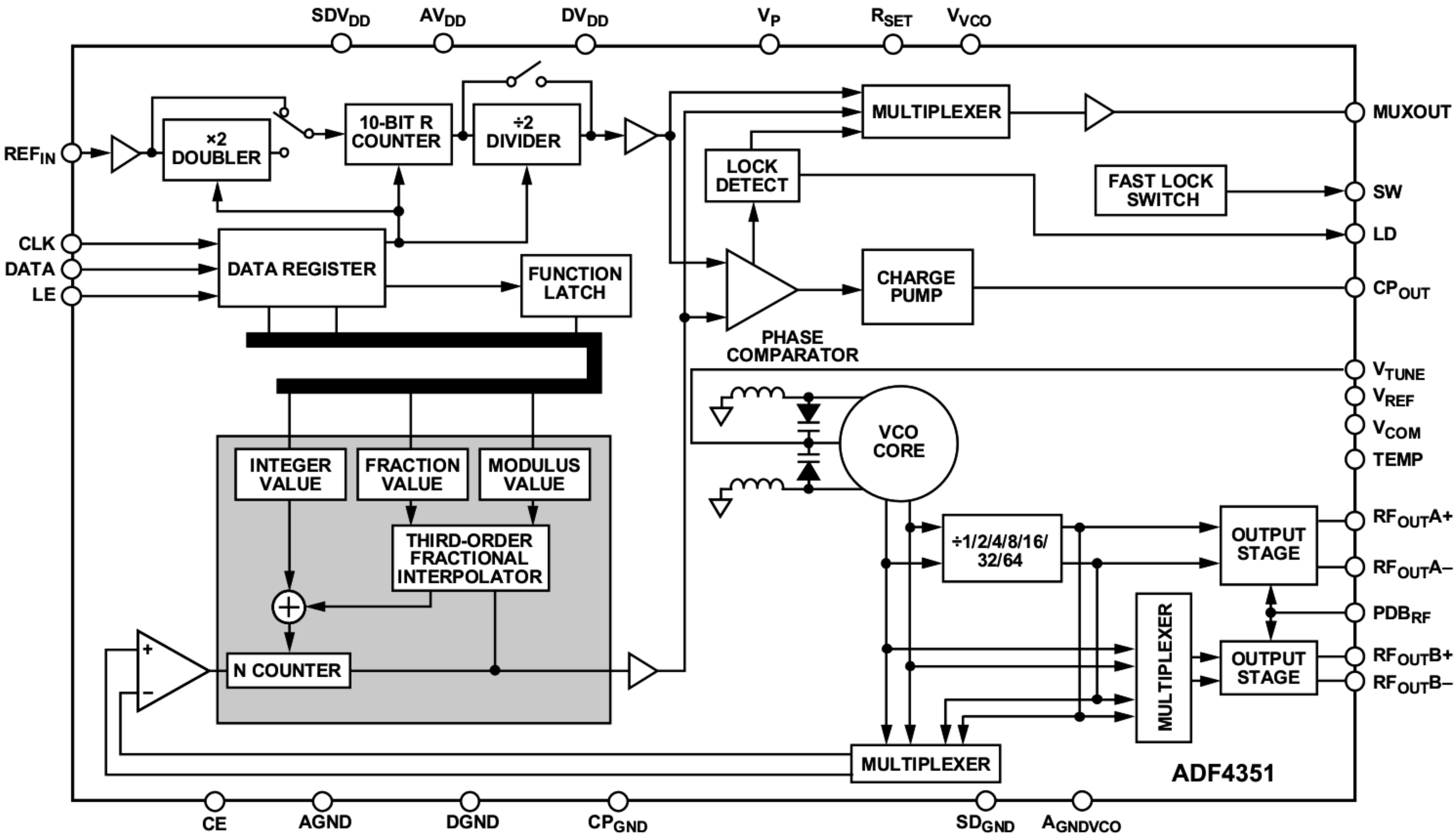
deviation $\Delta f = \pm 5\text{kHz}$

Large N & R → Small B_{loop}



Fractional part
F
Interpolator modulo M
±Δ N
+
N
Integer part
Clock
N ' = N ± Δ N ≈ 100
f REF ≈ 50MHz
Charge pump
Divider f ÷ N '
f VCO = (N + F/M) · f REF
Reference (crystal)
± I CP
R 3
VCO
U V
Interpolation noise : third − order loop filter
C 1
R
C 3
C 2
Im [H (ω)]
j
Nyquist
Divider R usually NOT used i n fractional loops
0 ← ω
−1
ω → ∞
1
Re [H (ω)]
Low N → Large B loop
Phase margin
φ m
− j
Fractional PLL

Pin−compatible clone MAX2871 (*Maxim*) *better than the original ...*



Fractional PLL ADF4351 *from Analog Devices*

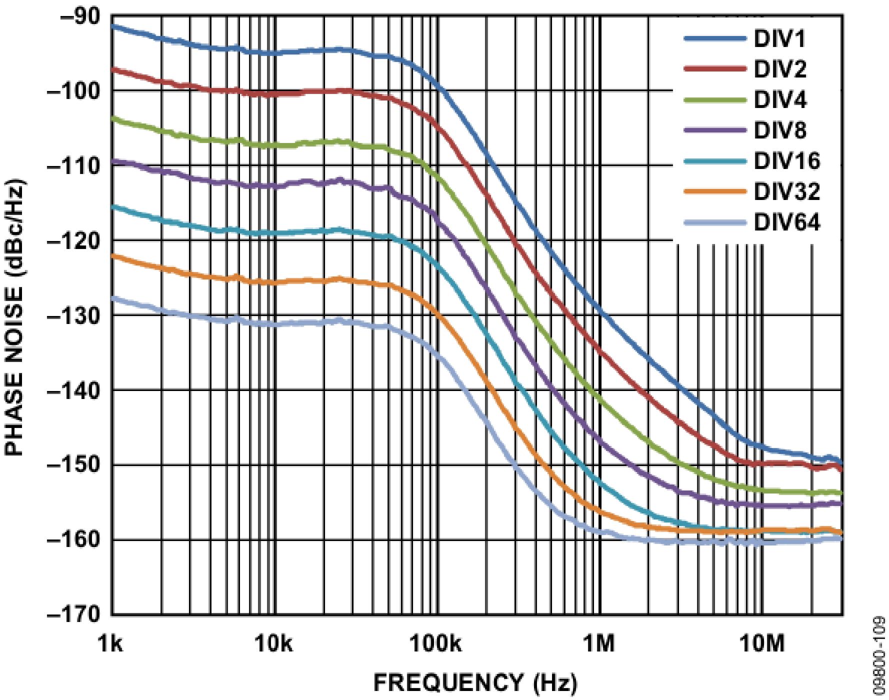


Figure 9. Closed-Loop Phase Noise, Fundamental VCO and Dividers, VCO = 4.4 GHz, PFD = 25 MHz, Loop Filter Bandwidth = 63 kHz

$C_1 = 3.3\text{nF}$

$C_2 = 47\text{nF}$ $\quad R_3 = 1.5\text{k}\Omega$

$R = 390\,\Omega$ $\quad C_3 = 470\text{pF}$

$\tau_1 = 1.2\,\mu\text{s}$ $\quad \tau_3 = 0.7\,\mu\text{s}$

$\tau_2 = 18\,\mu\text{s}$

LO with ADF4351