A 350μW CMOS MSK Transmitter and 400μW OOK Super-Regenerative Receiver for Medical Implant Communications

Jose L. Bohorquez,

Joel L. Dawson,

Anantha P. Chandrakasan

Microsystems Technology Laboratories,
Massachusetts Institute of Technology

Outline

- Motivation: MICS band
- Transmitter architecture
- Super-Regenerative Theory
- Receiver architecture
- Measurement results

Wireless Communications with Medical Implants

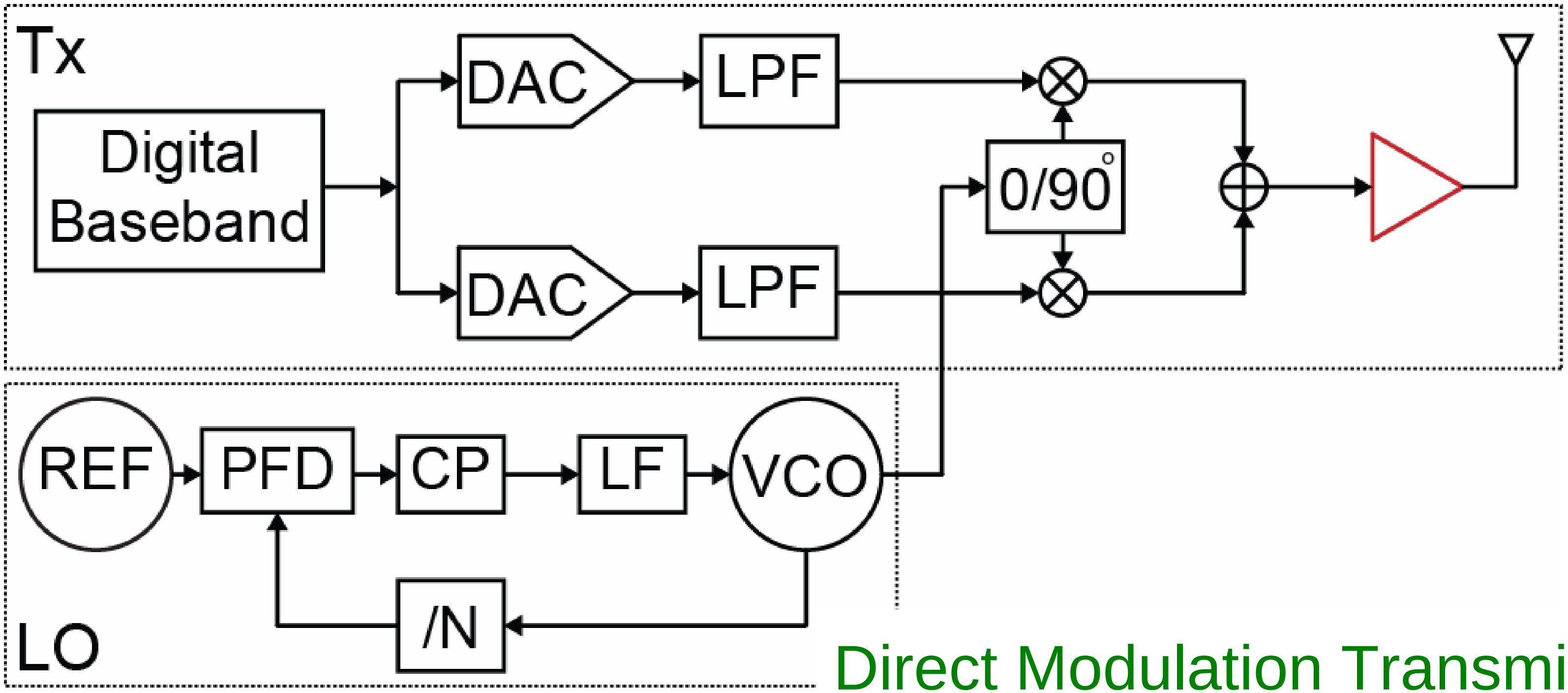
MICS band

- Medical Implant Communications Service
- Commissioned by FCC in 1999
- 402-405 MHz band
- 10 channels, 300 kHz bandwidth each
- Maximum EIRP = 25μW (-16dBm)

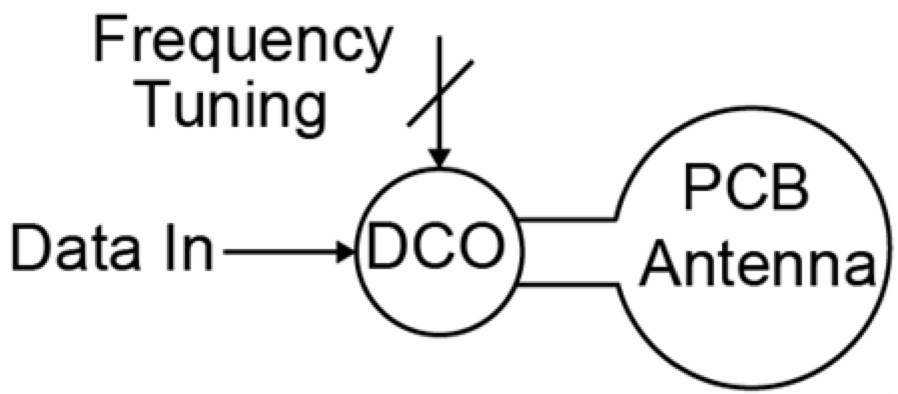
“MICS Band Plan,” Part 95, FCC Rules and Regulations, Jan. 2003.

Transmitter Topology

Classical Homodyne Transmitter



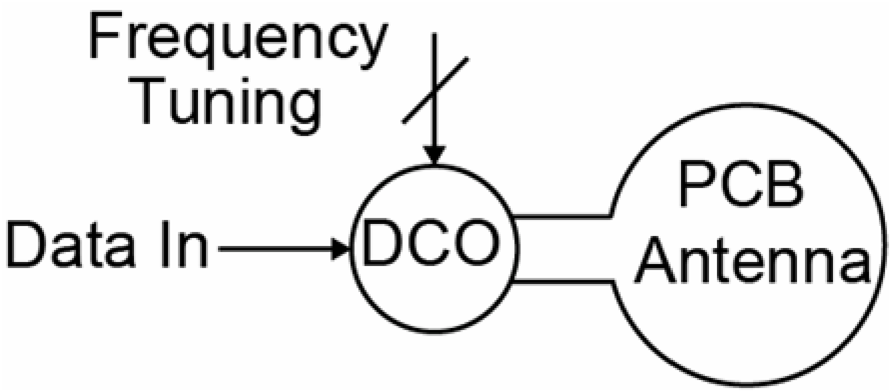
Direct Modulation Transmitter



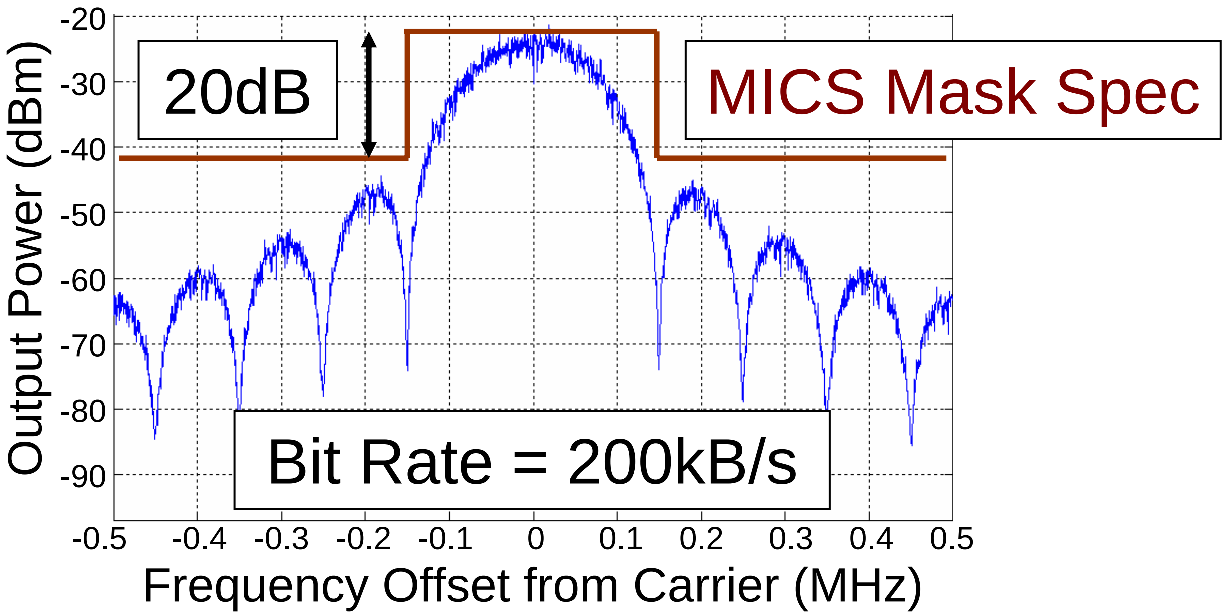
Observation:
Maximum output power: 25μW EIRP

MSK: Minimum Shift Keying

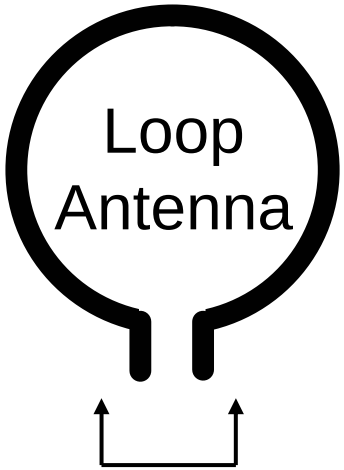
Direct Modulation Transmitter

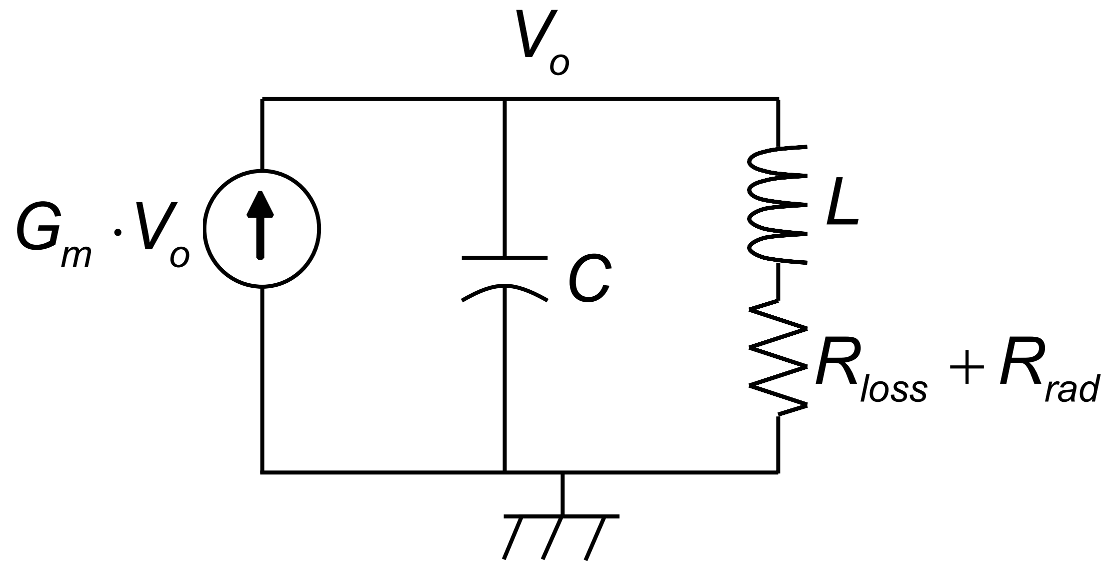


- 0's represented by $f_{LO}=f_0-\Delta F$
- 1's represented by $f_{HI}=f_0+\Delta F$



Oscillator Using Loop Antenna





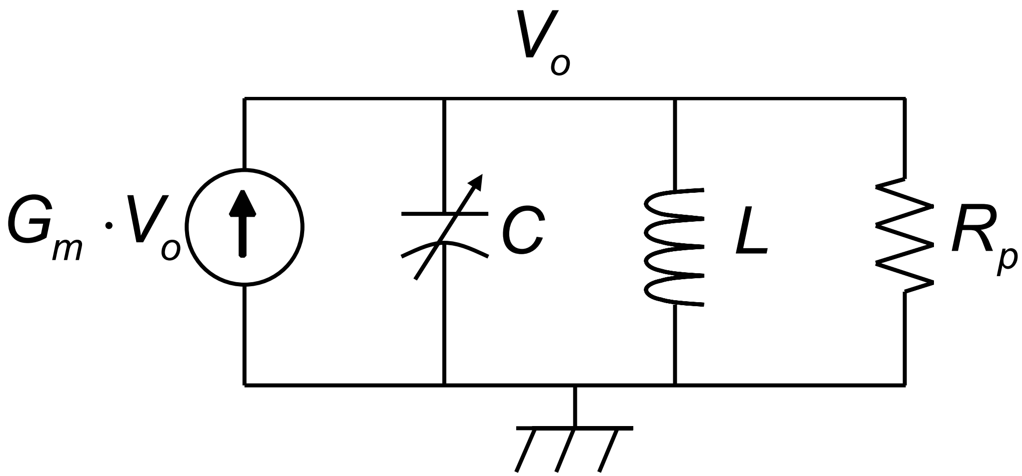
$$Z_{in} = jX_L + R_{loss} + R_{rad}$$

$$Q = \frac{\omega_0 L}{R_{loss} + R_{rad}}$$

$$\eta = \frac{R_{rad}}{R_{loss} + R_{rad}}$$

radiation efficiency

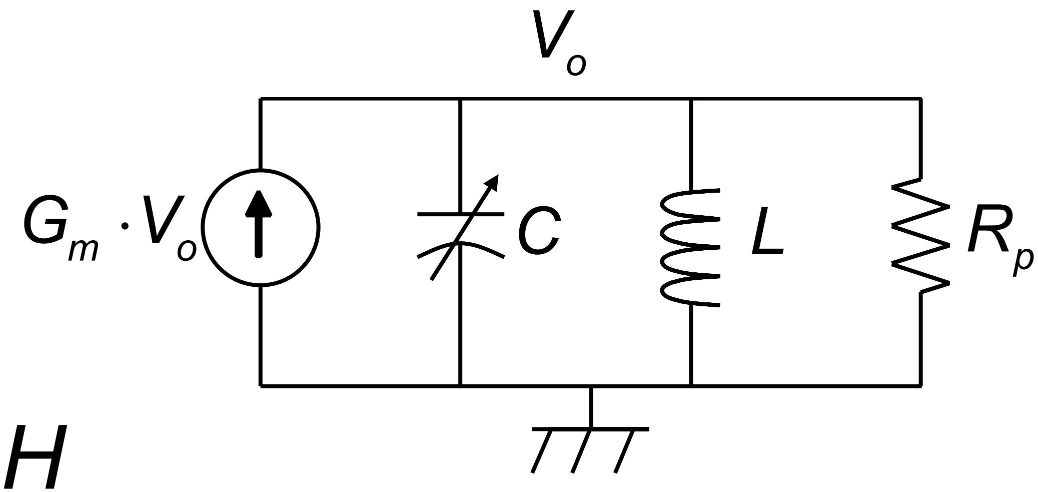
Digitally Controlled Oscillator



MICS requirements
Frequency range: 402-405MHz
Frequency stability: +/- 100ppm = +/- 40kHz

Design goal:
Frequency range: 392—415MHz
Frequency steps : < 2kHz

Digitally Controlled Oscillator



$$L = 20nH$$

$f_{\max} = 415MHz$ → $C_{\min} = 7.35pF$

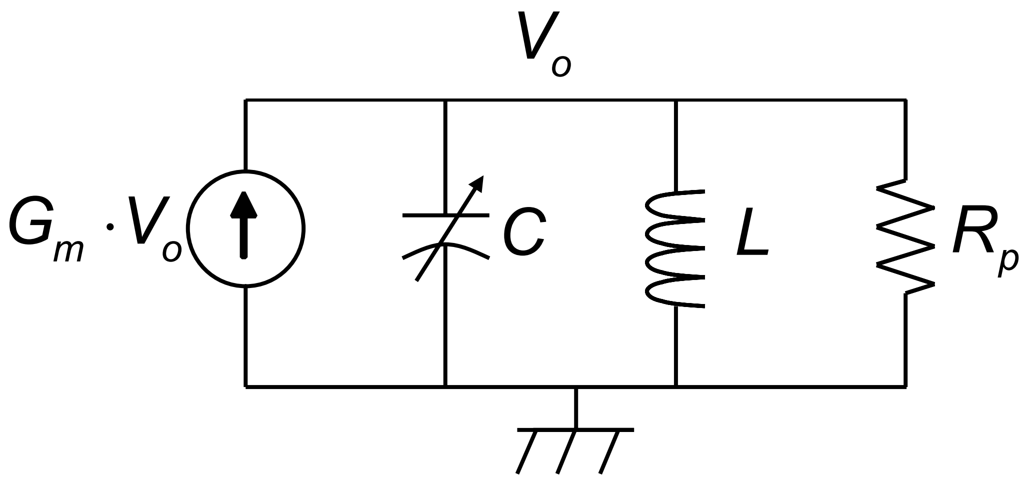
$f_{\min} = 392MHz$ → $C_{\max} = 8.24pF$

$\Delta f < 2kHz$ → $\Delta C_{\min} = 71aF$

$$\frac{C_{\max} - C_{\min}}{dC} \approx 12.5e3$$

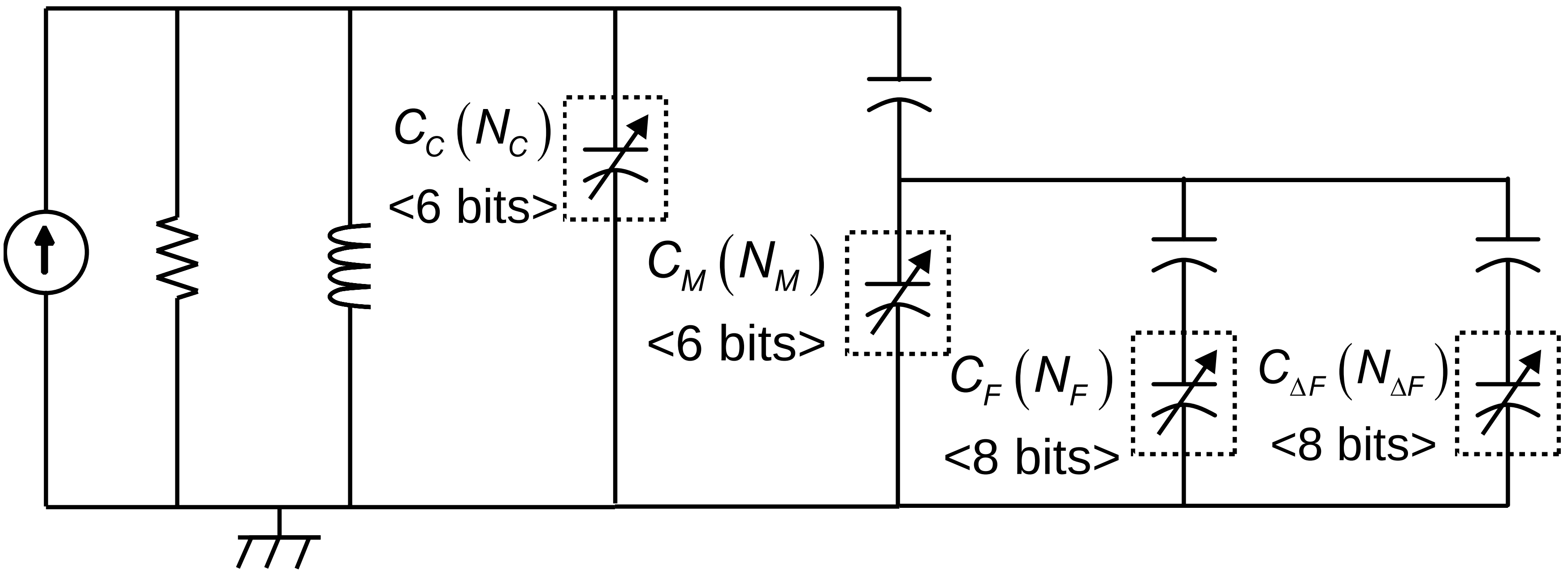
14 bits of resolution

Capacitor Array

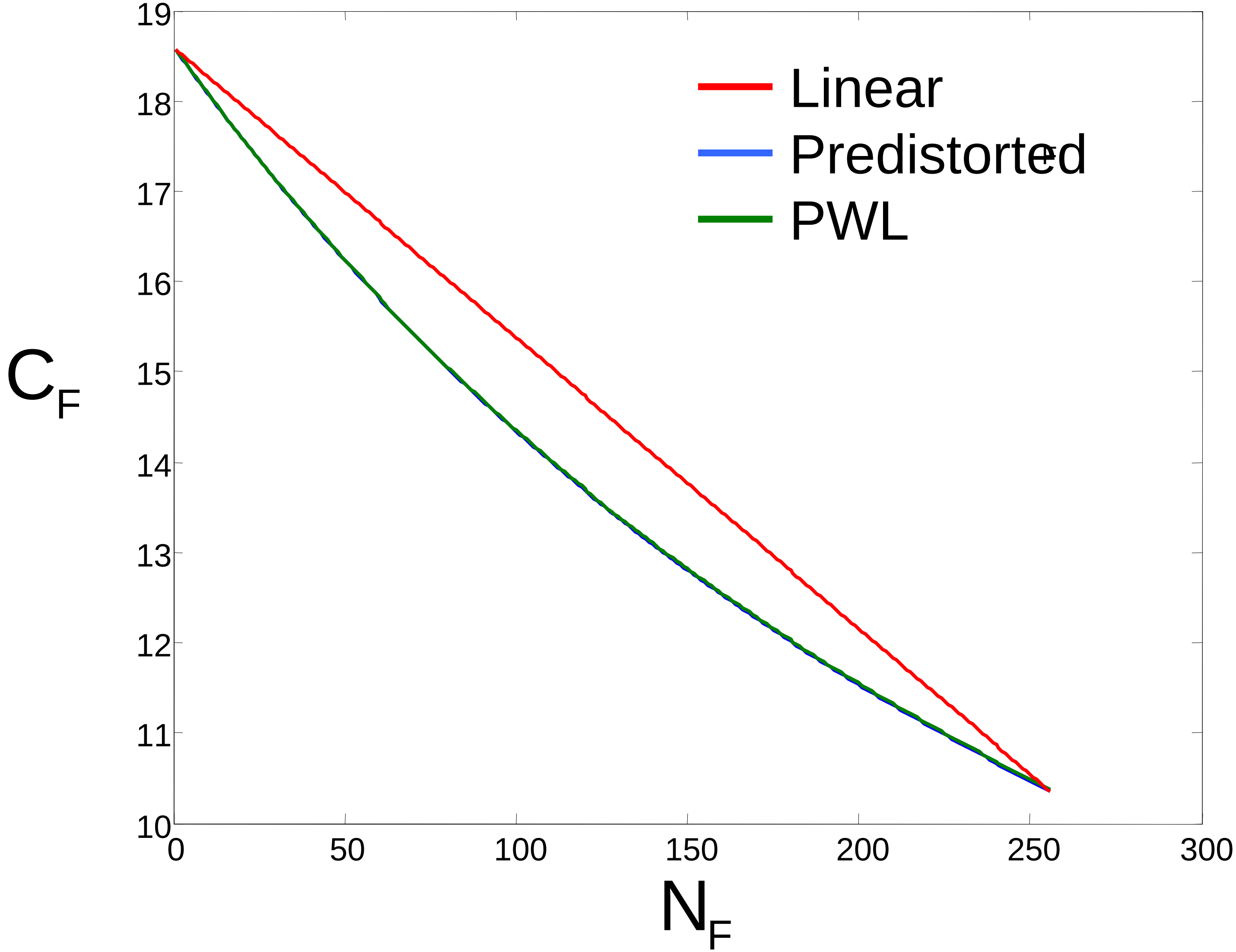


f_0 is a nonlinear function of:

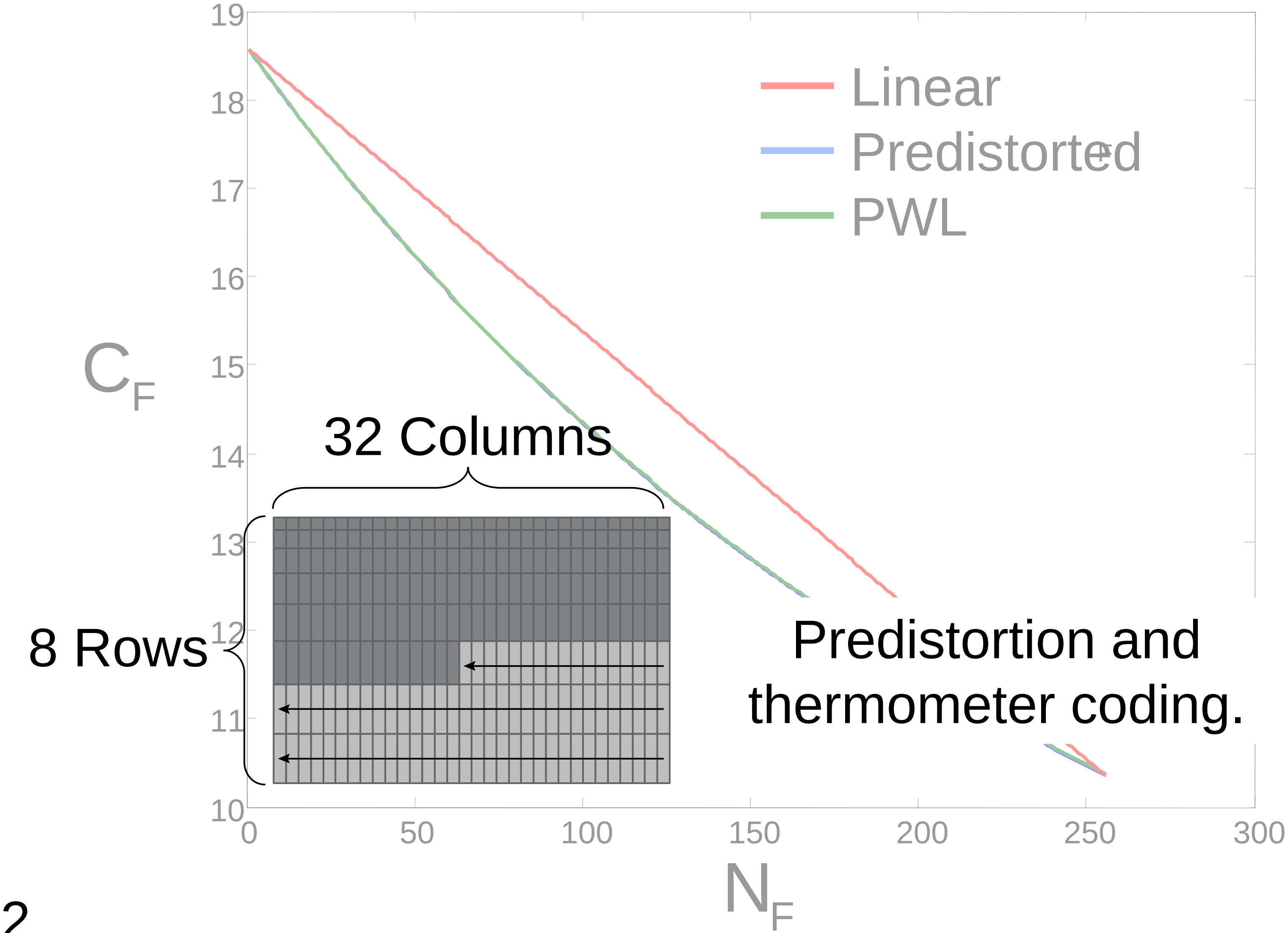
C_C, C_M, C_F, and $C_{\Delta F}$



Capacitor Array Predistortion

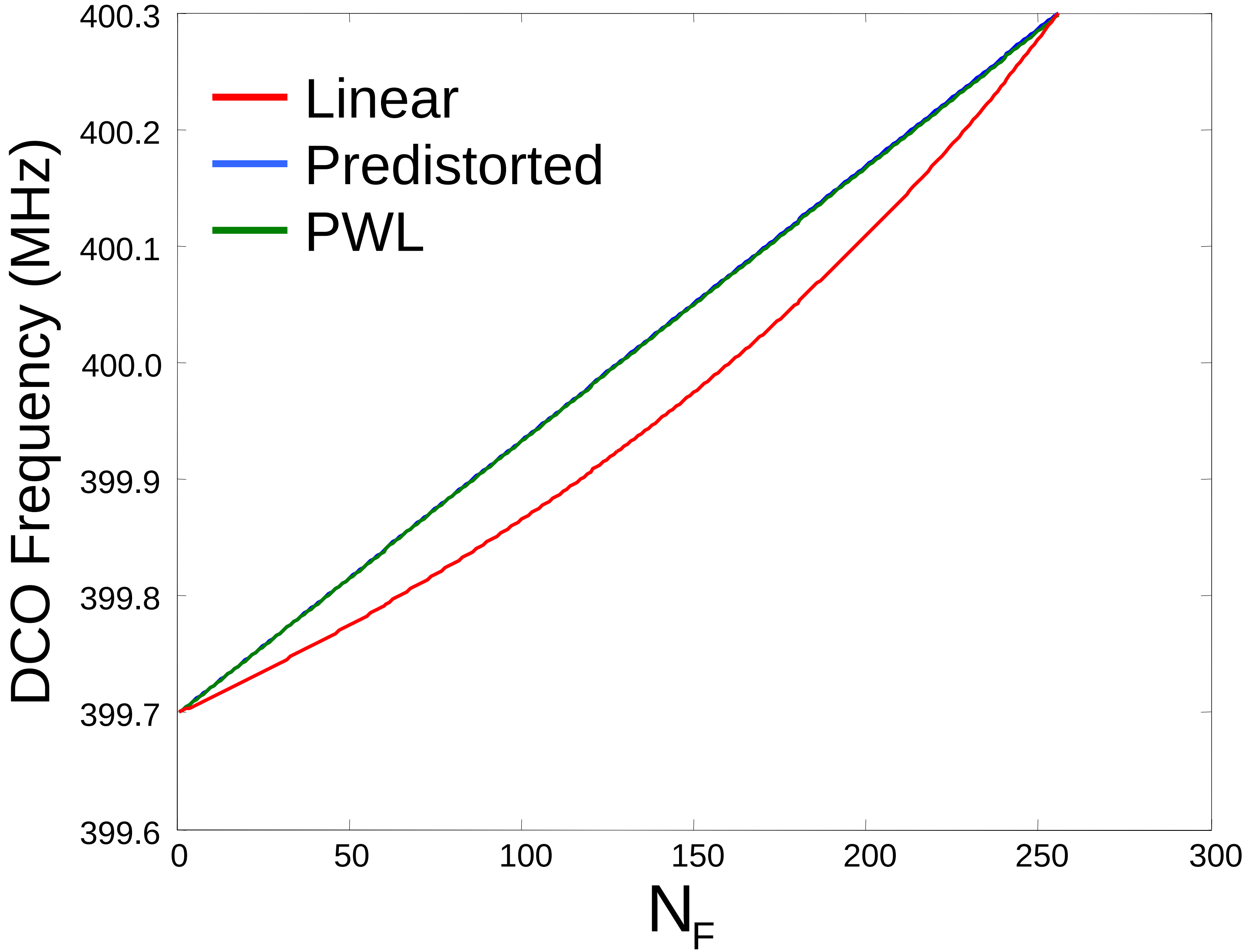


Capacitor Array Predistortion

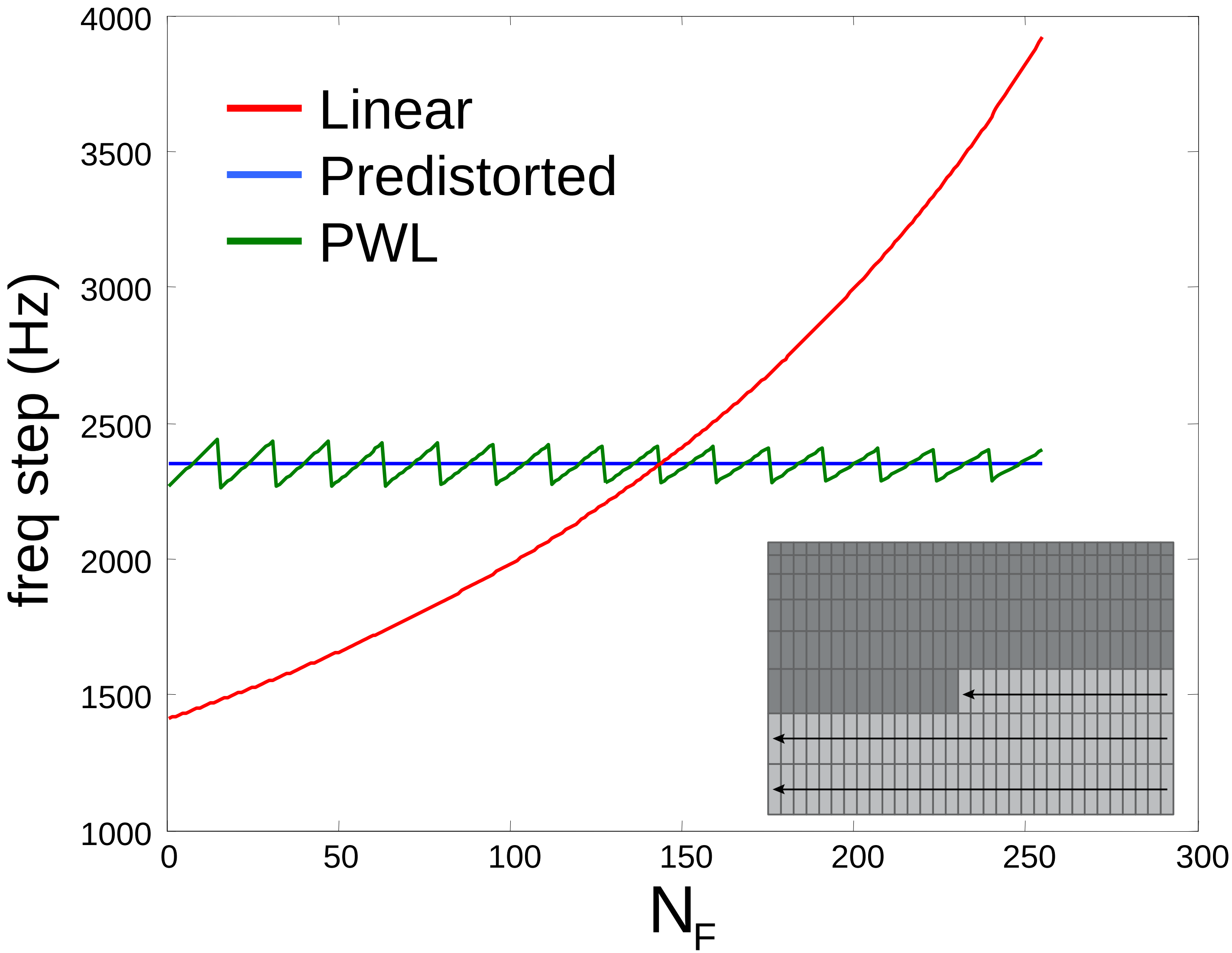


Predistortion and thermometer coding.

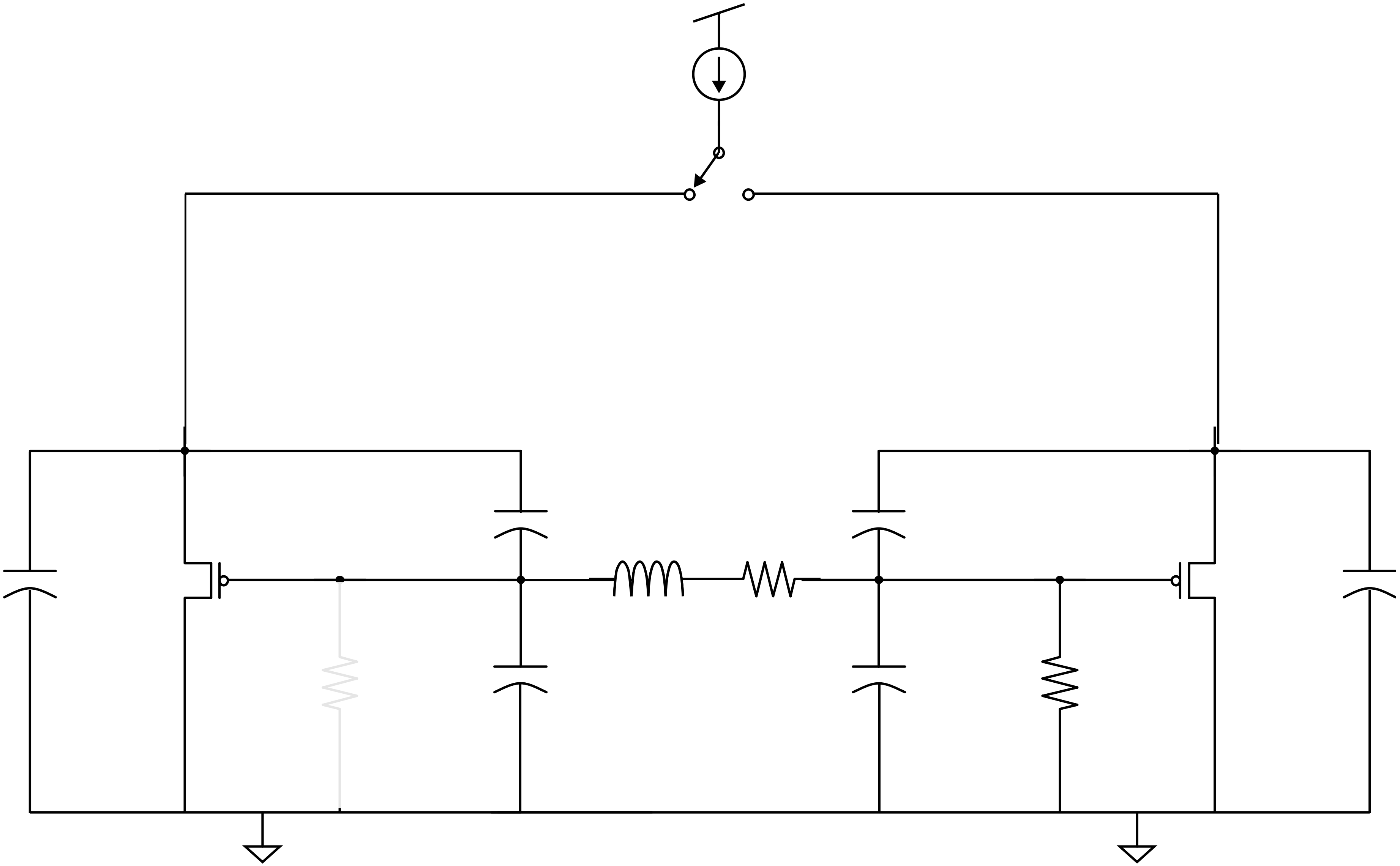
Capacitor Array Predistortion



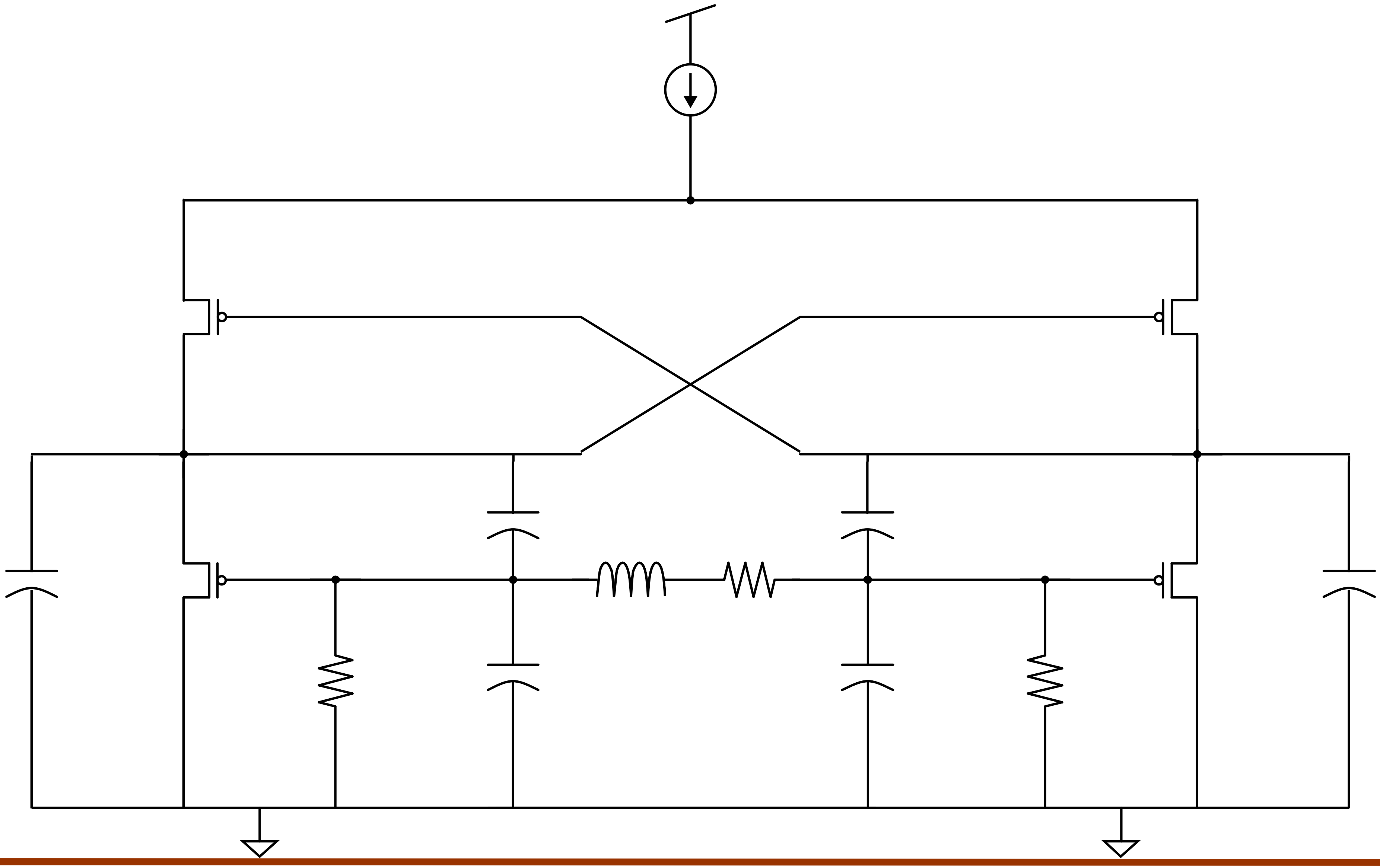
Capacitor Array Predistortion



DCO Architecture

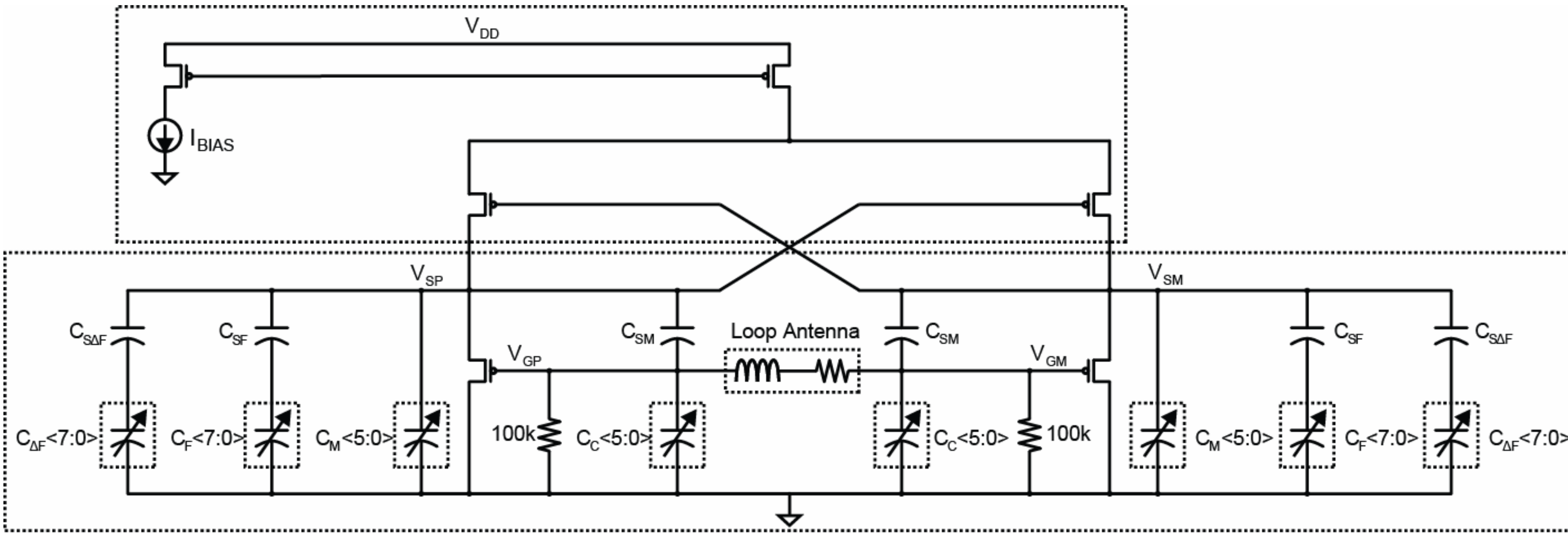


DCO Architecture

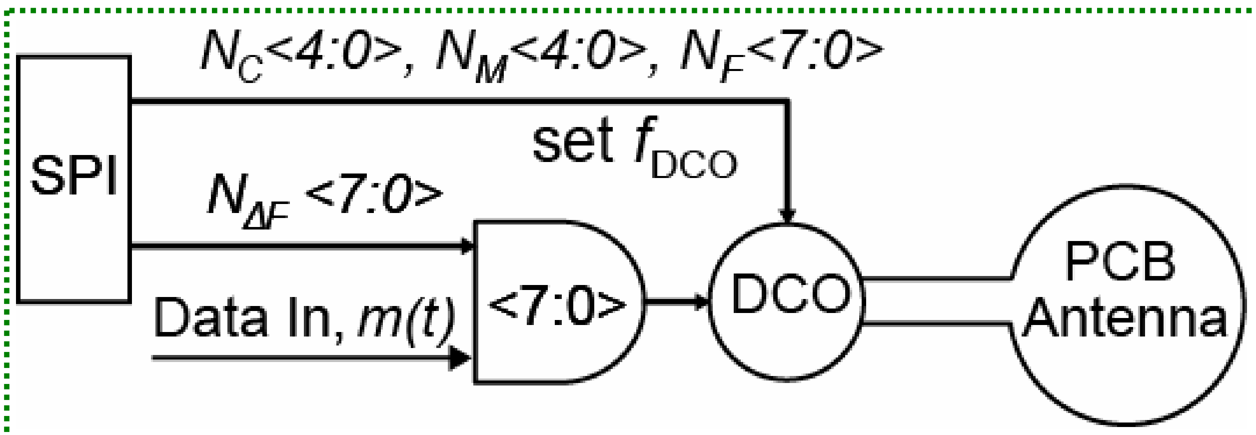


 R. Aparicio and A. Hajimiri, JSSCC, Dec. 2002.

DCO Architecture

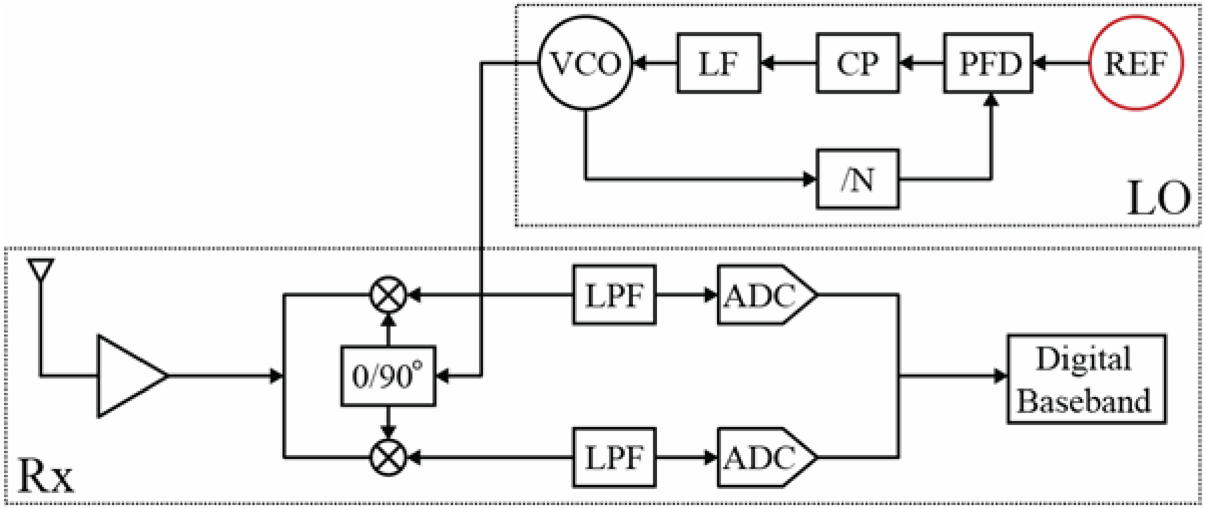


Direct Modulation Transmitter

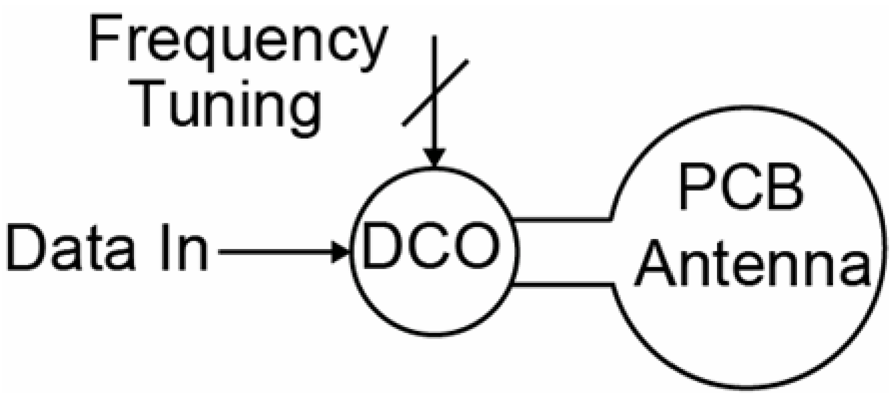


Receiver Topology

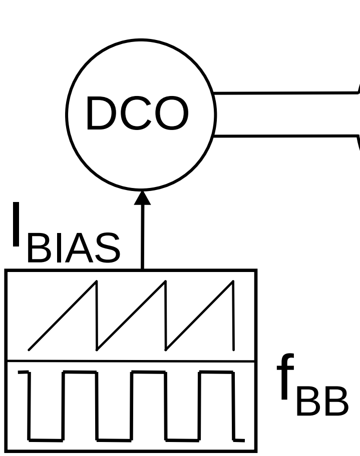
Classical Homodyne Receiver

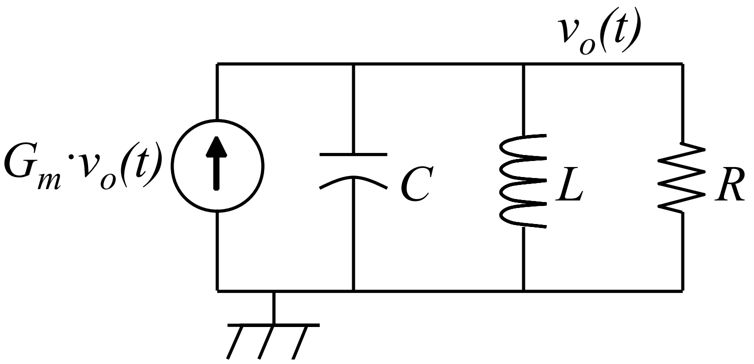


Direct Modulation Transmitter

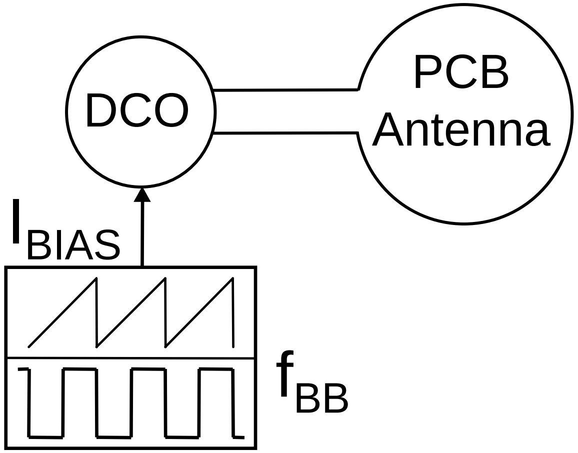


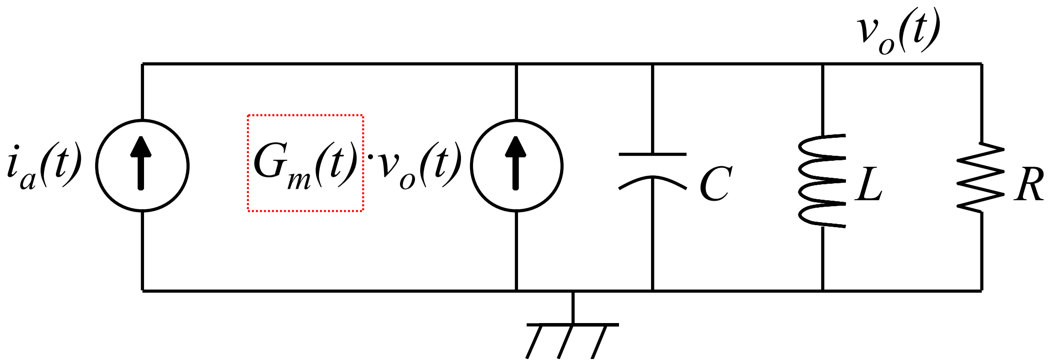
Super Regeneration Theory



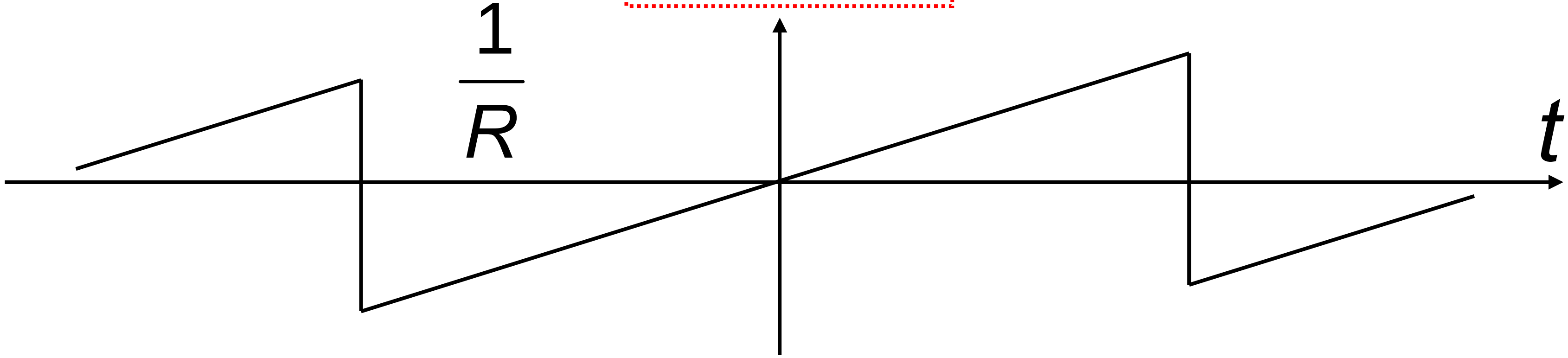


Super Regeneration Theory

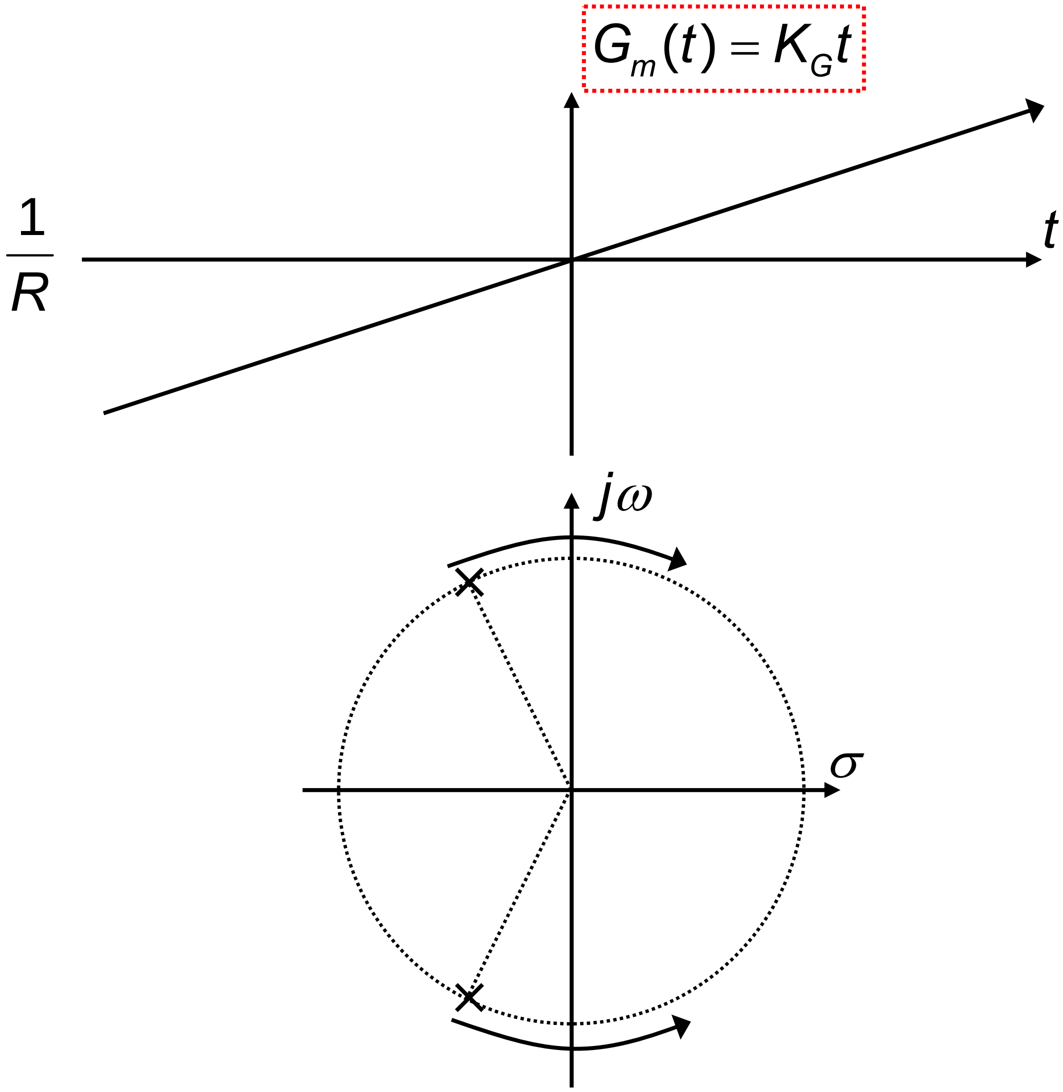




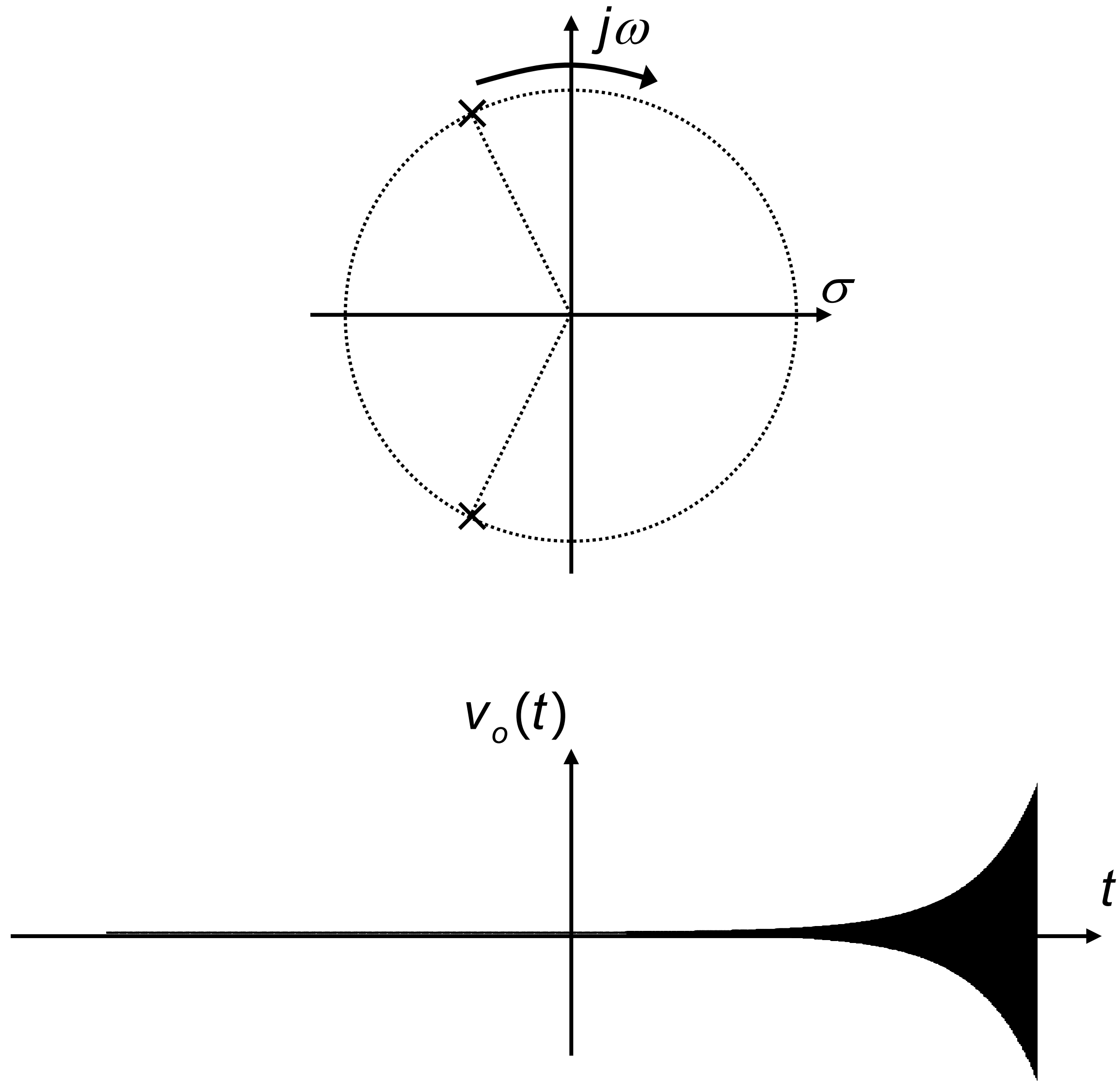
$$G_m(t) = K_G t$$



Root Locus for Time Varying G_m



Root Locus for Dynamic Damping Function

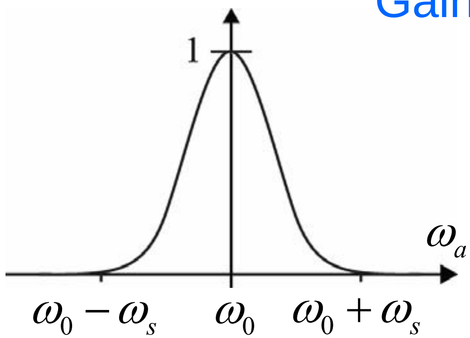


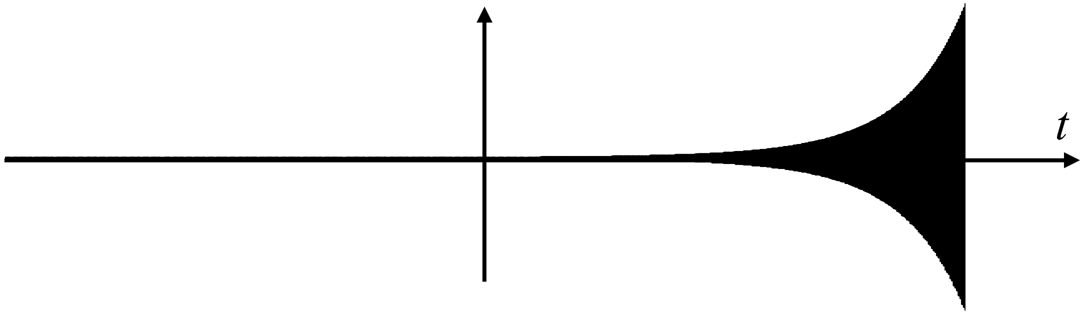
SRR Response to Sinusoidal Input

Sinusoidal Input Current $i_a(t) = I_a \sin(\omega_a t + \phi_a)$

$$v_o(t) \propto I_a \cdot Z_0 \left(\sqrt{\frac{\pi}{2}} \frac{\omega_a}{\omega_s} \right) \left(e^{-\frac{(\omega_a - \omega_0)^2}{2\omega_s^2}} \right) \left(e^{\frac{t^2}{2\tau_s^2}} \right) \sin(\omega_0 t + \phi_a)$$

Static Gain | Filtering | Time-dependent Gain | Oscillation





SRR Response to Sinusoidal Input

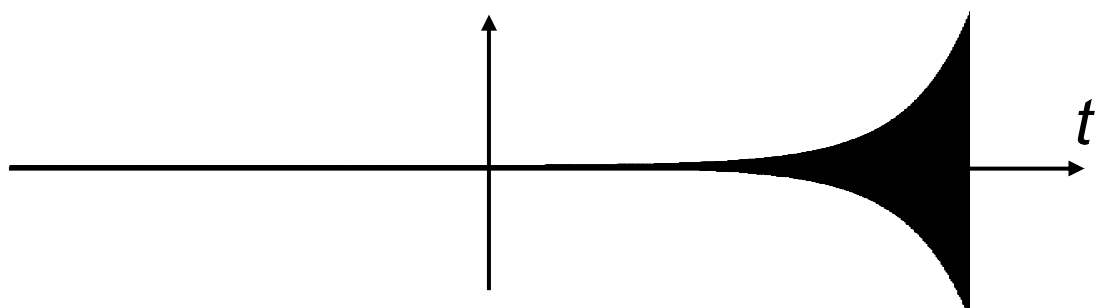
Sinusoidal Input Current $i_a(t) = I_a \sin(\omega_a t + \phi_a)$

$$v_o(t) \propto I_a \cdot Z_0 \left(\sqrt{\frac{\pi}{2}} \frac{\omega_a}{\omega_s} \right) \left(e^{-\frac{(\omega_a - \omega_0)^2}{2\omega_s^2}} \right) \left(e^{\frac{t^2}{2\tau_s^2}} \right) \sin(\omega_0 t + \phi_a)$$

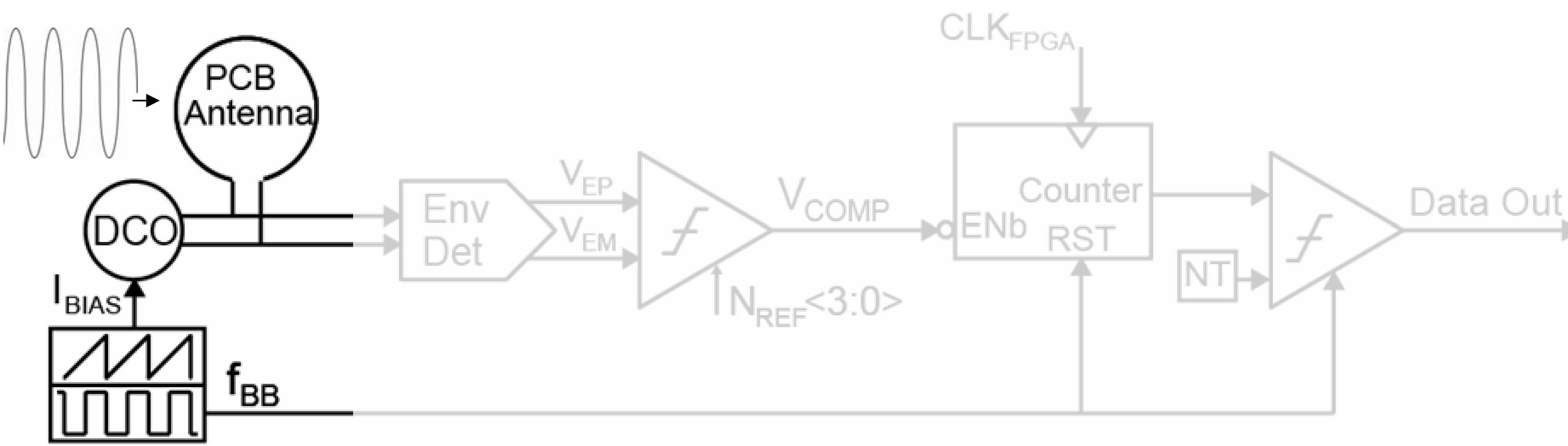
Static Gain | Filtering | Time-dependent Gain | Oscillation

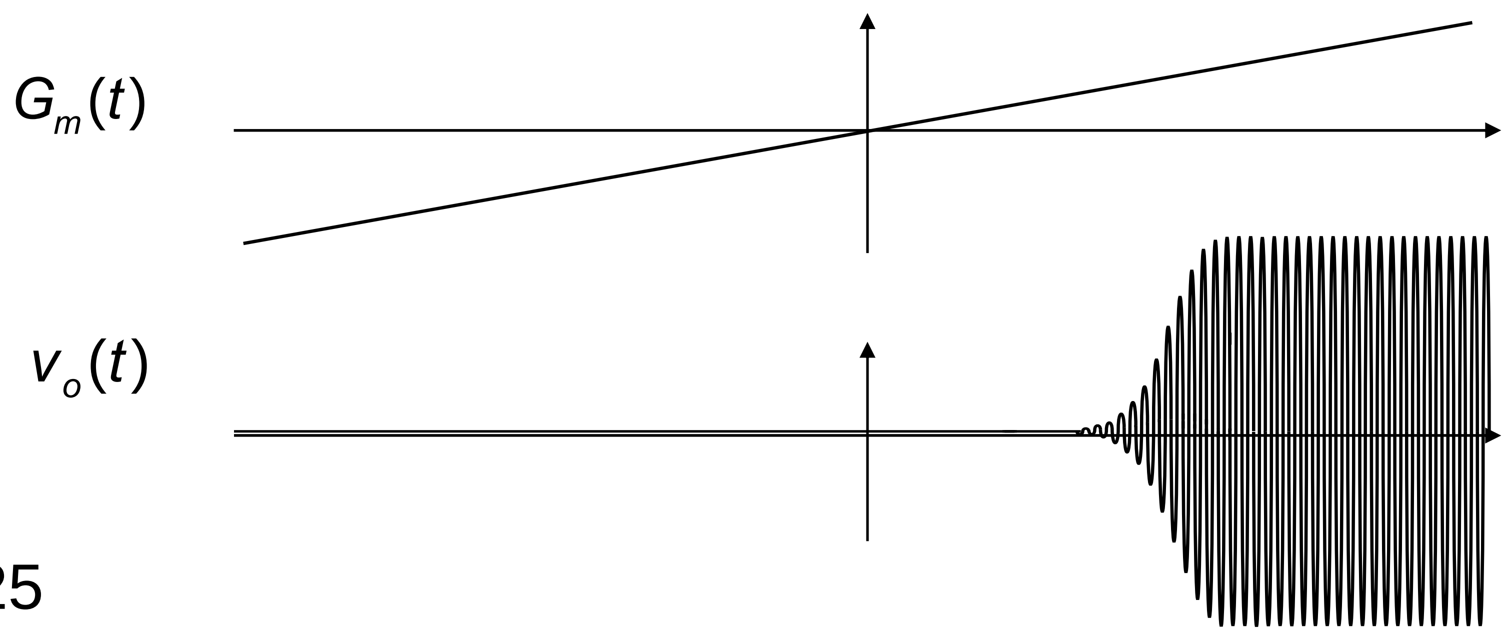
Time-dependent Gain

$$e^{\frac{t^2}{2\tau_s^2}} \Rightarrow t = 5\tau_s, \quad G_{dB} = 70dB$$

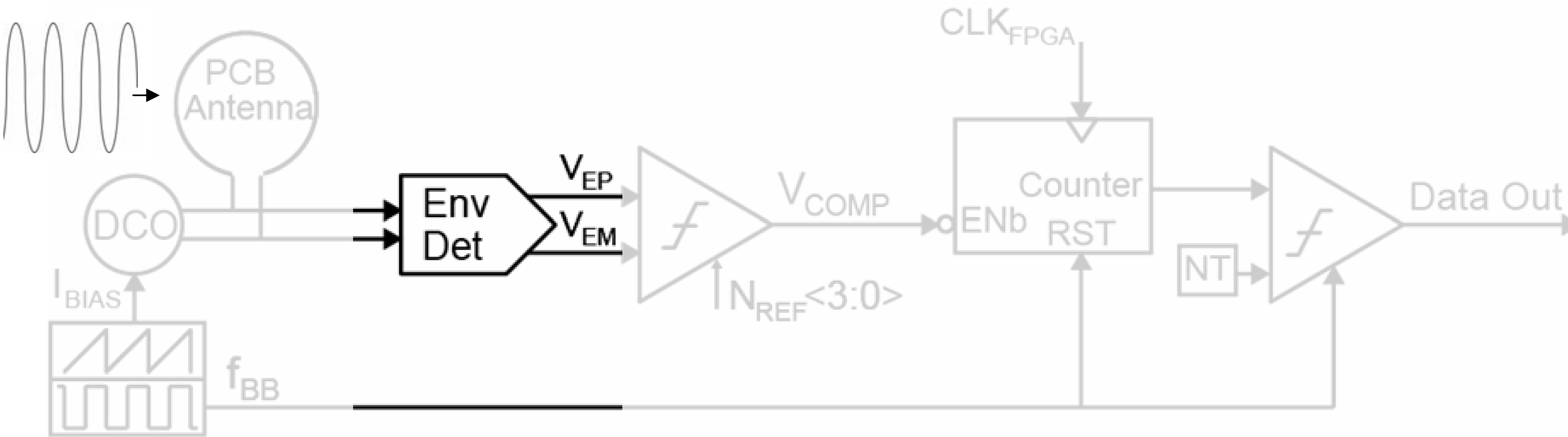


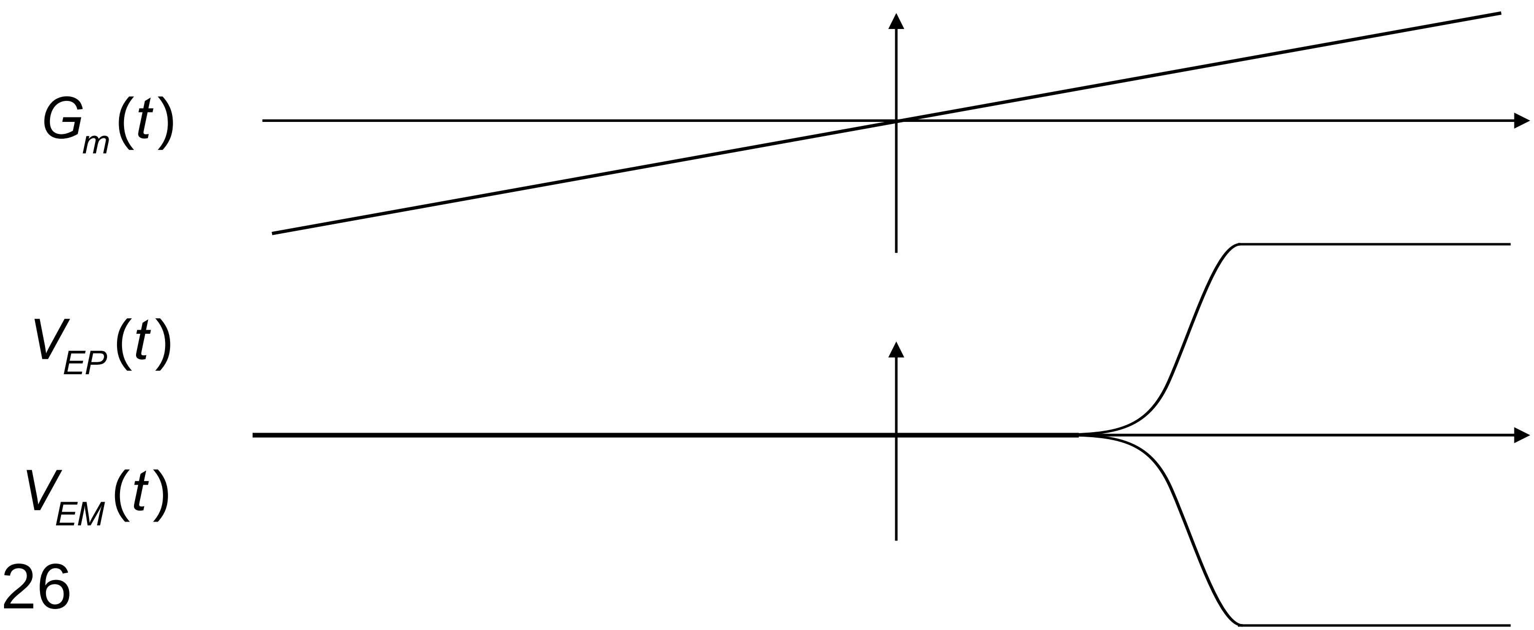
Receiver Topology



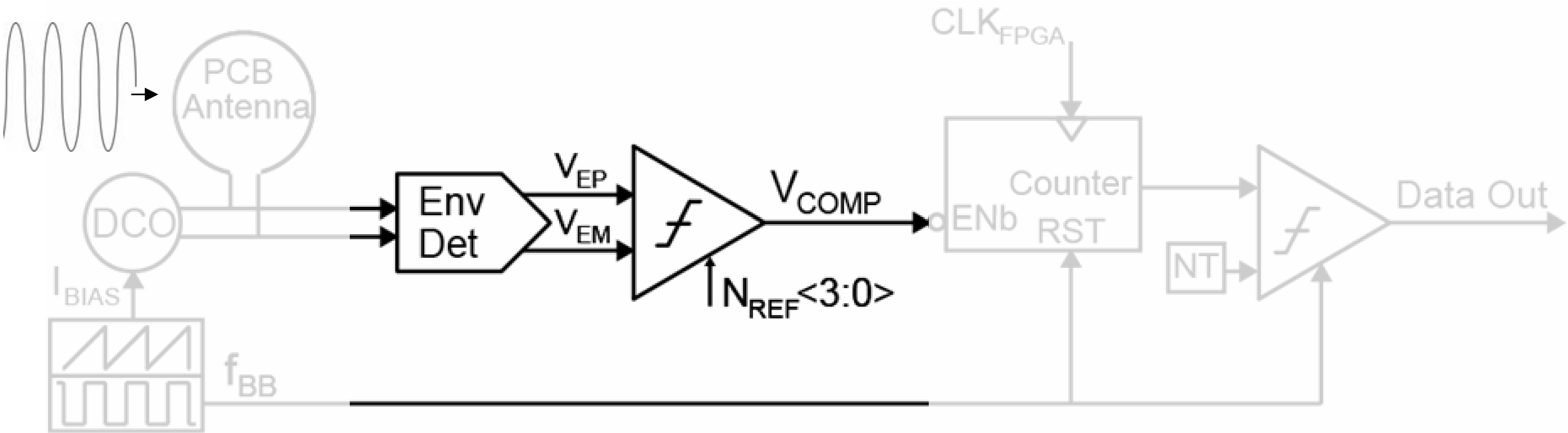


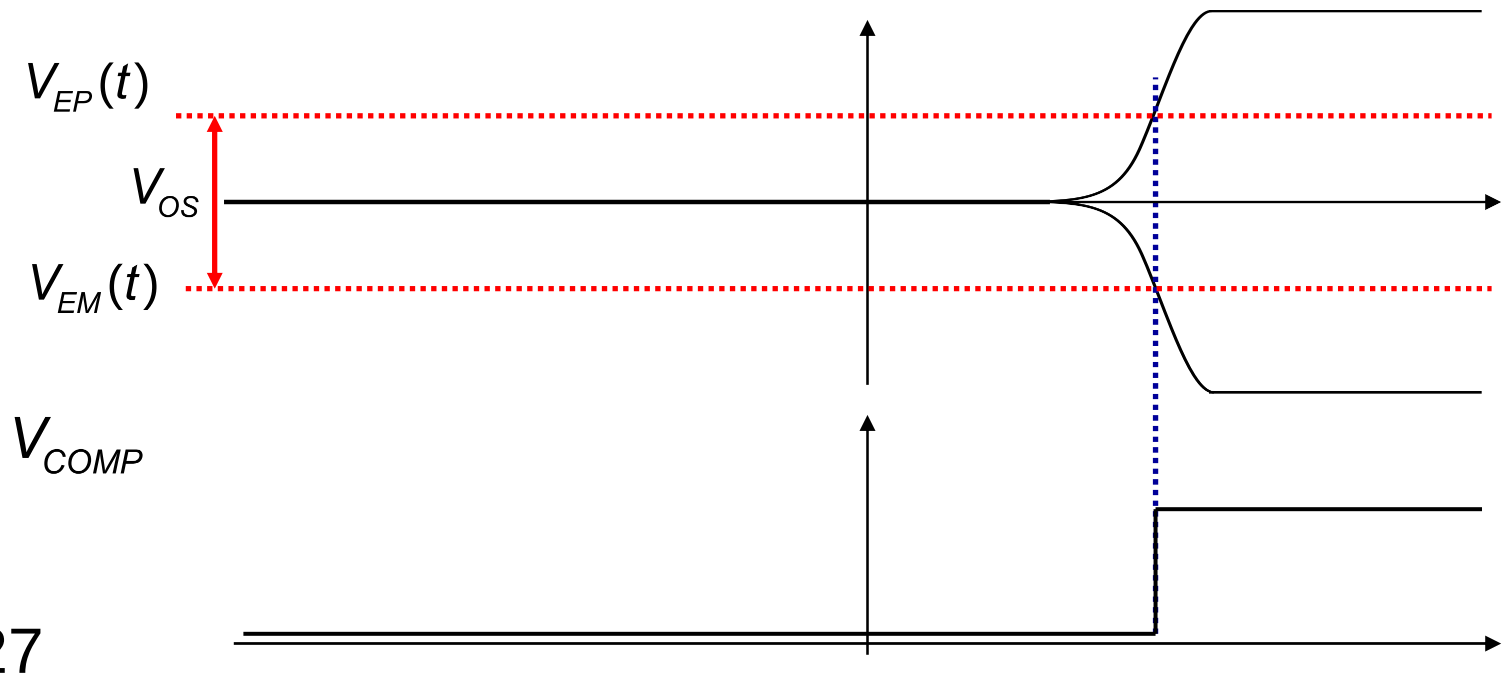
Receiver Topology



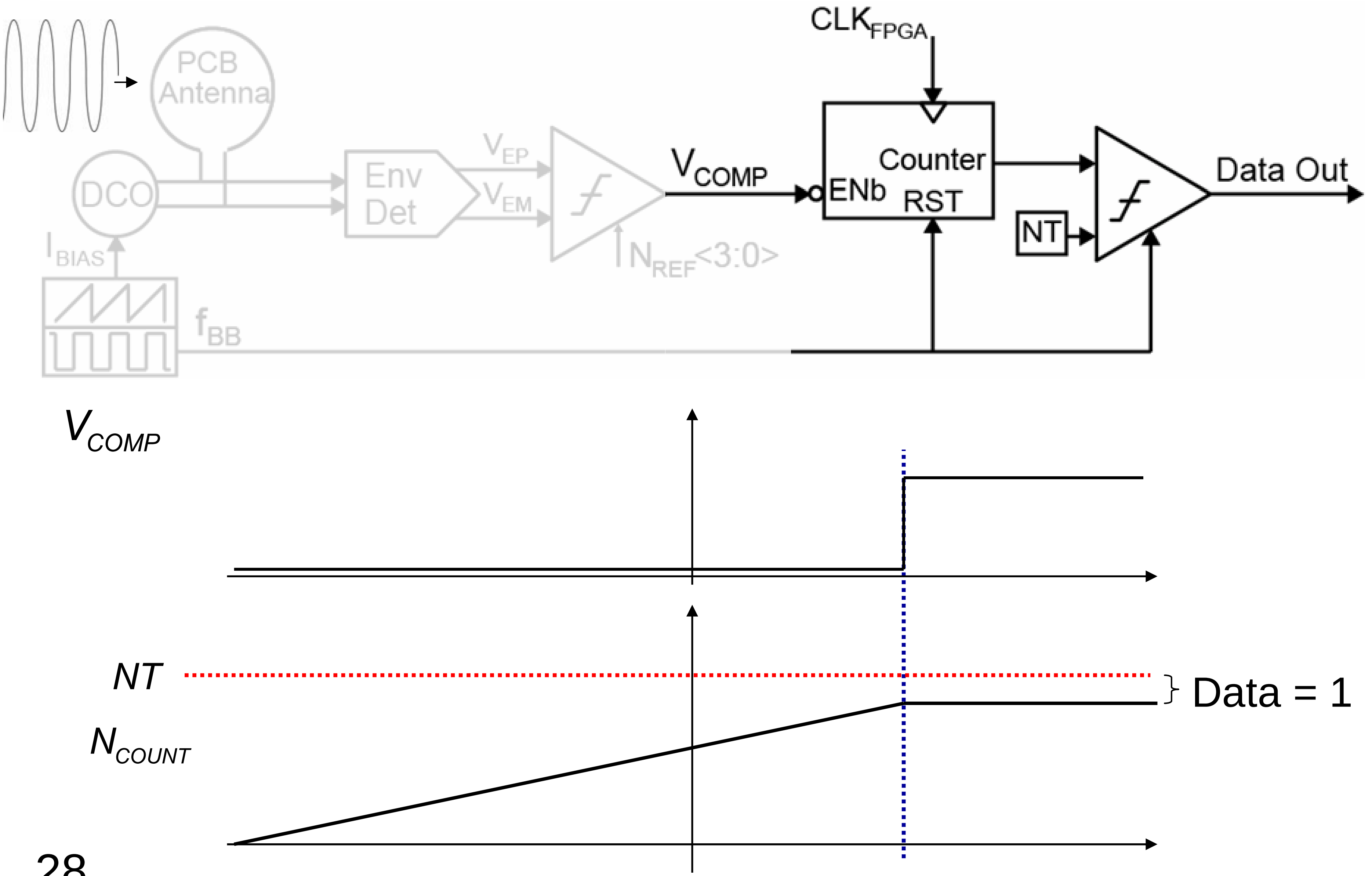


Receiver Topology

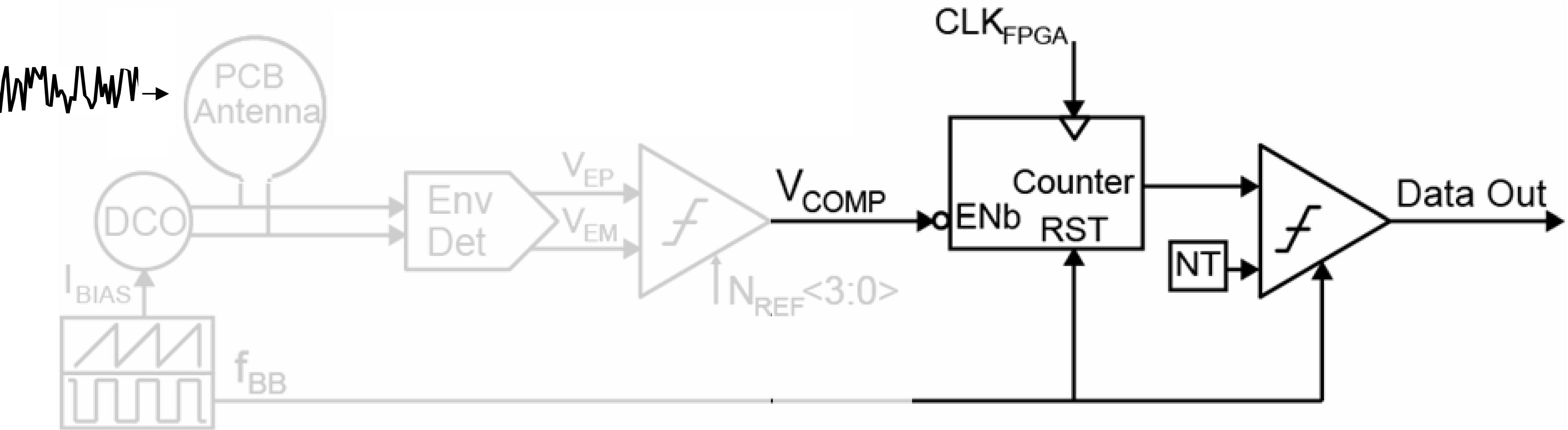


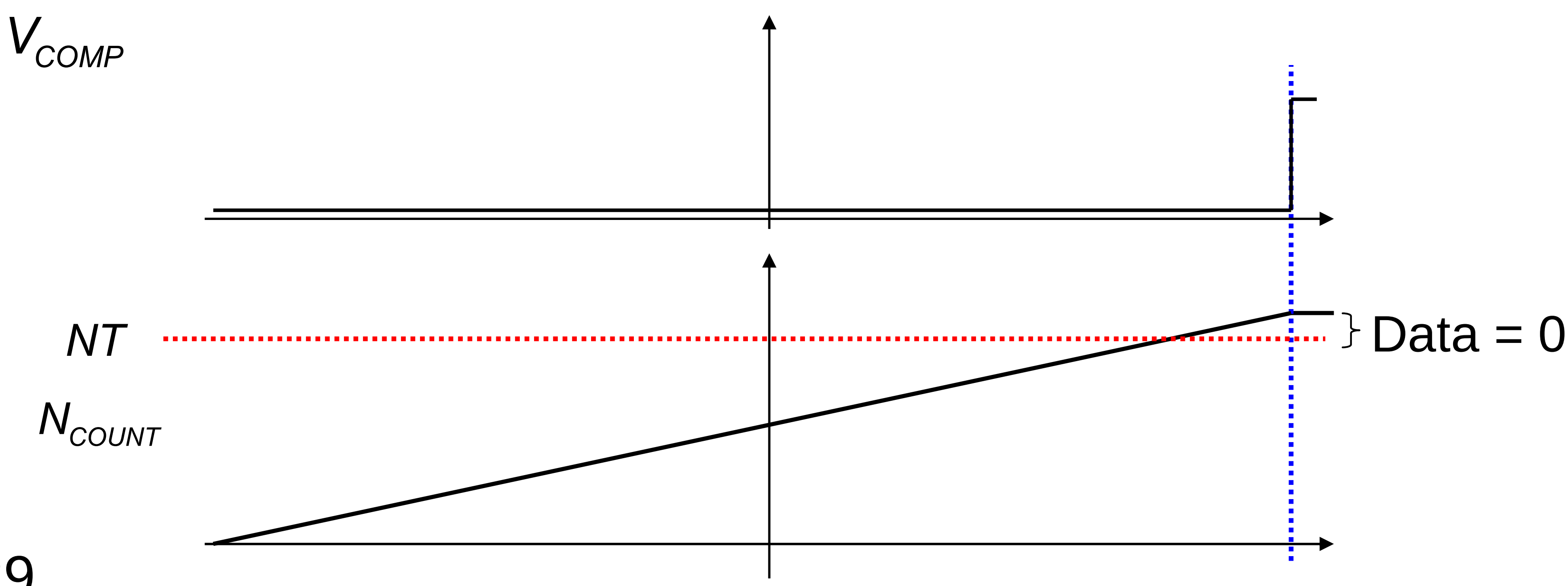


Receiver Topology

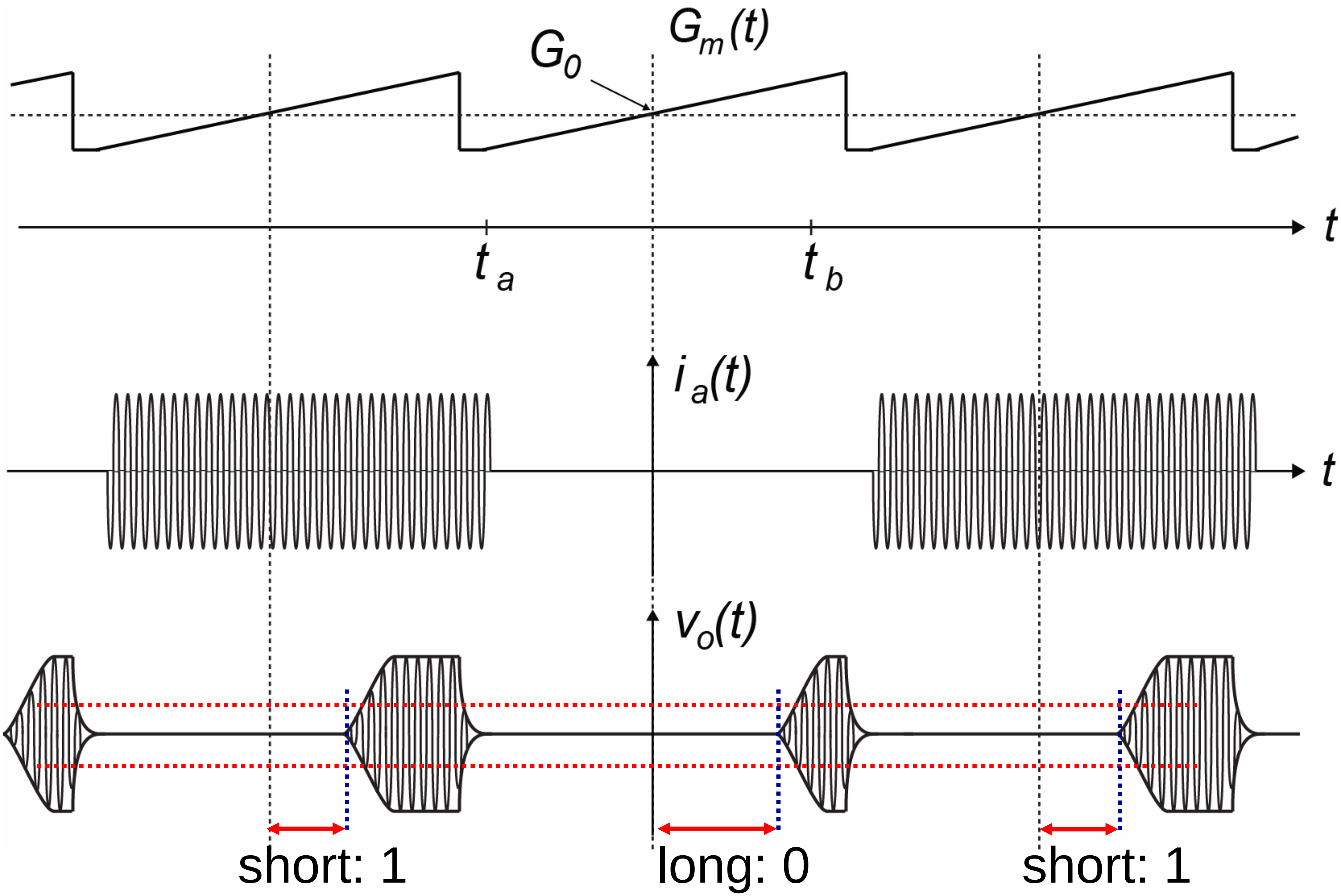


Receiver Topology

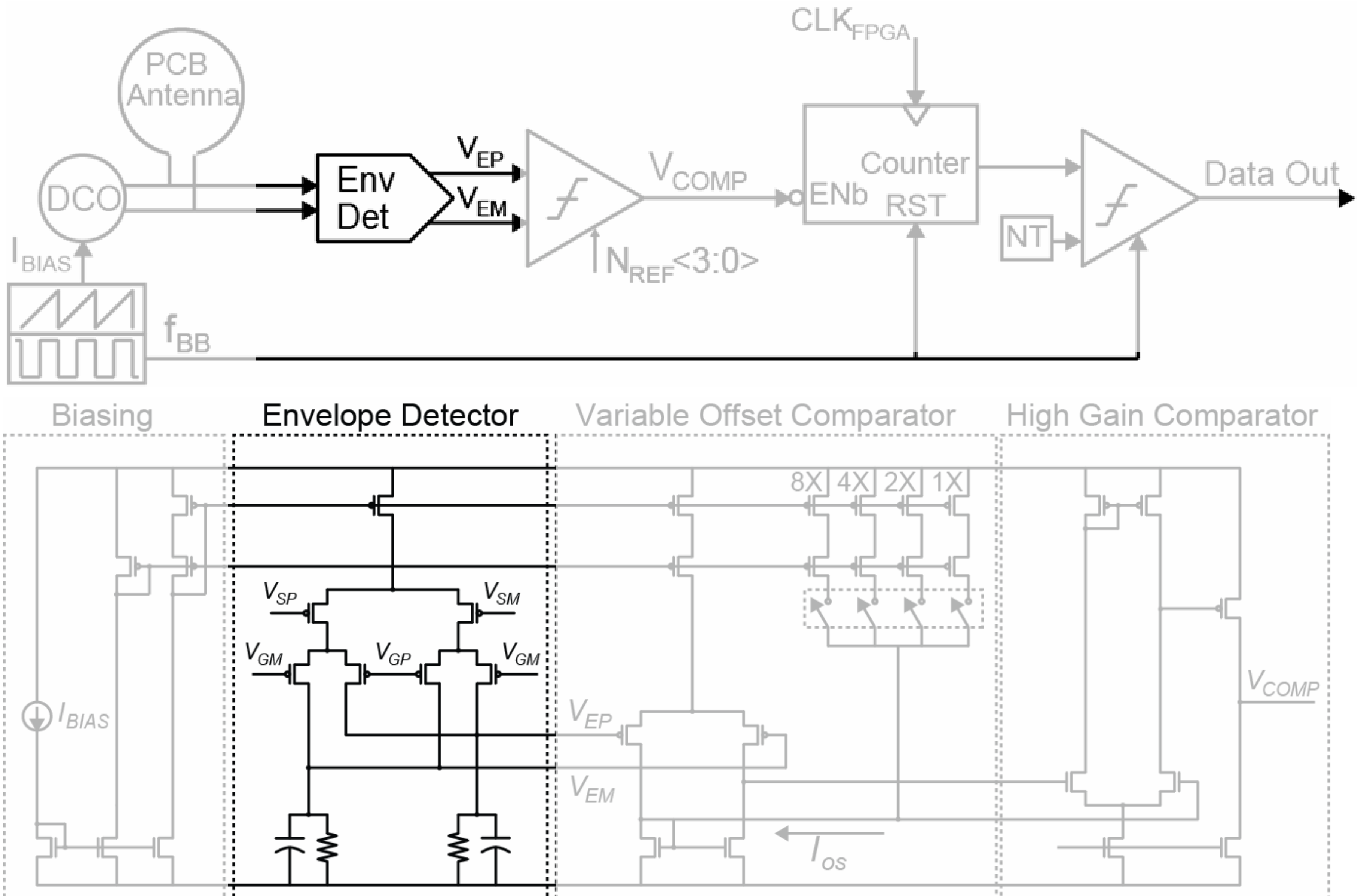




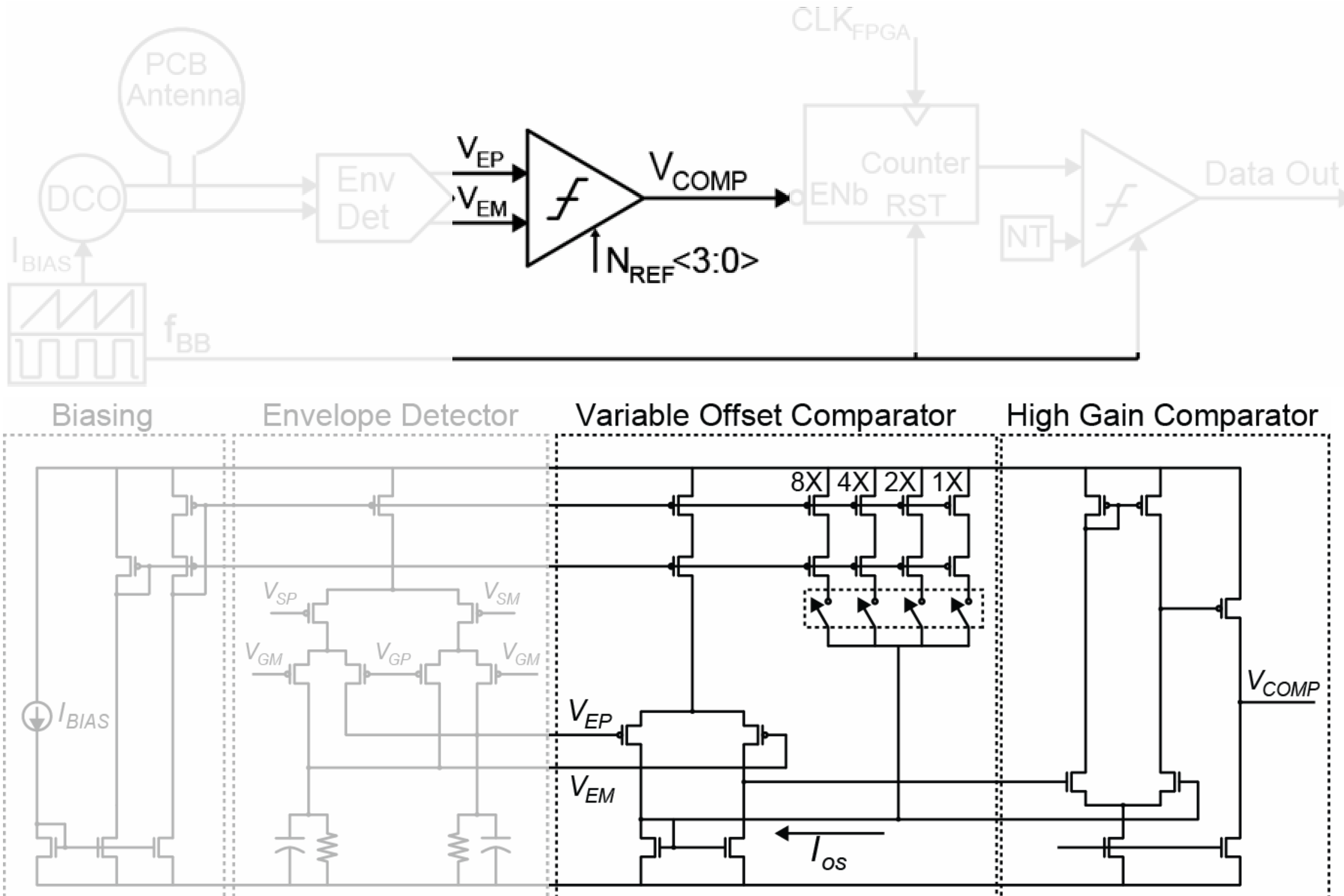
Receiver Topology



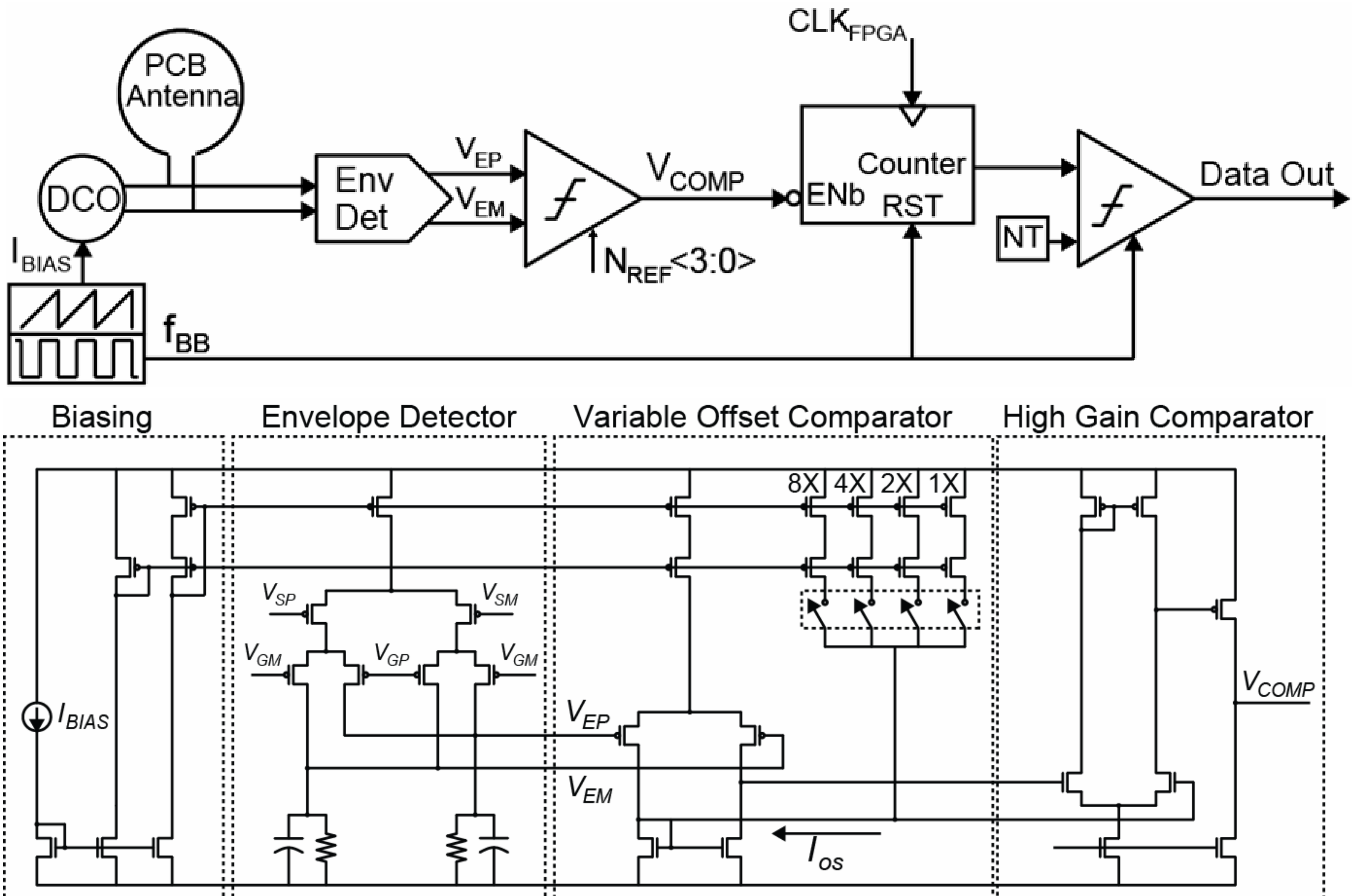
Receiver Topology



Receiver Topology

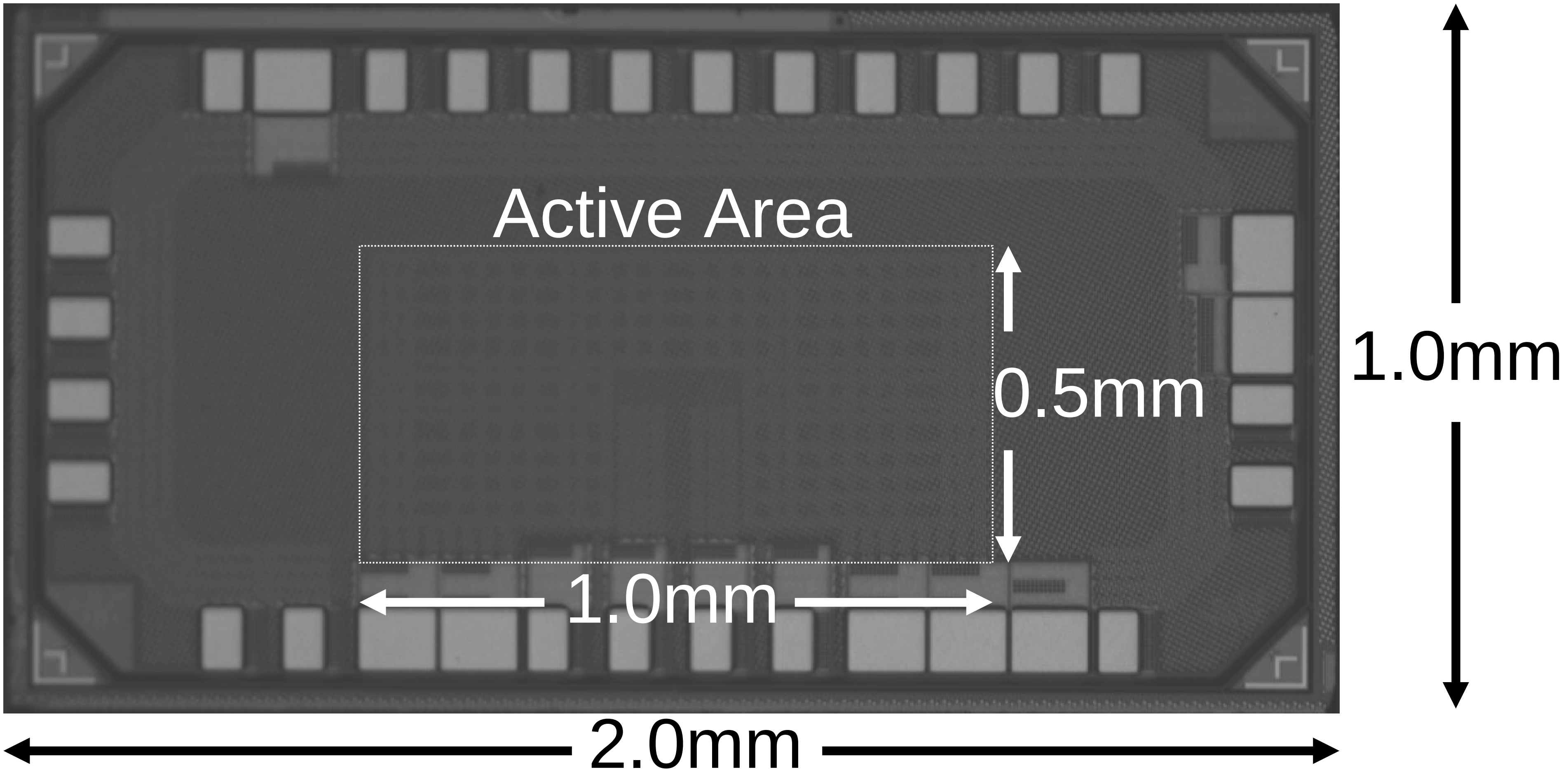


Receiver Topology

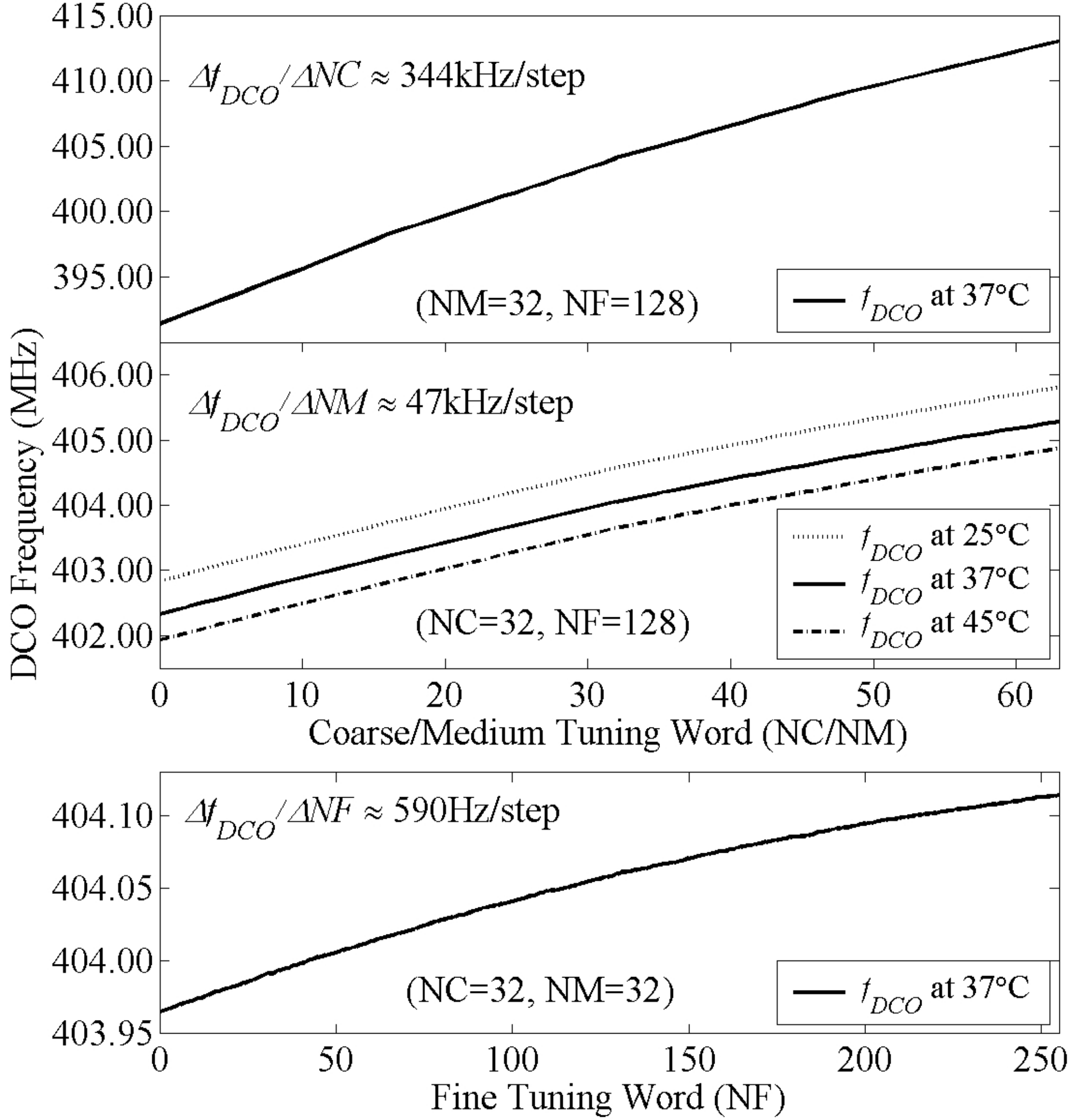


Die Photo

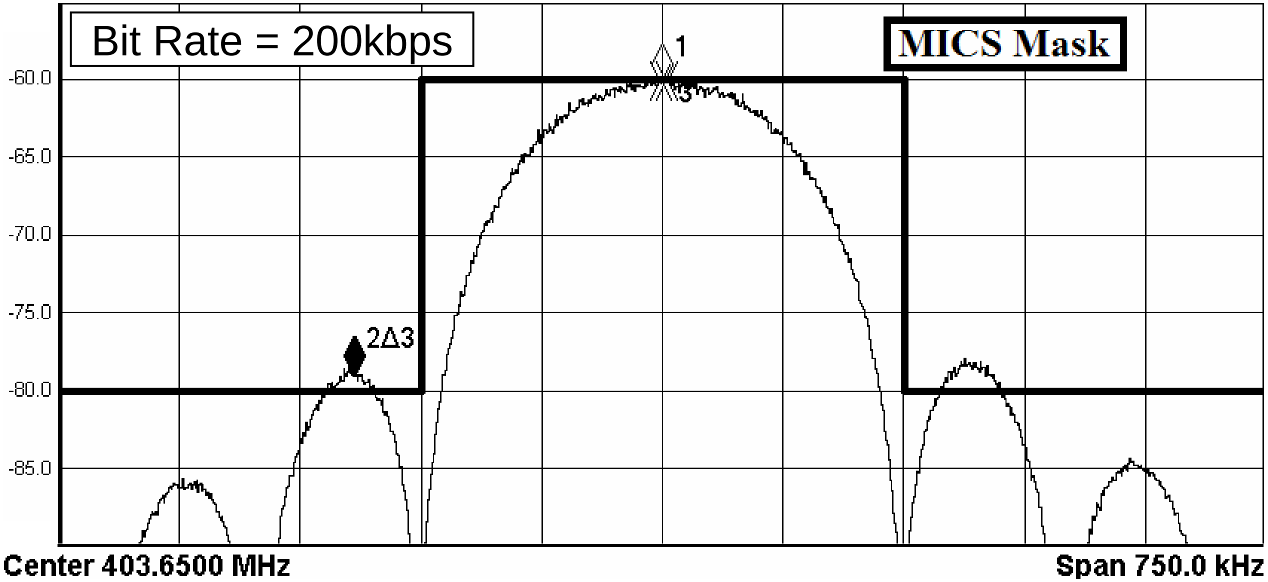
Fabricated in IBM 90nm CMOS

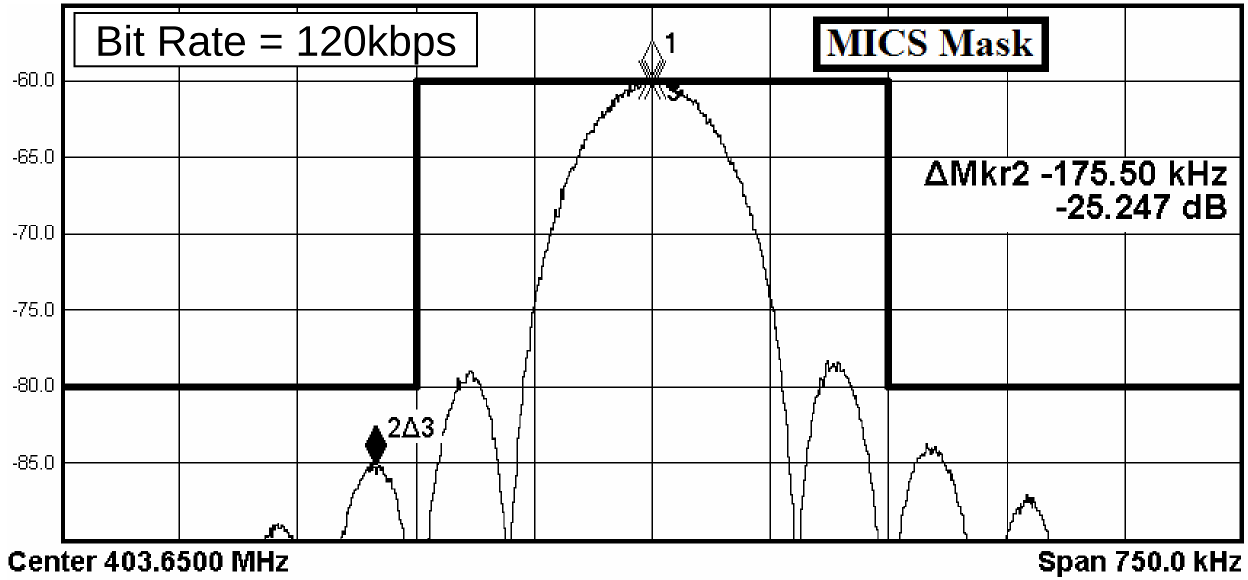


Measured DCO Tuning Curves



Measured Spectral Mask





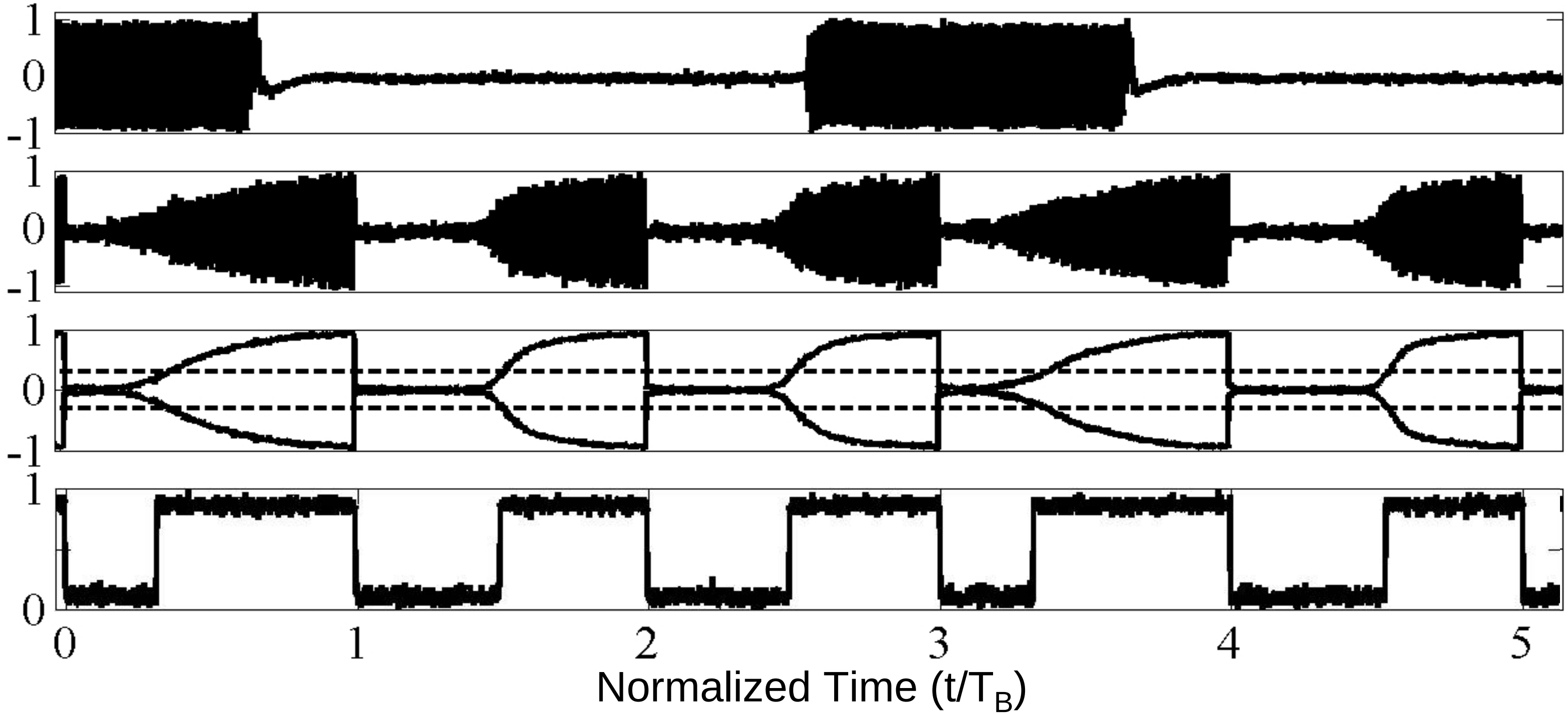
Measured Receiver Time Signals

RF Signal at Antenna

DCO Output

Env. Det. Output

Comparator Output



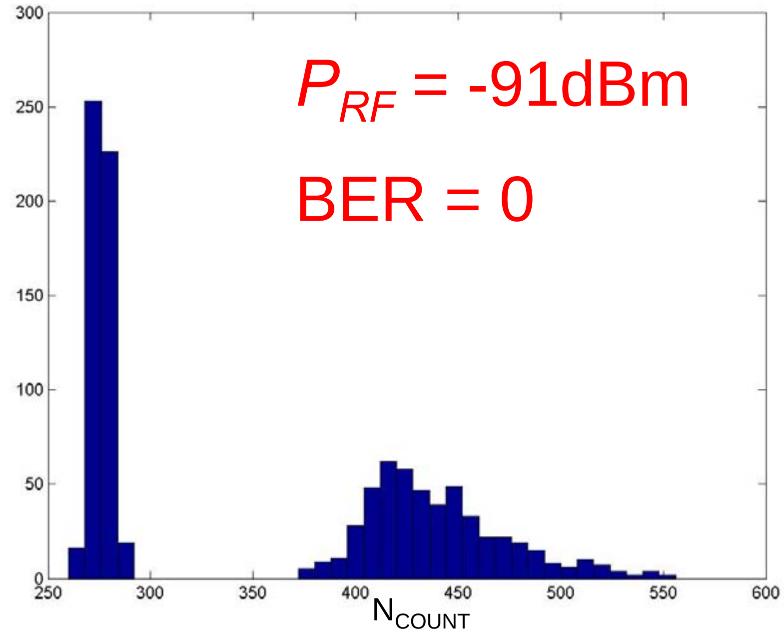
Counter	count = 173	count = 335	count = 327	count = 177	count = 342
Data Out (N_T=250)	Data Out = 1	Data Out= 0	Data Out = 0	Data Out = 1	Data Out = 0

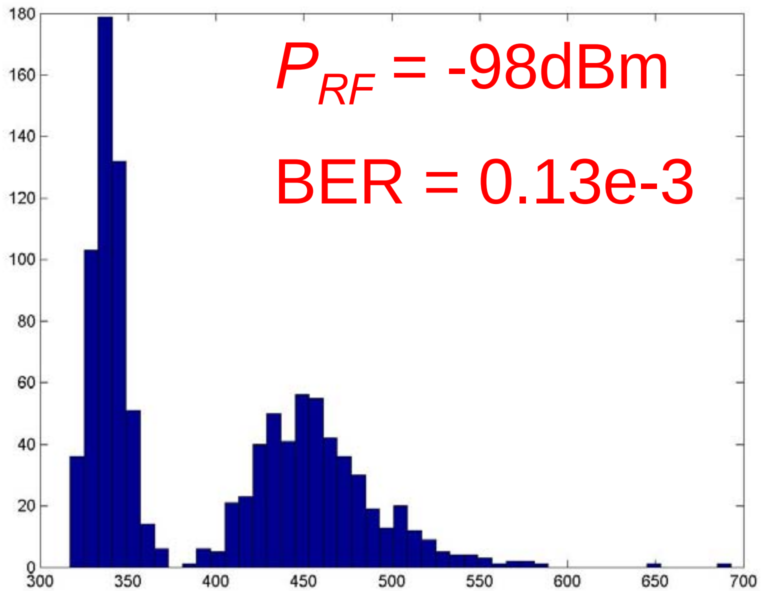
Rx Histogram

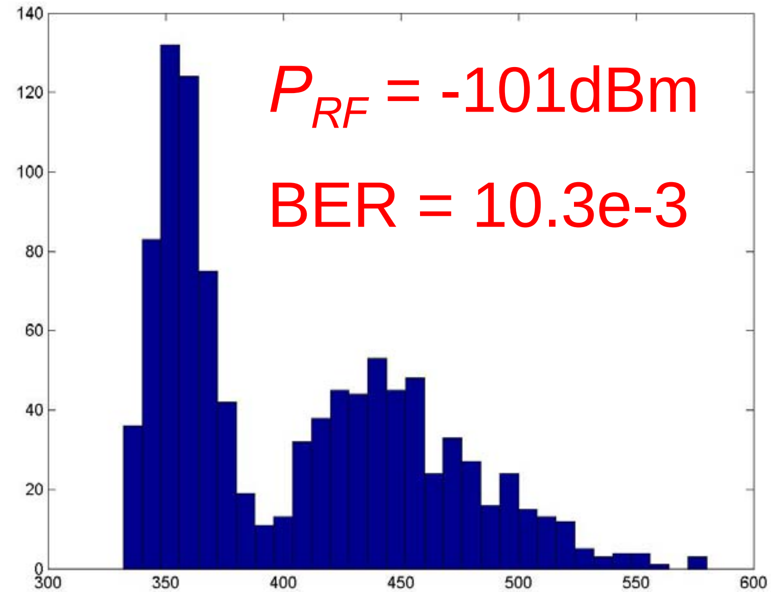
f_o = 403.65 MHz

Bit Rate=30kbps

P_{DC} = 373µW







Conclusions

- Ultra-low power transceiver for medical implant communications
- Transmitter
  - consumes less than 350μW
  - uses direct MSK modulation
  - meets MICS spectral mask specifications
- Receiver
  - consumes less than 400μW
  - uses super-regeneration to demodulate OOK signals
  - -99dBm sensitivity at 30kbps (BER=10^{-3})
  - -93dBm at 120kbps (BER=10^{-3})
- Capacitor predistortion
- A PCB loop antenna as part of the DCO resonator

Acknowledgements

- The authors acknowledge the support of the Focus Center for Circuit & System Solutions (C2S2), one of five research centers funded under the Focus Center Research Program, a Semiconductor Research Corporation Program.
- IBM and TAPO for chip fabrication.