CMOS Active Transformers and Applications

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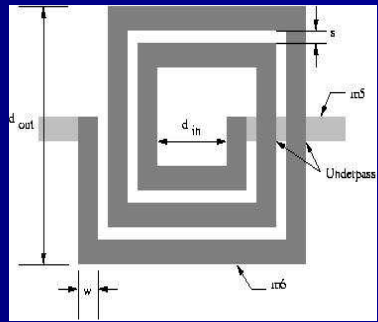
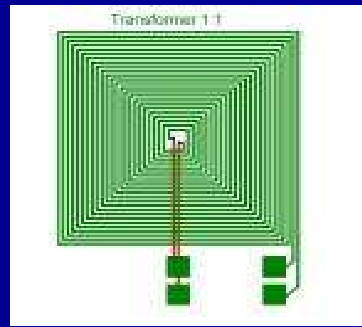
Outline

- Spiral/MEMS inductors and transformers
- Active inductors
- Ideal active transformers
- Non-ideal active transformers
- Active transformers with multiple windings
- Implementation of active transformers
- Applications of active transformers
- Conclusions
- References

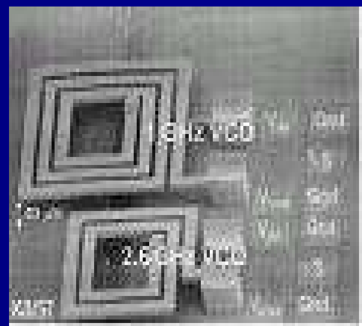
Spiral inductors / transformers

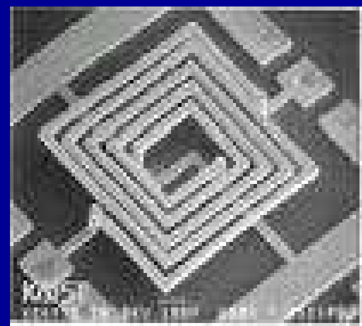
- Spiral inductors / transformers
  - Superior linearity
  - Excellent noise performance
  - Large L with stacked spirals
  - Extremely silicon consuming
  - Non-tunable inductances and coupling factors
  - Low Q (typically Q<20)
  - Cannot realized using digital CMOS processes.





- MEMS inductors/transformers
  - Excellent performance (Q and noise).
  - Tunable inductances
  - Expensive – require monolithic CMOS-MEMS processes
  - Extremely silicon consuming

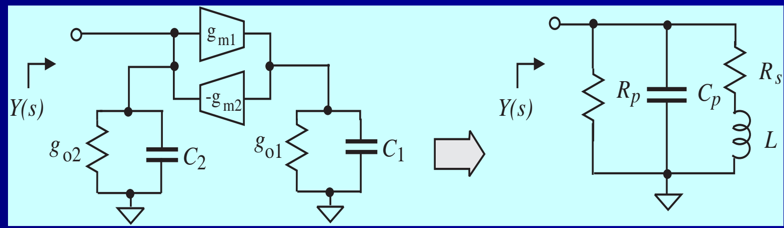




Active inductors

- Gyrator-C configuration exhibits an inductive characteristic in a specific frequency range.

$$R_p = \frac{1}{g_{o2}}, C_p = C_2, R_s = \frac{g_{o1}}{g_{m1}g_{m2}}, L = \frac{C_1}{g_{m1}g_{m2}}.$$

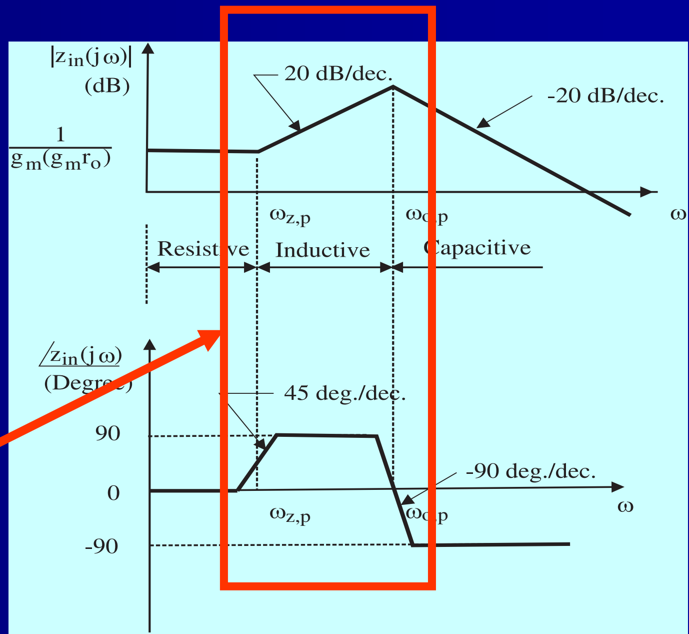


- Frequency range

$$\omega_z = \frac{g_o}{C} < \omega < \omega_p = \frac{g_m}{C}$$

- To maximize frequency range
  - Upper bound set by the cut-off frequency of transconductors
  - Transconductors
    - Generic transconductors
  - Capacitors
    - Device intrinsic capacitances

Inductive



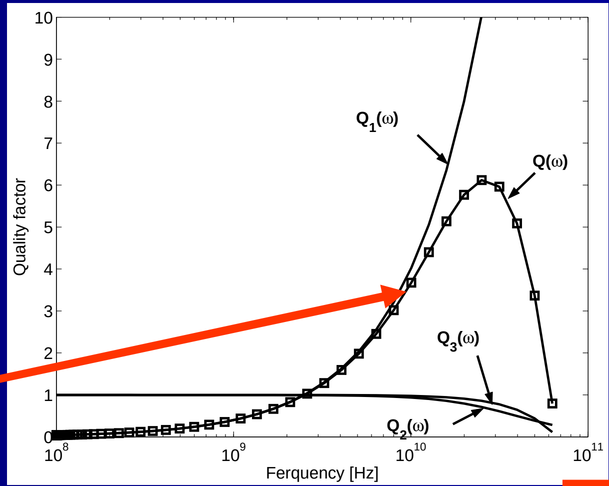
Active inductors (cont'd)

- Quality factor

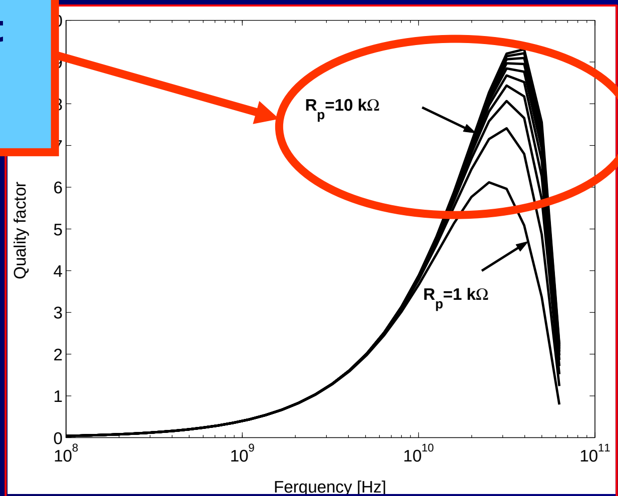
$$Q=\left(\frac{\omega L}{R_s}\right)\frac{R_p}{R_p+R_s\left[1+\left(\frac{\omega L}{R_s}\right)^2\right]}\left[1-\frac{R_s^2C_p}{L}-\omega^2LC_p\right]$$

$$=Q_1Q_2Q_3$$

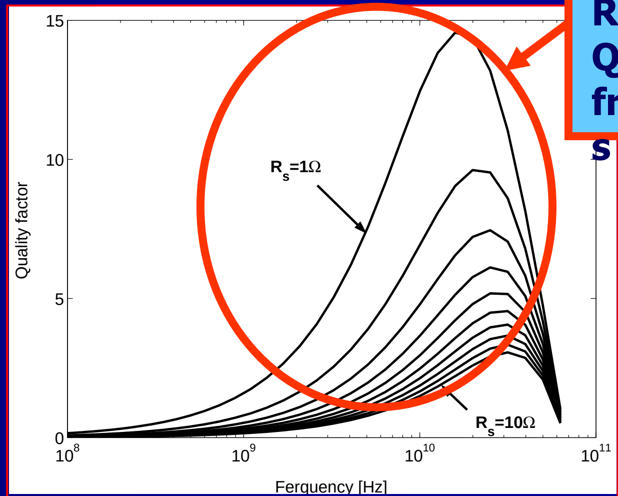
Q is dominated by $Q_1=\frac{\omega L}{R_s}$ at low frequencies. Reducing Rs is critical.



Rp affects Q at high frequencies only



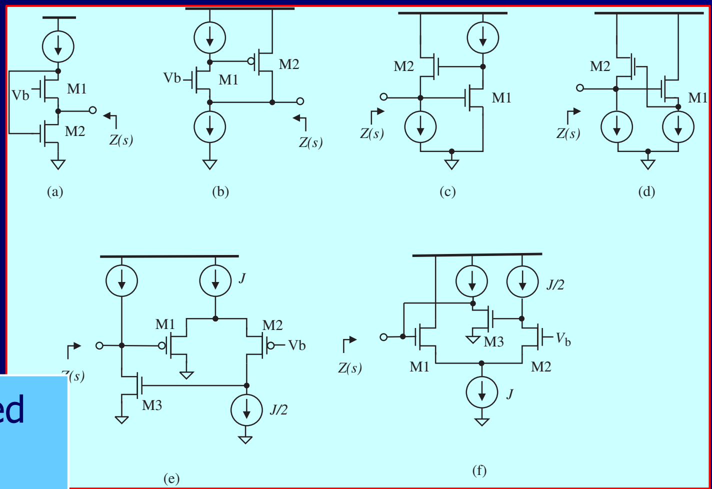
Rs affects Q at low frequencie s



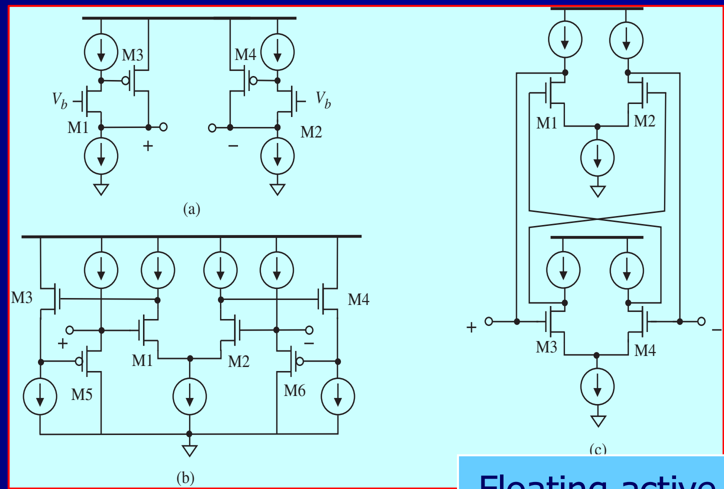
Q increases as Rs decreases

Active inductors (cont'd)

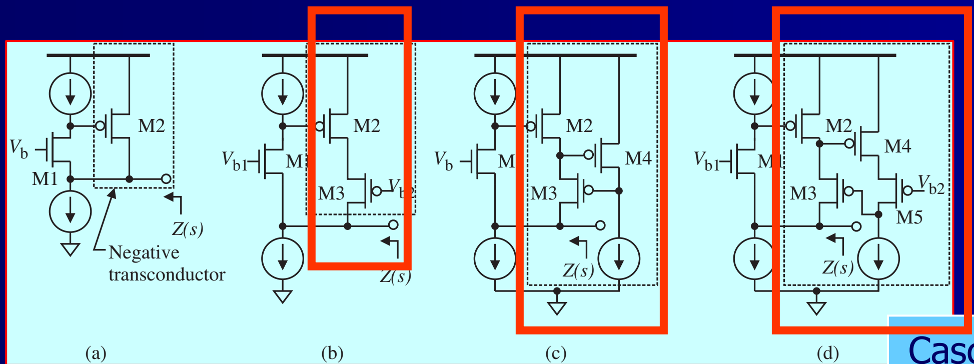
- Implementation of CMOS active Inductors



Grounded active inductors



Floating active inductors

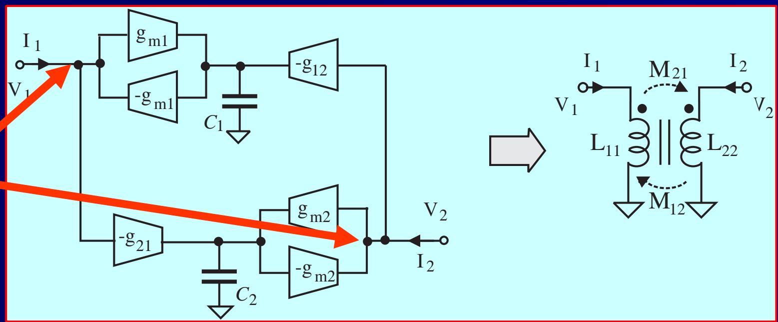


Cascode active inductors

Ideal active transformers

- Consist of two active inductors coupled via transconductors
- Ideal active transformers - only the capacitors of transconductors are considered
- Topology 1 – active inductors are coupled via interface nodes

Interface nodes



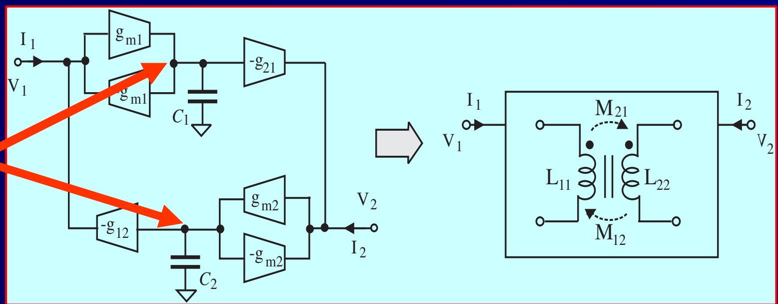
$$L_{11}=\frac{C_1}{g_{m1}^2\Delta},\qquad M_{12}=\left(\frac{g_{12}}{g_{m1}}\right)\frac{C_2}{g_{m2}^2\Delta},$$

$$L_{22}=\frac{C_2}{g_{m2}^2\Delta},\qquad M_{21}=\left(\frac{g_{21}}{g_{m2}}\right)\frac{C_1}{g_{m1}^2\Delta},$$

$$\text{where}\qquad \Delta=1-\frac{g_{12}g_{21}}{g_{m1}g_{m2}}$$

- Topology 2 – active inductors are coupled via internal nodes

Internal nodes



$$L_{11}=\frac{C_1}{g_{m1}^2\Delta},\qquad M_{12}=\left(\frac{g_{12}}{g_{m1}}\right)\frac{C_1}{g_{m1}^2\Delta},$$

$$L_{22}=\frac{C_2}{g_{m2}^2\Delta},\qquad M_{21}=\left(\frac{g_{21}}{g_{m1}}\right)\frac{C_2}{g_{m2}^2\Delta},$$

$$\text{where}\qquad \Delta=1-\frac{g_{12}g_{21}}{g_{m1}g_{m2}}$$

Ideal active transformers (cont'd)

- Relation between self and mutual inductances

$$M_{12} = \left(\frac{g_{12}}{g_{m1}}\right) L_{22}, \qquad M_{21} = \left(\frac{g_{21}}{g_{m2}}\right) L_{11}.$$

- Turn ratio

$$n_{21} = \sqrt{\frac{L_{22}}{L_{11}}} = \left(\frac{g_{m1}}{g_{m2}}\right)\sqrt{\frac{C_2}{C_1}}$$

- Coupling factors

$$k_{21} = \frac{M_{21}}{\sqrt{L_{11}L_{22}}} = \left(\frac{g_{21}}{g_{m1}}\right)\sqrt{\frac{C_1}{C_2}},$$

$$k_{12} = \frac{M_{12}}{\sqrt{L_{11}L_{22}}} = \left(\frac{g_{12}}{g_{m2}}\right)\sqrt{\frac{C_2}{C_1}}.$$

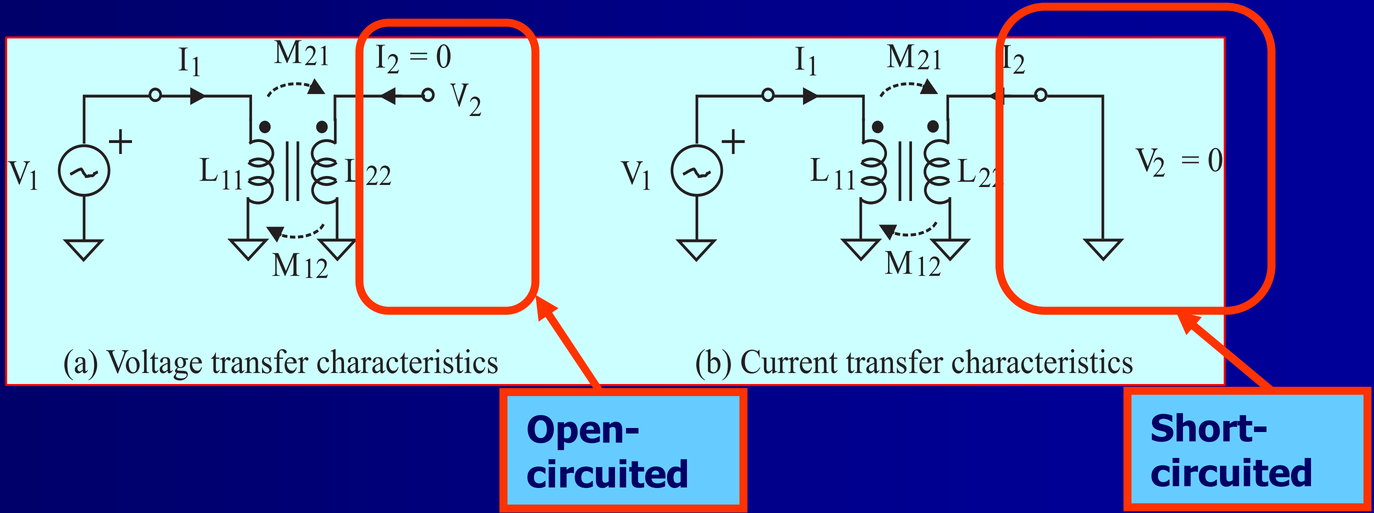
- Impedance transformation

$$Z_{22} = n_{21}^2 Z_{11},$$

$$Z_{12} = \left(\frac{g_{12}}{g_{21}}\right) n_{21} Z_{21}.$$

Ideal active transformers (cont'd)

- Voltage / current transfer characteristics
  - Passive transformers – scaled by turn-ratio only.
  - Active transformers - scaled by both turn-ratio and coupling coefficient.

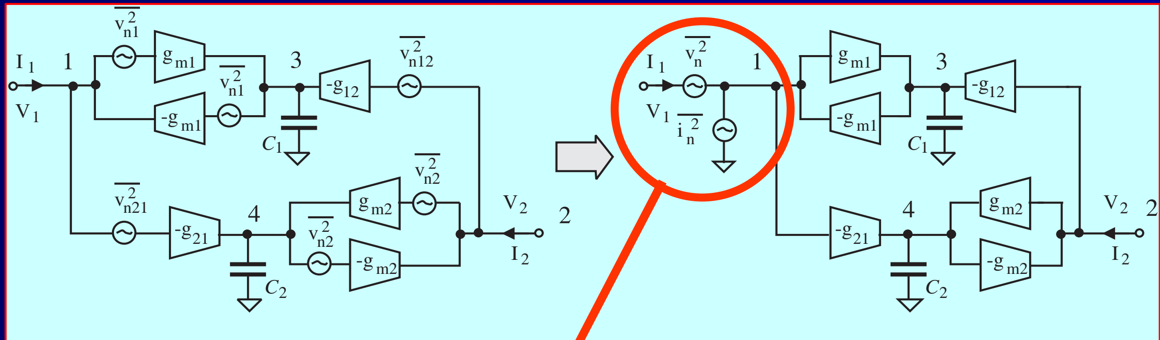


Passive transformers ⇒ $V_2 = n_{21}V_1, \qquad I_2 = \frac{I_1}{n_{21}}.$

Active transformers ⇒ $V_2 = k_{21}(n_{21}V_1), \qquad I_2 = k_{21}\left(\frac{I_1}{n_{21}}\right).$

Ideal active transformers (cont'd)

- Noise
  - Input-referred noise current generator of trans-conductors is neglected.



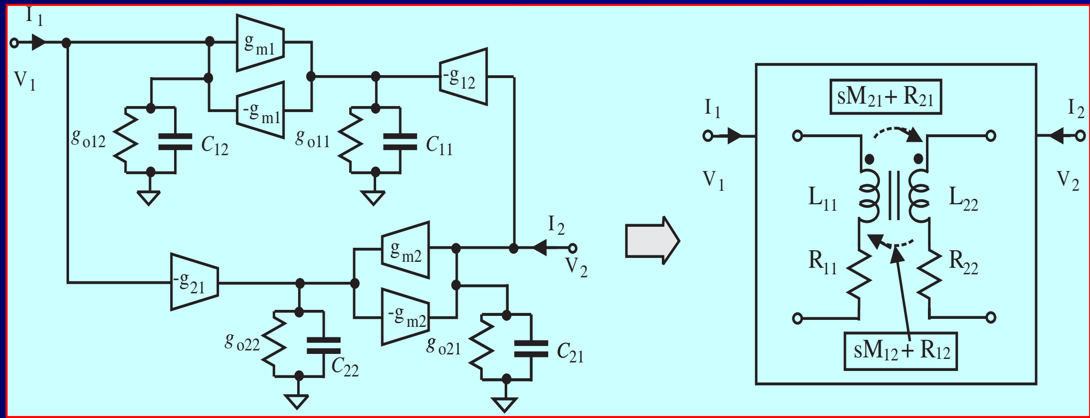
  - Input-referred noise voltage & current generators of active transformers

$$\overline{v_n^2} = \overline{v_{n21}^2} + \left(\frac{g_{m2}}{g_{21}}\right)^2 \left[1 + \left(\frac{\omega}{\omega_{t2}}\right)^2\right] \overline{v_{n2}^2},$$

$$\overline{i_n^2} = \left(\frac{\omega_{t2}}{\omega}\right)^2 \left[\left(\frac{g_{m1}^2}{g_{m2}}\right)^2 \overline{v_{n1}^2} + \left(\frac{g_{m1}^2}{g_{21}}\right)^2 \overline{v_{n2}^2} + \left(\frac{g_{m1}^2}{g_{m2}}\right)^2 \overline{v_{n21}^2} + \left(g_{12}\frac{g_{m1}}{g_{m2}}\right)^2 \overline{v_{n12}^2}\right]$$

Non-ideal active transformers

- Both capacitance & conductance of transconductors are considered



- Self/mutual inductances and resistances
  - Resistances exist – finite Q.

$$L_{11} = \frac{C_{11}}{g_{m1}^2 \Delta}, \quad R_{11} = \frac{g_{o11}}{g_{m1}^2 \Delta}, \quad M_{12} = \left(\frac{g_{12}}{g_{m1}}\right) \frac{C_{22}}{g_{m2}^2 \Delta}, \quad R_{12} = \left(\frac{g_{12}}{g_{m1}}\right) \frac{g_{o22}}{g_{m2}^2 \Delta}$$

$$L_{22} = \frac{C_2}{g_{m2}^2 \Delta}, \quad R_{22} = \frac{g_{o22}}{g_{m2}^2 \Delta}, \quad M_{21} = \left(\frac{g_{21}}{g_{m2}}\right) \frac{C_{11}}{g_{m1}^2 \Delta}, \quad R_{21} = \left(\frac{g_{21}}{g_{m2}}\right) \frac{g_{o11}}{g_{m1}^2 \Delta}$$

Non-ideal active transformers (cont'd)

- Stability
  - Assumptions to simplify analysis:
    - go11=go12=go21=go22=go
    - gm1=gm2=gm
    - g12=g21=gc
    - C11=C22=C
  - Characteristic equation

$$s^2\left(\frac{4g_o^2}{\omega_t^2 g_m^2}\right)+s\left(\frac{4g_o}{\omega_t g_m}\right)+\Delta=0$$

  - Poles are in left s-plane
    - Stable

$$s_{1,2}=\frac{\omega_t g_m}{2g_o}\left(-1\pm\frac{g_c}{g_m}\right)$$

  - Frequency range

$$\frac{g_o}{C}<\omega<\left(\frac{g_m}{2g_o}\right)\omega_t\text{, where }\omega_t=\frac{g_m}{C}$$

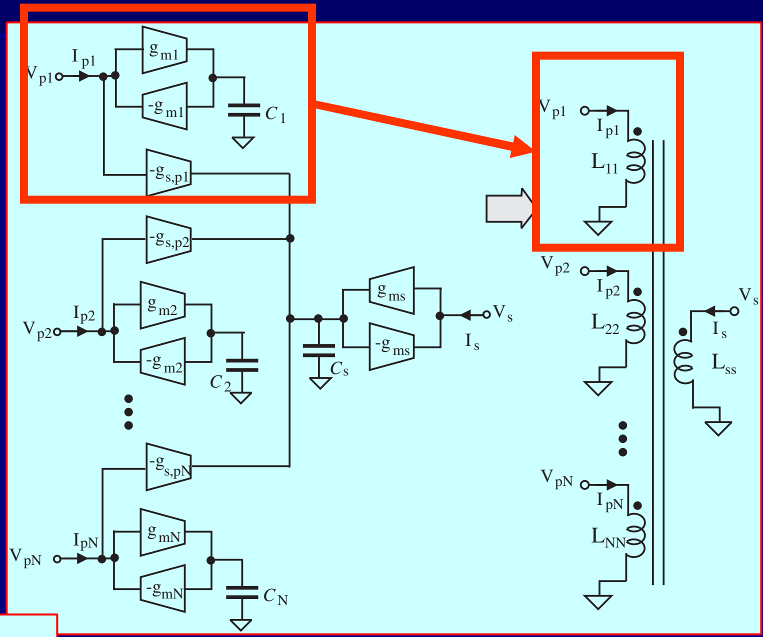
  - Quality factors
    - Self quality factors
    - Mutual quality factors

$$Q_{12}=\frac{\omega M_{12}}{R_{12}},\qquad Q_{21}=\frac{\omega M_{21}}{R_{21}},$$

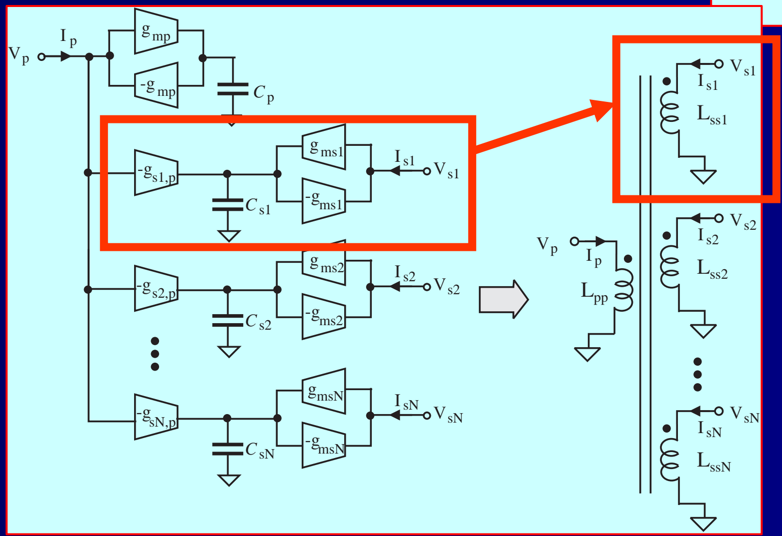
$$Q_{11}=\frac{\omega L_{11}}{R_{11}},\qquad Q_{22}=\frac{\omega L_{22}}{R_{22}},$$

Active transformers with multiple windings

Multiple primary windings
Single secondary winding

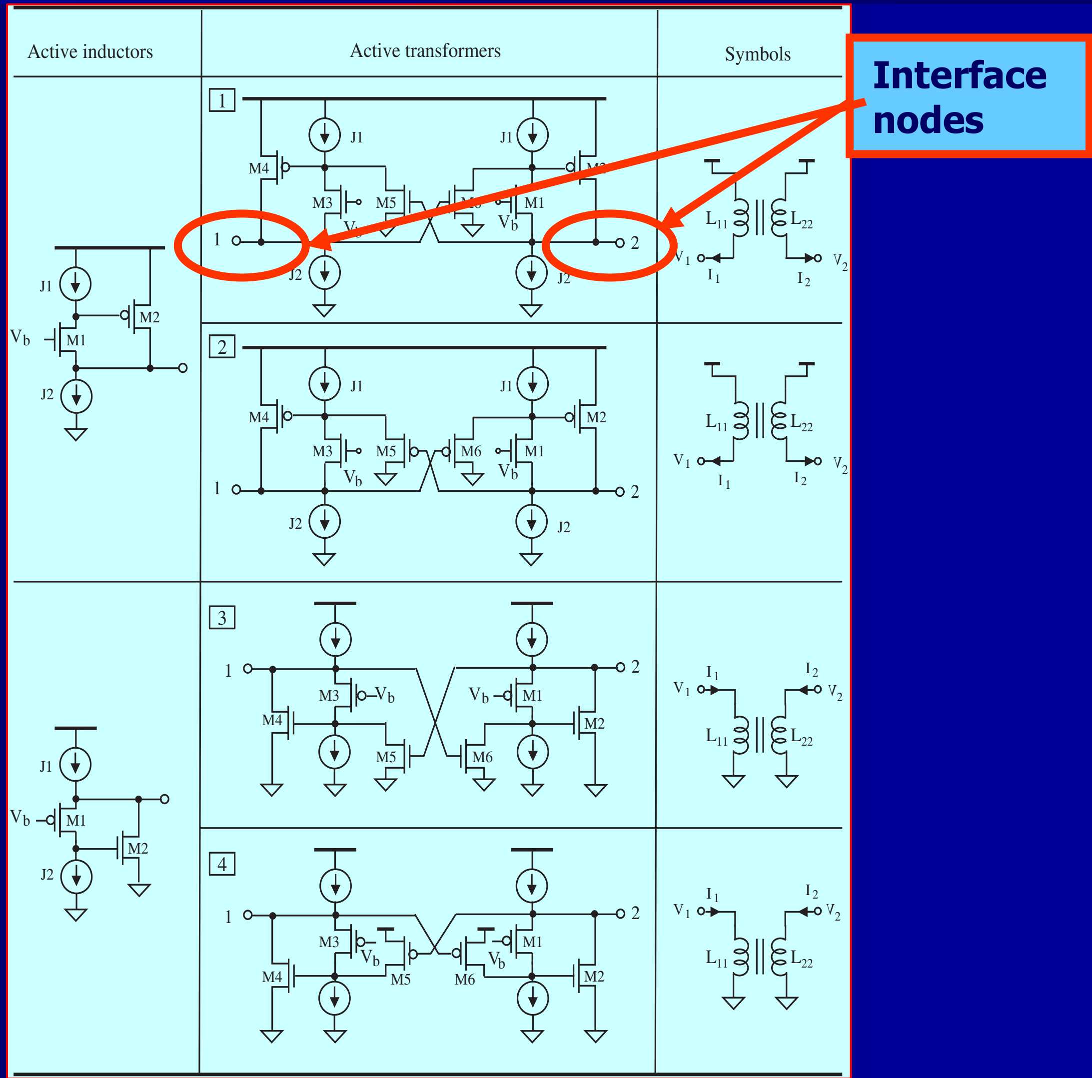


Single primary winding
Multiple secondary windings



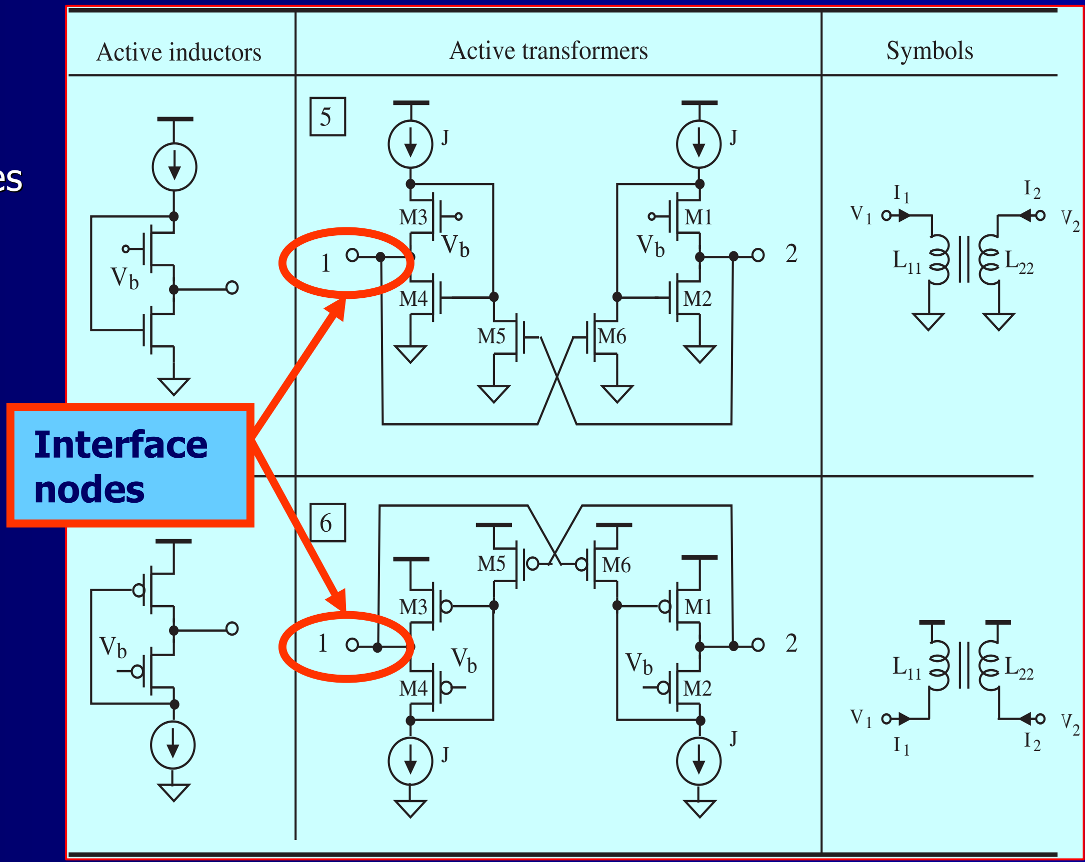
Implementation of active transformers

- Class A active transformers
  - coupled via interface nodes



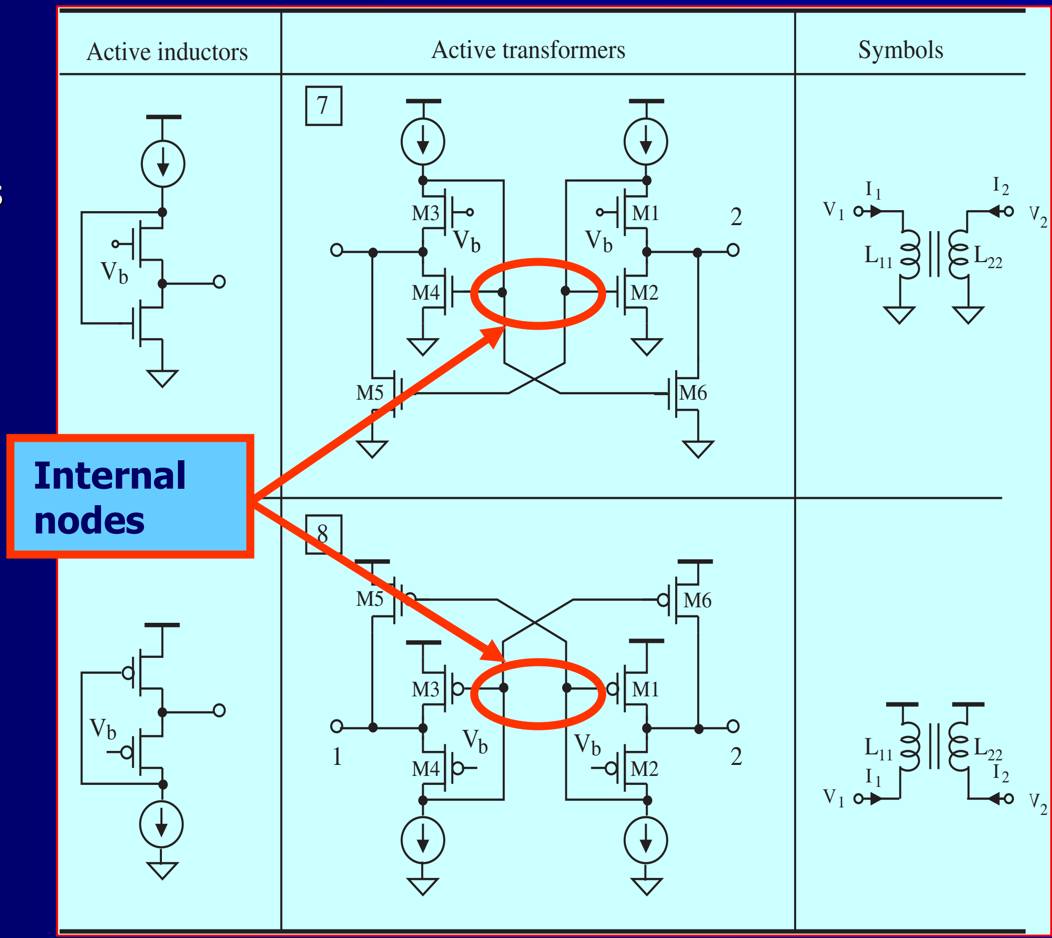
Implementation of active transformers (cont'd)

- Class A active transformers
  - coupled via interface nodes



Implementation of active transformers (cont'd)

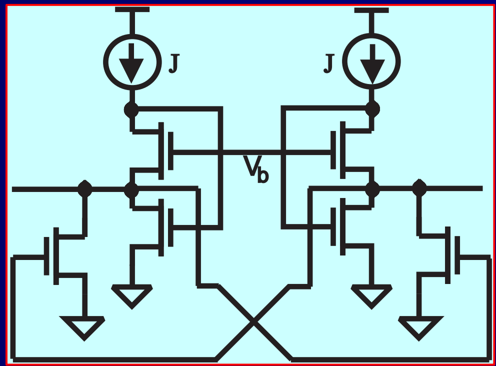
- Class A active transformers
  - coupled via internal nodes



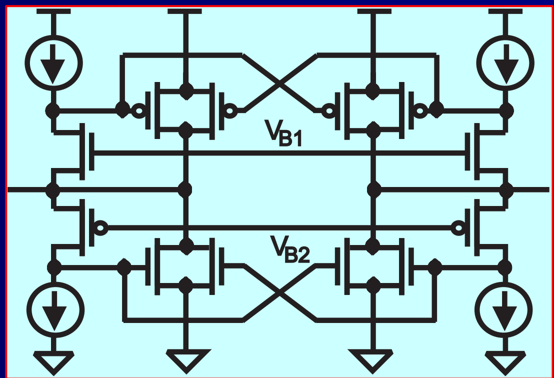
Implementation of active transformers (cont'd)

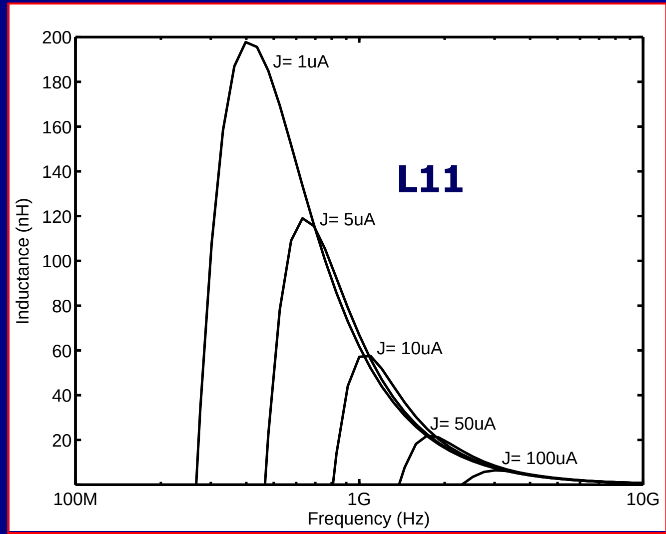
- Class AB active transformers
  - Improve dynamic range and Q.

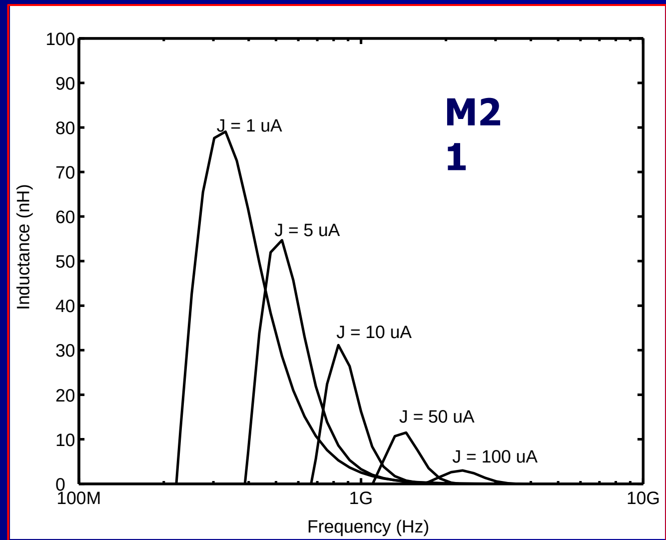
Class A



Class AB

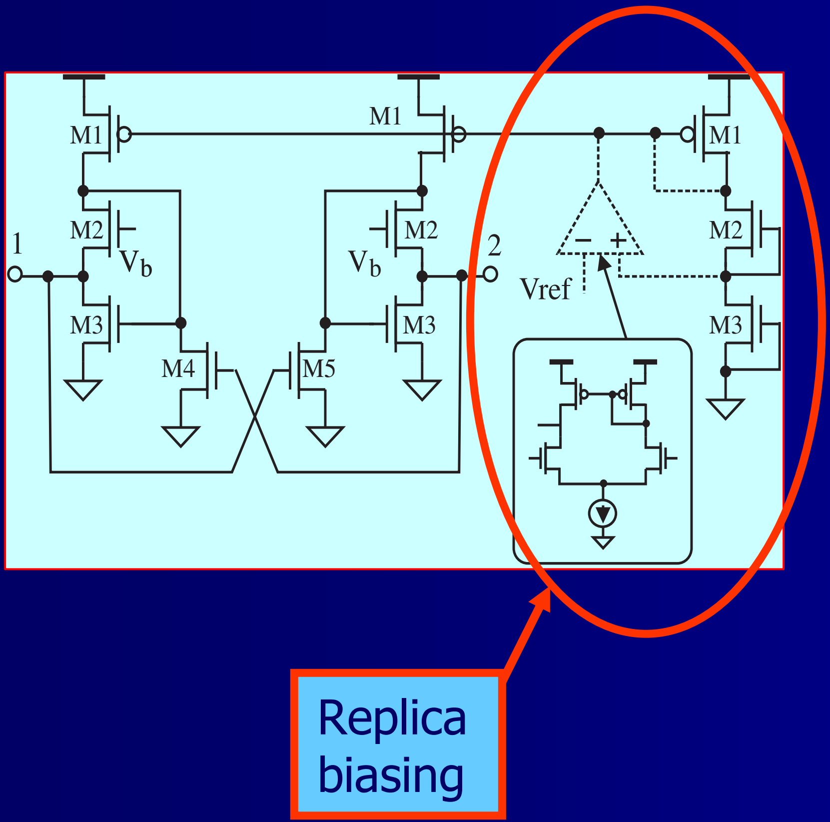


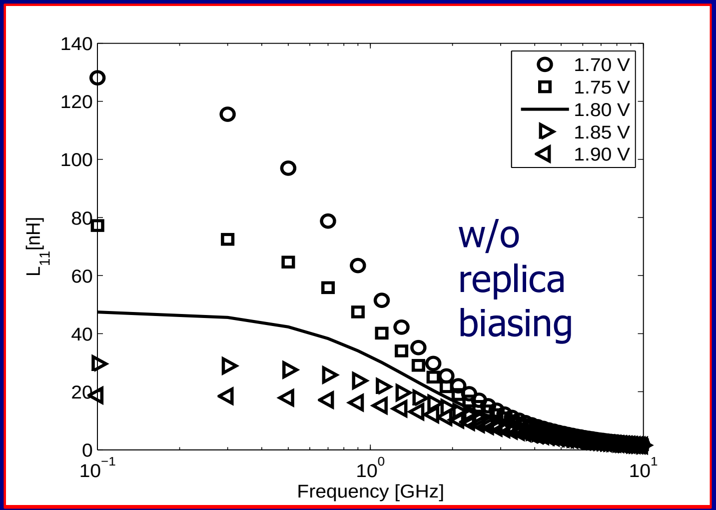


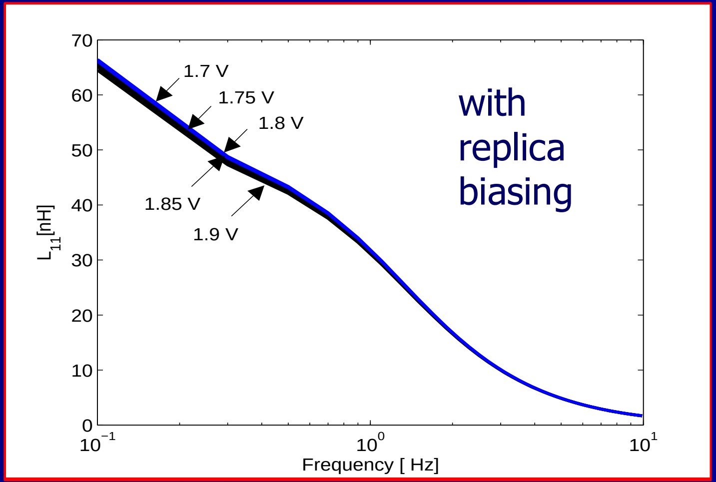


Implementation of active transformers (cont'd)

- Inductances are sensitive to VDD fluctuation
  - Use replica biasing to minimize the effect of VDD fluctuation

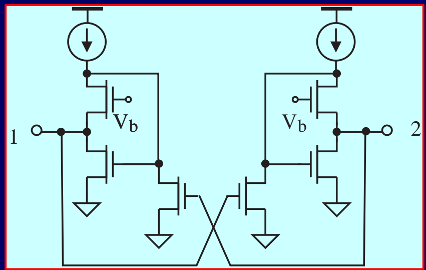


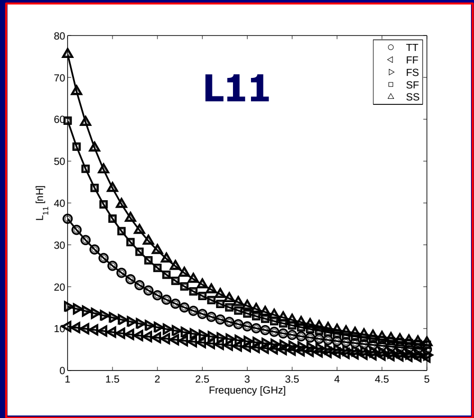


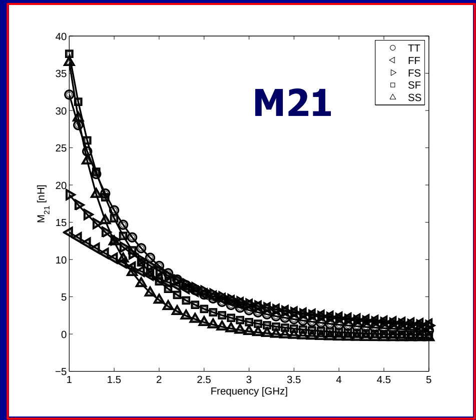


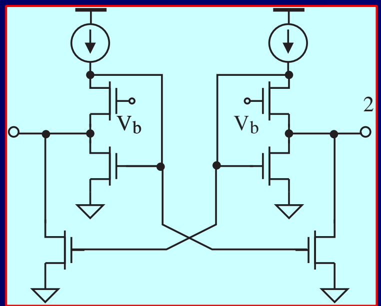
Implementation of active transformers (cont'd)

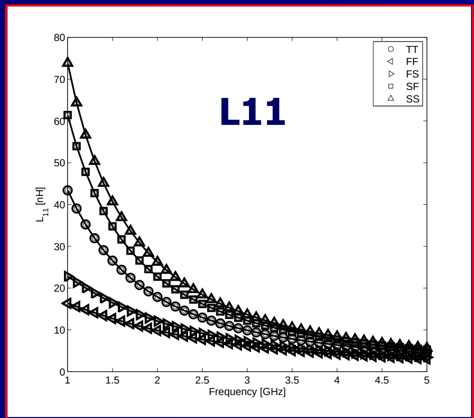
- Inductances are sensitive to process variation
  - Self inductances are more sensitive to process variation

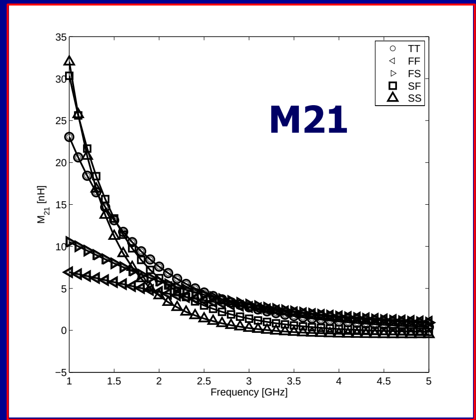










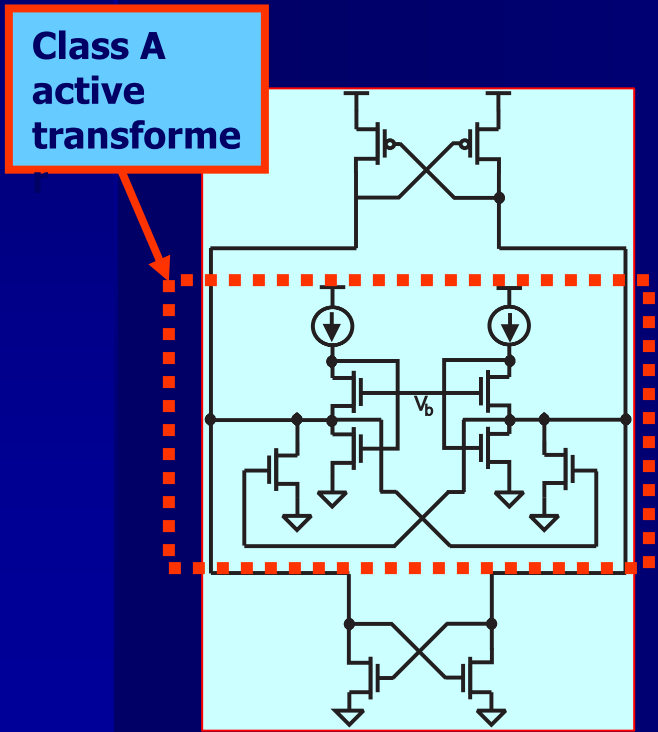


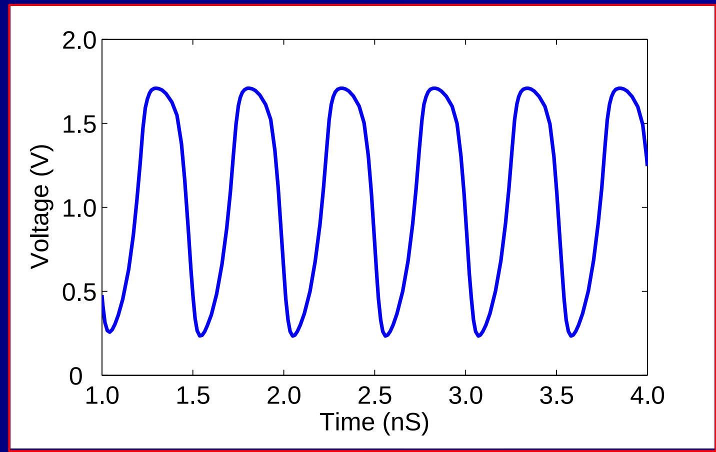
Applications of active transformers

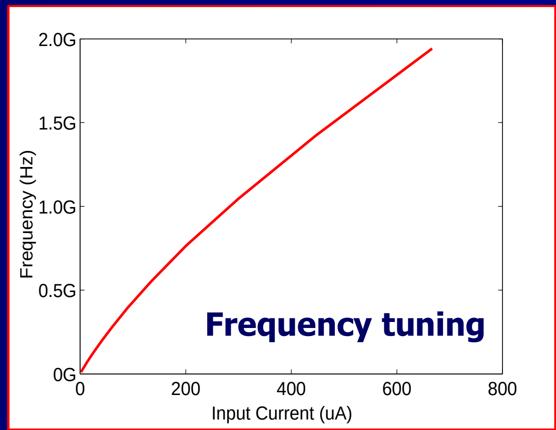
- LC oscillators
- LC quadrature oscillators
- Current-mode phase-locked loops
- QPSK modulators

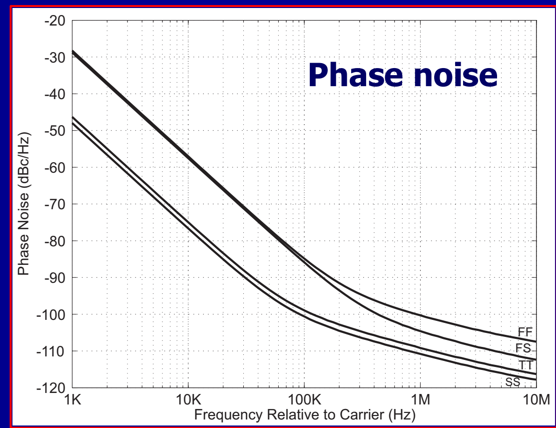
LC oscillators

- Class A active transformer LC oscillators
  - 1.6 GHz oscillator
  - TSMC-0.18um 1.8V CMOS.
  - Phase noise < -100 dBc/Hz @ 1 MHz frequency offset.





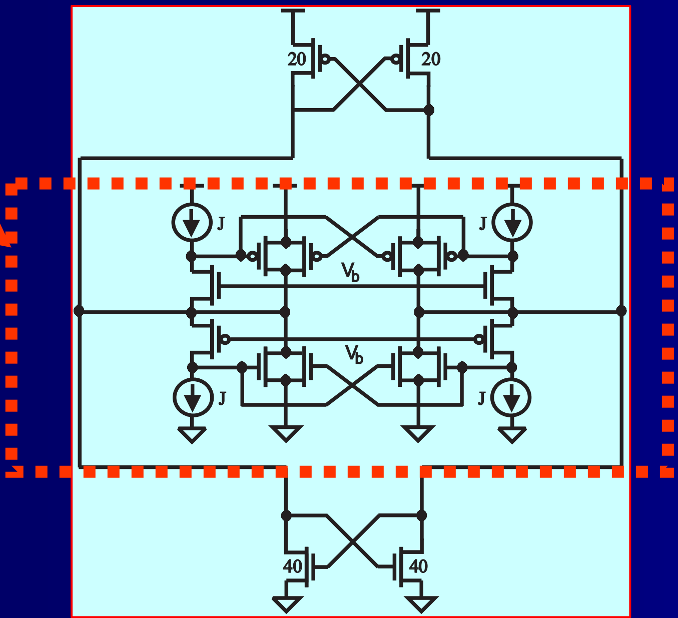


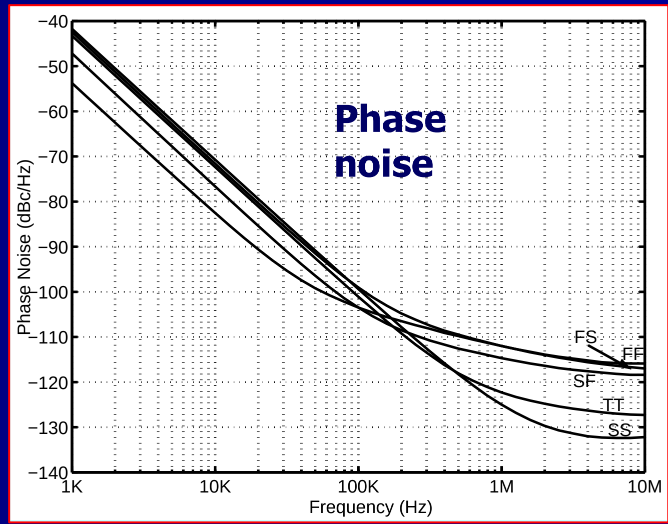


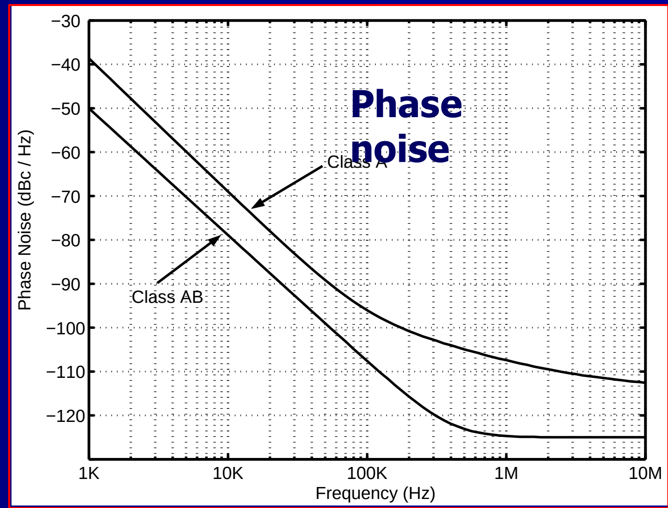
LC oscillators (cont'd)

- Class AB active transformer LC oscillators
  - 1.6 GHz oscillator
  - TSMC-0.18um 1.8V CMOS.
  - Phase noise < -110 dBc/Hz @ 1MHz freq. offset.
  - Improved phase noise as compared with class A active transformer LC oscillators

Class AB active transformer

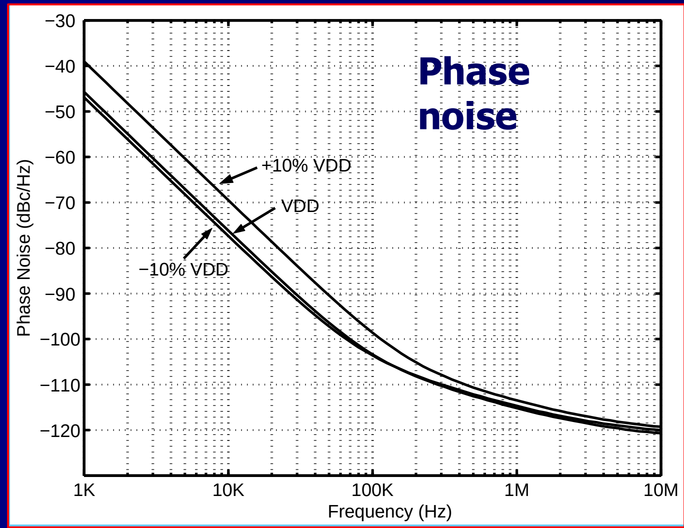


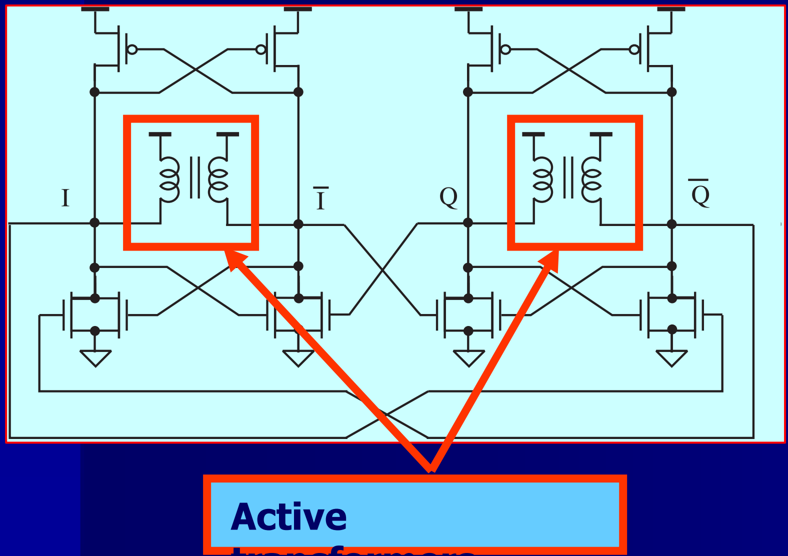


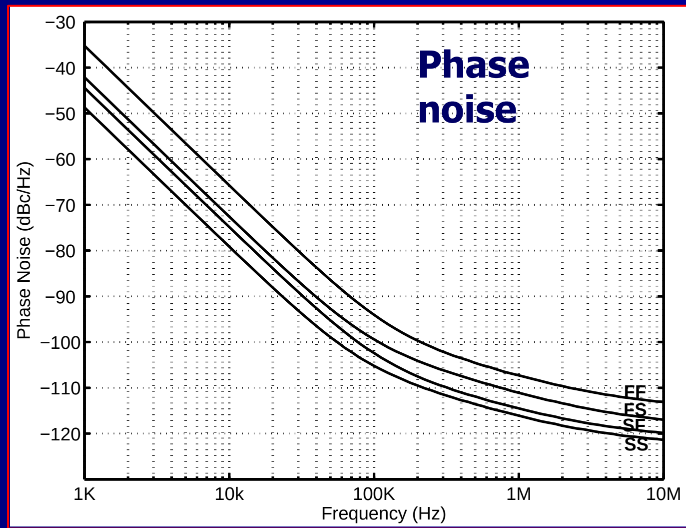


LC quadrature oscillators

- The same configuration as quadrature with passive transformers
  - 1.6 GHz oscillator
  - TSMC-0.18um 1.8V CMOS.
  - Phase noise < -110 dBc/Hz @ 1MHz freq. offset.

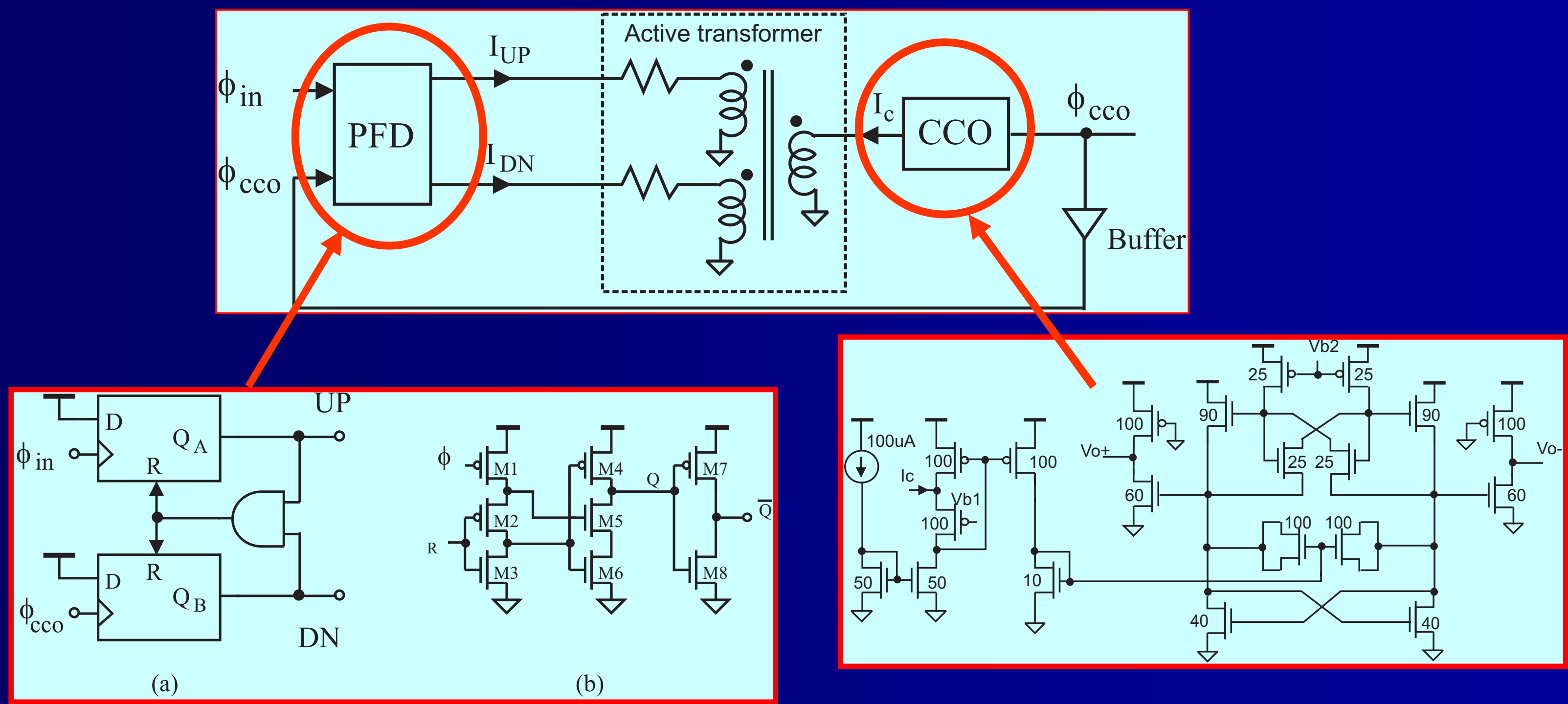






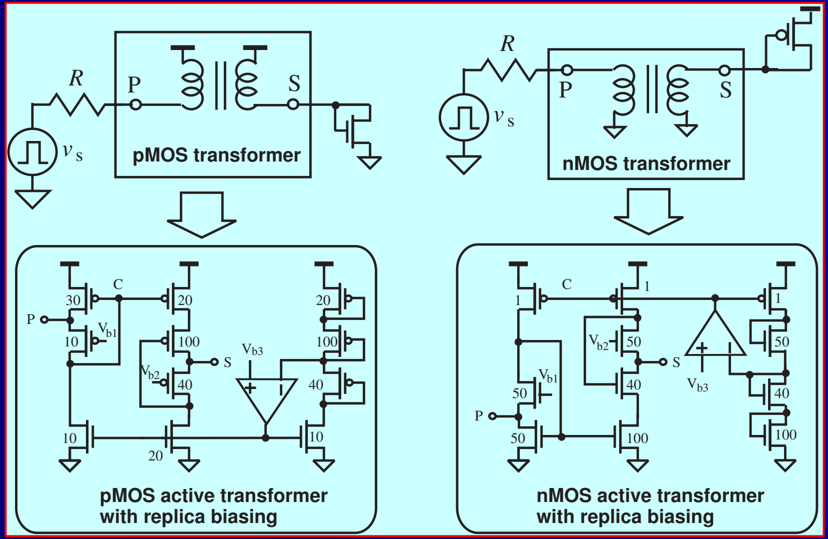
Current-mode PLLs

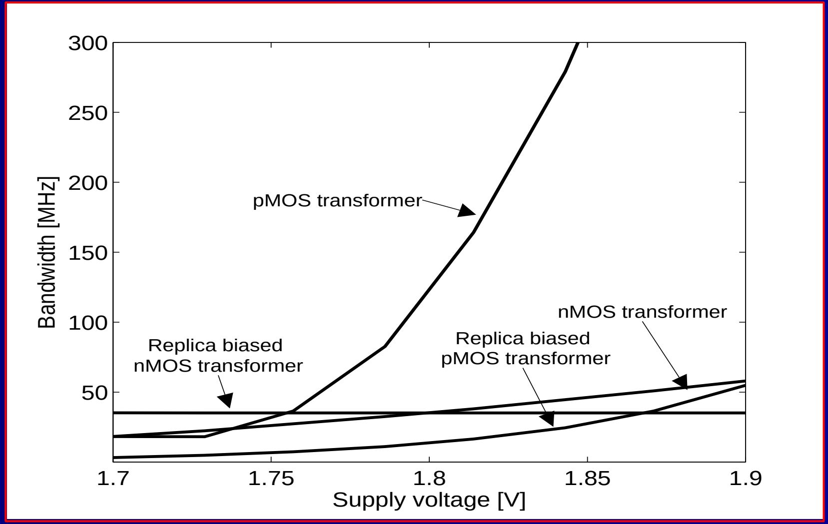
- Current-mode PLLs
  - Voltage-mode loop filters – voltage output to control downstream VCO.
  - Current-mode loop filters – current output to control downstream CCO.



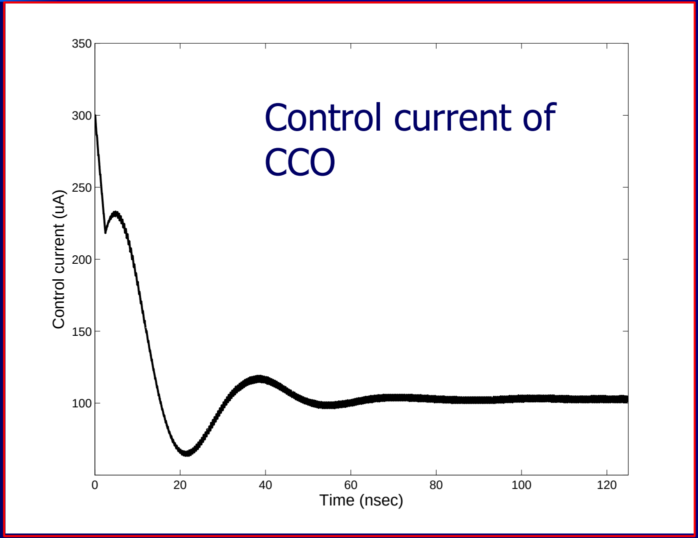
Current-mode PLLs (cont'd)

- Sensitivity of current-mode loop filter to VDD fluctuation
  - nMOS active transformers are less sensitive to VDD fluctuation as compared with pMOS active transformers.
  - Replica biasing is effective in reducing sensitivity to VDD fluctuation

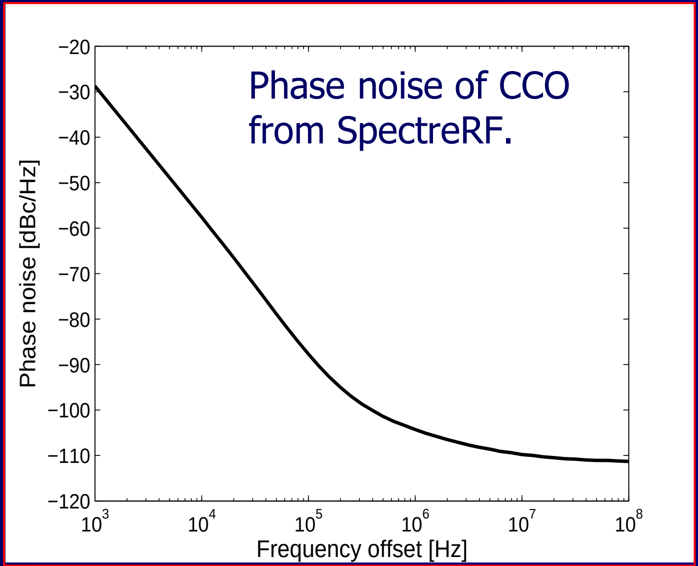


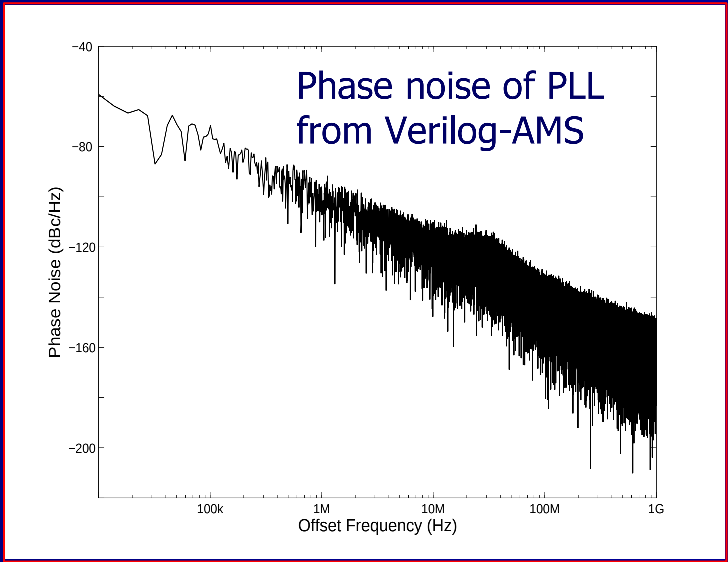


Current-mode PLLs (cont'd)



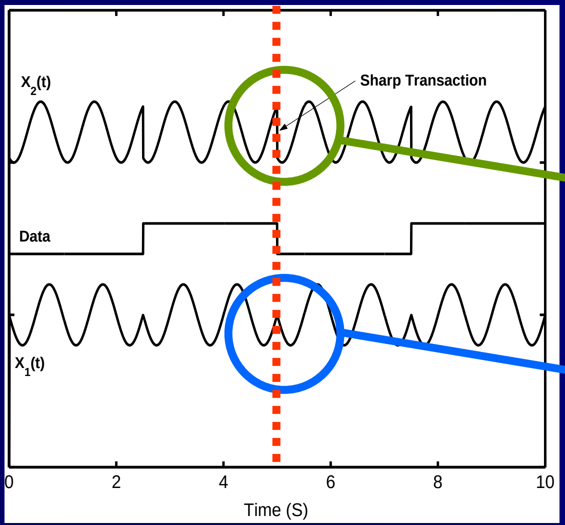
Lock time : 60 ns
Phase noise of CCO : <-100 dBc/Hz @ 1 MHz freq. offset.
Phase noise of PLL : < -100 dBc/Hz @ 1 MHz freq. offset.
Phase noise of PLL is dominated by that of CCO.

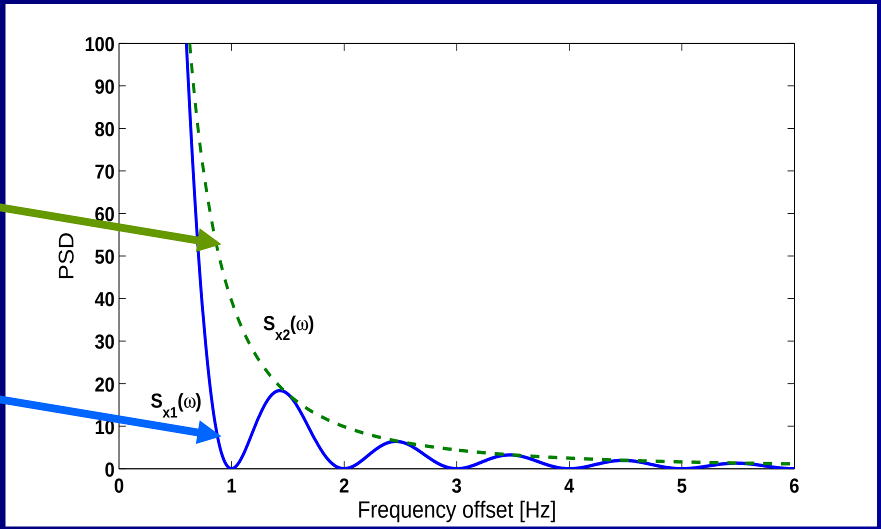




QPSK modulators

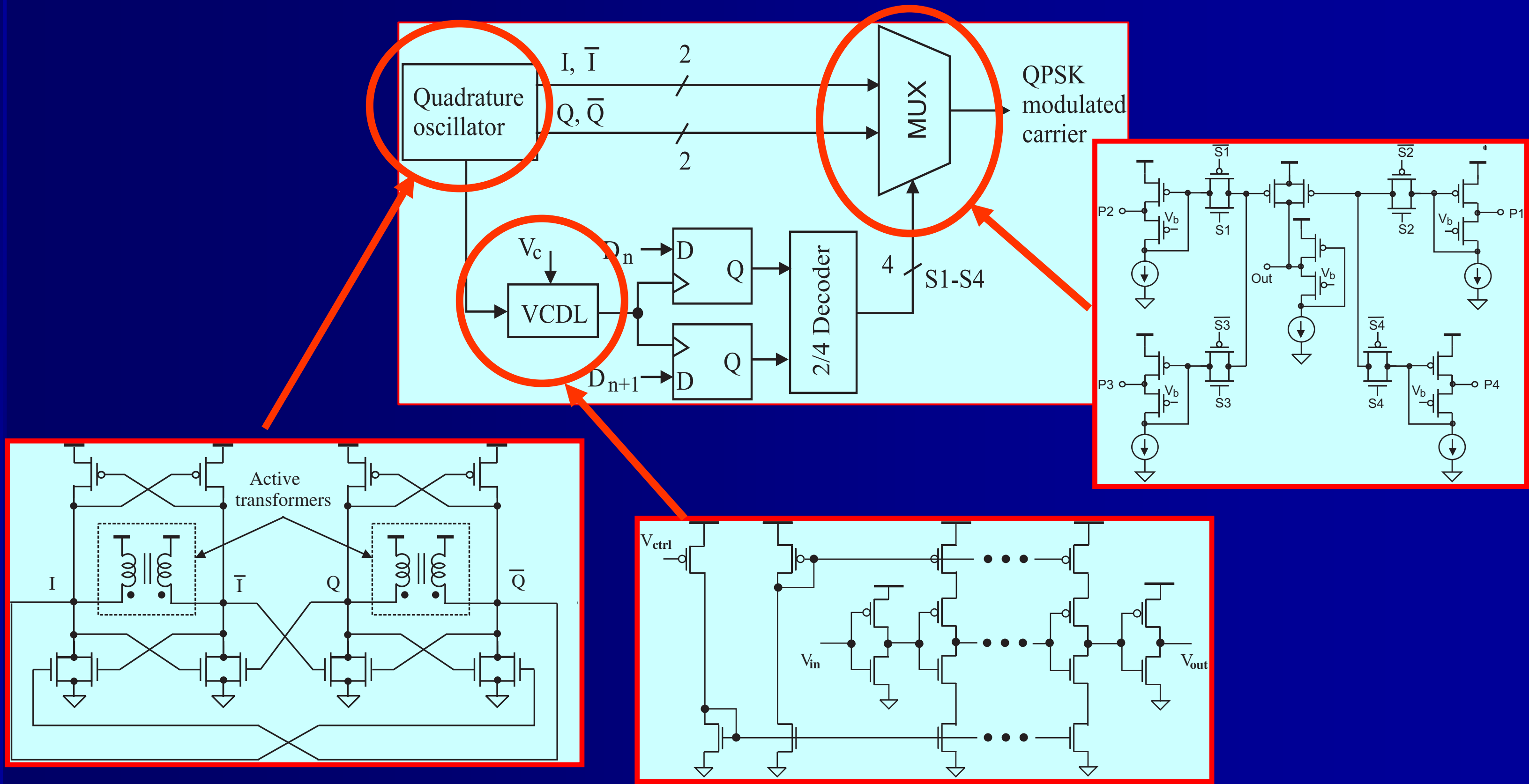
- Minimize bandwidth of modulated signals
  - Modulating at peaks – large bandwidth
  - Modulating at zero-crossings – small bandwidth



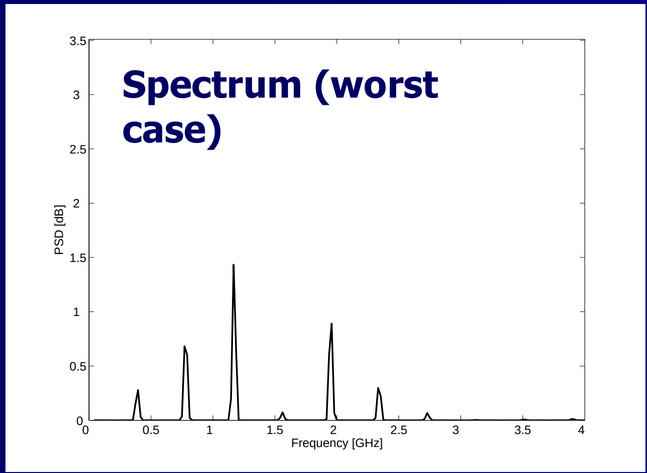


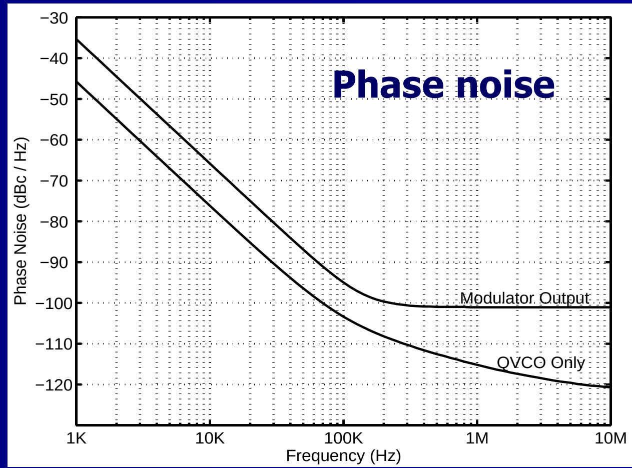
QPSK modulators (cont'd)

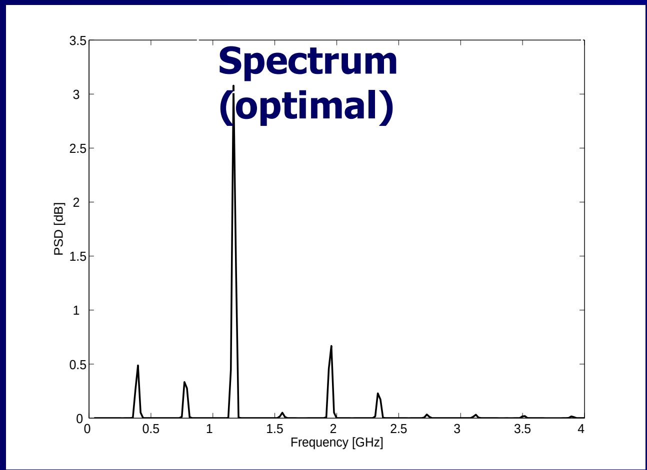
- Active transformer quadrature oscillator generates quadrature signals.
- VCDL provides the optimal modulating points

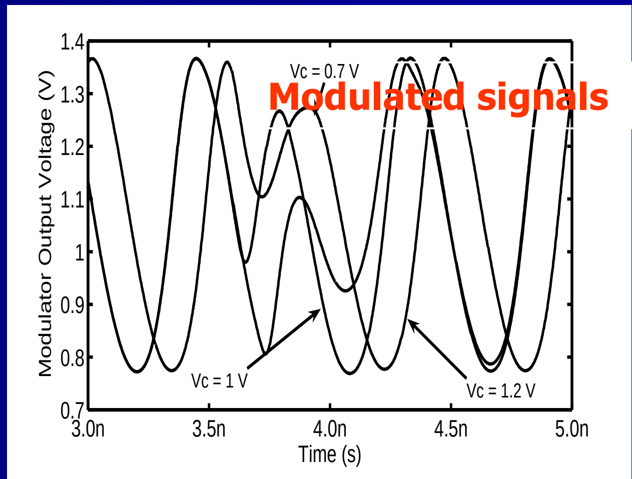


QPSK modulators (cont'd)









Conclusions

Advantages:

- Little silicon requirement
- Tunable self and mutual inductances
- Large Q achievable
- Fully realizable in digital CMOS technologies
- Good noise performance when noise-shaping techniques (high-Q and sigma-delta modulation) are used.
- Good dynamic range
  - gyrator-C is inductive even when devices are in triode

Disadvantages:

- Poor noise performance for wideband applications
- DC power consumption
- Inductances are frequency-dependent
- Sensitive to VDD fluctuation
- Sensitive to process variation

Conclusions:

- An economical way to build VCOs, especially quadrature VCOs.
- Improved phase noise with noise-shaping techniques.

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Thank You !