LECTURE 200 – CLOCK AND DATA RECOVERY CIRCUITS

(References [6])

Objective

The objective of this presentation is:

1.) Understand the applications of PLLs in clock/data recovery

2.) Examine and characterize CDR circuits

Outline

- Introduction and basics of clock and data recovery circuits
- Clock recovery architectures and issues
- Phase and frequency detectors for random data
- CDR architectures
- Jitter in CDR circuits
- VCOs for CDR applications
- Examples of CDR circuits
- Summary

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INTRODUCTION AND BASICS

Why Clock and Data Recovery Circuits?

In many systems, data is transmitted or retrieved without any additional timing reference. For example, in optical communications, a stream of data flows over a single fiber with no accompanying clock, but the receiver is required to process this data synchronously. Therefore, the clock or timing information must be recovered from the data at the receiver.

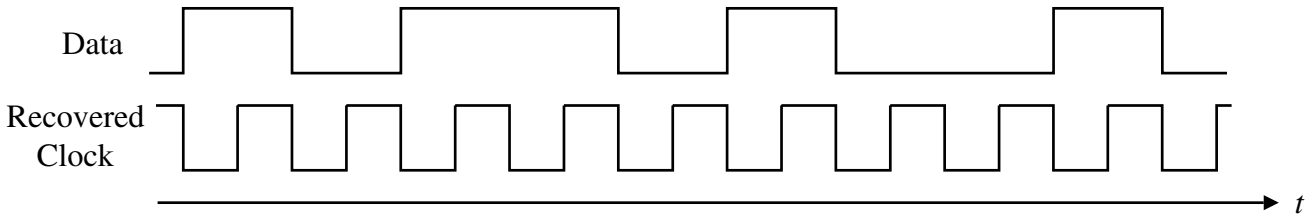

Fig. 4.2-01

Most all clock recovery circuits employ some form of a PLL.

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Properties of NRZ Data

Most binary data is transmitted in a "nonreturn-to-zero" (NRZ) format. NRZ data is compared with "return-to-zero" (RZ) data below.

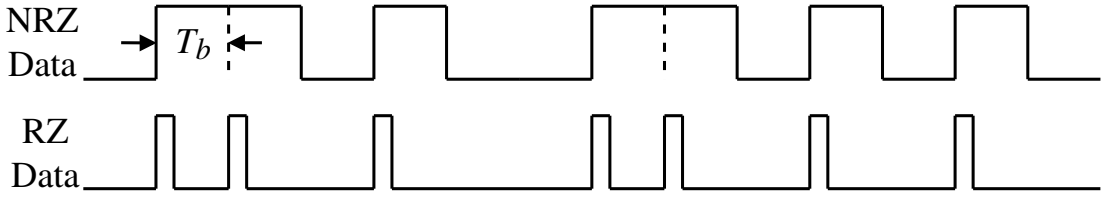

Fig. 4.2-02

The NRZ format has a duration of T_b for each bit period. The bit rate, $r_b = 1/T_b$ in bits/sec.

The bandwidth of RZ data > bandwidth of NRZ data

Maximum bandwidth of NRZ data is determined by a square wave of period $2T_b$.

In general, NRZ data is treated as a random waveform with certain known statistical properties.

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The Challenge of Clock Recovery

1.) The data may exhibit long sequences of ONEs or ZEROs requiring the CRC to "remember" the bit rate during such an interval. The CRC must not only continue to produce the clock, but do so without drift or variation in the clock frequency.

2.) The spectrum of the NRZ data has nulls at frequencies which are integer multiples of the bit rate. For example, if r_b = 1Gb/s, the spectrum has no energy at 1GHz.

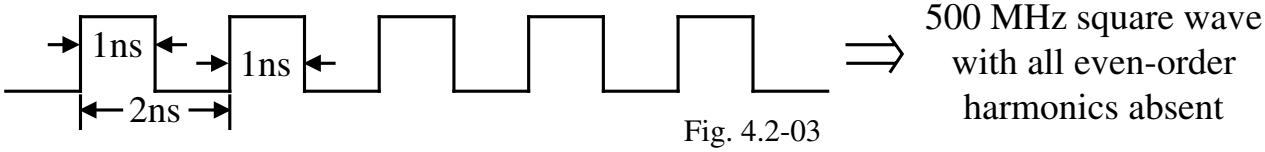

Fig. 4.2-03

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NRZ Data Spectrum

The autocorrelation function of a random binary sequence can be written as[†]

$$R_x(\tau) = 1 - \frac{|\tau|}{T_b}, \quad |\tau| < T_b$$
$$= 0, \quad |\tau| = T_b$$

From this, the power spectral density of a random binary sequence is written as,

$$P_x(\omega) = T_b\left[\frac{\sin(\omega T_b/2)}{\omega T_b/2}\right]^2$$

which is illustrated as,

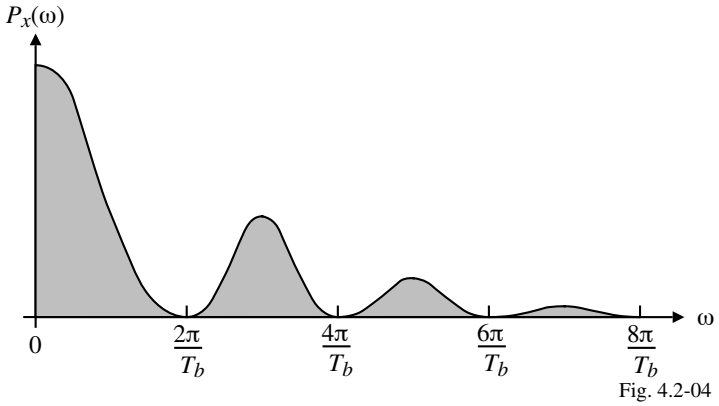

Fig. 4.2-04

[†] S.K.Shanmugam, *Digital and Analog Communication Systems*, New York: Wiley &Sons, 1979.

Edge Detection

CRC circuits require the ability to detect both the positive and negative transitions of the incoming data as illustrated below,

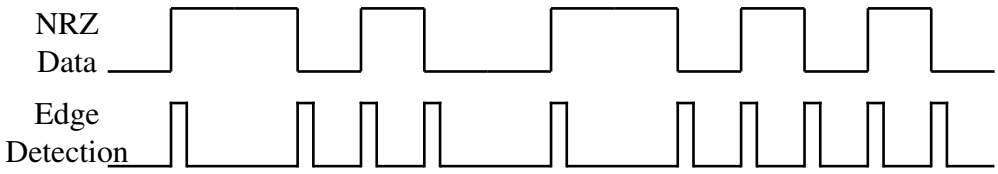

Fig. 4.2-05

Methods of edge detection:

1.) EXOR gate with a delay on one input.

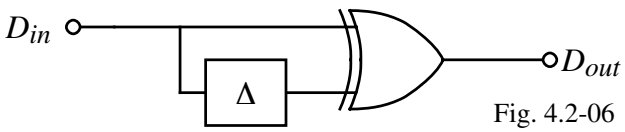

Fig. 4.2-06

2.) A differentiator followed by a full-wave rectifier.

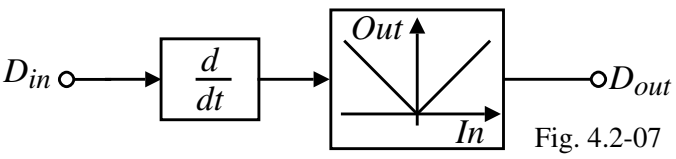

Fig. 4.2-07

Edge Detection and Sampling of NRZ Data - Continued

3.) Use a flipflop that operates on both the rising and falling edges.

This technique takes advantage of the fact that in a phase-locked CRC, the edge-detected data is multiplied by the output of a VCO as shown.

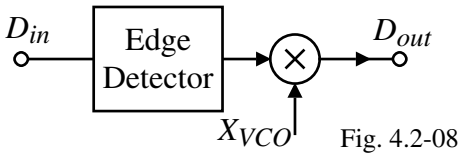

Fig. 4.2-08

In effect, the data transition impulses "sample" points on the VCO output.

a.) Master-slave flipflop consisting of two D latches.

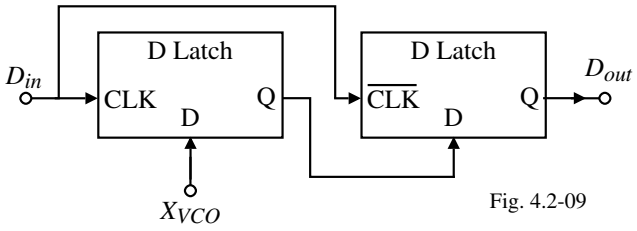

Fig. 4.2-09

b.) Double-edge-triggered flipflop.

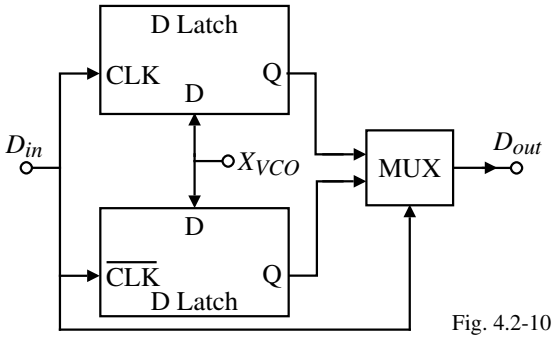

Fig. 4.2-10

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CLOCK RECOVERY ARCHITECTURES AND ISSUES

Clock Recovery Architectures

From the previous considerations, we see that clock recovery consists of two basic functions:

1.) Edge detection

2.) Generation of a periodic output that settles to the input data rate but has negligible drift when some data transitions are absent.

Conceptual illustration of these functions:

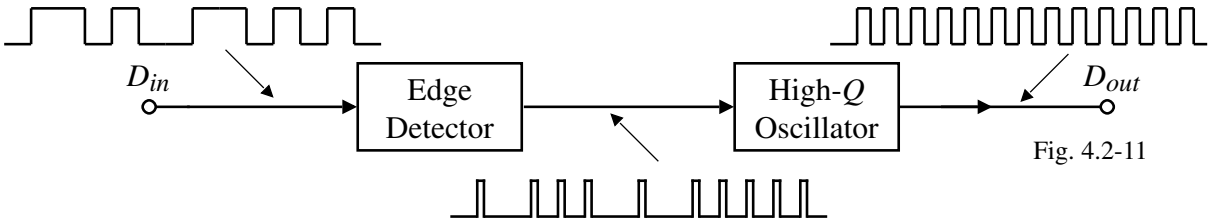

Fig. 4.2-11

In essence, the high-Q oscillator is "synchronized" with the input transitions and oscillates freely in their absence. Synchronization is achieved by means of phase locking.

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Phase Locked Clock Recovery Circuit

Circuit:

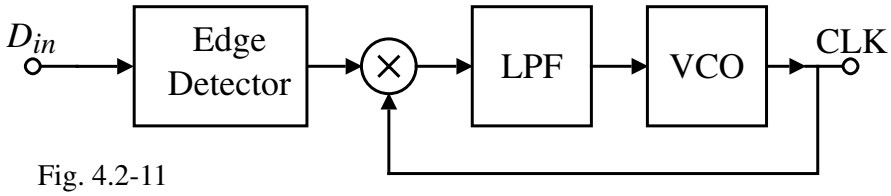

Fig. 4.2-11

Operation:

1.) Assume the input data is periodic with a frequency of $1/T_b$ (Hz).

2.) The edge detector doubles the frequency causing the PLL to lock to $2/T_b$ (Hz).

3.) If a number of transitions are absent, the output of the multiplier is zero and the control voltage applied to the VCO begins to decay causing the oscillator to drift from $1/T_b$ (Hz).

4.) To minimize the drift due to the lack of transitions,

τ_{LPF} >> Maximum allowable interval between consecutive transitions.

5.) The result is a small loop bandwidth and a narrow capture range. Fortunately, most communication systems guarantee an upper bound of the allowable interval between consecutive transitions by encoding the data.

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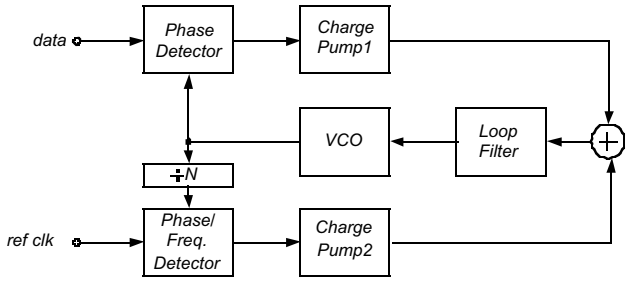
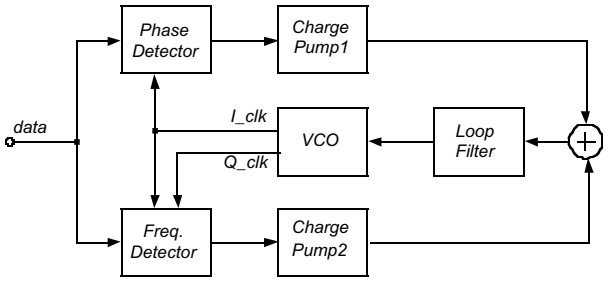
Frequency Aided Acquisition

Frequency acquisition can be accomplished with and without an external reference. If an external reference clock is available, frequency acquisition can be done with a secondary PLL loop having a PFD.

Frequency acquisition with an external reference:



Frequency acquisition with a frequency detector:



If no reference clock is available, a frequency detector has to be used which requires I and Q clocks and for typical implementations, the VCO frequency cannot be off more that about 25% of the data rate.

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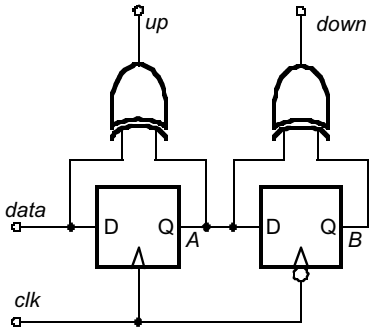
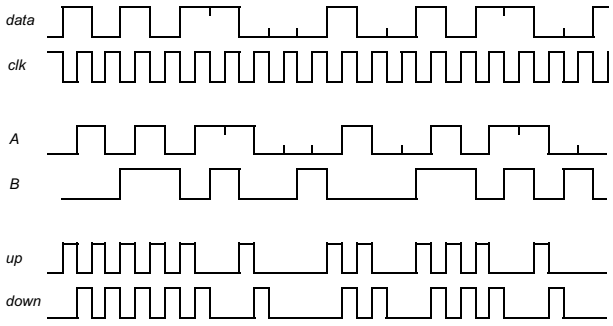
PHASE DETECTORS FOR RANDOM DATA

Linear Phase Detectors

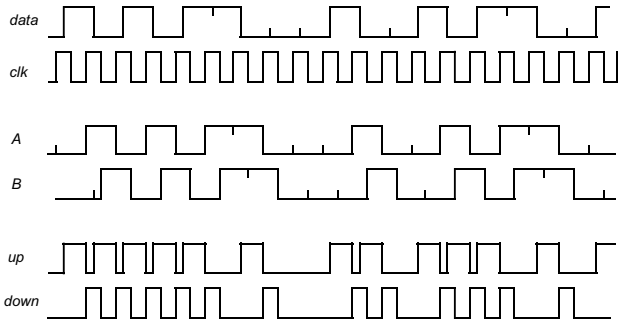
This type of detector is represented by the Hogge detector.[†]



Clock rising edge is at data center:



Clock is 0.5 period ahead of data center.



[†] C. R. Hogge, *IEEE J. Lightwave Technology*, pp. 1312-1314, 1985.

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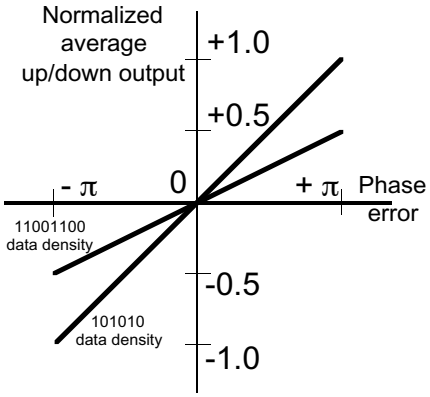
Linear Phase Detector – Continued

Transfer characteristics of the Hogge phase detector:



- Linear gain characteristics
- Phase detector gain is 0.5 for 11001100 data transition density
- Small jitter generation due to PD
- Suffers from bandwidth limitations
- Have static phase offset due to mismatch

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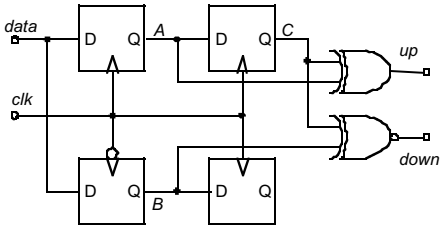
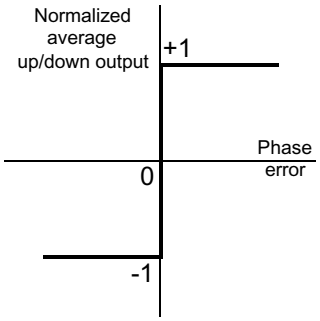
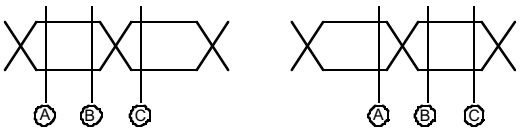
Binary Phase Detectors

This type of phase detector is represented by the Alexander type of phase detector.†







Binary Phase Detector Truth-Table		
ABC	Decision	Output
000	Tri-state	- - - - - - -
001	Clock is ahead	Down
010	Error	- - - - - - -
011	Clock is behind	Up
100	Clock is behind	Up
101	Error	- - - - - - -
110	Clock is ahead	Down
111	Tri-state	- - - - - - -

- High phase detector gain
- Causes higher output jitter compared to linear phase detectors
- Static phase offset set by sampling aperture errors
- Widely used in digital PLL and DLL's

† J.D.H. Alexander, *IEE Electronics Letters*, pp. 541-542, 1975.

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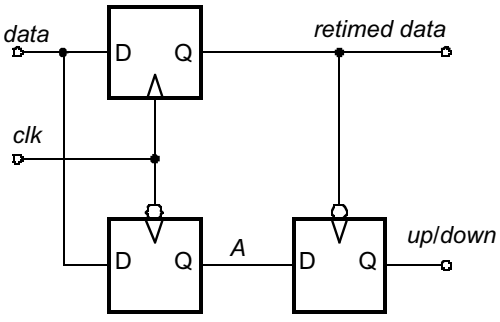
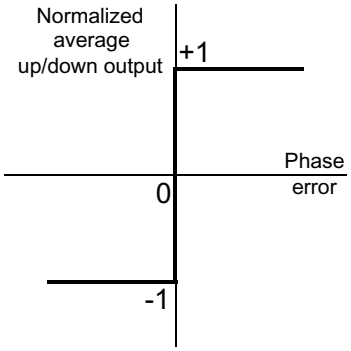
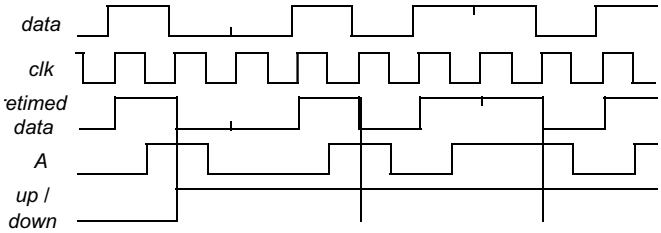
Binary Phase Detectors – Continued

Meghelli Phase Detector†

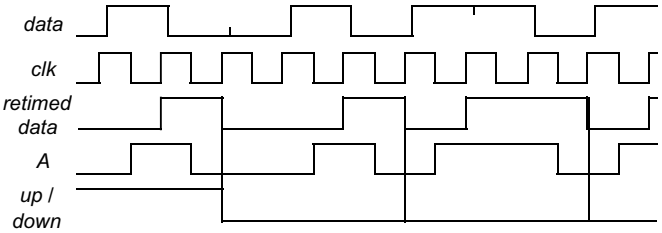




Clock lagging data:



Clock leading data:



- Similar to the Alexander phase detector
- Simpler implementation

† M. Meghelli, et. al. *ISSCC*'2000, pp. 56-57.

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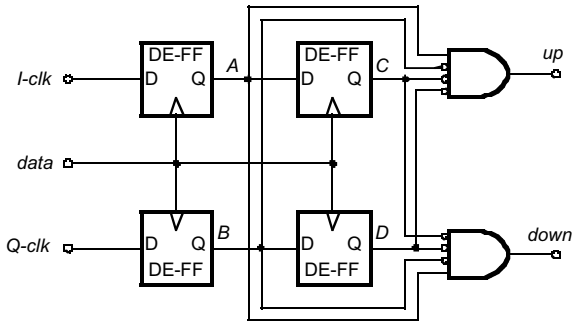
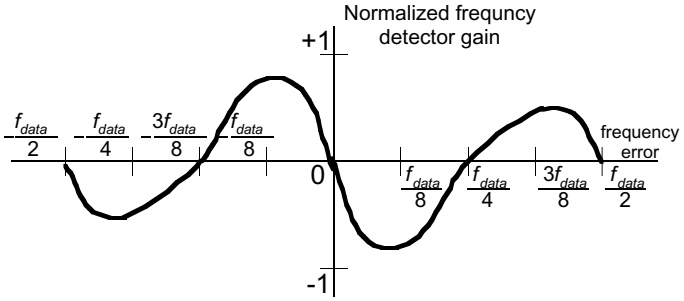
FREQUENCY DETECTORS FOR RANDOM DATA

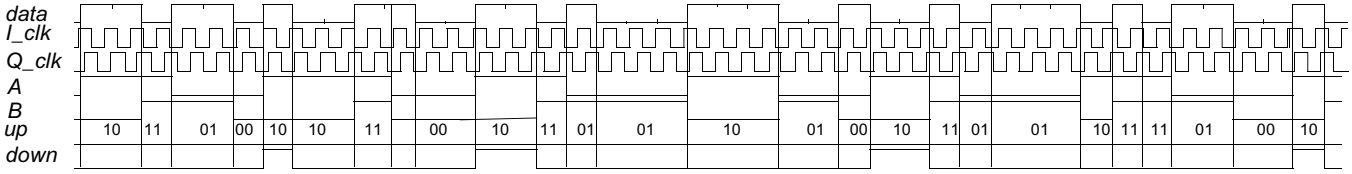
Rotational Frequency Detectors

Block diagram (Richman)†





Timing diagram example: (VCO clock is faster than the data rate)



- Pull in range: ±25% of data rate
- Prone to false locking in presence of jitter and/or short data pattern
- AB changing from 00 to 01 → DOWN pulse, AB changing from 10 to 00 → UP pulse

† D. Richman, *Proc. of IRE*, pp. 106-133, Jan. 1954.

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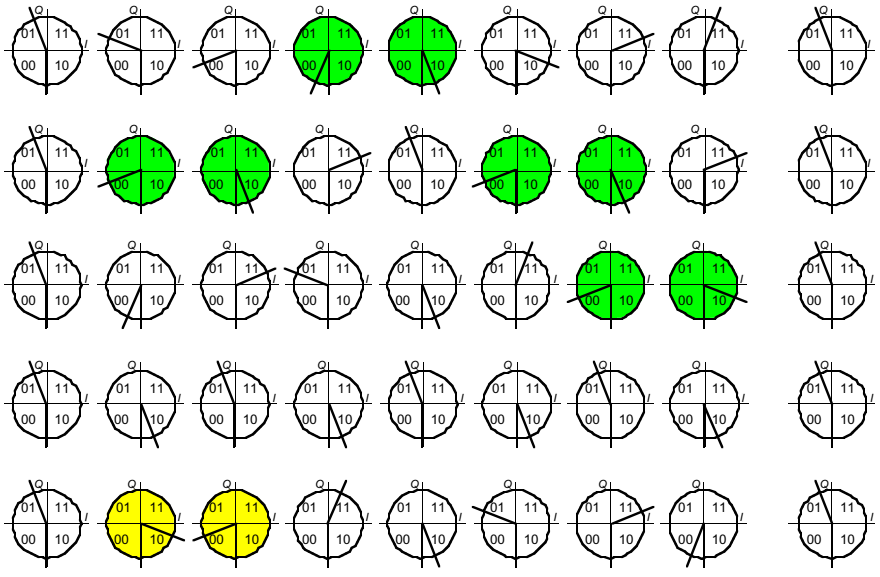
Phasor DiagramExamples of Rotational Frequency Detectors

Phasor diagrams for a 0101 data pattern:



f_{VCO} = 1.125 x data rate

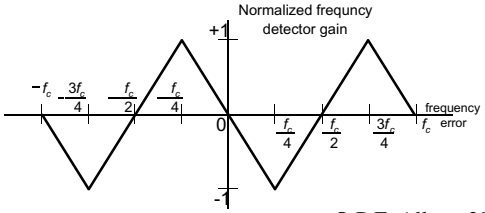
f_{VCO} = 1.250 x data rate

f_{VCO} = 1.375 x data rate

f_{VCO} = 1.500 x data rate

f_{VCO} = 1.625 x data rate

If the VCO frequency is off more than 50%, the frequency is in the wrong direction.



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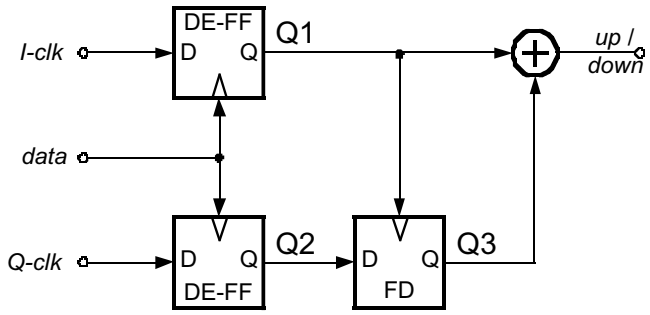
Rotational Frequency Detectors – Continued

A simpler implementation of the Richman frequency detector (Pottbacker)†. The data samples the clock.



Logic Table of Pottbacker's Frequency Detector		
Q1	Q2	Q3
X	1	0
Rising	0	-1
Falling	0	+1

- Very similar characteristics to that of Richman's frequency detector, however, the implementation is simpler.
- Pull-in range: ±25% of data rate
- Prone to false locking in the presence of jitter and/or short data patterns

† A. Pottbacker, et. al., *IEEE JSSC*, pp. 1747-1751, Dec. 1992.

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CDR ARCHITECTURES

Clock Recovery – Spectral Line, Early-Late

Enam, Abidi 1992

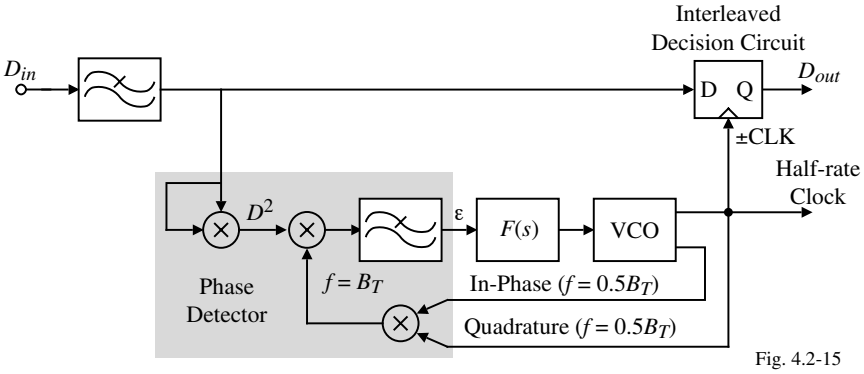

Fig. 4.2-15

Interleaved decision circuit

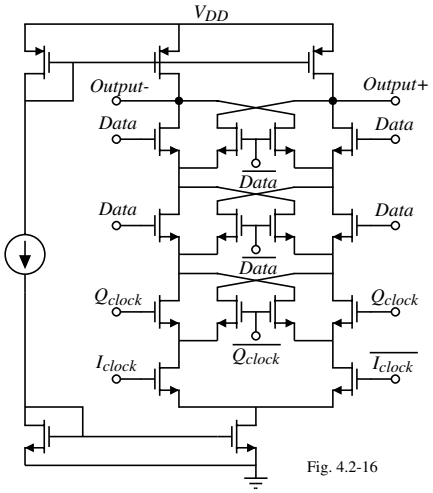

Fig. 4.2-16

Comments:

- Good example of CMOS solution to practical clock recovery circuits
- Circuit can be analyzed as spectral line or as early-late.

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Clock Recovery - Quadricorrelator

Analog version has three loops sharing the same VCO.

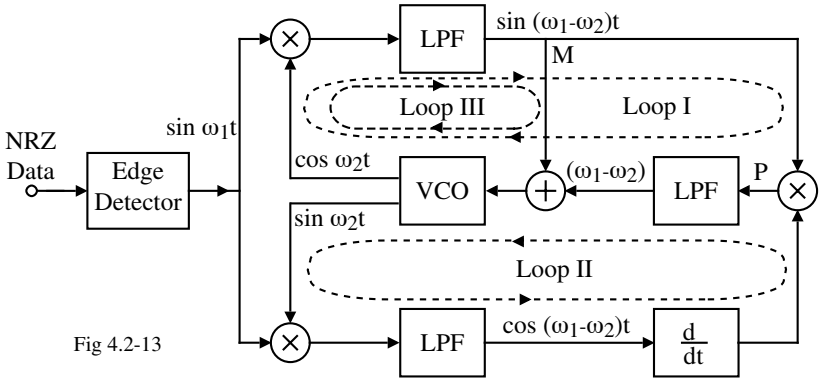

Fig 4.2-13

Edge detector plus three loops-

Loops I and II perform frequency detection

Loop III performs phase detection

Operation:

The signal at P is $(\omega_1-\omega_2)\cos^2(\omega_1-\omega_2) \Rightarrow$ VCO is driven by $\sin(\omega_1-\omega_2)t + (\omega_1-\omega_2)$

Loops I and II drive the VCO to lock when $\omega_1 \neq \omega_2$. As $|\omega_1-\omega_2|$ approaches zero, Loop III begins to generate an asymmetrical signal at node M assisting the lock process. Finally, when $\omega_1 \approx \omega_2$, the dc feedback signal produced by Loops I and II approaches zero and Loop III dominates, locking the VCO output to the input data.

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Quadricorrelator – Continued

The use of frequency detection in the quadricorrelator makes the capture range independent of the locked loop bandwidth, allowing a small cutoff frequency in the LPF of Loop III so as to minimize the VCO drift between data transitions.

Because Loops I and II can respond to noise and spurious components, it is desirable to disable these loops once phase lock has been attained.

Since the combination of an edge detector and a mixer can be replaced with a double-edge triggered flipflop, the quadricorrelator can be implemented in a digital form as shown below.

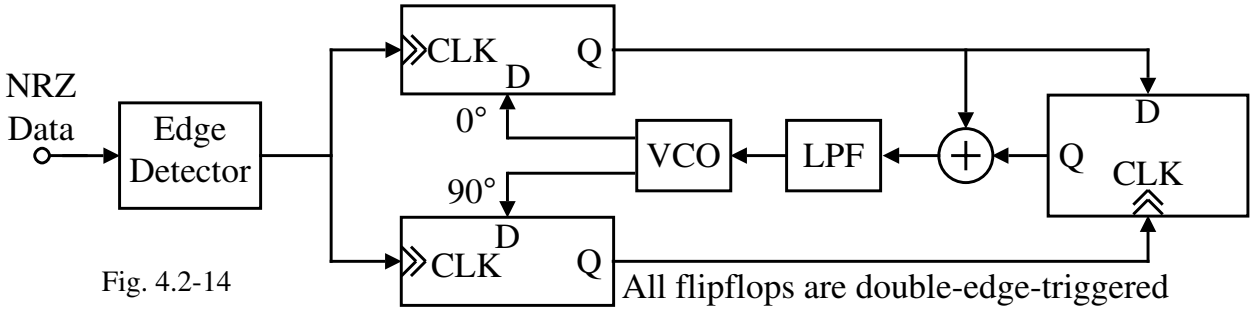

Fig. 4.2-14

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JITTER IN CDR CIRCUITS

Jitter Influence on Clock Recovery

Types of jitter:

- Long term jitter

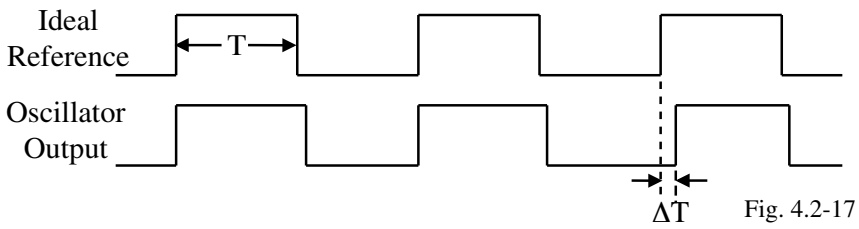

Fig. 4.2-17

  - Diverges for a free-runnng oscillator
  - Meaningful only in a phase-locked system
  - Depends on PLL dynamics

- Cycle-to-cycle jitter

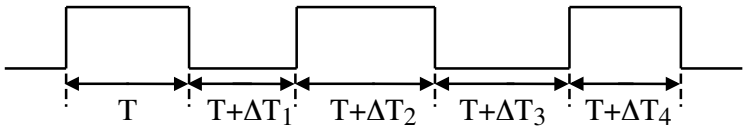

Fig. 4.2-18

  - Of great interest in many timing applications
  - Mostly due to the oscillator
  - Usually too fast for the PLL to correct

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Jitter Due to Device Noise

1/f noise:

1/f noise is inversely proportional to frequency and causes the frequency to change very slowly. Easily suppressed by a wide PLL bandwidth.

$$e_{ni}^2 = \frac{B}{fW_iL_i} \quad (V^2/Hz) \qquad \text{and} \qquad i_{ni}^2 = \frac{2BK'I_i}{fL_i^2} \quad (A^2/Hz)$$

where

$$B = \frac{KF}{2C_{ox}K'}$$

Thermal noise:

Thermal noise is assumed to be "white" and is modeled in MOSFETs as,

$$e_{ni}^2 \approx \frac{8kT}{3g_m} \quad (V^2/Hz) \qquad \text{and} \qquad i_{ni}^2 \approx \frac{8kTg_m}{3} \quad (A^2/Hz)$$

The relationship between phase noise and cycle-to-cycle jitter is,

$$\Delta T^2(\text{rms}) \approx \frac{4\pi}{\omega_o{}^3} S\phi(\omega)\,(\omega\text{-}\omega_o)^2$$

(Razavi: *IEEE Trans. on Circuits and Systems, Part II*, Jan. 99)

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Sources of Jitter

- Input jitter

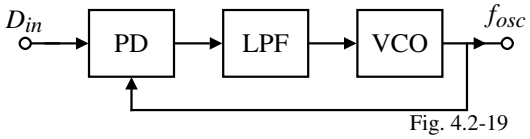

Fig. 4.2-19

- VCO jitter due to device noise

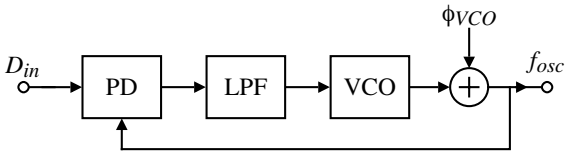

Fig. 4.2-20

- VCO jitter due to ripple on control line

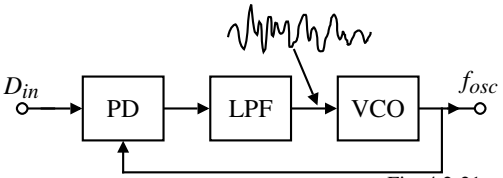

Fig. 4.2-21

- Injection pulling of the VCO by the data

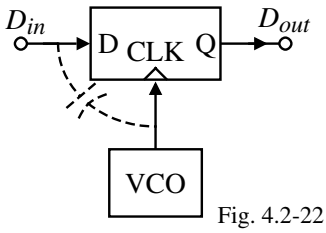

Fig. 4.2-22

- Substrate and supply noise

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Substrate and Supply Noise

How Do Carriers Get Injected into the Substrate?

1.) Hot carriers (substrate current)

2.) Electrostatic coupling (across depletion regions and other dielectrics)

3.) Electromagnetic coupling (parallel conductors)

Why is this a Problem?

With decreasing channel lengths, more circuitry is being integrated on the same substrate. The result is that noisy circuits (circuits with rapid transitions) are beginning to adversely influence sensitive circuits (such as analog circuits).

Present Solution:

Keep circuit separate by using multiple substrates and put the multiple substrates in the same package.

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Hot Carrier Injection in CMOS Technology without an Epitaxial Region

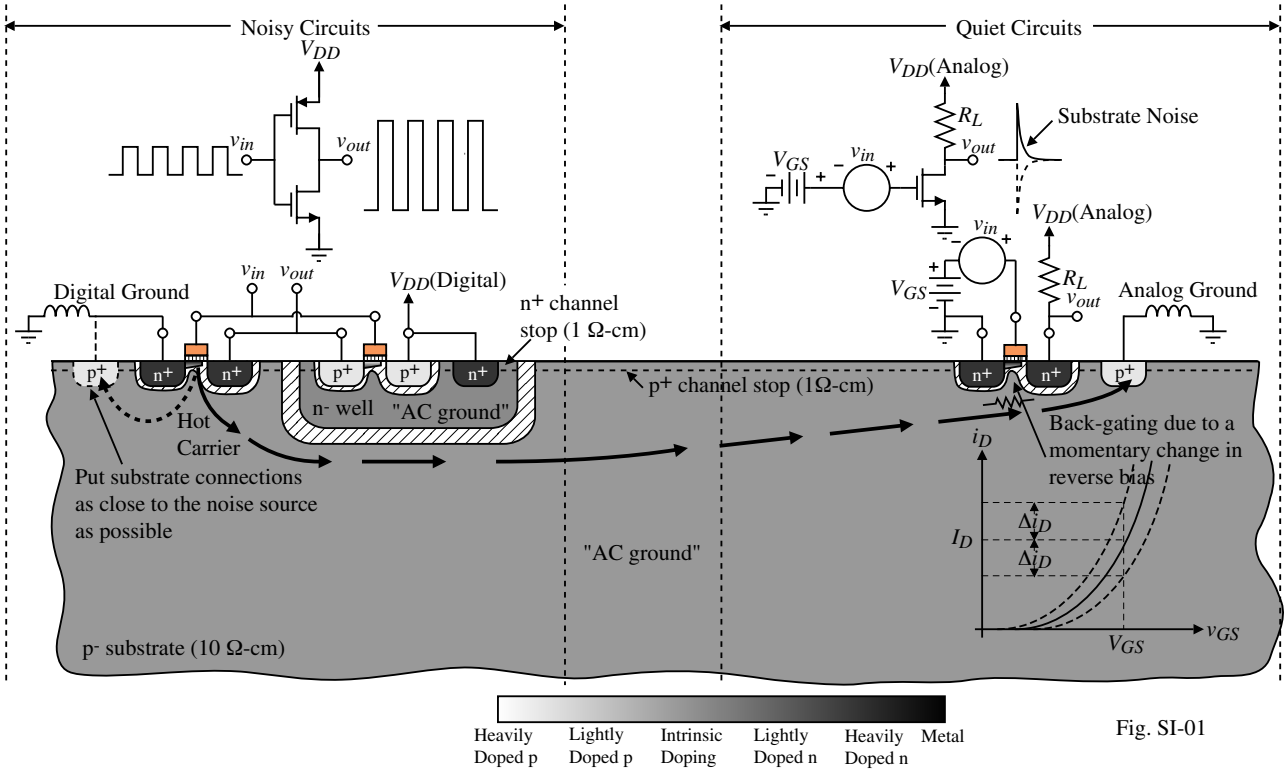

Fig. SI-01

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Hot Carrier Injection in CMOS Technology with an Epitaxial Region

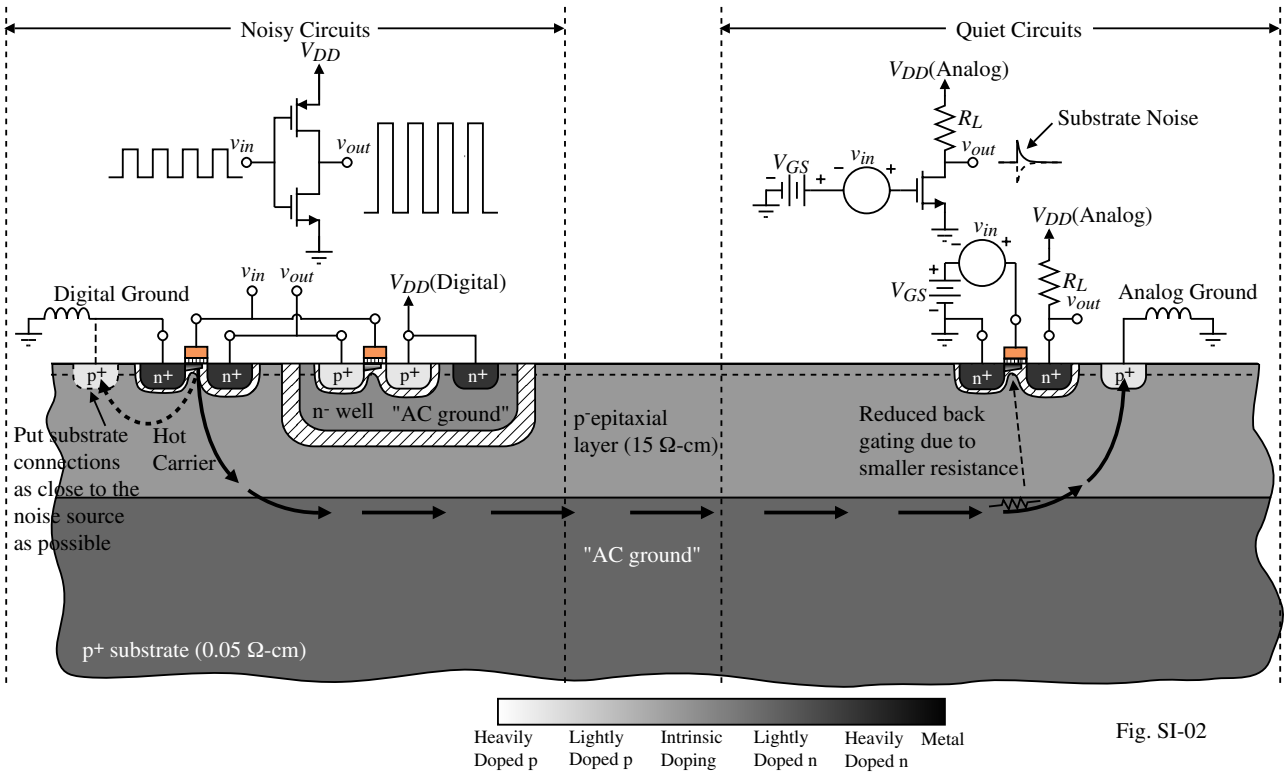

Fig. SI-02

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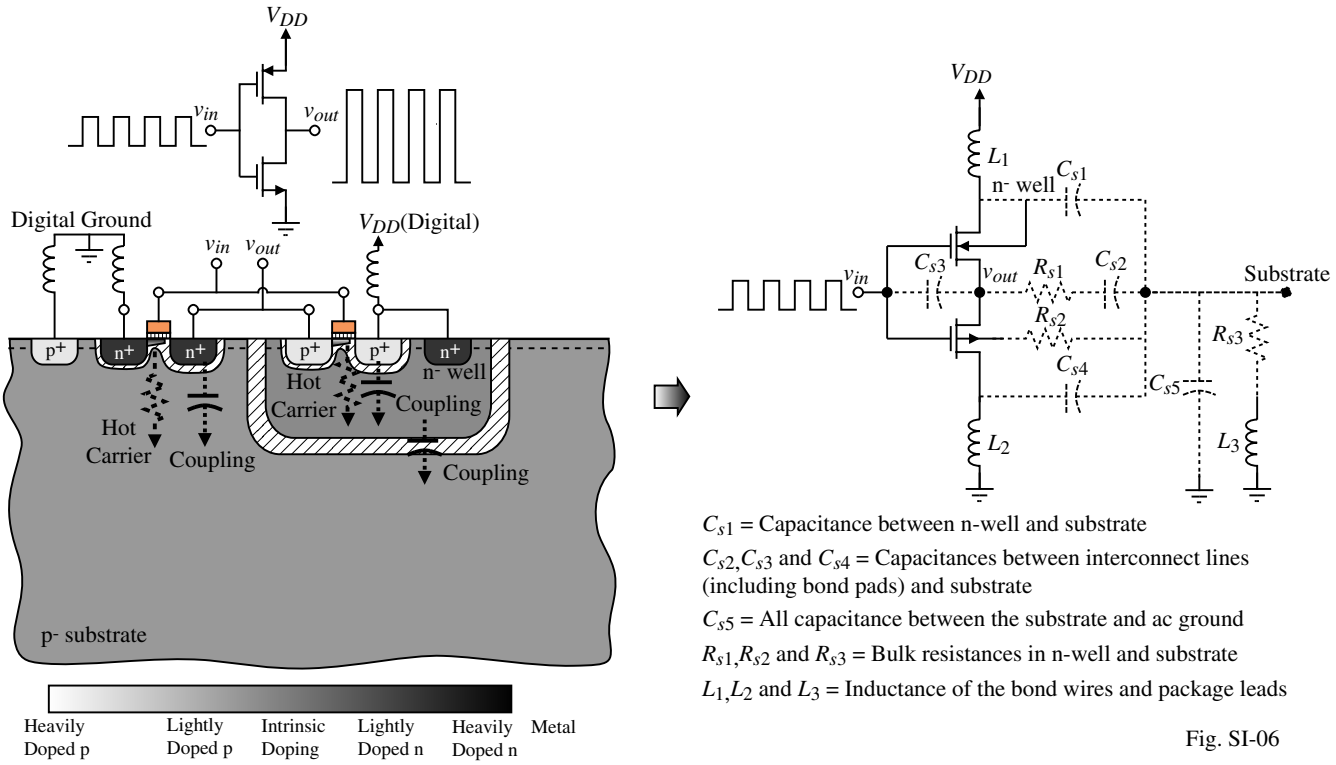
Computer Model for Substrate Interference Using SPICE Primitives

Noise Injection Model:



C_{s1} = Capacitance between n-well and substrate

C_{s2},C_{s3} and C_{s4} = Capacitances between interconnect lines (including bond pads) and substrate

C_{s5} = All capacitance between the substrate and ac ground

R_{s1},R_{s2} and R_{s3} = Bulk resistances in n-well and substrate

L_1,L_2 and L_3 = Inductance of the bond wires and package leads

Fig. SI-06

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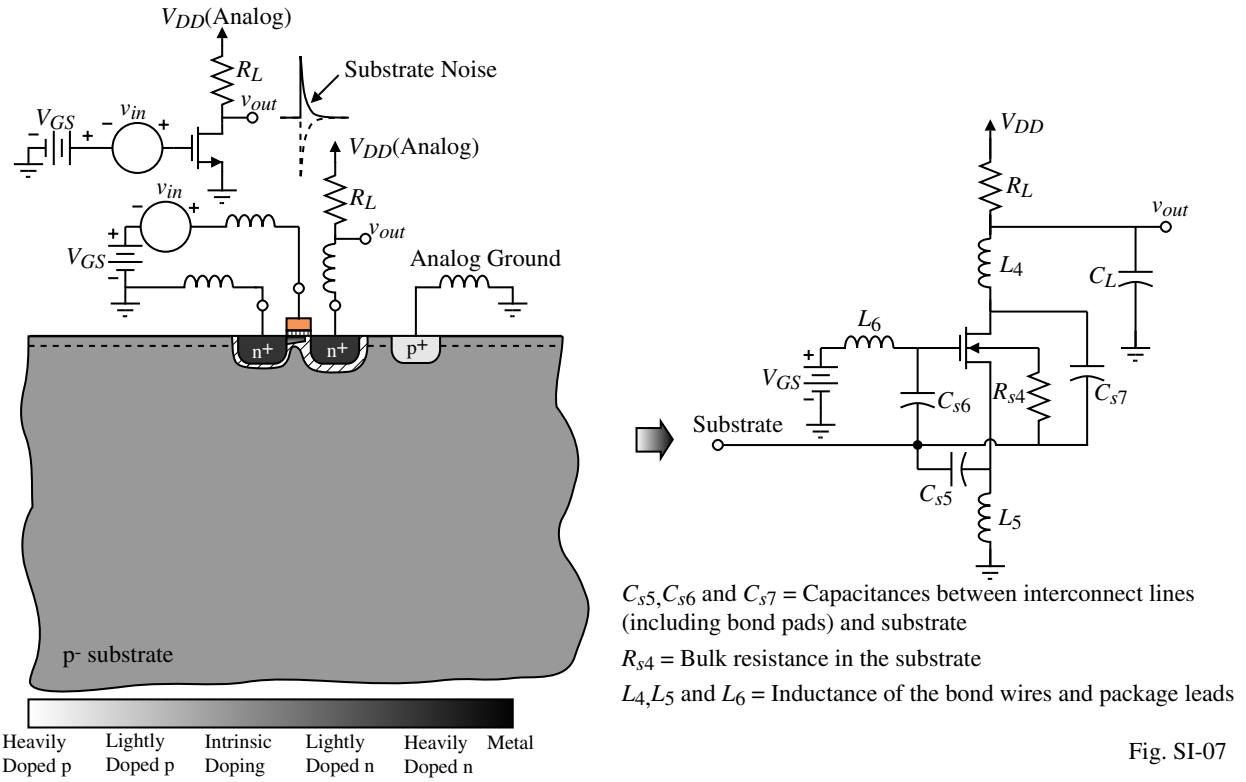
Computer Model for Substrate Interference Using SPICE Primitives

Noise Detection Model:



C_{s5},C_{s6} and C_{s7} = Capacitances between interconnect lines (including bond pads) and substrate

R_{s4} = Bulk resistance in the substrate

L_4,L_5 and L_6 = Inductance of the bond wires and package leads

Fig. SI-07

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Other Sources of Substrate Injection

(We do it to ourselves and can't blame the digital circuits.)

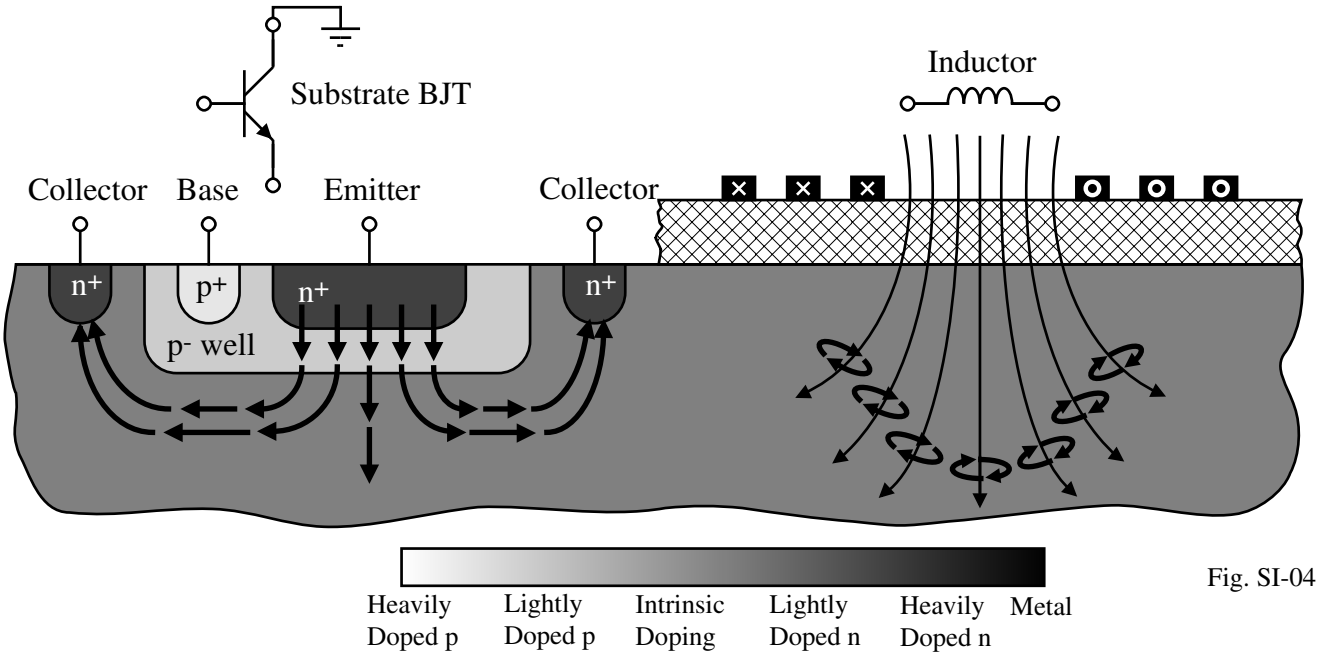

Fig. SI-04

Also, there is coupling from power supplies and clock lines to other adjacent signal lines.

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What is a Good Ground?

- On-chip, it is a region with very low bulk resistance.

  It is best accomplished by connecting metal to the region at as many points as possible.

- Off-chip, it is all determined by the connections or bond wires.

  The inductance of the bond wires is large enough to create significant ground potential changes for fast current transients.

  $$v = L\frac{di}{dt}$$

  Use multiple bonding wires to reduce the ground noise caused by inductance.

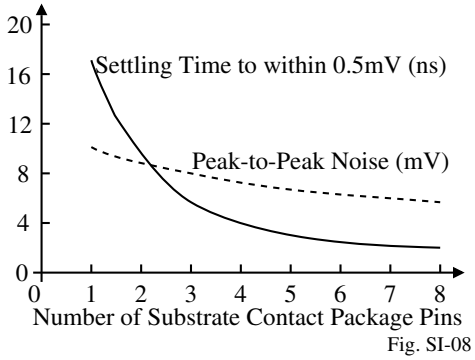

Fig. SI-08

- Fast changing signals have part of their path (circuit through ground and power supplies. Therefore bypass the off-chip power supplies to ground as close to the chip as possible.

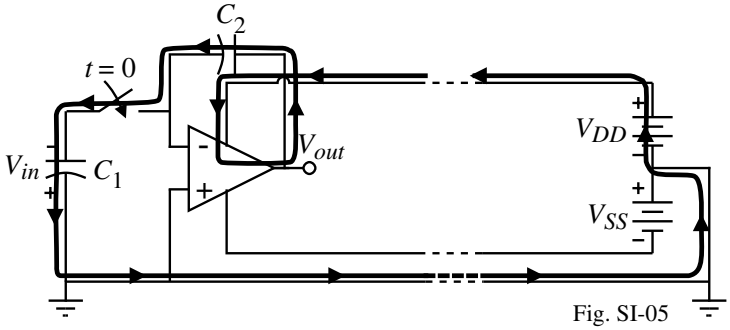

Fig. SI-05

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Summary of Substrate Interference

- Methods to reduce substrate noise
  1.) Physical separation
  2.) Guard rings placed close to the sensitive circuits with dedicated package pins.
  3.) Reduce the inductance in power supply and ground leads (best method)
  4.) Connect regions of constant potential (wells and substrate) to metal with as many contacts as possible.
- Noise Insensitive Circuit Design Techniques
  1.) Design for a high power supply rejection ratio (PSRR)
  2.) Use multiple devices spatially distinct and average the signal and noise.
  3.) Use "quiet" digital logic (power supply current remains constant)
  4.) Use differential signal processing techniques.
- Some references

1.) D.K. Su, M.J. Loinaz, S. Masui and B.A. Wooley, "Experimental Results and Modeling Techniques for Substrate Noise in Mixed-Signal IC's," *J. of Solid-State Circuits*, vol. 28, No. 4, April 1993, pp. 420-430.

2.) K.M. Fukuda, T. Anbo, T. Tsukada, T. Matsuura and M. Hotta, "Voltage-Comparator-Based Measurement of Equivalently Sampled Substrate Noise Waveforms in Mixed-Signal ICs," *J. of Solid-State Circuits*, vol. 31, No. 5, May 1996, pp. 726-731.

3.) X. Aragones, J. Gonzalez and A. Rubio, *Analysis and Solutions for Switching Noise Coupling in Mixed-Signal ICs*, Kluwer Acadmic Publishers, Boston, MA, 1999.

(To be continued)