Topics in Integrated Circuit Design (Wireline Transceiver Design)
School of Electrical Engineering and Computer Science
Seoul National University

Fall 2020 D.K. Jeong

Final Exam

Dec. 7, 11:00 am-1:00 pm (in-class test)

Dec. 7, 1:00pm-Dec. 8, 11:00 am (take-home test, hand in to TA in the Room 218, Bldg. 104-1.)

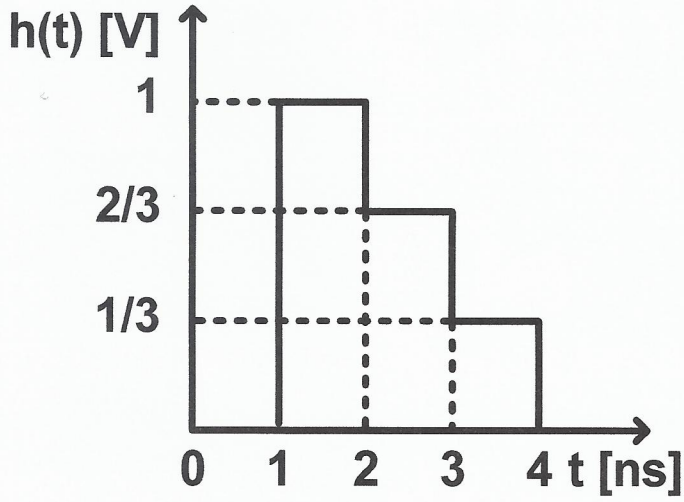
Books, notes, and tablets allowed in class.,

Take-home test 에 타인과 상의하지 않았음을 서약합니다.

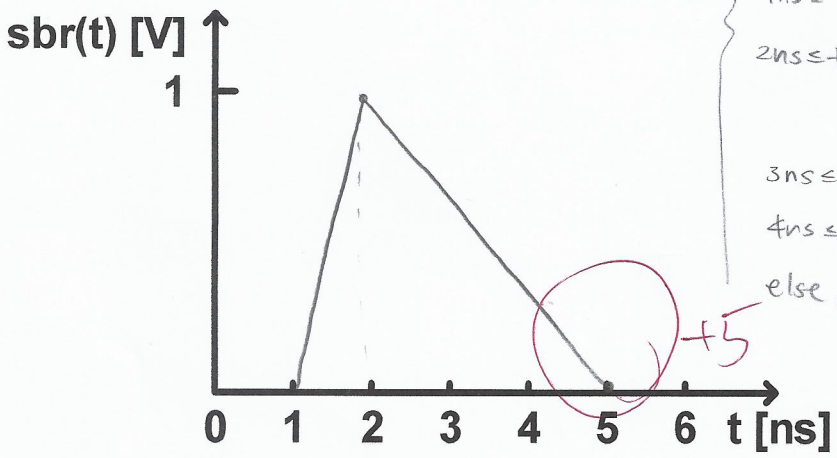
Name: 이윤노 Signature: 이윤노

Check one: In-Class Test ( ) Take-Home Test (✓)	
Problem	Score
1	35 /35
2	15 /15
3	25 /25
4	20 /20
5	33 /35
Total	/130

1. Answer the questions on the channel with the following impulse response to a delta function (1nV)·δ(t).



A. Draw a single-bit response (1-bit, 1V-rectangular pulse) of a 1-Gbps NRZ transmission. (5 points)



$1ns \le t < 2ns$, $\int_1^t h(\tau)d\tau = t-1$

$2ns \le t < 3ns$, $\int_{t-1}^2 h(\tau)d\tau + \int_2^t h(\tau)d\tau = -\frac{1}{3}t + \frac{5}{3}$

$3ns \le t < 4ns$, $-\frac{1}{3}t + \frac{5}{3}$

$4ns \le t < 5ns$, $-\frac{1}{3}t + \frac{5}{3}$

else, 0.

+5

B. What is the gain at the DC and at the Nyquist frequency including the effect of the ZOH of the rectangular pulse? (5 points)

input : 1 1 1 1 ... 일 때, output : 2 2 2 2 ...

input : 1 -1 1 -1 ... 일 때, output : $\frac{2}{3}$ $-\frac{2}{3}$ $\frac{2}{3}$ $-\frac{2}{3}$ ...

$(1+\frac{2}{3}+\frac{1}{3}) = 2$, $(1-\frac{2}{3}+\frac{1}{3}) = \frac{2}{3}$ $(-1+\frac{2}{3}-\frac{1}{3}) = -\frac{2}{3}$

+5

∴ gain at DC = 2 = 6dB, gain at Nyquist freq = $\frac{2}{3}$ = (-3.52 dB)

C. Find C_0 and C_1 of an TX FIR filter that minimize the mean square value of ISI. Assume that main cursor is maximized. (5 points)

$$H(z) = 1 + \frac{2}{3}z^{-1} + \frac{1}{3}z^{-1}, \quad C(z) = C_0 + C_1 z^{-1}$$

$$H(z)\cdot C(z) = C_0 + \left(C_1 + \frac{2}{3}C_0\right)z^{-1} + \left(\frac{1}{3}C_0 + \frac{2}{3}C_1\right)z^{-2} + \frac{1}{3}C_1 z^{-1}$$

$\rightarrow \left(C_1 + \frac{2}{3}C_0\right)^2 + \left(\frac{1}{3}C_0 + \frac{2}{3}C_1\right)^2 + \left(\frac{1}{3}C_1\right)^2$ 이 최소 ,, where $|C_0| + |C_1| = 1$

$$\therefore C_0 = \frac{22}{35}, \quad C_1 = -\frac{13}{35}$$ +5

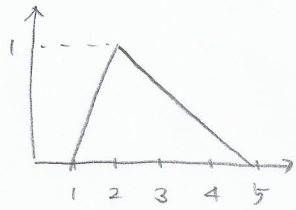
D. What is the desired location of the zero of a CTLE for the flat response at the Nyquist frequency? (5 points)

loss at Nyquist frequency $= 6\,dB - (-3.52\,dB)$
$= 9.52\,dB$

$$20 \log \frac{500M}{f_z} = 9.52$$

$$\therefore f_z = 167\ MHz$$ +5

E. When an Alexander PD is used in the PLL-based timing loop, what is the optimum coefficient of a 2-tap DFE for the maximum eye height? Assume no edge equalization. (5 points)



$t_0 - 1 = -\frac{1}{3}(t_0 + 1) + \frac{5}{3}$ ($h_{-\frac{1}{2}} = h_{\frac{1}{2}}$ 로 구하면.)

$t_0 = \frac{7}{4}$ ns.

$\Rightarrow$ (main cursor 위치) $= \frac{7}{4}$ns $+ \frac{1}{2}$ns $= \frac{9}{4}$ns.

이 때, $h_0 = \frac{11}{12}$, $h_1 = \frac{7}{12}$, $h_2 = \frac{3}{12} = \frac{1}{4}$

$\therefore$ optimum coefficient of a 2-tap DFE $(h_1, h_2) = \left(\frac{7}{12}, \frac{1}{4}\right)$

F. How much gain boost at the Nyquist is expected with 2-tap DFE coefficient derived E? (5 points)

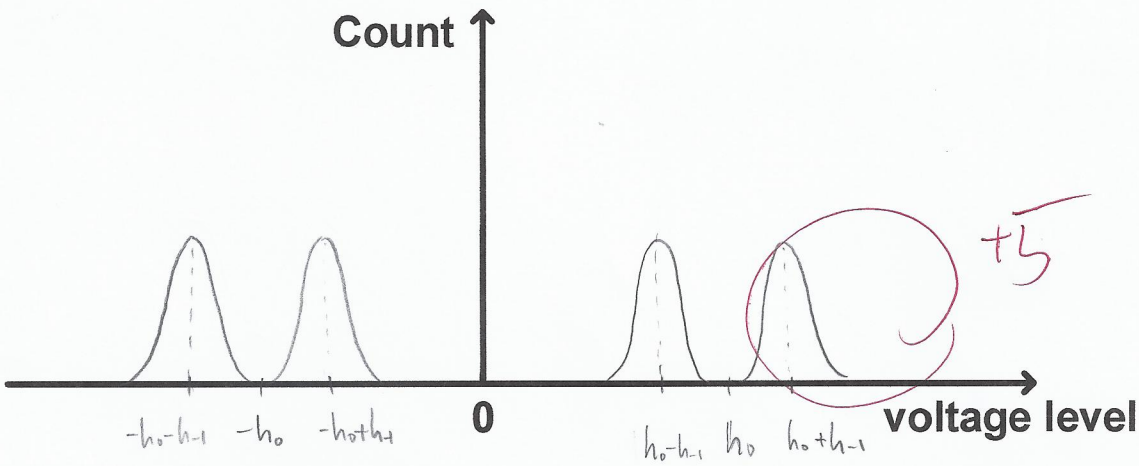
$$\text{Gain} = \frac{1}{\left| h_{-1} e^{j\omega T} + h_0 + h_1 e^{-j\omega T} + h_2 e^{-j2\omega T} \right|}$$

$$\therefore \text{gain boosting} = \frac{|h_{-1} + h_0 + h_1 + h_2|}{|-h_{-1} + h_0 - h_1 + h_2|} = \frac{\left|\frac{1}{4} + \frac{11}{12} + \frac{7}{12} + \frac{1}{4}\right|}{\left|-\frac{1}{4} + \frac{11}{12} - \frac{7}{12} + \frac{1}{4}\right|}$$

$$= 6 = 15.56 \text{ (dB)}$$

+5

G. Sketch a histogram at sampling point for a equalized signal with 2-tap DFE with coefficient derived E. Assume that Gaussian noise is small enough. (5 points)

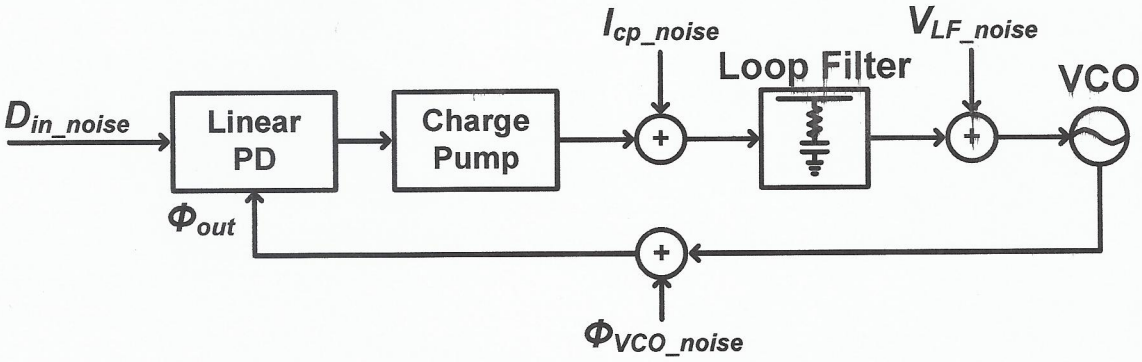


+5

$h_0 = \frac{11}{12}$, $h_{-1} = \frac{1}{4}$

$$\Rightarrow \begin{cases} h_0 - h_{-1} = \frac{8}{12} = \frac{2}{3} \\ h_0 + h_{-1} = \frac{14}{12} = \frac{7}{6} \end{cases}$$

2. For the following PLL-based CDR for 1Gbps bandwidth, assume linear PD gain (K_{PD}) of 1, charge-pump current (I_{cp}) of 40 uA, loop filter resistor (R_{LF}) of 500 Ω, loop filter capacitor (C_{LF}) of 5 nF and VCO gain (K_{VCO}) of 0.5 GHz/V. Beware of units.



A. Find the open-loop gain H(s) and damping ratio ξ. (5 points)

$$H(s) = K_{PD} \cdot \frac{I_{cp}}{2\pi} \cdot \left(R + \frac{1}{sC}\right) \cdot \frac{2\pi K_{VCO}}{s}$$

$$= 1 \times \frac{40 \times 10^{-6}}{2\pi} \times \left(500 + \frac{1}{s \times 5 \times 10^{-9}}\right) \cdot \frac{2\pi \times 0.5 \times 10^{9}}{s}$$

$$= \frac{4 \times 10^{12} + 10^{7} \times s}{s^2}$$

$$\zeta = \frac{\sqrt{I_{cp} \cdot 2\pi \cdot K_{VCO} C} \cdot R}{2\sqrt{2\pi}} = \frac{\sqrt{40 \times 10^{-6} \times 2\pi \times 0.5 \times 10^{-9} \times 5 \times 10^{-9}} \times 500}{2\sqrt{2\pi}}$$

$$= 2.5$$

B. Derive the transfer functions using H(s) for following input noise. Draw the Bode plot. (10 points)

(a) $\dfrac{\phi_{out}}{D_{in_{noise}}} = \dfrac{H(s)}{1+H(s)}$

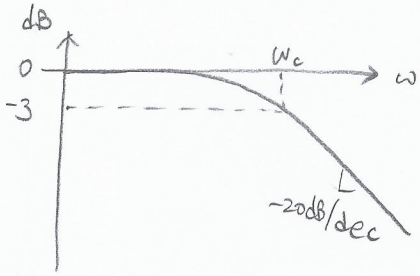
(b) $\dfrac{\phi_{out}}{I_{CP_{noise}}} = \dfrac{H(s)}{1+H(s)} \cdot \dfrac{2\pi}{I_p}$

(c) $\dfrac{\phi_{out}}{V_{LF_{noise}}} = \dfrac{H(s)}{1+H(s)} \cdot \dfrac{2\pi}{I_p} \cdot \dfrac{1}{R+\frac{1}{sC}} = \dfrac{1}{1+H(s)} \cdot \dfrac{2\pi \cdot K_{VCO}}{s}$

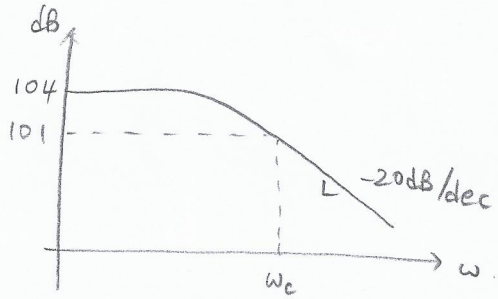
(d) $\dfrac{\phi_{out}}{\phi_{VCO_{noise}}} = 1 - \dfrac{H(s)}{1+H(s)} = \dfrac{1}{1+H(s)}$

$$\omega_c = \omega_0 \cdot \sqrt{1+2\zeta^2+2\sqrt{\zeta^4+\zeta^2+\frac{1}{2}}}$$
$$= 10.4\ \mu\ (\text{rad/s})$$

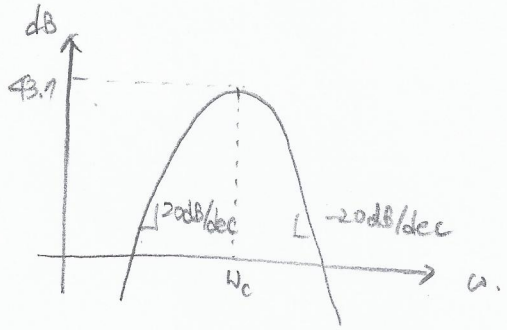
(a)



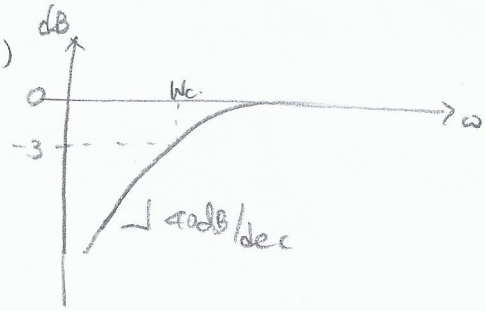
(b)



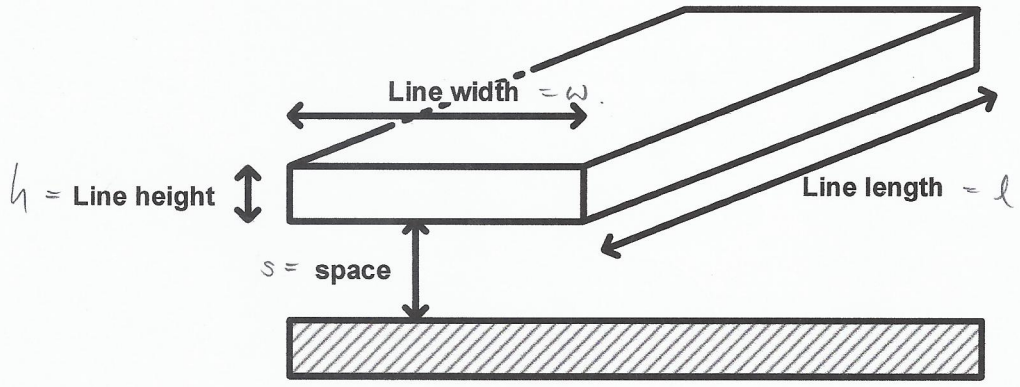
(c)



(d)



3. Goal is to sketch the attenuation characteristic for the following "microstrip" copper line with FR-4 medium of $e_r = 4.0$. [Line width – 200 um, line height – 20 um, space – 100um, line length = 1m, loss tangent = 0.01]



$$\rho = 1.7 \cdot 10^{-8}\ \Omega\ , e_0 = 8.854 \cdot 10^{-12}\ F/m\ , \mu_0 = 4\pi \cdot 10^{-7}\ H/m$$

A. What is its capacitance, DC resistance, inductance per meter? (5 points)

$$C = \frac{\varepsilon_r \cdot l \left[w/s + 1.393 + 0.667 \cdot \ln\left(\frac{w}{s} + 1.444\right) \right]}{120\pi v_0} = 1.493 \times 10^{-10}\ (F/m)$$

$$v_0 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8\ m/s.$$

$$L = \frac{\varepsilon_0 \varepsilon_r \mu_0}{C} = 2.98 \times 10^{-7}\ (H/m)$$

$$R_{DC} = \rho \cdot \frac{l}{wh} = 4.25\ (\Omega/m)$$

+5

B. What is its characteristic impedance Z_0? (5 points)

$$Z_0 = \sqrt{\frac{L}{C}} = 44.1\ (\Omega)$$

+5

C. Calculate the skin effect frequency f_s. (5 points)

skin effect frequency $f_s = \dfrac{t}{\pi \mu_0 \sigma \cdot h^2}$

$= \dfrac{4\rho}{\pi \mu_0 \cdot h^2}$

$= 1.12$ MHz +5

D. Find out the equation for the attenuation and sketch the attenuation in [dB] vs log f. (5 points)

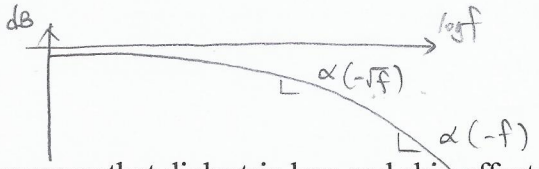
$R_{AC} = \dfrac{L\sqrt{\rho \pi \mu f}}{\text{width}} = 0.0013\sqrt{f}$

$G_{AC} = \omega C \tan\delta = 9.36 \times 10^{-12} \cdot f$

skin effect attenuation $= \dfrac{R_{AC}}{2Z_0} = 1.45 \times 10^{-5} \cdot \sqrt{f}$

dielectric loss attenuation $= \dfrac{G_{AC} Z_0}{2} = 2.09 \times 10^{-10} f$

+5



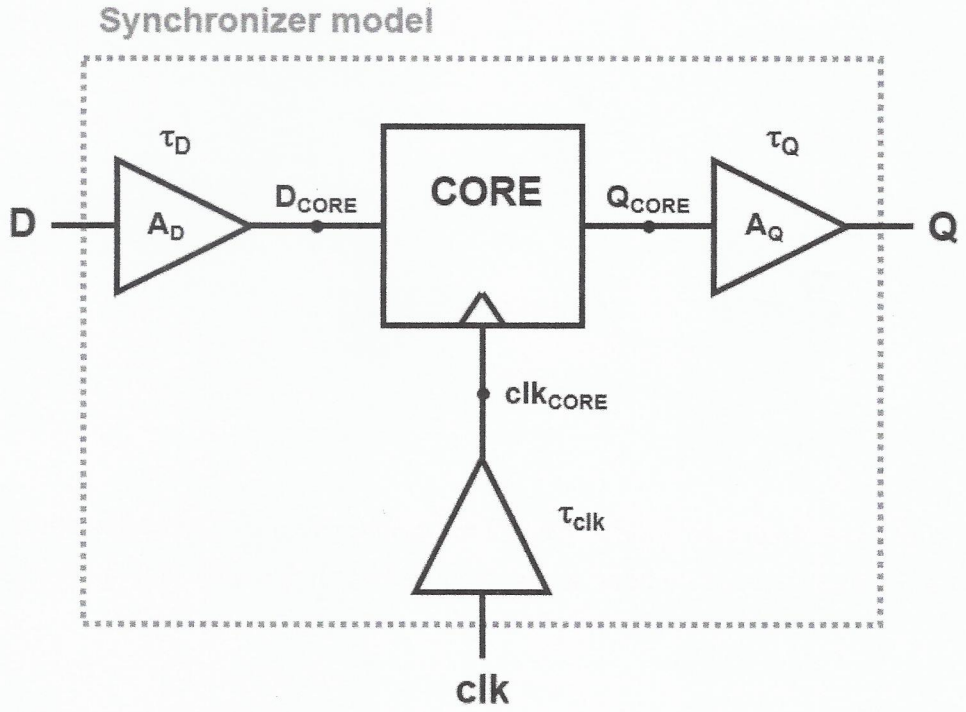
E. Find the frequency that dielectric loss and skin effect loss are the same. (5 points)

$1.45 \times 10^{-5}\sqrt{f} = 2.09 \times 10^{-10} f$

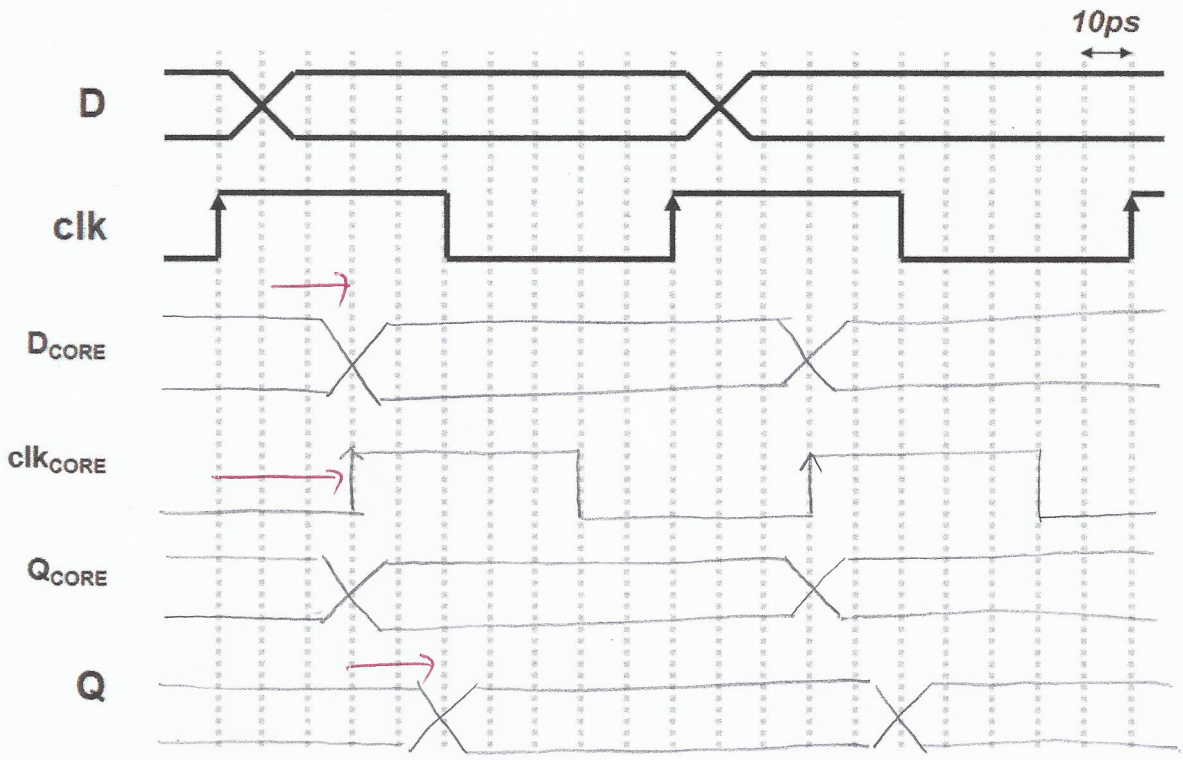
∴ 같아지는 frequency $= 4.82$ GHz.

+5

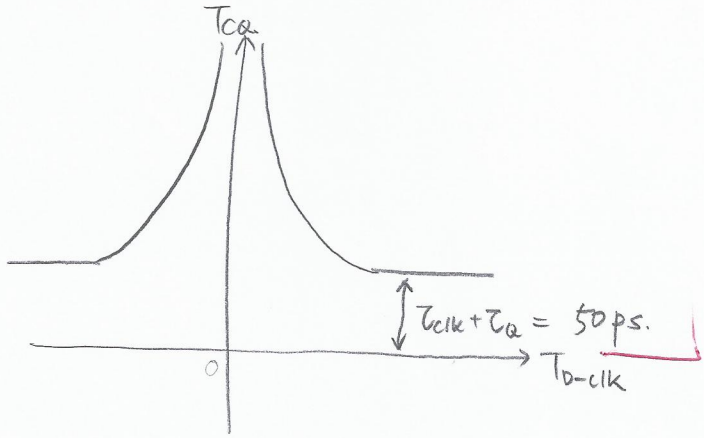
4. For the following basic model of a synchronizer, assume $\tau_D = \tau_Q = 20$ ps, $\tau_{clk} = 30$ ps, $A_D = A_Q = 6$ dB, clk frequency = 10 GHz and rise/fall time of D = 15 ps. Beware of units.



(a) Draw the waveform of D_{CORE}, Q_{CORE}, clk_{CORE} and Q when close to metastability. (5 points)



(b) Draw the curve of T_{CQ} (clk-to-Q delay) vs. $T_{D\text{-}clk}$. (Note that $T_{D\text{-}clk}$ is the time difference between the transitions of D_{CORE} and clk_{CORE}.) (5 points)



(c) When the values of the curve obtained in (b) are as follows, calculate the time period of forbidden sampling window. (Note that forbidden sampling window means "setup time + hold time".) (5 points)

- $T_{CQ} = 0.15$ns at $T_{D\text{-}clk} = 0.5$ps
- $T_{CQ} = 0.1$ns at $T_{D\text{-}clk} = 2$ps

$$T(\Delta t) = \tau_{clk} + \tau_Q + \max\left(\tau \ln\left(\frac{t_r}{A_Q A_D \Delta t}\right), 0\right)$$

when $T(\Delta t) = \tau_{clk} + \tau_Q$, $\underbrace{T_{D\text{-}clk}}_{\Delta t} \geq \frac{t_r}{A_Q A_D} = 3.75$ ps.

$$\therefore T_{\text{forbidden sampling window}} = 2 \times 3.75 \text{ ps} = 7.5 \text{ ps.}$$

(d) Calculate the error probability at Q node. (5 points)

$$\text{Prob}(\text{Error @ Q}) = \frac{\frac{2t_r}{A_D A_Q} e^{(\tau_{clk} + \tau_Q - (T_{period} + \tau_{clk} - \tau_D))/\tau}}{T_{period}}$$

(c)의 두 사이에서,

$$\tau_{clk} + \tau_Q + \tau \ln\left(\frac{t_r}{A_D A_Q \Delta t_1}\right) = t_{D1}$$

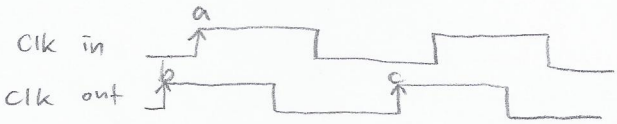
$$\tau_{clk} + \tau_Q + \tau \ln\left(\frac{t_r}{A_Q A_D \Delta t_2}\right) = t_{D2}$$

$$\Rightarrow \tau = \frac{t_{D1} - t_{D2}}{\ln(\Delta t_2/\Delta t_1)} = \frac{0.05n}{\ln(2p/0.5p)} = 0.036 \text{ (ns)}$$

$$\therefore \text{Prob}(\text{Error @ Q}) = \frac{\frac{30ps}{4} \cdot e^{-2}}{100 ps} \approx 0.014$$

5. 다음 각각의 문제에 대해 설명하시오. (Internet 에서 copy 하지 말고 나름대로 설명할 것)

a. DLL 에 PD 대신 PFD 를 사용할 경우 문제점은? (5 points)



DLL의 경우 a와 c를 비교해야 하는데,
PFD를 사용하면 a와 b를 비교하게 된다.
이 경우 stuck problem 문제가
생길 수 있다.

b. DLL 의 harmonic locking 문제를 개선하기 위한 방법을 설명하시오. (5 points)

multi phase를 이용하여 harmonic lock을 detection 한다.
harmonic lock을 detection 했을 때 PFD를 reset 시켜
원하는 lock point로 갈 수 있도록 initialize 해준다.

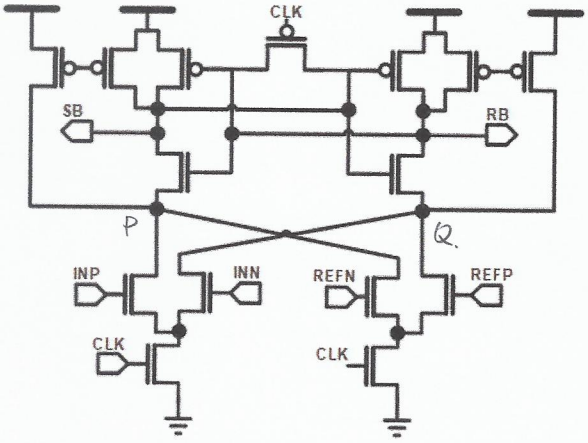
c. Optical receiver interface 에서 Si 을 사용하는 시도에 대한 장단점을 기술하시오. (5 points)

Si를 사용하면 Si공정과 같이 이용할 수 있기 때문에 공정상 이점이
존재한다. 결과적으로는 저렴한 Cost로 사용가능하다.
하지만 wave length가 큰 경우 absorption 계수가 낮기 때문에
사용하기 어렵다. 그 경우 Ge과 같은 대체 물질을 쓰곤 한다.

-1

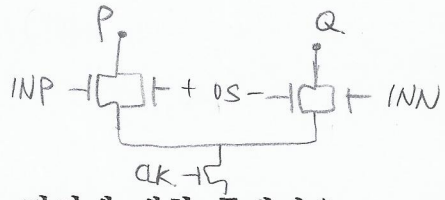
Good crystallinity required for optical propagation

d. **다음의** Strong arm latch **의** offset compensation **방법에 대해 두 가지 이상 설명하시오.** (5 points)



① P, Q node 에 charge difference 를 보상해주는 control 가능한 capactor를 연결해준다.

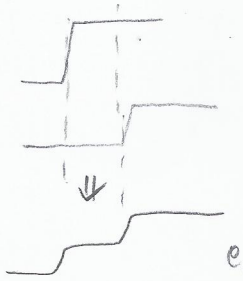
② input transistor 의 Vth mismatch 에 의한 strength를 보상해줄 수 있도록 offset compensation transistor를 달아준다.



e. Phase interpolator **의** input slew rate **를 높이거나 낮추는 경우, 각각에 대한 문제점은? 그리고 그러한 문제가 발생하는 이유에 대해 설명하시오.** (5 points)

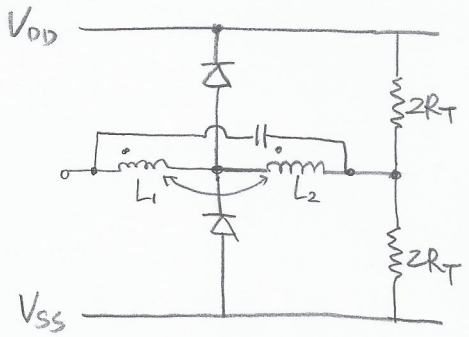
input slew rate를 너무 높이면 phase interpolation이 제대로 이루어지지 않는다. 이 경우 INL, DNL 특성이 안 좋아진다.

반대로 input slew rate 가 너무 낮으면 random jitter에 취약해지는 단점이 있다. → $\Delta t(\text{jitter}) \propto \frac{1}{\text{slew}}$ 이기 때문에.

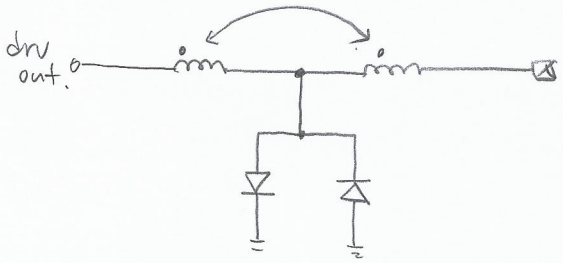


와 같은 output이 나타나게 됨.

f. T-coil 을 input buffer 와 output driver 에 사용할 때의 회로를 각각 그리시오. T-coil 을 사용하여 얻을 수 있는 유용한 특성을 2 가지 이상 기술하시오. (5 points)



<input buffer>



< output driver >

T-coil 을 사용하면 bandwidth extension 이 가능하다.

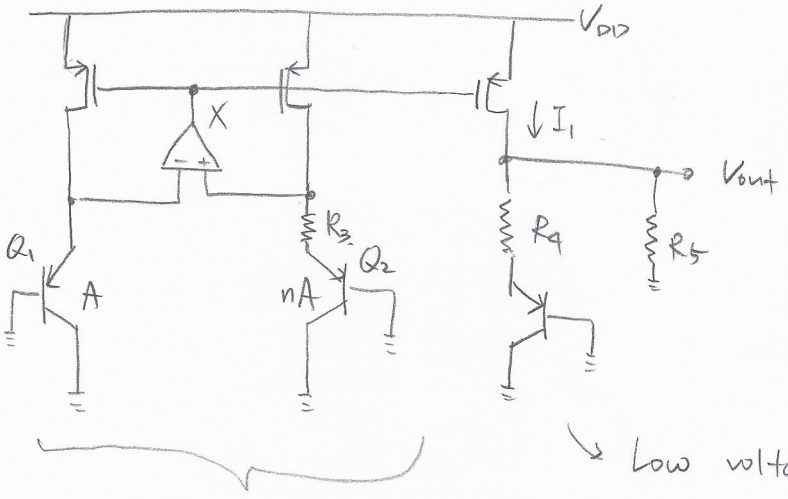
ESD protection 에 더 유리하게 사용할 수 있다.

?

-1

return loss 최소화

g. Low voltage (e.g. 1.0V) bandgap reference 를 만드는 방법을 그림과 함께 설명하시오. 그리고 해당 회로에서 start up 이 필요한 이유는 무엇인가? (5 points)



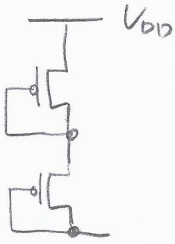
I_1 generation circuit

Low voltage reference 를 위한 circuit

$$V_{out} = \frac{R_5}{R_4+R_5}\left(V_{BE3} + \frac{R_4}{R_3} V_T \ln n\right)$$

node X 가 VDD 가 되면 PMOS 가 꺼져서, 제대로 동작이 이루어질 수 없다.

따라서 start up 이 필요하게 된다.



<End of Final exam>