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(2-page formula sheet,  
 calculator)

--- Answer all questions in the space provided. Use appropriate assumptions if needed ----

**Questions 1: (20marks)**

An op-amp has the following open-loop transfer function:

$$A(j\omega) = \frac{v_{out}}{v_{in}} = \frac{10^5}{(1 + j\frac{\omega}{\omega_1})(1 + j\frac{\omega}{\omega_2})(1 + j\frac{\omega}{\omega_3})}$$

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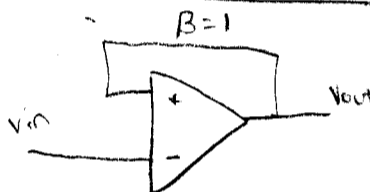
where  $\omega_1 = 100\text{rad/s}$ ,  $\omega_2 = 10^3\text{krad/s}$ , and  $\omega_3 = 10^5\text{krad/s}$ .

- i. If the op-amp is connected in a unity positive feedback configuration. What is the output frequency of the op-amp?

$$A(j\omega) = \frac{10^5}{(1 + j\frac{\omega}{100})(1 + j\frac{\omega}{10^6})(1 + j\frac{\omega}{10^8})}$$

note:  $10^3\text{ krad/s} = 10^6\text{ rad/s}!$

unity feedback:



$$A_{180} \approx \frac{10^5}{(1 + j\frac{10^3}{100})(1 + j\frac{10^3}{10^6})(1 + j\frac{10^3}{10^8})}$$

$$A_{180} \approx 0.1$$

$$B = 10$$

$$A_{180} B \leq 1$$

$$A_{fb} = \frac{A}{1 - AB}$$

$$= \frac{10^5}{(1 + j\frac{\omega}{100})(1 + j\frac{\omega}{10^6})(1 + j\frac{\omega}{10^8})}$$

$$1 - \frac{10^5}{(1 + j\frac{\omega}{100})(1 + j\frac{\omega}{10^6})(1 + j\frac{\omega}{10^8})}$$

$$\omega = 4635\text{ rad/s} = 737.68\text{ Hz}$$

- ii. If the op-amp is to be connected in a negative feedback configuration. What is the maximum feedback coefficient that can be tolerated before instability results? What is the minimum closed-loop gain of this op-amp without oscillation?

$$A_o B \leq 1 \quad (\text{for stability})$$

$$B = \frac{1}{A_o}$$

$$B = \frac{10^5}{(1 + j\frac{\omega}{100})(1 + j\frac{\omega}{10^6})(1 + j\frac{\omega}{10^8})}$$

$\omega = \text{operating frequency}$

$$B = .0004636 \quad \text{max } B$$

min  $B$ :

$$-180^\circ = -\tan^{-1}\left(\frac{\omega}{100}\right) - \tan^{-1}\left(\frac{\omega}{10^6}\right) - \tan^{-1}\left(\frac{\omega}{10^8}\right)$$

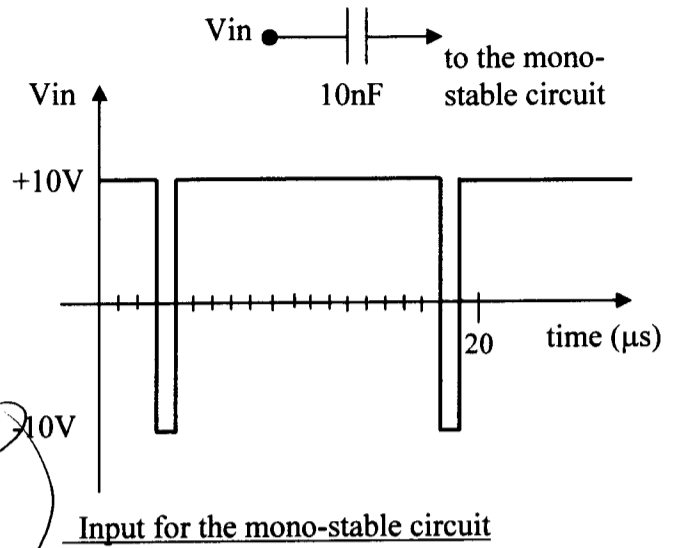
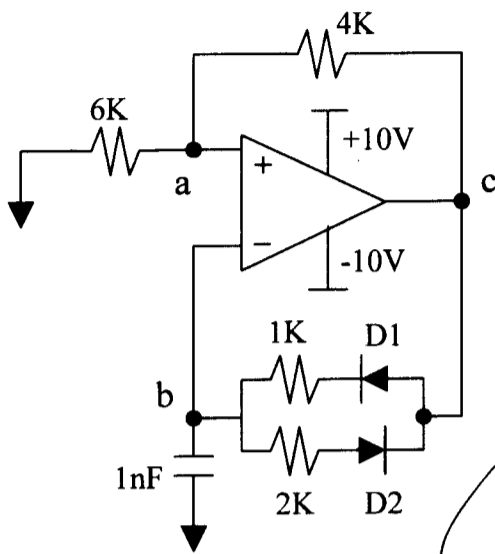
solve using TI:  $\omega = 1 \times 10^7 \text{ rad/s}$

$$B = \left| \frac{(1 + j\frac{10^7}{100})(1 + j\frac{10^7}{10^6})(1 + j\frac{10^7}{10^8})}{10^5} \right|$$

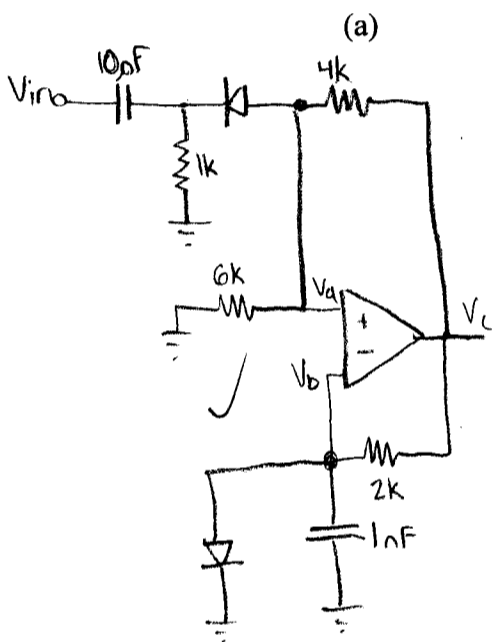
$B = 10.10$   $\leftarrow$  should be smaller, for no oscillation to occur

**Question 2: (15marks)**

Using the circuit (a) shown below, without adding or deleting any component, re-arrange the circuit to make it function as a mono-stable circuit. Connect your circuit to the input  $V_{in}$  given in (b), sketch the waveforms at the op-amp terminals a, b, c of your modified circuit (i.e., the monostable circuit).



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(b) assuming  $V_D = 0.7V$

$$B = \frac{6}{4+6} = .6$$

$$T = (1nF)(2k\Omega) \ln \left( \frac{.7V - (-10V)}{.6(-10V) - (-10V)} \right)$$

$$T_1 = 1.968 \mu s$$

recovery period:

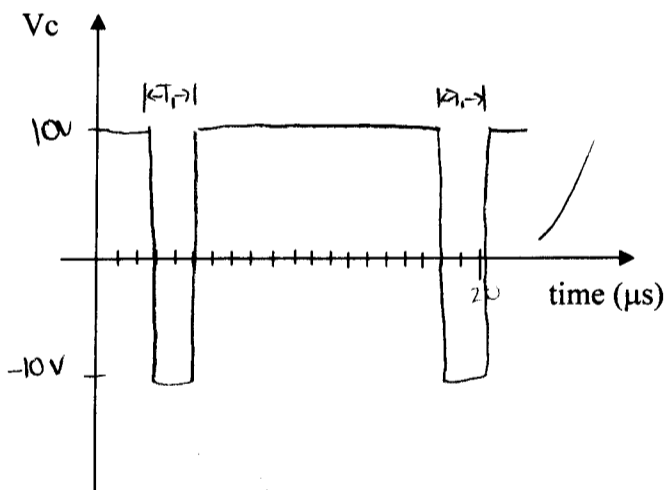
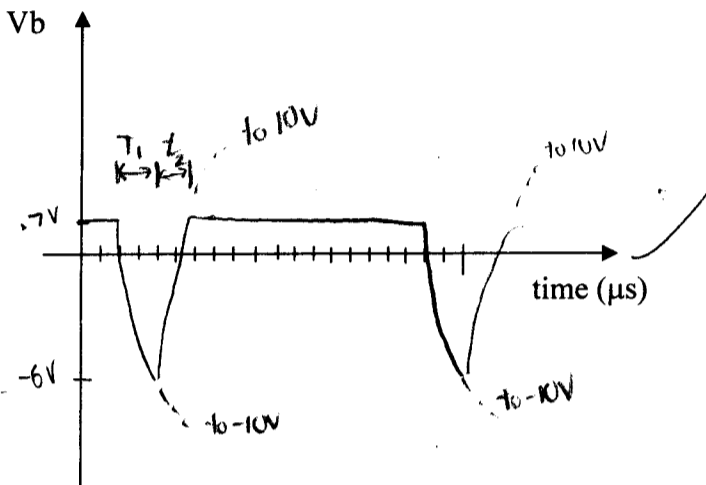
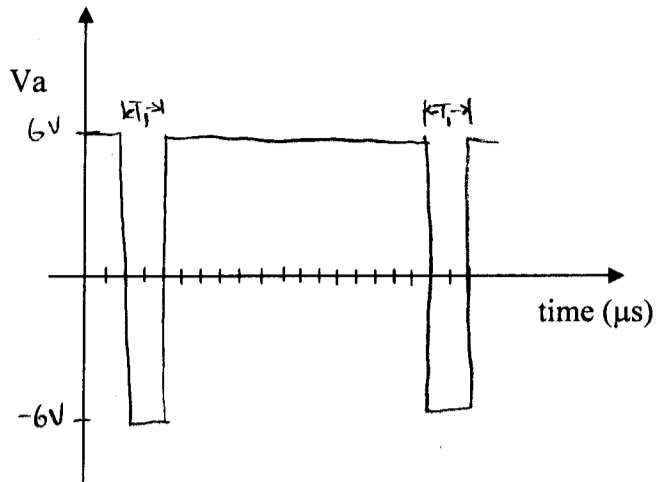
$$V_b = V_F - (V_F - V_i) e^{-t/RC} \quad RC = (1nF)(2k\Omega) = 2 \mu s$$

$$V_b = .7V \quad V_i = -6V \quad V_F = 10V$$

$$t = RC \ln \left( \frac{V_i - V_F}{V_b - V_F} \right)$$

$$t = (2 \mu s) \ln \left( \frac{-10V - 10V}{.7V - 10V} \right)$$

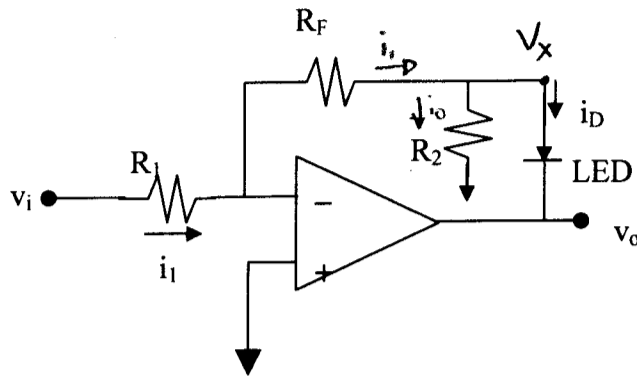
$$t_2 = 1.53 \mu s$$



(Use the other side of the paper if needed)

**Question 3: (10+15 marks)**

- a. The circuit below is used to drive an LED with a voltage source. The circuit can be thought as a current amplifier in that, with the proper design,  $i_D > i_1$ .
- Derive the expression for  $i_D$  in terms of  $i_1$  and the resistors.
  - Design the circuit such that  $i_D = 12\text{mA}$  and  $i_1 = 1\text{mA}$  for  $v_i = 5\text{V}$ .



i)  $i_1 = \frac{v_i}{R_1}$       $V_x = -\frac{v_i R_F}{R_1}$       $i_D = i_1 - i_o$

$i_D = i_1 + i_1 \frac{R_F}{R_2}$

$i_o = \frac{V_x}{R_2}$

$= -\frac{v_i R_F}{R_1 R_2}$

$= -\frac{v_i R_F}{R_1 R_2}$

$v_i = i_1 R_1$ , so

$i_o = -\frac{i_1 R_F}{R_2}$

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ii)  $i_D = 12\text{mA}$   
 $i_1 = 1\text{mA}$   
 $v_i = 5\text{V}$

$R_1 = \frac{v_i}{i_1} = \frac{5\text{V}}{1\text{mA}} = 5\text{k}\Omega$

$12\text{mA} = 1\text{mA} + 1\text{mA} \left(\frac{R_F}{R_2}\right)$

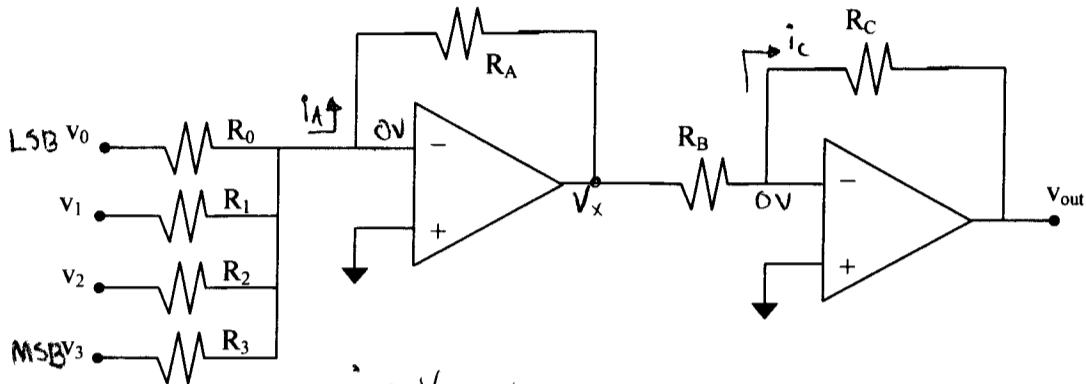
$11\text{mA} = 1\text{mA} \left(\frac{R_F}{R_2}\right)$

$11 = \left(\frac{R_F}{R_2}\right)$

pick:  $R_F = 11\text{k}\Omega$   
 $R_2 = 1\text{k}\Omega$



- b. A digital-to-analog converter can be designed from op-amps using the summation amplifier configuration as shown below. This circuit illustrates the implementation of a 4-bit converter.
- Find an expression for  $v_{out}$  as a function of the inputs  $v_0$  through  $v_3$  and the various resistors.
  - Assume that the voltage  $v_0$  through  $v_3$  have the values of either 5V (logic H) or 0V (logic L). Find the required relationship between resistors  $R_0$  through  $R_3$  if  $v_{out}$  is to represent an analog version of the 4-bit digital word formed by  $v_0$  through  $v_3$  where  $v_0$  is the least significant bit.
  - Choose values for all resistors so that  $v_{out}$  remains within the op-amp saturation limits when all inputs are high (binary word 1111). The minimum permissible resistor value is 1K.



i)

$$i_A = \frac{V_0}{R_0} + \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$V_x = -i_A R_A$$

$$i_c = \frac{V_x}{R_B}$$

$$V_{out} = -i_c R_C$$

$$V_x = -R_A \left( \frac{V_0}{R_0} + \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

$$i_c = -\frac{R_A}{R_B} \left( \frac{V_0}{R_0} + \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

$$V_{out} = \frac{R_A R_C}{R_B} \left( \frac{V_0}{R_0} + \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

ii)  $V_{out}$  needs to be in a form such that each unique input (word) has a unique output ( $V_{level}$ )

MSB  $\rightarrow$  most current ✓  
LSB  $\rightarrow$  least current ✓

$i_3 = 10 \text{ mA}$	$R_3 = \frac{5 \text{ V}}{10 \text{ mA}} = 500 \Omega$
$i_2 = 5 \text{ mA}$	$R_2 = \frac{5 \text{ V}}{5 \text{ mA}} = 1 \text{ k}\Omega$
$i_1 = 2 \text{ mA}$	$R_1 = \frac{5 \text{ V}}{2 \text{ mA}} = 2.5 \text{ k}\Omega$
$i_0 = 1 \text{ mA}$	$R_0 = \frac{5 \text{ V}}{1 \text{ mA}} = 5 \text{ k}\Omega$

iii) Assuming saturation occurs when input current is very high, choose

$R_3 = \frac{5 \text{ V}}{5 \text{ mA}} = 1 \text{ k}\Omega$     $R_2 = \frac{5 \text{ V}}{2 \text{ mA}} = 2.5 \text{ k}\Omega$     $R_1 = \frac{5 \text{ V}}{1 \text{ mA}} = 5 \text{ k}\Omega$

$R_0 = \frac{5 \text{ V}}{0.5 \text{ mA}} = 10 \text{ k}\Omega$

So max current is 8.5 mA

2nd OP-Amp is a basic inverter, so choose  $R_B = R_C = 10k\Omega$

$$i_{max} = 8.5mA$$

$$V_{out} = R_A i_{max}$$

for a max 8.5V signal (easy to read, such as  
on a scope or DVM)

$$R_A = \frac{8.5V}{8.5mA} = 1k\Omega$$

