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# EECS 211

# TA/Professor Laboratory Manual

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# TA Preparation for Experiment #1
# Low-Pass Filters: Step Response vs. Q

Read Experiment #1 write up, and make sure that you understand the time and frequency response of low pass filters. One of the most important thing is that it is better to determine Q from the overshoot value in the time domain response as long as it is below 5. For the high-Q case (Q>5), it is better to determine it using the decay of the ripple peaks. Notice also that the phase at $\omega_0$ ($f_0$) is $-90^\circ$ and that $H(\omega)= KQ$ at this frequency. This is one sure way to determine $\omega_0$; just look at the phase and measure a phase change of $-90^\circ$. Another point is that for the low-Q case, one pole is at $Q\omega_0$ and the other pole is at $\omega_0/Q$. This means that for Q=0.2, one pole is at 0.2 $\omega_0$ and the other pole is at 5 $\omega_0$. Therefore, the first pole (0.2 $\omega_0$) completely dominates the response of the circuit, and the circuit has a first-order (single-pole) response.

The circuit is that of a Sallen Key low-pass filter. The 1µF capacitor is for a DC block and must be used in real measurement. Otherwise, any DC offset from the HP waveform generator will result in a DC offset at the output of the op-amp. The 1µF capacitor is a short circuit at all frequencies of interest, and its corner frequency is given by $f=1/2\pi\,(R_{11}+R_{12})(1\mu F)$. Capacitors $C_1$ and $C_2$ control the poles of the low-pass filter, and the equations are given in the manual. Notice that if the components are chosen for a low-Q filter (that is two very distinct poles), then the first pole at $f_1=1/2\pi\, R_2C_2$ dominates the response and $C_1$ has virtually no effect on the circuit.

The low frequency gain is given by $(1+R_4/R_3)$ multiplied by the input voltage divider composed of $R_{12}$ and $R_{11}$. Notice that $R_{12}$ is essential to the operation of the filter, otherwise there is no dc path from the positive op-amp terminal to ground (and therefore the op-amp will not work).

An important point on the Sallen-Key filter topology is that it can oscillate for high-Q cases. Look at page 39 and see that the denominator factor of (s) can become negative for $R_4>R_3$. Therefore, always choose $R_4<R_3$ (slightly smaller) for stable high-Q systems (assuming that $C_1=C_2$). Since $C_1$ and $C_2$ have around 20% component accuracy, it is also important to choose $C_2 > C_1$ in high-Q systems. Therefore, measure the capacitors, and make sure that they are nearly the same value, but always choose $C_2$ to be slightly larger than $C_1$.

Another point, also available on p. 39-40, is that the filter Q is very sensitive to the component values (in the high-Q case). Do not be surprised to get a measured Q between 4 and 17 in the lab, even if the design is at Q=7.7. If the measured Q is below 4, then change the component values (mostly the capacitors) to get Q in the range specified above. When the students are making the experiment, ask them about their measured high-Q case and again, change one of the capacitors to get $4<Q<17$.

It is time to do the pre-lab for Experiment No. 1. You should know well MATLAB by now and be able to do all the pre-lab problems. Pay attention to problem No. 3. We will be using it for the rest of the term.

Build the circuit now, make the experiment, and take all the date on your laboratory notebook. Make sure that it looks nice since it will be a reference to you and to your students in your section. In the high-Q case, you will find that if you put a square-wave (or a triangular wave, etc…) at $f_0$, it will come out as a sinusoidal signal. The reason is that all of the harmonics are attenuated with the slope of –40 dB/dec. of the high-Q filter.

Make sure that the circuit is not oscillating and that $4<Q<17$ in the high-Q case. If the circuit is oscillating, you will not be able to trigger properly and the output voltage will always move a bit on the screen. Also, you have an output with no input signal (but surely with the circuit biased). You can also look at it in the frequency domain and see the spectrum of oscillation.

The lab report is standard and you should do it while the experiment is fresh on your mind. Problem 2c. is difficult for some students (and for some TA's too!). To calculate $V_{oppk}$, you should do it in the time domain and solve for $V_o(t)$ for at least two cycles until it stabilizes, using the initial conditions at each half-cycle. Problem 4a should not be difficult anymore since you have covered how to calculate $V_0=H(\omega).V_i$ in the preceding lecture. Still, you will get many questions on this one since many students do not get this concept at the end of EECS 210.

As part of preparation for experiment #1, the TA should build 10 Sallen-key filters (9 for the lab and one back-up), and make sure that they are working properly with a high-Q case between 4 and 17. The reason is that the students do not have time to build the circuit and take all the measurements (they are still a bit rusty with the proto-boards and the measurement equipment). Also, doing this will ensure that the students get good high-Q filters and that the TA does not have oscillation problems in the lab. Make sure that the low-Q case resistors are inserted in the board and give them the high-Q case resistors attached to a small masking tape section.

# TA Preparation for Experiment #2
# Active Bandpass Filters; Frequency Shift Keying Communications

You will find that experiment #2 is easier on yourself and on the students. You have seen the concepts in experiment #1 and now, you are applying it again to a band-pass filter.

First, read Experiment #2 write up, and make sure that you understand FSK modulation. You will get a lot of questions on it. The band-pass filter response (time and frequency domain) follows a similar approach to the low-pass case except that the slope is +20 dB/dec. and –20 dB/dec. in the band-pass case (and not –40 dB/dec. as in the low-pass case). Also, for a band-pass filter, the final value in time domain is zero (it cannot pass a DC signal). The determination of Q and $\omega_0$ from the time domain response is similar to the low-pass filter. Notice that the phase response in the frequency domain starts at +90° and goes to zero at $\omega_0$. Again, this is a sure way of determining $\omega_0$ ($f_0$). Just look at the 90° change in the phase!

The circuit of the band-pass filter is standard and well behaved (it will not oscillate). $R_3$ is connected to the positive terminal to make sure that the DC voltage (due to the bias current) at this terminal is equal to the DC voltage at the negative terminal (again due to the bias current). This will make sure that the DC output voltage is nearly zero, even if the filter has a high gain. The equations of the filter response are given in the manual. Notice that this is an inverting filter and therefore, you have a 180° phase shift that is added to the phase response.

Please do pre-lab #2. Hopefully, you will find it to be much easier than pre-lab #1 since you are now "used" to this topic. There is a small trick in the pre-lab. The input impedance of the filter for $f >> f_0$ (caps are short-circuited) is $R_1$ (think about it).

Build the circuit now, make the experiment, and take all the date on your laboratory notebook. Make sure you know how to use FSK modulation well and how to use the SYNC signal for an external trigger. You will get a lot of questions on this part of the experiment, so be prepared!

The lab report should now be easy to do. You will find that problem 3a is very similar to the one in lab #1 report, and I put it again in lab #2 just to drill it more into the student's minds. Problem 5b. can be solved either using Matlab or analytically using $\omega=\omega_0+\Delta\omega$ and inserting it in the transfer function of the band-pass filter.

# TA Preparation for Experiment #3 Diodes and Bridge Rectifiers

I personally believe that this is a complicated and interesting experiment. Sure, it is quite easy to build and to measure, but a lot happens "behind the scene" in this experiment.

First, read Experiment #3 write up, and make sure that you understand the difference between half-wave and full-wave rectifiers. Look at the equations for both topologies. You will get a lot of questions on $V_{opk}$ and $V_{oav}$, and really, for the case of a small ripple, they are the same and the equations are applicable if you use either one of them. The main point is that these equations are very approximate. Also, read carefully the linear regulator section and the use of variable-tap transformers. These will not be covered in the lectures.

There are five points that you need to understand well, and they are included in this TA manual (and you will lecture on them):

1. The bridge rectifier equations (see p. xx in the lab manual) are very approximate and conservative. When you build and measure the rectifier, you will find that the ripple voltage and output voltage are decently predicted by the equations, but the values of turn-on time of the diode and the current peak in the diode are very different from calculations. This is due to the very simple approximations done in the calculation of the turn-on time of the diode, which affects the calculations of the current peak in the diode. This is OK since the calculated values give you a conservative estimate, and therefore are never wrong!
2. When you model this circuit with Spice, you will see large initial currents in the diode/capacitor. This is needed to initially charge the capacitor to $V_{opk}$, and after it arrives to this voltage, the steady-state analysis and the approximate formulas apply.
3. There are several ways to calculate the current in the load. Either from $V_o/R_L$, or from the discharge slope of the capacitor voltage waveform, or from the measured discharge current of the capacitor (when the diodes are OFF).
4. MOST IMPORTANT: It is never possible to ground both the transformer and the output node in power supplies. If you do this, then you short the diodes ($D_2$ in this case) and you get a half-wave rectifier! The voltages, referenced to ground at the load, are shown on the handout for a 16 V peak input voltage.
5. Full-wave rectifiers have $1/\sqrt{2}$ less peak current in the diode than half-wave rectifiers. The explanation is that the capacitor discharges for only half a cycle (and not a full cycle as a half-wave rectifier), and therefore requires half of the charge (of a capacitor in a half-wave rectifier). This results in $1/\sqrt{2}$ less in turn-on time and $1/\sqrt{2}$ less in peak current value!

Please do pre-lab #3. Be careful on problem #2 since this is a special case of a half-wave rectifier. It uses the half-wave rectifier equations but with two diode voltage drops.

Build the circuit, make the experiment, and take all the dates on your laboratory notebook. Notice the distortion in the output voltage of the transformer, with resulting frequency components at 180 Hz and 300 Hz. This will not affect $V_o$ since it will be filtered out by the low pass capacitor at the output. The lab report is standard and only problem 4 is a bit different. You will see that the measured turn-on time of the diodes and peak current values in the diode or capacitor are very different than the calculated ones due to the simple approximations done in the equations.

# TA Preparation for Experiment #4
# Diode Small-Signal Measurements, Amplitude Modulation, Envelope and Square-Law Diode Detectors

This is, in my opinion, the best experiment of the term. It is simple, yet it introduces so many concepts in linear and non-linear systems.

First, read Experiment #4 write up, and make sure that you understand the difference between the linear and non-linear regimes of diodes. As you see, non-linear is a relative term and can be defined for a voltage of $1mV_{pk}$ to an input of $10\ mV_{pk}$ (across the diode). Typically, a $10mV_{ppk}$ ($A=5mV_{pk}$) is considered the maximum linear voltage across a diode junction, and this results in –28 dB second harmonic level. Also, learn how to measure and extract the dc parameters of diodes ($n$, $I_s$, $R_s$). Then comes Amplitude Modulation. It is an important topic and you will be lecturing about it. Therefore, study it well and learn how a square law detector (and a diode) can demodulate the AM and get back the baseband signal.

Please do Prelab #4. You will find that problem 1 is very important and you will get a lot of questions on it. Be careful, not all of the voltage across the diode is really across the junction. Some of the voltage drops in the series resistance of the diode, and therefore reduces the junction voltage. Problems 2-4 are related to AM signals and the AM detector, and are a simple application of the equations presented in the manual. Problem 3b is interesting and makes a plot of the frequencies available in the current spectrum.

Build the circuit, make the experiment, and take all the date on your laboratory notebook. The lab report is not long and is pretty standard. Students may have problems in problems 2c and 3b. In order to calculate the corner frequency of the 4.7µF DC blocking capacitor, determine the effective resistance, $R_T$, seen by the capacitor (Thevenin's equivalent circuit from the capacitor nodes), and $f= 1/2\pi R_T C$. Also, the same technique is used to determine the corner frequency of the 4.7nF used in the AM demodulator. In this case, you know the output DC voltage and thus the dc current in the diode. You can then calculate its equivalent $r_d$ in the circuit, and get the equivalent resistance seen by the capacitor. (Both of these are done in the lab solutions.)

# TA Preparation for Experiment #5
# LEDs, Phototransistors and an AM Photonic Link

This is the simplest and most fun experiment in the semester. It is easy and it applies the AM concepts learned in experiment #4 for an optical AM link.

First, read Experiment #4 write up, and make sure that you understand LED's and phototransistors. Study well their data sheets since you will be lecturing on them. (If you have not taken EECS 210, you may want to look at the LM 380 audio power amplifier data sheet too).

LED's are different than diodes in the fact that they require a large bias current (around 15 mA) so as to produce a sufficient light output. The LED junction resistance rd is around 3 Ω and since $R_s$ is around 10-16 Ω, we find that a large portion of the LED ac-voltage is across $R_s$ and not $r_d$! Also, LED's do not have an exponential output light intensity vs. bias current (it is much more linear as seen in Fig. 3b) and therefore can handle a large current variation with no appreciable distortion. This means that the LED junction voltage can be quite large (around 30 $mV_{ppk}$), which results in an *input* LED voltage of 400-800 $mV_{ppk}$ before any distortion is detected!

Although the data sheet talks about the Siemens BPX 81-3 phototransistor, we really do not use it in the lab, and we use a radio-shack phototransistor. Still, the data sheet is applicable since both of these units are infrared devices which peak at 860 nm (infrared) and not 630 nm (red).

Please do prelab #5. Problem 1 is very similar to problem 1 of prelab #4 except with LED values for n, $I_{bias}$, $R_s$, etc… . Problem 3 is solved with the help of the phototransistor data sheet. It is not a hard pre-lab.

Build the circuit, make the experiment, and take all the data on your laboratory notebook. The lab report is actually the shortest of the semester. Be careful when taking measurements. The 120 Hz pick-up from the fluorescent lighting translate to a ripple and slowly shifting level on the scope. Actually, you will measure this pick-up in the lab. Turn the lights off or cover the LED very well so as to reduce this noise.

The TAs should have at least one optical AM transmitter which is attached to a portable CD or tape layer and has a directive lens in front of it. The TA's will shine the music on the student's experiment and the student can listen to the music using the optical link. The students *love* this part of the experiment!

# TA Preparation for Experiment #6
# Frequency Modulation (FM), Generation and Detection, FM Optical Link

This is an optional experiment and no grades are assigned to this lab. However, around 60% of the students answered “Yes” when I circulated a paper in the class asking who would like to do it. Therefore, do expect to hold 3 lab sessions for this experiment.

There is a lot to prepare and the best thing is to meet with me and build/test the circuits. Please contact me a couple of weeks before this experiment to schedule a convenient meeting time.

# General Laboratory Policies and Administrative Issues

Administrative Issues:

a) Email groups: There will be an email group including all EECS 211 GSI's and the 211 professors (tbd by the TAs/professors).

There will also be an email group including all students and faculty (tbd).

b) Office Hours: Each laboratory GSI is responsible for holding 3 hours of office hours per week in the lab, room EECS. There is ample time to hold the OH and still hold the labs in the same room. The OH time selection will be discussed/planned with the professor.

c) Keys / Books: GSI's should see Karen Liska (EECS 3300, liska@eecs.umich.edu) for keys to the lab room and the lab cabinet. You can obtain the course books from Karen Merte (3rd floor Southwest wing).

Class Policies:

a) Lab cleanliness: Make sure you stress lab cleanliness and organization to your students. It is their responsibility to keep their area clean and safe. No backpacks are allowed on the work-benches. When the students finish the experiment, they are responsible for turning off all electrical equipment and putting away all components/equipment in the order that they found it. GSI's should prepare the lab prior to the beginning of class arranging equipment and setting up each lab bench.

b) Grading: The laboratory is worth 20% of the overall grade for the class. There will be three sections to each lab report: Prelab, Data, and Postlab. I encourage my students to make comments on what they see (physically and data) and will award an extra points for good comments on trends in data. If a student has wrong data, I'll be more lenient if they comment on their data noting what seems wrong and what the correct data should look like. GSI's should compile grades and send them to the head TA using electronic means.

   i) Prelab: The prelab is worth 25% of the lab grade and should be done prior to the start of class. GSI's should go around the room checking off that the students have completed the prelab once they begin the experiment. If the prelab is partially completed, then make note of the uncompleted portions. If the student has (honestly) attempted a prelab problem but did not complete it, then ask them to finish the problem for the lab report and give them partial credit for that problem when grading it. Use your own discretion for how much credit to give them.

   No late prelab problems will be credited (not even partial credits). However, they will be corrected.

   ii) Data: Lab Data taken during class hours is worth 25% of the lab grade. GSI's should check that all measurements were made and recorded in an organized manner. Also check to see that all questions asked in the manual are answered either in the data section or in the postlab. GSI's will sign the students' data section in their lab notebooks before they leave class.

   iii) Postlab: A postlab report worth 50% of the lab grade will completed by each student answering the questions/problems at the end of each lab in the manual. I also encourage them to answer all unanswered questions from the data section and to explain/comment on trends, errors, or discrepancies in the data. Students should list equations used in the postlab in algebraic format with definitions of the variables next to them. All numeric answers should contain units.

Stress that no papers can be attached to the lab notebook. Everything has to be cut and glued to the lab notebook.

c) Missed Lab / Late Policy: Labs are due exactly one week from the start of class. Labs can be handed in early, but must be turned into one of the 211 GSI's or Professor's which should then be dated, signed and put (by the GSI or Prof.) in the lab cabinet. If a lab is handed in late, there is a 25% penalty (deduct 25 points from grade) for the first day late, and a 50% penalty for two days late. If a lab is 3 or more days late, the student will receive a 0/100 for that lab but still must complete the lab. If a lab is missed, the student will receive a 0/100 for the lab and their grade will drop by one full letter (A->B, B+->C+,…). If two labs are missed, the student will fail the course. If a student is unable to attend a lab, then they should contact the professor or the head TA at least 3 days in advance of the lab (unless there are extreme circumstances).

d) Lab Notebooks: Students are required to have two bound notebooks. The notebooks should be such that pages can not be added to them. One notebook will be used for Labs 1,3,5, and the other for Labs 2,4, and 6. All work must be done in either blue or black ink. No work in pencil will be graded. All lab pages should be numbered and dated. Notebooks should be big enough so that large figures can be pasted, stapled, or whatever into them. All figures and tables should be titled and given a figure or table number (e.g. Figure 4-2: Low Pass Filter Frequency Response). Figures should have the axis labeled (with units) and the figure should be understandable without reference lab manual or lab write-up. Equations used during the lab should also be listed in algebraic form and given an equation number. Students should reference data by page, figure, table, or equation number.

e) ALL LABS INCLUDING LAB LECTURES ARE REQUIRED! Just because a lab is not performed that week does not mean attendance isn't required. The same policy will be used if you miss a lab lecture (Your overall grade will by lowered by one letter). So don't miss ANY labs! You also cannot attend any lab you feel like. You must get specific permission by the HEAD TA or Professor to attend another lab section. If you attempt to attend another section without my permission to do so, the TA will not let you in. If you do get my permission, it is best to make a printout of the email stating so and show the TA of the respective lab.

f) Laboratory grades will be normalized at the end of the semester. We understand that different TA's grade differently so grades will be adjusted such that your final lab grade will depend on your relative standing to the other students of your TA. So don't compare your lab grades to another section with a different TA than yours. The Head TA (or the assigned TA) will pay attention to this throughout the term and report any large discrepancies.

g) TAs: After you read a pre-lab, you should make sure that you put enough clues or writing that they cannot write more and then submit it as a pre-lab. For example, cross all open-spaces (with a nice dash), or make a note with your handwriting that problem # X is missing, then sign at a certain space and do not accept anything below this space for a pre-lab. No late prelab problems will be credited (not even partial credits). However, they will be corrected.

h) TAs: Make sure you bring your lab notebooks to class. Document everything out of the ordinary (late lab, student from another lab, absent students). Do not allow any students to attend your class unless they have the head TA permission.

# How To Give a Good Lecture

1. *Be prepared!* The best lectures are given when you are very comfortable with the material and have worked it out in your mind.
2. *Be organized* on the board. Always start writing from the left and move in rather small characters (but not too small, since this is a medium room) from left to right. Never start on the right. If you need to draw a circuit, draw it on the far right or far left and keep it there.
3. *Use handwritten notes*. These will help in case you lose your line of thought.
4. Remember to speak *loud and clearly*. Do not mumble! Somebody at the end of the room must be able to hear you. When speaking to the class, face the class and not the board. Look into their eyes…the eyes tell you if they are understanding the material or not. If someone asks you a question that you do not know, tell them that you will look into it and answer them by email or in office hours. (If you have trouble speaking publicly, practice in front of a mirror at home or with friends, or come and talk to me).
5. You are the teacher and the role model. Dress and behave accordingly. Do not make fun of any question even if it is very simple. Just answer it, or tell them to wait and you will answer it later. Do not allow any bad words in the lab. Also, no food, no drink and surely no chewing gum allowed in the lab.
6. You will see that it takes practice to give a good lecture. At the beginning, life will be tough and you may not be happy with yourself. At the end of the term, you will be a good lecturer!

# Lab Schedule

| | | |
|---|---|---|
| Sept. 7 | Week 1 | Classes start. Professor-TA Meeting |
| Sept. 14 | Week 2 | Lab Introduction and Review of EECS 210 |
| Sept. 21 | Week 3 | Lab Lecture; More Review, Preparation for Exp. #1 (Low-Pass Filters; Step Response vs. Q) |
| Sept. 28 | Week 4 | Experiment #1 (Low-Pass Filters; Step Response vs. Q) |
| Oct. 5 | Week 5 | Lab Lecture; Preparation for Exp. #2 (Active Bandpass Filters; Frequency Shift Keying Communications) |
| Oct. 12 | Week 6 | Experiment #2 (Active Bandpass Filters; Frequency Shift Keying Communications) |
| Oct. 19 | Week 7 | Lab Lecture; Preparation for Exp. #3 (Diodes and Bridge Rectifiers) |
| Oct. 26 | Week 8 | Experiment #3 (Diodes and Bridge Rectifiers) |
| Nov. 2 | Week 9 | Lab Lecture; Preparation for Exp. #4 (Diode Small-Signal Measurements, Amplitude Modulation, Envelope and Square-Law Diode Detectors) |
| Nov. 9 | Week 10 | Experiment #4 (Diode Small-Signal Measurements, Amplitude Modulation, Envelope and Square-Law Diode Detectors) |
| Nov. 16 | Week 11 | Lab Lecture; Preparation for Exp. #5 (LEDs, Phototransistors and an AM Photonic Link) |
| Nov. 23 | | Thanksgiving Week |
| Nov. 30 | Week 12 | Experiment #5 (LEDs, Phototransistors and an AM Photonic Link) |
| Dec. 7 | Week 13 | Demo for Experiment #6. Classes end. |

# Week 1:
# Professor-TA Meeting

Classes start on a Wednesday (or a Tuesday).

The professor should meet with the TAs (maybe on Thursday or Friday afternoon), assign the lab sections, the head TA, discuss the rules of the lab, the grading policy, etc… and give the TAs the lab manuals and the TA manual. Most important, the TA's should agree on a time where they will meet to make the lab experiments all together, and understand them well. The experiments are not easy, not even for the TAs, and therefore a lot of effort should be put preparing for them.

There will also be many students who want to switch lab sections, who were on the waiting list, etc… and this should be done also in the first week (and possibly in Week 2).

Finally, the TA's should study the notes for lab lecture 1, which is coming very quickly (Week 2).

# Week 2:
# Lab Introduction and Review of EECS 210

Organization Issues:

There are some organizational tasks for the TA to do at the beginning of the lab (30-40 minutes).

Have them sign in (sign-in sheets should be provided on the lab desk) when they enter the lab. Some students are changing labs, so check that they are registered in your section. Talk to the head TA on how to handle student lab changes.

Introduce yourself and make sure to mention the following points:

- your name and ways to contact you
- your office hours
- lab section number (remind them!)
- safety (no messing with electrical outputs!)
- cleanliness (no backpacks/jackets on benches, leave the bench clean)
- lab notebooks (two lab notebooks, one for Exp.# 1,3,5 and the other for Exp.# 2,4,6). They can continue using EECS 210 lab notebooks if they wish to.
- write in ink only
- grading policies
- late/missed lab policies (stress that late students may be denied access to the lab).
- expectations (how to write a lab, units, label figures and tables, also that a lab report is a reflection on yourself and how you understand the material).
- stress that no papers can be attached to the lab notebook. Everything has to be cut and glued to the lab notebook.
- lastly, have them select their partners for the rest of the semester (unless serious problems occur).

Review Lecture:

After the organizational items are finished, the TA will start a review of EECS 210. The students have already taken EECS 210 but are a bit rusty (especially in the Fall term after a summer of no classes). The professor has already spent two lectures reviewing EECS 210 (and maybe more). The notes to be used are attached. Please study them well. This review session should take around 40 minutes, and be receptive to questions from the students.

Oscilloscope Review:

Also, the TA should also ask the students to do the experiment on p.16-21, which is a review on the oscilloscope operation. This should not take more than 20 minutes.

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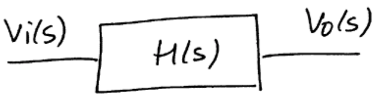
## Week-2 lab lecture:

This lecture will review the last lab in EECS 210 (Treble Control) with emphasis on the transfer function, signals and Fourier-Series.

If you have a circuit with a transfer function $H(s) = \frac{V_o(s)}{V_i(s)}$



$s = j\omega$

$\Rightarrow \quad V_o(s) = H(s) \cdot V_i(s)$ $\qquad dB \equiv 20 \log(V)$

$$\Rightarrow \quad V_o\big|_{dB} = H(\omega)\big|_{dB} + V_i\big|_{dB} \quad \text{Amplitude (Magnitude)}$$

$$\angle V_o = \angle H(\omega) + \angle V_i \quad \text{Phase}$$

Example: Treble Cut

$$H(\omega) = \frac{\left(1 + \frac{j\omega}{2\pi \times 10{,}000}\right)}{\left(1 + \frac{j\omega}{2\pi \times 1{,}000}\right)}$$

$\equiv \left(1 + \frac{j\omega}{\omega_1}\right)$ ← zero at $f = 10\,\text{kHz}$

← pole at $f = 1\,\text{kHz}$ $\equiv \left(1 + \frac{j\omega}{\omega_2}\right)$

$$|H(\omega)| = \frac{\sqrt{1 + \frac{\omega^2}{(2\pi \times 10{,}000)^2}}}{\sqrt{1 + \frac{\omega^2}{2\pi \times 1{,}000}}}$$

Magnitude of $H(\omega)$

$$|H(\omega)| = \frac{\sqrt{1 + \left(\frac{\omega}{\omega_1}\right)^2}}{\sqrt{1 + \left(\frac{\omega}{\omega_2}\right)^2}}$$

$$\angle H(\omega) = \tan^{-1}\left(\frac{\omega}{2\pi \times 10{,}000}\right) - \tan^{-1}\left(\frac{\omega}{2\pi \times 1{,}000}\right) \quad \text{Phase of } H(\omega)$$

$$\equiv \tan^{-1}\left(\frac{\omega}{\omega_1}\right) - \tan^{-1}\left(\frac{\omega}{\omega_2}\right)$$

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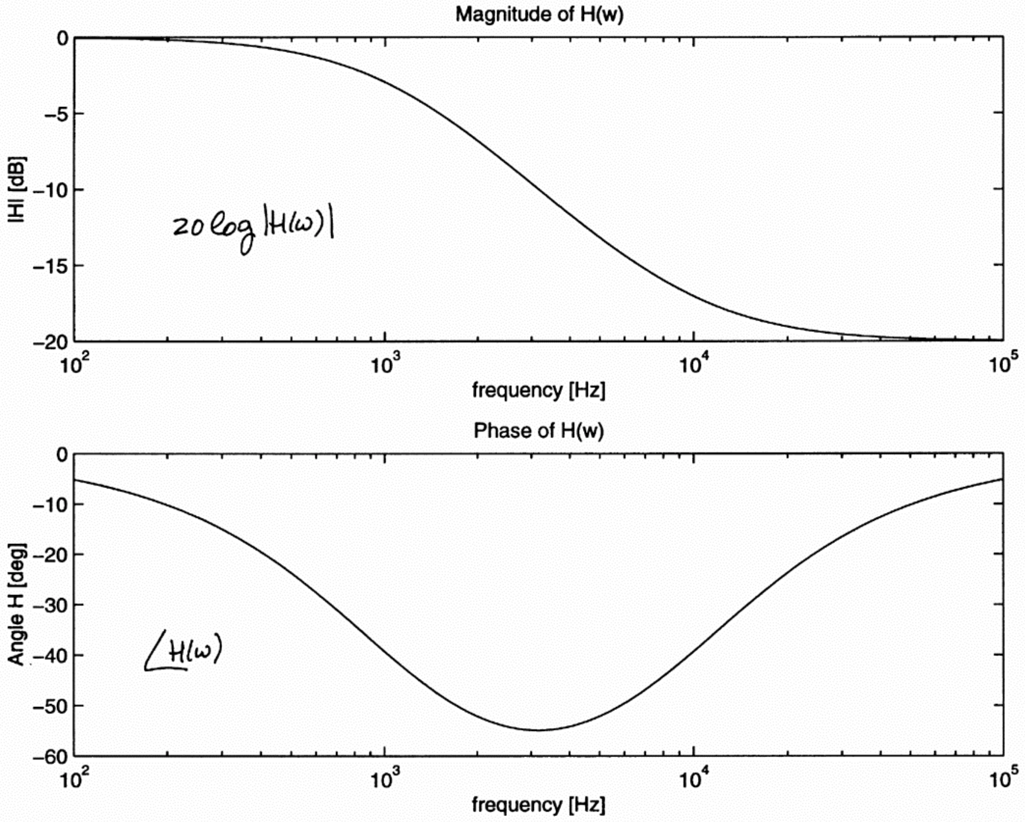


Let us say that a certain music instrument has an input frequency spectrum (or time domain waveform) given by:

| | | $|V_i|$ Ampl (dB) | Phase (°) $\angle V_i$ |
|---|---|---|---|
| 800 Hz | Fundamental ($f_0$) | 4 | 0 |
| 1600 Hz | 2 $f_0$ | −3 | 0 |
| 2400 Hz | 3 $f_0$ | 0 | 40 |
| 3200 Hz | 4 $f_0$ | −8 | 90 |
| 4000 Hz | 5 $f_0$ | −12 | 30 |
| ~~4800 Hz~~ | ~~6 $f_0$~~ | ~~17~~ | ~~180~~ |
| 4800 Hz | 6 $f_0$ | −17 | 180 |

3/5

Basically, in time domain,

$$
\begin{aligned}
V_{in}(t) = {} & 2.51 \cos(2\pi \times 800\, t + 0^\circ) \\
& + 0.50 \cos(2\pi \times 1600\, t + 0^\circ) \\
& + 1.00 \cos(2\pi \times 2400\, t + 40^\circ) \\
& + 0.16 \cos(2\pi \times 3200\, t + 90^\circ) \\
& + 0.063 \cos(2\pi \times 4000\, t + 30^\circ) \\
& + 0.020 \cos(2\pi \times 4800\, t + 180^\circ)
\end{aligned}
$$

---

And now, we need to calculate $V_o$! Remember, $V_o(\omega) = H(\omega) . V_i(\omega)$

→ Find $H(\omega)$, Amplitude & Phase, at $f_0, 2f_0, \dots 5f_0, 6f_0$

| | | $\lvert H(\omega)\rvert$ dB | $\angle H(\omega)$ |
|---|---|---|---|
| $f_0$ | 800 | 2.1 | 34 |
| $2f_0$ | 1600 | 5.4 | 49 |
| $3f_0$ | 2400 | 8.1 | 54 |
| $4f_0$ | 3200 | 10.1 | 55 |
| $5f_0$ | 4000 | 11.7 | 54 |
| $6f_0$ | 4800 | 12.9 | 52.6 |

Read from graph
or put f = 800, 1600, etc.. in equations.

& now,

$$V_o(f_0) = H(f_0) + V_i(f_0) \Big|\, \text{dB} \qquad \angle V_o(f_0) = \angle H(f_0) + \angle V_i(f_0)$$

$$V_o(2f_0) = H(2f_0) + V_i(2f_0) \,\Big|\, \text{dB} \qquad \vdots$$

$$\vdots$$

$$V_o(6f_0) = H(6f_0) + V_i(6f_0) \,\Big|\, \text{dB} \qquad \angle V_o(6f_0) = \angle H(6f_0) + \angle V_i(6f_0)$$

4/5

| | | $V_o$ (dB) | $\angle V_o$ |
|---|---|---|---|
| ⇒ $f_o$ | 800 | $2.1+4=6.1$ | $34+0=34$ |
| $2f_o$ | 1600 | $5.4-3=2.4$ | $49+0=49$ |
| $3f_o$ | 2400 | $8.1+0=8.1$ | $54+40=94$ |
| $4f_o$ | 3200 | $10.1-8=2.1$ | $55+90=145$ |
| $5f_o$ | 4000 | $11.7-12=-0.3$ | $54+30=84$ |
| $6f_o$ | 4800 | $\underbrace{12.9}_{H(\omega)} - \underbrace{17}_{V_i} = \underbrace{-4.1}_{V_o}$ | $\underbrace{52.6}_{H(\omega)} + \underbrace{180}_{V_i} = \underbrace{232.6}_{V_o}$ |

⇓

Translate to volts  $\text{Volts} = 10^{dB/20}$

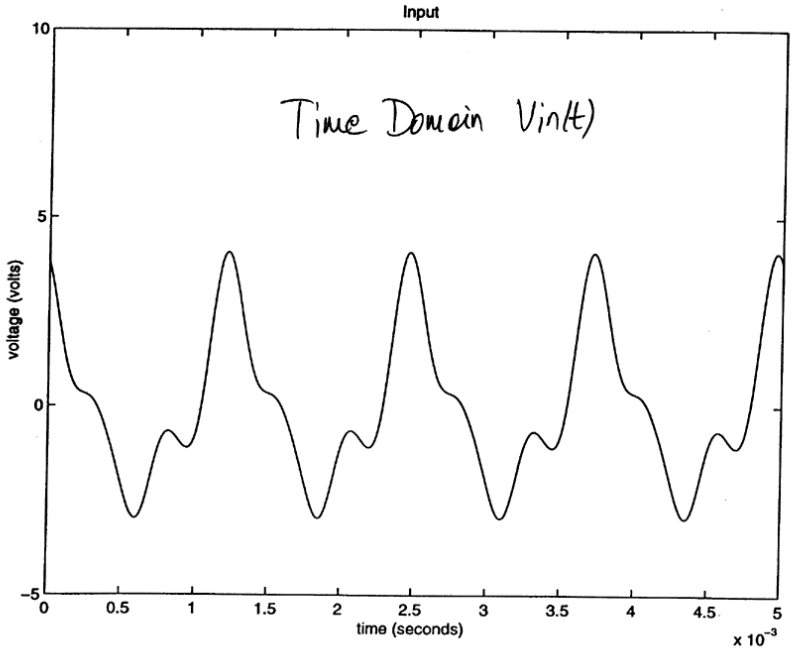
$$\Rightarrow V_o = 3.21\cos(2\pi \times 800t + 34^\circ)$$
$$+ 0.93\cos(2\pi \times 1600t + 49^\circ)$$
$$+ 2.52\cos(2\pi \times 2400t + 94^\circ)$$
$$+ 0.51\cos(2\pi \times 3200t + 145^\circ)$$
$$+ 0.24\cos(2\pi \times 4000t + 84^\circ)$$
$$+ 0.088\cos(2\pi \times 4800t + 232.6^\circ)$$

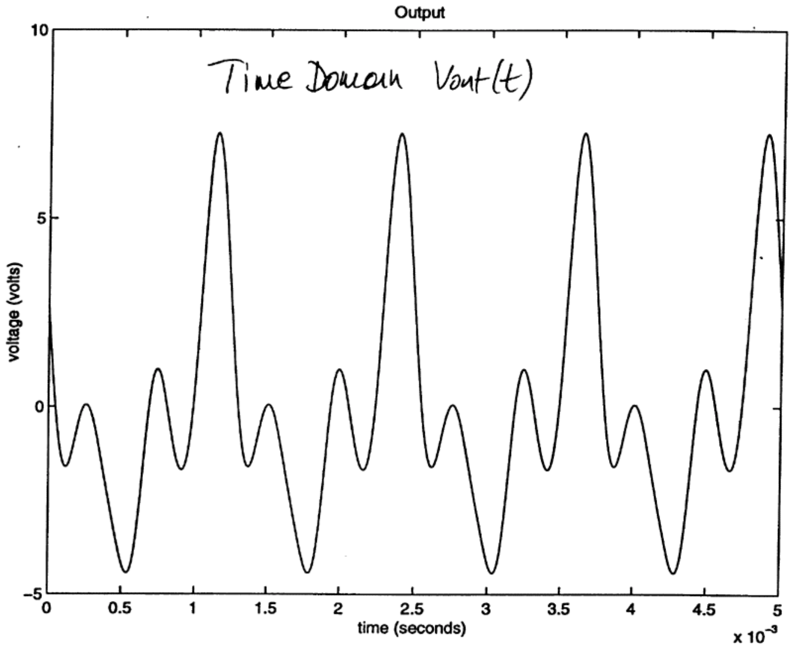
See time & freq. domain representation → of Vi & Vo –

---

You can do the same thing with any input signal & any transfer function (Treble cut, bass boost, etc...). Just follow the same approach.

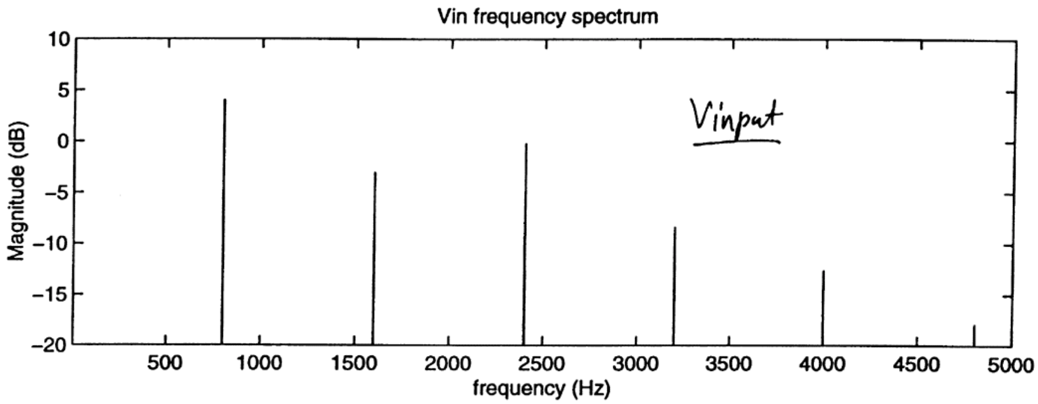
5/5

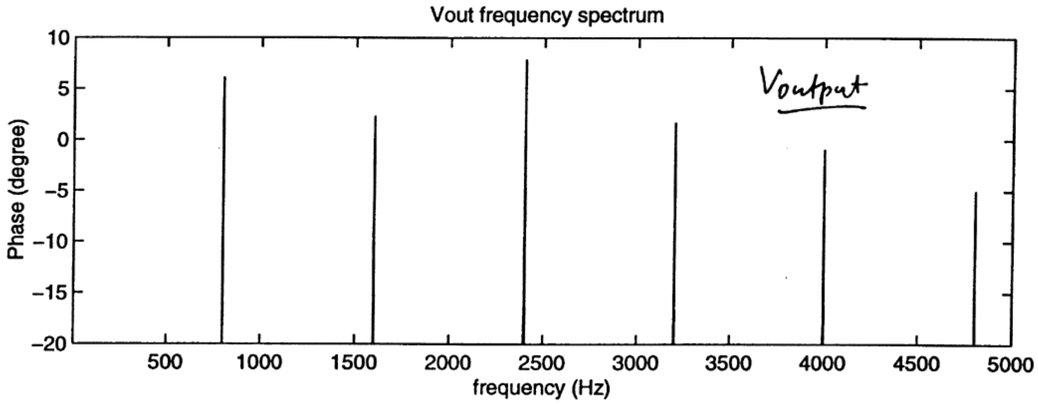

Input
Time Domain Vin(t)
voltage (volts)
10
5
0
−5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
time (seconds)
x 10^−3


Output
Time Domain Vout(t)
voltage (volts)
10
5
0
−5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
time (seconds)
x 10^−3

5B/s

## Frequency Domain





$$V_o(\omega) = H(\omega) + V_i(\omega) \Big|_{dB}$$

# Week 3:
# Lab Lecture; More Review, Preparation for Exp. #1 (Low-Pass Filters; Step Response vs. Q)

Arrive early, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc.). When the students arrive, check their name in the log-in sheet and ask them to take a seat. All the student section changes should be completed by this week, so this is your final student count (you could have as low as 14 and as much as 18).

For the material below, read the attached notes and present them in the lab. This lecture should take around 60 minutes with questions/answers, etc…

1. Cover the bandpass filter (as a review of EECS 210). Again, talk about $V_o=H(\omega).V_i$ and how the amplitude is added in dB and the phase is added in degrees. Give an example.
2. Cover the nodal equations of the Sallen-Key low pass filter and its frequency response for different Q values. Talk about the time domain response for low-Q case (that is, single pole). Do not talk about the time domain response for high-Q case, since they have not covered it in class yet.

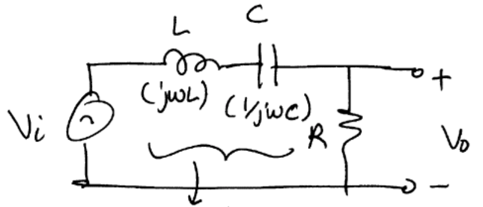
   Talk about the filter circuit at $\omega >> \omega_0$ and $\omega << \omega_0$.
3. Review some Op-amp non-idealities such as input DC bias currents (and the role of $R_{12}$), output voltage clipping and the bandwidth of the op-amp.

Finally, take any questions related to EECS 210 (frequency response, nodal analysis, phasors, etc.). Stay in the lab if students want to ask more questions.

## WEEK 3 Lab-Lecture:

1/6

- Cover the RLC bandpass filter. This is an EECS 210 review.



resonates as a short ⇒ $\underline{V_o = V_i \ @\omega_o}$

$$H(\omega) = \frac{V_o}{V_i} = \frac{R}{R + j\omega L + \frac{1}{j\omega C}} = \frac{R}{R + sL + \frac{1}{sC}}$$

$$\Rightarrow H(s) = \frac{sRC}{1 + sRC + s^2 LC} \equiv \frac{j\omega RC}{(1-\omega^2 LC) + j\omega RC}$$

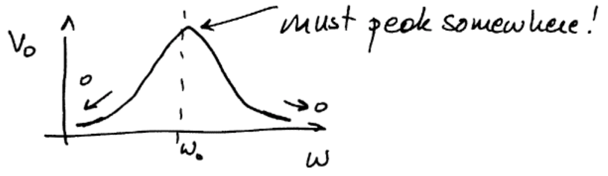
$$|H(\omega)| = \frac{\omega RC}{\sqrt{(1-\omega^2 LC)^2 + (\omega RC)^2}}$$

$$\angle H(\omega) = \underbrace{90^\circ}_{j} - \tan^{-1}\left(\frac{\omega RC}{1-\omega^2 LC}\right)$$

at $\omega \to 0$ (look at circuit); Cap. is open-circuit & $V_o \to 0$

at $\omega \to \infty$ ( " " " ); Ind. " " " & $V_o \to 0$

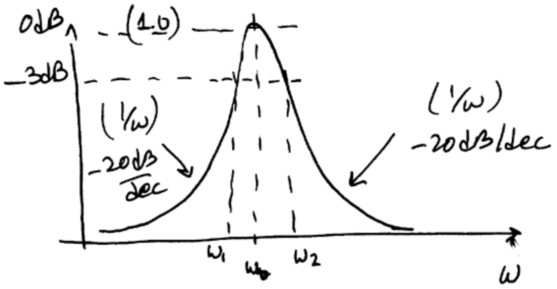
⇒ Bandpass Filter



at $\omega = \omega_o$ where $1 - \omega_o^2 LC = 0$ or $\omega_o = \frac{1}{\sqrt{LC}}$

we have $H(\omega) = \frac{j\omega_o RC}{0 + j\omega_o RC} = \underline{\underline{1}} \Rightarrow |H(\omega)| = 0\,dB$

$\angle H(\omega) = 0^\circ$



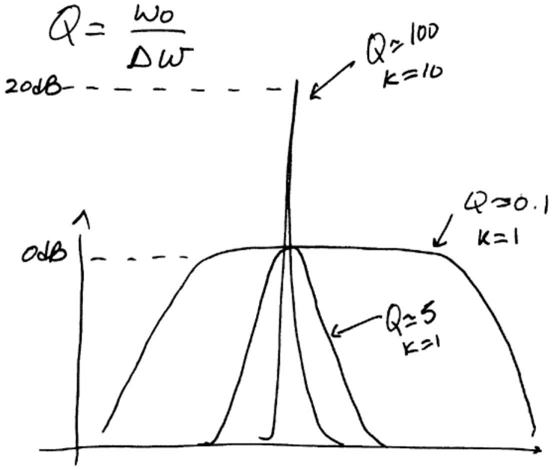
Put $|H(w)| = 0.707$ (-3dB)
& find $w_1$ & $w_2$

Define $\underline{Q}$ of filter as

$$Q = \frac{w_0}{\Delta w}$$

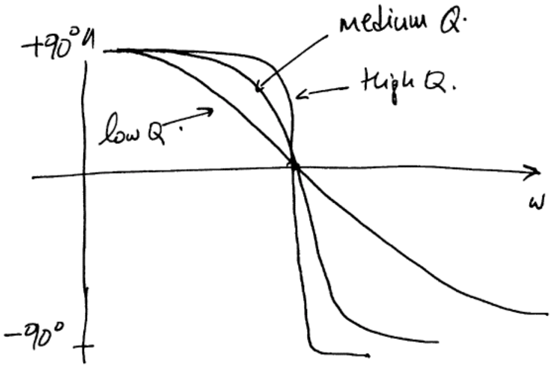
Q ≡ Indicates how sharp a filter is
≡ quality factor.

| | |
|---|---|
| $Q \simeq 100^+$ | Very sharp |
| $Q \simeq 10$ | Sharp |
| $Q \simeq 1$ | Medium Broad |
| $Q < 1$ | Broad |
| $Q \simeq 0.1$ | Very wide |



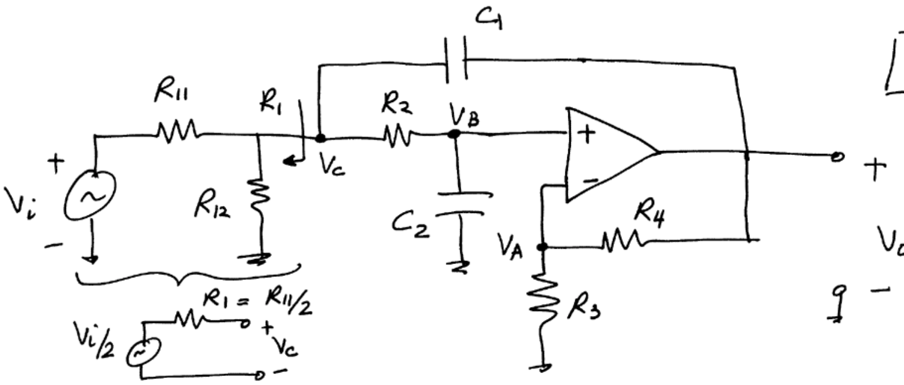
$$\text{Phase of } H(w) = 90^\circ - \tan^{-1}\left(\frac{wRC}{1-w^2LC}\right)$$

$w \to 0$ $\angle H(w) = 90^\circ$
$w = w_0$ $= 0^\circ$
$w \to \infty$ $= -90^\circ$



## Sallen-Key Low-Pass Filter:

3/6



$\boxed{R_{11}=R_{12}}$

Analysis using nodal equations:

Node A: $$\frac{V_o - V_A}{R_4} = \frac{V_A}{R_3}$$

Node B: $V_B = V_A$ and $$\frac{V_B - V_c}{R_2} + \frac{V_B}{\frac{1}{sC_2}} = 0$$

Node C: $$\frac{V_c - V_o}{\frac{1}{sC_1}} + \frac{V_c - V_i/2}{R_1} + \frac{V_c - V_B}{R_2} = 0$$

Solve for $\frac{V_o}{V_i}$ = - - - - - - - - - - Given in lab Notebook Low-Pass Filter Response →

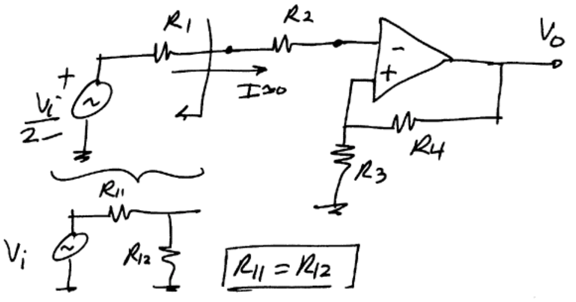
For the case of $C_1 = C_2 = C$, $R_4 = R_3$ & $R_{11} = R_{12}$,

we have $$\underbrace{K=1}_{\text{Low Frequency Gain}}, \quad \omega_o = \frac{1}{\underbrace{C\sqrt{R_1R_2}}_{\text{Controls corner frequency ALONE!}}} \quad \& \quad Q = \sqrt{\frac{R_1}{R_2}}$$

4/6

## Explain Circuit :

$\omega \to 0$ , Caps ≡ open-circuit ⇒



$V(-) = V_i/2$

& $V_o = \left(1 + \frac{R_4}{R_3}\right) V(-)$

(Non-inverting Amplifier)

$$\Rightarrow \quad V_o = \left(1 + \frac{R_4}{R_3}\right)\left(\frac{V_i}{2}\right) \quad \& \quad \boxed{\frac{V_o}{V_i} = \frac{1}{2}\left(1 + \frac{R_4}{R_3}\right)}$$ Low Frequency Gain

$\omega \to \infty$ , Caps ≡ Short-circuit

⇒ $C_2$ ≡ short V(-) to Ground ⇒ $\boxed{\frac{V_o}{V_i} \to 0}$ High Frequency Gain

⇒ Low-Pass Filter.

---

Now, $\frac{V_o}{V_i} = H(s)$ has the form:

$$H(s) = \frac{K \omega_0^2}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \equiv \frac{K \omega_0^2}{(\omega_0^2 - \omega^2) + j\omega\left(\frac{\omega_0}{Q}\right)}$$

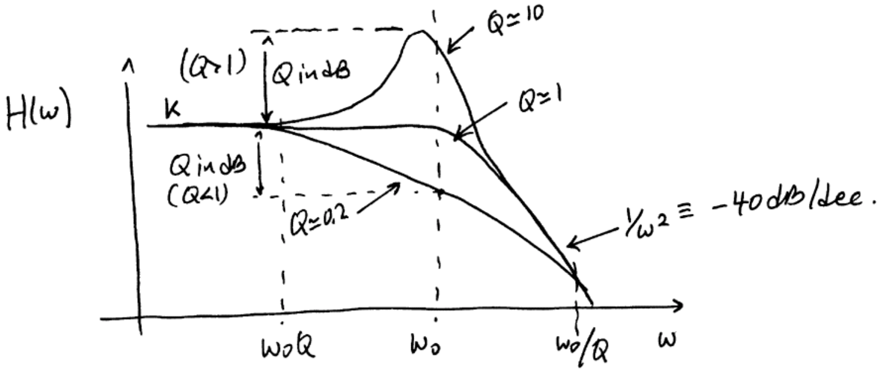
$\overset{(\omega)}{S} \to 0$ $\quad H(\omega) = K$ ≡ low Freq. Gain $\quad \angle H(\omega) = 0^\circ$

$\overset{(\omega)}{S} \to \infty$ $\quad H(\omega) \to \frac{K\omega_0^2}{-\omega^2} \to \frac{1}{-\omega^2} \to 0 \quad \angle H(\omega) = -180^\circ$

and at $\overset{(\omega)}{S} \to \omega_0$ $\quad H(\omega_0) = \frac{K\cancel{\omega_0^2}}{j\cancel{\omega_0^2}/Q} = \underbrace{-j}\, KQ$

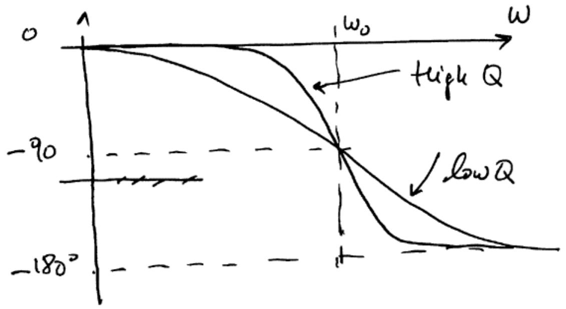
$|H(\omega_0)| = KQ \qquad \angle H(\omega_0) = -90^\circ$

5/6



Ampl:

At resonance, the value of $H(\omega_0) = KQ \Rightarrow$ increase or decrease of Q in dB from low-frequency gain.
$(\omega = \omega_0)$



Phase:

For low Q $(Q \ll 1)$, we can write

$$H(s) = \frac{k\omega_0^2}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \equiv \frac{k\omega_0^2}{\underbrace{\left(1 + \frac{s}{\omega_0 Q}\right)\left(1 + \frac{s}{\omega_0/Q}\right)}_{\text{TWO POLE RESPONSE}}}$$

(you will derive this in pre-lab #1)

Dominated by lower pole $\omega_1 = \omega_0 Q$

$\Rightarrow$ Time domain is like a first-order low-pass circuit with a pole at $\omega_1 = \omega_0 Q$ -

DO NOT COVER TIME DOMAIN OF HIGH-Q CASE - PROF. WILL DO THIS

## Cover Op-Amp Non-Idealities : (Review)

6/6

1- Op-Amp always needs input DC bias current to work properly. THis is the role of $R_{12}$! If $R_{12}$ is not present, then no dc current can pass by $C_1$ or $C_2$ to enter the (+) terminal & the op-amp will not work!

2- Remember the gain bandwidth product of the 741 to be around 1MHz. This means that if $f_0 = 40\,kHz$, then the maximum Q that one could build is $Q = \overset{25}{\text{[illegible]}}$ (with $k=1$). If $f_0 = 200\,kHz$, then $Q_{max} = 5$ (with $k=1$).

3- Be careful with high gain (or high Q). The maximum voltage swing at the output is $\pm|V_{cc} - 1.5^V|$, and after this, the output voltage will saturate (clip). Therefore, for high Q (or high gain), the input must always be kept small.

# Week 4:
# Experiment #1 (Low-Pass Filters; Step Response vs. Q)

Arrive early, turn on all of the equipment, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). When the students arrive, check their name in the log-in sheet and ask them to take a seat.

1. After they sit down, explain to them that this is a serious lab and that they should not waste time.
2. Tell them where the components are (but they will not need them) and where the cables are. Each one should get two coax-banana plug cables, and at least three banana-banana cables (and alligator clips) for the power supply.
3. Give them the filters already assembled on the proto-boards (do not let them choose). Point out the resistors (attached to the small piece of masking tape) for the high-Q filter case.
4. Ask them to use the handout and to trace the board before starting to measure the circuit. Make sure that they tell you which one is $V_{in}$ and $V_o$ (They should tell you !), $V_{cc}^{+}$, $V_{cc}^{-}$, etc. .
5. Let them start the experiment, and while the experiment is going on, pass one by one and check their pre-lab. Do not correct the pre-lab, just check that it is done, and sign in the book noting any missing problems.
6. If someone did not do their pre-lab, tell them that they must talk to the Professor. Generally, they are so scared that they straighten up quickly.
7. Be receptive to questions and always walk and see what is happening at the scopes. Do not sit down for a long time. Pass by the stations and ask questions if you wish to see that they understand their measurements.
8. Send an email to the rest of the TAs and the Professor detailing your lab section (time it took, any problems, etc…).

Before you leave, make sure that the resistors in each filter correspond to the low-Q filter case. Also, attach the resistors for the high-Q case on a small piece of masking tape. This will make life very easy for the next section.

# Week 5:
# Lab Lecture; Preparation for Exp. #2 (Active Bandpass Filters; Frequency Shift Keying Communications)

Arrive early, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). When the students arrive, check their name in the log-in sheet and ask them to take a seat.

This lab lecture is divided into two parts. The first part is a review of experiment #1 and the solution of some problems in lab-report #1. The second part covers experiment #2. It should take around 2x30 minutes, with a 10 minute break in the middle. Read the attached notes and present them in the lab.

1. Talk about the low-pass filter circuit and calculate the corner-frequency of the 1µF capacitor and tell them that it does not matter.
2. Talk about the low-Q case, how it is dominated by the first pole (looks just like a simple low-pass filter) and solve problem 2c in the lab report in time domain.

   Take any questions related to experiment #1.

   Take a 10 minute break.
3. Talk about Experiment #2 (band-pass filter). Draw the frequency response for low-Q and high-Q cases and the resulting time domain response. Review how to calculate Q from the time domain response. Also, most important is that the final value in the time domain is zero for a band-pass filter (cannot pass dc).
4. Draw the band-pass circuit on the board and discuss the role of $C_1/C_2$ at low and high frequencies. Notice how C controls $\omega_0$, that is, you can change C and change the center frequency without changing K and Q. Do not calculate the input impedance of the filter. Talk about $R_3$ which is connected to the (+) terminal. Talk about gain bandwidth product.
5. Talk about FSK telecommunications and how bandpass filters are used to detect the received signals.

Finally, tell them to come promptly for Experiment #2 since they will have to build the circuit themselves now.

# Week 5 lab Lecture:

1/4

## Some notes on Exp # 1.

1) The low-pass filter, high-Q case, had a large range of measured Q. The reason is explained on p. 39-40 in the manual. As noted, for

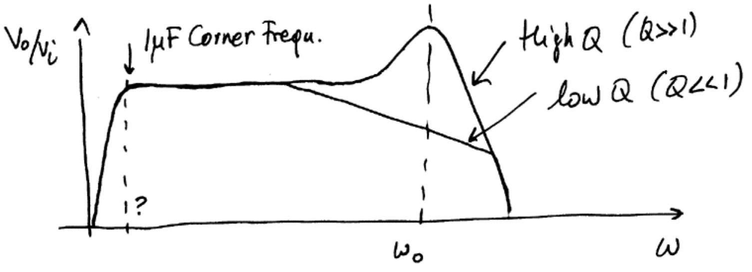
$C_1 = C_2 = C$, $\quad Q = \dfrac{1}{\sqrt{\frac{R_2}{R_1}} + \sqrt{\frac{R_1}{R_2}}\left(1 - \frac{R_4}{R_3}\right)}$

but $\underset{\substack{60\,k\Omega \\ (120\,k\Omega \| 120\,k\Omega)}}{R_1} >> \underset{1\,k\Omega}{R_2}$ in high-Q designs, $\quad Q = \dfrac{1}{\sqrt{\frac{60}{1}}} = 7.7$ $\underline{\underline{\text{if}}}$ $R_4 = R_3$

However, if $R_4 = 1.02\,R_3$, we have $Q =$
$R_4 = 0.98\,R_3$, we have $Q =$

$\Rightarrow$ very sensitive to $R_4/R_3$ $\Rightarrow$ Choose 1% metal resistors & not 5% Carbon resistors.

2) The 1μF DC block sets a low-corner frequency. The response is really



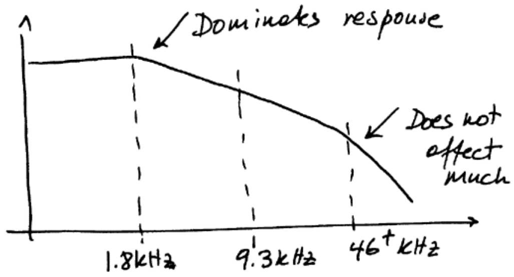
To calculate it, find equivalent resistance seen by 1μF Cap.
(C1 & C2 are open-circuited at very low frequ.)

$$\boxed{R_T(\text{seen by } 1\mu F) = R_{11} + R_{12}}$$

& $f_c = \dfrac{1}{2\pi(1\mu F)(R_{11} + R_{12})}$ $\begin{cases} \xrightarrow{\underline{R_{12}=R_{11}=2.4\,k\Omega}} = 33\,\text{Hz (low-Q)} \\ \xrightarrow{\underline{R_{12}=R_{11}=120\,k\Omega}} = 0.6\,\text{Hz (High-Q)} \end{cases}$

$\boxed{\text{DOES NOT AFFECT AT } W_D!}$

3) For $Q=0.2$ & $f_0 = 9.3\,kHz$, the response looks like a single-pole 2/4 at $\omega_1 = \omega_0 Q = 1.8\,kHz$



$f_1 = 1/2\pi C_2 R_2$

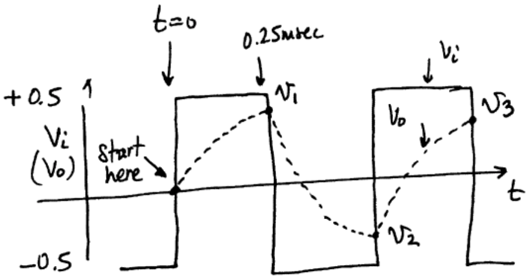
To solve problem 2(c), go back to first-order differential equations.

Time constant $\tau \equiv (RC) = \frac{1}{\omega_1} = \frac{1}{2\pi f_1}$

$\tau \simeq 88\,\mu s$ (meas.)

$V_i = 1\,V_{ppk}$

$f_i = 4\,kHz$



$$V_o(t) = A + B\,e^{-t/\tau} \qquad \tau = 88\,\mu sec$$

$$A = v(\infty)$$

$$A + B = v(0)$$

1rst half-cycle: $v(t) = 0.5 - 0.5\,e^{-t/88\mu sec} \Rightarrow v_1(0.25ms) = 0.471^V$

2nd half-cycle: $\left.\begin{array}{l} A = v(\infty) = -0.5 \\ A+B = v(0) = 0.471 \Rightarrow B = 0.971 \end{array}\right\} \Rightarrow v(t) = -0.5 + 0.971\,e^{-t/88}$ @ $t=0.25msec$, $v_2 = -0.443^V$

3rd half-cycle: $\left.\begin{array}{l} A = v(\infty) = {}^{+}0.5 \\ A+B = v(0) = -0.443 \Rightarrow B = -0.943 \end{array}\right\} v(t) = 0.5 - 0.943\,e^{-t/\tau}$ @ $t=0.25msec$, $v_3 = 0.445^V$

4th " " : $v_4 = 0.445^V$

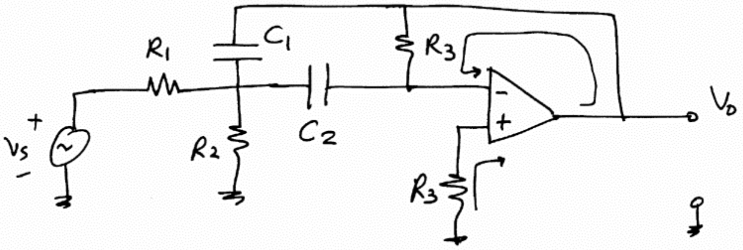
& $V_o(ppk) = 0.445 - (-0.445) = \underline{890\,mV}$ close to measured -

## Some notes on Exp. #2 :

3/4

1) Open the lab manual & go through the equation & the figures. No need to write something on the board unless asked. Stress that final value of B.P.F. in time domain is zero! —

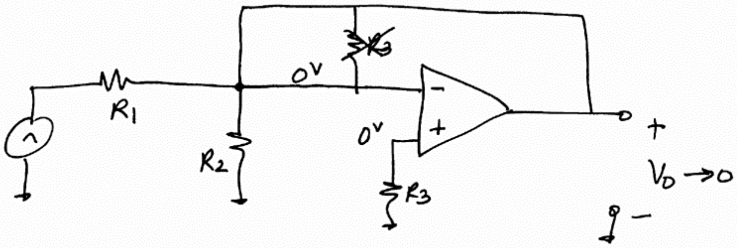
2)



a) DC bias currents to op-amp possible ⇒ Good operation.

b) $\omega \to 0$ , $C_1$ & $C_2$ ≡ Open Circuit & $V_o \to 0$ (easy)

$\omega \to \infty$ , $C_1$ & $C_2$ ≡ Short circuit & $V_o \to 0$



c) Notice that we put $R_3$ on the (+) terminal to make sure that the dc voltages at (−) & (+) terminals are the same

⇒ $V_o(dc) \simeq 0$ even if high gain is present.

d) Gain·bandwidth product ≡ 1 MHz . ⇒ Cannot get high gain with high Q at 100 KHz! Design in lab is Gain = 10 at f = 8.5 KHz —

4/4

e) look at equations for $C_1 = C_2 = C$ & relatively large $Q$:

$$\omega_0 \simeq \frac{1}{C\sqrt{R_2 R_3}} \qquad Q = \frac{1}{2}\sqrt{\frac{R_3}{R_2}} \quad \& \quad K = \frac{1}{2}\frac{R_3}{R_1}$$

Controls Resonant Freq. ALONE!

Controls $K$ (gain) ALONE!

Very good characteristics! Can move resonant frequency by changing $C$ only. Can control gain by changing $R_1$ only! Cannot control $Q$ independently of $\omega_0$ or $K$ —

3) Open the lab notebook & talk about FSK Communications & the use of band-pass filters to detect the received signals —

# Week 6:
# Experiment #2 (Active Bandpass Filters; Frequency Shift Keying Communications)

Arrive early, turn on all of the equipment, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). Make sure that each bench has the correct components for the band-pass filter (placed in a small dish).

When the students arrive, check their name in the log-in sheet and ask them to take a seat.

1. After they sit down, explain to them that this is a serious lab and that they should not waste time.
2. Tell them where the components are (but they will not need them) since they have them on their bench. Each one should get two (or three) coax-banana plug cables, and at least three banana-banana cables (and alligator clips) for the power supply.
3. Ask them to assemble the filter, and then to show it to you before connecting the circuit to the power supply. Make sure that they tell you which node is $V_i$ and $V_o$ , $V_{cc}^{+}$, $V_{cc}^{-}$, etc… . Check the polarity of the capacitors.
4. Let them start the experiment, and while the experiment is going on, pass one by one and check their pre-lab. Do not correct the pre-lab, just check that it is done, and sign in the book noting any missing problems.
5. If someone did not do their pre-lab, tell them that they must talk to the Professor. Generally, they are so scared that they straighten up quickly.
6. Be receptive to questions and always walk and see what is happening at the scopes. Do not sit down for a long time. Pass by the benches and ask questions if you wish to see that they understand their measurements.
7. Send an email to the rest of the TAs and the Professor detailing your lab section (time it took, any problems, etc.).

Generally, this lab goes very smoothly since the students are seeing the time domain again, and now are familiar with the equipment.

# Week 7:
# Lab Lecture; Preparation for Exp. #3 (Diodes and Bridge Rectifiers)

Arrive early, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). When the students arrive, check their name in the log-in sheet and ask them to take a seat.

This lab lecture is divided into two parts. The first part is a short review of experiment #2. The second part covers experiment #3. It should take around 60 minutes, with a short break in the middle. Read the attached notes and present them in the lab.

Since Exp. #2 is so well behaved and is the second experiment on filters, there are generally very few things that one needs to cover. So, this portion should be very short.

1. Ask if there are any questions on experiment #2.
2. Cover Problem 5b in the lab report #2 (see attached notes).

Now, move to diodes and bridge rectifiers. The students are pretty confused on this topic and you need to go through all the papers that are included in your own preparation of this lab to be comfortable in this lecture.

1. Draw the bridge rectifier circuit on the board and talk about the currents in the load, capacitor, etc.
2. The bridge rectifier equations (see p. 62 in the lab manual) are very approximate and conservative. When you build and measure the rectifier, you will find that the ripple voltage and output voltage are decently predicted by the equations, but the values of turn-on time of the diode and the current peak in the diode are very different from calculations. This is due to the very simple approximations done in the calculation of the turn-on time of the diode, which affects the calculations of the current peak in the diode. This is OK since the calculated values give you a conservative estimate, and therefore are never wrong!
3. When you model this circuit with Spice, you will see large initial currents in the diode/capacitor. This is needed to initially charge the capacitor to $V_{opk}$, and after it arrives to this voltage, the steady-state analysis and the approximate formulas apply.
4. MOST IMPORTANT: It is never possible to ground both the transformer and the output node in power supplies. If you do this, then you short the diodes ($D_2$ in this case) and you get a half-wave rectifier! The voltages, referenced to ground at the load, are shown on the handout for a 16 V peak input voltage.
5. There are several ways to calculate the current in the load. Either from $V_o/R_L$, or from the discharge slope of the capacitor voltage waveform, or from the measured discharge current of the capacitor (when the diodes are OFF).
6. Full-wave rectifiers have $1/\sqrt{2}$ less peak current in the diode than half-wave rectifiers. The explanation is that the capacitor discharges for only half a cycle (and not a full cycle as a half-wave rectifier) and therefore, requires half of the charge (of a capacitor in a half-wave rectifier). This results in $1/\sqrt{2}$ less in turn-on time and $1/\sqrt{2}$ less in peak current value!
7. Finally, talk about the pre-lab problem #2. This is a special case of a half-wave rectifier. It uses the half-wave rectifier equations but with two diode voltage drops.

## Week 7 Lab Lecture :

1/5

1) Problem 5(b), in Lab Report #2 is interesting. Read it again in class & ask how many derived it analytically & ~~not~~ did not use MATLAB to determine Q. The solution is quite straightforward –

$$|H(\omega)| = \frac{\left(\omega_0/Q\right)(\omega)}{\sqrt{(\omega_0^2-\omega^2)^2 + \left[\left(\frac{\omega_0}{Q}\right)\omega\right]^2}}$$

Band-Pass Filter

Put $\omega = \omega_0 + \Delta\omega$

$= \omega_0\left(1+\frac{\Delta\omega}{\omega_0}\right)$

with $\frac{\Delta\omega}{\omega_0} \ll 1$

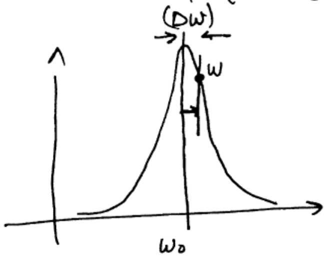
& $Q \gg 1$

After expansion, you find

$$H(\omega) = \frac{\left(\frac{1}{Q}\right)\left(1+\frac{\Delta\omega}{\omega_0}\right)}{\sqrt{4\left(\frac{\Delta\omega}{\omega_0}\right)^2 + \cancel{\frac{1}{Q^2}\left(1+\frac{2\Delta\omega}{\omega_0^2}\right)}}}\ \text{negl.} = \frac{\frac{1}{Q}\left(1+\frac{\Delta\omega}{\omega_0}\right)}{2\left(\frac{\Delta\omega}{\omega_0}\right)}$$

$$\Rightarrow \boxed{H(\omega) = \frac{1}{2Q}\left(1+\frac{\omega_0}{\Delta\omega}\right)}$$

← Close to the resonant frequency $\left(\frac{\Delta\omega}{\omega_0} \ll 1\right)$



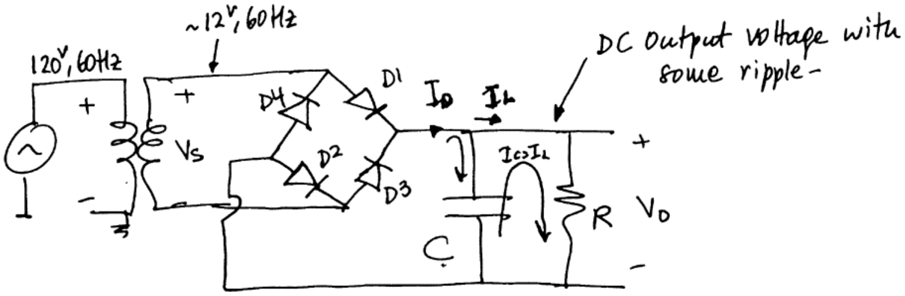
For $\omega_0 = 10$ MHz $(\times 2\pi)$

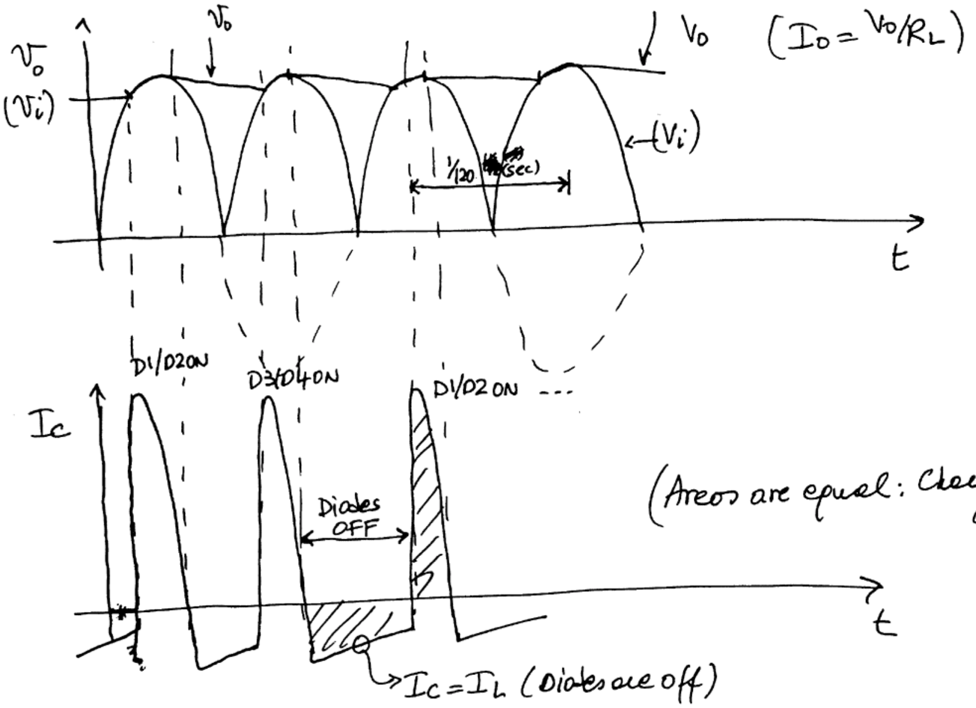
$\Delta\omega = 0.2$ MHz $(\times 2\pi)$

& $H(\omega) = 0.1$ (−20dB)

One can find $0.1 = \frac{1}{2Q}\left(\frac{10}{0.2}+1\right) \Rightarrow \boxed{Q = 255}$

Summary of currents in rectifiers (Full-Wave): (Handout in class) (In lab) (WEEK 7 Lab 2/5 Lecture





(Areas are equal: Charge In = Charge Out).

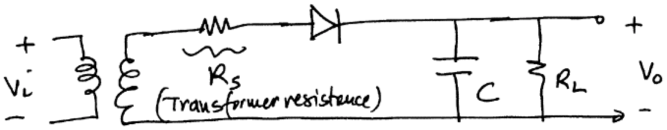
$I_D = I_C + I_L$ (when Diodes are ON).

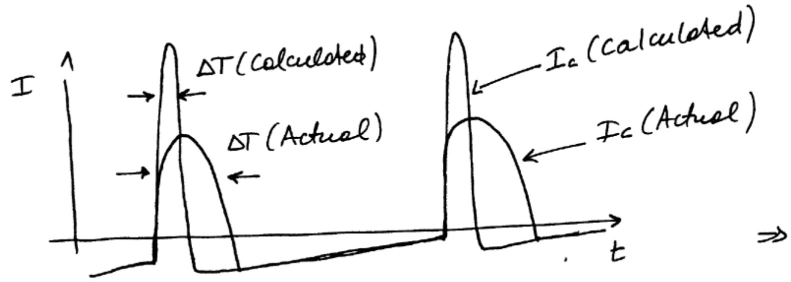
$I_D = 0$ (Diodes OFF).

## Notes on Diode Bridge Rectifiers: 3/5 WEEK 7 lab Lecture

1- The equations for Δt and the currents ($I_D$, $I_C$) are very approximate. The reason is the simplification $\cos(\omega\Delta t) \simeq 1-\frac{1}{2}(\omega\Delta t)^2$ used to derive the equations. this is not very accurate & results in a small value for ΔT. The real bridge rectifier will have a larger ΔT, and therefore a smaller peak current. (Also, the series resistance in the transformer winding will limit the current & increase ΔT, a bit).

Ex: A half-Wave Rectifier





ΔT(calc) << ΔT(actual)
2-3 times less
⇒ $I_{c_D}$ (calc) >> $I_{c_D}$ (actual)
⇒ Conservative Estimate !

For example, in Pre-lab#3 (Problem 1);

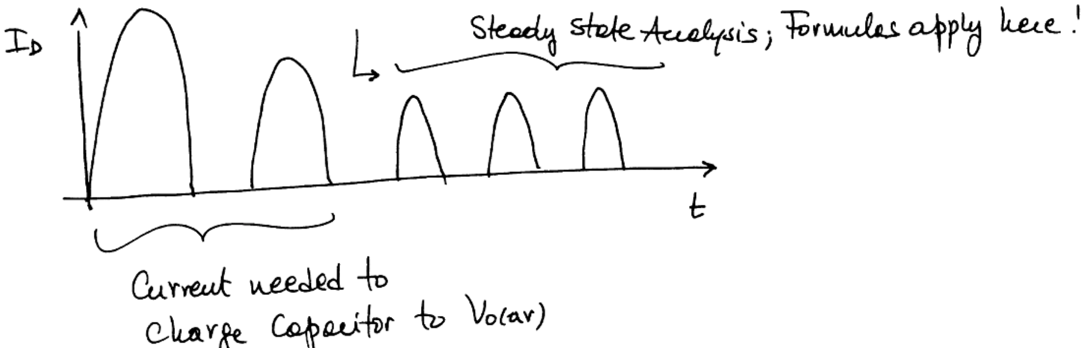
you will calculate: $\Delta T_{(cal)} = 1.20\ \text{ms}$ & $I_{C(pk)(cal)} = 404\ \text{mA}$

But using exact formulas, you will find (calculate) that:

($R_S = 0$) $\Delta T_{(actual)} = 1.7\ \text{ms}$ & $I_C(pk) = 275\ \text{mA}$

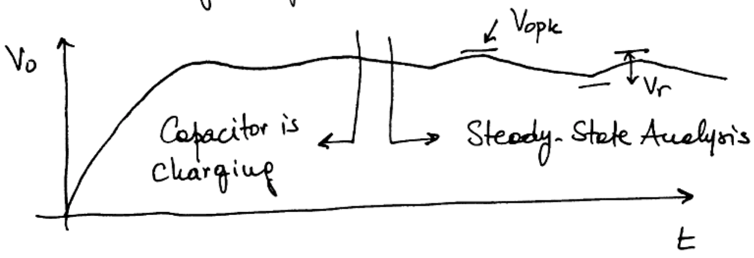
Notice: $275\ \text{mA} \simeq (404\ \text{mA}) \times (1.2/1.7)$ ⇒ Area rule still applies.

2- When you model the circuit in SPICE, you will find: 4/5



Steady state Analysis; Formulas apply here!

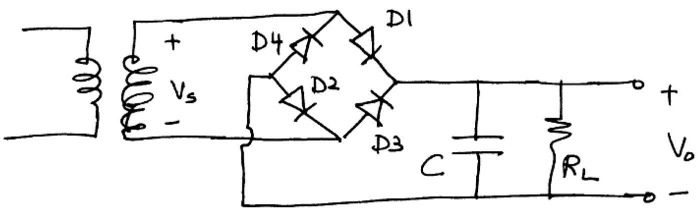
Current needed to charge Capacitor to $V_o(av)$



Capacitor is charging

Steady-State Analysis

3- Correct Voltages on the circuit (what textbooks do not tell you):



Let us say:

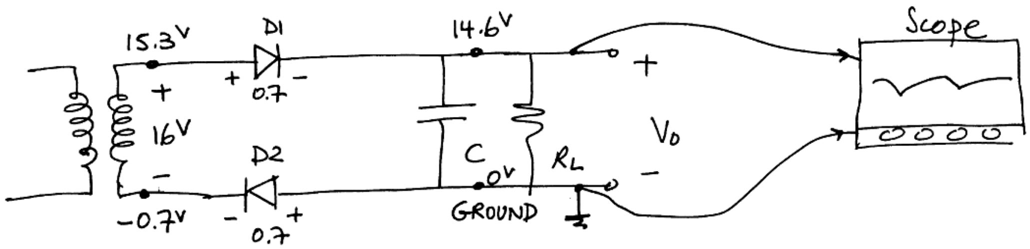
$V_s(rms) = 11.3^V$

or $V_{spk} = 16^V$

$V_{opk} = V_{spk} - 2V_D$ ($V_D = 0.7$)

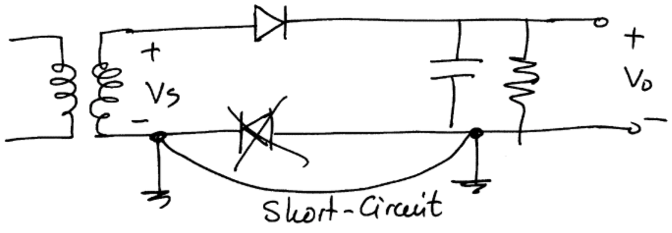
$= 14.6^V$

For the half-cycle where D1 & D2 are ON, the circuit becomes:



(for the other half cycle, D3/D4, all voltages are reversed).

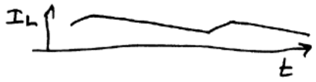
Notice that you cannot ground both Vs & Vo. If you do this, you will short-circuit D2 (& D4) and the circuit becomes a half-wave rectifier!



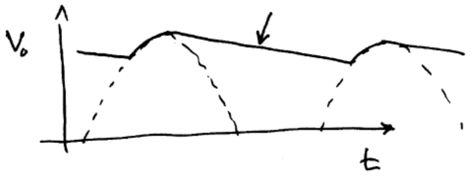
⇒ You can measure Vo or Vs, one at a time, but never together. This is very important! —

## 4- How to Calculate $I_L$ accurately:

a) $I_L = \frac{V_o}{R_L}$ ⇒ know $V_o(t)$ ($V_{opk}$, $V_{oav}$), know $R_L$ ⇒ Get $I_L(t)$

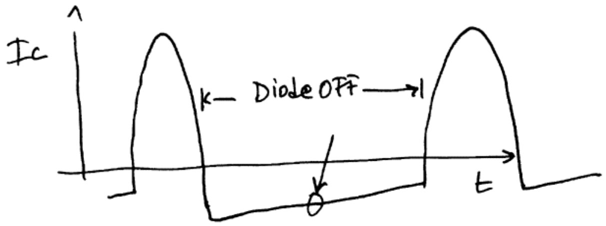


b) Use the slope of the discharge portion of the capacitor



$$I_c(disch) = I_{Load} = C\underbrace{\frac{\Delta V}{\Delta T}}_{slope}$$

c) Measure $I_c$ in the discharge portion



$$I_c(disch) = I_{Load}$$

# Week 8:
# Experiment #3 (Diodes and Bridge Rectifiers)

Arrive early, turn on all of the equipment, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). Make sure that each bench has the correct components (transformer, etc…) for the bridge rectifier lab. Check the fuse on each transformer is working properly and change fuses if necessary.

When the students arrive, check their name in the log-in sheet and ask them to take a seat.

1. Tell them where the components are (but they will not need them) since they have them on their bench. Ask the students to use a small corner of the proto-board since the diodes do damage the small pin-holes of the board.
2. The students should use two banana-banana cables (and alligator clips) to test the diodes. These cables should be removed from the bench once the dc diode test is complete.
3. Perhaps the most important thing to tell the students is that when they start the measurement of the bridge rectifier, ONLY ONE coax-banana plug cable is allowed for each bench. This will prevent them from shorting out the nodes (by trying to make two node measurements at the same time) and blowing out the fuse.
4. Let them start the experiment, and while the experiment is going on, pass one by one and check their pre-lab. Do not correct the pre-lab, just check that it is done, and sign in the book noting any missing problems.
5. If someone did not do their pre-lab, tell them that they must talk to the Professor. Generally, they are so scared that they straighten up quickly.
6. Be receptive to questions and always walk and see what is happening at the scopes. Do not sit down for a long time. Pass by the benches and ask questions if you wish to see that they understand their measurements.
7. Send an email to the rest of the TAs and the Professor detailing your lab section (time it took, any problems, etc…).

This lab has received a mixed response. Some groups find it very easy and some groups find it hard!

# Week 9:
# Lab Lecture; Preparation for Exp. #4 (Diode Small-Signal Measurements, Amplitude Modulation, Envelope and Square-Law Diode Detectors)

Arrive early, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). When the students arrive, check their name in the log-in sheet and ask them to take a seat.

This lab lecture is divided into two parts. The first part is a short review of experiment #3. The second part covers experiment #4. It should take around 90 minutes, with a short break in the middle. Read the attached notes and present them in the lab.

1. Start by talking again on the power supplies, but this time include some numbers to compare the measured and calculated turn-on times of the diodes and the peak current values.
2. Ask if there are any questions related to the experiment #3.
3. Now, move on to diode small signal analysis. Talk about the circuit on page 80 and how it can be divided into dc and ac circuits. Talk about linear and non-linear regimes of the diode and how a 5-10 mV peak signal across the diode junction is considered as the limit of the diode linear operation.

   Take a 10 minute break.

   Ask the students to come closer to your bench.
4. Present the concept of AM signals on the board. Draw it in time and frequency domain. Show it on the scope with $f_c$=100 KHz and fm=4 KHz and carrier amplitude of 2$V_{ppk}$ for different values of m (0.4, 0.8, 1.0 and 1.2), in time and frequency domain. Make sure to use the sync. signal in order to see the AM modulation on the scope. Discuss the peak/minimum values (A(1+m) and A(1-m)) and show it for m=0.6 and m=1.0 ($V_{pk}$=2A and $V_{min}$=0). Show them the m=1.2 case and how the modulation goes negative in time domain (this is very bad for distortion and therefore is never used).
5. The AM detector should be built and on the bench. Show them AM detection for the case of with $f_c$=1 MHz and $f_m$=4 KHz and carrier amplitude of 2$V_{pp}$k, and m=0.4-1.0. Measure $V_0$ at 4 KHz in time and frequency domain, and note the change in the distortion components as m increases/decreases. Tell them that it is the $V^2$ component in the diode I-V equation that is demodulating the AM signal. Finally, talk about the DC component of the output voltage and therefore the DC current in the diode circuit. Note that the AM source has no DC voltage, therefore, the DC current in the diode is coming from the demodulation process!

# Week 9 Lab Lecture

Diode Bridge Rectifier: Comparison between Approx. Calculation, Spice ($R_S=0$), Spice ($R_S=12$) & Measurements.

## Full-Wave Rectifier

| | Simple Calc | Spice ($R_S=0$) | Spice ($R_S=12$) | Measurements |
|---|---|---|---|---|
| $\Delta T_{(ON)}$ | 1.1–1.20 ms | 1.7ms | 2.2ms | 2.3–2.4ms |
| $I_C(pk)$ | ~ 410–430mA | 275mA | 95–120mA | 95–120mA |

~~Change~~ Spread depends on $V_i(ppk)$, Cap. value, O.S.S
series resistance, etc...

But notice how conservative the calculations are !!

# Week 10:
# Experiment #4 (Diode Small-Signal Measurements, Amplitude Modulation, Envelope and Square-Law Diode Detectors)

Arrive early, turn on all of the equipment, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). Make sure that each bench has the correct components for the experiment.

When the students arrive, check their name in the log-in sheet and ask them to take a seat.

1. After they sit down, explain to them that this is a serious lab and that they should not waste time. In general, this lab takes 3 hours and for some students, a bit more!
2. Tell them where the components are (but they will not need them) since they have them on their bench. Each one should get two coax-banana plug cables, one coax-coax cable for the sync signal to the scope and one banana-banana cables (and alligator clips) for the power supply.
3. Let them start the experiment, and while the experiment is going on, pass one by one and check their pre-lab. Do not correct the pre-lab, just check that it is done, and sign in the book noting any missing problems.
4. If someone did not do their pre-lab, tell them that they must talk to the Professor. Generally, they are so scared that they straighten up quickly.
5. Be receptive to questions and always walk and see what is happening at the scopes. Do not sit down for a long time. Many students still do not understand linear and non-linear analysis of diode circuits. Therefore, pass by the benches and ask questions if you wish to see that they understand their measurements.
6. Send an email to the rest of the TAs and the Professor detailing your lab section (time it took, any problems, etc…).

This lab has received a very good response. The students are excited about AM modulation and demodulation.

# Week 11:
# Lab Lecture; Preparation for Exp. #5 (LEDs, Phototransistors and an AM Photonic Link)

Arrive early, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). When the students arrive, check their name in the log-in sheet and ask them to take a seat.

This lab lecture is divided into two parts. The first part is a short review of experiment #4. The second part covers experiment #5. It should take around 90 minutes, with a short break in the middle. Read the attached notes and present them in the lab.

1. It is important to talk again on linear and non-linear response of diodes, the dc and ac circuits for diodes, and the maximum voltage ($V_{spk}$ ) that can be applied and still keep the diode in linear operation. Also, say again that the voltage $V_{spk}$ is across the diode junction, that is, one should take into account the voltage drop across the series resistance of the diode so as to determine the exact junction voltage.
2. Solve problem 3b in the post-lab, which is to calculate the corner frequency of the AM detector. (It does not agree perfectly with measurements because the diode is really not in small-signal mode and therefore the equivalent resistance is not perfectly accurate. Still, it is quite close.)

You can take now a 5 minute break.

3. Explain the operation of LED as per the manual. Go to the data sheet and start by explaining the graphs:
   - Fig. 1: Show the spectral response of the different LED's.
   - Fig. 2: Forward I-V curve with a 2.0 V drop for a 15 mA bias current. Note that I-V curve is not exponential
   - Fig. 3: The output luminous intensity vs. dc current. Note that it is quite linear for 15 mA and above.
   - Fig. 6: The pattern of the LED diode. Note that half power angle is at +/- 22° (this is quite a directive LED).
4. Then go to the LED table and concentrate on the HP 3316 specifications (luminous intensity, i.e., as perceived by the eye; half luminous intensity points; peak wavelength, spectral line wavelength; speed of response; capacitance; forward voltage; and reverse breakdown voltage).
5. Talk now about the linearity of LED's. From your lab preparation notes, I include the following paragraph:
6. "LED's are different than diodes in the fact that they require a large bias current (around 15 mA) so as to produce a sufficient light output. The LED junction resistance $r_d$ is around 3 Ω and since $R_s$ is around 10-16 Ω, we find that a large portion of the LED ac-voltage is across $R_s$ and not $r_d$! Also, LED's do not have an exponential output light intensity vs. bias current (it is much more linear as seen in Fig. 3b) and therefore can handle a large current variation with no appreciable distortion. This means that the LED junction voltage can be quite large (around 30 $mV_{ppk}$), which results in an *input* LED voltage of 400-800 $mV_{ppk}$ before any distortion is detected!"

7. Talk about phototransistors and how they detect light and convert it to an electrical signal. Go to the data sheet and start by explaining the graphs:
   - Relative Spectral Sensitivity: How it peaks at 850 nm (infrared) but is good from 500-1000 nm.
   - Photocurrent (BPX 81-3- middle line): the phototransistor results in 0.12 mA of output current for an incident power density of 0.1 mW/cm$^2$ on its aperture (that is at 850 nm).
   - Dark Current: This is a measure of the noise and it is 30 nA at 25C.
   - Directional Characteristics: This device is quite directional and is sensitive to around +/-20˚.
8. Talk about the square-law detection in phototransistors and how they demodulate the carrier (light) immediately. This means that the phototransistor really responds to the envelope of the modulated light and not the light itself!

# Week 12:
# Experiment #5 (LEDs, Phototransistors and an AM Photonic Link)

Arrive early, turn on all of the equipment, make sure that the lab is clean (no paper on benches, chairs in their correct places, etc…). Make sure that each bench has the correct components for the experiment and do not forget the headphones.

Also, make sure that there is at least one optical AM transmitter which is attached to a portable CD or tape layer and has a directive lens in front of it. (You will “shine” music to the student’s bench and they should receive it with their set-up and listen to it on the headphones.

When the students arrive, check their name in the log-in sheet and ask them to take a seat.

1. After they sit down, explain to them that this is a fun lab and that they are encouraged to experiment after taking their data. Most of the students will be finished in two hours.
2. Tell them where the components are (but they will not need them) since they have them on their bench. Each one should get two coax-banana plug cables and one banana-banana cables (and alligator clips) for the power supply.
3. Let them start the experiment, and while the experiment is going on, pass one by one and check their pre-lab. Do not correct the pre-lab, just check that it is done, and sign in the book noting any missing problems.
4. If someone did not do their pre-lab, tell them that they must talk to the Professor. Generally, they are so scared that they straighten up quickly.
5. Be receptive to questions and always walk and see what is happening at the scopes. Pass by the benches and ask questions if you wish to see that they understand their measurements.
6. Shine your output (with a nice CD/tape music) on the student bench and ask the student to point his phototransistor in your direction. He/she should clearly hear the music you are broadcasting. Lower the room lights for more signal/noise ratio.
7. Send an email to the rest of the TAs and the Professor detailing your lab section (time it took, any problems, etc…).

This lab has received the best response of all labs. The students simply have fun in this lab.