University of Minnesota

Department of Electrical and Computer Engineering

EE 3101 Lab Manual

A Second Laboratory Course in Electronics
Introduction

You will find that this laboratory continues in the mode initiated in EE2002. It is intended to supplement the Junior microelectronics course sequence and to familiarize you with instruments that will be used in later labs. It is also intended to further develop your self-confidence in laboratory procedures and in drawing conclusions from observations. As a consequence the instructions are very spare and assume you will be able to extract conclusions from each experiment and will relate parts of the total lab to each other without being explicitly asked to do so.

Important Points

- Your grade in this course will depend principally on your in-lab work.

- You are expected to maintain a lab notebook. Your lab notebook must contain a running account of the experiment. It is not intended to be a book into which you copy notes previously gathered on the back of an envelope. It must however be legible and coherent. Write in such a way that another person could perform the same experiment based on your account and that same person could understand the conclusions that you drew from your data. It is not necessary to hide your mistakes. If you make a mistake in an entry simply draw a line through that entry and start over - you will not be penalized for this.

- The lab notebook should have the following characteristics:
  - It should be a bound notebook (spiral bound is ok).
  - Lab entries should be dated, and should include:
    - Complete circuit diagrams.
    - Explanation of circuit, methods, procedures, etc.
    - All calculations for designs.
    - All measurements (including component values).
    - All analysis and comparisons of data with theory.

- There are no formal lab homeworks or pre-labs in this course, but it will pay great dividends for you to make a careful reading of the experiment description before arriving in the laboratory. You will also note that some parts of the "experiments" involve analytical work which can be better done elsewhere. **Most problems students have with this course are due to lack of preparation prior to coming to lab.** If after reading through the lab and consulting the relevant section of your EE2001, EE2011, and EE3115 text you do not understand something, seek out either your TA or the faculty member in charge of the lab.

- MILESTONES. In each experiment there will be a few “milestones”. These are specific tasks which must be accomplished and demonstrated to the TA or professor before going on to the next item. All milestones must be completed or you will not pass the course. If the milestones are not completed by the end of the quarter you will receive an F for the course. While the milestones are not a part of the grade formula, delays in milestone completion will unavoidably delay the submission of your lab notebook with the corresponding grade penalty. **Lab notebooks and lab write-ups will not be accepted if more than one milestone remains to be completed for the corresponding lab.**

- Grades. Grades will be determined from the following components of the course:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Lab Notebooks</td>
<td>30%</td>
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<tr>
<td>Lab Practical Exams</td>
<td>40%</td>
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<tr>
<td>Lab Reports</td>
<td>30%</td>
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**Take them seriously, they are forty minutes to one hour in duration and account for a significant portion of your final grade.**

Lab notebooks will be collected up to three times during the quarter. They will be due at 4:30 pm three working days after the scheduled completion date of a lab.

Lab write ups will be collected one week after scheduled completion of the lab.

You will be given a schedule during the first week of class which contains all lab practical exam dates and notebook and lab write-up due dates.

- Late Penalties. The penalties for late notebooks or lab write-ups are as follows:
1 or 2 days late: 3% deducted from your FINAL GRADE.

3 or 4 days late - an additional 3% deducted from your FINAL GRADE.

and so on...

-You will receive a separate handout to characterize the lab write-ups
Experiment #1

Familiarization with the Digital Oscilloscope

Duration: 2 weeks

Introduction

This lab will help you become familiar with one of the more complicated instruments to be encountered in this course - the Tektronix analog/digital storage oscilloscope. During the first scheduled meeting you will view a demonstration explaining the features of the Tektronix 2211 digital oscilloscope and those of the slightly newer 2216's. The following measurements should help to reinforce the concepts involved.

Experiment

Digital Oscilloscope Familiarization

1. Sine wave measurement

Set up the signal generator to provide a sine wave at approximately 1 kHz and use the oscilloscope to determine its period and amplitude. Use the preset conditions for basic self-triggered operation. Compare analog (real time) and digital storage acquisitions. Reduce the frequency to about 1 Hz and observe the waveform using the roll chart mode.

2. View a 1 kHz sinusoid

Return to viewing the 1 kHz sine wave but use the TTL output from the signal generator to trigger the scope sweep. View the triggering waveform on the second scope channel. Be sure that you understand the different types of triggering and the functions of the trigger controls, such as coupling type, level, slope, etc.

3. Scan a V-I curve

Design an arrangement to plot on the scope face the V-I curve for a silicon diode. Repeat for one of your LED’s. (Be careful that you do not exceed the current limitation of the diodes!)

MILESTONE #1-1: Demonstrate to your instructor or TA the operation of the circuit you designed in Item 3.

HP 35660A Familiarization

The HP is a menu-driven digital instrument of great versatility. It requires some time to become proficient in its use. A brief in-class demonstration will be given. Before continuing it is strongly recommended that you go through the step-by-step familiarization described in sections 5 and 8 of the HP "Getting Started Guide". These sections are entitled "Measurement of Spectral Purity of a Sine Wave" and "Filter Characterization".

4. Extract the first two harmonics of a square wave.

In this section we will examine the harmonic content of a square wave. Apply an approximately 1 KHz, 2 V peak-to-peak square wave to the input of the spectrum analyzer. Determine which frequencies are present out to about 50 kHz.

MILESTONE #1-2: Show the display of your spectrum analyzer with the above spectrum captured.

5. Evaluate the performance of an inverting operational amplifier.

Construct an inverting operational amplifier with a gain of about 100. Apply an approximately 20 Hz, 10 mV peak-to-peak sine wave to the input. Observe the spectral purity of the input and the output with the spectrum analyzer. How do they compare?

6. Frequency response of the operational amplifier.

Using the filter characterization techniques explained above examine the frequency response of the operational amplifier from low frequency to 50 kHz. What happens to the high frequency response of this amplifier? Remember, the output supplied by the spectrum analyzer to the input of the op amp has to be small enough so as not to cause the output to hit power supply limits.

MILESTONE #1-3: Demonstrate your method of determining the frequency response of the amplifier.
Experiment #2
RC Circuits
Duration: 2 weeks

Experiments

1. Construct a simple RC single time constant circuit of the form shown.

Choose component values such as to make the time constant about 0.1 ms and determine the time constant experimentally by observing resistor and capacitor voltages when a square wave is applied to the input port.

2. Determine the extent to which the output resistance of the signal generator has affected the result of item 1.

3. Many applications require that a sharp pulse be generated to mark the time at which a rapid change occurs in a signal. Design a simple circuit based on the work of the preceding items which will generate a sharp spike whenever the square wave input changes sign.

4. Investigate the magnitude and phase of the output of the original RC circuit as the frequency of the driving sinusoid is varied over a suitably wide range. Determine the frequency at which the magnitude is down to 0.707 of its frequency-independent value. Determine the frequency at which the output is phase shifted by 45 degrees with respect to the input.

5. Return to your circuit of item 3 and repeat the measurements of item 4.

6. Construct and test a circuit which generates a 5 + 1 sin(2πft) V signal, with f = 10 kHz. Do not use the signal generator dc offset for this purpose.

7. Design a circuit which will take the dc + ac signal generated by the circuit constructed in item 7 and pass only its ac component along to a 100 kΩ load resistor.

8. Design a circuit which will take the dc + ac signal generated by the circuit constructed in item 7 and pass only its dc component along to a 100 kΩ load resistor.

Week #4 Demonstration
The instructor will demonstrate how frequency responses may be displayed on the scope.

Experiments

9. Design an RC high-pass section which will have a corner frequency at about 200 Hz and a midband input resistance of 10 KΩ. Display the response on the scope.

10. Design an RC low-pass section which will have a corner frequency at about 2 KHz and a high-frequency input resistance of 10 KΩ. Display the response on the scope.

11. Design an RC network having a midband input resistance of 10 KΩ and whose transmission falls by 3 dB at 100 Hz and 10 KHz. Display the response.

12. Investigate the effect of your “filter” of item 3 on square waves of various frequencies.

13. Design a series RLC circuit which has resonant frequency of 2 KHz and a Q of 5.

MILESTONE #2-2: Demonstrate the circuit of item 5 to your instructor.

Experiment #3

Non-ideal Behavior of Electronic Components at High Frequencies and Associated Measurement Problems
Duration: 3 Weeks

Introduction

Electrical measurements at high frequencies are significantly more difficult than are those at dc or low frequencies. Shunt capacitance in interconnect cables and in measuring instruments present unknown shunt impedances at the measurement terminals. These load impedances decrease (and thus the loading increases) as the frequency increases. In this experiment you will investigate the use of the compensated attenuator or voltage probe as a means of minimizing shunt capacitance problems.

Another effect observed at high frequencies is resonance in circuits which contain both capacitance and inductance. Resonance in series and parallel RLC circuits will be examined.
Finally, at high frequencies, resistors and inductors will manifest non-ideal behavior. The magnitude of the parasitic elements, particularly capacitance, which are the sources of the non-ideal behavior will be measured and equivalent circuit representations for the non-ideal behavior will be established.

**Experiment**

**Shunt Capacitance and the RC Compensator**

1. **Measure the transfer function** $|V_o/V_i|$ **of the circuit shown from 1 kHz to 1 MHz.**

Use the experimental results to estimate the shunt capacitance of the oscilloscope and interconnecting cable.

**MILESTONE #3-1**: Demonstrate on the o-scope how $V_o$ changes as a function of frequency.

2. **Check whether the probes for your oscilloscope are properly compensated.**

Use the 0.5V, 1 kHz square wave available on the front panel of the oscilloscope to do this. The 3 figures below show the o-scope traces which should be observed for the various degrees of compensation.

**Resonance in RLC Circuits**

4. **Design a series RLC circuit (similar to that shown) which has a resonant frequency of 2 kHz and $Q=5$.**

Measure the magnitude and phase of the impedance $Z_{in}$ over a wide enough frequency range so that the complete frequency-dependent behavior of the impedance is determined.
MILESTONE #3-2: Demonstrate that the circuit has the intended resonant frequency and Q.

5. Drive the circuit of Item 4 with a 2 kHz square wave and observe the current waveform. Measure the spectra of the waveforms of the current and of the input voltage.

6. Determine the resonant frequency $f_0$ of the circuit of Item 4 for C values from 0.001 uF to 0.1 uF.

Determine the functional relationship between $f_0$ and C.

7. Design a parallel resonant circuit with a resonant frequency of 2 kHz and $Q=5$.

Measure the magnitude and phase of the admittance of this circuit over the same frequency range as used in Item 4.

MILESTONE #3-3: Demonstrate, on the spectrum analyzer, your result for Item 7.

Nonideal Frequency Behavior of Passive Components

8. Measure $V_o/V_i$ as a function of frequency for this circuit with $R > 500 \text{ k}_\Omega$ and $R_L = 5 \text{ k}_\Omega$.

Measure well beyond the -3 db frequency. Use the data to determine the parasitic capacitance in shunt with the resistor R.

MILESTONE #3-4: Demonstrate, on the o-scope, the frequency response obtained for Item 8.

9. Use the digital LCR meter in the laboratory to determine the shunt capacitance of the resistor $R$ used in Item 8.

10. Use the digital LCR meter to measure the capacitance and dissipation factors of two different types of capacitors e.g. Mylar and ceramic.

Calculate the values of the circuit components in the series and parallel equivalent circuits of the two capacitors.

11. Use the LCR meter to determine the inductance $L$ and series winding resistance $R_w$ of a fixed value inductor which is provided in the laboratory.

A model (adequate for many purposes) of a real inductor is shown below.

12. Use the circuit shown below to determine the magnitude $|Z(j\omega)|$ of the impedance of the inductor used in part 11 from 100 Hz to 1 MHz. Use the data to estimate the $L$, $R_w$, and $C_w$ of the equivalent circuit shown in part 11.

Experiment #4

Power Supplies

Duration: 2 Weeks

Introduction

In this lab you will examine the basic building blocks of circuits that effect ac to dc conversion.

Experiment

Transformer and auto-transformer
Each station is supplied with a box containing a variac (variable transformer) and a step-down transformer. These units are fused at 1 amp and it is easy to blow these fuses. Your TA will give you a short list of no-no’s which (if you follow them) will save you a good deal of trouble.

1. Measure the voltage across the secondary of the transformer as a function of the primary voltage.

![Variac](image1)

2. Connect this circuit and examine the diode and resistor voltage waveforms.

![Variac/Transformer](image2)

Capacitive Filtering

3/ Place a suitable capacitor across the load (the resistor) of the previous item (observe the polarity).

Choose a capacitor that will give an RC time constant of about 15 ms. Again examine the waveforms.

4/ Repeat item 3 using a different capacitor.

5/ Repeat item 3 using a different load resistance.

MILESTONE #4-1: Demonstrate and explain the circuit of Item 5.

6/ Choose from the circuits of items 3, 4 and 5 the one that shows the minimum ripple (peak-to-peak) in the load voltage and check the effect of reversing the polarities of both the diode and the capacitor.

Full Wave Rectifier

7/ Now construct a circuit, driven from the center-tapped secondary winding, that contains 2 diodes and 1 resistor (the load) and is such that load current flows on both half-cycles of the 60 Hz input.

8/ Add to the circuit of Item 7 so as to make the load voltage the best possible approximation to a DC voltage.

![Full Wave Circuit](image3)

Investigate the dependence of the resulting ripple voltage on the load current.

9/ Investigate the following power supply circuit (known as a "bridge" circuit).

10/ Add capacitive filtering to the circuit of Item 9.

MILESTONE #4.2: Demonstrate the output voltage you have achieved in the circuit of Item 10.

Voltage Regulators

11. Investigate the “power supply” obtained by adding a Zener regulator to the output of either of the full-wave circuits above.

![Power Supply](image4)

Design the regulator (and modify the full wave circuit, if necessary) so that the load current may be varied from 0 to 20 ma while the load voltage varies by no more than 1%.

12/ Measure the output voltage of the 7805 voltage regulator over appropriate ranges of input voltage and load current.
Experiment #5

Differential Amplifiers

Duration: 1 Week

Introduction

The differential amplifier is one of the most important and widely-used circuits in electrical engineering. In this experiment, you will design, construct, and test such an amplifier.

Experiment

1. Design the differential amplifier shown so that $I_o$ is less than 10 mA and $R_e$ less than 2 kΩ, and the output voltage swing $V_{CL} > 10$ V peak-to-peak.

Use power supplies $V_{CC}$ and $V_{EE}$ of 15 V. The 2 kΩ resistors are used to provide a DC path to ground. Verify your dc design.

![Differential Amplifier Circuit](image)

Q1 and Q2 are a matched pair from the CA3096N array

2. Measure the single-ended common mode gain

$$A_c = \frac{2V_o}{(V_{i1} + V_{i2})}$$

at 1 KHz.

3. Measure the single-ended differential mode gain

$$A_d = \frac{V_o}{(V_{i1} - V_{i2})}$$

4. Measure the output signal swing capability before clipping occurs. Use differential input signals.

5. Replace the emitter resistor $R_e$ with the current source shown below.

![Current Source](image)

Q3 and Q4 are a matched pair from the CA3096N array

Design the current source so that the current $I_o$ remains the same. Verify the correct dc operation of the modified differential amplifier.

6. Determine the common mode rejection ratio CMRR at 1 kHz for the modified differential amplifier.

MILESTONE #5-1: Demonstrate that your final circuit functions well as a differential amplifier.
Experiment #6
High-frequency Behavior of BJT's
Duration: 2 weeks

Introduction
The objective of this lab is to measure the components in the hybrid-\(\pi\) small-signal model of the BJT and to investigate the high frequency response of some amplifier circuits using it. The diagram shows a somewhat simplified model which ignores the component \(\eta\mu\) which is sometimes shown in parallel with \(C\mu\). Furthermore the component \(r_o\) will be ignored in the early part of the experiment because it will be shunted by a much smaller resistor.

Experiment

Hybrid-\(\pi\) Model
1. Use the following circuit to measure the input resistance of the transistor at low frequencies, i.e. in a frequency range where the device capacitances will have a negligible effect.

Notice that \(C_e\) and \(C_s\) are intended to be short circuits at the measurement frequency so choose them wisely. Bias the transistor so that the collector current is about 1 ma. Notice that \(R_B\) shunts the input so it will have to be chosen so as to have a negligible effect. In the later stages of the experiment the combination of the voltage source and \(R_s\) will need to approximate a current source so you may as well choose \(R_s\) appropriately at this time. Identify the model parameters determined in this experiment.

**MILESTONE #6-1**: Demonstrate your measurement of the BJT input resistance.

The current gain of the BJT shows single-pole behavior with the frequency of the pole given by (see text)

\[
\frac{1}{f_H} = 2\pi r_\pi (C_\pi + (1+g_m R_L) C_\mu)
\]

\(f_H\) is of course the frequency at which the current gain has fallen 3 dB from its midband value.

2. Measure the frequency \(f_H\) using a value of \(R_L\) just large enough to enable you to measure the small signal collector current.

You now have one equation in the 3 unknowns \(r_\pi\), \(C_\pi\) and \(C_\mu\).

3. Now measure \(f_H\) again, this time with a capacitor inserted between the collector and the base of the transistor, i.e. in parallel with \(C_\mu\).

The capacitor should be such as to make \(f_H\) change by approximately a factor of 2. Now you have a second equation in the 3 unknown quantities, provided that you know the value of the added capacitor.

4. Remove the capacitor added in the previous item and increase the value of \(R_L\) by about a factor of 10. (But it certainly must not be greater than about 1KΩ.)

Again it should be such as to change \(f_H\) by a factor of about 2, compared to the result obtained in item 2.

5. Solve the 3 equations that result from the measurements (items 2, 3 and 4) for the 3 unknown quantities and, using the result of item 1, also determine the value of \(r_x\).

Cascode Amplifier

The circuit used in the foregoing was basically a common-emitter amplifier. You have observed the connection between its midband gain and its bandwidth, the latter decreasing as the former increases. A circuit which allows greater bandwidth
at a given gain is the cascode which is a common emitter / common base pair (CE-CB)

6. Build a cascode amplifier using the figure below as a guide. Measure the gain and bandwidth of this circuit and compare with the values obtained earlier in this lab. Use a \( V_{cc} \) of at least 10v and design for a collector of about 1 ma.

MILESTONE #6-2: Demonstrate that your cascode amplifier has a reasonable dynamic range and explain how the gain and bandwidth were measured.

MILESTONE #6-3: Demonstrate that your CC-CB amplifier has a reasonable dynamic range.

7. Measure the gain and bandwidth of a CC-CB pair for comparison with previous results.

8. Make a set of measurements to compare the CC-CB pair with the 2 amplifiers investigated in the previous items.

Experiment #7

Operational Amplifiers

Duration: 2 weeks

Introduction

This lab will investigate some of the non ideal operating behavior of the 741 opamp, with particular emphasis on frequency response characteristics. In addition, opamp use in the design of active filters will be studied. The opamps are to be operated from 15 V supplies, unless otherwise stated.

Experiment

Operating Characteristics

1. Construct an inverting amplifier with a voltage gain of 5 and investigate the linearity and dynamic range of its output as a function of op amp supply voltages for an input sinusoidal signal at 1 kHz. Use both the oscilloscope and the spectrum analyzer for this purpose.
2. Measure the voltage gain vs. frequency for an amplifier having gains of 1, 5, 20 and 40.

In particular, determine for each case the frequency at which the gain falls to 0.707 of the low frequency value.

3. Determine the slew rate of the op amp using a unity-gain voltage follower with a square wave input signal \( v_s(t) \) at 50 kHz.

Also investigate the effect of the slew rate on sinusoidal input signals of various amplitudes and frequencies. Does the relationship between the slew rate, the signal frequency, and the maximum undistorted output amplitude agree with theory?

**MILESTONE #7-1:** Demonstrate the slew rate limitation effect to your instructor or TA.

**Active Filters**

4. Construct the circuit shown below and determine its transfer characteristic and its cutoff frequency \( f_{3dB} \).

What filtering function does this circuit implement?

Compare the low frequency gain and the cutoff frequency with the theoretical value of:
\[
\omega_{3dB} = 1/(\sqrt{2}RC)
\]

Compare the roll off (in dB/decade) of this filter with that of Item 4.

5. Construct the circuit shown below and determine its transfer characteristic and its cutoff frequency \( f_{3dB} \).

What filtering function does this circuit implement?

Compare the low frequency gain and the cutoff frequency with the theoretical value of:
\[
\omega_{3dB} = 1/(\sqrt{2}RC)
\]

Investigate the effect on the parameter \( Q = \omega_o/\Delta\omega \) of varying R and compare with theory.

**MILESTONE #7-2:** Demonstrate the transfer characteristic of the active filter of Item 6.

**MILESTONE #7-3:** Demonstrate the transfer characteristic of the active filter of Item 6.

6. Construct the circuit shown below. Determine its transfer characteristic and the center frequency \( f_o \) at which the gain is a maximum.

What filtering function does this circuit implement?

Compare the mid band gain H (the gain at \( \omega_o \)), the center frequency \( \omega_o \), and the bandwidth \( \Delta\omega \) with the theoretical values of:
\[
H = 1 \\
\omega_o = \sqrt{1 + R/R_r}/(\sqrt{2}RC) \\
\Delta\omega = 1/RC
\]

Investigate the effect on the parameter \( Q = \omega_o/\Delta\omega \) of varying R and compare with theory.

**MILESTONE #7-2:** Demonstrate the transfer characteristic of the active filter and its cutoff frequency. PSPICE DEMO: Bring a PSPICE schematic file of the amplifier on a floppy disk and demonstrate that an AC sweep reproduces what you have just demonstrated on the lab bench. (Do the schematic entry BEFORE lab starts).