Introduction

This lab exercise will provide you with two important experiences. First, you will assemble an amplifier circuit on a printed circuit board fabricated using modern methods, which should give you an appreciation of some of the challenges of prototyping. Then you will investigate a potential source of measurement error and learn the importance of using appropriate measurement tools for demanding tasks. Lab groups are listed at the end of this handout.

Background

Figure 1 shows a common-emitter amplifier with the bias resistors designed to obtain the quiescent values $V_C = 8$ V (collector voltage), $I_C = 1$ mA, and $V_E = 2$ V (emitter voltage). The DC blocking capacitors $C_i$ and $C_o$ and the emitter bypass capacitor $C_E$ have been chosen to set the lower cut-off frequency to approximately 300 Hz (90% contribution from $C_E$ and 5% each from $C_i$ and $C_o$).

![Figure 1. Common-emitter amplifier with capacitive load. The load represented by $R_L$ and $C_L$ models the combination of the test probe and the input port of the oscilloscope.](image)

The load in Figure 1 includes a capacitance $C_L$. In general, this could represent the capacitance between a circuit board trace and the ground plane, the input capacitance of a following amplifier stage, or the capacitance of an interconnecting cable (e.g., coaxial cable). In this lab exercise, it represents the capacitance of the test leads connected to the oscilloscope.
The lower frequency limit of the amplifier is determined by the capacitors \( C_i \), \( C_o \), and \( C_E \). The equivalent resistances seen by the three capacitors are:

\[
R_{\text{eq}-i} = R_{\text{sig}} + R_i \| R_2 \| \frac{r_\pi}{\beta + 1} = 50 + 30,000 \| 100 \| 3750 = 2.46 \, \text{k}\Omega
\]

\[
R_{\text{eq}-o} = R_c + R_L = 3900 + R_L
\]

\[
R_{\text{eq}-E} = R_E \left( \frac{r_\pi + R_{\text{sig}}}{\beta + 1} \right) = R_E \left( \frac{3750 + 50}{150 + 1} \right) = 24.5 \, \Omega,
\]

where in all of these expressions the BJT is assumed to have a \( \beta \) of 150. In this case, the load resistance \( R_L \) is most likely to be 1 M\( \Omega \), the equivalent input resistance of the oscilloscope. If so, then the three associated pole frequencies are \( f_{pi} = 14 \, \text{Hz} \), \( f_{po} = 16 \, \text{Hz} \), and \( f_{pe} = 295 \, \text{Hz} \); note that their sum is 325 Hz, which is close to the desired 300 Hz.

The upper frequency limit of the amplifier is determined by the internal capacitances \( C_\pi \) and \( C_\mu \) of the BJT and the test lead capacitance \( C_L \). Using the intermediate values

\[
R'_L = R_c \| R_L \quad \text{and} \quad R'_{\text{sig}} = R_{\text{sig}} \| R_i \| R_2 \| \frac{r_\pi}{\beta + 1},
\]

the equivalent resistances seen by these three capacitances are:

\[
R_{\text{eq}-\mu} = R'_L + g_m R'_{\text{sig}} R'_L + R'_{\text{sig}} = 3885 + (0.041)(49)(3885) + 49 = 11.7 \, \text{k}\Omega
\]

\[
R_{\text{eq}-\pi} = R'_{\text{sig}} = 50 \| 30,000 \| 100 \| 3750 = 49.0 \, \Omega
\]

\[
R_{\text{eq}-L} = R'_L = 3900 \| R_L.
\]

You are strongly encouraged to verify on your own these results as well as the ones for the low-frequency limit. Recall that the internal capacitances \( C_\pi \) and \( C_\mu \) are related to the transition frequency of the BJT by

\[
f_T = \frac{g_m}{2\pi(C_\pi + C_\mu)}.
\]

Experimental Procedure

You must arrive at the lab session by 8:00 am. Complete the following steps:

- Assemble the amplifier circuit shown in Figure 1 using the printed circuit board you laid out previously. Soldering instructions are available on the Laboratory web page of the course web site. **Be very careful when you install the 2N3904 and the polarized capacitors.** Double-check their orientation before soldering. A data sheet for the 2N3904 is available on the Laboratory web page of the course web site.
Remember that $V_{sig}$, $R_{sig}$, $R_L$, and $C_L$ are not physical components mounted on the PC board. They represent the function generator and the oscilloscope. To allow for connections to the test equipment, you should form small wire loops on the PC board as shown in Figure 2. The power leads (to the + and − sides of $V_{CC}$) should be made from roughly 1-meter lengths of #20 or #22 insulated wire. Twisting the leads together along their lengths is recommended to minimize noise pick-up and wire tangles.

![Diagram of wire loop connection points](image)

**Figure 2.** Suggested method for providing wire loop connection points for external test equipment.

- Verify by measurement that the quiescent voltages listed in the “Background” section are reasonably close to their design values. These measurements must be taken with no source voltage $V_{sig}$ applied to the amplifier. Identify the cause(s) of any serious deviations before moving on to the next step.

- Use the function generator and oscilloscope to verify that the amplifier is working properly for small-signal input voltages. To begin with, use the simple test leads with BNC connectors on one end and alligator clips on the other for the connections to the generator and the oscilloscope. You might have to add a voltage reduction circuit (with an output resistance of 50 $\Omega$) to the output of the function generator to obtain a sufficiently low input voltage ($V_{in}$) amplitude. The midband gain should be roughly $-150$ V/V, and the lower cut-off frequency should be around 300 Hz. The upper cut-off frequency will be determined in a later step.

- Demonstrate your operating amplifier with proper midband gain and lower cut-off frequency to the instructor or TA.

- Capture a clean screen image of the input and output voltage waveforms at some frequency in the midband region, and determine the voltage gain from your measurements. Compare the measured gain to the estimated gain determined earlier by analysis, and comment on the results. Be sure to record any relevant additional data such as the frequency of operation.

- Using the alligator clip-terminated test leads to connect the output of the amplifier to the oscilloscope, determine the upper cut-off (3-dB) frequency of the amplifier. Assuming that
the cable capacitance (represented by $C_L$) introduces the dominant upper-frequency pole, what is the approximate value of $C_L$? Consult the information on coaxial cable properties available via the link on the Laboratory page, and determine whether or not your results are consistent with the data for the test lead cable and the equivalent input circuit of the oscilloscope.

- Now use a ×10 test probe to connect the output of the amplifier to the oscilloscope. If you can, determine the upper cut-off frequency of the amplifier with the new configuration. The new cut-off frequency might be above the upper limit of the function generator. If that is the case, try to estimate the cut-off frequency, and explain in your summary how you do it. Also discuss whether you think the cut-off frequency is now dominated by the test probe capacitance, one or both of the internal capacitances $C_\pi$ and $C_{\mu}$, or a combination of all three. Provide some analysis (including equations) to back up your conclusion.

- Demonstrate the high-frequency performance of the amplifier with both types of test leads to the instructor or TA.

**Lab Summary**

After your group has completed the assigned tasks and demonstrated a properly operating circuit, compile the following items into a single document:

- Record of midband gain and lower and upper cut-off frequency measurements.
- Properly annotated screen captures of the input and output waveforms at midband.
- Analysis of the upper cut-off frequency, including rough estimates of $C_\pi$ and $C_{\mu}$ and reasonable values for the alligator-clip and ×10 test probe capacitances (cite sources, if necessary)
- Interpretation of results and discussion of implications and observations. Try to explain any significant discrepancies between your calculated and measured data.

The summary is due in class on Monday, April 29, 2013. One summary per group should be submitted and may be handwritten on notebook paper. Summaries will not be graded directly for writing issues, but they must be legible and understandable.

**Grading**

Each group member will receive the same grade based on the following criteria. Scores for the four lab summary items will be quantized at the 0, 2, 5, 8, and 10-point levels.

30% Properly assembled circuit
30% Demonstration of properly operating circuit
10% each Bulleted items listed in the “Lab Summary” section above

As outlined in the lab policies and guidelines, any group member who misses any portion of the lab session and is not excused will receive a grade penalty proportional to the time absent.
Lab summaries submitted after the deadline but before 5 pm on the following Tuesday will have a 20% grade deduction applied. No credit will be given for a summary submitted later, although credit for successful assembly and demonstration (60% maximum) will still be given.

If the demonstration is not completed by the end of the lab session but is completed by 4:00 pm the following Friday, a 10% grade deduction will be applied. If the demonstration is completed by 5:30 pm the following Monday, a 20% grade deduction will be applied. No demonstration credit will be given thereafter.

Group Assignments

The randomly generated groups for this lab exercise are listed below:

Levine-Selvaggio
Dost-Abels
Wetzel-DeMelis
Chhean-Hoolachan-Swaim
Donatelli-Selevan
Reisser-Collins-Fast

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