Physics 120A
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Due: At the start of lab section, the week of May 24, 2004 (two weeks)

Experiment #6: Feedback Stabilized Light Source

Purpose:

In this experiment you will utilize a feedback circuit to stabilize the output from a light source. There are several different components to this lab, so you will be led through several steps in which you will build and test subsections of the final circuit.

Equipment:

This lab will require the following items:

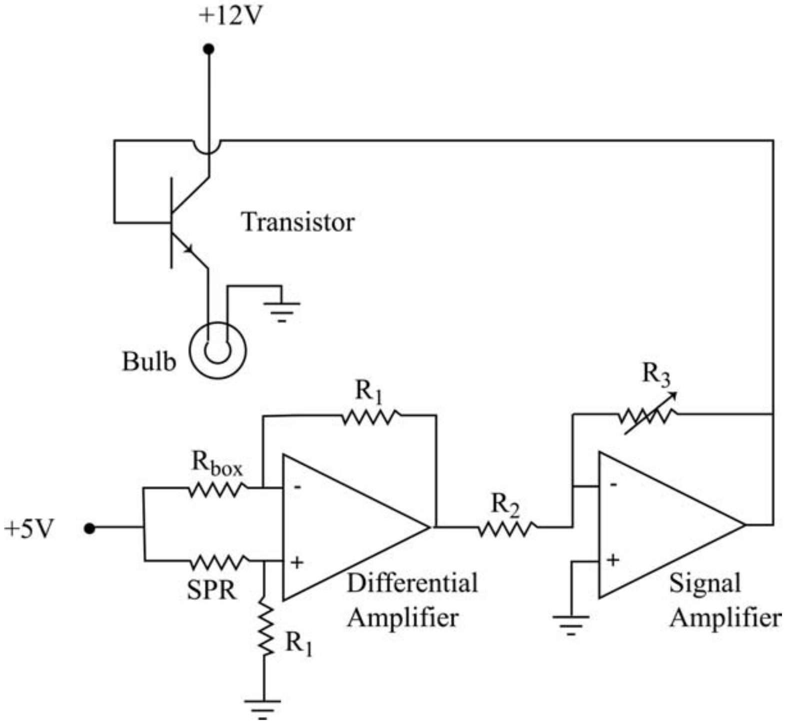
- Oscilloscope
- Appropriate clip-leads and banana cables
- Power supply
- Function generator
- Digital multi-meter
- Assorted resistors and capacitors
- Two TL081 operational amplifiers
- A 1MΩ potentiometer (variable resistor)
- A 2N3055 NPN power transistor
- Light bulb
- Sensing PhotoResistor

Introduction

In this experiment we study a circuit for which the feedback loop is closed, not by an electrical connection, but by light traveling from a source (light bulb) to a detector (Sensing PhotoResistor) as shown in the figure below. Our aim is to keep the light output constant, even in the presence of external perturbations (in this case introduced by ourselves).

In Exp. 5 with the *phase shift oscillator*, the relevant frequency was determined by the RC time constant of the feedback network. Here it is the time constant for increasing or decreasing the light output, i.e. for heating or cooling the filament of the light bulb.

We will first attempt to characterize the behavior of the different system elements separately. After that we will assemble the feed-back "network" and measure its transfer function. From these measurements will be able to predict the system behavior after closing the feed-back loop. We will do that and find out whether (or not) our predictions agree with the measurements on the final system.



Light Source and Sensors

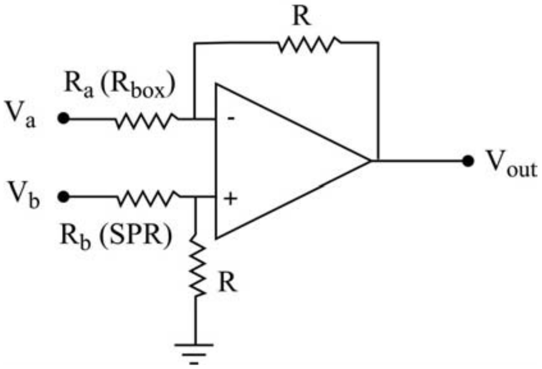
- The light source is an incandescent light bulb.
- The light sensor is a **photoresistor**. Its resistance *decreases* as more light is incident on it.
- The *perturbation* is provided by a 2.7 Ω resistor in series with the light bulb. This resistor can be shorted out with a toggle switch.

- The voltage across the light bulb and resistor (if present) determine the light output; this voltage is controlled by a 2N3055 power NPN transistor.

- The light bulb and two photoresistors, the *sensing* photoresistor **SPR**, and the (nearly identical) *monitoring* **MPR** (for sensing and monitoring the light output) are mounted in a light-tight box. The fraction of the light from the bulb which hits each photoresistor depends on the relative distance between MPR and SPR, which is likely to be different for different assemblies. Each of the boxes has a label: **be sure to use the same box throughout the experiment!**

- The transistor, its heat sink, and the 2.7 Ω resistor are assembled separately. Note that the heat sink and collector are electrically connected; i.e., the heat sink is at the collector voltage, so make sure it does not touch any grounded surface.

Differential Amplifier: Theory



We analyze the circuit in the above figure as an inverting amplifier in the standard amplifier approximation, i.e. $V_+ = V_-$ and $I_a = I_{Rfb}$. This gives

$$V_+ = V_b \frac{R}{R + R_b}$$

and

$$\frac{V_a - V_-}{R_a} = \frac{V_- - V_{out}}{R}$$

Setting $V_+ = V_-$, we solve for the output voltage as

$$V_{out} = \frac{R}{R_a}\left[(V_b - V_a) + V_b \frac{R_a - R_b}{R + R_b}\right]$$

If $R_a=R_b$, this circuit just amplifies V_b-V_a. If, on the other hand, we connect the two inputs to a common voltage source such that $V_a = V_b = V_i$, then we have a "differential" amplifier whose difference is proportional to the difference $(1/R_b - 1/R_a)$, or

$$V_{out} = V_i \frac{1/R_b - 1/R_a}{1/R + 1/R_b}$$

Given an op-amp with good offset compensation, this circuit can replace the Wheatstone bridge, studied in experiment 2, with the advantage that we have available the output current (about 10 mA) of the op-amp.

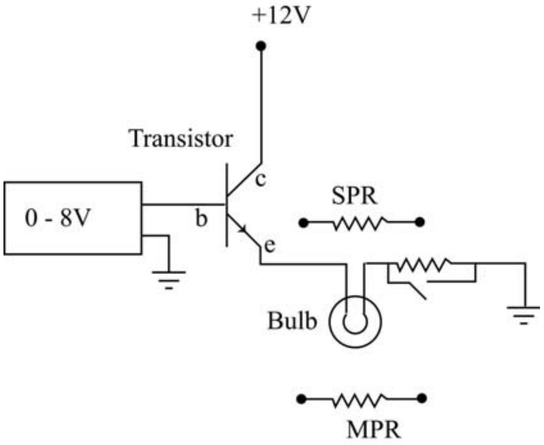
Standard resistors have a resistance reasonably independent of extraneous influences, such as temperature. However, there are "resistors" whose resistance is a well controlled function of some environmental variable, such as light (photoresistor), magnetic field (magnetoresistor), temperature (thermistor), etc. These devices go by the generic name of **sensor**. When we put a sensor in place of R_b, the above circuit can be used to sense light, magnetic field, temperature, etc.

Here, we use the light-sensing SPR for R_b, and use R_{box} for R_a. In order to keep the current in SPR (i.e. R_b) small, V_- and V_+ must be close to +5V. This requires $R >> R_b$.

For stable light output from the complete feedback circuit, we must *increase* the light drive whenever a fluctuation causes a decrease in light out, which is sensed as an *increase* in R_{SPR}. Our final circuit will invert V_{out} before driving the light bulb. Thus, we want V_{out} to *decrease* when $R_{SPR} = R_b$ *increases*. Recalling that $1/R_b >> 1/R$, this requires $1/R_b > 1/R_a$, or $R_{SPR} = R_b < R_a = R_{box}$.

First, we will characterize the components of our feedback loop (light bulb, photoresistors, transistor and 2.7 Ω resistor) as a function of the voltage across the bulb and as a function of time after a voltage change.

Using the two sections of your dual power supply, the transistor and the box with the light bulb and photoresistors, assemble the circuit shown in the figure below.



Basically your NPN transistor (2N3055) is a current amplifier. As shown in the specification sheet, the current I_{ce} from collector to emitter (and hence through the light bulb) is 100 times the current I_{be} into the base. This current is determined as follows:

- The emitter voltage will be $V_e = I_{ce} R_{bulb} + R_{sw}$ when current I_{ce} flows through the bulb and (switchable) resistor.
- For base current to flow, allowing the larger collector-emitter current I_{ce} to flow, the base voltage must be $V_b \sim V_e + 0.8$.

Light leaks?

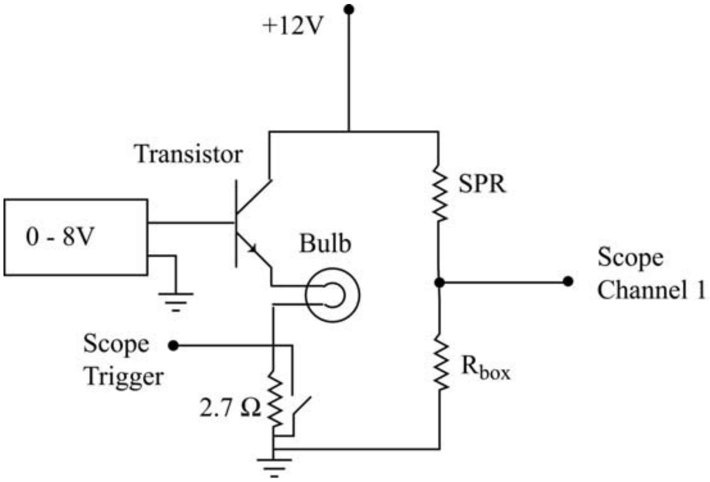
First we must check whether we are sensitive to ambient light, using the circuit above. With V_{base}=0 V (light bulb "off"), using our DMM, we measure the resistances of the SPR and the MPR with the outside of the box exposed to room light and with the box covered up. Any noticeable difference should be eliminated with appropriate application of black tape.

MPR = SPR?

With the 2.7 Ω resistance shorted out, increase V_{base} in steps; record and plot both R_{SPR} and R_{MPR} and the voltage across the bulb, for values of the R_{SPR} resistance between 100 Ω and 1000 Ω. Also, plot the ratio R_{SPR}/R_{MPR} against the value of R_{MPR}. This will allow you to infer the value of R_{SPR} (not available for measurement when in the feedback loop) from your measurement of R_{MPR}.

Heating?

When the SPR is part of the differential amplifier circuit, the current through it will cause power dissipation, and hence may cause a rise in temperature. It is important to ascertain that this temperature rise will not change the resistance of the SPR.



Wire up the circuit shown above, with a DMM to measure the current through SPR. Set V_{base} such that $R_{SPR} \sim 200\ \Omega$. Monitor R_{MPR} to make sure the light output stays constant. Use R_{box} to vary the current through SPR. Measure the voltage V_{SPR} across SPR and the current I_{SPR} through the SPR over a range $0.1\text{ mA} < I_{SPR} < 15\text{ mA}$. Plot $R_{SPR} = V/I$, against I_{SPR}. As long as R_{SPR} is independent of I_{SPR}, we are within *safe* limits.

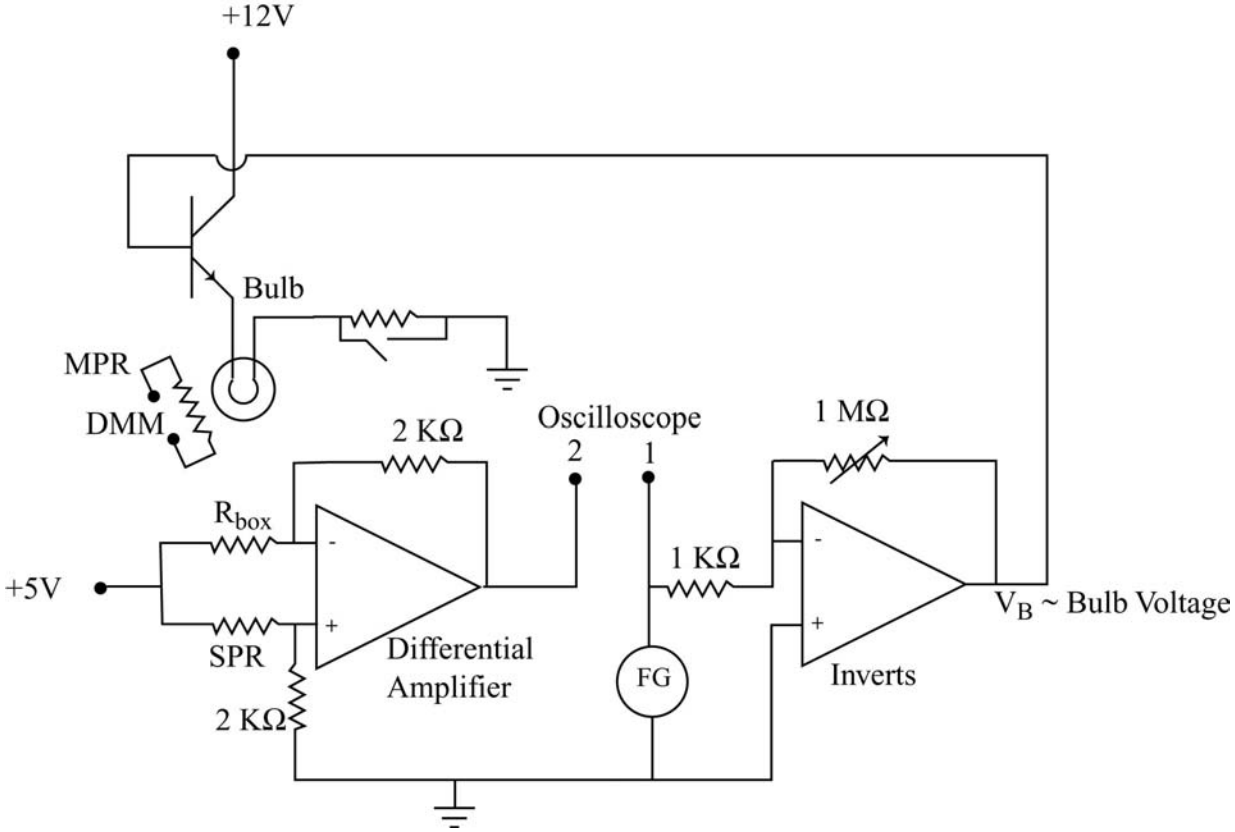
Response Time

With the same setup, but replacing the resistor box with a 2KΩ resistor, we now connect the oscilloscope as shown above. We still have V_{base} set so that $R_{MPR} \sim 200\ \Omega$. In order to measure the characteristic response time of the [light bulb + photoresistor] system, we introduce an abrupt change in the current through the light bulb by opening and closing the shorting switch across the 2.7 Ω series resistor. By triggering the oscilloscope on a rising (falling) signal, we observe the response to a decrease (increase) in light bulb current.

Measure and record the time difference for a 10% to 90% shift in the oscilloscope level across the 2 KΩ resistor. Is there a difference between these time measurements for increasing/decreasing light output? Are these time constants dominated by the behavior of the bulb or the photo resistor?

H(ω), the Complex Transfer Function of the System

We will now measure H(ω) as in experiment 5 ("Feedback induced oscillations"), using the circuit below.



1. Set up your differential amplifier for measurement of the resistance differences. One of the resistors will be SPR and the other the resistance box. Be certain that:
   - the op-amp offset is compensated so that $V_{out} = 0$ when $V_+ = V_-$.
   - the assignment of the SPR and the resistor box to the V_+ and V_- inputs to the differential amplifier are such that an increase (decrease) in the light level will generate a compensating decrease (increase) in the bulb current.
2. Set up a variable gain inverting amplifier (with the offset compensated) to drive the [transistor + light bulb] system.
3. Connect the function generator to the input of the inverting amplifier. Set the DC offset of the function generator so as to give a DC light output producing $R_{SPR} \sim 200\ \Omega$, as derived from a measurement of the MPR resistance with your DMM.
4. Monitor the output of the function generator on channel 1 of the oscilloscope, and the output of the differential amplifier on channel 2 of the oscilloscope. Vary the function generator frequency to measure, record and plot the transfer function $H(\omega)$ (magnitude and phase) of your system.

You will have to do some of these measurements with the oscilloscope in the DC coupled mode, since at the low end of the frequency range the impedance of the scope's coupling capacitor (refer to experiment 1) will be a significant fraction of the $1M\Omega$ input resistance of the oscilloscope. At these low frequencies you'll have to use the oscilloscope at low gain (relatively large V/cm) and center the trace on the screen using the oscilloscope vertical positioning feature. At frequencies in excess of approximately 100 Hz, when the magnitude of the transfer function becomes quite small, you can switch the oscilloscope to the AC coupling mode (the DC offset of the signal is blocked) and increase the oscilloscope gain.

How does the corner frequency of your Bode plot compare with your expectations from the time constant measured above?

Closing the Feedback Loop

In what follows, check repeatedly that the outputs of both the differential and the final amplifiers are *well below saturation*.

1. From the magnitude of the transfer function, at the frequency where the phase shift is ~180°, compute the gain of your amplifier (i.e. the setting of the $1M\Omega$ potentiometer) at which the system would become unstable. Set the potentiometer for approximately 75% of that value, so as to assure stability.
2. Remove the function generator and close the feedback loop (see figure below).
3. Adjust the resistor box such that $R_{SPR} \sim 200\ \Omega$, as inferred from R_{MPR}.

4. Check that all the DC voltages agree with your expectations.

5. Perturb the system, by opening and closing the toggle switch across the 2.7 Ω resistor. Measure and record the resulting steady-state change in light level as shown by R_{MPR}. How do these changes compare to similar changes observed in the open loop configuration?