Lab 1: Optoelectronics

Objectives

- Introduce the characteristics and applications of LEDs and photodiodes.
- Design a photo-coupler usable for basic infrared communication.
- Predict the coupling coefficient between emitter and detector based on physical propagation of light and selective absorption in the photodiode.
- Extend the simulation capabilities of SPICE by using standard components as **models** for optical interaction.
- Observe the relationship between signal amplitude and linearity in electronic circuits.

Parts and Equipment Required

Components and Materials Needed:

- 1kΩ resistor (2)
- 10 kΩ resistor (1)
- 100kΩ resistor (1)
- 1MΩ resistor (1)
- 100kΩ potentiometer (1)
- 100μF capacitor (1)
- 1μF capacitor (1)
- OSRAM SFH 486 Infrared LED, $\lambda = 880$nm (1)
- OSRAM SFH 235 Infrared PIN Photodiode, $\lambda = 900$nm (1)
- 741 OP AMP (1)
- solderless breadboard/superstrip (1)

Equipment to be Used:

- Digital Multimeter (1)
- Oscilloscope (2 channels)
- Function generator (1)
- Banana-to-alligator cables (1 pair, red and black)
- BNC-to-BNC cable (2)
- BNC-to-alligator cable (1)
- Oscilloscope probe (2)

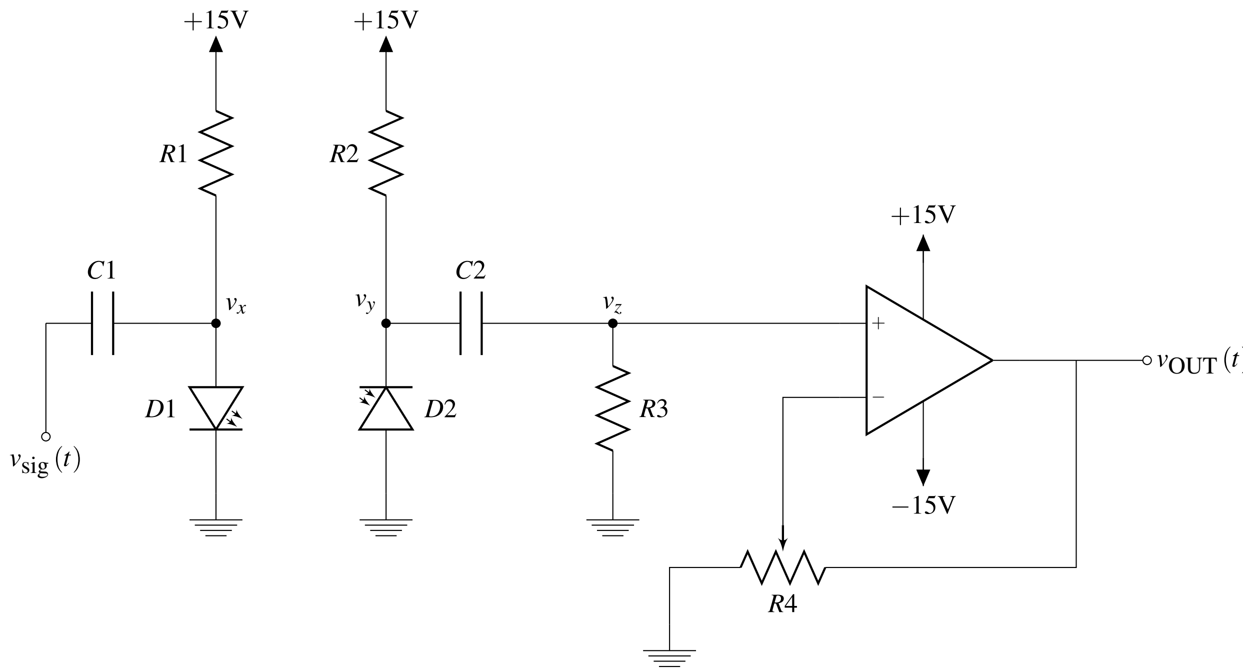


Figure 1: Optical transceiver circuit. Component values are $R1 = 1\text{k}\Omega$, $R2 = 100\text{k}\Omega$, $R3 = 1\text{M}\Omega$, $R4 = 100\text{k}\Omega$, and $C1 = 100\mu\text{F}$, $C2 = 1\mu\text{F}$. $D1$ is an infrared light-emitting diode (LED) with peak emission at $\lambda = 880\text{nm}$, and $D2$ is an infrared photodiode with peak sensitivity at $\lambda = 900\text{nm}$.

1 Prelab

Exercise 1. Study the datasheet parameters for the LED and photodiode. Some important characteristics are reproduced in Fig. 2. In this exercise, we will estimate the *coupling coefficient* between the LED emitter and the photodiode detector when they are positioned at a specified distance d. The coupling coefficient is defined as

$$K = \frac{i_{P,PD}}{i_{F,LED}}, \tag{1}$$

where $I_{F,LED}$ refers to the forward current in the LED, and $I_{P,PD}$ is the photocurrent induced in the photodiode under reverse bias.

According to the datasheet, the LED emits a radiant intensity of $I_e = 70\text{mW/sr}$ when operating at a pulsed forward current of 100mA. When operating at lower currents, the radiant intensity should be approximately proportional to the

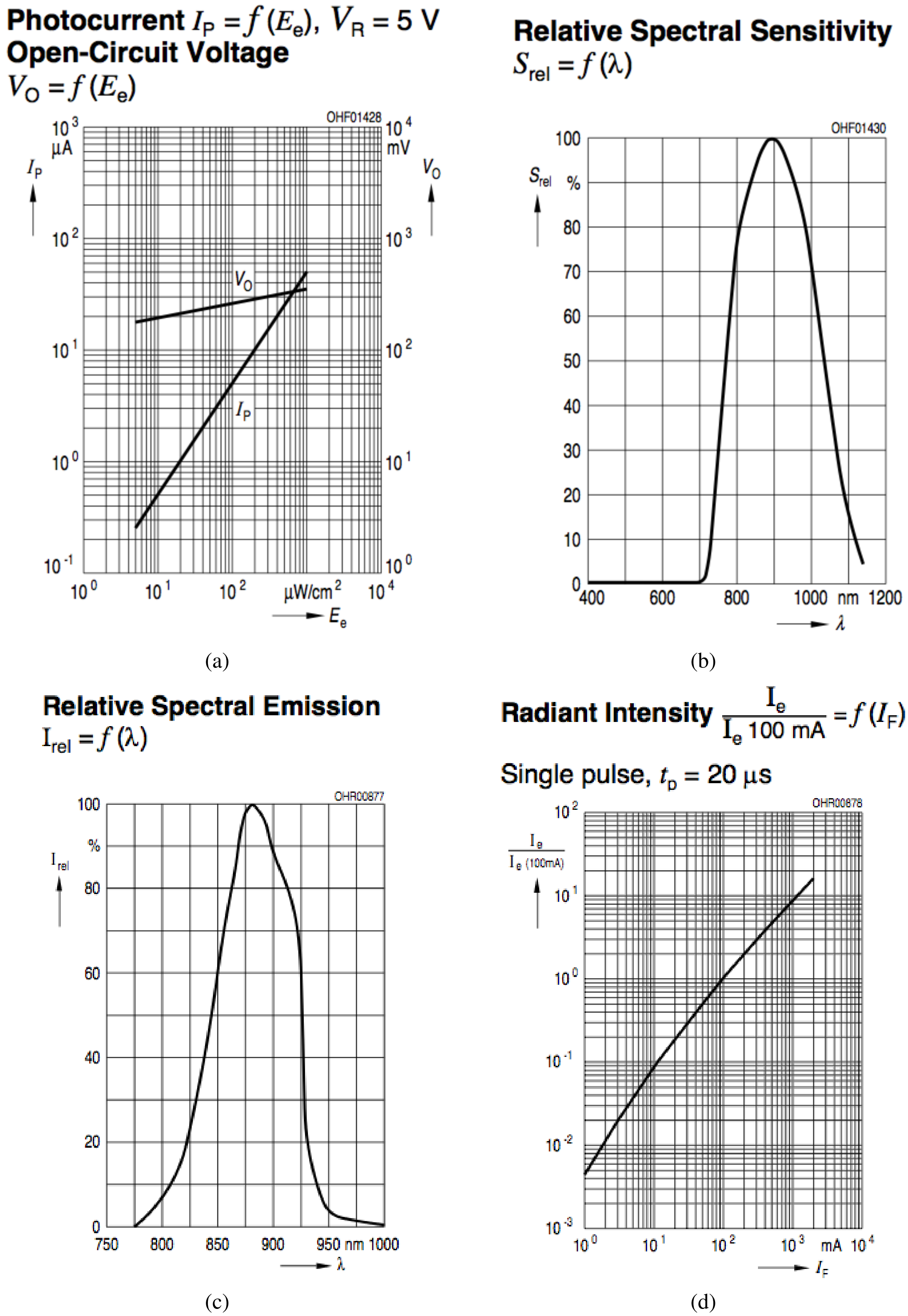


Figure 2: (a–b) Characteristics of the OSRAM SFH 235 FA photodiode. (c–d) Characteristics of the OSRAM SFH 486 LED.

LED's forward current:

$$I_e \approx I_{F,LED}\left(\frac{70\text{mW/sr}}{100\text{mA}}\right) \tag{2}$$

The photons emitted by the LED are dispersed across a spherical surface that expands as they travel outward from the device. In order to calculate the actual optical power delivered to the photodiode, it is necessary to compute the *solid angle* spanned by the photodiode. The total *radiant power* is then

$$\phi_e = I_e\Omega, \tag{3}$$

where Ω is the solid angle, which you will calculate in steps (a) and (b) below.

The *irradiance* (E_e) at the detector is defined as the actual power per surface area of the photodiode. This is obtained by dividing the photodiode's area from the total incident power:

$$E_e = \frac{\phi_e}{A_{pd}}, \tag{4}$$

where A_{pd} is the photodiode's sensitive surface area. According to the datasheet, our diode has $A_{pd} = 7\text{mm}^2$.

Finally, from Fig. 2(a) we see that when the irradiance is $E_e = 1\text{mW/ cm}^2$, a photocurrent of $I_P = 50\mu\text{A}$ is induced in the photodiode. We may extrapolate from this and obtain an approximate general formula for the photocurrent:

$$I_{P,PD} = E_e\left(\frac{50\mu\text{A}}{1\text{mW/ cm}^2}\right). \tag{5}$$

Putting these equations together, we may obtain a solution for the coupling coefficient as a function of the solid angle Ω:

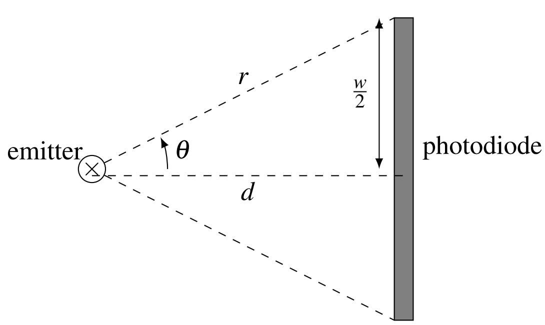
$$I_{P,PD} = I_{F,LED}\left(\frac{70\text{mW/sr}}{100\text{mA}\times A_{pd}}\right)\left(\frac{50\mu\text{A}}{1\text{mW/ cm}^2}\right)\Omega \tag{6}$$

$$\Rightarrow K = \left(0.035\text{cm}^2\text{/sr}\right)\frac{\Omega}{A_{pd}}, \tag{7}$$

where the surface area A_{pd} must be given in cm^2.

If the photodiode and LED are placed d cm apart and facing each other, use the following procedure to solve for Ω and K:

(a) Calculate the angle θ traversed by the photodiode surface, using this figure:



where w is the width of the photodiode surface. Write your calculations in the box below.

d (cm)	=	2 cm	4 cm	6 cm
w (cm)	=			
r (cm)	=			
θ (rad)	=			

(b) The *solid angle* Ω is equal to the portion of surface area of unit-sphere that lies within the cone swept out by angle θ. This is calculated as $\Omega = 2\pi(1 - \cos\theta)$. Calculate the Ω corresponding to $d = 2$, 4 and 6 cm, and write your answers in the table below.

d (cm)	=	2 cm	4 cm	6 cm
Ω (sr)	=			

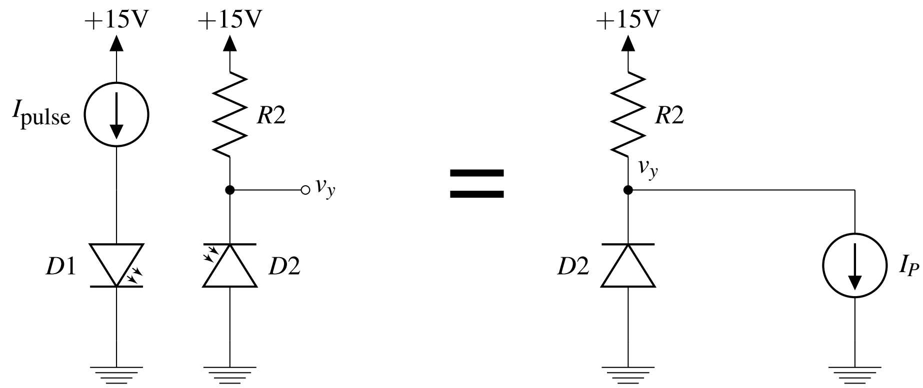
(c) From your calculations, obtain an estimate for the coupling coefficient:

d (cm)	=	2 cm	4 cm	6 cm
K (unitless)	=			

Exercise 2. Suppose the LED is pulsed with a current of 10mA. What are the expected radiant intensity (I_e), irradiance (E_e) and photocurrent (I_P) for this case? Assume the LED and photodiode are spaced as before.

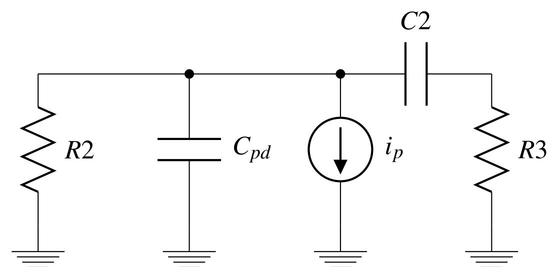
d (cm)	=	2 cm	4 cm	6 cm
I_e	=			
E_e	=			
I_P	=			

Exercise 3. If the LED is pulsed between 0 and 10mA, what is the expected peak-to-peak voltage amplitude appearing at v_y in this circuit? Note that the photocurrent is modeled as a current source placed in parallel with $D2$:



d (cm)	=	2 cm	4 cm	6 cm
v_y (p-to-p)	=			

Exercise 4. The photodiode $D2$ has a reverse-bias capacitance of $C_{pd} = 72\text{pF}$, as specified in the datasheet. In this exercise, you will show that the receiver's bandwidth is limited by $R2$ and C_{pd}. To do this, we first consider the *small signal* model of the receiver circuit from Figure 1:



Note that the current source is labeled with the small-signal photocurrent, i_p, which represents a small AC fluctuation. To estimate the 3dB cutoff frequency, we observe that $C2$ and $R3$ form a high-pass filter. If i_p has a high enough frequency, then we may approximate $C2$ as a short-circuit. In that case, $R3$ appears in parallel with $R2$, and since $R3 \gg R2$, their parallel combination is approximately equal to $R2$. With these approximations, the 3dB cutoff frequency is roughly given by

$$\omega_{3\text{dB}} \approx \frac{1}{C_{pd} R2}$$

We can do little to affect the value of C_{pd}, but we can adjust the bandwidth by changing $R2$. Calculate the 3dB frequency for $R2 = 100\,\text{k}\Omega$, $10\,\text{k}\Omega$ and $1\,\text{k}\Omega$, assuming a distance $d = 4\,\text{cm}$. Give answers in both radians per second and Hertz. Also calculate the corresponding peak-to-peak amplitude seen at v_y for these cases:

$R2$	=	$100\,\mathrm{k}\Omega$	$10\,\mathrm{k}\Omega$	$1\,\mathrm{k}\Omega$
$\omega_{3\mathrm{dB}}$ (rad/sec)	=			
$f_{3\mathrm{dB}}$ (Hz)	=			
v_y (p-to-p)	=			

Comment on the tradeoffs that are related to $R2$.

Exercise 5. Suppose the LED has a forward-bias scale current of $I_S = 4.55\text{pA}$ and is driven with a sinusoidal voltage described by

$$V_{LED} = 0.35\text{V} + 0.1\sin(2\pi f t), \tag{8}$$

where the frequency $f = 10\text{kHz}$. Use Matlab to plot the expected LED current based on the standard diode equation, $I_{F,LED} = I_S \exp(V_{LED}/U_T)$, where U_T is the thermal voltage (0.026V at room temperature). Plot the waveform for $t = 0$ up to $t = 500\mu\text{s}$. Then, based on your solution for the coupling coefficient K, generate a waveform for the induced photocurrent $I_{P,PD}$. The waveform should be noticeably distorted. Can you explain the observed distortions?

2 Modelling and Simulation

Procedure 1. Create a SPICE netlist for the circuit shown in Figure 1. You may use a schematic entry tool or you may write the netlist by hand. Follow these additional procedures:

(a) To model the LED, place a diode with model name **SFH486**.

(b) To model the photodiode, place a diode with model name **SFH235**.

(c) To model the potentiometer, place two resistors in series, with the wiper (i.e. the "arrow" terminal) connected in the center. The sum of these resistors should equal $R_4 = 100\text{k}\Omega$.

(d) Use the **vsource** component to create instances of all voltage sources. In the vsource properties, select "DC" source type for constant sources, and select the "sine" source type for the input signal.

(e) Specify the input source as a 50kHz sine wave with amplitude 100mV.

Procedure 2. By itself, SPICE is only capable of simulating standard electrical circuits. It is not able to simulate optical or mechanical interactions. To model the optical interactions in our circuit, we observe that the photodiode's reverse-bias photo-current I_P is proportional to the LED's forward current I_F. Hence we can simulate the optical effect by adding two parts:

(a) Insert a **meter source** – a 0V DC voltage source – **in series** with the LED. Set the source's instance name as "Vm1".

(b) Insert a **current-controlled current source (cccs)** in **parallel** with the photodiode. In the cccs properties window, set the **current gain** equal to the coupling coefficient you calculated in the prelab. Set the **reference voltage**

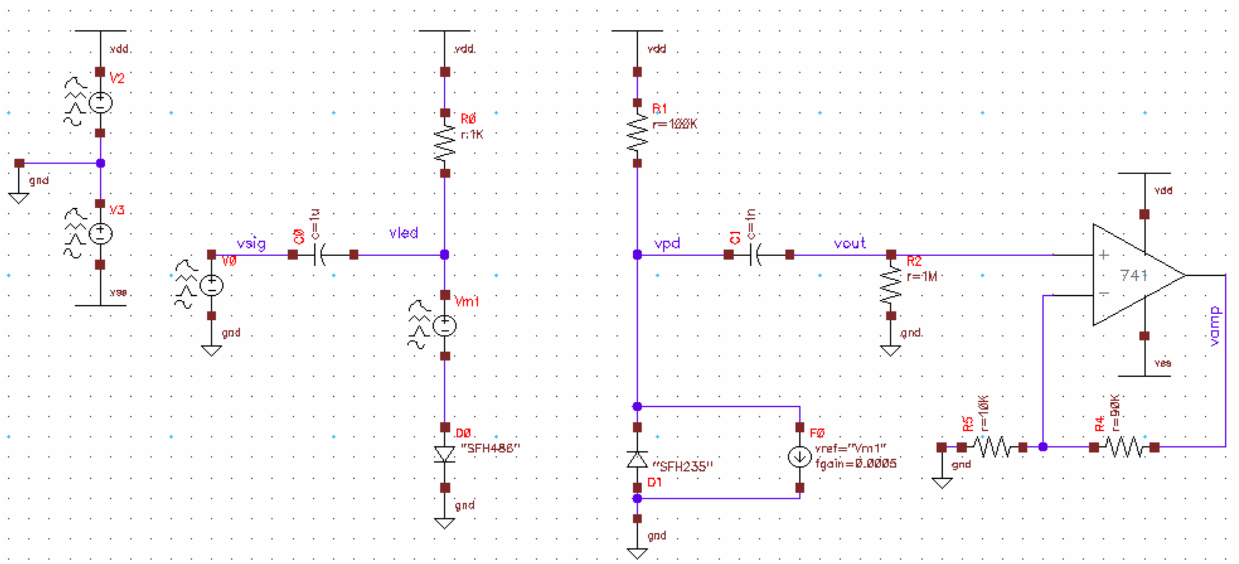


Figure 3: Circuit schematic showing model for optical interaction, drawn in Cadence Virtuoso.

source to “Vm1”.

Remember to include DC sources for both VDD and VSS. Your finished schematic should look like the one shown in Fig. 3. Once the schematic is complete, launch the simulator and perform a transient simulation for 600µs. Record the waveform at v_{sig}, v_x, v_y and v_{OUT}. Do any of the waveforms appear distorted? Explain the observations. Lastly, use an **fft** expression to observe the spectrum of v_{OUT}. You should see a large fundamental spectral component at 50kHz, and harmonic components appearing at multiples of the fundamental. The harmonics indicate how much distortion is present. Obtain the Spurious-Free Dynamic Range (SFDR) by measuring the difference between the fundamental and the largest harmonic, in dB. A small SFDR indicates a highly distorted signal.

Procedure 3. Reduce the input amplitude to 10mV and repeat the transient simulation. Record the waveforms at v_x, v_y and v_{OUT}. Describe how these results differ from the previous simulation. Can you perceive any distortion? Perform the fft analysis and measure the SFDR. How does it compare to the previous measurement?

Procedure 4. Perform AC simulations to verify your predicted 3dB cutoff frequency. Sweep the frequency from 100kHz up to 10MHz and produce a Bode plot. Repeat the AC simulation for each of the $R2$ values considered in your prelab analysis. For each simulation, measure the 3dB cutoff frequency and state how it compares to your prediction.

3 Physical Experiments

3.1 Part 1

Procedure 1. First, **measure the precise values of all resistors** and record them in your lab notebook. Construct the circuit shown in Fig. 1. Place D1 and D2 so that they are directly facing each other at a distance of 2cm.

Procedure 2. Use the lab's function generator to create a 50kHz sinusoid at 1V peak-to-peak amplitude. Apply this signal as v_{sig}.

Step A. Using the oscilloscope, probe the waveform at the anode of $D1$ (i.e. v_x) and at the cathode of $D2$ (i.e. v_y), using AC coupling in both cases. Adjust the function generator's amplitude setting until an amplitude of 100mV appears at v_x (the function generator's output impedance may interact with the capacitive coupling to create a lesser amplitude than what is indicated on the dial). Also, adjust the potentiometer so that op amp stage has a gain of 2V/V. Examine the waveforms at v_x, v_y and v_{OUT}. Are any of the waveforms distorted? Can you explain why? Record your observations.

Step B. Use the oscilloscope's FFT display (in the MATH menu) to display the spectrum of v_{OUT}, and measure the SFDR.

Step C. Adjust the input so that v_x has an amplitude of 10mV, and repeat the above steps. How do the results compare with the simulator predictions?

Step D. Using the known values of R_1 and R_2, convert the observed voltage waveforms to obtain the LED's forward current and the photodiode's reverse current. (You can calculate these values for the maximum and minimum points on the observed waveforms). From these calculations, calculate the coupling coefficient $K = I_P/I_F$. How well does it match to your prediction from the prelab exercises?

Procedure 3. Obtain the circuit's frequency response as follows: Measure the signal amplitude at v_{sig} and v_y for frequencies from 10kHz up to 1MHz, using a logarithmic step (e.g. measure at 1, 1.8, 3.16, 5.62, 10, 18, 31.6, ...). From these measurements, obtain the gain $\left|v_y/v_{\mathrm{sig}}\right|$ in dB at each frequency. Repeat this procedure for all values of R2 considered in the prelab. State how closely your measurements match the simulated predictions, and offer hypotheses to explain any discrepancy. You may repeat SPICE simulations using your measured resistor values to see if they improve the match.

4 Report

Your report should be a brief summary of your results. Report the measured distortion-free amplitude and the measured gain of your photocouple. Explain the sources of observed distortion (Note: you should see different forms of distortion in Part 2 vs Part 1. Explain why these cases are different). Report the bandwidth of your photocouple. Describe your procedure for increasing the bandwidth, and report how successful you were. If your procedure didn't work out as expected, make a plausible hypothesis as to what went wrong.