Photodiode: Analog Optical Link

Introduction

Many modern devices communicate using optical communication links comprised of a light emitting diode (LED) or laser diode source, a transmission medium (usually glass or plastic fibre) and a photodiode or phototransistor receiver. Most systems transmit digital data, but an optical link can also be used to transmit analog information. Building an analog optical link will allow us to gain experience in signal conditioning a photodiode signal and will demonstrate the noise reduction possible using a carrier amplifier.

Coupling

To describe the output of a light source like our photodiode, it is helpful to introduce the notion of solid angle. Consider a transparent sphere of radius \( r \), and suppose that an area \( A \) on the surface of the sphere is painted black. We then say that the blacked out region subtends a solid angle of \( \Omega \) steradians (str), where \( \Omega = A/r^2 \). According to this definition the whole sphere subtends a solid angle of \( 4\pi \) str. One steradian is an area of \( r^2 \), just as one radian is an arc of length \( r \).

The concept of solid angle is essential in separating the two units in which light is customarily measured. Both the lumen and the candela originated in the 18th century when the eye was the primary detector of electromagnetic radiation.

The lumen (lm) is a measure of the total light power emitted by a source. This means lumens can be converted to the more familiar unit of Watts, with a conversion factor 683 lm/Watt. However, things are a bit more complicated because this conversion factor is only used for light with a wavelength of 550 nm, the yellow-green color that our eyes are most sensitive to. For other colors the conversion factor is multiplied by a dimensionless number \( RR(\lambda) \) called the relative response of the adjusted human eye. A rough plot of \( RR(\lambda) \) is shown in Figure 1. The point of this is that two sources described by the same number of lumens (the same “luminous flux”) will have the same subjective brightness to a human observer, even if they are of different colors. This kind of color corrected unit is very helpful if you want to design a control panel with lots of colored lights, and you want them all to have the same perceived brightness. To summarize, if the luminous flux of your source is described as \( F \) lumens, then you convert this to Watts using the formula:

\[
F(W) = \frac{1}{683 \cdot RR(\lambda)} F(\text{lm})
\]  

(1)

Notice that more power is required for a given luminous flux as the color gets farther and farther away from yellow-green, to make up for the declining sensitivity of the eye.

However, this is not the whole story for describing light sources, because the amount of light emitted varies with direction, and how much light we intercept in a given direction will depend upon how much solid angle our detector covers. Thus we need a measure of light power per solid angle, and this unit is called the candela, equal to one lumen/str. A light source that emits one candela in every direction emits a total of \( 4\pi \) lumen, since there are \( 4\pi \) str in the whole sphere. The quantity measured by the candela is called the “luminous intensity”. If you look at the data sheet for a typical LED you will see that it uses the unit “mcd” or millicandela to describe the brightness. The values given are for light emitted along the axis of the LED. For other directions you multiply by the Relative Intensity given the data sheet. By dividing Eqn. 1 above by the...
solid angle we can rewrite it as a relation between the luminous intensity \( J \) in mcd and the power per unit solid angle:

\[
J(\text{mW/str}) = \frac{1}{683 \cdot RR(\lambda)} J(\text{mcd})
\]

(2)

Suppose now we place our photodiode a distance \( r \) from the LED, and we want to find the intensity \( N \) [mW/cm\(^2\)] at the photodiode. We first find \( J \) in millicandela on the LED data sheet. The data sheet gives the dependence of \( J \) [mcd] on the diode current and on direction. We then convert \( J \) [mcd] to \( J \) [mW/str], using Equation 2 and \( RR(\lambda) \) for the appropriate wavelength. (For our LED, \( RR(635 \text{ nm})=0.2 \).) Finally we divide \( J \) [mW/str] by \( r^2 \) to get \( N \) [mW/cm\(^2\)].

![Figure 1 The CIE curve. From Optoelectronics, Vaughn D. Martin, p. 12.](image)

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**Prelab:**

Complete all design calculations in the three sections below. Review the data sheets for the LED, pin diode and AD630.

1. **The LED (LTL2R3KRK)**
   
   a. Choose a bias point for the LED (D1). You’d like linear response for a small input \( V_{AC} \), and you want to make sure you don’t exceed the peak current for the LED.

   b. Connect the LED to the 5V power supply through resistor R1 as shown in Figure 2. Place a 33 \( \mu \)F capacitor (DC block) between the diode and the input signal source.

   c. Connect the function generator to the input side of the capacitor.

   d. Turn on the power supply. Your LED should illuminate. Turn on the function generator and reduce the frequency until you can see the generator modulating the LED output.

   e. What is the diode current? What is the average optical output power?

   f. Turn off the power supply.
2. The Photodiode (SFH213)

a. You will build a detector circuit with the photodiode about 3 cm from the LED. Given the LED bias point used in section 1, calculate the intensity at the photodiode, the power captured, and the expected photocurrent.

b. Calculate the required value for the feedback resistor for an output of 1 to 3 V.

c. Connect the diode and the current to voltage converter using the TL082/084 op amp as shown in Figure 4.

d. Turn on the power supply and signal generator. Record the output of the amplifier.

e. Make sure the output is due to the LED by blocking the optical signal. Check for interference from ambient light by covering the circuit with your hand.

f. Is the output linear? Determine the input signal amplitude for which output becomes nonlinear.

g. What is the frequency response of this circuit? What limits the frequency response?

h. What is the resolution of this circuit? What limits the resolution?
3. A Photonic Analog Link

a. For this part you’ll need to find your own MP3 or other audio file, and some headphones. Ensure that your MP3 player is working properly. In the absence of an MP3 player, you can use the headphone jack on the computer speakers. Last resort is the headphone out on the front panel of the computer. In all cases ensure that audio is being produced.

b. Now connect an audio cable from the headphone jack to your breadboard and use either channel to drive the LED (V\(_{AC}\)). Please check connections carefully to ensure you don’t connect any hazardous voltages to the computer.

c. Connect the second audio cable from the output of your photodetector circuit to a microphone input on the PC. Once again, be very careful about your connections. Note that if you record in mono, one channel will not be recorded.

d. You need to make sure you select the microphone as your recording input. Right click the volume icon in the taskbar and check “Recording devices”.

e. You should be able to play your audio file (media player) and at the same time record using Windows sound recorder (Start Menu ➔ Accessories ➔ Sound Recorder).

f. Note you have several controls including the playback volume (amplitude of modulating signal), the recording volume (amplification of input signal) as well as the bias point of your LED and the gain of your detector circuit. Your previous calculation was for the required DC gain. Your modulating signal is smaller and will probably require a higher gain.

g. Record a segment of your audio file transmitted through your optical link (10 or 15 seconds should be enough). Stop playback of the original file, connect your headphones to the computer, and listen to your transmitted file.

h. Unless you block DC at the output of your circuit, you will have a DC offset. How will this influence your recording?

i. Describe how and why your recording will change as you increase distance from source to receiver.
4. The Lock-In Amplifier

a. On the same breadboard used for your LED and photodiode, build the circuit shown in Fig. 5.

b. Set the HP32201A waveform generator to produce a 1kHz 100mVpp sine wave with no DC offset (this is the default setting when the generator is powered up). Connect the HP32201A output to both the reference (pin 9) and signal (pin 1) inputs of the AD630. Monitor and record the unfiltered output waveform $v_{out}$ on the oscilloscope. Explain the shape of the waveform. Next record the low-pass filtered output $v_{out}’$. Again explain the waveform. When you have finished recording the waveforms, disconnect the HP32201A and turn it off.
c. We will now explore the ability of the lock-in amplifier to recover a signal buried in noise. We will generate the required waveforms using the sound card on your labbench PC. The MATLAB code below generates amplitude modulated (AM) sine waves along with in-phase reference sinusoids. One file produced is called “outputSound1Hz.wav” while the second file is called “outputSound1HzNoise.wav”. Both files contain the same amplitude modulated signal however, the latter buries the signal in white noise. What is the carrier frequency? What is the modulated frequency? Either download the sample .wav files from the course website, or use the code to generate your own. Stereo signals have two channels (e.g., left and right). The generated wave files are stereo and one channel contains the reference while the other contains the AM modulated signal.

```matlab
clear
fs = 44100;
time = [0:1/fs:150];
fcarrier = 1000;
leftChannel = sin(2*pi*fcarrier*time);

fmod = 1;
noise = wgn(1,length(time),1,0.06);
rightChannel = 0.1*sin(2*pi*fcarrier*time).*sin(2*pi*fmod*time);
wavwrite([leftChannel;rightChannel]',fs,'outputSound1Hz.wav');
wavwrite([leftChannel;rightChannel+noise]',fs,'outputSound1HzNoise.wav');
```

d. Plug in one audio cable to the headphone output jack of your computer speakers. Plug the other side into your breadboard. The black pin is ground. Play “outputSound1Hz.wav” and use an oscilloscope to determine which pin is the reference and which is the AM signal. Plot both the reference signal and AM signal on the same plot. Which colour pin is the reference, and which is the AM signal? Connect the AM signal pin to the AC coupling capacitor of your LED just as you have done in Part 1 of this lab. Connect the reference signal pin through a 68nF DC blocking capacitor to the reference input (pin 9) of the AD630. Connect the output of the transimpedance amplifier to signal input (pin 1) of the AD630.

e. Attach three separate oscilloscope probes to $v_{signal}$, $v_{ref}$ and $v_{out}$. All probes must be DC coupled to the circuit.

f. Using Windows Media Player, play “outputSound1Hz.wav” and adjust the oscilloscope settings to demonstrate proper operation of the lock-in amplifier. Be aware that the reference signal must be sufficiently large to drive reference pin on the IC with positive and negative voltages. Over time, the AC coupling capacitor can build up charge and a DC offset occurs in the reference signal. When this happens, turn off the power supply for a moment and allow the capacitor to discharge.

g. Capture a screen illustrating the lock-in amplifier working. Explain the output. Describe each trace and demonstrate an understanding of what the lock-in amplifier is doing.

h. A screen shot showing sample output of a working lock-in amplifier is shown below in Figure 6.
i. Now for the incredible part. Using the same setup as before, play “outputSound1HzNoise.wav”. Note how the signal is completely buried in noise, but the lock-in amplifier is still able to capture the AM signal. Capture the waveform showing $V_{\text{signal}}$, $V_{\text{ref}}$ and $V_{\text{out'}}$. Provide a rough estimate of the signal to noise ratio in dB.

j. Two bonus marks will be awarded for introducing a phase difference of 180 degrees between the reference and AM signals, capturing the output and properly explaining the results.