Optical Fiber Communication System

OBJECTIVES

1. To explore how information can be transmitted using light
2. To design simple optical source (Light Emitting Diode “LED” & laser diode) and optical detector (phototransistor) circuits
3. To demonstrate optical modulation/demodulation (that is, converting an electronic signal into an equivalent optical signal, and then converting the optical signal back into an electronic signal)
4. To demonstrate the concept of information coding
5. To explore the factors that limit the rate at which information can be transmitted from transmitter to receiver
6. To explore how the amount of information transmitted down an optical fiber can be increased
7. To explore the dispersion of light
8. To explore color addition
9. To investigate the unique properties of light that allow Wavelength Division Multiplexing (WDM)
10. To demonstrate WDM
11. To explore practical WDM systems

Activity 1: An Optical Fiber Communication System

Place one end of an optical fiber close to the LED transmitter and the other end close to the phototransistor receiver to form a simple optical fiber-based optical telegraph.

Prediction 1: Will the light level illuminating the phototransistor receiver increase or decrease compared to the case of using just the long air path?

The size of the core of the optical fiber is large (approximately 2 mm in diameter) and its two ends are placed as close as possible to the transmitter and receiver (which themselves are some distance apart).

Question 1: Compare the signals received by the receiver with and without the optical fiber in place. Does the detected signal level change?

Note: The optical fiber you are using in this module has a 2 mm diameter plastic core that has an index of refraction of approximately 1.49. A cladding made of a different plastic that has an index of refraction of approximately 1.40 surrounds the core. A cross-sectional view of the fiber is shown in the figure below.

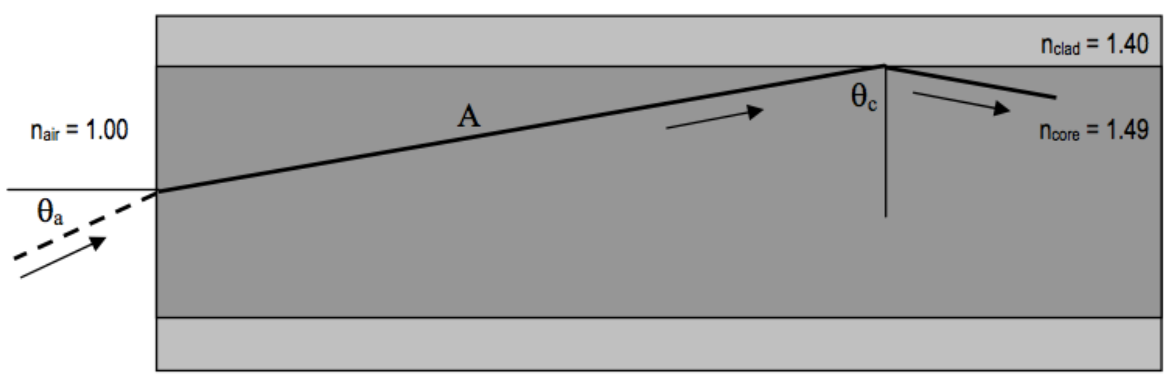


Figure 1. Cross section of a plastic fiber

Question 2: Using Snell's law ($n_1\sin\theta_1 = n_2\sin\theta_2$), determine the critical angle θ_c for a light ray A (as shown in Figure 1) traveling in the fiber core when it meets the boundary between the core and the cladding materials. Show your calculation below. (Recall that the critical angle is the smallest angle (θ_c) for which no light is transmitted into the cladding material, i.e., for which total internal reflection takes place.)

Question 3: What happens to any light rays incident on the core-cladding boundary at an angle greater than the critical angle ($\theta > \theta_c$)? What happens to rays incident at less than the critical angle?

Comment: Total internal reflection at the core-cladding boundary of the optical fiber provides a means whereby all light incident at greater than the critical angle is trapped and channeled within the fiber—none of it is transmitted out of the core. (With the particular fiber used here some of the light can also be channeled in the cladding, but this is not very effective as the cladding air boundary has many imperfections, scratches, dust and other sources of light loss.)

Question 4: Again using Snell's Law, determine the angle θ_a of the external light ray that enters the fiber core and then is refracted to become the critical angle ray A. This angle is known as the acceptance angle (θ_a) of the optical fiber.

Question 5: What happens to light rays entering the fiber core at angles less than the acceptance angle? At angles greater than the acceptance angle?

Question 6: Explain why coupling an optical fiber between the LED and the photodetector gives a stronger signal than just using a long air path.

Activity 2: A Simple Laser Diode "Optical Voice Communication System"

WARNING: The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.

A simple laser diode module as is found in inexpensive laser pointers is ideal as a voltage-controlled light modulator. The light output of the laser diode is directly proportional to the current flowing through it, which itself is directly proportional to the supply voltage over a fairly large range. This means that if you add a small, varying modulation voltage (which itself is proportional to an audio signal) onto the supply voltage of the laser pointer, the light output of the laser diode will vary linearly with this varying modulation voltage.

Attach the audio source being careful to connect the signal and ground wires the correct way.

Question 7: How well does this system work to transmit sound from the audio source to the amplifier?

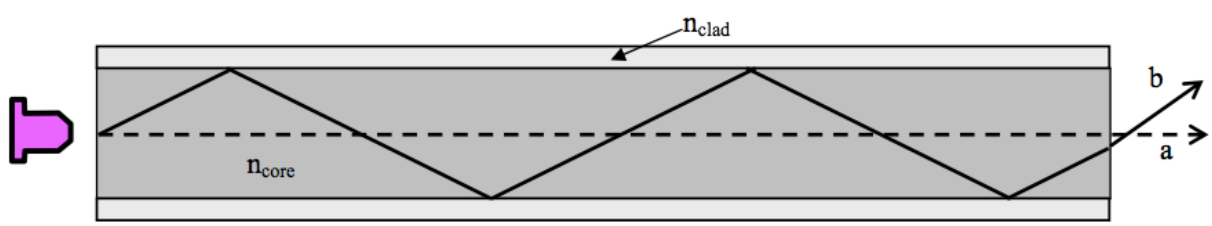
Question 8: Is there any limit to the amount of information that can be transmitted over a system like this? Explain.

In Activity 2, you examined how information can be sent over a fiber optic transmission line. In order to make an efficient communication system, it is necessary to maximize the amount of information that can be sent over such a line. In this module you will look at one important method for doing this, wavelength division multiplexing. This is an important component of photonics, the optical technology that is at the heart of all optical transmission systems.

Activity 3: Pulse Spread

Consider an LED that has its light coupled into the core of an optical fiber. The light can travel down the fiber following many possible paths. You examined total internal reflection at the boundary between a medium with a higher index of refraction and one with a lower index of refraction. You applied these ideas to the optical fiber used in Activity 2. Total internal reflection will occur as long as the light is incident on the core-cladding boundary at angles greater than the critical angle. Then the light will be channeled down the fiber without loss.

The diagram below shows two of the possible rays for light traveling down a straight length of fiber. The dashed ray (a) is along the optical axis of the fiber. The solid ray (b) follows a zig-zag path through the fiber and undergoes a number of (total internal) reflections.

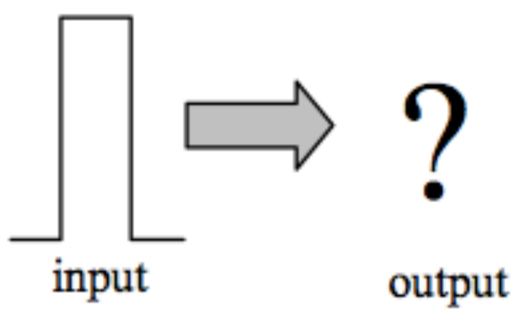


The core of the fiber has a constant index of refraction (n_{core}) which is a little larger than the index of refraction of the cladding (n_{clad}). Such a fiber is called a step-index multimode fiber.

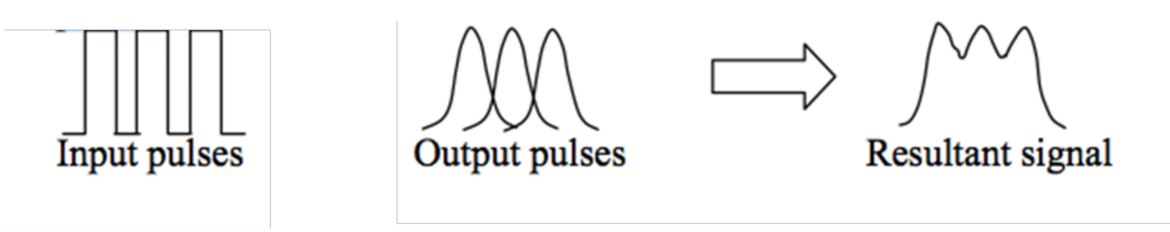
Assume the LED is switched on and off very rapidly giving a very narrow pulse of light. Light from the LED enters the entrance end of the optical fiber along rays at many angles.

Question 9: For the two light rays shown—along paths (a) and (b), which light traverses the length of the fiber in the shortest time? Explain.

Question 10: If the LED emits short rectangular light pulses (as shown below) that illuminate the entrance end of the fiber, what happens to the shape of these pulses after the waves that make up the pulses have traveled to the exit end of the fiber along many different ray paths? Explain.



Comment: The difference in transit times for the two paths (a and b) shown in the previous diagram is very small but will result in some spreading out of the pulses. If the pulses are very narrow and close to each other, the pulse spread may make it difficult to identify individual pulses.



A modern digital optical fiber transmission system uses ultra-narrow pulses of light to convey information. Each pulse or its absence can represent a binary digit or bit (a “1” or a “0”). These pulses of light are sent down the fiber from transmitter to receiver.

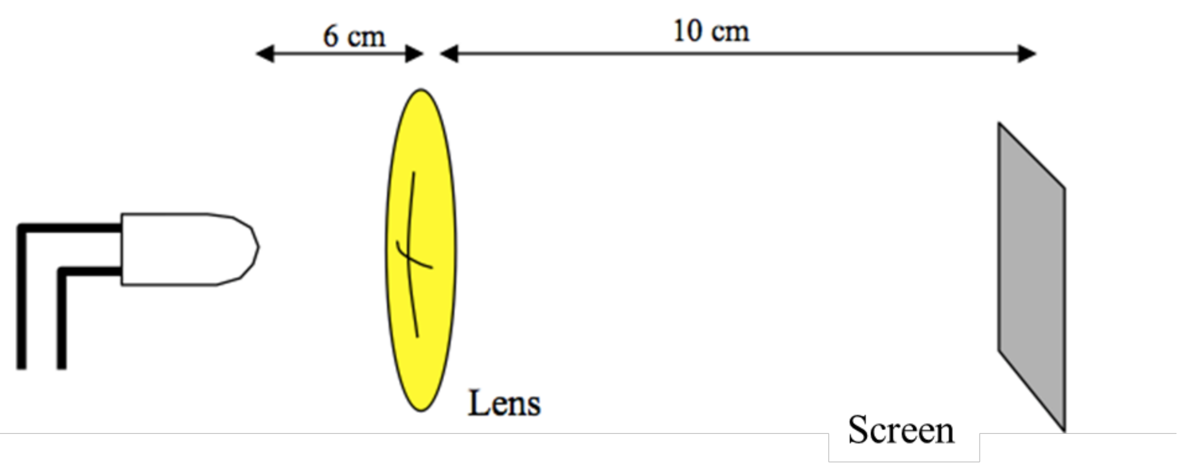
Question 11: With a given fiber, how can we transmit information at a faster rate (i.e., more bits per second) from transmitter to receiver?

Question 12: What will eventually limit the rate of information transfer (i.e., the maximum number of pulses that can be sent down the fiber per second)?

Comment: There are many other causes of pulse spread in optical fibers, so this is a real limitation to high data transfer rates in fiber optic systems!

Activity 4: Exploring the Red-Green-Blue (RGB) LED

Use the lens to focus the white light from the surface of the RGB LED module to form an image on a screen so we can observe the output of the LED more clearly.



Prediction
Observation

Prediction: What do you think will be observed on the screen? Draw your prediction in the box on the right.

Set up the plastic lens approximately 6 cm from the LED. Make sure the less curved surface of the lens is facing the LED. Place the screen approximately 10 cm from the lens and move it backward and forward until the LED image is clearly visible.

What do you observe on the screen? Draw it in the box on the right.

Question 13: What colors can be seen in the image?

Discuss the following questions with your partner(s), and then answer them.

Question 14: Are all the colors equally sharp? If not, why not? Does scattering have anything to do with it?

Question 15: Why does the LED look "white" when we look at it? What process makes it appear white?

Activity 5: Sending RGB LED Light down an Optical Fiber

You will next position the 2 mm plastic optical fiber on the center of the surface of the RGB LED. Again you will use the simple lens to focus the white light from the exit surface of the optical fiber to form an image on a screen so you can observe the fiber's output more clearly.

Prediction: What do you think will be observed on the screen? Draw your prediction.

Couple the optical fiber to the LED by using the plastic coupler. Thread the other end of the fiber through the holes in the fiber holder. Position the lens approximately 3.5 cm from the tip of the fiber and the screen approximately 13 cm from the lens. Adjust the position of the screen to obtain a sharp image

Discuss the following questions with your partner(s), and then answer them.

Question 16: Explain why the image on the screen is different from the image in the Activity 4 without the optical fiber? Are they not both images of light coming from the same LED!?

Question 17: What is happening to the signals from the Red, Green and Blue sources in the LED when they pass through the optical fiber?

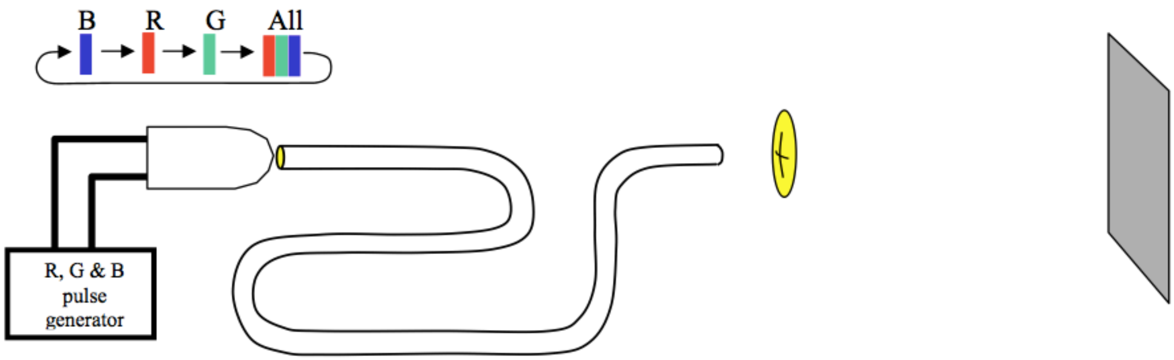
Activity 6: Sending Information down an Optical Fiber

If we have some information, we can encode it into a sequence of light pulses and send it down the optical fiber. The source of these coded light pulses is called the transmitter.

These pulses are channeled down the fiber without loss and can be detected and decoded at the other end. The device that does this is called the receiver.

Each of the three tiny sources in the RGB LED can be controlled independently, so we can send various R, G or B pulses of light down the fiber. In this manner information can be sent down any or all of these three different color channels.

We can use the microcontroller to generate different sequences of R, G and B light pulses from the RGB LED. (These represent three different information streams.)



Prediction: What sequence of colors and shapes do you think would be observed on the screen?

1. Press the push button on the microcontroller ***once only***. This will activate the required sequence B pulse, R pulse, G pulse, (R+G+B) pulse.

Question 18: What sequence of colors and shapes do you actually observed on the screen?

2. Place the red cellophane sheet between the lens and screen.

Prediction: Continuing to use exactly the same sequence of pulses down the fiber (B pulse, R pulse, G pulse, (R+G+B) pulse), what sequence of colors and shapes do you think will now be observed on the screen?

Question 19: What sequence of colors and shapes do you actually observe on the screen?

Question 20: What effect does the red cellophane sheet have on the image sequence? Why does this happen? What function does the cellophane sheet perform?

Comment: The optical fiber is combining the information pulses from the R, G and B sources together down one transmission line. This process of combining many input information streams into one output stream is called multiplexing.

If “1” represents “light pulse” and “0” represents “no light pulse”, then the information sent down the different channels for the sequence of pulses used in previous activities is:

BLUE channel 1001 1001 1001 etc

RED channel 0101 0101 0101 etc

GREEN channel 0011 0011 0011 etc

The red filter allows us to separate out the information on the red channel from that on the other two (green or blue) channels. That is, only the RED channel 0101 0101 0101 reaches the screen when the red filter is in place. We could replace the red filter with a green or blue one and separate out the information streams for these other colors.

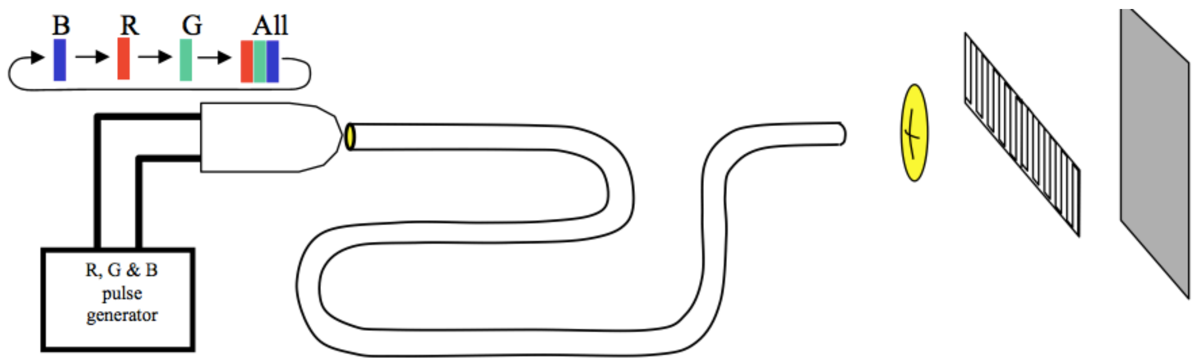
Question 21: Would the use of filters (as described above) allow us to increase the information carrying capacity of our optical fiber?

Question 22: What could we do to increase the information carrying capacity of our optical fiber by a factor of three?

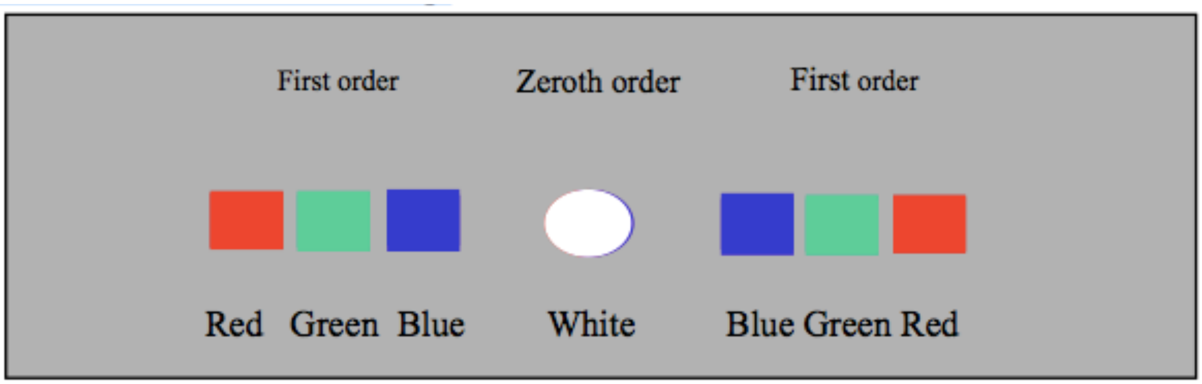
Activity 7: Using a Diffraction Grating to Retrieve the Information

There are two devices that you can use to spread out (or disperse) the light from the output of the optical fiber into separate R, G and B spots on the screen: *a prism or a diffraction grating*. This would allow us to see all the information contained in the red, green and blue pulse streams simultaneously.

We will use a diffraction grating placed between the lens and the screen.

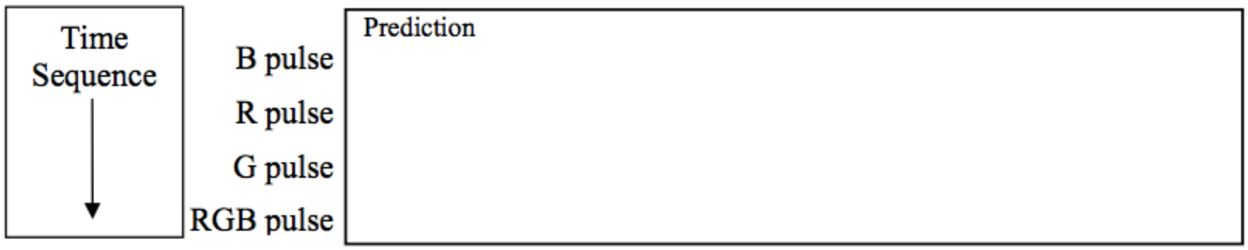


If a white light pulse was being transmitted, the pattern on the screen would look like the following:



Question 23: Explain why the pattern for a white light pulse would look like this. Consider both the position and shape of the various colored patterns.

Prediction: What sequence of colors and shapes would be observed on the screen for the same sequence of pulses used in the previous activity: Blue pulse, then Red pulse, then Green pulse, then combined (R+G+B) pulse? Sketch below, next to the name of each pulse its position relative to the center of the screen.

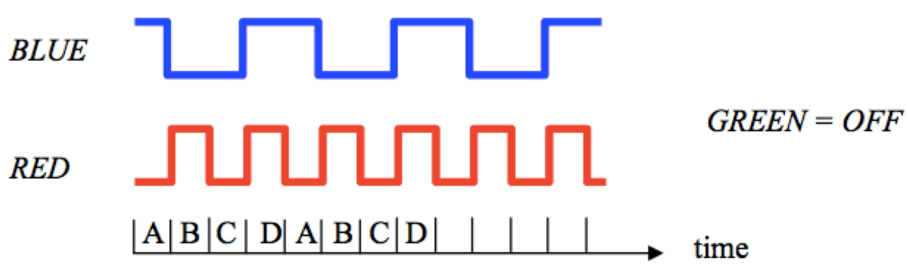


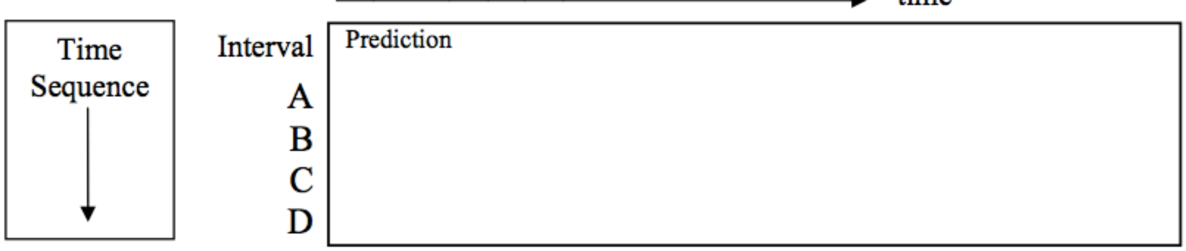
Activity 8: Wavelength Division Multiplexing using a Diffraction Grating

With the grating, we are now able to send different pulse sequences on different color (RGB) channels, carrying independent information. This technique is called Wavelength Division Multiplexing (WDM).

Question 24: Does WDM increase the information carrying capacity of the optical fiber? Why or why not?

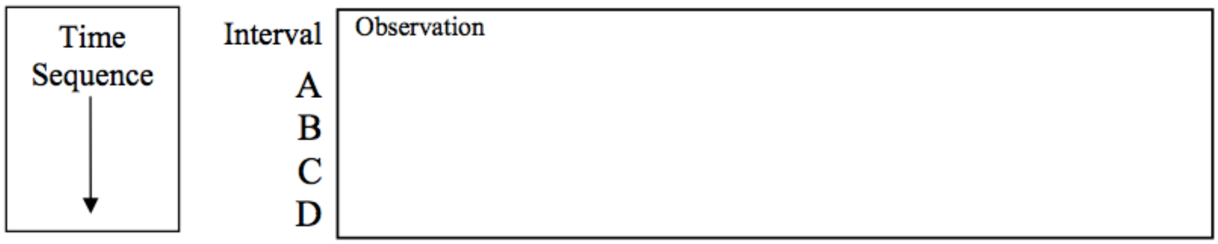
Prediction: What would you observe on the screen if the following blue and red pulse sequences were sent down the fiber simultaneously?





Again press the push button on the microcontroller ***once only***. (This means that this is the second time the button has been pushed since the device was turned on). This will activate the microcontroller to generate the required Red-Blue LED sequence shown above.

Sketch below the sequence of colors and shapes observed on the screen.



Question 25 As well as red and blue, a new color is also observed. What is this color? How is it generated?

Activity 9: Audio Demonstration of WDM

In this demonstration, two separate digital audio codes are sent down the fiber via WDM (one signal is sent in green light and the other is sent in red light.) The diffraction grating is used to separate out these two signals at the receiver.

When the phototransistor-based audio amplifier is moved from the green to the red spot, the audio tone changes accordingly.

Replace the Mylar screen with the phototransistor detector and audio amplifier system. This system converts the green and red high frequency light pulses into two distinct audio tones.

Question 26: What do you hear as the phototransistor is moved from the first order red diffraction region to the first order green diffraction region? Explain why you observe this change as you move the detector from one region to the other.