CNS Institute for Physics Teachers

Title:	**Communicating with Light: From Telephony to Cell Phones**
Original: **Revision:**	1 June 2006 28 June 2010
Authors:	Jim Overhiser, Luat Vuong
Appropriate Level:	Physics, Grades 9-12
Abstract:	This series of six station activities introduces the physics of transmitting "voice" information using electromagnetic signals or light. Students explore how light can be modulated to encode voice information using a simple version of Bell's original photophone. They observe the decrease of the intensity of open-air signals by increasing the distance between source and receiver, and learn the advantage of using materials with different indices of refraction to manipulate and guide light signals. Students are introduced to the concept of bandwidth by using two different wavelengths of light to send two signals at the same time. Finally, students explore how optical signals are manipulated in a photonic chip.
Time Required:	Two 80-minute periods
NY Standards Met:	4.1b Energy may be converted among mechanical, electromagnetic, nuclear, and thermal forms 4.1j Energy may be stored in electric or magnetic fields. This energy may be transferred through conductors or space and may be converted to other forms of energy. 4.3b Waves carry energy and information without transferring mass. This energy may be carried by pulses or periodic waves. 4.3i When a wave moves from one medium into another, the waves may refract due a change in speed. The angle of refraction depends on the angle of incidence and the property of the medium. 4.3h When a wave strikes a boundary between two media, reflection, transmission, and absorption occur. A transmitted wave may be refracted.
Special Notes:	**Communicating with Light** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/.

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Behavioral Objectives:

Upon completion of this lab activity, the student should be able to:

- Explain the different components of an optical network, how they function, and how they work together to build a telecommunications system.
- Understand basic optics concepts including wavelength, amplitude, refraction, reflection, and total internal reflection within a technological context.
- Understand that light guides (such as optical fibers) prevent signals from dispersing and thereby allow them to be transmitted over large distances.

Historical Background:

Alexander Graham Bell invented and tested a device called a photophone in 1880. Bell's device consisted of a cylinder with at piece of light-reflecting metal foil cover one end. Bell spoke into the other end of the cylinder and directed sunlight reflected off the foil on to a crude selenium cell (precursor to the modern photocell) that was connected in series to a battery. The battery provided the voltage to power one of Bell's telephone receivers, and the selenium cell provided the voltage spikes necessary to produce intelligible sound. Changes in the intensity of the light beam were used to transmit the information.

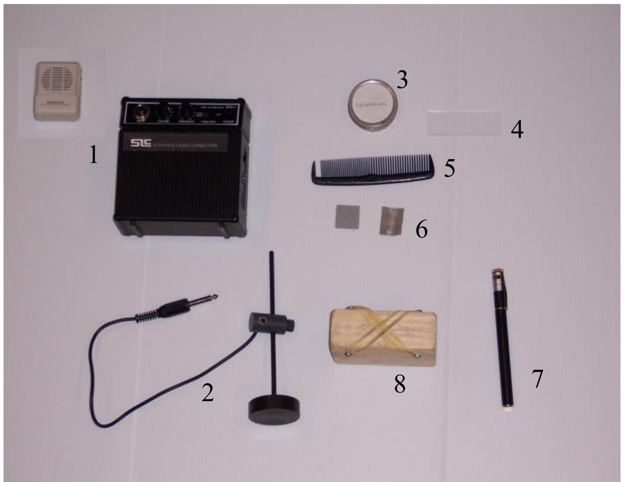
Modern telecommunication systems change, or modulate, the light intensity of the beam. However, light was not used to carry voice and other signals until recently. Although Bell considered this his most ingenious invention, it never took off. The photophone could transmit voice signals only 200 meters through free space, which was a critical limitation. It would take the invention of optical fibers and fiber amplifiers, capable of guiding light thousands of kilometers, before light was again used to carry communications signals.

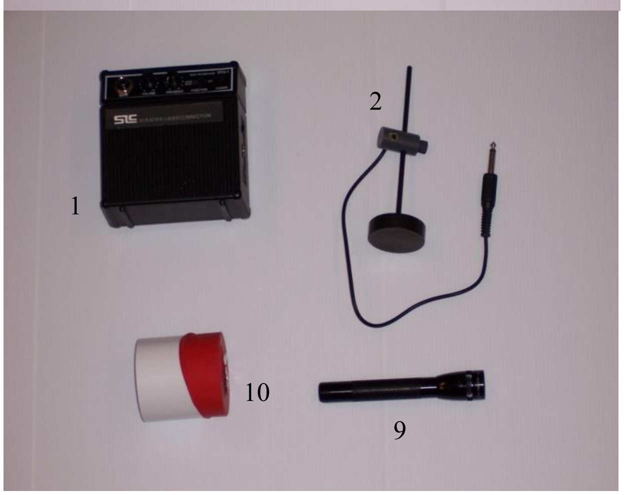
Meanwhile, the radio was invented and held the technological upper hand in communications for decades. Reginald Aubrey Fessenden (1866-1932) is given credit for the first attempt to transmit voice via a radio signal (telephony). He employed a spark transmitter (invented by Heinrich Hertz) that operated at approximately 10,000 sparks/second. To modulate his transmitter he inserted a carbon microphone in series with the antenna lead. He experienced great difficulty in achieving intelligible sound.

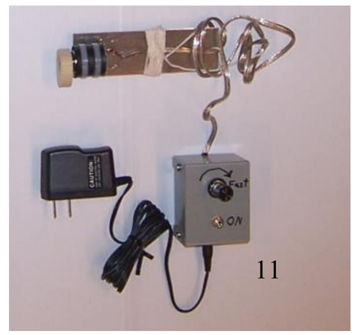
On the 23 December 1900, Fessenden, after many unsuccessful tries, transmitted words without wires. The first radio transmission was the following: "Hello test, one, two, three, four. Is it snowing where you are, Mr. Thiessen? If it is, telegraph back and let me know." Mr. Thiessen telegraphed back immediately. It was indeed snowing where he was. After all Mr. Thiessen and Professor Fessenden were only one mile apart! But not withstanding the short distance and the poor quality of the transmission, this date heralded the beginning of radio telephony, which dominated distance communication for several decades.

Equipment

Station 1

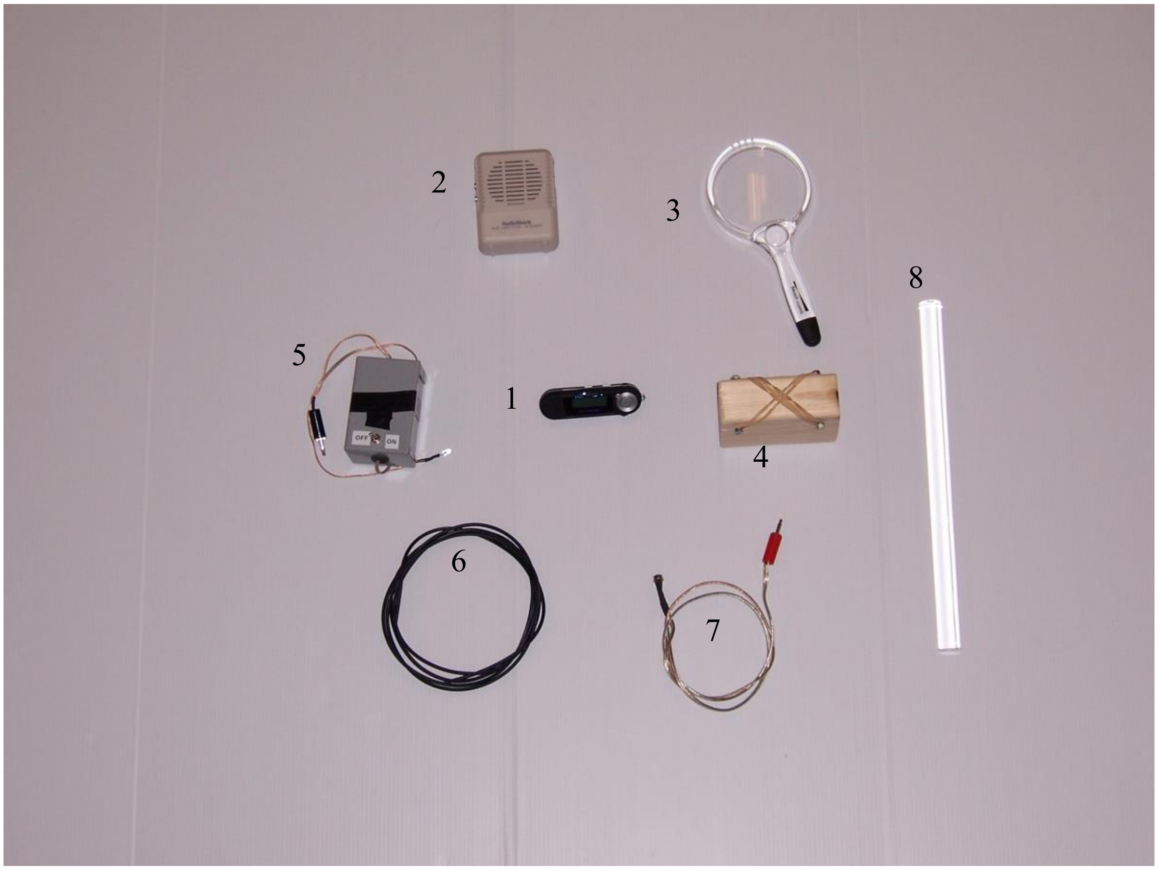






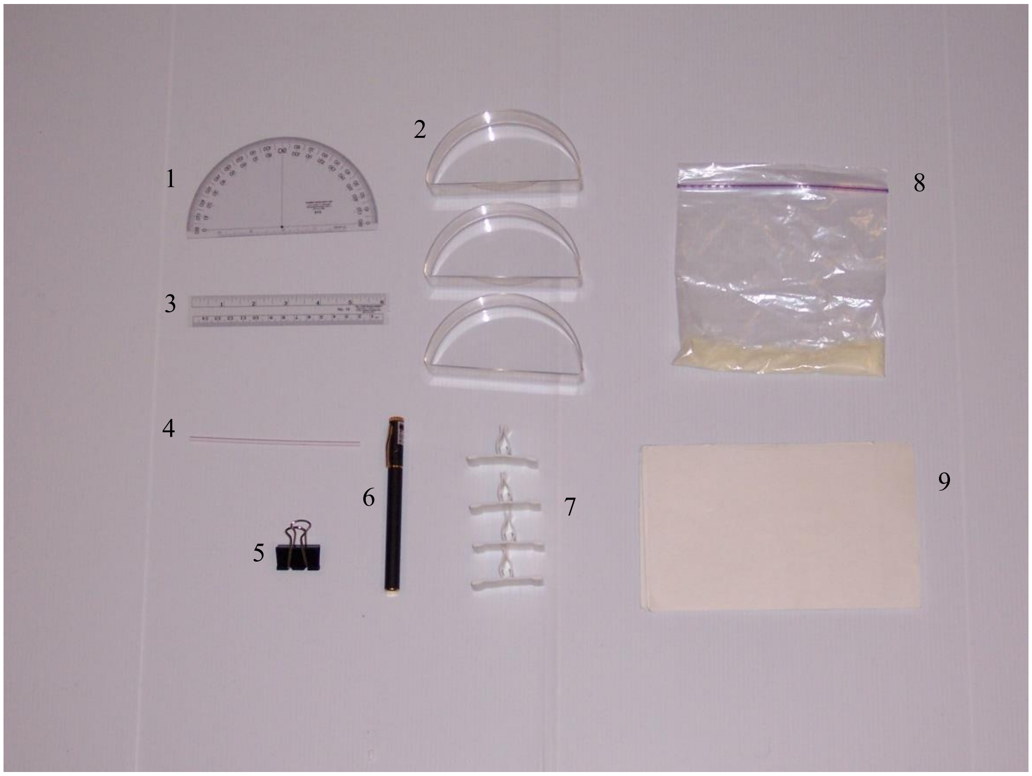
Item Number	Quantity	Item
1	1	Desk top or mini amplifier/speaker
2	1	Photodiode with stand
3	1	Lycopodium powder
4	1	Glass slide
5	1	Comb
6	4	Wire mesh – 4 grades
7	1	Red laser
8	1	Laser mount
9	1	Mini Maglight flashlight
10	1	PVC pipe with balloon and foil square
11	1	Resonator set-up

Station 2



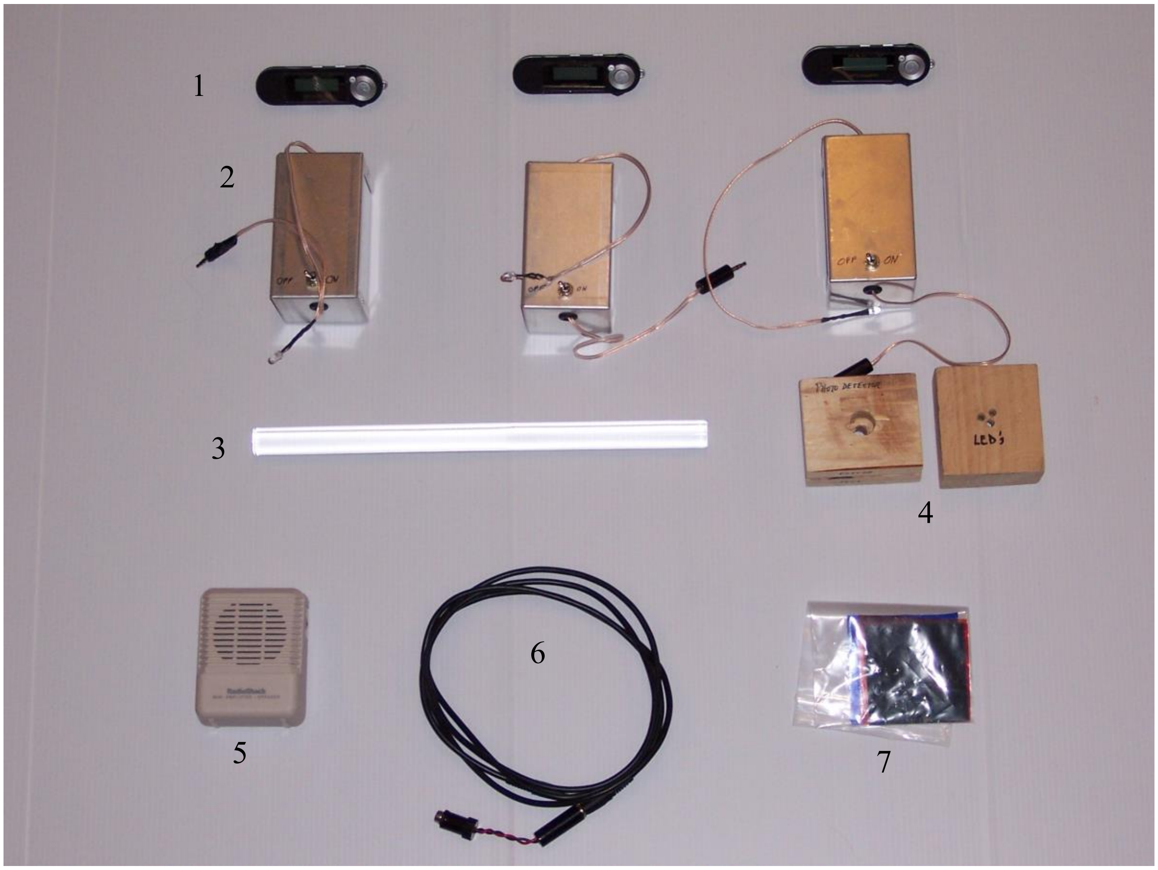
Item Number	Quantity	Item
1	1	MP3 Player or transistor radio
2	1	Mini amplifier/speaker
3	1	Magnifying glass
4	1	Magnifying glass support
5	1	Red LED signal box/power source
6	1	2 m fiber optic cable
7	1	Photodiode with connection cable
8	1	30cm long 7mm diameter Lucite rod

Station 3



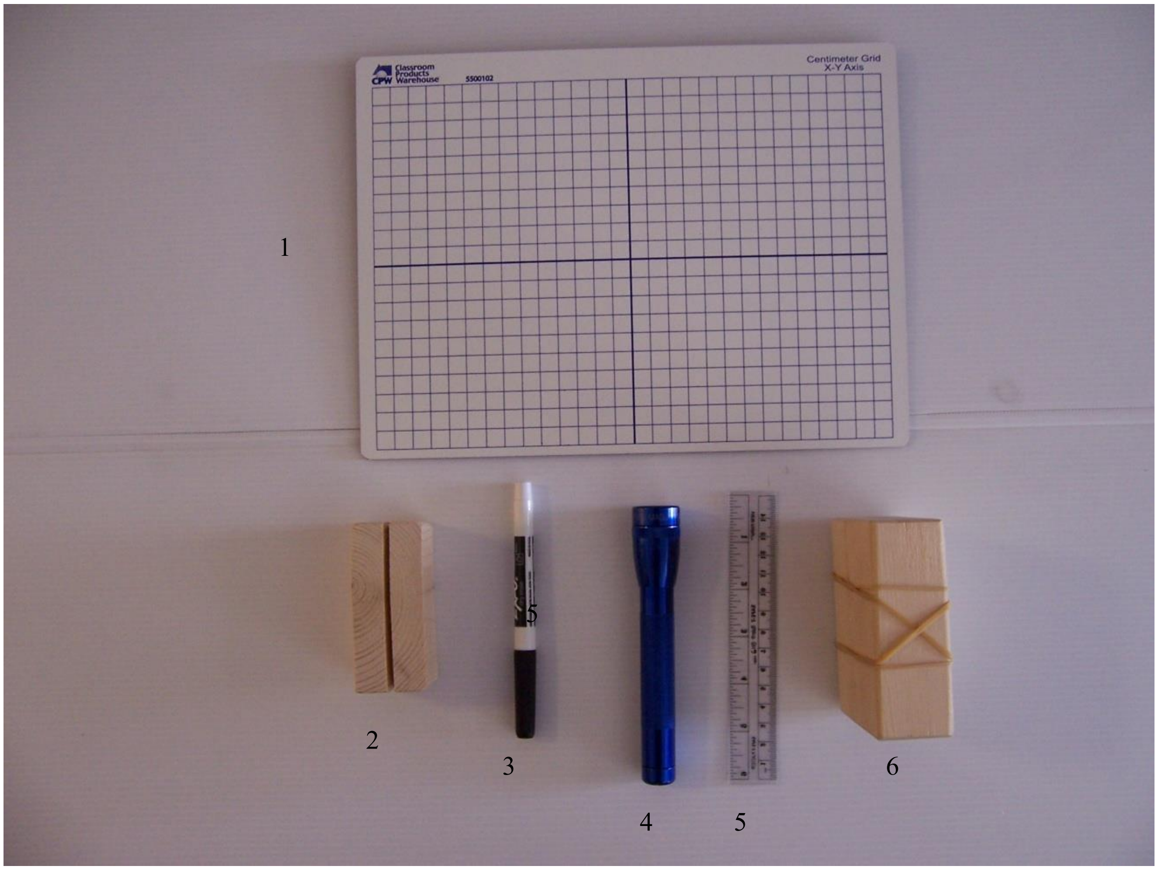
Item Number	Quantity	Item
1	1	Protractor
2	3	Semicircular refraction dishes
3	1	Small plastic ruler
4	1	Coffee stirrer
5	1	Binder clip
6	1	Red laser
7	4	Card holders
8	1	Powdered milk
9	4	Large index cards or poster board

Station 4



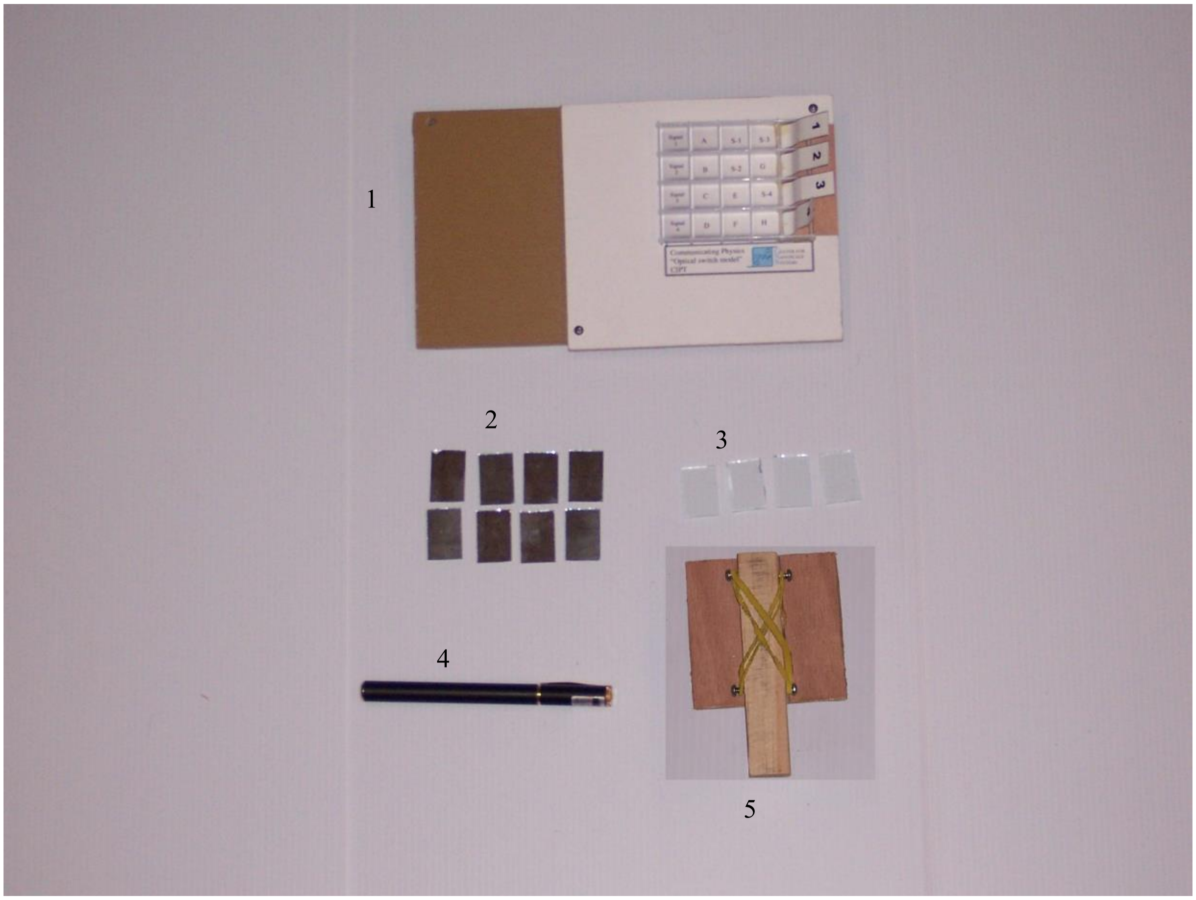
Item Number	Quantity	Item
1	3	MP3 Player or transistor radio
2	3	LED light emitter units (red, blue, yellow)
3	1	30 cm long 7 mm diameter Lucite rod
4	1	Wooden support blocks
5	1	Mini amplifier/speaker
6	1	Photodiode with connection cable
7	1	Set of various color filters

Station 5



Item Number	Quantity	Item
1	1	Grid board, erasable
2	1	Wooden grid board holder
3	1	Dry erase marker
4	1	Mini Maglight flashlight with square filter
5	1	Small plastic ruler
6	1	Wooden flashlight holder

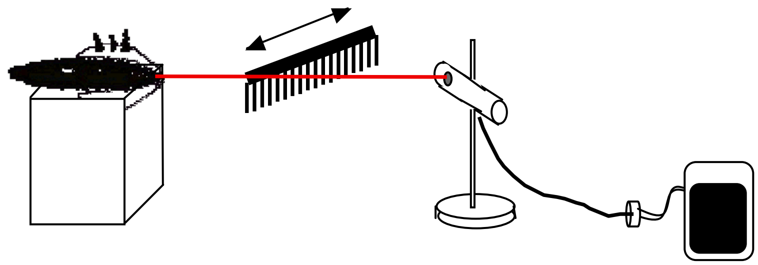
Station 6



Item Number	Quantity	Item
1	1	CIPT “Optical Switch Model” board
2	8	Mirrors
3	4	Glass
4	1	Red laser
5	1	Wooden laser mount

Station 1: Talking With a Beam of Light

Part A: Modulation



Materials:

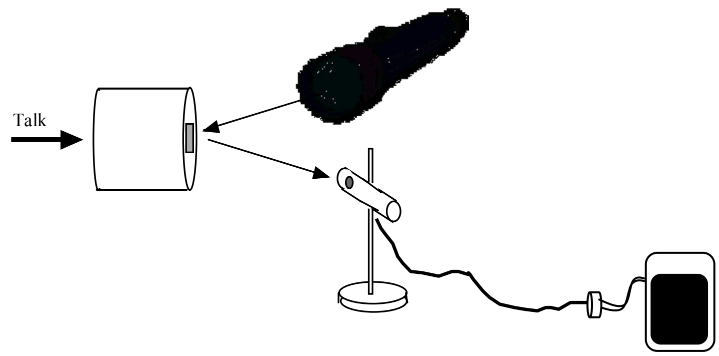
- laser
- laser mount
- photodiode with stand
- desk top amplifier or mini amplifier
- various accessories: plastic comb, glass slide, lycopodium powder, wire mesh, resonator

Instructions:

1. Place the laser under the rubber bands on the laser mount. To turn on the laser, rotate the pointer until the on/off button is in contact with the wooden holder.
2. Attach the photodiode to the data input on the amplifier.
3. Aim the laser beam at the photodiode.
4. Turn on the speaker.
5. Observe the effects of interrupting the laser beam the various items in the kit.
6. Using the resonator:
   - Hold the string and let the resonator hang.
   - Turn on the resonator and turn the dial to tune to the fundamental frequency.
   - Listen to the fundamental frequency by placing the standing wave for the fundamental frequency in the path of the beam.
   - Adjust the frequency of the resonator to find the various harmonics and listen to them as you did for the fundamental frequency.
7. Answer related questions on the *Student Data Sheet.*
8. ***TURN OFF THE LASER, RESONATOR, AND DESK TOP AMPLIFIER WHEN FINISHED***.

<u>Station 1</u>: Talking With a Beam of Light

Part B: Alexander Graham Bell's Photophone



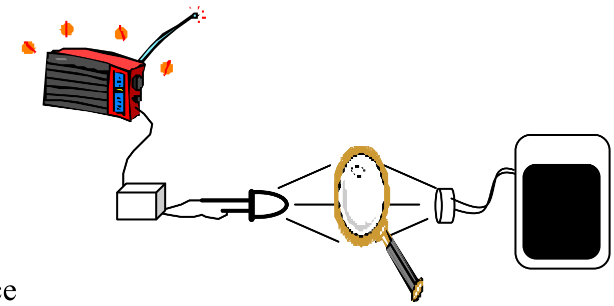
<u>Materials</u>:

- PVC pipe section with a latex balloon stretched over one end and a piece of aluminum foil attached to the balloon in the center of the tube
- photodiode with stand
- desk top amplifier or mini amplifier
- Mini Maglight flashlight

<u>Instructions:</u>

1. PVC pipe: if unassembled then assemble by:
   - Cutting off the end of a balloon
   - Stretching the balloon over the PVC pipe ensuring the surface is smooth and taut
   - Glueing a small piece of aluminum foil to the surface of the balloon
2. Hold the open end of the PVC device up to your mouth.
3. Have a partner aim the Mini Maglight at the aluminum foil and focus the beam to a bright spot.
4. Aim the photodiode to receive the reflected beam of light.
5. Make sure the speaker is on.
6. Talk into the PVC device and observe what happens.
7. Answer related questions on the *Student Data Sheet.*
8. ***TURN OFF THE DESK TOP AMPLIFIER AND MAGLIGHT WHEN FINISHED***.

<u>Station 2</u>: Good Transmission



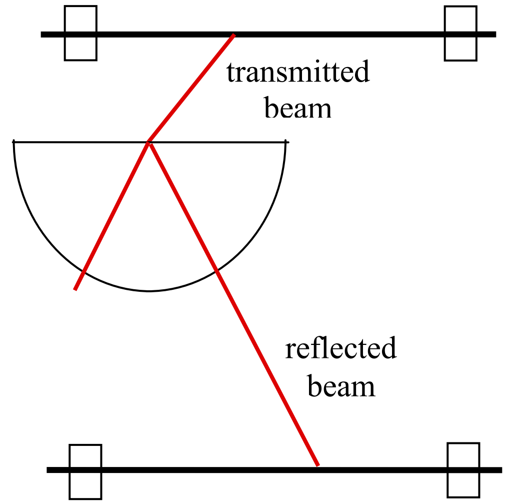
<u>Materials</u>:

- MP3 player or transistor radio
- red LED signal box/power source
- photodiode
- mini amplifier/speaker
- magnifying glass with support
- 30 cm long 7 mm diameter Lucite rod
- 2 m fiber optic cable

<u>Instructions</u>:

1. Select a song on the MP3 player or transistor radio and plug in the LED signal box.
2. Turn on the LED circuit and observe—can you see the light flicker? (Hold the red diode against a sheet of white paper to try to see this more easily, as it is a subtle effect.)
3. Connect the photodiode to the input of the mini amplifier/speaker.
4. Turn on the amplifier/speaker unit and aim the LED at the photodiode.
5. Observe what happens as you increase the distance between the LED transmitter and the photodiode receiver. (This distance may be larger if you darken the room.)
6. Place the magnifying glass between the LED transmitter and the photodiode receiver. Using the ability of the magnifier to focus light, can you improve the transmission?
7. See what happens to the transmission from the LED to photodiode when you put the Lucite rod between them. Is the transmission with the Lucite rod better or worse than the transmission with the magnifying glass? Compare the transmission with and without the Lucite rod.
8. Finally, try to improve transmission with the fiber optic cable. Does bending the fiber affect the transmission?
9. Answer related questions on the *Student Data Sheet.*
10. ***TURN OFF THE MINI AMPLIFIER AND THE MP3 PLAYER WHEN FINISHED.***

<u>Station 3</u>: Trapping Light

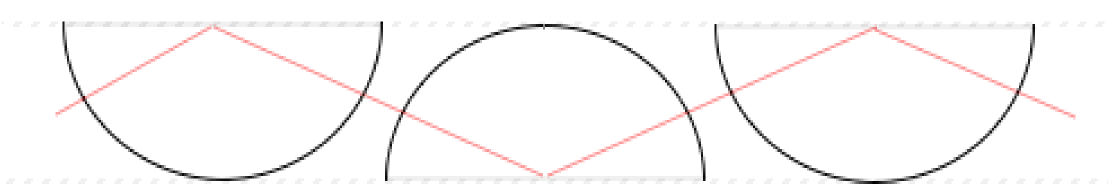


<u>Materials</u>:

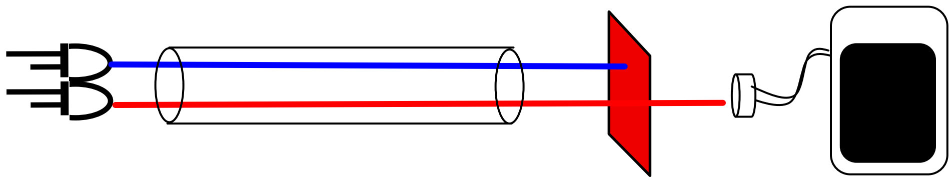
- small plastic metric ruler
- 3 semicircular dishes
- water
- powdered milk
- protractor
- laser
- white poster paper or large index cards
- 4 index card holders
- plastic coffee stirrer
- binder clip

<u>Instructions</u>:

1. Fill one semicircular dish with water, add 2 or 3 grains of powdered milk to the water, and stir to dissolve. The water should still look clear.
2. Place the semicircular dish on the protractor as pictured with the flat side directly over the 0° — 180° line.
3. Set up two barriers as pictured, each using 2 index card holders and poster paper.
4. Use the binder clip to keep the laser turned on as it lays flat on the table.
5. Shine the laser through the water, aiming it from the 90° mark through the origin of the protractor.
6. Move the laser slowly to larger angles, keeping the beam aimed at the origin.
7. Observe the dots where the transmitted beam and the reflected beam fall on the barriers. Compare the brightness of each dot as the angle gets larger. Observe the intensity of the incident and reflected beams within the water.
8. Increase the angle until the transmitted dot disappears. (You may need to adjust a barrier if the beam moves off of it.) Check to make sure your beam is still aimed at the origin point of the protractor and record the critical angle.
9. Prepare two more semicircular dishes as in step #1 and build the set-up pictured below. Move a barrier to check along the flat sides of the dishes and see if any light leaks out of the sides.
10. Answer related questions on the *Student Data Sheet*.



<u>Station 4</u>: Packing the Information Highway



<u>Materials</u>:

- 3 MP3 players or transistor radios
- 3 light emitting diode (LED) units (red, yellow, blue)
- photodiode with mini amplifier/speaker
- various color filters
- 30 cm long 7 mm diameter Lucite rod
- 2 wooden blocks

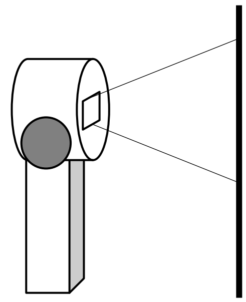
<u>Instructions</u>:

1. Tune each of the MP3 players or transistor radios to very different sounding songs or stations. Plug the three LED circuits into the phono jack of the three players.
2. Toggle all LED boxes to the OFF position.
3. Insert the three LEDs into the three small holes on the block.
4. Insert the Lucite rod into the large hole in each block.
5. Tuning the system: One at a time, toggle each LED box to the on position and adjust the volume on the player and mini-amplifier to get the clearest sound. Once this is accomplished, toggle all the LED boxes to the OFF position.

<u>CHALLENGE:</u> Devise a way to separate three simultaneously sent signals.

6. Shine only the red LED on the photodiode. Place the color filters one at a time in front of the photodiode to determine which filters stop the red LED signal from being transmitted to the photodiode. Record your results in the table on the *Student Data Sheet.*
7. Repeat step #6 with the yellow and blue LEDs. Record your results on the *Student Data Sheet.*
8. Use this information to formulate a hypothesis on which filters you need to select each individual station when all three are being simultaneously transmitted. Record your hypothesis on the *Student Data Sheet*.
9. Now, send the light from all three LED/songs through the Lucite rod and into the photodiode. Test your hypothesis on filter selection to hear each song individually and record your results.
10. Answer related questions on the *Student Data Sheet.*
11. ***TURN OFF THE MINI AMPLIFIER AND THE MP3 PLAYERS WHEN FINISHED***.

<u>Station 5</u>: Not Enough Bars (Signal Loss)



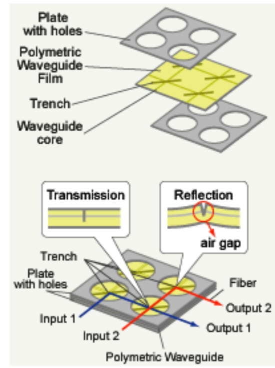
<u>Materials</u>:

- grid board
- wooden grid board holder
- dry-erase marker
- flashlight light w/square filter
- wooden flashlight holder
- ruler

<u>Instructions</u>:

1. Place the grid board into the slot on the wooden holder. Secure the flashlight under the rubber bands on the wooden flashlight holder. Turn on the flashlight and point it toward the grid board. Rotate the flashlight slightly so that the illuminated area is a rectangle and not a trapezoid. Position the flashlight 4 cm away from the grid board.
2. Trace the illuminated area on the grid board with the dry-erase marker.
3. Count the number of squares inside the illuminated region and record this information on the data table on the *Student Data Sheet*. Count portions of squares by estimating the amount of square being illuminated by light. (i.e. 50% of square illuminated = 0.5 square).
4. Repeat this process at 6 cm, 8 cm, 10 cm and 12 cm.
5. In the space provide on the student sheet, graph *Distance vs. # of Squares*.
6. Answer related questions on the *Student Data Sheet.*
7. ***TURN OFF THE FLASHLIGHT WHEN FINISHED.***

Station 6: Light on a Chip



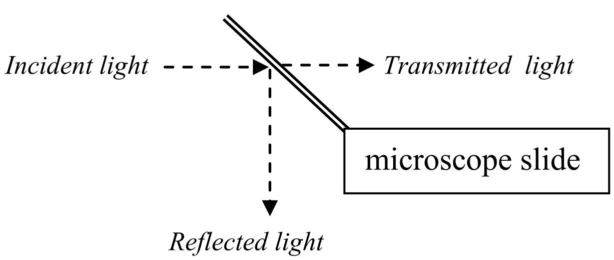
Materials:

- 8 mirrors
- 4 microscope slides
- laser
- laser mount
- CIPT "Optical Switch Model" board

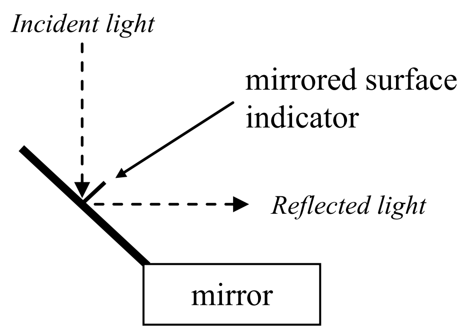
Instructions:

This station models an optical switch (photonic chip) containing eight reflector switches and four beam splitter switches. Mirrors represent the reflector switches and glass slides represent beam splitters. Their actions are illustrated in the figures below.

Beam Splitter



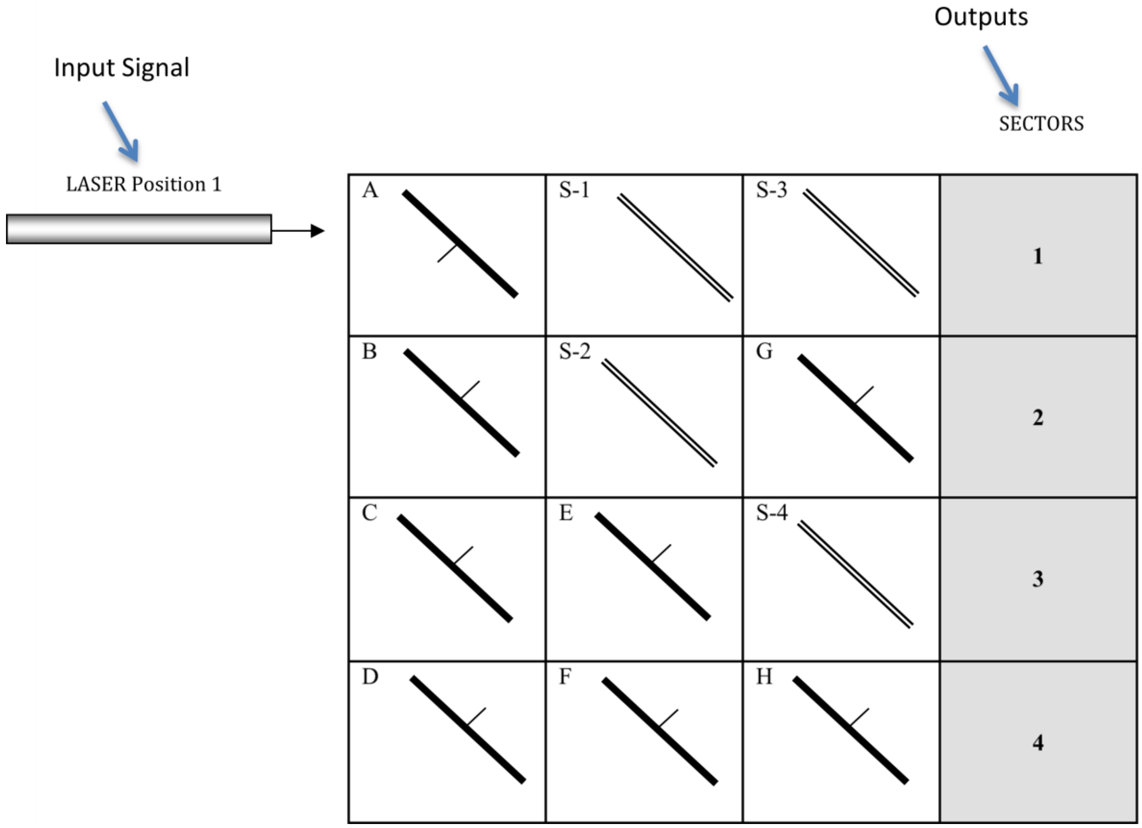
Reflector Switch



Study the following chart to see the descriptions of the actions for each kind of switch on the "optical switch model" board.

Switch	Switch Action
REFLECTOR ON	Mirror in place
REFLECTOR OFF	Mirror removed
BEAM SPLITTER ON	Microscope slide splitter in place
BEAM SPLITTER OFF	Microscope slide splitter removed

Position the laser directly across from Sector 1 and fill the optical switch model according to the following illustration.



Your task is to light the following individual sectors or combinations of sectors by removing the appropriate beam splitters and reflectors from the board.

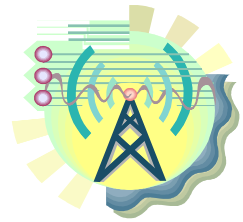
Lighted sector(s):

- **Sector 1 only**
- **Sector 2 only**
- **Sector 3 only**
- **Sector 4 only**
- **Sectors 1 and 2 simultaneously**
- **Sectors 1 and 3 simultaneously**
- **Sectors 1 and 4 simultaneously**
- **Sectors 2 and 3 simultaneously**
- **Sectors 2 and 4 simultaneously**
- **Sectors 3 and 4 simultaneously**
- **Sectors 1, 2 and 3 simultaneously**
- **Sectors 1, 2, 3 and 4 simultaneously**

Record your results in the table on the student sheet and answer the related questions.

<u>Student Data Sheet</u>

Communicating with Light: From Telephony to Cell Phones



Name: ____

te·leph·o·ny *n.*
The transmission of sound between distant stations, especially by radio or telephone.

<u>Station 1</u>: Talking with a beam of light

Part A: Modulation

1. Describe what you did to the light to make sound from the speaker.

2. The comb and the wire mesh can create a certain pitch or tone. Describe how you can increase the pitch. Also describe how to increase the pitch with the resonator.

3. In this activity, you "modulated" the light to produce sound. Give your own definition of the word "modulation."

Part B: Alexander's photophone

4. Describe how your voice affects the light beam and gets encoded on it.

5. Describe all the energy conversions that take place to transmit your voice to the speaker.

<u>Station 2</u>: Good transmission

1. What is the effect of increasing the distance between the LED emitter and photodiode receiver? Give an explanation as to why this happens.

2. The magnifying glass, the Lucite rod, and the optical fiber all improved the transmission between the LED emitter and photodiode receiver. How did these objects improve the transmission?

3. Of the magnifying glass, the Lucite rod, and the optical fiber, which was most effective at improving transmission? Give an explanation why.

4. Why is optical fiber used to guide light signals around the world, not something larger in diameter like the Lucite rod?

5. Cell phone reception can be a problem. Why do you think the traditional "landline" telephones have clearer, non-interrupted signals?

<u>Station 3</u>: Trapping Light

1. What happened to the comparative brightness of the transmitted and reflected beams as you moved the laser beam more parallel to the flat side of the dish?

2. Just before the transmitted beam disappeared, what was its angle relative to the flat side of the dish?

3. Record the angle at which the transmitted dot disappeared: __________°. This is called the "critical angle."

4. For what range of angles was all the light reflected? ______° to ______°. This is called total internal reflection.

5. Would you expect the critical angle to change if a fluid other than water were placed inside the dish?

6. Explain how an optical fiber guides light without letting any leak out.

7. What could happen to the light if the fiber gets bent too sharply (assuming it does not break)?

<u>Station 4</u>: Packing the information highway

1. What is the advantage of sending several wavelengths of light through one fiber?

2. "Bandwidth" refers to the range of wavelengths that can be transmitted through a fiber. Explain why greater bandwidth is better.

3. Complete the following table for testing filters:

Color of LED transmitter	Filter colors that allow transmission	Filter colors that prevent transmission
RED		
BLUE		
YELLOW		

4. Complete the following guide for your hypothesis on selecting only one color of light if the red, yellow and blue LED is all being transmitted.

To transmit only...	I need the following filters...
RED	
BLUE	
YELLOW	

5. If you had two additional photodiodes with amplifier/speakers, diagram how you would set them up so that each speaker plays a different station at the same time.

6. The process of separating signals carried by different wavelengths of light is called "demultiplexing." Why is demultiplexing important?

Station 5: "Not enough bars" (Signal loss)

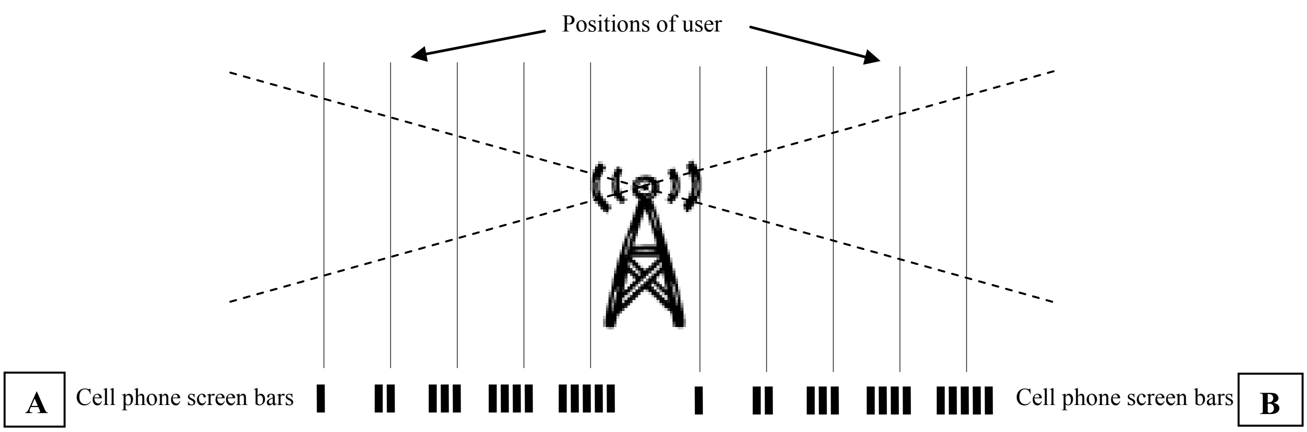
1. Complete the following data table.

Distance (cm)	Surface Area (# of squares)
4	
6	
8	
10	
12	

2. What happened to the light intensity as the distance from the screen decreased?

3. Construct a line graph of *distance vs. surface area* using graph paper or a computer. What does this graph tell you about the relationship between distance and area?

4. In the illustration below, cell phone screen bars and different positions of a cell phone user (vertical lines) are shown. Which group of bars (A or B) more accurately represents the relationship between the cell tower location, user location, and the number of bars?



5. "I only have 2 towers! Hope this call goes through." Some people actually think that the 'bars' on their cell phone represent the number of cell towers they are using. In light of this lab activity and using the illustration above, describe how you would explain to someone the loss of signal as it relates to the 'bars' on the phone.

<u>Station 6</u>: Light on a chip

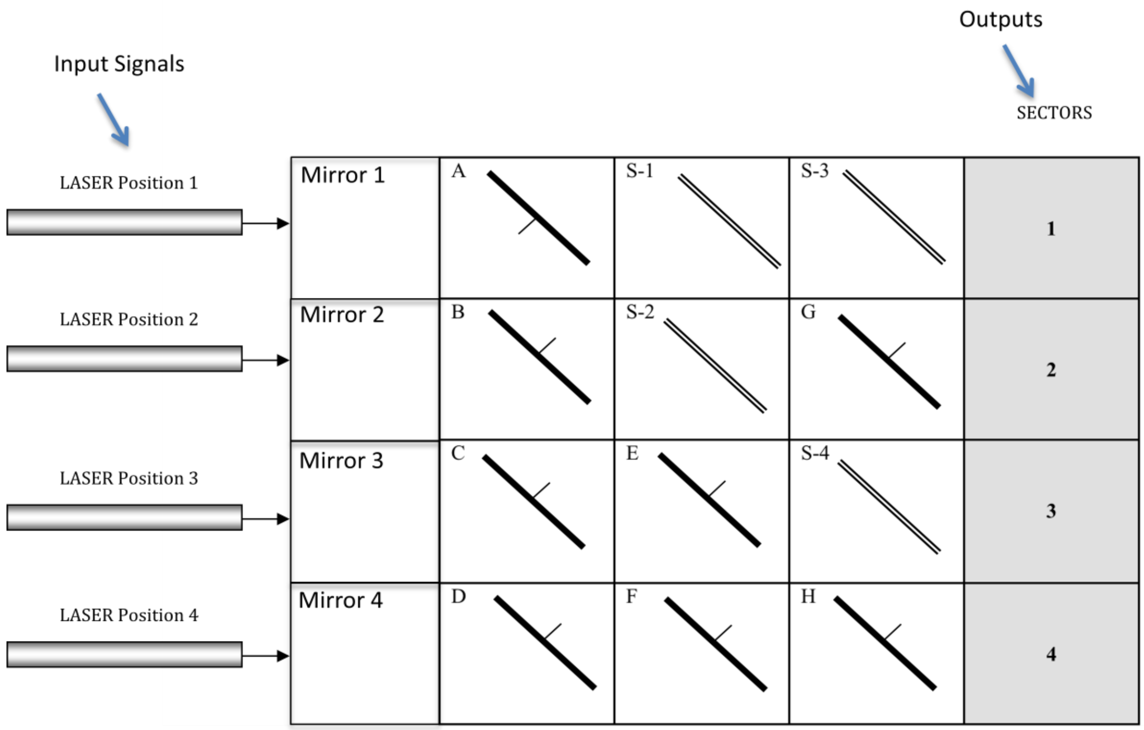
1. What are some possible advantages of a chip that uses light to process information rather than electrons?

2. Mark with an X the switches you removed (turned off) to achieve the desired sector activation.

Switch → **Sectors activated**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**S-1**	**S-2**	**S-3**	**S-4**
1												
2												
3												
4												
1+2												
1+3												
1+4												
2+3												
2+4												
3+4												
1+2+3												
1+2+3+4												

3. The signals reaching sectors 1-4 have different intensities. Why would some signals be brighter than others?

4. In reality, photonic switches may have multiple input channels (lines) of optical information. Consider three additional LASER positions opposite sector positions 2-4 to represent three such additional inputs. (See illustration on the next page). Imagine that you want the three additional inputs to activate the same output sectors as that of LASER position 1. Model this action by extending the photonic chip to include another column of switches (mirrors), here shown as blank boxes labeled ‘Mirror 1-4’.



5. Draw in the orientation of each of the four (4) ***mirrors*** that would allow the output from LASER positions 2, 3, and 4 to produce the same output (light the same sectors) as that of LASER position 1. Just as you did before, determine which of these mirrors need to be activated (left in) or deactivated (removed) for each LASER position. ***(Check your answer by placing the four (4) extra mirrors on the photonic switch model.)***

   Using the same format as the chart above, complete the following table relative to switching between the four (4) signals entering the chip.

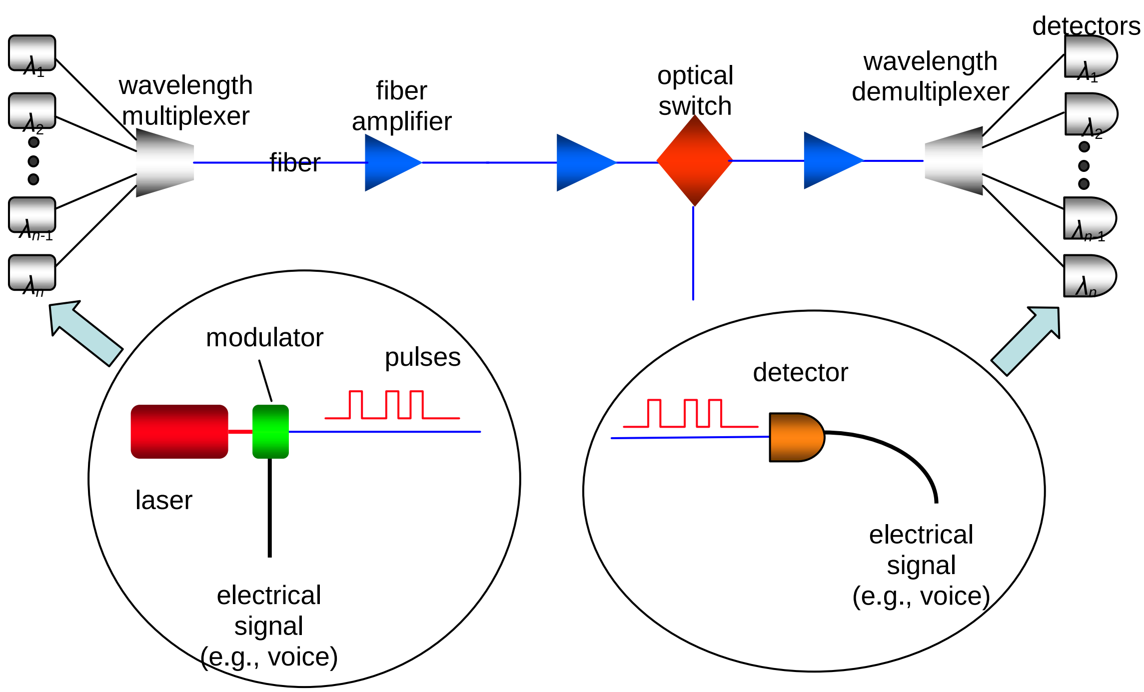
Light source	**Mirror Number**			
	1	**2**	**3**	**4**
Laser Position 1				
Laser Position 2				
Laser Position 3				
Laser Position 4				

<u>Post-Lab Analysis</u>: Optical networks

Optical communications networks are used to transmit information all around the world at literally the speed of light. Without them, the internet would not be possible.

Optical communications networks have the following components:

- **Modulator**—encodes an electrical signal (e.g. from a telephone) on light by varying its intensity
- **Fiber**—transmits the signal and guides it
- **Wavelength multiplexer**—combines many signals, each encoded on its own wavelength of light, to travel simultaneously through one fiber
- **Fiber amplifier**—increases the amplitude of the signal after it diminishes from traveling several kilometers through the fiber
- **Optical switch**—routes a signal to a different fiber to reach its final destination
- **Wavelength demultiplexer**—separates light from a fiber into its different wavelength components in order to separate the many signals that travel simultaneously down one fiber
- **Detector**—senses the variations in light intensity and converts this to an electrical signal (e.g. to hook up to a speaker)



In the table below, describe all the activities you performed in this lab to demonstrate the functioning of the basic components of an optical network:

Function	Activity you did to demonstrate this function
Modulation	
Guiding light (with a fiber)	
Wavelength multiplexing	
Amplification	
Switching	
Wavelength demultiplexing	
Detection	