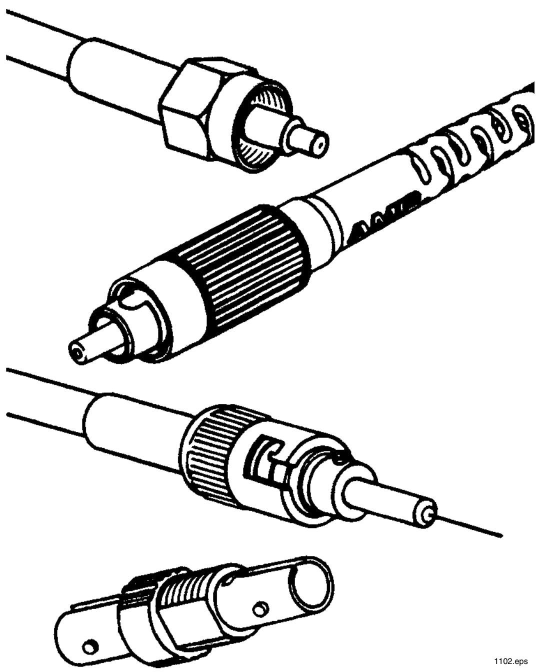
ANSWER GUIDE

Fiber Optic Lab Manual

Fifth Edition



INDUSTRIAL FIBER OPTICS

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ACTIVITIES

Activity I: Component Identification

In this activity students will identify and inventory all items in the *Lab Kit*. This will introduce them to the nomenclature used in this manual and help them in the following activities when a particular item is called for. In the unlikely event that any kit components are found to be missing or damaged, please refer to the "*Missing Parts Claims*" section on page 51 of the main manual.

ACTIVITY II: MAKING A LIGHT GUIDE

Table 2.1 Empirical data for 10 cm (4-inch) light guide with air core.

LEDs	LED OFF	LED ON
Red	**0***	**.02 mA**

Table 2.2 Empirical data for 10 cm light guide with water core.

Source	LED OFF	LED ON
Red	**0***	**.61 mA**

Table 2.3 Empirical data for 10 cm light guide with90-degree bend.

Source	LED OFF	LED ON
Red	**0***	**.46 mA**

* This current should measure very close to zero, or less then 1 µA .If the current is not this low, dim the room lights or cover the light guide and associated electronics with a dark cloth to obtain best results.

Analysis & Questions

What is the amount of light in milliwatts (mW) which falls on the phototransistor when using the red LED with the 10 cm light guide and water core [assuming the responsivity of the phototransistor is 50 milliamperes/milliwatt (mA/mW)]? What is it with no water in the core?

$$= \frac{.070mA}{50mA/mW}$$
$$= 1.4\mu W$$

phototransistor illumination with water core = .61 mA/ (50 mA/mW) = 12.2 µW

phototransistor illumination with no water in core = .02 mA/(50mA/mW) = 0.4 µW

Does the light guide couple more or less light onto the phototransistor with water in the core? Why?

More light .The water has a higher refractive index than air, so less light is lost at the boundary with the vinyl tubing. As a result more light travels down the light guide from the LED to the phototransistor.

Did the 90-degree bend significantly change the amount of light hitting the phototransistor? Why or Why not?

The 90-degree bend did reduce the amount of light hitting the phototransistor. The bend caused some of the light rays traveling down the light guide to fall inside the critical angle for total internal reflection. These rays escaped the light guide, reducing the amount of light falling on the phototransistor.

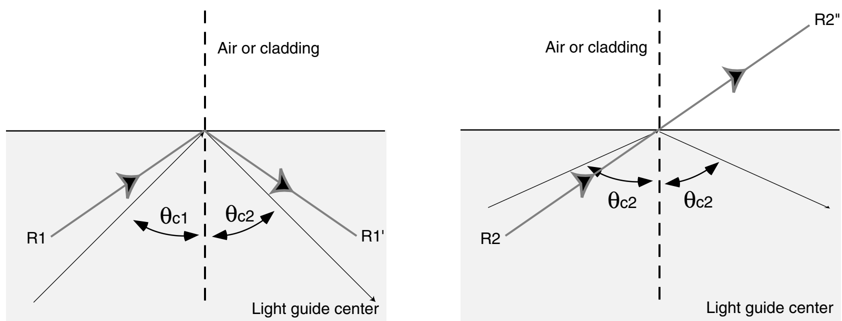
Calculate the critical angle of the light guide when water is used as the core. Assume the refractive index of water is 1.33.

$$\theta_c = \sin^{-1}\frac{1}{1.33}$$

$$= 48.8°$$

Do you know of any other liquids that may trap more light inside the vinyl tubing than the water used in this experiment?

To trap more light inside the vinyl light guide one should choose a liquid with a higher refractive index than that of water. The higher the refractive index, the better the liquid will trap light (without considering the effects of attenuation). To find more information about liquids with a high refractive index, one of the best areas to look is the reference section of a library. A common book found in this section is the "*Handbook of Physics and Chemistry.*" Examples of liquids with a refractive index greater than 1.33 include Pentachloroethane (n=1.501), Xylidine (n=1.557) and Quinoline (n=1.622).



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HOMEWORK PROJECT

Following are some typical fiber core/cladding outer diameters:

Single mode glass fiber:
9/125 µm or 8/125 µm

Multimode glass fiber:
50/125 µm
62.5/125 µm
100/140 µm

Multimode plastic:
230/250 µm
480/500 µm
730/750 µm
980/1000 µm (fiber used in the kit)
1980/2000 µm

ACTIVITY III: FIBER OPTIC CABLE TRANSMISSION

Table 3.1 Measured phototransistor current with 3- and 1-meter lengths of 1000 µm core plastic fiber.

LED	$i_{3-meter}$	$i_{1-meter}$
Red	**8.2 mA**	**10.2 mA**
Green	**.117 mA**	**.143 mA**
Infrared	**.416 mA**	**3.53 mA**

Analysis & Questions

Complete ***Table 3.2*** *to calculate the fiber attenuation coefficients for each of the LEDs from the data recorded in* ***Table 3.1****.*

Table 3.2 Table for calculating attenuation coefficients.

LED	$\frac{i_{(3-meter)}}{i_{(1-meter)}}$	$\ln\frac{i_{(3-meter)}}{i_{(1-meter)}}$	$\alpha = \frac{\ln\frac{i_{(3-meter)}}{i_{(1-meter)}}}{2}$
Red	**.803**	**-.219**	**.112**
Green	**.818**	**-.201**	**.101**
Infrared	**.118**	**-2.137**	**1.069**

Are the attenuation coefficient values the same for the different LEDs? Why or why not?

No. The optical fiber has an acrylic core in which light transmission varies for different wavelengths. The attenuation coefficients that students will calculate from their empirical data should show the coefficients for the red and the green LEDs to be very close to each other. The attenuation coefficient for the infrared LED should be much higher than the coefficient for the red or green LEDs.

*Calculate the launch power for each LED using **Table 3.3**. (Substitute the phototransistor current for power in this equation because the phototransistor current is linearly proportional to the optical power.)*

Table 3.3 Calculation of launch power (equivalent current) for each LED.

LED	$P_{1-meter}$	α	$e^{\alpha(1)}$	$P_o = P_{1-meter} \cdot e^{\alpha(1)}$
Red	10.2 mA	.112	1.119	11.41 mA
Green	.143 mA	.101	1.106	.158 mA
Infrared	3.53 mA	1.069	2.913	10.28 mA

*Calculate the phototransistor current produced by the light from the three LEDs traveling down a 5-meter plastic optical fiber. Use **Table 3.4** as a guide. (Obtain a from **Table 3.2** and P_O from **Table 3.3**.)*

Table 3.4 Calculation of phototransistor current for a 5-meter fiber length.

LED	P_o	α	l	$e^{-\alpha(5)}$	$P_{5-meter} = P_o \cdot e^{-\alpha(5)}$
Red	11.41 mA	.112	5	.571	6.515 mA
Green	.158 mA	.101	5	.604	0.095 mA
Infrared	10.28 mA	1.069	5	.0048	0.049 mA

*Calculate the phototransistor current produced by the light from the three LEDs having traveled down a 10-meter plastic optical fiber. Use **Table 3.5** as a guide. (Obtain a from Table 3.2 and P_O from Table 3.3.)*

Table 3.5 Calculation of phototransistor current for a 10-meter fiber length.

LED	P_o	α	l	$e^{-\alpha(10)}$	$P_{10-meter} = P_0 \cdot e^{-\alpha(10)}$
Red	11.41 mA	.112	10	.326	3.720 mA
Green	.158 mA	.101	10	.364	.058 mA
Infrared	10.28 mA	1.069	10	0.000023	.00024 mA

*Plot measured phototransistor currents for the 1-meter and 3-meter lengths, and the calculated phototransistor currents for the 5- and 10-meter fiber lengths for all three LEDs in **Figure 3.2**.*

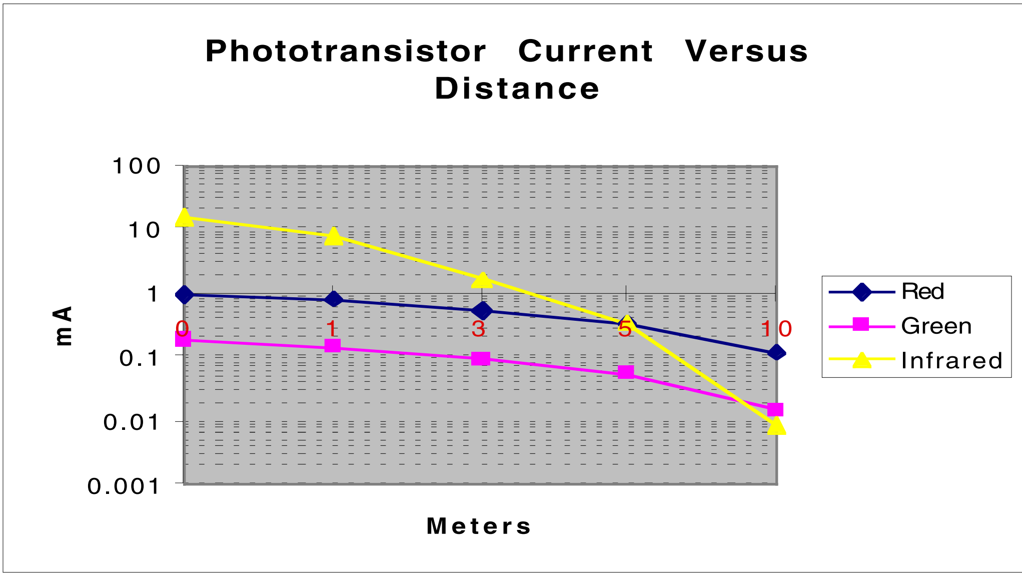


Figure 3.2 Phototransistor current created at the end of various fiber lengths for three different LED light sources.

Although this question did not ask students to include the LED launch power (P_o) on the chart, it is included on the one above. The purpose of the graph was to illustrate that the infrared LED initially produced the most phototransistor current and the green LED the lowest. Then for any distance greater than 5 meters the red LED produced the most phototransistor current.

The most commonly used wavelength for long distance transmission in plastic fiber is the 650/660 nm window. This wavelength band offers the lowest material attenuation and readily available LEDs with good optical output power. The graph above verifies that the 650/660 nm wavelength band is the best choice to maximize the working distance with plastic fiber for the three light sources tested.

HOMEWORK PROJECT

The color red has a wavelength from 630 to 670 nm and the color green from 490 to 540 nm.

ACTIVITY IV: CONNECTORS AND SPLICES

Table 4.1 Measured phototransistor current with 2-meter and 1-meter fibers joined with a simplex receptacle.

LED	Position	$i_{simplex}$
Red		**3.5 mA**
Infrared	#1	**0.22 mA**
	#2	**0.20 mA**
	#3	**0.17 mA**
	#4	**0.19 mA**

Table 4.2 Measured phototransistor current with 2-meter and 1-meter optical fibers spliced together.

LED	i_{splice}
Red	**3.9 mA**
Infrared	**0.25 mA**

Analysis & Questions

Is the fiber's transmission more or less after the fiber connector is installed in the 3-meter fiber? Why?

A fiber's transmission of light is less after a connector has been installed. Interconnection losses include those caused by:

- **Fresnel reflections.**
- **Fiber ends not perfectly polished or cleaved.**
- **An air gap between the fibers causing the light rays to diverge more than they would have if they had been inside the fiber core.**
- **Lateral and angular misalignment of fiber axis allowing light to leak out from the fiber joint.**

What happens to the measured phototransistor current when the simplex assembly and 1-meter fiber are rotated to different positions within the simplex receptacle? Describe below the physical conditions that are occurring and why. (Drawing a picture might be helpful.)

The phototransistor current changes. As the simplex assembly and fiber are rotated in 90° steps, changes occur in the lateral and angular alignment which cause variations in the amount of light coupled from one fiber to another. These physical variations cause changes in the amount of coupled light which travels down the optical fiber and is absorbed by the phototransistor.

Table 4.3 Comparison of transmission characteristics of a continuous 3-meter fiber optic cable to those of a 3-meter fiber length with fiber optic connector installed.

LED	Rotation	$i_{Activity\ III}$	$i_{simplex}$	% Transmission
Red		**8.2 mA**	**3.5 mA**	**42.6**
Infrared	#1	**.416 mA**	**0.22 mA**	**52.9**
	#2	**.416 mA**	**0.20 mA**	**48.0**
	#3	**.416 mA**	**0.17 mA**	**40.9**
	#4	**.416 mA**	**0.19 mA**	**45.7**

Table 4.4 Comparison of the transmission characteristics of a continuous 3-meter fiber optic cable and those of a length with a splice in it.

LED	$i_{Activity\ III}$	i_{splice}	% Transmission
Red	**8.2 mA**	**3.9 mA**	**47.6**
Infrared	**.416 mA**	**0.25 mA**	**60.1**

Is the transmission greater for the 3-meter fiber with the splice installed or with the simplex receptacle? Is this what you expected? Why or why not?

The transmission is greater, or there is less loss, for a splice. Yes. Because the physical tolerances are smaller for the splice, which tends to align fibers more accurately and allows light to be better coupled from one fiber to another.

In your own words, state at least two advantages and disadvantages of fiber connectors versus fiber splices. List at least two for each.

The advantages and disadvantages of fiber splices and connectors can be described in many ways. Below is a comparison of main features of splices and connectors from which you can interpret students' answers.

Connectors	Splices
Non-permanent	Permanent
Factory installable on fiber cables	Easier to obtain low loss in field
Easy reconfiguration	Lower attenuation
Simple to use	Spliced fibers can fit inside conduit
Field installable	Less expensive per interconnect
	Stronger junction
	Some are hermetically sealed

HOMEWORK PROJECT

We suggest that you review students' company selections so that their information requests arrive in time to complete ACTIVITY IX, and so you can ensure the selections they have made are within the scope of your class.

ACTIVITY V: INDEX MATCHING

Table 5.1 Measurements of photo-transistor current when 2-meter and 1-meter fibers are spliced together with and without index-matching.

LED	i_{splice}	$i_{index-matched}$
Red	**3.9 mA**	**6.0 mA**
Infrared	**0.25 mA**	**0.36 mA**

Analysis & Questions

Table 5.2 Comparison of the transmission characteristics of a fiber splice with and without index-matching.

LED	i_{splice}	$i_{index-matched}$	% Improvement
Red	**3.9 mA**	**6.0 mA**	**53.8**
Infrared	**0.25 mA**	**0.36 mA**	**44.0**

*Explain the change in transmission indicated by Column 4 in **Table 5.2**.*

Glycerin improved the transmission because its index of refraction was very close to that of the fiber core. This reduced the Fresnel reflections, compensated for less-than-perfect fiber ends, and reduced light spreading at the splice. The glycerin in this activity acted as a refractive index-matching compound to demonstrate the procedure commonly called "index-matching" in the fiber optics industry. The students' most common answer should be "to reduce Fresnel reflections."

Explain in your own words what "index-matching" means.

An index match compound is liquid or gel with a refractive index close to that of fiber core materials. It eliminates the fiber core/air boundary conditions in splicing and is occasionally used in connectors. Its main purpose is to reduce Fresnel reflections (although it sometimes reduces other losses as well).

Index-matching is sometimes used as a verb and refers to the procedure of using an index-matching compound to minimize the loss between the junction of two fibers.

Calculate the magnitude of a Fresnel reflection using the equation at the introduction to this activity. Assume the refractive index of Medium #1, the fiber core, to be 1.49 and Medium #2, air, to be 1.0.

The ratio of the reflected power to the incident power is:

$$R = \left[\frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}\right]^2$$
$$= \left[\frac{1 - 1.49}{1 + 1.49}\right]^2$$
$$= 3.87\%$$

*By the boundary conditions shown in **Figure 5.2** how many Fresnel reflections are there for an optical ray passing from one fiber into the other? Calculate the increase in fiber transmission if a perfectly index-matched gel filled the gap between the fibers.*

There are two Fresnel reflections. The first occurs when light passes from the first fiber core into the air gap; the second occurs when light passes from the air gap into the second fiber core.

In glass fiber where tolerances of the components are much smaller and fiber ends are truly polished or cleaved, a much smaller increase in transmission occurs when index-matching a fiber junction (than was observed in this activity). This is not to say that index-matching is not important in glass fiber.

Calculating the increase in fiber transmission due to Fresnel reflections will not show all of the improvements measured in this activity because the gel fills in small imperfections in the plastic fiber core, which reduces losses even further.

Often people calculate the increase in transmission simply by multiplying two times the loss, which would be an increase of 7.74%. Although this is approximately right for small losses, the more accurate method of determining the increase in transmission is:

$$= 1 - \frac{1}{(1 - R)^N}$$

where N is the number of boundaries and

R is the loss due to Fresnel reflections

The increase in this case would be 8.21%.

HOMEWORK PROJECT

Fresnel reflection equations have several forms. In reality there are only two fundamental equations. One for each state of optical polarization. These equations are listed below.

$$R_s = \left[-\frac{\sin\left(\theta - \theta^{'}\right)}{\sin\left(\theta + \theta^{'}\right)} \right]^2$$

$$R_p = \left[\frac{\tan\left(\theta - \theta^{'}\right)}{\tan\left(\theta + \theta^{'}\right)} \right]^2$$

R_p *is the ratio of reflected light to incident light for s polarization plane*

R_s *is the ratio of reflected light to incident light for p polarization plane*

θ *is angle of incidence*

θ' *is angle of reflection*

If one can assume that the light rays' polarization is uniformly distributed, then a single equation can be used:

$$= \frac{1}{2}\left[\frac{\sin^2\left(\theta - \theta^{'}\right)}{\sin^2\left(\theta + \theta^{'}\right)} + \frac{\tan^2\left(\theta - \theta^{'}\right)}{\tan^2\left(\theta + \theta^{'}\right)} \right]$$

θ *is angle of incidence*

θ' *is angle of reflection*

This Fresnel equation can be further reduced if we assume all light rays are normal to the surface. (This is the equation which we used in this lab manual.)

$$= \frac{(N' - N)^2}{(N' + N)^2}$$

N' *is incident light ray's material refractive index*

N *is refracted light ray's material refractive index*

In practical applications, many fiber optic light rays are not normal, so the simplest equation which we used here underestimates the loss due to Fresnel reflections. Unfortunately there is not a much better way without defining an equation for the distribution of optical rays and doing some rather tedious Calculus integrals (which might require a computer program to approximate, in any event). It has generally been accepted that the simple equations are accurate enough for most fiber optics work.

ACTIVITY VI: FIBER TERMINATIONS

Table 6.1 Transmission data measured for a 1-meter optical fiber with three different end preparations.

Fiber Termination	Phototransistor Current
Wire cutter	**2.1 mA**
Sharp knife	**3.6 mA**
Polished	**4.4 mA**

Analysis & Questions

In the space below draw pictures to show the differences between the fiber end polished with 600 grit paper and the end polished with the 3 µm polishing film.

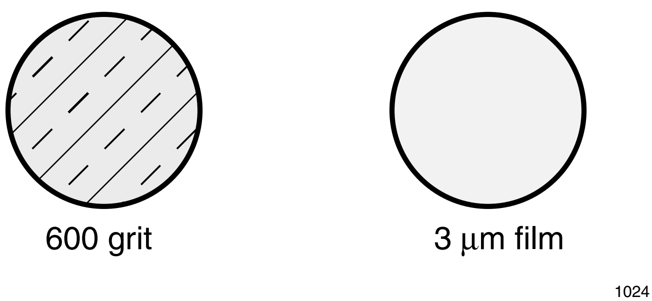


Table 6.2 Calculations for determining losses due to fiber end preparation.

Fiber Termination	Phototransistor Current	Column #3	Losses %
Wire cutter	**3.92 mA**	**0.459**	**54.1**
Sharp knife	**7.25 mA**	**0.849**	**15.1**
Polished	**8.54 mA**		

Are the increased losses with poorer fiber termination what you expected? Why or why not?

Yes. This activity illustrates through measurements that the flatter and smoother the fiber end or tip, the higher the transmission. The data in *Table 6.2* show that fiber ends with poor ends or finishes have more losses.

Describe how the surface texture caused low phototransistor current with poorer terminations in this activity. Relate your answer to critical angle and fiber end termination. Drawing an illustration may be helpful.

The surface texture at the fiber ends directly determines losses when light exits a fiber. The rougher surface texture will cause the light to scatter more, as was shown in *Figure 6.1* of the main manual. More scatter has an effect similar to increasing the numerical aperture inside the fiber. Fibers with large numerical apertures require photodetectors with very large active areas to absorb all of the rapidly diverging light rays. In this experiment, when light rays are diverging at a greater rate than is the case with normal operation, some of the rays are not absorbed by the photodetector or, as in this experiment, the phototransistor.

Describe how poor fiber termination on both ends, along with light exiting and entering, causes reduced optical power at the photodetector.

Poor fiber terminations cause scatter in the incident angle for light rays entering an optical fiber. This scattering is generally uniform and will produce more light rays that are not within the acceptance angle of the fiber core and cladding. These rays, or optical energy, are lost and will not travel down the optical fiber to the photodetector.

Poor termination at the photodetector fiber end was described in previous questions. This question is a rewording of a previous question as related to both fiber ends to make the students really think and fully understand what is happening at the optical fiber ends

For very short fiber lengths where design margins are good, poor fiber termination is not an issue, but for long-distance telecommunications projects, every bit of optical power must be conserved and utilized. Excess loss anywhere along a fiber system causes system degradation. An example of system degradation might be a very noisy telephone line. For some reason, that line is less than ideal or was poorly designed and has poor signal-to-noise ratio.

HOMEWORK PROJECT

There are many different fiber optic connectors and splice manufacturers. If a student comes up with a company that manufactures fiber optic fusion splicers, we feel that answer counts. The real purpose of the project is to teach students how to find resources. Sources for fiber optic connector and splice companies include:

AT & T Microelectronics
3M, Private Network Products
Amphenol Corporation
Augut Communications Group
Ensign-Bickford Optics Company
Hewlett-Packard
Methode Electronics
Norland Products
OZ Optics, Ltd.
Rifocs Corporation
Seastar Instruments Ltd., Optics Division
Thomas & Betts Corp., Electronics Division

ACTIVITY VII: SPEED OF OPTO-ELECTRONIC DEVICES

Table 7.1 Measured values of photodetector rise and fall times, with an infrared LED as the optical source.

Detector	Rise time	Fall time
Phototransistor	**3.4 µs**	**2.6 µs**
Photodarlington	**20.0 µs**	**4.0 µs**
Photodiode	**1.5 µs**	**1.5 µs**

Table 7.2 Measured values of rise and fall times of four optical sources using the photodiode as the optical detector.

LED	Rise time	Fall time
Infrared	**1.5 µs**	**1.5 µs**
Red	**1.7 µs**	**1.7 µs**
Green	**4.0 µs**	**2.0 µs**
Pinlight	**20.0 ms**	**15.0 µs**

Analysis & Questions

Which of the photodetectors tested in ***Table 7.1*** *had the fastest rise and fall times?*

The photodiode, although its speed is much quicker than can be measured in the circuit shown. The 10 kΩ resistor allows enough magnitude for oscilloscope display of the signal, but limits the photodiode speed because of breadboard and oscilloscope probe capacitance.

Are there any detectors tested in ***Table 7.1*** *in which the rise and fall times are significantly different? If so, which ones?*

Yes. The data in Table 7.1 show a much slower rise time than fall time for the photodarlington. In reality the rise time measured at the collector of the photodarlington is actually the turn-off time for the photodarlington; and the fall time measured at the collector is the turn-on time of the device. This slower turn-off time versus turn-on time is typical of all photodarlingtons.

Table 7.3 Calculation of detector upper frequency 3 dB bandwidth using an infrared LED as the optical source.

Detector	Rise time	Fall time	f_{3dB}
Phototransistor	**3.4 µs**	**2.6 µs**	**103.0 kHz**
Photodarlington	**20.0 µs**	**4.0 µs**	**17.5 kHz**
Photodiode	**1.5 µs**	**1.5 µs**	**233.3 kHz**

Which photodetector has the largest bandwidth?

The photodiode.

Table 7.4 Calculations of light source upper frequency 3 dB bandwidth using a photodiode as the optical detector.

LED	Rise time	Fall time	f_{3dB}
Infrared	**1.5 µs**	**1.5 µs**	**233.3 kHz**
Red	**1.7 µs**	**1.7 µs**	**205.9 kHz**
Green	**4 µs**	**2 µs**	**87.5 kHz**
Pinlight	**20.0 ms**	**15 ms**	**17.5 Hz**

*Which LED is the fastest in **Table 7.4**? Is this what you expected? Why?*

The infrared LED. Yes. Data sheets for LEDs affirm that infrared types are normally faster than visible ones. Intuitively one might deduce this because, generally speaking, most product specifications supplied by manufacturers are targeted at performance characteristics which buyers/users are most interested in. With infrared LEDs, which are used for communications, we would intuitively expect a higher bandwidth than with visible LEDs. In the case of visible LEDs which are designed for producing the most amount of visible light, it would be an anomaly to find one with fast rise and fall times. Engineers may actually give up speed or bandwidth during the design of a visible device to maximize the visible light output.

Why are incandescent bulbs not used as fiber optics light sources? (Use the data in this activity to formulate your answer.)

From the data it can be seen that incandescent bulbs are very slow and operate only at very low frequencies. Incandescent bulbs are so slow because current flowing into the bulb heats the bulb filament to a temperature sufficiently high to produce radiation in the visible range. Electrical current into the bulb's filament does not directly produce electrons, unlike

LEDs' response to current. Incandescent bulbs are also not suited for fiber optics because they have short lifetimes and poor linearity.

*Using information as required from **Activity III**, determine if a particular LED emits the greatest amount of optical power, has the best optical fiber transmission and the fastest rise/fall times. Which one? If one doesn't meet all the criteria, pick the best LED in each category and list it below.*

There is no one best LED. Students will need to put on their thinking caps. The answer depends on what performance characteristic the student feels is most important (and which they may include as part of their answer). The infrared LED clearly produces the most phototransistor current as seen in *Table 3.1*, and has the fastest rise and fall times. However, the infrared light also has the highest attenuation coefficient of all the LEDs tested (poorest transmission). The red LEDs do not have as high starting optical power, but do have a much lower attenuation coefficient. For applications using long fiber lengths, they may the best choice. The green LED, although an interesting color, offers no advantage in output power, fiber transmission or speed.

HOMEWORK PROJECT

Answers to this question may vary widely. Variables that can affect the student's answers include manufacturer, package type, size, and some devices are optimized for a particular configuration. Ranges that we have found are listed below. You may choose to have students list their sources of information as part of the project.

Device	Rise time	Fall time
Photodiode	1 ns to 3 μs	1 ns to 3 μs
Phototransistor	2 to 30 μs	2 to 30 μs
Photodarlington	40 μs to 1.5 ms	40 μs to 1.5 ms
Infrared LED	1 ns to 1 μs	2 ns to 1 μs
Red LED	120 ns to 300 ns	50 ns to 300 ns
Green LED	450 ns	200 ns

Table 8.1 Measured data taken from the circuit shown in *Figure 8.3*.

Measurement	Data
V_{ce} (LED on)	**158 mV**
V_{LED}	**1.96 V**
V_{ce} (LED off)	**5 V***
Rise time	**240 ns**
Fall time	**50 ns**
$\text{Period}_{3\ dB}$	**670 ns**

* Voltage at the collector of this transistor should theoretically be 5 volts. In reality, when a multimeter is installed to read this voltage, a small amount of current flows through the LED. The current is not enough that the LED produces light, but it does cause a small voltage drop. Therefore, measurements between 3.5 and 5 volts will be typical for this entry.

Table 8.2 Measured data on the LED drive circuit shown in *Figure 8.4*.

Measurement	Data
V_{ce}	**219 mV**
V_f	**1.97 V**
Rise time	**120 ns**
Fall time	**100 ns**
$\text{Period}_{3\ dB}$	**500 ns**

Table 8.3 Measured data for the high-speed LED drive circuit shown in *Figure 8.5*.

Measurement	Data
V_c (LED on)	**3.36 V**
V_c (LED off)	**1.56 V**
Rise time	**20 ns***
Fall time	**4 ns***
Period_{3dB}	**50 ns***

* 40 MHz oscilloscope may not be able to measure these fast transition times, but that is revealed as the circuit capability when using a 350 MHz oscilloscope as a measuring instrument.

Table 8.4 Measured data for the analog LED drive circuit shown in *Figure 8.6*.

Measurement	Data
I_c	**7.9 mA**
V_c (.5-volt input)	**3 $V_{p\text{-}p}$**
V_c (distorted)	**7.8 $V_{p\text{-}p}$**
V_i (distorted)	**1.4 $V_{p\text{-}p}$**
$\text{Period}_{3\ dB}$	**128 ns**

Analysis & Questions

*Does the measured voltage across the collector of 2N3904 transistor in **Figure 8.3** for the LED "on" and "off" compare favorably to what you expected? Why or why not?*

Yes. When the transistor is in saturation, V_{ce} should be very close to the .2 volts that most textbooks use. The collector voltage with the LED "off" does not measure +5 volts because the multimeter draws a small current through the LED, causing a voltage drop.

*With the LED "on" in **Figure 8.3** calculate the "on" current using the measured data in this activity for $V_{ce\ (sat)}$ and V_f.*

$$I_c = \frac{5 - 1.96 - .158}{150}$$
$$I_c = 19\ \ mA$$

*Using the measured rise time from **Table 8.1**, calculate the 3 dB bandwidth for the circuit shown in **Figure 8.3**.*

$$f_{3dB} = \frac{.35}{240 \cdot 10^{-9}}$$
$$f_{3dB} = 1.45\ \ MHz$$

How does the calculated bandwidth compare to the measured bandwidth?

The measured bandwidth can be calculated from the following equation. (It is assumed that students will have knowledge of this general equation from their electronics experience.)

$$MEASURED\ \ f_{3dB} = \frac{1}{670\ \ ns}$$
$$= 1.49\ \ MHz$$

The calculated 3 dB bandwidth from the rise time was determined to be 1.45 MHz and measure was 1.49 MHz. It would not be uncommon for the students' measured 3 dB bandwidth and calculated bandwidth from risetime to be ± 10% apart from each other.

*Calculate the average current used by the LED driver in **Figure 8.3**, assuming it is being driven at a 50 percent duty cycle.*

$$I_{avg} = I_{PEAK} \cdot Duty\ \ cycle + I_{MIN}\ (1 - Duty\ \ cycle)$$
$$I_{avg} = 19.2\ \ mA \cdot\ .5 +\ 0 \cdot\ .5$$
$$I_{avg} =\ 9.6\ \ mA$$

*Using the measured value for V_f, calculate the current through the LED in **Figure 8.4**.*

$$I_c = \frac{5 - 1.97}{150}$$
$$I_c =\ 20.2\ \ mA$$

*Calculate the current through 2N3904 in **Figure 8.4** when it is on and the LED is off.*

$$I_c = \frac{5 - .219}{150}$$
$$I_c =\ 31.9\ \ mA$$

*What is the average current though the circuit shown in **Figure 8.4**, assuming that it is being driven at a 50 % duty cycle?*

$$I_{avg} = \frac{31.9\ \ mA\ + 20.2\ \ mA}{2}$$
$$I_{avg} =\ 26.1\ \ mA$$

*Comparing the peak current and average current for the circuits in **Figures 8.3** and **8.4**, which would cause the greatest power supply ripple? By how much?*

To compare power supply ripple we shall use the ratio of the peak current divided by the average current. Shown below is the ripple factor for the circuits in *Figure 8.3* and *8.4*.

$$rf_{Figure\ \ 8.3} = \frac{19\ \ mA}{9.6\ mA} = 2 \qquad rf_{Figure\ \ 8.4} = \frac{31.9\ \ mA}{25.6\ mA} = 1.25$$

The circuit in *Figure 8.3* has a much higher power supply ripple, as can be seen by the equation which shows the I_{peak} to $I_{average}$ ratio to be 2, as compared to the same ratio for *Figure 8.4*, which is 1.25.

*What is the difference between the circuits in **Figure 8.3** and **8.4**? (HINT: Consider inverted and non-inverted functions.)*

In *Figure 8.3*, the LED operation follows the drive signal state, i.e., driver signal high = LED on; drive signal low = LED off. In *Figure 8.4* the LED operation is inverted from the drive signal state. Also, the circuit of *Figure 8.3* draws supply current only when the drive signal is high. The circuit of *Figure 8.4* always draws current, either through the LED or transistor.

*Assuming h_{fe} is 100 for the PN2222, calculate the DC LED current drawn for the circuit shown in **Figure 8.6** with no input signal.*

$$I_c = \frac{\left(\frac{560\ \Omega}{560\ \Omega + 4700\ \Omega} \cdot 10\ V\right) - .7\ V}{47\ \Omega + \frac{(560\ \Omega \cdot 4700\ \Omega)/(560\ \Omega + 4700\ \Omega)}{100}}$$

$$= 7.0\ mA$$

*What is the maximum linear voltage swing of the circuit shown in **Figure 8.6**? (HINT: Determine the answer from empirical data.)*

The value of the output voltage just below where signal distortion occurs, or slightly less than 7.8 volts peak-to-peak.

*What is the 3 dB bandwidth of the circuit shown in **Figure 8.6**?*

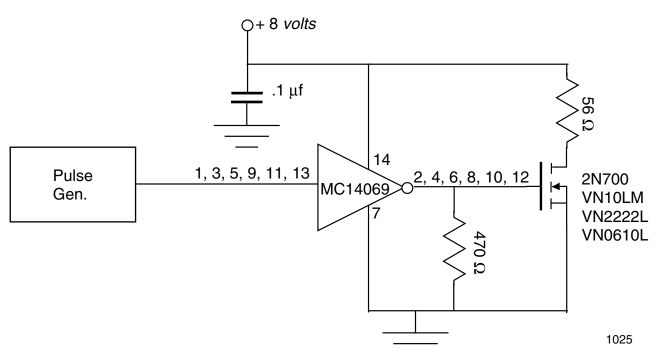
$$Measured\ \ f_{3dB} = \frac{1}{Period_{3dB}}$$

$$= \frac{1}{128\ ns}$$

$$= 7.81\ MHz$$

HOMEWORK PROJECT

As is typical with design problems there is often more than one solution. Here is one possible solution, shown with different transistor part numbers suitable for this circuit.



ACTIVITY IX: RECEIVER AMPLIFIER DESIGN

Table 9.1 Measured data for various termination resistors, R_x, in the circuit shown in *Figure 9.2.*

R_x	V_{p-p}	t_r	t_f
100 kΩ	**5.0 V**	**5.4 µs**	**7.0 µs**
47 kΩ	**3.2 V**	**4.5 µs**	**3.6 µs**
10 kΩ	**0.69 V**	**1.8 µs**	**1.3 µs**
10 kΩ ||.001 µf	**0.65 V**	**23 µs**	**21 µs**

Table 9.2 Measured data for various termination resistors, R_f, in the circuit shown in *Figure 9.4.*

R_f	V_{p-p}	t_r	t_f
100 kΩ	**4.5 V**	**7.2 µs**	**7.4 µs**
47 kΩ	**3.1 V**	**4.2 µs**	**5.0 µs**
10 kΩ	**0.66 V**	**1.6 µs**	**1.1 µs**
10 kΩ ||.001 µf	**0.66 V**	**1.5 µs**	**1.1 µs**

Table 9.3 Measured data for various termination resistors, R_f, in the circuit shown in *Figure 9.5.*

R_f	V_{p-p}	t_r	t_f
100 kΩ	**2.5 V**	**1.6 µs**	**1.1 µs**
47 kΩ	**1.9 V**	**1.3 µs**	**1.5 µs**
10 kΩ	**0.6 V**	**1.0 µs**	**1.2 µs**
10 kΩ ||.001 µf	**0.6 V**	**1.0 µs**	**1.2 µs**

Table 9.4 Measured data for various termination points in the circuit shown in *Figure 9.6 (a).*

Location	$V_{p\text{-}p}$	t_r	t_f
$V_{emitter}$	**4.8 V**	**4.0 µs**	**7.0 µs**
V_{4069}	**5.0 V**	**0.5 µs**	**0.4 µs**

Table 9.5 Measured data for various termination resistors, R_f, in the circuit shown in *Figure 9.6 (a).*

Resistance	Value
Phototransistor	**213 Ω**
Photodarlington	**22 Ω**

Analysis & Questions

*What happens to the rise and fall times at the receiver as the resistor value is reduced in **Figure 9.2**? What happens to the peak-to-peak voltage?*

The rise and fall times decrease as the resistor value is reduced, which increases the bandwidth. The peak-to-peak voltage, however, is also lowered.

*What happens to the rise and fall times across the termination resistor (R_X) when capacitance is added in the circuit shown in **Figure 9.2**?*

The rise and fall times increase when capacitance is added, decreasing the bandwidth.

*What are the advantages and disadvantages of the receiver circuit shown in **Figure 9.4** compared to the circuit shown in **Figure 9.2**?*

The circuit in *Figure 9.4* reduces the effect of load resistance and capacitance on the voltage developed across the transimpedance resistor R_f. As a result, the gain and bandwidth are significantly improved over the circuit in *Figure 9.2.* A disadvantage of *Figure 9.4* is added complexity in the circuit and power supply.

*How does the addition of load capacitance affect the rise and fall times in the circuit shown in **Figure 9.4** as compared to **Figure 9.2**? Why?*

Load capacitance has less effect on *Figure 9.4* because the amplifier has a lower output impedance which isolates R_f from the load. This permits the load capacitance to be charged and discharged more quickly, increasing the bandwidth.

*Calculate the bandwidth of the receiver shown in **Figure 9.4** with the 10 kΩ gain resistor installed using the equation:*

$$f_{3dB} = \frac{.35}{1.6 \cdot 10^{-6}} = 219 \ kHz$$

*Calculate the bandwidth of the bipolar transistor receiver in **Figure 9.5** using the 10 kΩ feedback resistor installed.*

$$f_{3dB} = \frac{.35}{1.0 \cdot 10^{-6}} = 350 \ kHz$$

*How much more gain does the photodarlington have than the phototransistor in the circuit in **Figure 9.6 (a)**? (Hint: Use the ratio of the resistors that were in parallel with the 390 Ω resistor which remove periodic signal at the output of 4069.)*

With a given optical input, the photodarlington requires a smaller load resistance than the phototransistor to develop the same output voltage. The relative gain can be found by determining the ratio of the resistors that results in the same signal level for each device:

$$G_{\mathrm{Re}l.} = \frac{R_{l(phototransistor)}}{R_{l(photodarlington)}} = \frac{213 \ \Omega}{22 \ \Omega} = 9.7$$

The photodarlington in this activity had a gain 9.7 times greater than the phototransistor.

HOMEWORK PROJECT

Students' written paragraphs must be interpreted by the instructor. A quick overview of many fiber optic companies is found in the *Photonics Corporate Guide, Volume I* and the *Fiberoptic Product News Technology Reference*. You may find it useful to purchase these publications. To order, see page 53 of the main manual for more information.

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