

6.007 – Electromagnetic Energy: From Motors to Lasers
Spring 2011

Lab 4 Pre-Lab: Spectrometer

Tuesday and Wednesday, April 12 and 13, 2011

Introduction

- **The pre-lab component of the lab (the questions and the take home kit) should be completed before coming to the lab.**
- **Have one of the TAs check you off for the prelab**
- **Have one of the TAs check you off for the completion of the lab component before leaving the lab**

In this lab you will be exploring many aspects of optics. In class you learned about light polarization, Snell's law, critical angle, interference, Fresnel equations and Brewster's angle. We will now be experimentally verifying all of these concepts!

Answer the pre-lab questions, work through the Matlab analysis, and complete the lab kit. The take-home lab entails coupling light from a standard LED into a 1000 μm multimode fiber. In lab, you will use this LED-fiber link to estimate the index of the fiber cladding.

Lab Kit Contents

- (2) White LEDs (one spare)
- (1) 200 Ω resistor.
- (1) 9V battery
- (1) 1000 μm multimode fiber
- (1) epoxy packet or single-use superglue
- (2) sand paper
- (1) battery strap
- (1) wooden stir stick

1 Theory and Background

Fiber and integrated light-guiding technology has many applications in telecommunications, sensing, and electro-optic devices. The basic physical process in guided wave optics is total internal reflection. The simplest way to understand total internal reflection is through ray-tracing. In ray tracing, we model light as rays traveling in straight lines between different interfaces. When the ray meets an optical element or interface, its direction is changed. The direction of the resulting ray depends upon the angle of incidence and the properties of the material that exists at the interface.

What happens when a ray meets an interface between two media with different indices of refraction? We know from lecture that in the ray picture we can use Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Let us now consider an interface between a denser material with index n_1 and a less dense material with a smaller index n_2 . The ray is bent away from the normal, or in other words, $\theta_2 > \theta_1$. At the critical angle ($\theta_1 = \theta_c$), the angle of the refracted ray is exactly 90° from the normal ($\theta_2 = 90^\circ$). Using Snell's law we can solve for θ_c :

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

If we increase θ_1 beyond the critical angle, the refracted ray exponentially decays and no power is transmitted to the second medium. This is the phenomenon called total internal reflection.

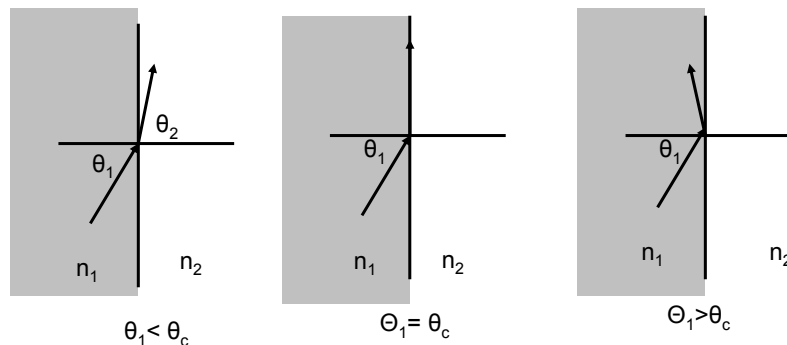


Figure 1: Ray description of the critical angle and internal reflection

When two interfaces that both create total internal reflection traps a ray between the two surfaces, a waveguide is created.

Fibers are designed with a high index 'core' region and lower index 'cladding' layer. Optical fiber is an ideal material for telecommunications and networking because it is flexible and can be bundled together into cables. Typical step index fiber has an index contrast on the order of 0.01. For long-distance communications, light can propagate with very little loss if the correct fiber is chosen. Telecommunications links can be created from long lengths of fiber connected with repeaters. Light signals propagating in fiber can be modulated up to rates of 40 Gb/s and a single fiber can carry multiple wavelengths with different information in different signals.

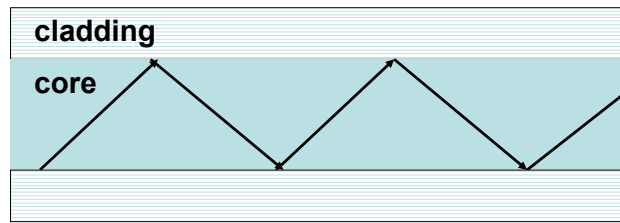


Figure 2: Ray description of the critical angle and internal reflection

2 Pre-lab Questions

- (1) One way to measure refractive index is using the setup below. The prism is made of an epoxy material.

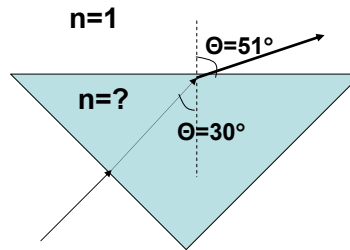


Figure 3: Epoxy prism of unknown refractive index.

As shown in Figure 3, the laser beam is normal to the first surface of the prism, so the angle of refraction is zero. The beam is refracted at the second surface, since it is incident at a different angle. Suppose the beam is at 30° with respect to the epoxy-air interface. If the refracted angle in air ($n_{air} = 1$) is 51.2° , what is the index of the epoxy making up the prism?

- (2) Now suppose a block of glass with index of refraction 1.51 is placed against the surface of the prism as shown in Figure 4.

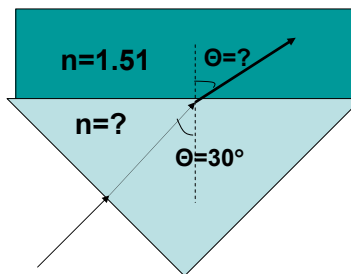


Figure 4: A block of glass is placed against the prism.

Calculate the angle of the new refracted beam.

- (3) Using the refractive indices from parts (1) and (2), find the critical angle for an epoxy-air interface.

 Find the critical angle for an epoxy-glass interface. -----
- (4) A very common parameter for characterizing waveguides is the numerical aperture. The numerical aperture defines the maximum acceptance angle of a waveguide. It is defined as follows:

$$NA = \sin(\theta_{max}) = \sqrt{n_1^2 - n_2^2}$$

where n_1 is the index of the guiding material (the core) and n_2 is the index of the cladding material. When the incident ray is greater than the acceptance angle, it will not satisfy the condition for total internal reflection, and the wave will partially transmit into the cladding, causing loss at each interface. When the incident ray is less than or equal to the acceptance angle, the ray will satisfy internal reflection and propagate down the waveguide.

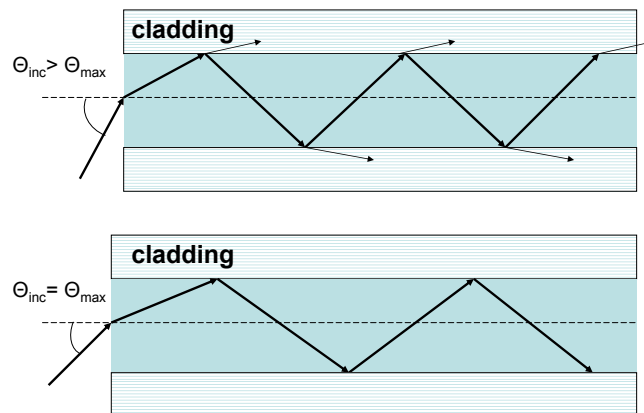


Figure 5: Numerical aperture (NA) is the sine of the acceptance angle θ_{max} .

Suppose for the fiber waveguide the maximum acceptance angle is $\theta_{max} = 15^\circ$, and you know that the index of the cladding is 1.50. Calculate the index of the core. -----

3 Spectrometer calibration

In lab, we will be building a simple spectrometer for measuring the wavelength distribution of your LED as well as a dye found in food coloring. At the end of the day, you will be essentially taking pictures of rainbows with a digital camera. We will need to figure out how to convert those rainbows into quantitative data plots of intensity versus wavelength.

1. Download the sample spectra images from the website (whiteLED.jpg, violet430nm.jpg, and redlaser650nm.jpg).
2. Load these files into matlab by typing the following commands.

```
whiteLED = double(rgb2gray(imread('whiteLED.jpg')));
violet430nm = double(rgb2gray(imread('violet430nm.jpg')));
redlaser650nm = double(rgb2gray(imread('redlaser650nm.jpg')));
```

The first command (`imread`) loads the image into matlab as a 3 dimensional matrix of size x by y by 3. The third dimension stores the intensity of red, green, and blue.

Since we are interested in absolute intensity, the second command (`rgb2gray`) is a typical conversion for color images to grayscale intensities. The third command (`double`) converts the data from an 8 bit integer to a double so that we can perform math on our picture.

We have loaded 3 images into matlab. The first image, `whiteLED`, is the spectrum of a typical white LED. The other two images, `violet430nm` and `redlaser650nm`, are images that we will use to calibrate our spectrum output. Since we know what the wavelengths of the peaks are (namely 430nm and 650nm), we can figure out how to convert pixels to wavelength units.

- Let's look at one of the images that we have loaded into matlab.

```
figure; image(whiteLED)
```

Notice how the rainbow only takes up a small fraction of the image. We will need to crop our image to isolate the rainbow. In order to determine what the intensity of each color is, we will be averaging our intensity in the vertical direction since the wavelength only varies in the horizontal direction.

- Now we need to pick coordinates for our crop. **IMPORTANT!** These crop coordinates will be used in all subsequent images since the rainbow should not have changed position between images. In the figure window, select the data cursor tool and pick a point on the top left of the area you want to crop. I chose $X = 1$, $Y = 2140$. Then select a point on the bottom right of the area you want to crop. I chose $X = 3648$, $Y = 2240$.
- Now that we have our coordinates, we can crop the images and take an average to get our intensity. Remember that Y is the row and X is the column.

```
colmin = 1;  
colmax = 3648;  
rowmin = 2140;  
rowmax = 2240;  
whiteint = mean(whiteLED(rowmin:rowmax,colmin:colmax),1);  
violetint = mean(violet430nm(rowmin:rowmax,colmin:colmax),1);  
redint = mean(redlaser650nm(rowmin:rowmax,colmin:colmax),1);
```

The index (`rowmin:rowmax,colmin:colmax`) says to make a vector from `rowmin` to `rowmax` stepping by a distance 1 as our row selection and a vector from `colmin` to `colmax` stepping by a distance 1 as our column selection. You can make other steps as well with `a:s:b` where `a` and `b` are the start and end of the vector and `s` is the step size. We could have equivalently wrote (**`rowmin:1:rowmax, colmin:1:colmax`**) as our vector of points to use for the mean calculation.

The function `mean(vector,dimension)` says to take the mean of the vector along the dimension, where a dimension of 1 means rows. The way we have called the function will result in an average of each column of the picture.

- Let's plot our data. It should look something like Figure 6.

```
figure; plot(colmin:colmax,whiteint,'k',colmin:colmax,violetint,'b',colmin:colmax,redint,'r');
```

Notice that the x-axis of our plot is not wavelength, but is instead pixels. In order to turn this into a spectrum, we need to convert our pixel spacing into wavelength spacing.

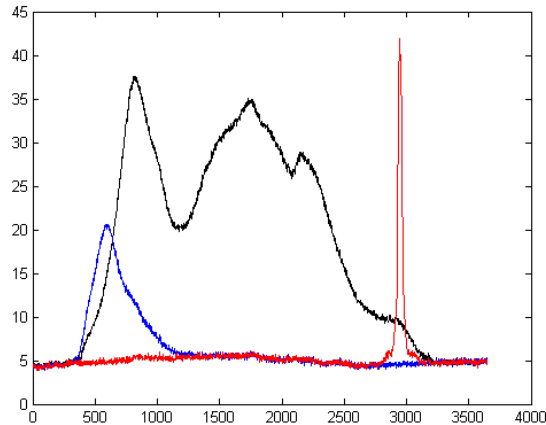


Figure 6: The spectra with the x axis as pixels.

7. Looking at the figure, find the center (in pixels) of the violet and red spectrum output using either the zoom tool or the data cursor. I found $x = 597$ for the violet and $x = 2944$ for the red spectrum. We will treat the grating as spreading our spectrum linearly with distance. We need to find the slope and y-intercept of our pixel to wavelength conversion.

$$\lambda = m * x + b; \quad (1)$$

$$m = \frac{\lambda_1 - \lambda_2}{x_1 - x_2} \quad (2)$$

$$b = \lambda_1 - m * x_1 \quad (3)$$

Find m and b . Then create the a vector called `lambda`.

```
x = [colmin:colmax];
lambda = m*x + b;
```

Now we can plot the data with the correct x axis.

```
figure;plot(lambda,whiteint,'k',lambda,violetint,'b',lambda,redint,'r');
xlabel('Wavelength [nm]');
```

Turn in the final plot of the three spectra versus wavelength.

4 Take Home Lab

- (1) You will begin making your own communications link by first connecting the LED to one end of the fiber. By doing so you are creating the signal end of the link. **(Never connect the LED directly to the battery or the signal generator without the resistor! You will push too much current through it.)**
- (2) Using the rough sand paper, sand down your LED until the diode itself is visible. A close up picture of the LED is shown in Figure 7. You will sand down the top plastic part so that you get a flat surface and stop before you expose the bond wire. The bond wire may be difficult to see (try looking for it

now). Exposing the bond wire will cause the LED to malfunction. Be patient, the closer you can get to the diode without damaging the bond wire, the easier it will be to couple light into the fiber.

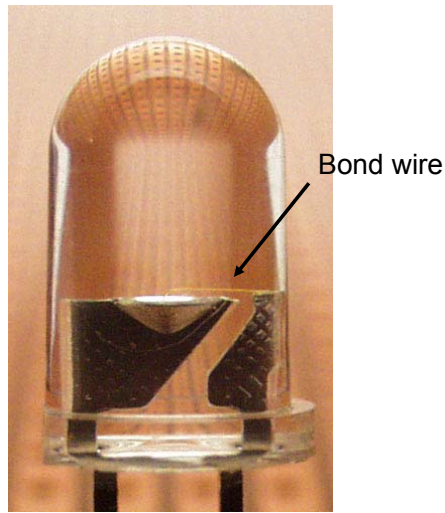


Figure 7: LED close-up

Once you are close to the diode, use the finer sandpaper to polish the surface a bit so that it will be easier to attach the epoxy. Wipe the surface clean.

- (3) Hook up the LED in the configuration shown below. The LED's positive lead is the longer lead at the round side of the LED. Don't forget to connect the resistor! Verify that the LED lights up. The battery supplies 9 V and the V_{on} of the diode is 3.5V. The resistor is $200\ \Omega$. How much current are you passing through the LED? -----
Put the fiber again e other end.

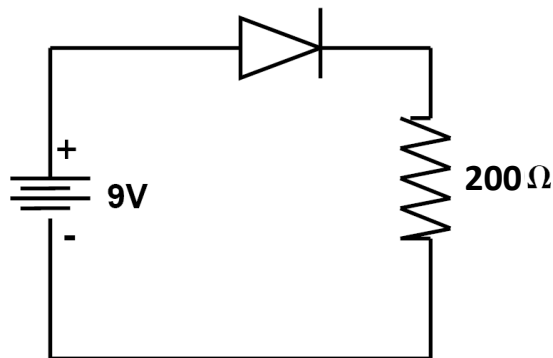


Figure 8: Basic LED circuit

- (4) Open and mix the packet of epoxy on a sheet of paper with the stir stick. Make sure not to inhale the fumes from the epoxy as it may irritate you. (If you have superglue, all you need to do is apply the glue with the stir stick.) With the LED on, place a generous portion of the epoxy or glue onto the sanded LED. Wait about one minute before attempting to position the fiber against the LED. Adjust the position of the fiber while looking at the LED output to find the best coupling, then leave the fiber in this position for about 5 minutes while the epoxy/glue hardens. You are done!
- (5) Bring the LED, battery, and fiber setup to lab, along with any extra LEDs.

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