Diffraction

PHYS 1301 F98
Prof. T.E. Coan
Last edit 6 Aug '98

Introduction

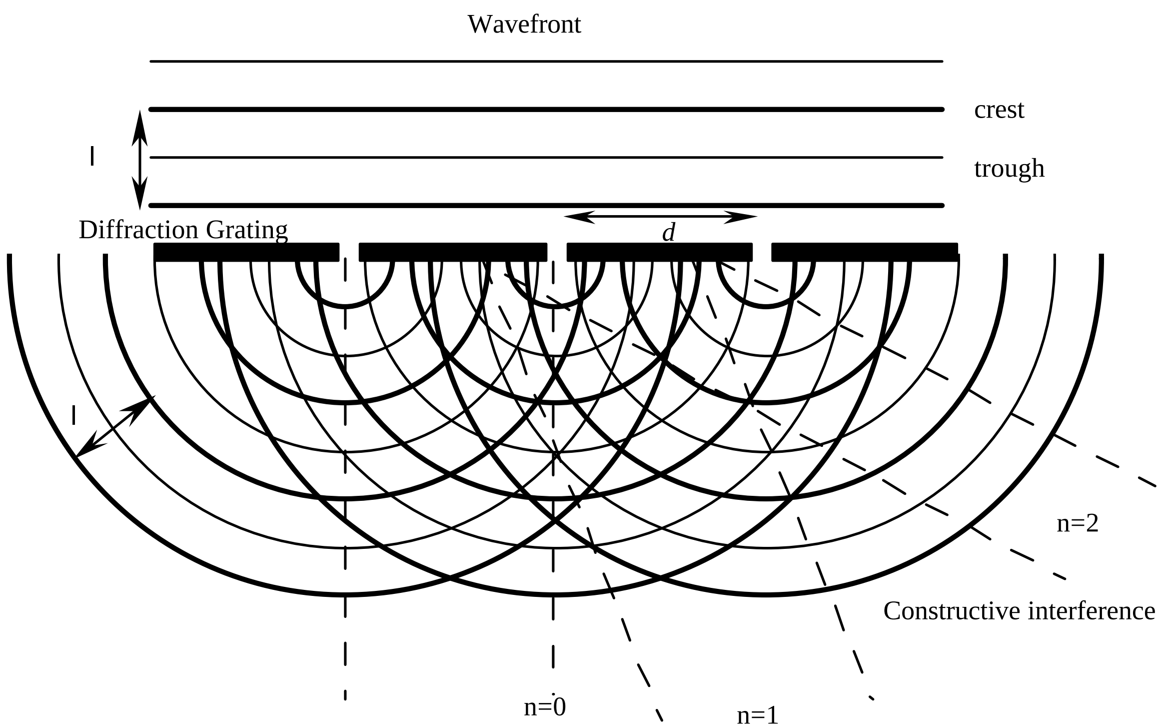
You have probably asked yourself at one time or another, "what is light." One way of thinking about light is that it is a kind of wave that propagates from its source (a light bulb, say) to your eye. Think of a water wave traveling on the surface of a lake or a pool produced by an object regularly bobbing up and down in the water. As the wave moves from left to right, the water moves up and down. (The maximum amount by which the water surface is displaced vertically from its flat and smooth position is called the *amplitude* of the wave.) Furthermore, the wave has a wavelength - the distance between neighboring crests - and a speed. Light waves also have these same properties. You have also probably noticed that when two water waves collide or overlap with one another, the motion of the water seems to be complicated. Actually, it *isn't* really complicated, it just looks that way. The vertical motion of the water at some location is just the sum of the individual vertical displacements the water would have due to each individual wave. For example, if at some place in the lake each wave would displace the water upwards by 0.1 meter, then the effect of the two waves where they interfere will be to produce a vertical displacement of 0.2 meters. It is also the case that if one wave wanted to displace the water downwards by some amount and the other wave anted to displace it upwards by the same amount, the result would be that water would have zero vertical displacement at the point where the two waves collide. In this special situation we say that the two waves destructively *interfere* with one another. We will also use this word interference to describe the situation where the total displacement of the water is the sum of the amplitudes of the two overlapping waves. In this case the waves are said to *constructively interfere*. Light waves also can overlap with one another and can destructively and constructively interfere.

Although it is tempting to think of light as a water wave, these two kinds of waves are *not* identical. A water wave needs water to exist but a light wave does not need any matter to travel through! A light wave can travel through empty space - we see starlight after all. What then, you might ask, is oscillating up and down in a light wave if the wave can travel through a vacuum? The "thing" is an *electric field*, which you can think of as an immaterial object whose most important property is that it can push or pull electric charges, such as the electrons that move around the atomic nuclei in the molecules that make up your eye. This definition is a bit vague but the important idea for us now is that when two light waves interfere with one another, the net electric field at the point of interference can be less than or greater than the electric fields of the individual waves. Another important difference between a light wave and a water wave is that a light wave really has two oscillating waves associated with it: the electric field we already talked about and a *magnetic* field, which has the same motion as the undulating electric field except that it is perpendicular to both the electric field and the direction of motion of the light wave. (See if you can visualize this. It is not too hard.)

Since we claim that light behaves as a wave, we ought to be able to see some of this wave behavior for ourselves if we are to take this idea seriously. Our goal for today is to observe some of the features of the wave nature of light. We will do this by letting light from a lamp strike an object which behaves like an opaque screen with lots of small windows in it spaced at regular intervals and observe the consequences. Where the screen is opaque, no light can pass through. Where there is a window then light can pass through. This kind of object is called a **diffraction grating**. It is an interesting fact that when light strikes any screen with holes in it, not just diffraction gratings, the holes behave as virtual sources of light in the sense that the holes act as if they are collections of little light bulbs producing as much light as fell on them from the original light source. An observer on the opposite side of the screen from the original source of light would see the same thing if someone replaced both the screen and original lamp with little light sources filling up the former positions of the screen holes. This principle is often called Huygen's principle after the person who first proposed it.

Our setup will be very simple. We will place diffraction grating about 1 meter from a mercury filled lamp. The mercury light waves will spread from the lamp in much the same way as water waves spread out circularly from the place where a rock is dropped into a lake. (Remember, for the light wave it is the electric field which oscillates up and down.) Far from the where the rock is dropped and over a small portion of the water wave, you would not notice very much that the wave has a circular shape. The successive wave crests would look something like successive waves crashing onto a beach. This is shown below in the first diagram, where I have drawn straight lines to mimic neighboring crests and troughs of the light wave as it strikes the diffraction grating. In reality the lines would not be perfectly straight but would be curved. The diagram is just an approximation, but a good one. Now, when the light wave strikes the diffraction grating Huygen's principle takes over. The small apertures (holes) in the grating will behave as light sources, which produce circularly outgoing waves that crest and trough at the same time as the original wave crests and troughs. These virtual light sources at the grating apertures are said to be **in phase** with the incident light wave. If you like the water wave analogy, you can imagine that there are little rocks positioned at the grating apertures which bob up and down synchronized to the up and down motion of the water wave striking the grating.

You can know mentally throw away the original lamp and even the diffraction grating and just keep the virtual light sources at the original aperture locations. The outwardly going light waves from each of the virtual light sources will eventually overlap one another. This is also shown in the first figure. What is interesting is that at certain positions the light waves will constructively interfere so that the electric fields of all the waves will add together, producing a very large electric field at these positions. You will actually be able to identify this position because a bright light will be present there, which is easily seen by your eye. It is also the case that the positions of this constructive interference depend on the size of the light wave wavelength. The positions of constructive interference are different for waves of different wavelengths. Since the eye (and/or brain) interprets visible light of different wavelengths as different colors, different colored light incident on the grating will produce constructive interference at different locations. You will also see this because mercury light contains different colors and so constructive interference will be present at more than one location.



The diagram above gives a close up view of a portion of a diffraction grating. In general, diffraction gratings have several thousands of apertures per centimeter. The dashed lines represent the directions of constructive interference. Notice that these are the regions where the thick circles (crests) intersect with thick circles and the thin circles (troughs) intersect with thin circles. It is here that the electric fields of the different waves add, producing an enhanced electric field. It is at these locations that you will see colors.

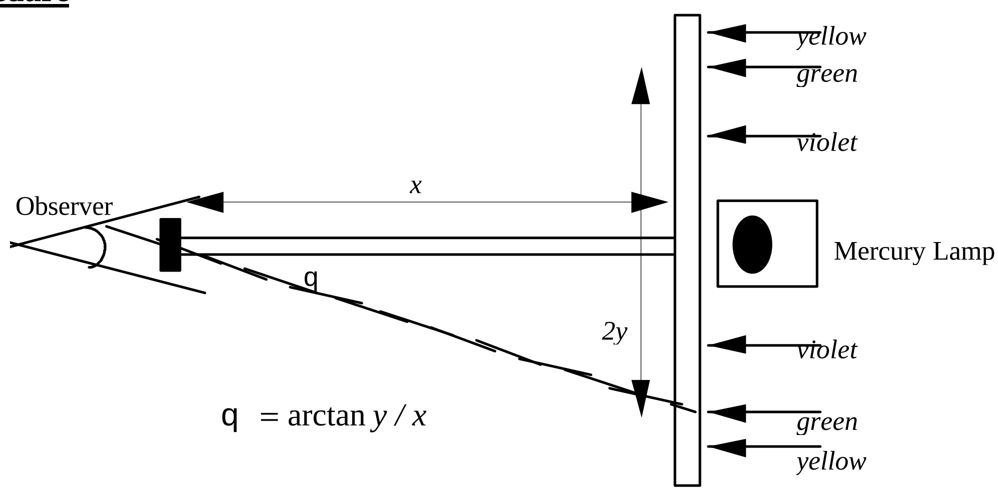
We need one more vocabulary word before we can start. If you place a screen - a white piece of paper will work fine - some distance away from the grating, on the side opposite your original lamp, you will notice that the light coming from the grating produces several bright spots or lines, each corresponding to a different **order** of constructive interference. The order is the way to describe which of the positions of constructive interference you are talking about (n=0, n=1, n=2). Indeed, a simple mathematical relationship relates the wavelength (λ) of the light incident on the grating, the angle at which constructive interference occurs *(q)*, the distance between two neighboring slits *(d)*, and the order of diffraction *(n)*. This **diffraction** equation is:

$$nl \;=\; d \sin q$$

Here we see explicitly that the angle θ at which constructive interference takes place is related to the wavelength of the light that passes through the grating, so that light waves which have different wavelengths - which means they have different colors - will produce constructive interference at different positions. Red light will not have its points of constructive interference at the same location as blue light. The diffraction equation is our sole mathematical tool for today’s lab. We will observe the effect produced when light from a mercury lamp is passed through a diffraction grating. We will record the various orders and angles of diffraction for the various spectral lines (distinct colors) produced by the lamp, and we will use these along with the appropriate *d* for the diffraction grating to calculate the wavelengths of these so-called spectral lines.

Since the title of this lab is “diffraction,” you may be wondering why we never actually defined the word. Well, now is as good a time as any. Just think of diffraction as constructive or destructive interference between many light sources. Or if you prefer, you can just use the word interference. (As a practical matter, diffraction is a very popular word). There really is no significant physical distinction between the words. They describe the same phenomenon.

<u>Procedure</u>



1. Place the meterstick flat on the table with the metric scale up. Let one end of the stick be flush with the table. Place a second meterstick on edge with the metric scale up, centered on and perpendicular to the other meterstick.

2. Insert the mercury vapor tube in the power supply. Notice how the tube is spring loaded. Place the power supply on end behind the second meterstick. The arrangement is shown in the diagram above.

3. **Caution!** The grating is a fragile photo-lithographic reproduction and **should not be touched with your fingers**. The diffraction grating is marked with a "down" side and

should be placed on the meterstick at the end of the table. The deep-recess side of the grating holder should be placed with its face away from the light source to avoid reflection of the light as it passes through the base material on which the grating is mounted. Use a piece of masking tape to secure the grating to the meterstick so that it is practically perpendicular to the rays of light from the source. The "spectrometer" is now ready for adjustments and use. The diagram illustrates the arrangement of the various components.

4. Place the eye on a level with the grating and look through it. Directly ahead, the light source should be visible. Viewing to the right should reveal at least three bright colored images of the tube. You should see the colors of violet, green, and yellow with violet closest to the center (diffracted the least). These compose the first order diffraction ($n = 1$). Looking farther to the right should reveal a second similar pattern. This is the second order diffraction ($n = 2$).

Analysis

There may be other colors present due to contamination in the tube, but these colors are to be ignored. To find the wavelengths of the three observed colors, you will need to find the angle of diffraction of the colors. You already know the orders of the diffractions. To find the angle, measure *x* and *y* as shown in the diagram and then calculate the angle from the formula:

$$\theta = \arctan (y/x)$$

Arctan is the inverse of the tangent function and may also be written as $\tan^{-1}$. The best method of taking data is to find the distance between the diffraction line to the left and the diffraction line to the right, and taking this value as *2y*. Dividing by two will yield *y*. The diagram above illustrates this method.

The grating spacing *(d)* from the manufacturer is (1/6000) cm, or 1666 nm. Utilizing the order number *(n)* the grating spacing *(d)* and the diffraction angle (θ) in the diffraction equation to find the wavelengths (λ) of the different colors of the mercury spectrum. You may want to calculate the wavelengths for two different orders of diffraction and compare the values.

Caution: Units are very important in this lab! Your value for the wavelength will be in the same unit as your number for the grating spacing.

Conclusions

Remember**,** what is well conceived is clearly expressed. So think before you write.

1. Explain, in your own words, what diffraction is.

2. Summarize your results from this experiment.

3. What did you notice about the relative sizes of λ and the angle of diffraction θ? (A single sentence can suffice.)

4. What similarity did you notice about the patterns of colored lines for the first and second orders?

5. How was λ related to the color of the line? (A single sentence can suffice.)

6. Suppose there were another element in the lamp beside Hg, possibly due to contamination. Would this affect your data? Explain.

7. If I told you that the wavelengths of visible light are all about the same size as the light you saw today from Hg, what then is the approximate wavelength of visible light. (I am looking for a *single* number here.)

Error Analysis

What were the major source(s) for error in this experiment? Explain why the things you claim as errors deserve the designation and what their significance is. Proper use of the English language is a plus.

Calculate the discrepancy between your measured wavelengths and the accepted values..
Accepted Values:
violet: 435.9 nm 404.7 nm
green: 546.1 nm
yellow: 578.0 nm

1 nm = 10^{-9} meter 1 cm = 10^{-2} meter

Diffraction

PHYS 1301 F98

Name: ____________________ **Section:_________**

Abstract:

Data: d = (1/6000) cm = 1666 nm

Color	n	2x	x	y	θ	λ

Calculations: (Use back if necessary. Show units!)

Conclusions:

Error Analysis: (Compute actual percent errors, and describe sources of error.)

Data/ Calculations (40):
Conclusions (40):
Error Analysis (20):
Grade: