Modern Physics Lab

Spectrophotometer

Introduction

This experiment explores the interaction of light with matter. Light incident on a material can be reflected, absorbed and transmitted. The amount of the incident light which undergoes any of these processes will depend on the wavelength of the light and how that particular wavelength interacts with the material. We will examine the amount of light transmitted using a transmission spectrophotometer. This instrument measures the intensity of the transmitted light as a function of the wavelength of the light.

By measuring the transmitted light spectrum we can learn something about how light interacts with different materials. Photon have an energy $E = h\nu$ where h is Planck's constant and ν is the frequency of the light. Thus different colors (frequencies) of light have different energies. The photons can interact with the electrons in the atoms of the material. Some frequencies will react strongly leading to absorption of light. Others will react more weakly leading to transmission of that color.

Classically we can picture the interaction of light with solids based on picturing light as a varying electric field. This electric field will interact with charges in the solid according to the laws of electrodynamics. We can picture the various charges bound into the solid by "springs" which have some critical frequency of vibration. When the frequency of the incident light is lower than the critical frequency of some type of charge in the solid, these charges can be excited.

Let's examine the types of charge and their critical frequencies. Electrons in the inner atomic shells have critical frequencies around 10^{19} Hz. Since visible light has frequencies in the the 10^{14} - 10^{15} Hz range, the inner shell electrons will vibrate with the applied electric field of the light. These electrons, however, are generally so tightly bound to the atoms that their contribution to the light-matter interaction is small.

The valence electrons in the outer atomic shells are less tightly bound. They have resonant frequencies in the optical range. The interaction of light with these electrons can be a significant source of absorption in materials. The details of these interactions are often discussed in optics and solid state physics books such as those listed in the references.

Another potential source of interaction of light with a solid is by vibrations of the atoms or ions in the crystal lattice. These typically have frequencies in the range 10^{12} - 10^{13} Hz which are generally too low to be excited by visible light. Some of these are in the infrared range and are one reason for the interest in infrared spectrophotometers.

Description of the apparatus

The Macbeth student spectrophotometer used in this experiment is quite simple to operate. The power switch is located on the back of the instrument. The sample compartement is located on top of the instrument. It can be opened by pulling up on the handle. A sample can then be inserted and the compartment can be pushed back down.

When the instrument is turned on, a bright spectrum can be seen on the left panel on the front of the instrument. A scale of wavelengths is marked directly below the spectrum. Further below the spectrum is a sliding knob which can be moved to select a particular wavelength of light to be measured. As the knob is moved left and right, a thin line moves across the spectrum indicating the wavelength selected. A small photocell is attached to this slider producing an electronic signal which is proportional to the amount of light reaching the sensor.

The intensity of the light incident on the sensor is displayed on the meter. Depending on how the instrument is calibrated this can be measured as percent transmittance or as absorbance. Under the meter is a zero adjust. In the center of the front panel is a calibration knob which is used to adjust the percent transmittance to a reading of 100% (or the absorbance to zero) during the calibration procedure (discussed later).

operating procedure

1. Check the zero on the instrument by inserting a black card in the sample holder. The meter should indicate zero transmittance at all wavelengths. If it does not, please notify the instructor before adjusting the zero adjust.

2. Whenever selecting a wavelength, move the indicator from the LEFT to the desired wavelength. If you need to move to a lower wavelength, move beyond the wavelength and then approach it from the left. This will help reduce the effects of mechanical hysteresis in your measurements.

3. The light source does not provide equal intensities of light at each wavelength. Most light sources have a peak intensity in the yellow or green and less at either end. (This is also true of the sun). The photocell sensor used to detect transmitted light is also sensitive to wavelength. For the same intensity of blue light and red light, it may give a different reading. We need to calibrate the instrument to take these instrumental variations into account. This can be done using the calibration knob

experiment 1: measurement of the spectral product

The spectral product is the combination of the spectrum produced by the light source and the detection efficiency of the photocell. This demonstrates a common problem in measuring light spectra: the measurement always involves a convolution of the detector efficiency with the actual output of the source. This experiment will give us some idea how the instrument responds with no sample in it.

1. With nothing in the sample holder, select a wavelength near the middle of the scale.
2. Turn the calibration knob until the meter indicates about 50% transmittance.
3. Adjust the wavelength to find the peak intensity.
4. Now turn the calibration knob to obtain a reading of 100% transmittance at this peak wavelength.
5. Return to a low wavelength and record the spectrum (% transmittance vs. wavelength) for the system. It may help to graph the results.

The spectral product is an important characteristic of the spectrophotometer. It can change when the light source or photocell are changed. The instrument will be most sensitive in regions where the spectral product is highest.

<u>IF</u> the detector has a constant detection efficiency, that is, it detects red light, green light, blue light, etc. equally well, then the curve which we measure could be approximated as a black body emission

curve. Making this assumption, determine the temperature of the light bulb filament from Wien's Law: $\lambda_{max} = 0.0029 / T$ where the wavelength at the maximum in the curve is given in meters and the temperature is in Kelvins. Does your answer seem reasonable ? Compare the shape of your curve, qualitatively, to a typical black body curve. Do you think your detector has constant detection efficiency ?

experiment 2: transmittance of colored filters

The transmittance is defined as the ratio of the amount of light transmitted to the amount incident on a sample. Now we will examine filters of various colors to determined which colors they allow to pass and which are absorbed. Of course, from looking at the filter we can get a pretty good qualitative idea of what we expect to see.

1. Place a colored filter in the sample holder but do not push it down into the beam.
2. Select a wavelength (start with 400 nm).
3. Turn the calibration knob to obtain 100% transmittance. (If the knob will not allow you to get that high then use the highest value possible). Record this value as your incident light.
4. Now lower the filter down into the instrument. Measure the transmitted light.
5. Calculate the transmittance at this wavelength.
6. Repeat steps 1 through 5 for each wavelength.

You might consider doing this experiment for several different color filters. You might try combining some of the filters. For instance, blue and yellow combined appear to be green. How does the transmittance of the green filter compare to a combination of blue and yellow? Again, it is probably best to communicate your results with graphs.

Experiment 3: Bouguer's Law

How will the transmittance change if we increase the thickness of the sample ? We expect it to decrease since we are passing through more material. If the transmittance of one layer was 70%, then we would expect another layer to reduce the transmittance by an additional 70%. If the transmittance of the first layer is T, then two layers should produce a transmittance of $T \times T = T^2$. Three layers would be T^3 and, in general, a sample which was n layers thick would be T^n.

Sample transmittance = T^n where n is the number of times thicker than some known standard sample our test sample is.

This was originally worked out in 1729 by a French scientist Pierre Bouger. (The relationship is also sometimes credited to Lambert and referred to as Lambert's Law).

We can approximate a thickness change by using several identical pieces of colored filter and placing them together in the instrument. How is this an approximation for a thicker sample? What errors are we introducing into the measurement ?

1. Place a single colored filter in the spectrophotometer. Find a wavelength for which the transmittance is between 0.50 and 0.80 (as we did in experiment 2).
2. At this same wavelength, measure the transmittance for 2, 3, 4, and 5 layers of colored filter.
3. Compare the measured transmittance with the theoretical transmittance determined from the measurement of the single colored filter.
4. Repeat this experiment at several wavelengths.

You probably did not get exact agreement between theory and experiment. Why not?

References:

1. R. Coelho, "Physics of Dielectrics for the Engineer", (Elsevier Scientific Publishing Co., Amsterdam, 1979).

2. G. R. Fowles, "Introduction to Modern Optics" 2nd ed. (Holt, Rinehart, and Winston, Inc., New York, 1975). (I believe this is now available through Dover Publications).

3. M. Born and E. Wolf, "Principles of Optics", 5th ed. (Pergamon Press, Oxford, 1975).

4. M. Ali Omar, "Elementary Solid State Physics" (Addison-Wesley Publishing Co., Reading, MA, 1975).

5. most Modern Physics books and many introductory Physics books will discuss black body radiation and Wien's law