AY 105 Lab Experiment #1: Photometry

As discussed in class, in this lab you will be using a silicon photodiode and a set of interference filters to determine the intensity I_λ of a quartz tungsten halogen (QTH) lamp. This lab will also introduce you to working on an optical table, and in Part B to using a laser with a spatial filter and collimator.

When using silicon diodes as photo detectors light incident on the diode produces a current flow from the cathode to the anode, proportional to the number of incident photons.

In this week's experiment, you will use a transimpedance amplifier to measure this current flow very accurately. This the important thing to understand is: how does a measurement of the current flow from the photodiode translate into the number of incident photons? Astronomers typically quantify the sensitivity of a detector using what is called the "quantum efficiency" (QE), which is the ratio of the number of detected photoelectrons to the number of incident photons. An ideal detector thus has a QE of 1.0, but of course in practice the QE is always less than 1. The QE depends on the wavelength of the incident photons, and can range over many orders of magnitude for various detectors: for example, photographic plates have QE < 0.01, photomultiplier tubes have QE < 0.2, and photodiodes and CCDs can have peak QE ranging up to 0.9 or so. Engineers, however, typically measure a quantity called the "responsivity" for photodiodes, in units of amperes/watt. This makes sense, as we are measuring the rate of generated photoelectrons (in amps, or coulombs/sec) in terms of the rate of incident photon energy on the detector (in watts, or joules/sec). Thus the QE is a unitless version of the responsivity, and an expression relating the two is:

$$R = \frac{q\eta\lambda}{hc}. \tag{1}$$

Note that λ appears explicitly in this relation—it's needed to convert an energy rate into a photon rate (as blue photons carry more energy than red ones).

This manual also contains a plot of the responsivity of your photodiodes as a function of wavelength, and a table of these values (with estimated uncertainties, Figure 1 and 2).

Part A

In the first part of this week's lab you will set up the quartz tungsten halogen lamp, relay lens, and photodiode in roughly the arrangement just discussed in class. The main difference will be that instead of one biconvex lens to reimage the filament of the QTH lamp onto the silicon photodiode, you will use two (more-or-less) plano-convex lenses separated by a short distance. In this manner you can establish a parallel beam between the two lenses (in optics terminology a parallel beam is often called a "collimated" beam). The best location for the interference filter which defines the spectral bandpass is in the collimated beam: interference filters are comprised of many "thin film" layers of a dielectric material. As you know from basic physics, constructive and/or destructive interference occurs as light passes through thin films, and the "interference filter" exploits this phenomenon using many layers having thicknesses designed so that only a narrow range in wavelengths is transmitted. But what matters optically is not the thickness of the layer but rather the path length (measured in wavelengths) of the light through the layer; the spectral bandpass will therefore be different from the design bandpass if the filter is not normal to the incoming light, and so the best location for the filter is in the parallel beam between the two lenses rather than in a diverging or converging beam (whose rays will not be everywhere normal to the filter).

A second twist on the radiometry method is the suggestion that you also place an iris in the collimated beam between the two lenses. You can adjust the diameter of this iris to a specified diameter independent of (but not greater than, obviously) the lens diameters. The experimental setup for Part A should therefore look something like Figure 1.

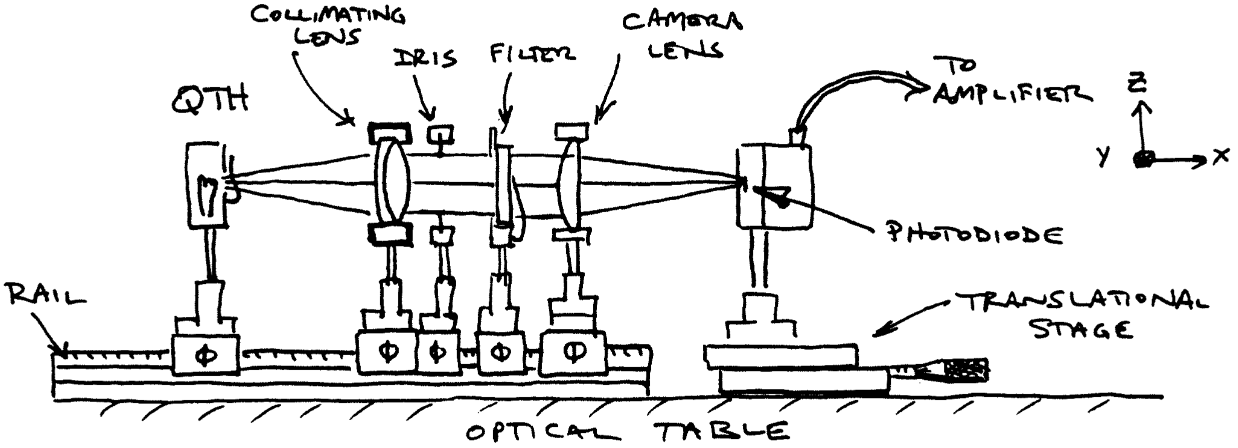

Figure 1: Experimental setup for Part A.

What follows are some instructions and suggestions on how to create this setup. You're free to do things differently, but please ask either the instructor or the T.A. if you're not sure how to implement your idea or to make sure that your approach doesn't risk damage to the equipment; at the very least you will have someone to take the blame instead of you if such damage should occur, and there's even the chance that the risk will be identified ahead of time.

Optical Bench. You will notice that the optical table has 1/4-20 (i.e. 1/4-inch diameter, 20 threads per inch) holes spaced 1-inch apart over almost its entire surface[1]. While often it is convenient to use these holes directly, for this lab you will probably find it better to first bolt the shorter of the two "optical rails" to the front left side of the table, and then mount your optics to "carriers" which can slide over the rail. You can then focus without being limited by the 1-inch hole spacing on the table itself. The lab drawers underneath the tables contains optical mounting hardware, and in particular a black box of 1/4-20 bolts (and an Allen ball-end screw-driver) to use when bolting the rail to the table.

Post Holders. These accept the 12 mm diameter posts which carry optics, and are screwed into "bases" which will attach both to the table directly and to the tops of the carriers. It's best to use flat washers underneath the bolts when attaching the bases, since the holes in the bases are slotted. Since moving the carriers along the rails gives you motion in the x-direction (say), you should orient the slotted holes in the base in the y-direction to allow you to align each component to the optical axis. Note that the unusually shaped hole in the post holder does not achieve this alignment automatically.

Translational Stage. Since you will be asked to make fine focus adjustments of the detector position, it is recommended that you attach the large translational stage directly to the optical table at the right end of the optical rail, with the translation direction aligned with the direction of the rail. Turning the micrometer adjustment to its extremes will reveal countersunk holes in the base for 1/4-20 screws to attach it to the table. Note that there are tapped holes in the top on which to bolt a post holder and base to support the photodiode assembly. Once the base is attached to the table, mount the photodiode assembly and set the micrometer to the mid-point of the focus travel.

Camera Lens. Working backwards (right to left) through the optical configuration, the next element is the "camera" lens. For the camera lens use the #32974 plano-convex lens (50 mm diameter; 150 mm focal length) in the cabinet drawer "Optics." Unwrap it, and insert it into one of the two adjustable lens holders, being careful not to touch the lens surfaces (keep the innermost layer of wrapping tissue between the lens and your fingers). The edge of the lens should seat in the lens holder V-grooves top and bottom; when this happens, tighten the two thumbscrews on the metal slide posts, and *gently* make the top thumbscrew "snug" so that the lens does not fall out. As should be obvious, you have a large mechanical advantage (like a vise) when turning that top thumbscrew, so even with finger pressure alone you could probably succeed in cracking the lens. The top thumbscrew only needs to be gently tightened just enough that the lens will not fall out, and preferably no more. Meanwhile attach a post holder

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[1] When using the table to work on parts, try to cover the work area of the table with the blue anti-static mat: Not only will this prevent static electricity from damaging any electronic components you might be working on (as compared to, say, a sheet of plastic under you), but it will also prevent you from dropping small parts and having them fall into the 1/4-20 holes in accordance with Murphy's Law.

and base to a rail carrier, and slide this onto the rail (e.g. from the left end). Approximately how far from the photodiode does this camera lens belong? Move the carrier to this spot and lightly clamp it in place, then mount the lens holder containing the lens into the post holder. As shown in the above drawing, the best optical performance will result when the convex side of the lens is facing the lamp and the flat side of the lens is facing the detector.

Filter Holder. On the shelf above the optical table you will find a post attached to a 50 mm square frame with two spring clips: this will serve as the filter holder, and should be located to the left of the plano convex lens on the rail. Mount it in place on a carrier now, but for the time being without any filter (this will keep the light beam bright during alignment yet to come).

Iris. Next comes the iris. Since the iris mount is not large, you may want to add a black sheet of paper having a 50 mm hole in it to the iris for better reduction of scattered light from the lamp passing around (instead of through) the iris and reaching the detector.

Collimating Lens. For this lens use the #31402 achromat (63 mm diameter; 356 mm focal length) from a cardboard box in the "Optics" drawer, and follow the same procedure as was used for the camera lens to mount it into the second lens holder and into position on the optical rail. You will have to look more closely to distinguish the more- and less-strongly curved convex surfaces of this lens; the more-strongly curved surface should face the iris.

QTH Lamp. This is the black unit #63200. Between the two spring clips on one side of the box is a round aperture through which light from the bulb emerges. Mount the post on a rail carrier at approximately the proper location on the rail with respect to the collimating lens. Locate the #6394 power supply at some convenient spot nearby, but *DO NOT PLUG IT IN YET.* Take the wire from the lamp unit and, following the black and white color coding, connect the leads to the power supply terminal lugs. This should agree with the 60 Hz label. With the lugs on the power supply facing you, on the back surface find the toggle switch and make sure it is in the "OFF" position (down). You may then plug in the power supply, and lastly turn it on.

The next step is to align everything in both y-direction and z-direction; if you have not been paying attention to the z-direction (height above the table) you may need to replace the tall post holders with short ones or vice versa before everything lines up. Note also that the top drawer underneath the optical table contains a bag of "post collars" which you can use to maintain the z-height when removing and reinstalling posts. The filter holder will be the main victim of this activity, and its post should already contain a post collar. But you may wish to add post collars to one or more of the other component mounts also. Be sure that, in addition to whatever else you may have written down in your lab notebook so far, you describe your procedure for aligning each component assembly (in order left to right this time, say) in the y- and

z-directions.

Adjusting the lamp-to-collimating lens focus (x-direction) distance to achieve a parallel output beam from the collimator comes next. Describe how you were able to verify that the output was indeed a parallel beam. x-direction locations of the iris and filter are not critical, so the remaining task is only to focus the camera lens and/or photodiode to achieve the smallest possible image of the lamp filament on the photodiode. It is probably best not to wander too far from the middle of the translational stage adjustment range, so make coarse adjustments by moving the lens and only fine adjustments by moving the detector.

The top drawer in the cabinets contains a 3-ring binder with your group's interference filter set. Remove the 50 mm filter holder from the bench setup, leaving the rail, base, and post holder in place. Starting either with the longest or shortest wavelength filter, remove it from its protective pouch and place it in the filter holder, *BEING VERY CAREFUL NOT TO TOUCH THE FILTER SURFACES (touch only the edges).* The bottom of the filter holder frame has a V-groove which will center the filter in the holder. Return the filter holder (now containing the filter) to the bench setup, and rotate the post so that the filter surfaces are normal to the optical axis before tightening the post holder thumbscrew.

Finally connect a BNC coaxial cable from the top of the photodiode housing to the “input” terminal of the high dynamic range transimpedance amplifier, plug the AC power adapter into the back of the amplifier and then into the AC outlet, and turn on the amplifier. Adjust the current range selection knob to the smallest setting for which you get a reading instead of a -1 on the display (why this setting and not one or two notches larger current range?). The -1 signifies that the signal exceeds the maximum current for that range. If you find a -1 value for all ranges, you will need to decrease the diameter of the iris opening. In any event, you should decide now upon a diameter for the iris opening, set the opening to this diameter, and record the value in your lab notebook. Before continuing on to make measurements, you should calculate the reimaged size of the filament on the detector, thereby determining whether or not the entire emitting area fits within the photosensitive area of the diode. The additional information you will need is: QTH filament dimensions: 0.6(H) x 2.3(V) mm size; detector: circular, 1.0 mm^2 area.

Measurements. For Part A, you should measure two quantities for each filter in your filter set and record these in your lab notebook along with the relevant properties of the corresponding filter. The first quantity is the translational stage micrometer “focus” reading which results in the maximum output current from the photodiode, and the second quantity is the value of this maximum current. Furthermore, for one particular filter, you should record the output current from the photodiode as a function of the micrometer focus reading using steps of 0.5 mm (or 0.025 inches) over a focus range of ± 2.5 mm (± 0.125 inches) from best focus.

Analysis[2]**.** It will be sufficient to simply plot the optimum focus readings versus wavelength as well as the photodiode current at one wavelength versus focus data, as long as your plot shows error bars and mention is made of how these (rough?) error estimates were obtained. The data for photodiode peak current with each filter, however, should be used to calculate the intensity of the QTH lamp at the (weighted?) center wavelengths of each filter. Plot these intensity points, and draw on the same plot the blackbody function for $T = 3300$ K. If it simplifies construction of the plot, you may use the emissivity at one particular wavelength λ_0 to normalize the blackbody curve to match the QTH intensity curve at this one wavelength. Then calculate the emissivity correction at other wavelengths (but do not apply these corrections when making your plot; use a single normalization factor $e(\lambda_0)$ throughout so you can compare the slopes of the QTH lamp and blackbody curves on the plot). Don't neglect experimental uncertainties here either.

Discussion. When writing your lab report, comment on your findings for Part A and what you've learned about the properties of the lamp, filters, and photodiode. Along with whatever else might occur to you to discuss, consider the following questions. What possible contributors to the instrumental sensitivity function $S(\lambda)$ have been left out? How significant do you think these omissions are in the context of this experiment? Does the QTH lamp temperature agree well with the 3300 K assumed, and if not is the lamp hotter or cooler than this temperature based on your analysis? What causes the variation in optimal focus with wavelength, and is the amount of this variation consistent with what you would expect?

YOU MAY STOP HERE AND CONTINUE WITH PART B IN THE SECOND CLASS.

Part B

In this part you will investigate the variation in detector response with angle by flooding (i.e. illuminating) the photodiode with a 50 mm diameter collimated beam and rotating the detector with respect to the direction of the incident parallel light.

By far the easiest and quickest way to produce the light source required in this part is to simply remove the "camera" lens from the optical bench setup used in Part A and open the iris to a diameter of roughly 2 inches if you made it substantially smaller during Part A. Such QTH-plus-filter illumination will be quite adequate for Part B, and you can skip down to the Rotational Stage section below (and come back to "play" with the laser setup at the end of lab if you have time). Alternatively, you can setup the laser now and use it instead of the QTH lamp (although in past years the intensity of the lasers have not proved stable enough for very accurate measurements).

Laser. If you have the time and care to learn how to produce a large-diameter

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[2] This you will work on at home, but having an appreciation for what's expected should guide you during lab.

parallel beam with a laser, spatial filter, and collimator, you may unbolt the optical rail from the table (loosen the carriers and slide them for access to the bolts as necessary) and move it back on the table, making room for a laser setup on the front portion of the table. In the drawers beneath the cabinet you will find a HeNe laser, power supply, and adjustable mount. Bolt the mount on the front left side of the table and assemble the laser tube inside it, keeping in mind that inside the metal laser tube is a glass tube, and hence the unit is fragile.

Spatial Filter. The same drawer from which you took the laser contains two wooden boxes which you should set on the table. The first box contains the spatial filter: basically a microscope objective (small diameter, large numerical aperture lens system) which takes the small-diameter parallel laser beam and makes it converge to a point, after which the light diverges. At the focal point of the microscope objective inside the spatial filter unit, however, is located an opaque disk containing a pinhole opening. When the opening coincides the focal point, most of the laser light goes through it and subsequently diverges as happens without the pinhole. Light surrounding the pinhole is blocked, removed by the "spatial filter." The result is a very "pure," well-defined diverging beam. The instructor will assemble the spatial filter unit for you from the individual pieces in the box. Once the unit is assembled, you can attach a post to it and locate it to the right of the laser.

Laser Collimator. This is a lens system which attaches to the output end of the spatial filter, and converts the diverging beam to a parallel beam. You can remove the collimator from the second wooden box and attach it to the spatial filter. If the weight of the collimator causes problems when supported only by the post at the input end of the spatial filter, the V-groove lower section of a 50 mm filter holder (with the rods removed; the instructor will provide you a wrench for the two Allen setscrews) can be used to add support beneath the output end of the laser collimator. Your setup should look more or less like Figure 2.

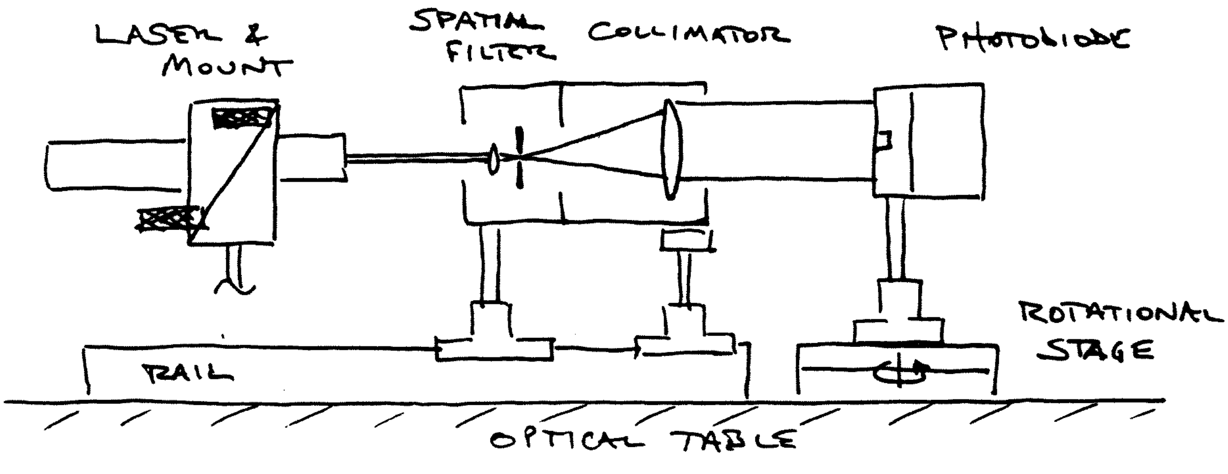


Figure 2: Experimental setup for Part B.

Warning. Turn on the laser using the key switch on the power supply.

NEVER LOOK DIRECTLY INTO THE LASER BEAM, NOR POINT IT AT ANYONE. Likewise, always be pay attention to where reflections send the laser beam. The power output of these lasers is low and will not hurt your hand (e.g.) if placed in the beam. Turn off the laser.

Rotational Stage. Replace the translational stage used underneath the photodiode in Part A with the rotational stage. Notice that by unlocking the turntable you can rotate it easily to align the large access hole on the top with the countersunk mounting holes in the base, and thereby attach it to the optical table at the right end of the rail. Mount the photodiode assembly on the rotational stage, trying as best you can to get the photodiode itself above the rotation axis. This will fix the x- and y-positions of the photodiode.

Alignment. Begin the alignment by removing the spatial filter and collimator (if you're using the laser) from their post holders, and adjusting the photodiode z-position to match that of the light source (laser or QTH lamp and collimating lens). If you're using the laser, you can now turn it on again and use its tilt adjustments to direct the laser beam directly at the photodiode; remember to pay attention to where any reflections go. If you are using the QTH lamp, you may need to adjust the lamp and collimating lens in the y-direction to align the collimated beam with the photodiode. With the laser, the next step is to insert the spatial filter and collimator and align these assemblies in the y- and z-directions with the laser beam. Once the outer assembly is aligned, you can make fine adjustments of the pinhole position inside the spatial filter using the two thumbscrews on the outside of the unit, and thereby maximize the laser light emerging from the collimator. The final step is to focus the collimator by turning the knurled ring until the output is precisely parallel. Be sure to record all of your alignment methods in your lab notebook.

Measurements. The measurements required for Part B are very simple: record the output current from the photodiode as a function of its angle with respect to the incoming parallel beam from the laser or QTH lamp. Steps of 5° are more than enough; 15° would still be sufficient if you are pressed for time. Continue for 90° in one direction, return to your starting position and repeat your measurement there (why is this a good idea?), and then make measurements in at least two steps the other way. By comparing measurements at ± 1 and ± 2 steps from center you can later determine how accurately you were aligned at the center position (how?).

After taking measurements, if you've been using the QTH lamp you may go back to the start of Part B and setup the laser, spatial filter, and collimator if this exercise in alignment interests you. Document in your lab notebook what (if anything) you do with the laser this week, for future reference.

Analysis. Plot your measurements of photodiode current as a function of angle, but normalize the current by dividing each measurement by the peak current observed (so that the y-scale of your plot goes from 0.0 to 1.0). Compute the center position "offset," and estimate errors in both x (angle) and y (photodiode current) on your plot.

Discussion. Suggest a theoretical model to explain the variation with angle observed, and work out the functional form of the variation based on this model. How well do your observed results agree with the model? (The best way to answer this question is to graph the function on your plot.)

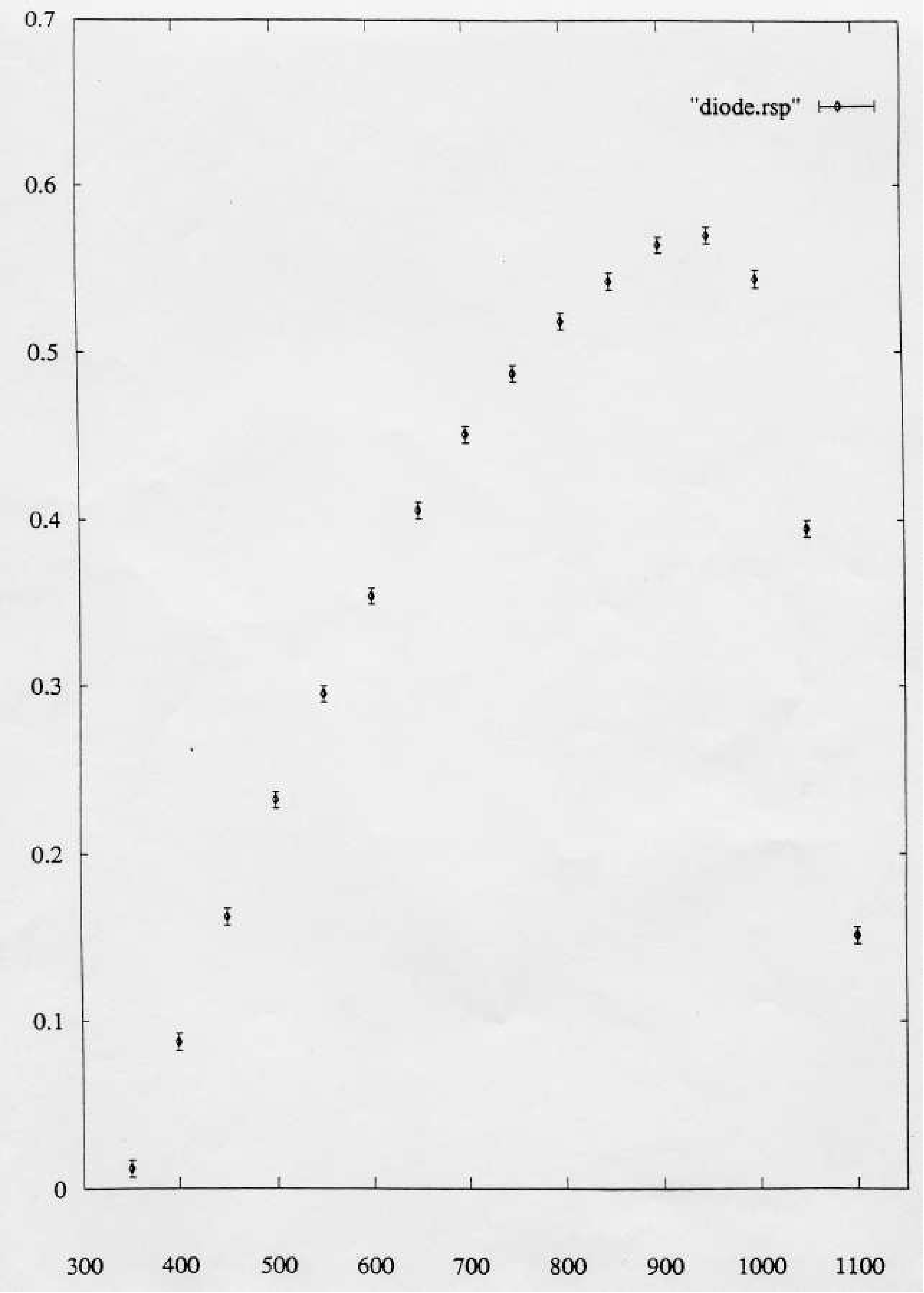
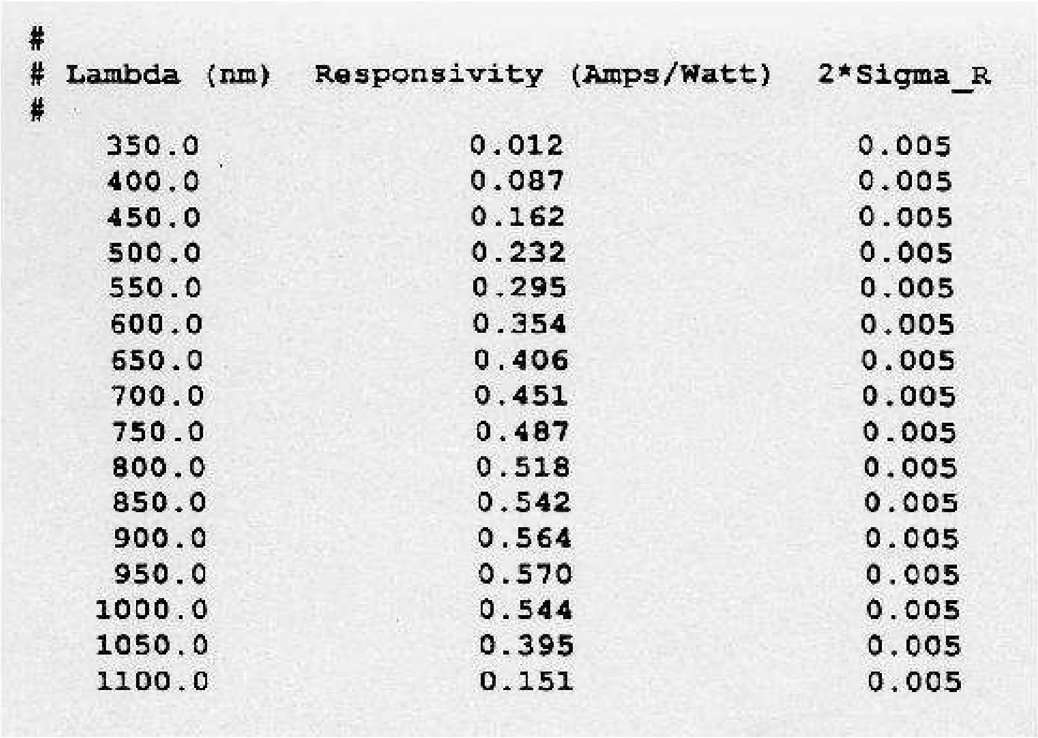


Figure 3: Responsivity curve for the diode



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#
# Lambda (nm)  Responsivity (Amps/Watt)  2*Sigma_R
#
    350.0            0.012                 0.005
    400.0            0.087                 0.005
    450.0            0.162                 0.005
    500.0            0.232                 0.005
    550.0            0.295                 0.005
    600.0            0.354                 0.005
    650.0            0.406                 0.005
    700.0            0.451                 0.005
    750.0            0.487                 0.005
    800.0            0.518                 0.005
    850.0            0.542                 0.005
    900.0            0.564                 0.005
    950.0            0.570                 0.005
   1000.0            0.544                 0.005
   1050.0            0.395                 0.005
   1100.0            0.151                 0.005
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Figure 4: Responsivity vs. Wavelength