Lab #2.5
Characterization of Spectral Output of Light Source *Using Lock-In Amplification*

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September 3, 2013

PHYS 4580, 6/7280

From Lecture #1 - Introduction and Course Overview

Include the following sections in each lab report:

Title Section: including (a) Title of your Report, (b) Your name and the names of lab partners (if any), (c) Date, and (d) Abstract (Purpose of Experiment(s) and major conclusions - approximately 100 - 200 words). The Title section should not be on a separate page – we like to conserve paper where possible.

Introduction: information on the need for, and value of, the experiments, and discussion of the general approach.

Experimental: details of samples and equipment, including a sketch of the layout and a few words on the function of each major component.

Results and Discussion: analysis, appropriate graphs, a thoughtful explanation of the significance of the results, sources of uncertainty, and strengths and weaknesses of the measurement approach.

Conclusion

References

Suggestions on how to prepare Good Lab reports:

(1) Prepare the Title section, and leave the **Abstract** blank.
(2) Write a quick **Introduction** that includes the main elements as understood by you form a general perspective at the time of the writing; why this lab was done, what you did, and what you learned. You will go back and revise this section after preparing the rest of the report, so don't worry about details or connecting everything together with good English at this point.
(3) List the experimental equipment with a very brief description in the **Experimental** section. If you did something unique, you should elaborate a bit. For example, if you implemented some improvement relative to what was suggested in the Lab Guide, you should highlight this here.
(4) Draft the **Results and Discussion** section. It should present the data you obtained, a discussion of the methods by which you interpreted the data and any critical thought processes. This section can be considered to be an elaboration of the **Introduction** and the **Conclusions.**
(5) Write the conclusions.
(6) Work through the entire report skipping over the **Abstract**; reorganize (if needed), proof read for grammar, spelling, and completeness.
(7) Write the **Abstract** with approximately one sentence per section of the report.
(8) Proofread all and finalize.

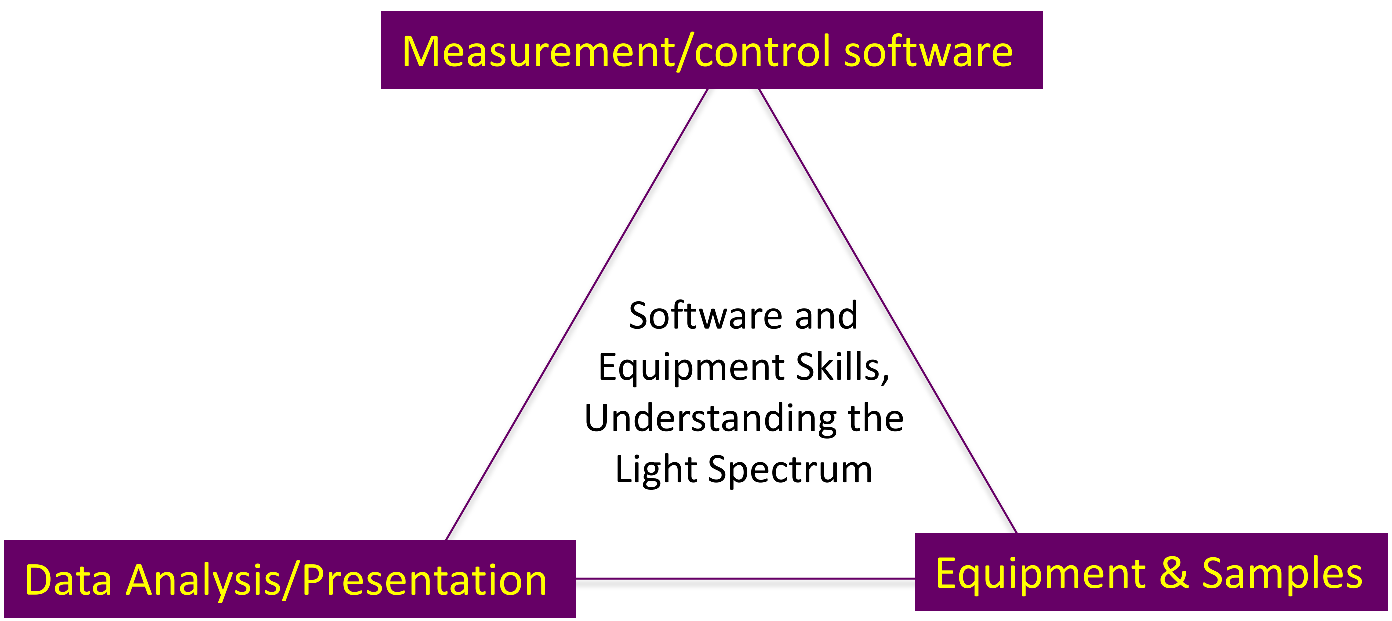
"Tell them what your going to tell them, tell them, and then tell them what you told them"

LabVIEW Information

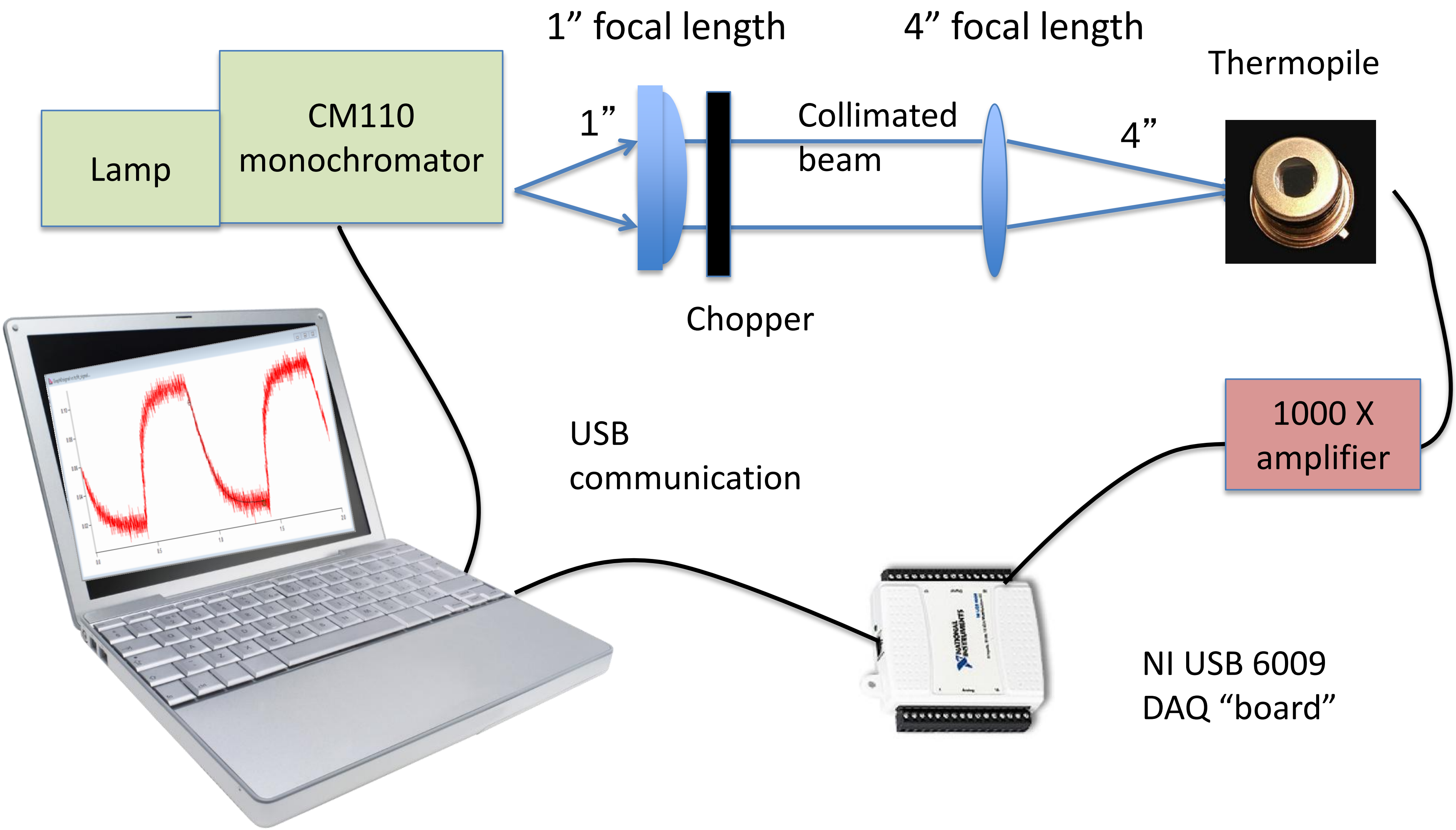
- LV Student editions on order and expected soon;
- http://www.ni.com/academic/students/learn/
- Execution structures in LV
  - Programming with Loops (video)
  - LabVIEW For Loops (video)

Last week's lab

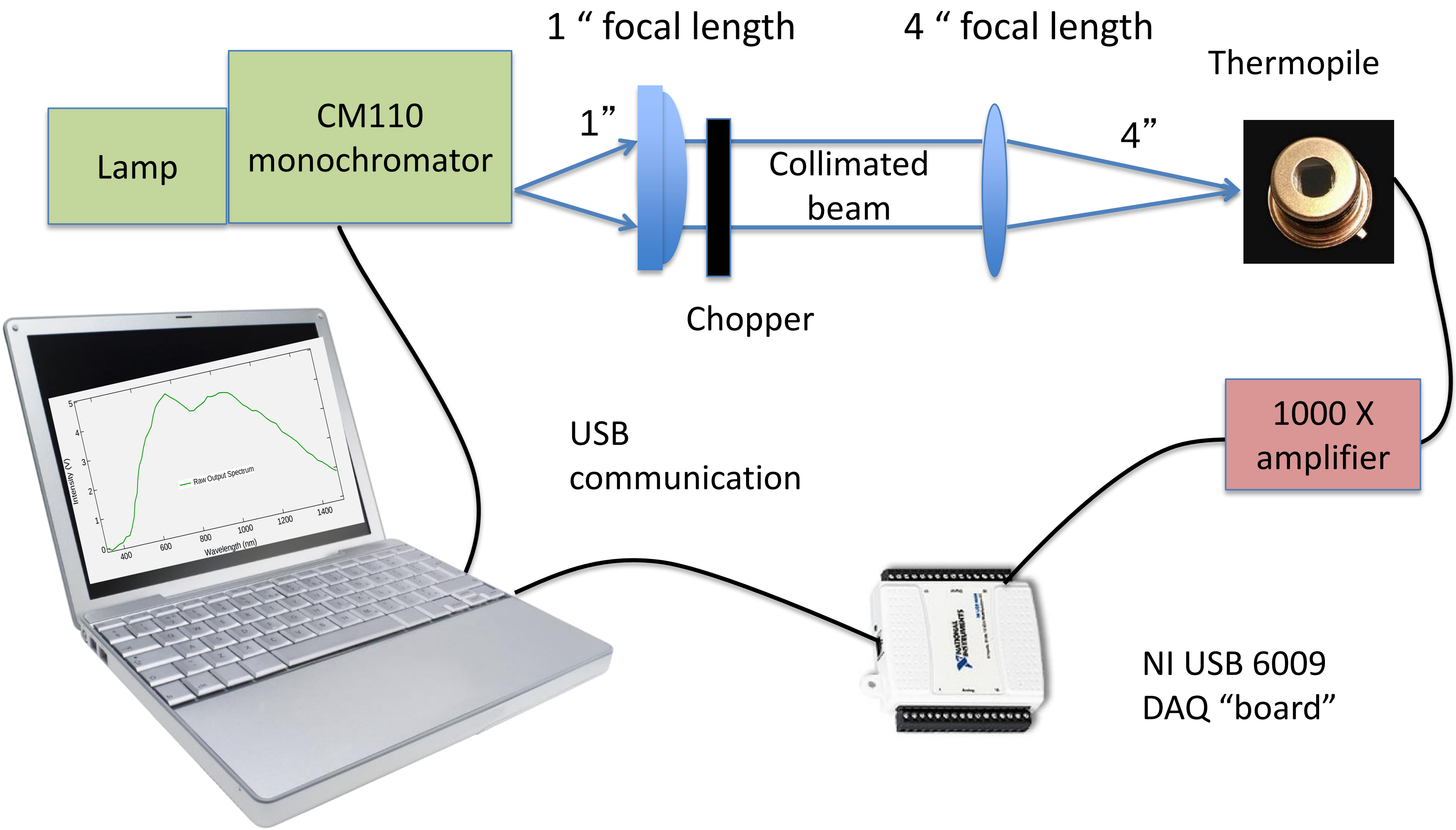
- Experimental determination of the output spectrum by "direct measurement":
- Iterative adjustment of wavelength and signal amplitude measurement using LabVIEW and DAQ
- Conversion from Watts to photons/s
- Effect of slit width on signal amplitude and spectral bandwidth



Lab #1: response time of the thermopile (at one wavelength)



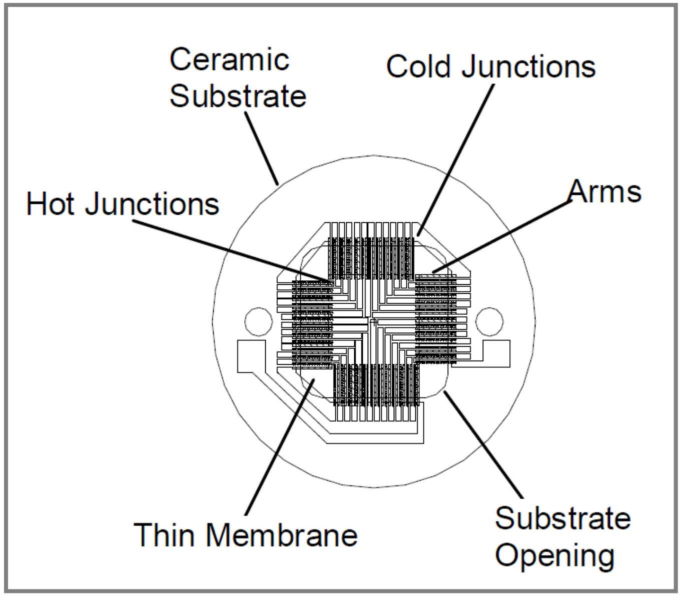
Lab #2: spectral distribution of power in illumination spectrum



Thermopile Detector: Physical Basis

Dexter 2M (thin film type)

A thermopile detector is an electronic device that converts thermal energy into an electrical potential (voltage). In our case, the detector is composed of several thermocouples connected in series as "differential pairs":

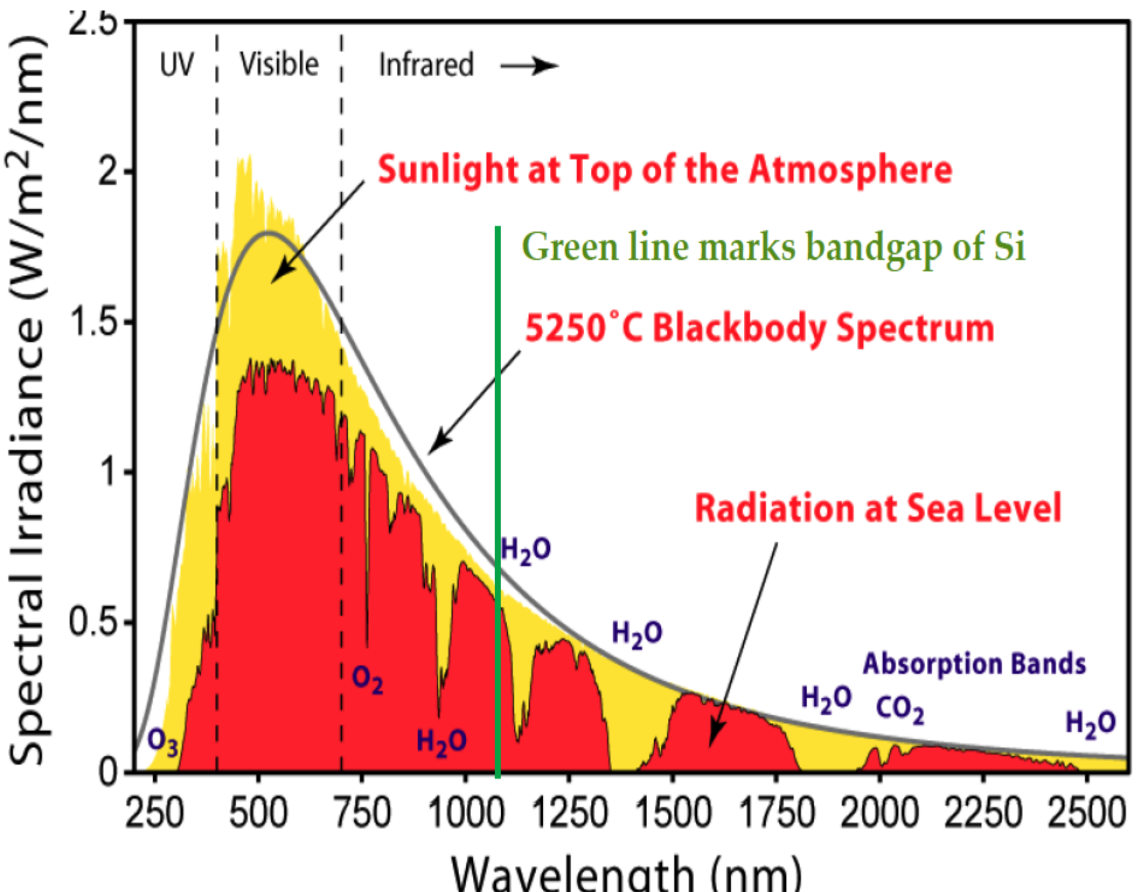


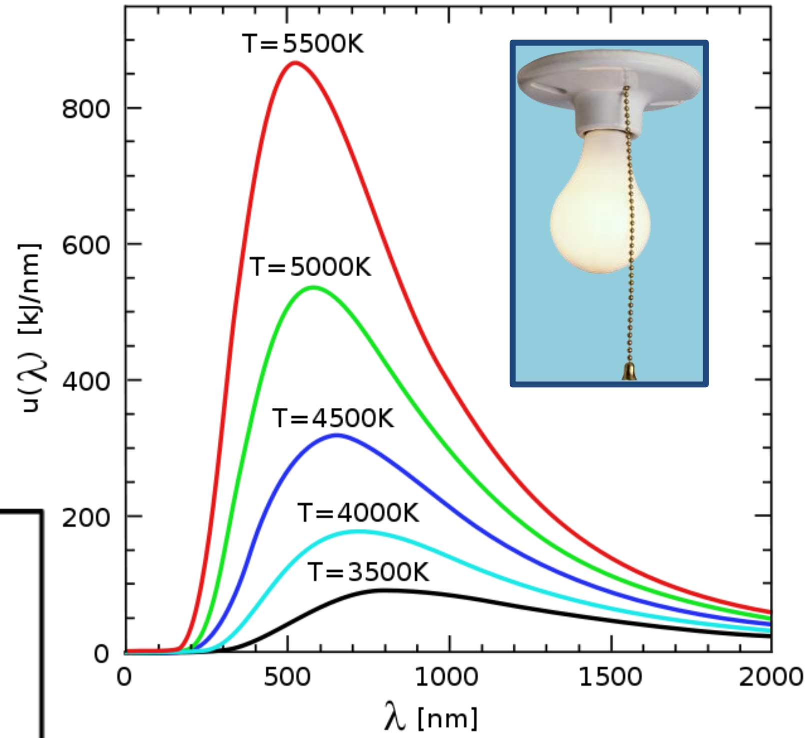
From the .pdf file linked above: "*These differential pairs make up the cold junctions and the hot junctions (see figure). In fact, the hot and cold junctions are connected by alternating n-type and p-type materials, called "Arms", creating a* ***Seebeck effect*** *between the junctions. A voltage is produced, proportional to the temperature gradient between the hot and cold junctions. For Thin Film based thermopiles, the arm materials are antimony (Sb) and bismuth (Bi).*"

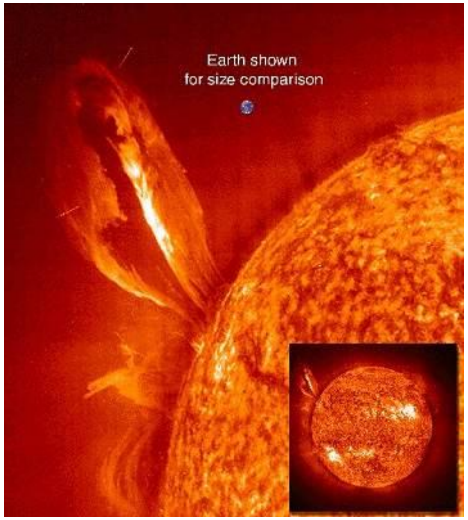
The Seebeck effect is a "thermoelectric effect": "In 1821, Thomas Johann Seebeck (1770-1831), a German scientist, discovered that a small electric current will flow in a closed circuit composed of two dissimilar metallic conductors when their junctions are kept at different temperatures." The emf (i.e., the voltage) varies as $V_{emf} = -S_{AB}\Delta T_{AB}$

http://scholar.lib.vt.edu/theses/available/etd-8497-205315/unrestricted/chap2.pdf

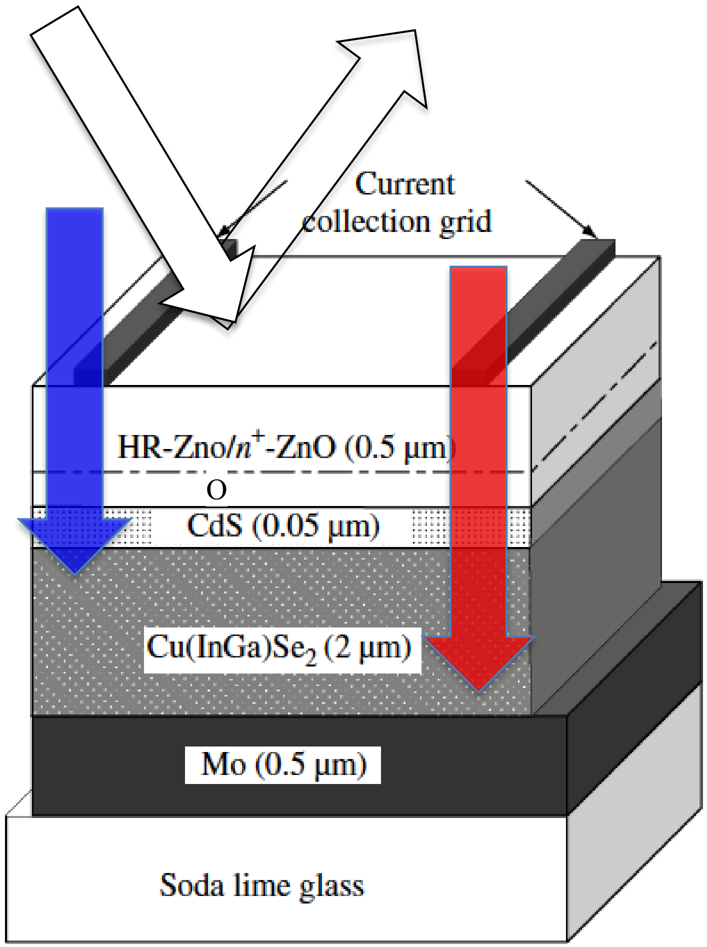
Our Sun, and other Blackbody light sources, emit more than one wavelength of light.

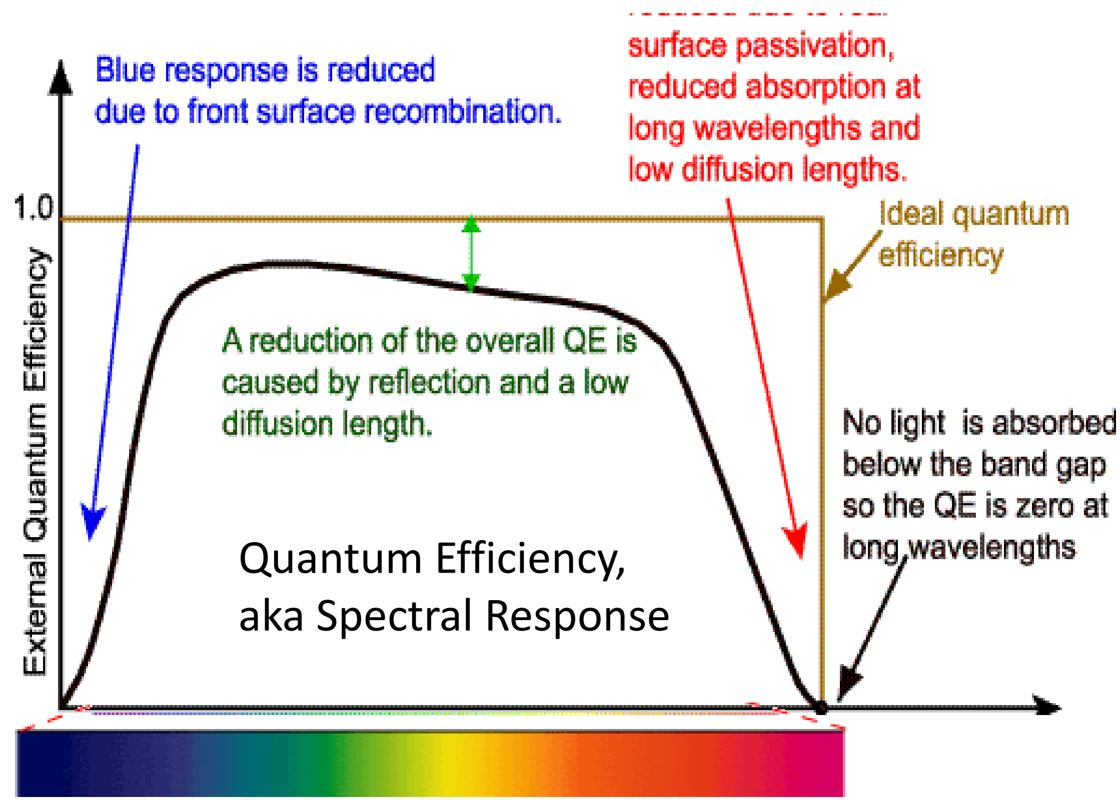






Wavelength Dependent Response of PV Materials and Devices





Schematic cross section of a typical $Cu(InGa)Se_2$ solar cell

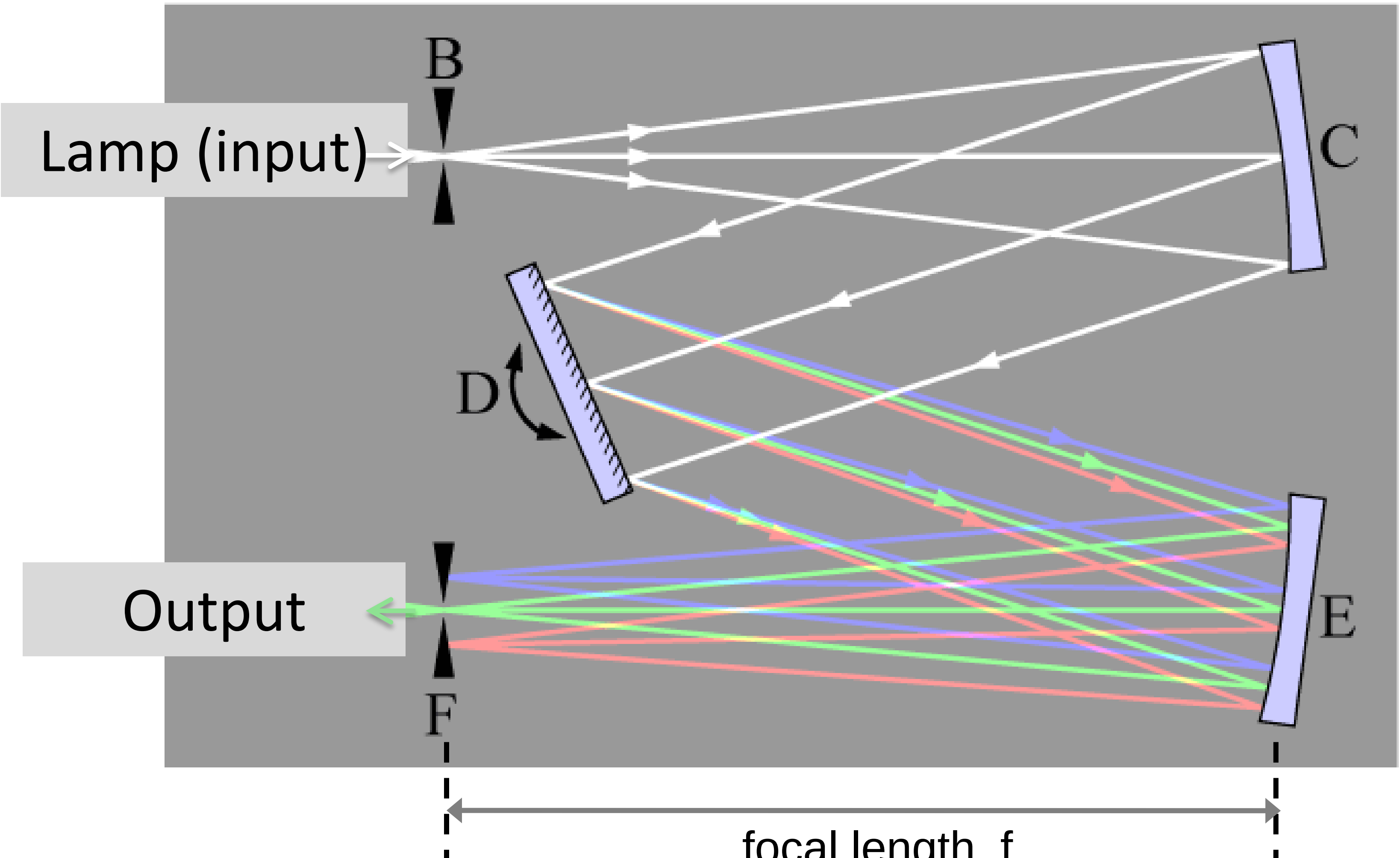
From "$Cu(InGa)Se_2$ Solar Cells", by Shafarman and Stolt and *PVEducation.org*

Spectral Products, CM110 1/8th meter monochromator

Feature	Value
Design:	Czerny-Turner, dual-grating turrets
Focal Length:	110mm
f/#:	3.9
Beam Path:	Straight through standard, right angle provided on request.
Wavelength Drive:	Worm and wheel with microprocessor control and anti-backlash gearing. Bi-directional. Usable in positive or negative grating orders.
Wavelength Precision:	0.2nm
Wavelength Accuracy:	± 0.6nm
Slewing Speed:	>100nm/second
Stray Light:	$<10^{-5}$
Slits:	Standard Set includes; 0.125mm, 0.15mm, 0.30mm, 0.6mm, 1.2mm and 2.4mm x 4.0mm. For other sizes, consult SP.
Max Resolution:	<1nm w/1200G/mm grating and standard slits
Gratings:	One to two gratings. (30 x 30mm) must be purchased. See Appendix A for options
Software:	Demonstration control program and LabView driver included.
Power:	UL listed 110/220V power pack
Interface:	RS232 standard
Warranty:	One year
Options:	• Hand-held control module with function keys and display for local control • IEEE-488 interface • Interface cables • Gold optics See options and accessories

Serial commands sent from computer to CM110 via USB, using LabVIEW.

Czerny-Turner Monochromator



Reciprocal Linear Dispersion (RLD)

Light dispersed at the output slit of the monochromator will show a linear dispersion of wavelengths with position across the slit.

Notice that when you are using the largest 2.4 mm slits, that when you set the monochromator wavelength to 500 nm, the output looks more blue on one end (shorter wavelengths), and more yellow on the other side (longer wavelengths).

For the CM 110 monochromator, the RLD is 6.52 nm/mm.

Therefore, when using the 0.15 mm slits, the spectral band pass of the CM 110 is:

$$\Delta\lambda = (6.52\ nm/mm) * 0.15\ mm = 0.978\ nm$$

Lab 2.5 (Spectral Measurement Using LIA) -- Steps

- Measure and characterize the lamp/monochromator output *using the lock-in amplifier (LIA)*;
- Correct the spectrum for the diffraction grating efficiency vs. wavelength;
- Convert spectrum amplitude from Volts to Watts, and then to photons/sec;
- Determine the peak wavelength and use Wien’s Law to estimate the corresponding lamp temperature in Kelvin.

Lock-In Amplification

Why Use a Lock-In? (simplified, from SRS Application Note #3)
Consider an example -- we have a 10 nV sine wave at 10 kHz (some amplification is clearly required to bring the signal above the noise). A good low-noise amplifier of gain = 1000x will yield a signal amplitude of 10 µV, but the noise will be about 1.6 mV.

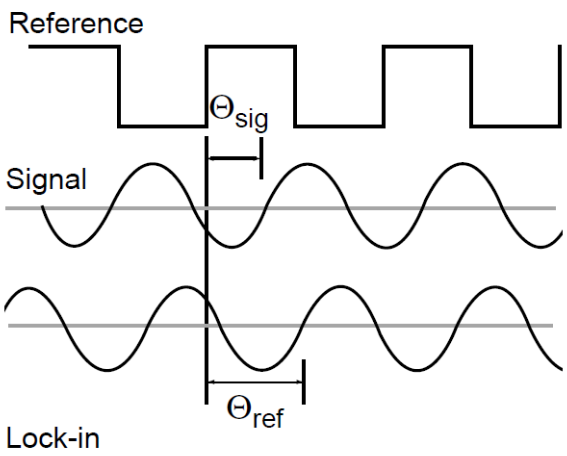
Can we measure that signal?

Not unless we can single out the frequency of interest.

Using a band pass filter with a Q=100 (a VERY good filter) centered at 10 kHz, any signal in a 100 Hz bandwidth will be detected (10 kHz/Q). The noise in the filter pass band will be 50 µV, and the signal will still be 10 µV. The output noise is much greater than the signal, and an accurate measurement can not be made. Further gain will not help the signal-to-noise problem.

Lock-In Amplification (cont.)

Phase-Sensitive Detection ([SRS Application Note #3])



Lock-in measurements require a frequency reference. The experiment will include a signal modulated at a fixed frequency, with a reference signal also available to the LIA. The signal is $V_{sig} \sin(\omega_r t + \theta_{sig})$ where V_{sig} is the signal amplitude, ω_r is the signal frequency, and θ_{sig} is the signal's phase.

LIA's generate their own internal reference signal based on the external reference. In the diagram, the external reference, the lock-in's reference, and the signal are all shown. The internal reference is $V_L \sin(\omega_L t + \theta_{ref})$.

The lock-in amplifies the signal and multiplies it by the lock-in reference; the output of is simply the product of two sine waves:

$$V_{psd} = V_{sig} V_L \sin(\omega_r t + \theta_{sig}) \sin(\omega_L t + \theta_{ref})$$

$$= \tfrac{1}{2} V_{sig} V_L \cos([\omega_r - \omega_L]t + \theta_{sig} - \theta_{ref}) - \tfrac{1}{2} V_{sig} V_L \cos([\omega_r + \omega_L]t + \theta_{sig} + \theta_{ref})$$

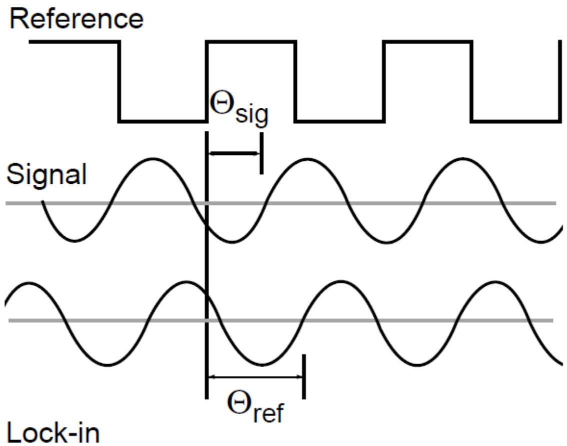
Lock-In Amplification (cont.)

Phase-Sensitive Detection (SRS Application Note #3)

$$V_{psd} = V_{sig}V_L\sin(\omega_r t + \theta_{sig})\sin(\omega_L t + \theta_{ref})$$

$$= \tfrac{1}{2}V_{sig}V_L\cos([\omega_r - \omega_L]t + \theta_{sig} - \theta_{ref}) - \tfrac{1}{2}V_{sig}V_L\cos([\omega_r + \omega_L]t + \theta_{sig} + \theta_{ref})$$

$$\sin(mx)\sin(nx) = \frac{1}{2}\left[\cos(m-n)x - \cos(m+n)x\right],$$



The Phase Sensitive Detector (PSD) output is two AC signals, one at the difference frequency ($\omega_r - \omega_L$) and the other at the sum frequency ($\omega_r + \omega_L$). Passing the PSD output through a low pass filter removes the AC signals. What's left? In general, nothing. However, if ω_r equals ω_L, the difference frequency component will be a DC signal. The filtered PSD output will be:

$V_{psd} = \tfrac{1}{2}V_{sig}V_L\cos(\theta_{sig} - \theta_{ref})$

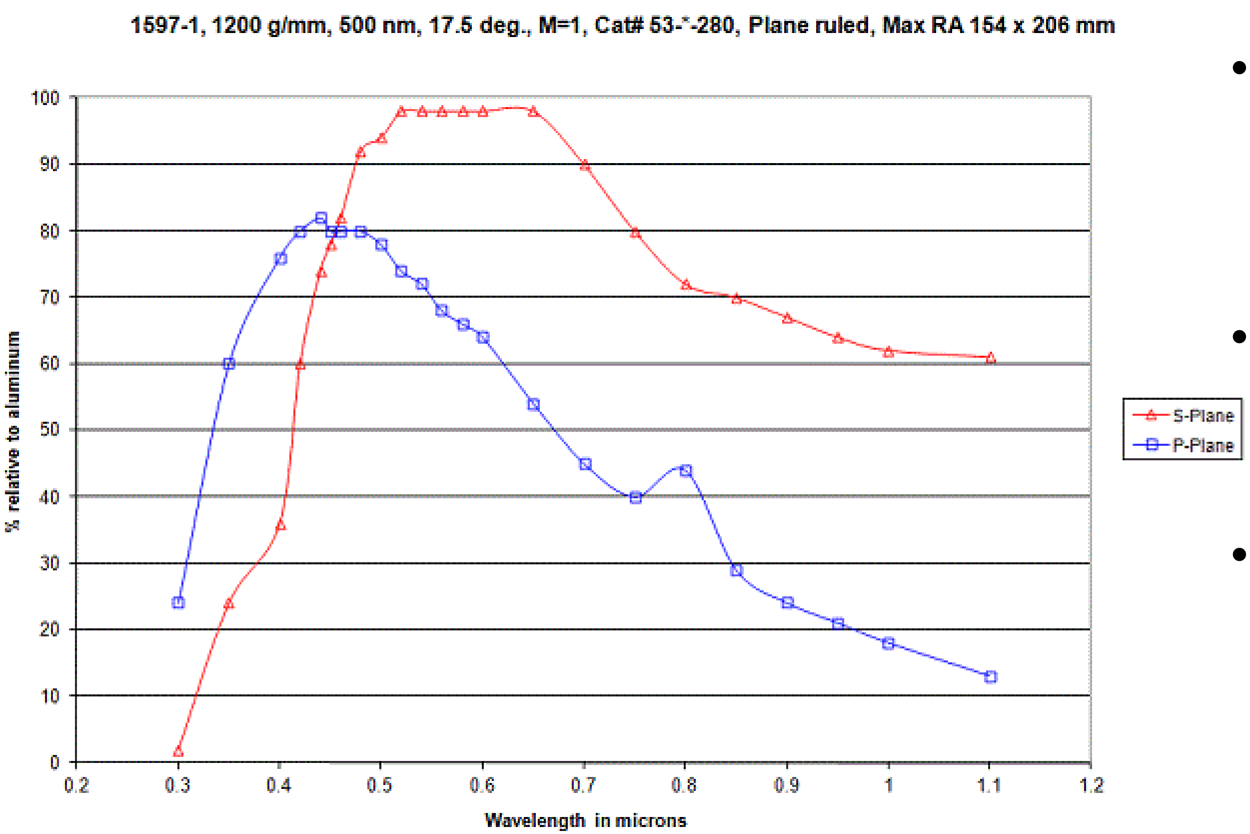
This is a very nice signal -- it is a DC signal proportional to the signal amplitude.

Note that noise will in general not occur at the same frequency; noise close to the reference frequency results in very low frequency AC outputs from the PSD ($|\omega_{noise} - \omega_{ref}|$ is small). Only the signal at the reference frequency will result in a true DC output and be unaffected by the low pass filter. This is the signal we want to measure.

DIFFRACTION GRATING SPECIFICATION SHEET

Catalog no.	**53-*-280R**		8/27/2013
Grating Description	1200 g/mm plane ruled reflection grating with 17.5° nominal blaze angle		
Master no.	1597		
	Maximum Ruled Area:	groove length:	154 mm
		ruled width:	206 mm

Efficiency Curve	spectral order:	m = 1	polarization(s):	S and P
	Coating:	aluminum		
Remarks				



Diffraction Grating Efficiency and Concepts

- **Groove Density**
  determines the dispersion since diffraction angle depends upon the value d (distance between grooves)
- **Blaze Wavelength**
  determines the wavelength of light for which the diffraction efficiency is maximized
- **Linear Dispersion**
  The dispersion of the spectrum at the exit slit, in terms of nm (of spectral content) per mm (of slit width).

Diffraction Grating Efficiency and Concepts

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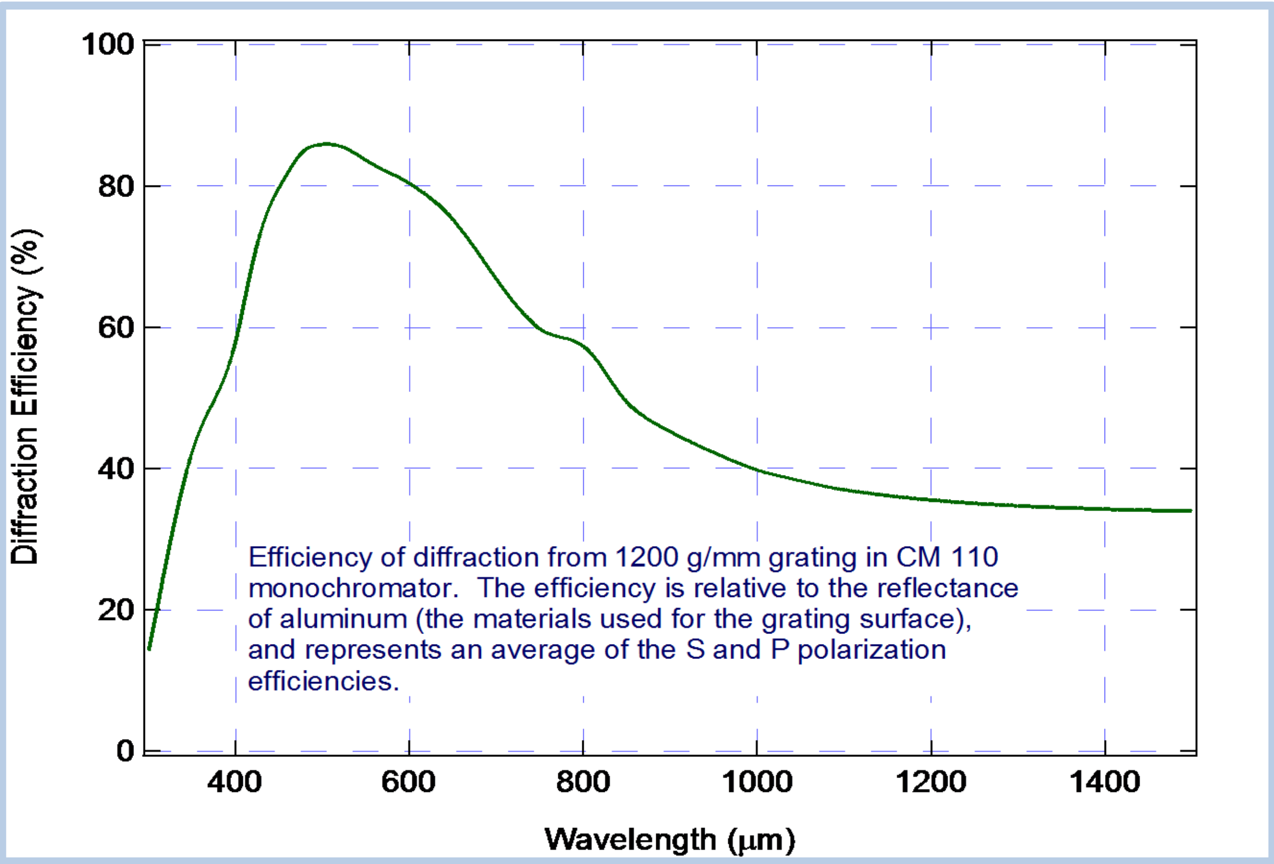

Groove Density

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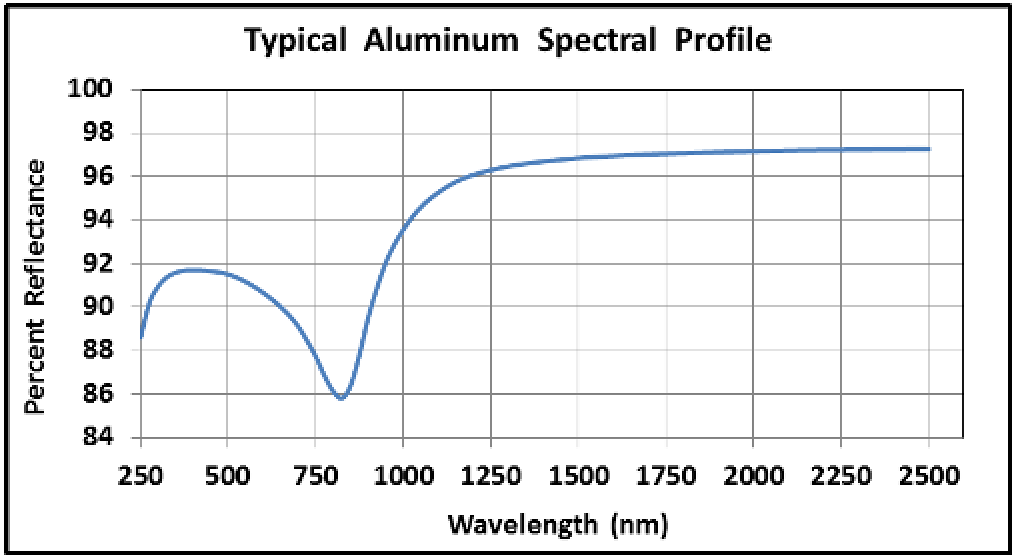
Reflectance of Al



http://opticalreferencelab.com/calibrated-specular-reflectance-standards/

Conversion from Volts to Watts to photons/s

Thermopile detector converts Watts to Volts:

2M Responsivity = 18.9 V/W

So a 1 μV signal *directly from* the 2M corresponds to how many Watts?

Power = $(1 \times 10^{-6}$ V)/(18.9 V/W) = 5.29×10^{-8} W, or 52.9 nW.

How many photons per second are in 52.9 nW ?

Photon rate: 52.9 nW = 52.9×10^{-9} J/s; now divide by the photon energy (500 nm) → (52.9×10^{-9} J/s)/(hc/500 nm) = 1.33×10^{11} photons/s.

Note that the 1010 amplifier changes things, because it has a gain of 1000x.

A 1 V signal out of the LIA corresponds to how many Watts?

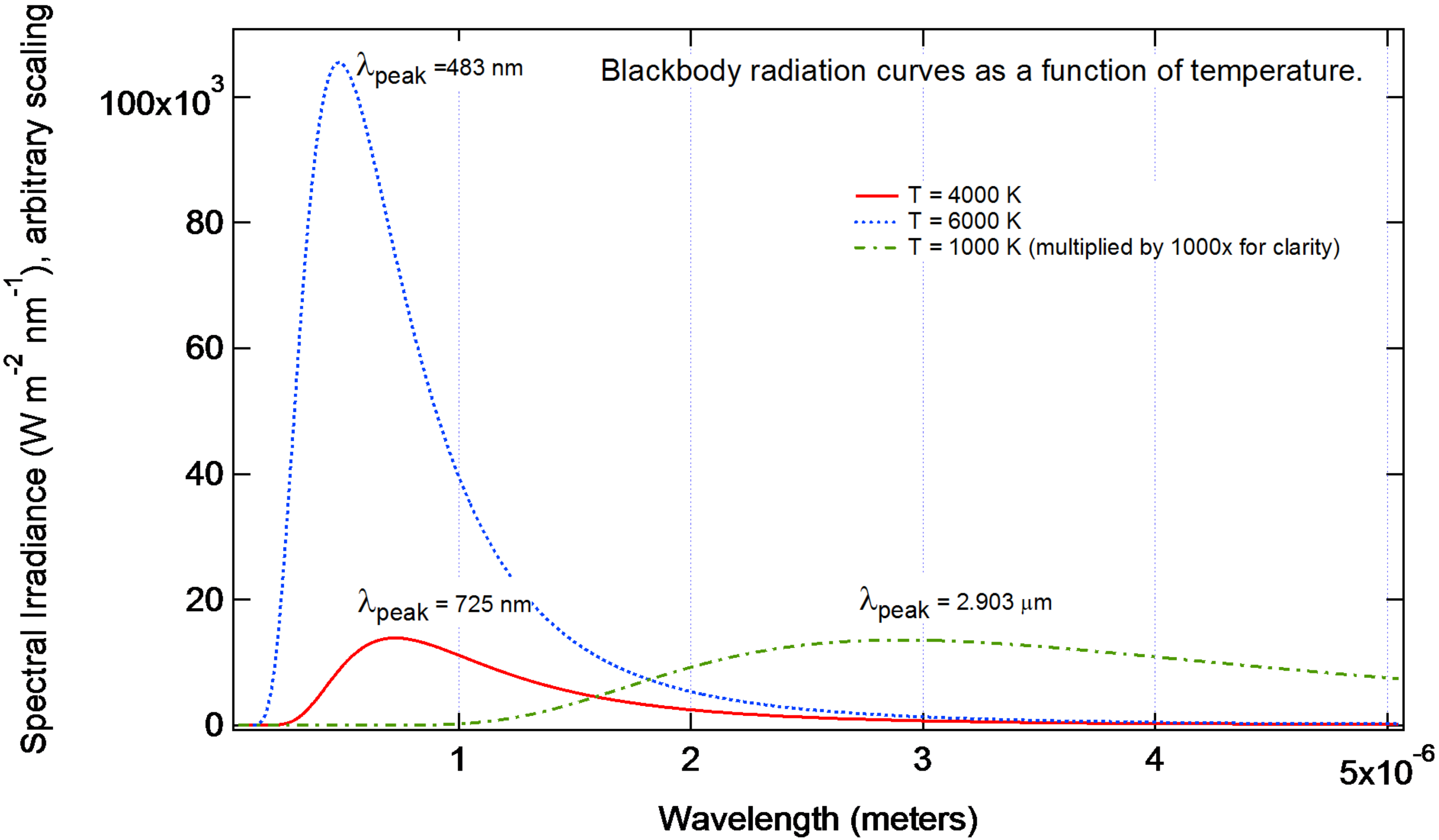
Blackbody Radiation and Wien's Law

Planck's Law, which describes the distribution as a function of frequency or of wavelength of a perfect blackbody radiator at a temperature T (in K), is given by:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(\exp\left(\frac{hc}{\lambda kT}\right) - 1\right)}$$

Analyzing the units, we find: $(J\ s)(m/s)^2(m^{-5})$, which can be expressed as J s^{-1} m^{-2} nm^{-1}, the units commonly used for spectral irradiance.

Blackbody Radiation and Wien's Law



Wien's Displacement Law

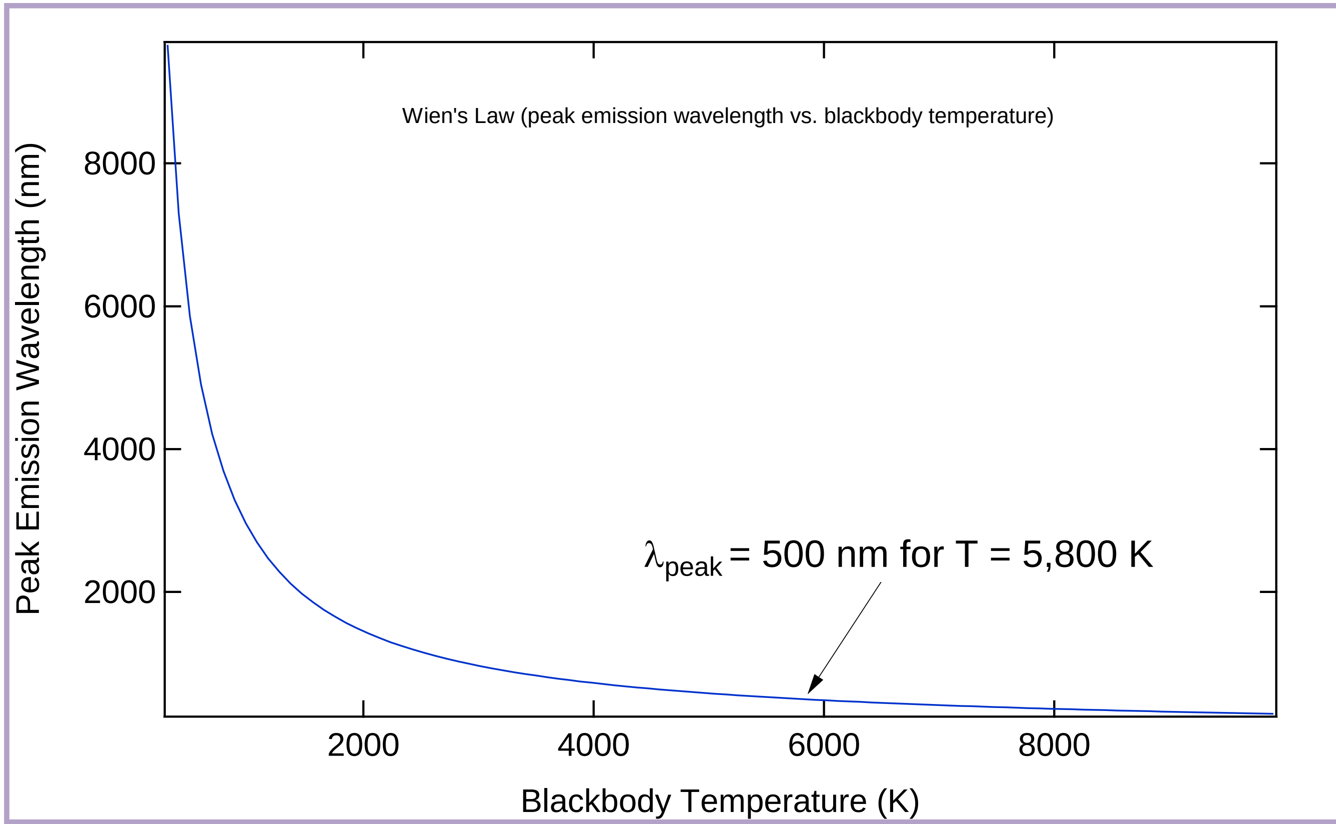
Finding the roots of the derivative of the Planck function allows one to determine the peak wavelength as a function of temperature, also known as Wien's Displacement Law. First, the derivative of Planck's Law, taken as

$$\frac{d}{d\lambda}\left(\frac{A}{\lambda^5\left(\exp\left(B/\lambda\right)-1\right)}\right)=A\left(-5\lambda^{-6}\left(\exp\left(\frac{B}{\lambda}\right)-1\right)^{-1}+B\lambda^{-7}\left(\exp\left(\frac{B}{\lambda}\right)\right)\left(\exp\left(\frac{B}{\lambda}\right)-1\right)^{-2}\right)$$

Setting the derivative vs. λ = 0, and following the derivation provided at http://en.wikipedia.org/wiki/Wien's_displacement_law, one finds that by solving numerically and converting wavelength to nanometers,

$$\lambda_{peak}=\frac{2.8978x10^6\,nm\cdot K}{T}$$

Note that an easier solution was presented by a UT undergrad: taking the log[B(λ, T)] and recognizing that the peak of the log will occur at the same λ as for B(λ), the problem is simplified greatly.



Normalizing Curves in Igor Pro

Normalization refers to adjusting values to a common scale. For example, if you have several spectra, you may wish to plot them all on a y-axis scale from 0 to 1 so that their shapes can be easily compared to one another.

Basically, $y \rightarrow y/y_{maximum}$

Example shown for Igor Pro…