14/14 very nice

Lab 3: Signal Recovery for In-Situ Reflectometry

MAT288S Optoelectronics Measurements

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Introduction:

The thickness of an in-situ film can be estimated from the wavelength with minimum reflectance. In this lab, a tunable wavelength source is created from a tungsten lamp and a monochromator with a built-in chopper as shown in figure 1. The output is directed at the sample under test and the reflection is collected by a photodiode and measured with a lock-in amplifier referenced to the chopper. The system is characterized and the resolution is measured using a known 10nm band-pass interference filter.

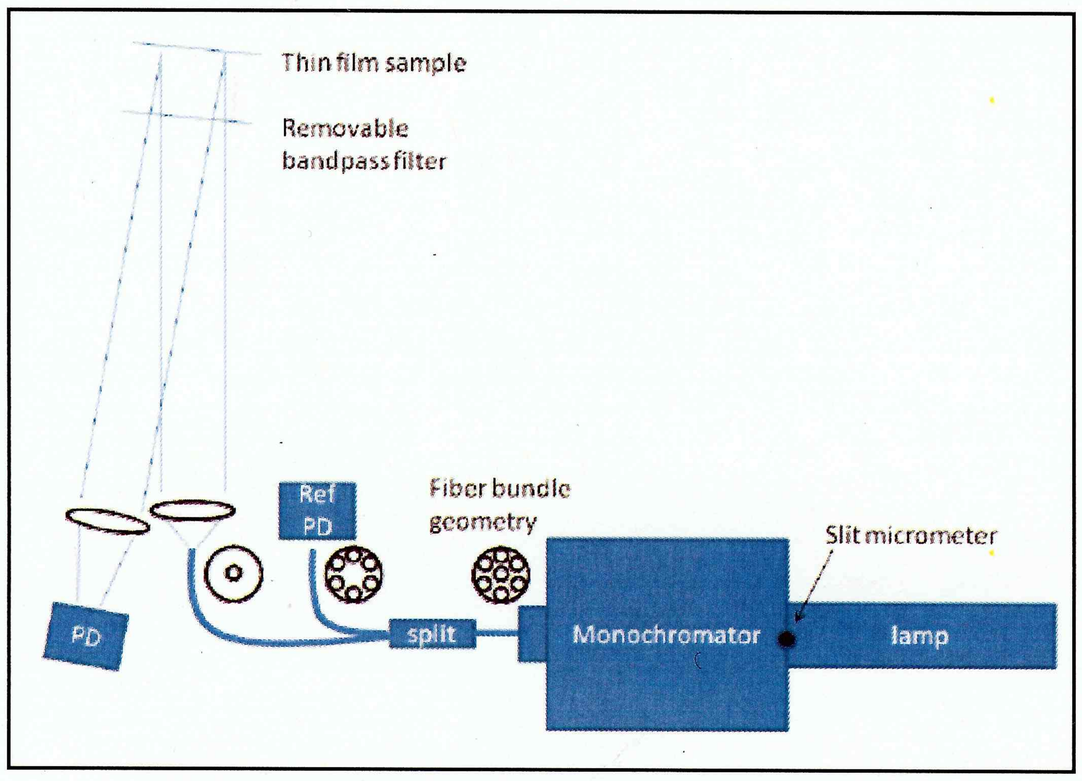


Figure 1: Monochromator testing set-up schematic

Experiments and Discussion:

(1) The chopper frequency was set to 35Hz to avoid the room lights oscillating at 60 and 120Hz while providing an adequate frequency offset from DC to avoid DC noise. The detector was unbiased to reduce noise from dark current since a fast time response was not necessary for the 35Hz signal. +1/1

(2) – (3)

The focal length of the monochromator was measured from the slit opening to the first curved mirror (lens); the output from the curved mirror will ideally have a near infinite focal length therefore the distance from the object (slit) to the curved mirror must be close to the focal length by the lens equation 1/f=1/s1+1/s2, where s2=inf, 1/f=1/s1. The

distance s1 was measured to be 20cm, which makes the focal length ~20cm. The f/# of the monochromator was measured from the clear aperture of the curved mirror (lens) and the focal length using f/#=f/clear_aperture=20cm/5cm=4. There was very little stray light inside the monochromator indicating that the monochromator f/# ≤ illumination f/#. If the illumination f/# is larger than the monochromator we will realize a loss in power throughput, but no stray light will be generated. +2

By adjusting the distance from the lamp to the slit, we found the minimum spot size at a distance of 15cm from the lamp condenser lens. The lamp lens had a diameter of ~3.8cm, and is set ~6cm from the bulb. We calculated the focal length of the condenser lens from: 1/f=1/s1+s/s2=1/15+1/6, therefore f=4.3cm and the f/#=4.3cm/4cm=1.1. Therefore, the f/# of the condenser was smaller than the monochromator which will cause some scattered light inside the monochromator and add noise to the measurement. We want to avoid this.

To match the illumination f/# to the monochromator f/#, a lens with f=100mm and clear aperture=25mm was placed in front of the condenser as shown in figure 2. The focus on the condenser was set as long as possible to produce near-collimated light at the condenser output. The added lens was completely filled by the condenser output and the lens was set at ~12cm from the slit such that the min. beam waist occurred at the slit. The lens has an f/# of 100mm/25mm=4, which allows us to match the illumination f/# to the monochromator f/#. This f/# matching was used for parts (A)-(C), but showed no improvement in resolution when testing for (D) so results from (D) and (E) do not use the matching optic.

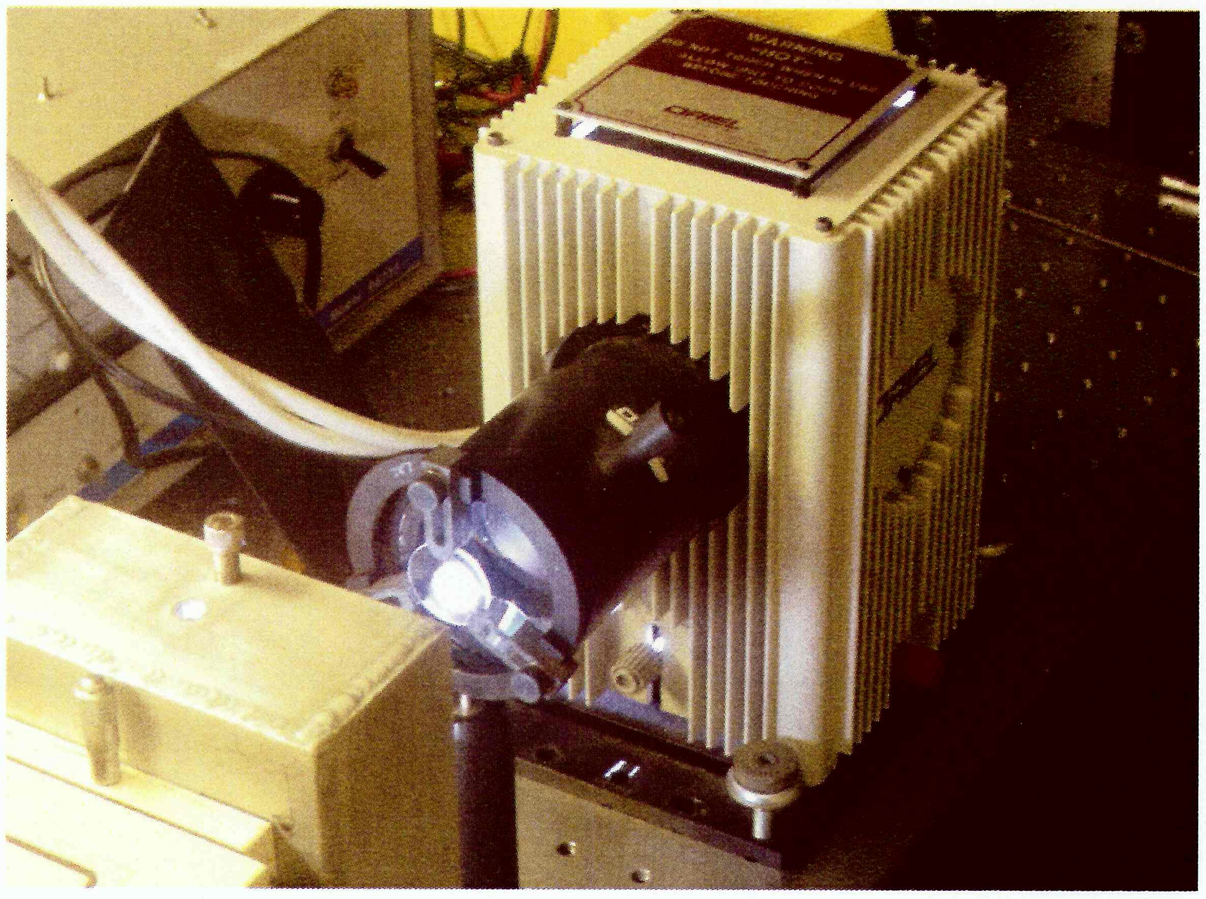


Figure 2: Matching optics used to set illum. f/# to monochromator f/#

(4) –(9)

The 600l/mm grating shows 4 orders with the last one very dim and only the green was clearly recognizable with the lights off. The first order had the least linear dispersion and

all of the colors are close together giving a color smearing appearance when observing the output of the grating diffraction. The 2nd order had much clearer lines for each color and had a larger linear dispersion. The 1200l/mm grating had only 2 orders which have more linear dispersion than the 600l/mm grating. For this experiment, the second order of the 600l/mm grating was chosen to give good throughput (higher than the 2nd order of 1200l/mm) and good resolution (better than the 1st order of the 600l/mm). +1/1

(10)

A. The aluminum mirror was placed in front of the interference filter to measure the un-normalized monochromator spectrum. The R value on the lock-in was recorded as a function of wavelength as shown in figure 3. There was no correction for the silicon photodetector's quantum efficiency (QE) variation between 400 and 700nm in this plot. We made a QE correction (QE=R*hv/q) to look at the monochromator response only without the added PD response as shown in figure 2, the PD responsivity was assumed to vary from ~0.1 to 0.8 A/W and the photon energy varies from 3 to 1.8eV over the 400-700nm range. +2

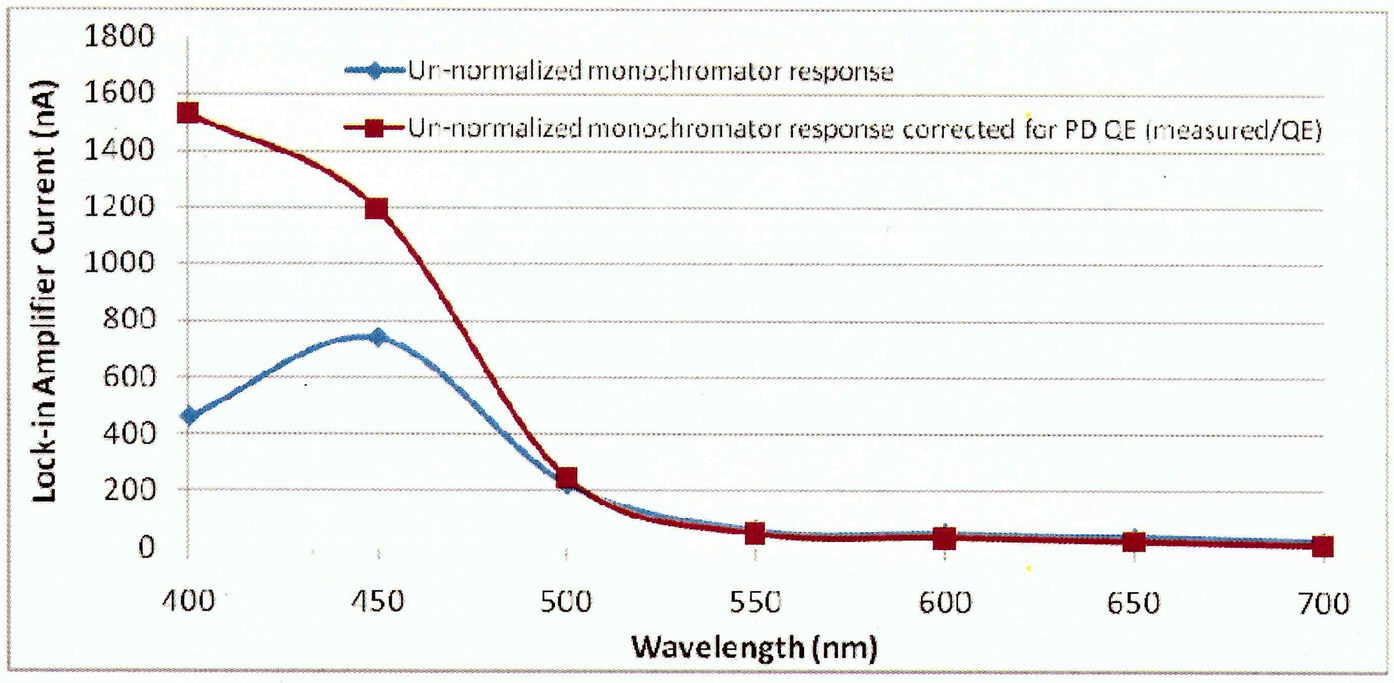


Figure 3: Un-normalized monochromator spectrum and response w/PD QE correction

B. The input slit width was varied and the un-normalized LIA current was recorded at 450nm set on the monochromator as shown in figure 4. The output slit width was determined by the central fiber bundle diameter attached to the monochromator. The fiber had a diameter of 400 microns. Therefore an input slit of ~400 microns was ideal to match the image size at the monochromator input to the image size at its output. When the input slit was smaller than the output slit, the output slit area (A_out) was only filled by the size of the input split (A_in). The measured relationship between the LIA response and slit width was linear from 100-400µm as we would expect.

$$throughput \propto \frac{A_{input_{slit}}}{A_{output_{slit}}},\ for\ A_{input} > A_{output},\ \text{where}\ \Omega_{input} = \Omega_{monochrom.}$$

The f/#'s (solid angles) of the monochromator and the light source have already been matched, so as the area of the slit is increased the throughput increases proportionally. The height of the input slit is fixed at a few cm's, and only the width is adjusted, therefore throughput ∝ slit width.

Once the input slit width is equal to the output slit we might expect the throughput to saturate since the image at the output increases outside the light area captured. However as shown by figure 4, the throughput continues to increase linearly without saturation. Our previous expectation was wrong as it was based on a fixed resolution monochromator. As shown by figure 5, given three near-monochromatic tones (red, green, and blue) the throughput will continue to increase linearly due to resolution degradation as the input slit is increased. Due to reduced monochromator resolution and color overlap as the input slit is increased, a linear relationship between input slit size and throughput is predicted (assuming the input slit is illuminated by a larger uniform spot size). +2

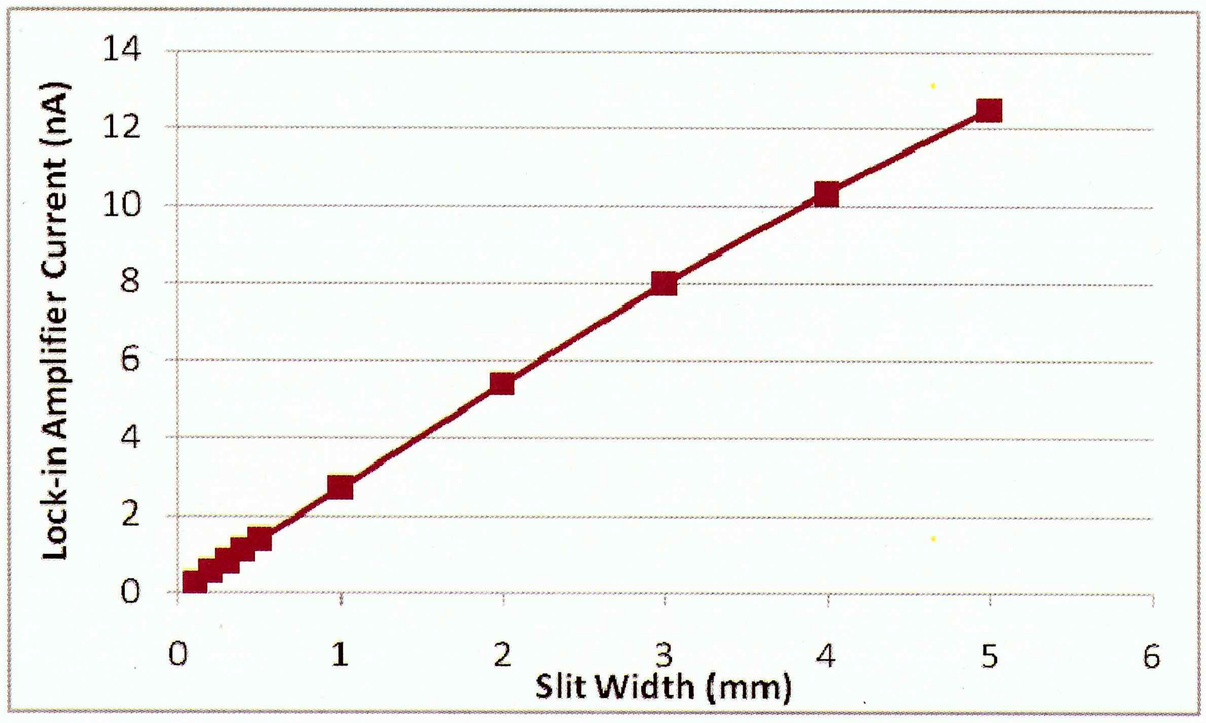


Figure 4: Un-normalized monochromator response vs. slit width (450 nm)

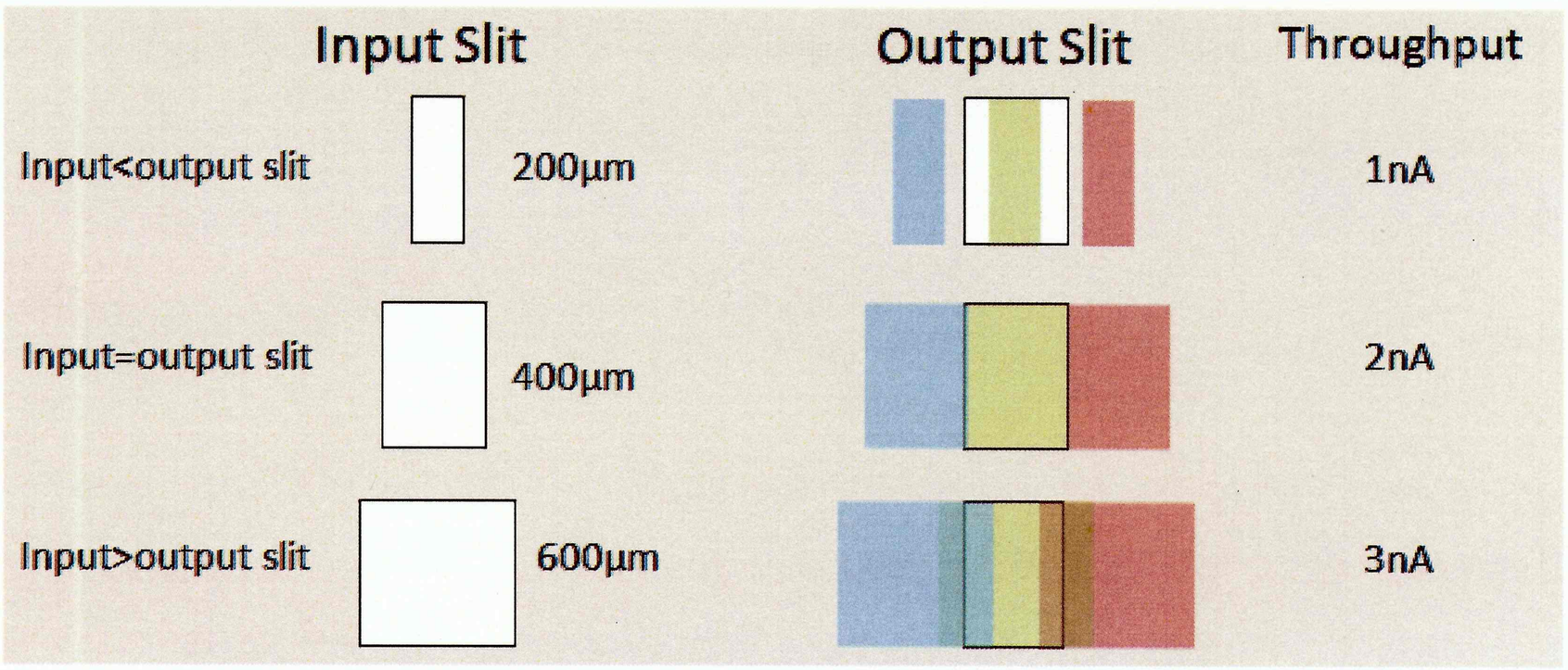
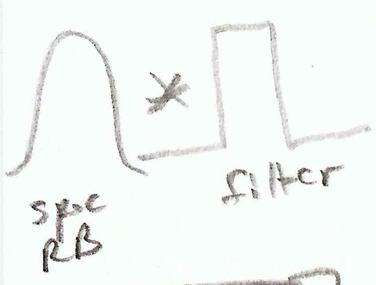


Figure 5: Three slit widths and corresponding throughput example

C. The normalization required a stable reference input on the auxiliary channel of the LIA. There was added phase noise in the reference channel due to it going through the PD transimpedance amp. and then into the LIA. This made the reference channel unstable at lower chopping rates, but the reference was more stable above 160Hz. The chopper was set to 190Hz which provided a very stable reference signal with <5% variation. The normalized signal was well behaved over part of working range 400-700nm, but some adjustment had to be made to accommodate the span of the reference transimpedance amplifier (TIA). The TIA output voltage was consistent from 200-2000nA PD input, but the output restarts at zero for the next span 2uA-20uA. This required that all normalization measurements were consistent within one span of the reference TIA. This was easily achieve by scanning first 400-500nm (200-2000nA on TIA), and then scanning 500-700nm (2uA-20uA on TIA) and correlating the two 500nm point on the LIA to correct for this discontinuity. Accounting for this discontinuity, the 400-700nm span of the normalized signal was well behaved and consistent. +2

D. A 10nm interference filter centered at 633nm was used to calculate the resolution of the monochromator. The minimum reflection from the filter was measured to determine where the maximum transmission occurred. Then the steady state values outside of the filter transmission bandwidth were measured to determine the maximum reflection. The half-way point between the maximum and minimum transmission corresponded to the filter's 3dB bandwidth. This 3dB bandwidth was measured to be 35nm for a 400µm input slit on the 2nd order of the 600l/mm grating as shown in figure 6; this corresponds to a 25nm resolution as the actual filter bandwidth plus the resolution determines the measured 3dB bandwidth (25+10=35nm). The 3dB bandwidth was also measured for a 50µm fiber with a 50µm input slit to be 18nm, which corresponds to a resolution of 8nm. +2

more precisely



$\approx \sqrt{RB^2+10^2} = 35$

$RB = \sqrt{35^2-10^2}$

$= 33nm$

The calculated dispersion is at worst (the actual $\theta_d \sim 5-10^o$ from measurements but we will assume $\cos(\theta_d)$=1 to find the worst dispersion possible):

$$lin.\,disp. = \frac{mf}{\text{acos}(\theta_d)} = \frac{2x20cm}{\frac{1.67\mu m}{line} * \cos(0)} = 2.39 * 10^5$$

We can now calculate the worst-case resolution:

$$resolution = \frac{slit\ width}{\text{lin.disp.}} = \frac{400\mu m}{2.39*10^5} = 1.67nm$$

The calculated "worst case" resolution is much better than the measured resolution. The optics inside the monochromator appear to the limiting the achievable resolution due to possible scattering off the curved mirrors and optical aberrations due to axially asymmetric optics; these were difficult to measure and quantify but seem likely based on consistent resolution degradation through variations of the

input light source and output fiber size leaving only the monochromator optics and grating as the constant. The resolution improvement going from 400µm to 50µm should have been a factor of 8, instead it was only 3; this reduction in resolution improvement as we go from the 400 to 50µm fiber indicates that the monochromator optics have their own resolution limitation.

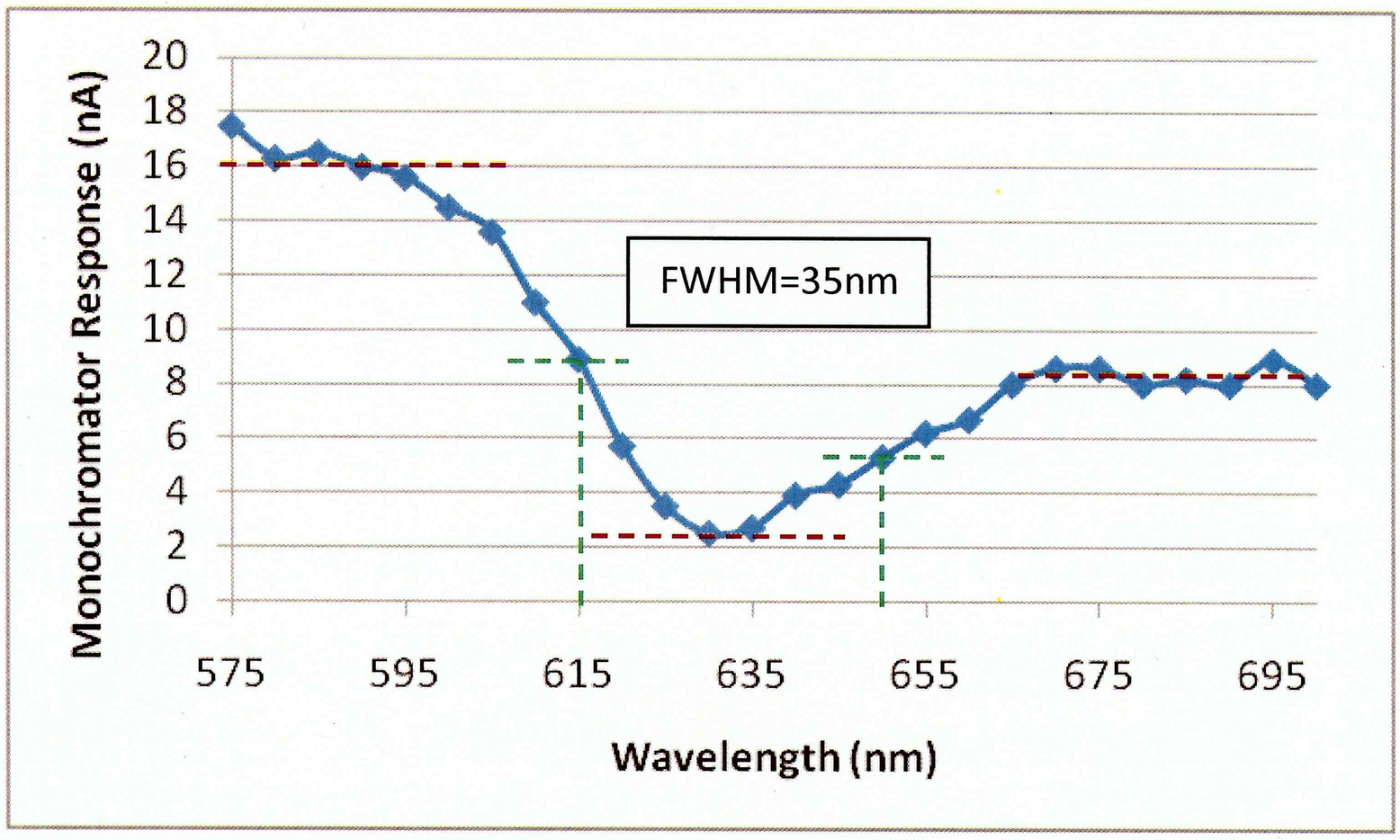


Figure 6: 10nm interference filter response vs. wavelength

E. We used the normalized response to search for a minimum reflectivity from the sample under test. The response of the monochromator was gradual around the minimum due to its large resolution. The minimum reflection point was estimated to be ~640-650nm. This corresponds to a quarter wave thickness of the film. Given the m-order=1, we can calculate nd=3*lambda/4=3*645nm/4=484nm, therefore the film thickness d=484nm/1.45=334nm. +2

$(m+1)\lambda/4$

0, 1, 2, ... not the same as the grating order. Actual film: m=0

d ~ 101 nm