Surface Plasmon Resonance (SPR) Lab

Student Version

Advanced Experimental Physics Lab
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Background

Plasmonics is the field of study and the fabrication of applications which utilize plasmons. Plasmons can be used as sensitive biosensors, thin film metrology tools, in imaging and detection enhancement techniques, temperature and pressure measuring probes, as well as many other applications. The advantage of using plasmons in a resonance condition is the extreme sensitivity over many other techniques available. By utilizing resonant plasmons in the biological field one can measure antigen binding down to the femto-molar concentration level, detection of single molecules using Raman spectroscopy, or allow imaging resolutions far below the diffraction limit, amongst many other milestones. The phenomena can be modeled utilizing many techniques available on basic home type computers.

The theory demonstrated here will allow the student to model the phenomena of light reflecting from a special metal-coated prism to see the effect of resonance. If the coating is done correctly and the optical setup properly put together, a laser will shine into a prism, and when rotated such that the light enters just beyond the critical angle, the reflected light will simply disappear into the prism, giving no transmitted or reflected light to be seen. The energy of the light will be dissipated into heat through driving charge along the metal air surface, and the light will not be reflected. Utilizing a classical theory for electrons alone, this phenomenon can be predicted.

Plasmons

Plasmons are a quantized collective oscillation of electrons; there are different types of plasmons;

- **Bulk Plasmons –** longitudinal oscillations of volume charge density.
- **Particle Plasmons –** oscillation of electrons in a small nanoscale object, such as a nanoparticle, nanowire ,etc.., Mie Scattering of metallic nanoparticles is a phenomenon based on this process of electrons bound to a small object and resonantly oscillating due to the geometrical constraints of the shape.
- **Surface Plasmon** – an oscillation of electrons confined to an interface, these can be generated with electrons or light, the concept of Surface Plasmon Resonance (SPR) comes into play when one refers to a very good coupling of electrons or light into driving the charge at the interface.

This lab focuses on the optical generation and modeling of Surface Plasmons, in particular the attempt of predicting and generating a resonance condition in a three layer system; glass, metal and air. The lab is designed to easily create a film and test it's resonance with minimal cost and time to prepare the setup between testing. This concept can be demonstrated in a more elaborate setup, but is not necessary unless this demonstration will be used as a research instrument afterwards. This lab is comprised of four main parts:

1. Understanding the theory of SPR, through deriving the Fresnel equations from Maxwell Equations.
2. Determining the optimal conditions for the Prism Coating (Modeling).
3. Fabricating the coated prism with a deposition system.
4. Comparing modeling and experiment, explain error.

Equipment List

Many different variations exist for this demonstration. The setup can range from the simple as shown here or the more advanced using a CCD for readout and calibration of intensity and angle of reflectance. Access to certain analytical and preparation tools is necessary if the thin film deposition process is being carried out by the student. The prism and or microscope slides can be ordered from many companies, but at a price. In contrast to Au coatings, Ag coatings will give the best SPR signal, but the coating will degrade the fastest, however Au coatings are very stable and normally require a 5 nm under layer of Cr or Ti for proper adhesion.

1. Small **Optical Breadboard** (1" or metric hole pattern-1'x2')
2. Small **Polarized Laser** (recommend cylindrical tube HeNe Laser 633 nm - CVI Melles Griot®, etc..)
3. **Beam Expander** (4x to 12x) – can make with two lenses.
4. Adjustable or Non-Adjustable **Slit**
5. Horizontal **sample rotator** with scribed gradient for measuring angle of rotation.
6. **Prism** of a known material (BK7 material recommended) with three polished sides (Hemi-cylindrical rather than right angle prism is recommended – ESCO Products® has made them).Get multiple units.
7. **Microscope slides** or **coverglass slips** to match the Prism (microscope slides made of float glass are similar to BK7 in index of refraction at 633 nm - Corning Microslide #2947).
8. **Index matching oil** for the Prism and microscope slide. Carguille Labs #1074 (index=1.5400).
9. **Misc optical mounting components** (see experimental setup).
10. **Access to a sputter** or **thermal evaporator** with a Ag target or Ag evaporation material (Gold works as well but will be much more expensive.)

11. **Access to an Atomic Force Microscope** (AFM) capable of measuring a sample the size of a microscope slide or coverglass slip.
12. **Access to modeling software** (Matlab®, Python, C#, Fortran, etc…) to model the theoretical reflectance curves.

• SPR Theory

The purpose of this section is to introduce the student to concept of modeling electromagnetic plane waves at interfaces in order to predict reflectances. The method being demonstrated utilizes Fresnel equations. The author has developed effective software to model these equations, however with the use of more modern modeling languages it is recommended that the instructor have the student utilize a programming technique which is appropriate to the program at that institution. Students often have to take courses in Matlab™ or Python as a program requirement and are perfectly suited to perform this task.

Material Parameters

The Fresnel equations are formulas that describe the behavior of light at interfaces between different materials; these equations can be utilized to describe both transparent as well as absorbing materials. A good starting point for describing the photon-material interaction are the optical constants *n* and *k*. The index of refraction, *n*, and the extinction coefficient, k, are used to describe many materials. These variables are normally experimentally determined and can be looked up in available tables[1]. The optical constants are a function of many physical properties, such as temperature, pressure, frequency, thickness, process used to make the material, etc.. We are only concerned with the frequency dependency, ω, hence, *n(ω) and k(ω).* We define the complex optical constant as

$$\tilde{n}(\omega) = n(\omega) + ik(w)\,. \qquad (1)$$

From the frequency dependent optical constants one then can define the complex permittivity (or dielectric function) as

$$\tilde{\varepsilon}(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega), \qquad (2)$$

Where

$$\tilde{\varepsilon}(\omega) = (n(\omega) + ik(w))^2\,, \qquad (3)$$

hence

$$\varepsilon'(\omega) = n^2 - k^2\,, \qquad (4)$$

and

$$\varepsilon''(\omega) = 2nk\ . \tag{5}$$

While from equations (1-5) one notes the dispersive description of materials due to the frequency dependence, do not confuse this with the concept of a material absorbing, this is due to the extinction term. In a nutshell, all materials have

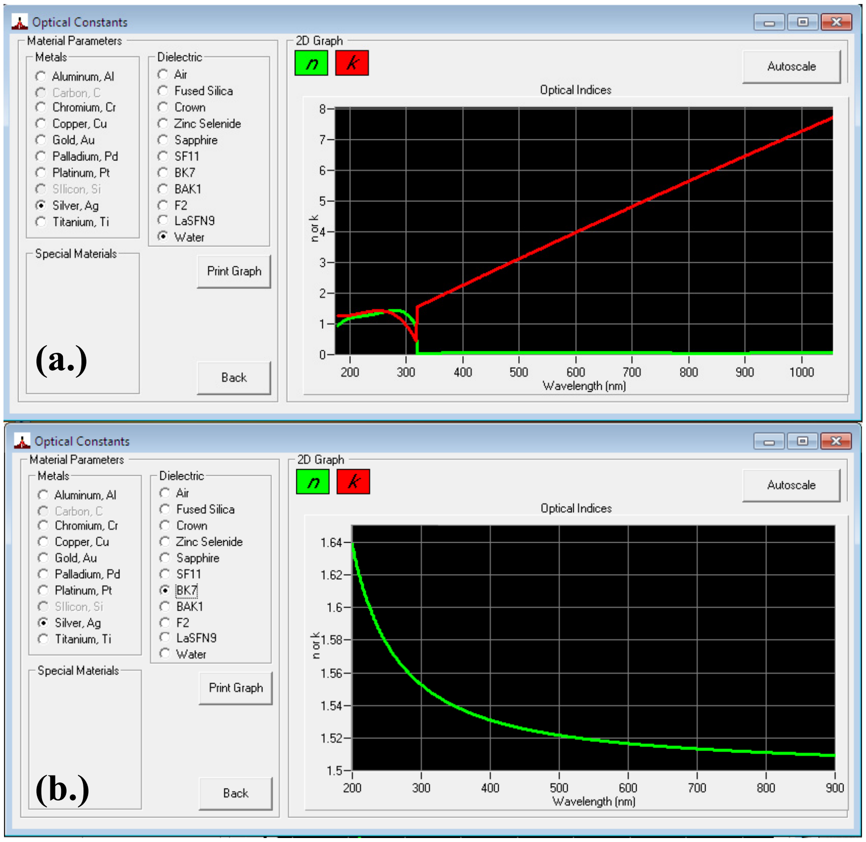

Figure 1, Optical constants, *n* and *k* ,for (a.) silver (Ag) and (b.) optical glass (BK7). Green denotes the real part of the complex index, *n* and red indicates the extinction coefficient, *k*.

some complex index of refraction although ones that absorb light have an additional imaginary term, the extinction coefficient, $k(\omega)$. Figure 1 shows the optical constants for Ag and BK7 glass. These values were extrapolated in cubic polynomials roughly every 100-200 nanometers in order to get the index as a function of frequency across such a large wavelength range. This term is directly used to describe absorption of light, given as the absorption coefficient, α_{abs}, it is defined as

$$\alpha_{abs} = \frac{4\pi k(\omega)}{\lambda}\ . \tag{6}$$

Most researchers are familiar with the concept of glass having an index of refraction of some simple number like 1.5, but when asked about the index of refraction of a metal it is not so obvious. When using light around the visible region, metals have both the real and imaginary term, the latter denoting the material has some degree of absorption. The Fresnel equations utilize the complex permittivity in order to determine the reflectance of light from the Prism/metal film combination.

Plasmons have certain criteria relating to these material parameters in order to be generated in a resonant fashion. Although some of these may interconnect, they are the following;

- $\mathrm{Re}[\tilde{\varepsilon}_{metal}(\omega)]$ must be negative.
- $|\tilde{\varepsilon}_{metal}(\omega)| > |\tilde{\varepsilon}_{air}(\omega)|$.
- The surface plasmon must have a shorter wavelength than the incident photon.
- The Incident field must have a perpendicular component of the wavevector which is perpendicular to the glass-metal-air interface which is imaginary in order to have an evanescent decay.
- For very large wavevectors along the surface, k_x, the frequency of the surface plasmon will go to $\omega_{sp} = \omega_p / \sqrt{2}$, where ω_p is the bulk plasma frequency.

The dispersion relation curve gives a more graphical representation; Figure 2 gives the relationship for a normal light where $\omega = ck$, where c is the speed of light

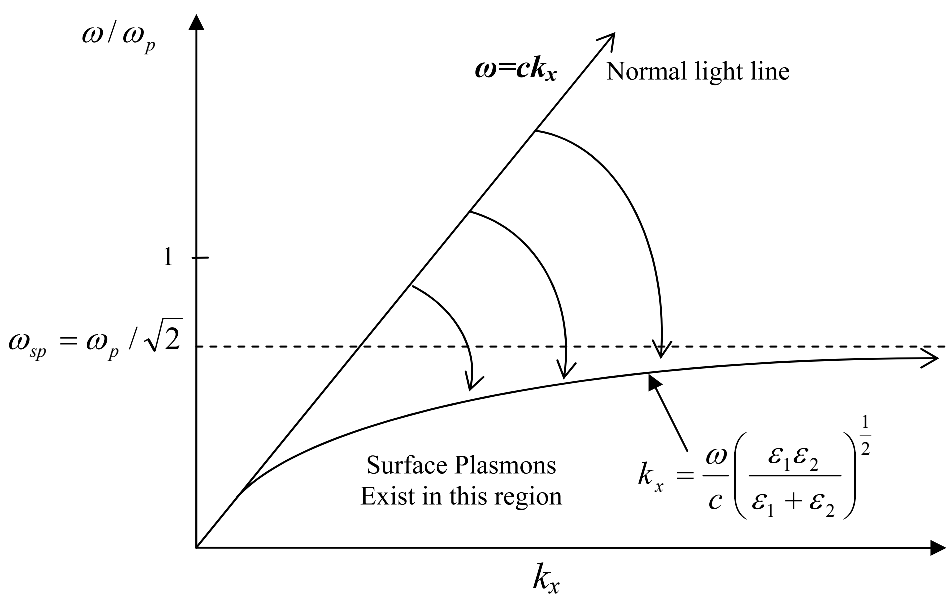

Figure 2, Dispersion relation, frequency, ω versus wavevector magnitude, k_x of the surface wave in the x direction. The surface plasmons exist in the region where the wavevector is larger than in the incoming incident field, since the permittivities have just the right values, the light line moves down.

in a vacuum and k is the magnitude of the wavevector. The values of the permittivities at the interface allow the horizontal component of the incoming field to increase the value of the wavevector magnitude, this turn causes the line to come down and allow the shorter wavelengths to be generated for the resonant plasma oscillation of the surface charge, in addition the vertical electric field component induces a charge density as a discontinuity at the dielectric-metal interfaces as shown by,

$$\sigma = \varepsilon_{metal} E_{metal,z} - \varepsilon_{prism} E_{prism,z}\,, \tag{7}$$

where $E_{prism,z}$ and $E_{metal,z}$ are the normal (z-component) electric field magnitudes of the incident fields at the prism-metal interface.

Fresnel Equations

Once the material parameters are known, they can be used for the Fresnel equations, which govern the reflectance between interfaces. In the programming, we neglect the first actual layer of the prism we intercept with the laser, we assume it originated in the glass, same for the exiting reflection. Oftentimes, one will find such equations given with subscripts of *s* and *p*, which indicate the orientation of the electric field vector with respect to the plane of incidence. For generating surface plasmons, only a *p* polarized beam can do this task, thus we will focus on Fresnel equations relating only to *p* polarization. The student should derive the following equations, starting from Maxwell's equations, deriving the wave equation and applying boundary conditions. A good reference for this task is given by O.S. Heavens in the reference section. The complex permittivities for the prism, metal and air are given as

Prism (BK7, n_0=*1.515 @ 633 nm*) with the Microscope slide (Soda Lime Glass, n_0=*1.522@ 633 nm*) - $\tilde{\varepsilon}_0(\omega)$
Metal (Ag) - $\tilde{\varepsilon}_1(\omega)$
Air - $\tilde{\varepsilon}_2(\omega)$

The reflectivity is the ratio of transmitted and reflected field amplitude at a particular interface and is a complex value, whereas the reflectance is the determined from the power ratio and is real positive value. The reflectivity of light from the glass/metal interface, $\Re_{01}$ is given by

$$\Re_{01} = \left[\frac{\sqrt{\tilde{\varepsilon}_1(\omega)}\cos\theta - \sqrt{\tilde{\varepsilon}_0(\omega)} \cdot \left(1 - \frac{\tilde{\varepsilon}_0(\omega)\sin^2\theta}{\tilde{\varepsilon}_1(\omega)}\right)^{\frac{1}{2}}}{\sqrt{\tilde{\varepsilon}_1(\omega)}\cos\theta + \sqrt{\tilde{\varepsilon}_0(\omega)} \cdot \left(1 - \frac{\tilde{\varepsilon}_0(\omega)\sin^2\theta}{\tilde{\varepsilon}_1(\omega)}\right)^{\frac{1}{2}}} \right]. \tag{8}$$

The reflection from the metal-air interface, $\Re_{12}$, is given by the following

$$\Re_{12} = \left[\frac{\sqrt{\tilde{\varepsilon}_2(\omega)} \cdot \left(1 - \frac{\tilde{\varepsilon}_0(\omega)\sin^2\theta}{\tilde{\varepsilon}_1(\omega)} \right)^{\frac{1}{2}} - \sqrt{\tilde{\varepsilon}_1(\omega)} \cdot \left(1 + \frac{\left(\sqrt{-1}\right)^2 \tilde{\varepsilon}_0(\omega)\sin^2\theta}{\tilde{\varepsilon}_2(\omega)} \right)^{\frac{1}{2}}}{\sqrt{\tilde{\varepsilon}_2(\omega)} \cdot \left(1 - \frac{\tilde{\varepsilon}_0(\omega)\sin^2\theta}{\tilde{\varepsilon}_1(\omega)} \right)^{\frac{1}{2}} + \sqrt{\tilde{\varepsilon}_1(\omega)} \cdot \left(1 + \frac{\left(\sqrt{-1}\right)^2 \tilde{\varepsilon}_0(\omega)\sin^2\theta}{\tilde{\varepsilon}_2(\omega)} \right)^{\frac{1}{2}}} \right]. \qquad (9)$$

The final equation for reflectivity, $\Re_{02,}$ is a function of the two interfaces and is given by

$$\Re_{02} = \left[\frac{\Re_{01} + \Re_{12} \cdot e^{\frac{-i4\pi d_{thickness}\sqrt{\tilde{\varepsilon}_1(\omega) - \tilde{\varepsilon}_0(\omega)\sin^2\theta}}{\lambda}}}{1 + \Re_{01} \cdot \Re_{12} \cdot e^{\frac{-i4\pi d_{thickness}\sqrt{\tilde{\varepsilon}_1(\omega) - \tilde{\varepsilon}_0(\omega)\sin^2\theta}}{\lambda}}} \right], \qquad (10)$$

where λ is the wavelength of the incident field, and $d_{thickness}$ is the thickness of the metal film. Note that in the exponential term there are terms equivalent to the angular wavenumber, k expressed in radians/meter, $2\pi/\lambda$, and is the magnitude of the wavevector,

$$\tilde{k} = \sqrt{k_x^2 + k_y^2 + k_z^2}\ , \qquad (11)$$

where k_x, k_y, and k_z are the magnitudes of the wavevectors in Cartesian coordinates. We will assume that the y-component is zero and thereby simplify the analysis. Equation 10 contains both real and imaginary terms; hence the complex conjugate must be taken in order to obtain the reflectance values;

$$R = \Re_{02} \cdot \Re_{02}^{*}\ , \qquad (12)$$

where $\Re_{02}^*$ is the complex conjugate of the overall reflectivity. It is this value that will have a direct correlation to the observed and measured experimental values. This should be plotted against Θ in order to obtain a graph demonstrating the SPR phenomena.

- Determining the optimal conditions for the Prism Coating

Two commonly used methods of coupling light into driving a resonant plasmon are the Otto, and the Krestchmann-Raether geometry. Figure 3 illustrates the two methods. The Krestchmann geometry involves a glass prism and thin metal coating on the flat surface. The Otto geometry also involves a prism and metal, however, the metal can be in bulk form but an air space between the metal and prism, roughly on the order of the wavelength, is required. For simplicity of fabrication and cost, the Krestchmann-Raether geometry is chosen. These methods utilize the concept of attenuated total reflection (ATR), which is a result of one criterion for plasmon generation; the light must be incident on the interface with an angle greater than the critical angle in order to generate the evanescent decay of the nonradiative surface charge field. The critical angle is given by

$$\theta_c = \arcsin\left(\frac{n_{air}}{n_{glass}}\right), \tag{13}$$

where n_{air} is the index of refraction for the air (assume $n=1$) and $n_{glass} = 1.515$ is the index of refraction for the prism. If the index of refraction is not known for the glass prism, it can be easily determined based on the angle by which the transmitted light disappears. This is the first measurement the student should make in order to determine the operation of the setup and verification of the values.

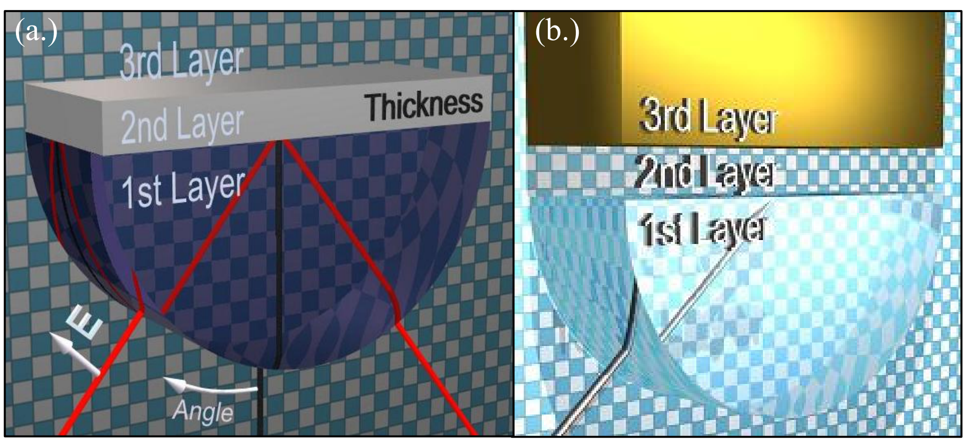

Figure 3, Two examples of Attenuated Total Reflection (ATR) SPR measureing techniques, the (a.) Krestchmann-Raether geometry and (b.) Otto Geometry.

The student will write code to implement the Fresnel equations as shown previously, being careful to properly implement the complex variables in the code. The author uses a code based on Microsoft's™ Visual Basic 6.0 code with National Instruments Measurement Studio™ for the nice graphic user interface (GUI). The main code implementation was done in Visual Fortran™. The Main GUI for the Surface Plasmon Analysis is shown in Figure 4. This part of the GUI allows the user to determine the materials of the three interfaces and is very flexible, allowing many different configurations to be utilized, as well as custom indices.

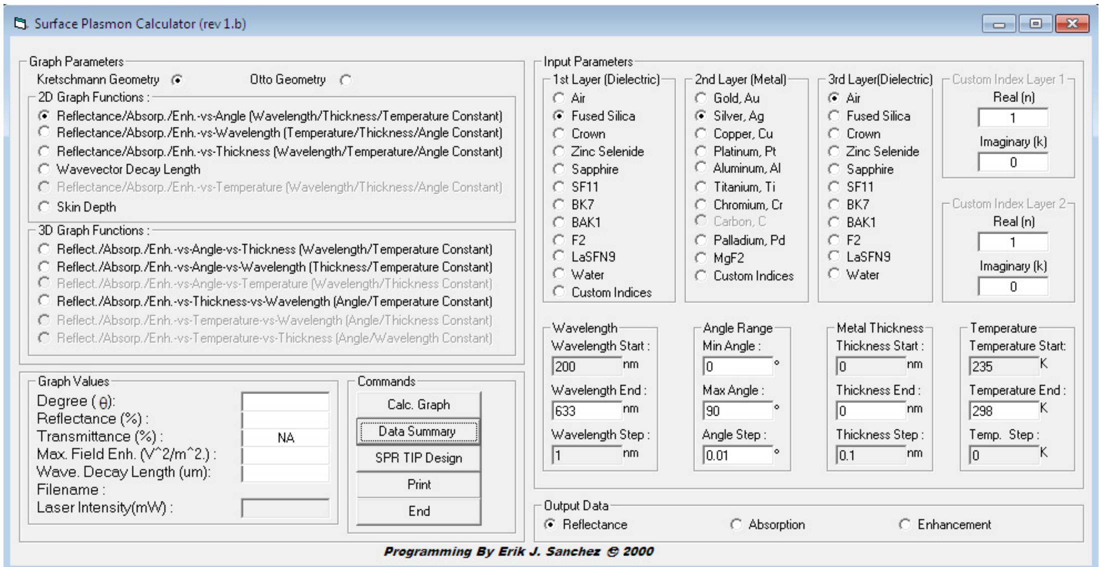

Figure 4, Example of the author's GUI, although this is very user friendly, any version including text would do the job. The user can choose 2D or 3D configurations as well as Kretschmann-Raether or Otto configurations for modeling. The custom indexes can be used for a specific material which is not in the database.

The first run with the program will be the case of a non-coated microscope slide on the surface of the prism, because of the closeness of the index of refraction of the BK7 prism, index matching fluid, and microscope slide, we will make the assumption our first layer is essentially BK7, although it is an important aspect to mention the effects of the mismatch in cases of very precise measurements. Removing the slit will allow one to see a range of angles and allows the change in the reflectance as one approaches the critical angle, Θ_C. This position should be nicely demonstrated and marked on the screen (with removable tape). In the GUI, choose the values for the configuration to reflect either a metal thickness of zero, or the custom index of $n_1=1$ and $k_1=0$. At the same time note the location with the minimum reflectance, the Brewster Angle, Θ_B ,

$$\theta_B(\omega) = \arctan\left(\frac{n_{air}(\omega)}{n_{glass}(\omega)}\right). \tag{14}$$

Another value of this simple test is the prediction of the simplest form of the Fresnel equation for a normal incidence reflectance from a surface of a dielectric. This annoyance happens to anyone not wearing glasses with an anti-reflectance coating. This should be reflected in the index of refraction of the glass with $\Theta = 0°$ and is given by the following simple Fresnel equation for *p*-polarized light at normal incidence,

$$R_p = \left(\frac{n_{glass} - n_{air}}{n_{glass} + n_{air}} \right)^2, \quad (15)$$

Since $n_{glass}=1.515$ *@ 633 nm and* $n_{air}=1$, equation 15 simplifies to,

$$R_p = \left(\frac{1.515 - 1}{1.515 + 1} \right)^2 = 4.19\%. \quad (16)$$

This result is seen in figure 4. The next case to look at is the case for a bulk metal on the prism. One would expect to simply reflect most of the light back regardless of critical angle.

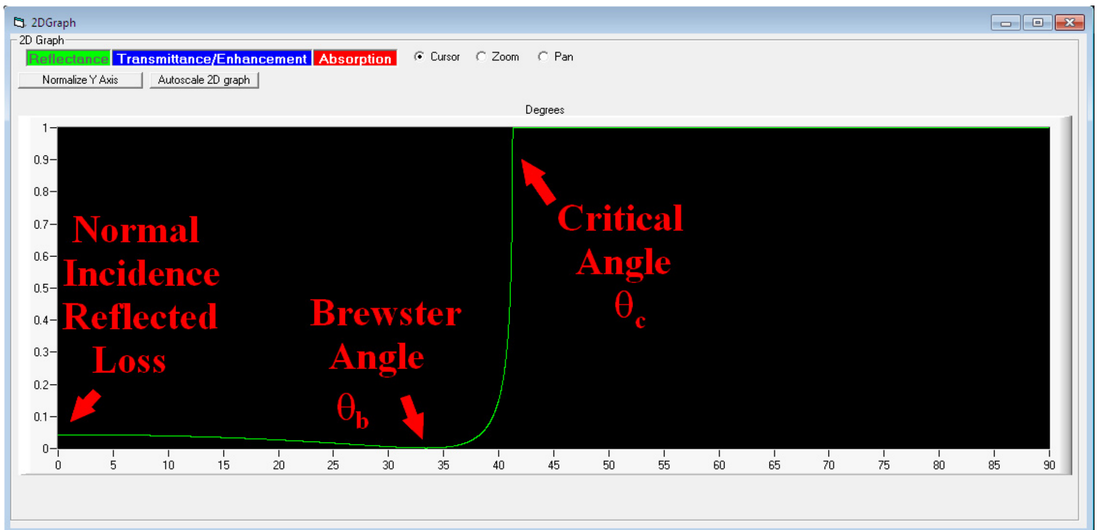

Figure 5, Theoretical modeling with Fresnel equations of Reflectance-vs-Incident angle. Three distinct regions are of importance; the normal reflection from an interface at normal incidence (glare), the angle with the minimal reflection of light (Brewster angle), and the point whereby any light after the angle gets totally reflected (Critical angle).

Figure 4 demonstrates this effect; it is essentially a mirror with a fairly good reflection. Now it is time to optimize the settings for a surface plasmon resonance case.

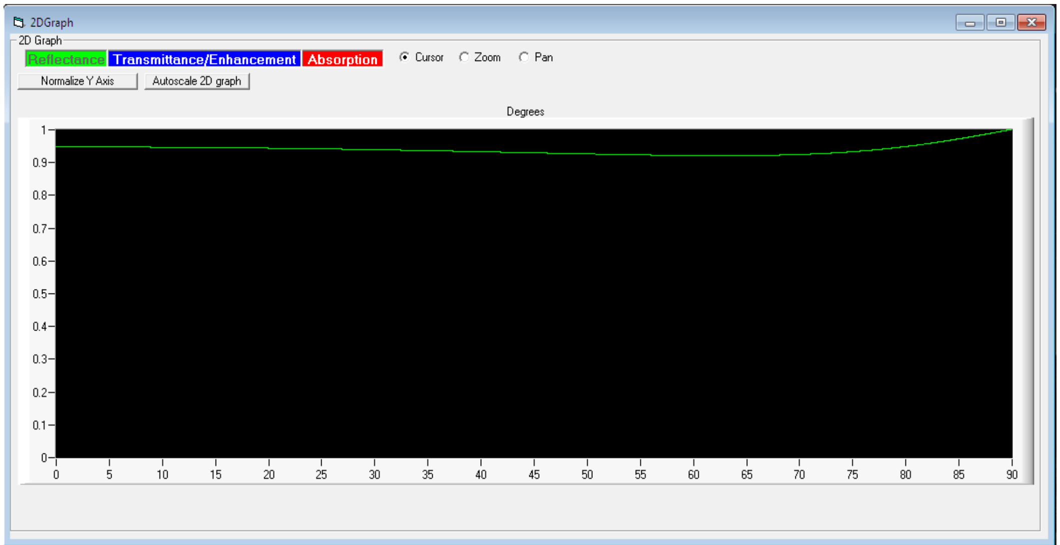

Figure 6, A theoretical modeling using Fresnel Equations of 300 nm of Ag on a BK7 prism as a function of incident angle. For the most part the light just reflects back as expected.

In order to determine the best condition of metal film thickness for a surface plasmon case as shown in Figure 6, it is worthwhile to perform a 3D sweep of multiple variables; however, if you have not generated code to perform such a function, 2D trial and error works with a large theta value. The 3D code allows the user to also find the optimal angle and thickness simultaneously, although care should be taken not to make the divisions too small, for otherwise even the fastest home computers will be challenged.

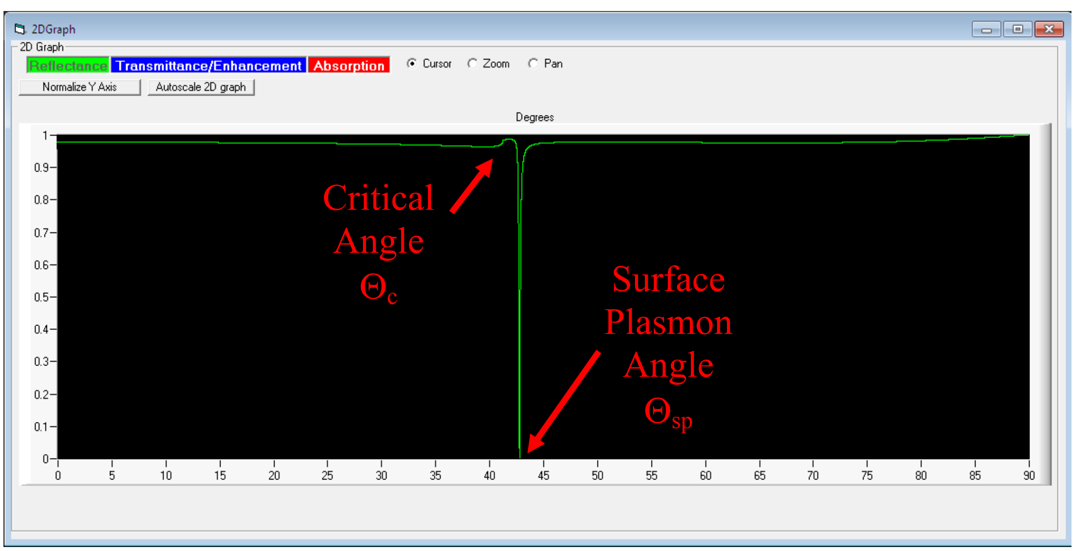

Figure 7, The Modeling of Fresnel equations to demonstrate the Surface plasmon resonance of a BK7 prism, Ag of an undetermined amount and Air as a three layer system. The level of resonance is oftentimes given as the narrowness and depth of the dip after the critical angle. The reflectance can be as low as $1x10^{-7}$ %.

Figure 8 shows the results of 3D space for determining the best thickness. The software allows for many different materials, angles, temperatures. These characteristics make the program useful for actual research, and should be considered as an essential lab tool for those intending to do any research in or with Plasmonics.

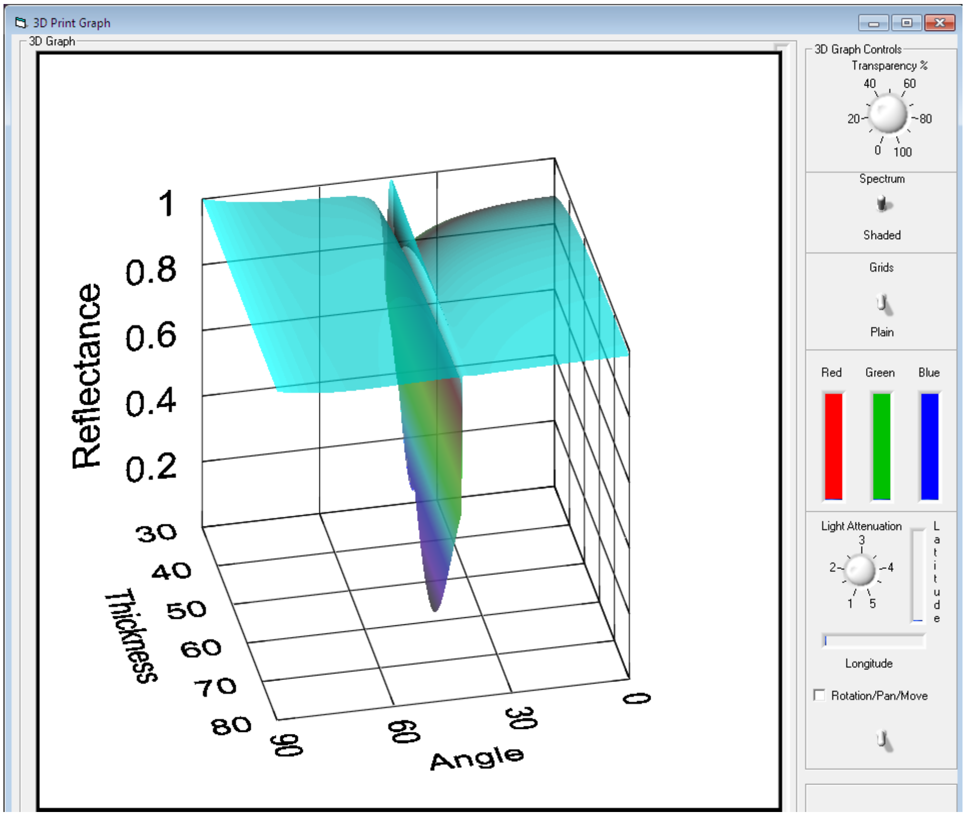

Figure 8, 3D modeling of the Fresnel equations for determining Reflectance as a function of Thickness of metal coating and Incident angle.

Once a minimum value has been determined, the prism is ready to be coated.

• Deposition of SPR Prism Coating

The purpose of this section is to introduce the student to vacuum technology and one particular use of a vacuum system, thin film deposition. The student will make multiple coatings. In addition, the student will learn theoretical modeling and SPM techniques. Refer to the Vacuum Deposition Lab Manual and Scanning Probe Lab Manual in order to properly execute these steps.

The goal is to make a coating on a glass microscope slide which has the correct thickness. At the same time, the student will learn how to make sure the coating is truly the thickness which is desired. On many deposition systems there exists a crystal microbalance type of thin film measuring system. This allows the user to reproducibly fabricating films within a couple of angstroms (although nm's would be more realistic).

In order for this tool to perform correctly, the user must input the density of material being coated, the acoustic impedance ratio (Z-ratio) and the tooling factor, the other inputs are usually for batch processing and not necessary. The density in our case is silver, (density = 10.49 g/mL).
The acoustic impedance ratio is the correction factor that tells the system how much of a mismatch in acoustic impedance between the quartz detection substrate and the material being coated. It compensates for the frequency to thickness change in the detection process, these values are found in tables for thin film deposition. For silver this value for Z-ratio is .529.

The tooling factor is the confusing parameter for most students, this is the calibration factor for where the material is being coated with respect to a fixed position of the quartz detector. The detector always reads exactly what is being coated on it, however the detector can't be directly on your sample where you care to know the thickness value at all times, so a compromise is made, you fix the detector somewhere in the chamber and then place a sample in a known location in the chamber that is always a known percentage off from the detector. It is helpful to set this to 100% first and then coat a sacrificial microscope slide somewhere in the chamber with at least a few hundred nm's if possible. Take the slide out and scratch it gently with a wire brush. At this point the Atomic force Microscope (AFM) is used.

The student must be trained on the use of the AFM so as to not to damage this expensive and sensitive piece of equipment. After performing a calibration on a height calibration standard, place the AFM cantilever near the scratched area and scan a large area (100x100 μm^2). The scratched area will leave behind a nice flat surface without gouges into the glass; however, the edges of the ripped metal will generally be fairly high, be careful not to exceed the maximum Z-range of the AFM (typically a few microns). Take a few averages of different close by locations, always using the flat glass "plain" regions as the baseline for the lowest level. Once a confident is found in the thickness level of the film, apply the following logic to the tooling factor (TF).

Tooling Factor (TF) Concept

For an example if you actually coated 50 nm of Ag according to the AFM, the Quartz Deposition thin film measuring unit told you 35 nm with a 100% TF. Put in a new TF of;

$$NewToolingFactor = (100\%) \cdot \left(\frac{ThicknessfromAFM}{ThicknessfromQuartzUnit} \right). \qquad (17)$$

For example, the new TF = (1.2 % /100)*(50 nm /35 nm)), therefore the new TF = 171%. (Beware some system reverse this ratio.) Perform another deposition to check validity of the TF. If the value is correct within a couple of percent, proceed to coat the actual prism. If not, contact the instructor.

Place the microscope slide that will be tested into the deposition system and proceed to deposit the necessary amount of Ag onto the slide. Remember that Ag reacts easily with sulfur compounds and oxidizes well, so keep it clean and use it soon after the coating. Now that the coating is done, one can proceed to the building of an optical setup.

• Setting up the SPR Optical System

The overall setup as presented here in this lab is a very simple version; it is intended to give insight and has very rough ability to measure with a high precision. It was designed with cost in mind. Figure 9 shows the basic overall side view of the setup. The system consists of a small polarized Helium Neon (HeNe) laser of modest power (5-10 mW and 633 nm). The laser could be a brighter 532 nm, a more recent solid state laser, but all the modeling has to change to the proper values for a good effect to be see. Too bright is also not very helpful, as the narrow dip will be lost in the blindness of the scattered light. A red diode laser, which is made linearly polarized and has good beam quality would work well and of course the same thing applies, not too bright. This brings up the next point, it is assumed that the students have gone through proper laser training through their institution.

The laser is placed in a holder which allows it to be easily rotated and tightened. The need for a cylindrical shaped laser tube allows the user to prove to oneself the results of using *p*-polarized versus *s*-polarized light. For *p*-polarized light, the laser is rotated with polarization in the plane of the table, in order to get the light to properly enter the prism.

The laser beam output is sent to the small opening of a laser beam expander; this can actually be just two lenses, one with a small focal length and one with a larger focal length, the ratio being the magnification. Having the beam

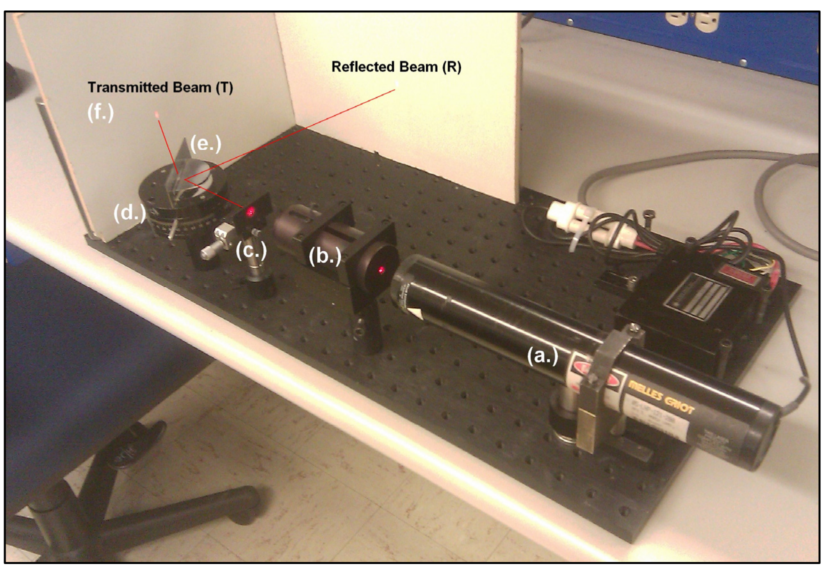

Figure 9, SPR optical experimental setup. (a.) Polarized HeNe 633 nm laser, (b.) beam expander, (c.) slit on a linear translator, (d.)

optical substrate rotator,(e.) optical prism (uncoated) with a Ag film coated microscope slide (oil coupled), (f.) white screens to easily view the transmitted and reflected beams.

expanded allows the user to use the light spread out to see transitions across certain angles and allows the beam to use a slit, which is the next component. The slit allows only a small sliver of light into the prism and maximizes the ability to see the surface plasmon dip. The angle tends to be very narrow, and is not easily seen with a bright beam. The beam shouldn't be completely collimated, as that would cause optical distortions in the prism. In order to properly enter the prism the light should enter normal incidence for the hemi-cylindrical prism. For a right angle or flat edge entry type prism, one must simply be aware of the distortion of the focus and compensate for it accordingly.

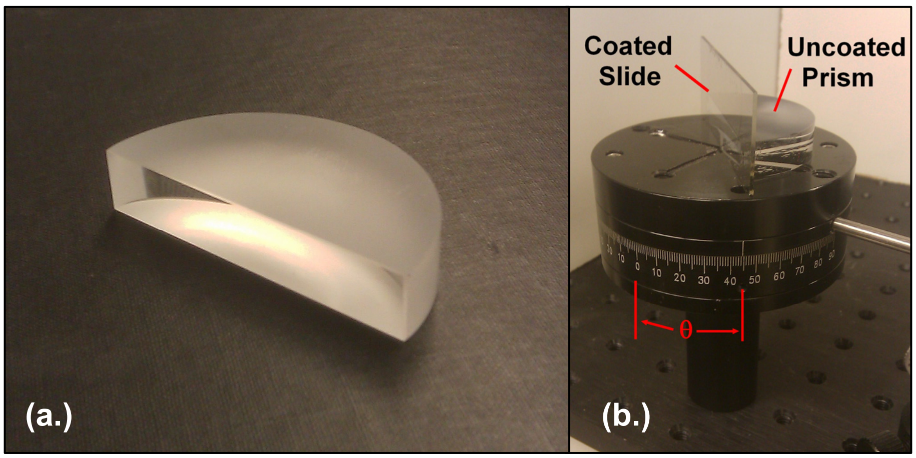

Figure 10, (a.) Optical glass prism used in the SPR setup, (b.) the optical rotator which holds the prism and can easily be read when it is rotated.

The prism, as shown in figure 10a is a custom purchase from ESCO Products. The prism must be held rigidly and properly centered. Note that these prisms have a small offset and aren't exactly half a sphere, but with the extra thickness of the microscope slide, they become almost the correct shape. Make sure you have this specified if you have them custom made.

The prism is placed onto a rotator that allows the user to easily read the amount it is being moved. The optical slide that has been coated will fit in and extend far beyond the edges for easy removal and placement. The oil should be carefully placed on the uncoated side of the microscope slide. Be careful not to get oil on the coated side, or the coating will be ruined. The microscope slide is now ready for testing, but minor adjustments are always needed. Make sure to write down the angles and how you aligned certain components. This whole setup takes a couple of hours to setup up from scratch, with all the components sitting in a box, it will certainly take less time.

- **Comparison of Experiment to theory**

The purpose of this is to make a comparison of how close to your modeling did you get. If the values were not close and the code seems to operate correctly, what could have been the issues? In addition to performing error analysis, perhaps you may want to consider the following;

- Polarization of the laser not being perfectly p-polarized.
- Improper Expansion of the beam might cause optical measuring artifacts.
- Prism not properly aligned.
- User is color blind (can be a serious problem).
- Thin film or AFM unit are defective,
- Metal film might have degraded.

With a little modification to the setup it can easily become a useful tool in the lab, how would you modify it to make it better, without having an infinite budget.

• References

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3. O.S. Heavens, "Optical Properties of Thin Solid Films", Dover Publications, (1991).