Reflection from metals and verification of Surface Plasmon Resonance phenomenon

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Abstract

In this experiment we analyze the polarization of light reflected from a metal for different initial polarizations of the incident light. This was used to calculate the refractive index of the metal. As a second part of the experiment, a thin film of silver was coated on a glass piece, which was then attached to the hypotenuse face of a right angle prism. We pointed the laser light at this face, from the prism side, and at a particular angle, reflected light intensity dropped, thus confirming surface plasmon resonance.

1 Aim

- To confirm that elliptically polarized light is obtained when linearly polarized light is reflected off a metal.
- To verify surface plasmon resonance.

2 Theory

The theory of this experiment is divided into two parts.

2.1 Reflection from metals

Polarisation Ellipse The polarization ellipse is fully described by the amplitudes and the phase difference of the transverse components. These parameters are utilized to calculate the inclination angle α and the angle of ellipticity η. The inclination angle is measured between the major axis of the ellipse and the positive $\hat{s}$ direction and describes the orientation of the ellipse(see Fig. 1).

Change of polarization on reflection When light is reflected, the s- and p-components undergo different phase shifts. Furthermore, different amounts of the s- and p-amplitudes are reflected. As a consequence, the polarization state of the incident wave changes. This is referred to as the depolarization effect of the mirror and is described by the

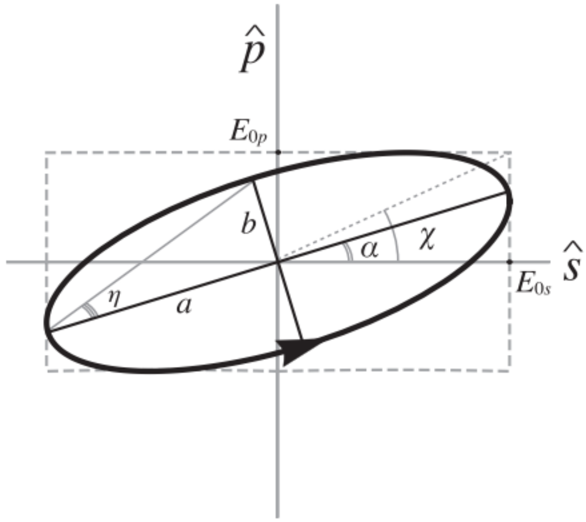

Figure 1: Polarisation ellipse

Fresnel amplitude coefficients of reflection (r_s, r_p) and transmission (t_s, t_p). The subscripts i, r, and t stand for incident, reflected, and transmitted (wave or medium), respectively, and are given by :

$$r_s = \frac{\tilde{E_{0r,s}}}{\tilde{E_{0i,s}}} = \frac{n_i cos\theta_i - n_t cos\theta_t}{n_i cos\theta_i + n_t cos\theta_t} = |r_s|e^{i\phi_s},$$

$$r_p = \frac{\tilde{E_{0r,p}}}{\tilde{E_{0i,p}}} = \frac{n_t cos\theta_i - n_i cos\theta_t}{n_t cos\theta_i + n_i cos\theta_t} = |r_p|e^{i\phi_p},$$

$$t_s = \frac{\tilde{E_{0t,s}}}{\tilde{E_{0i,s}}} = \frac{2n_i cos\theta_i}{n_i cos\theta_i + n_t cos\theta_t},$$

$$t_p = \frac{\tilde{E_{0t,p}}}{\tilde{E_{0i,p}}} = \frac{2n_i cos\theta_i}{n_t cos\theta_i + n_i cos\theta_t}.$$

Here, θ_i and θ_t are the angles of incidence and refraction, respectively, where θ_t is obtained from Snell's law,

$$n_i sin\theta_i = n_t sin\theta_t.$$

The magnitude of the reflection coefficients) determines the fraction of incident light that is reflected, and the power of the exponent contains the phase change encountered on reflection. For conducting media such as aluminum and gold, they are complex numbers because the index of refraction is a complex number: $\tilde{n} = n + i\kappa$, where κ is the extinction coefficient. In this case, the Fresnel equations are evaluated with a computer program.

Amplitude of the incident wave The mirror "sees" the incident light as linearly polarized at angle γ. If the amplitude of the incident beam is $E_{0,i}$, the amplitudes of the transverse components are found from geometry to be

$$E_{0i,s} = E_{0i} sin\gamma$$

and

$$E_{0i,p} = E_{0i} cos\gamma.$$

The Fresnel equations yield the reflection coefficient to be

$$r_j = \frac{\tilde{E_{0r.j}}}{\tilde{E_{0i.j}}} = |r_j| e^{i\phi_j}, j = s, p,$$

where r_j is calculated from the Fresnel equations. From here the complex amplitudes are calculated directly.

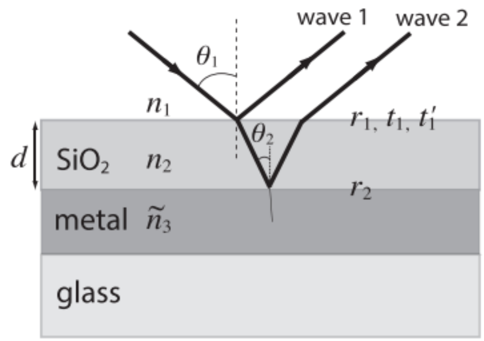

Figure 2: Reflection from a protected metal coated mirror

Calculating reflection amplitudes from experimental data The s- and p-amplitudes and the phase difference are calculated from the directly measured values of α and η according to the relations

$$E_{0,s} \approx \sqrt{0.5[1 + cos(2\alpha) + cos(2\eta)]}$$

$$E_{0,p} \approx \sqrt{1 - E_{0,s}^2}$$

and

$$cos\delta = \frac{E_{0,s}^2 - E_{0,p}^2}{2E_{0,s}E_{0,p}} tan(2\alpha).$$

2.2 Surface Plasmon Resonance

Plasmon Mechanism : Inside a conductor, negatively charged electrons exist which move freely in the environment. When an illuminator such as sunlight or laser is applied to the conductor and starts transferring energy, the movement of the free electrons gets affected by the positive ion background. The attraction combined with the electrostatic repulsive force on free electrons creates a phenomenon of delocalized electron oscillation . The interaction between the incident light and interface causes the photons to be absorbed and energy is transferred into electrons resulting in electrons excitation inside the metal. Electromagnetic waves are exerted along the surface and therefore they produce a strong concentration of electromagnetic field. As a result, the process generates heat and enhances local temperature which can be used for sterilization or antibacterial treatment. As the light source passes through the prism that has the

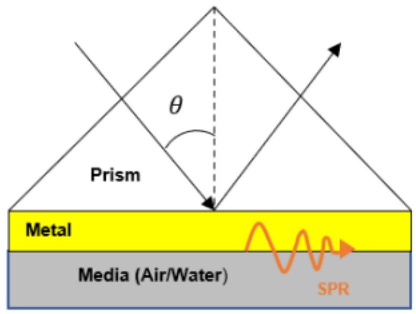

Figure 3: Kretschmann configuration producing surface plasmon resonance

surface coated with a thin film of metal, a specific incident angle is needed called the resonance angle where the energy of light is absorbed causing the electrons to oscillate, or surface plasmon resonance (SPR). At that point, the incoming light photons have the same momentum with the momentum of the surface plasmons. However, with a higher or lower degree of incident angle, the resonance would not be generated and hence resulting in the absence of the plasmonic effect. There are many factors that impact the process of determining the appropriate resonant angle including the material for the metal film, refractive index of the media, wavelength of incoming light source and temperature of the surrounding area. To be able to transfer the energy from photons and turn into plasmons, the resonance angle needs to exert the reflection ray within total internal reflection (TIR) area without exceeding the critical angle. By applying Snell's Law with given refractive index for different metals and the prism, it is possible with the help of this formula to calculate the range of angle to produce SPR:

$$\frac{n_1}{n_2} = \frac{sin(\theta_2)}{sin(\theta_1)}$$

1. Relation Between SPR and incident angle :
   Including the effect of dimensions such as thickness and length of the metal on the incident angle would overcomplicate the problem, therefore we neglect those factors as well as assume that the experiment is performed at room temperature. In addition, each metal has its unique properties and index of refraction. However, the value is complex and is described as the formula below, in which $n_o$is known as the ordinary refractive index and κ extinction coefficient:

$$n = n_0 + i\kappa$$

The metal used in this experiment is silver and the wavelength of light used is 632.8 nm.

2. Relation between SPR and permittivity of metal :
On applying Maxwell equations and condition for SPR, we obtain the following approximation:

$$\theta \approx \sqrt{\frac{\epsilon_2}{(\epsilon_2 + \epsilon_1)\epsilon_{prism}}}$$

where ϵ_1 = permeability of dielectric (air in our experiment), ϵ_2 = permeability of silver, $\epsilon_{prism} = 2.2946$ and θ is the angle of incidence beyond the critical angle.

3 Experimental Setup

3.1 Reflection From Metal

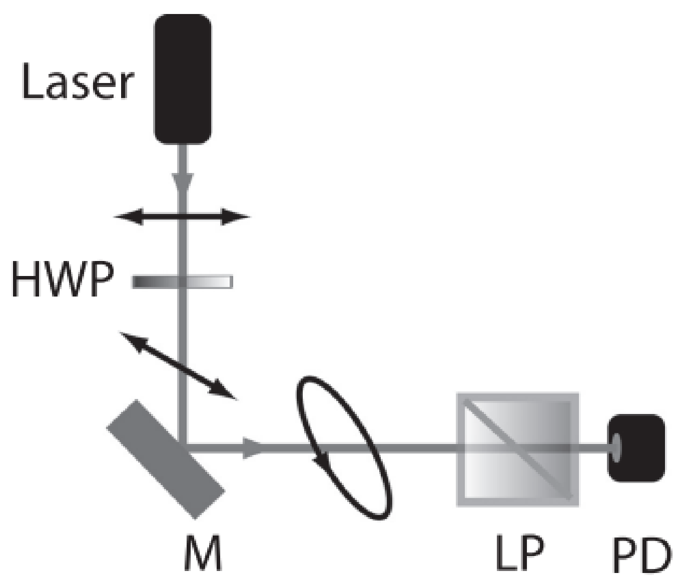

Figure 4: Experimental setup 1

We set a polarizer to transmit only vertically polarised light. Then half waveplate is used to rotate the incident polarization. The linear polarizer and photodiode combination is used to measure the elliptic nature of reflected light.

3.2 SPR Set Up

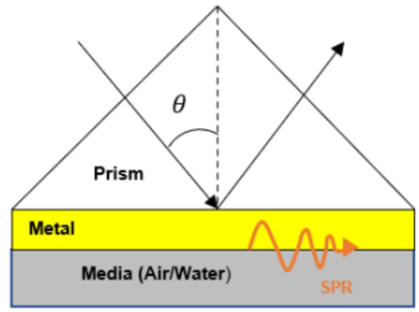

Figure 5: Experimental setup 2

4 Data

4.1 Polarization angle - 0 degrees

The output light was also linearly polarized.

4.2 Polarization angle - 60 degrees

See Table 1 for data. According to the data, the following ellipse is plotted :
For this ellipse

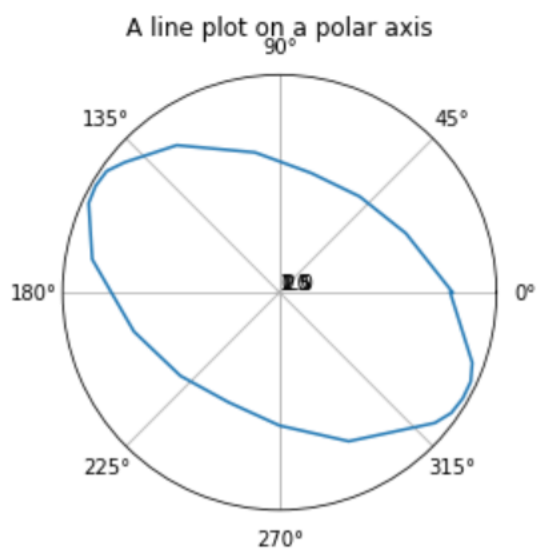

Figure 6: Polarization of output light

α = -28.97 degrees.
η = 30.0 degrees.
$E_{r,s} = 0.505$

Polarizer angle(degrees)	Intensity(mV)
0	191.5
25	154.2
50	138
75	136.2
100	156.8
125	198.2
140	223.4
145	233.4
150	235
155	233
170	210.5
195	166.8
220	143.2
245	133.7
270	146.9
295	181.2
320	224.1
325	231.9
330	234
335	233.3
340	226.9
360	188.8

Table 1: Polarization Angle 60 degrees data.

$E_{r,p} = 0.863$
Phase difference between the two components $\delta = 2.745$ radians.
Now, using Fresnel equations we can predict the refractive index of metal. For the above mentioned values of electric fields, the predicted refractive index of metal $= 0.08 + 3.9i$

4.3 Polarization Angle - 120 degrees

See Table 2 for data. According to the data the following ellipse is plotted. (See Figure 7)
For this ellipse
$\alpha = +28.97$ degrees.
$\eta = 30.0$ degrees.
$E_{r,s} = 0.505$
$E_{r,p} = 0.863$
Phase difference between the two components $\delta = 2.795$ radians.
Now, using Fresnel equations we can predict the refractive index of metal. For the above mentioned values of electric fields, the predicted refractive index of metal $= 0.07 + 4.0i$

Polarizer angle(degrees)	Intensity(mV)
0	191.4
25	232.4
27	237.1
29	235
31	232.1
33	231
35	230
60	184.6
85	149.7
110	133.2
135	136.5
160	160.1
185	202.9
206	235.7
207	236
208	235.1
209	236.8
210	232.8
212	228.5
214	228
240	189
265	149.6
290	135.6
315	138.2
340	161.5
360	189.6

Table 2: Polarization Angle 120 degrees data.

4.4 Surface Plasmon Phenomenon

We will use the formula $\theta \approx \sqrt{\frac{\epsilon_2}{(\epsilon_2+\epsilon_1)\epsilon_{prism}}}$. In our experiment the SPR angle was observed to be at 6 degrees beyond the critical angle.
$\epsilon_1 = \epsilon_{air} = 1$, $\epsilon_{prism} = 2.2946$.
From this we calculated $\epsilon_{silver} = 0.0257$.
Also, $n = \sqrt{\frac{\mu_{metal}\epsilon_{metal}}{\mu_0\epsilon_0}}$, therefore $n_{silver} = 0.16$

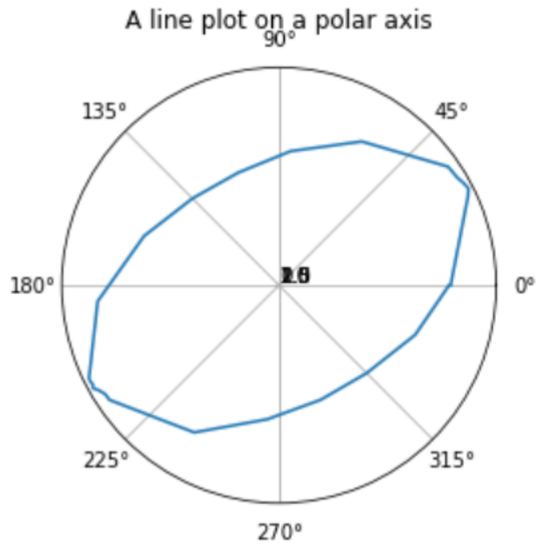

Figure 7: Polarization of output light

5 Error Analysis

In the reflection experiment the experimental precision limited our accuracy and the uncertainties were estimated to be $\Delta\gamma \pm 1^o$, $\Delta\alpha \pm 2^o$ and $\Delta\eta \pm 2^o$.

In Surface Plasmon experiment, error in measuring θ was $\pm 2^o$. The corresponding error in refractive index is 0.1.

6 Results And Discussion

The refractive index of silver as predicted by the plasmon resonance effect is 0.16 ± 0.1. The SPR phenomenon is only observed for p- polarized light wave and the dip in intensity of light disappears when we change the polarization from p to s. It was spectacular to watch the reflected intensity decrease in magnitude beyond the critical angle (pictures can be seen in Figure 8).
To plot a proper elliptic polarization of light, the square root of the intensity values were used. Otherwise, the intensity plot gave a cardiod like shape. Since, electric field amplitude is proportional to the square root of intensity, this observation makes sense.

7 Acknowledgements

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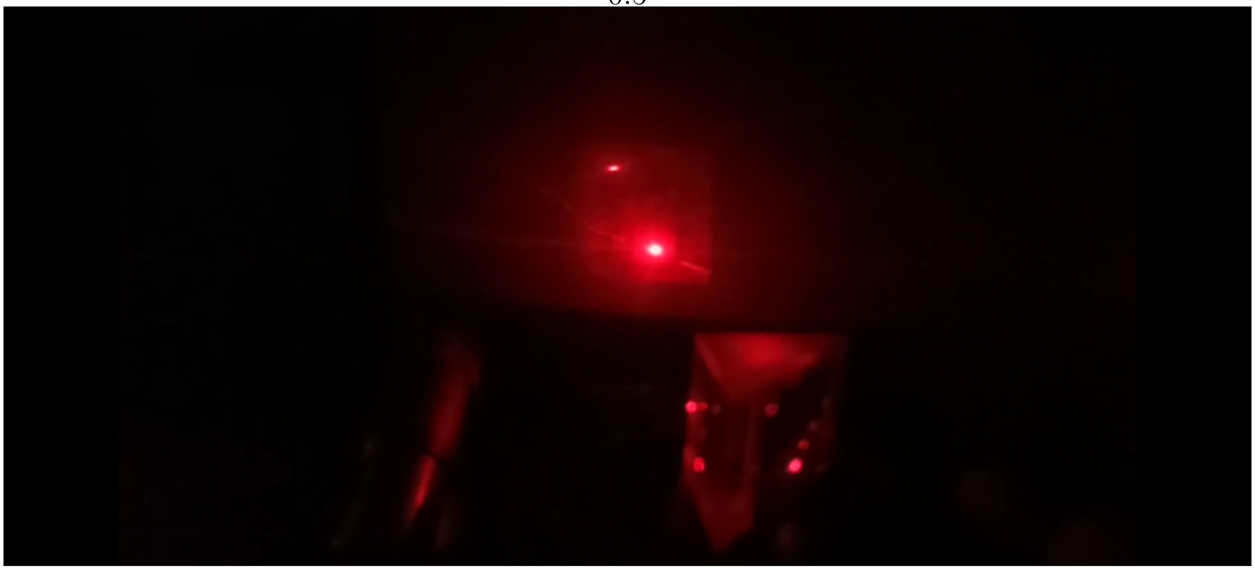
0.5



0.5

0.5

Figure 8: Images of SPR Experiment

resonance phenomenon, so that we could verify it in our project, and then helping us in setting up the experiment. The experiment was a delight to witness.

8 References

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