Specular and diffuse reflectivity

Experimental aim

1. To study the classic laws of specular reflection from a smooth surface.
2. To study diffuse reflectivity from various painted surfaces.
3. To practice the experimental technique of “lock-in” or “phase-locked” detection.

Skills under development

Through this experiment, we want you to develop your experimental skills further. This is what your lab demonstrator will be looking for when they mark your work.

By the end of the experiment;

- ☐ You will become competent and confident operating and adjusting the experimental apparatus, particularly for “lock-in” detection.
- ☐ You will have modelled specular reflectivity in python and, based on this, discussed the influence of key variables on specular reflectivity.
- ☐ You will have graphed your experimental data and interpreted them to compare theory to experiment, and specular to diffuse reflectivity.
- ☐ You will have designed your own experiment to investigate diffuse reflectivity further.
- ☐ You will clearly present information (including title, date, partner) in your lab book report and will communicate your efforts and achievements ethically.

Background

The Fresnel Equations

Light is a transverse, electromagnetic wave, and the electric field of this wave oscillates perpendicular to the direction of motion. There are two possible polarisations of the electric field direction; the p-component is parallel to the plane of incidence and the s-component is perpendicular to the plane of incidence, as shown in Figure 1.

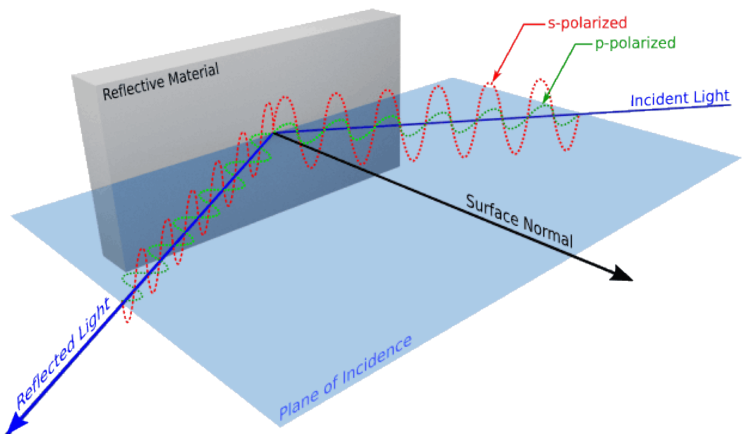

Figure 1: Illustrating the difference between p- and s-polarised light incident on a surface. Taken from [1]

When a beam of light strikes a smooth surface, as in Figure 1, some light is reflected and some is transmitted. The directions of the reflected and transmitted beams are shown in Figure 2.

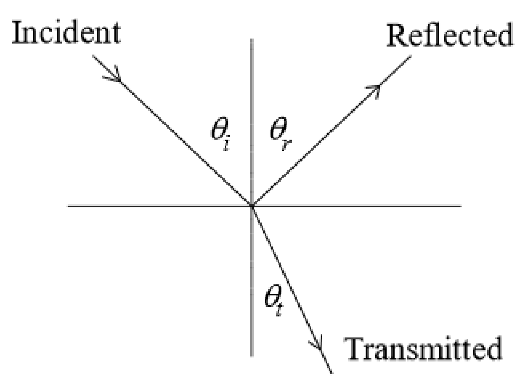

Figure 2: Relation of the beams of light reflected at a smooth surface (specular reflection).

The directions of the various beams are related by some laws which you would have met previously.

$$\theta_i = \theta_r, \tag{1}$$

$$n = \frac{\sin\theta_i}{\sin\theta_t}, \tag{2}$$

The fraction of the incident power reflected at the surface is given by the reflectivity, R, but this varies with the polarization of the light; R_p is the reflectivity of p-polarised light and R_s is the reflectivity of s-polarised light. In this experiment, you will be measuring R_p and R_s.Theoretically they are given by the Fresnel equations:

$$R_p = \left(\frac{\cos\theta_t - n\cos\theta_i}{\cos\theta_t + n\cos\theta_i}\right)^2, \tag{3}$$

and

$$R_s = \left(\frac{\cos\theta_i - n\cos\theta_t}{\cos\theta_i + n\cos\theta_t}\right)^2. \tag{4}$$

It is interesting to note that when the angle of incidence is equal to a material's "Brewster angle", $\theta_i = \theta_B$, the reflectivity $R_p = 0$. This means all the p-polarised light is transmitted at the surface. Only s-polarised light is reflected at the Brewster angle. The Brewster angle is related to the refractive index of the material by,

$$\theta_B = \tan^{-1} n\,. \tag{7}$$

There is **<u>no</u>** angle of incidence at which the s-polarised component is completely transmitted, that is $R_s > 0$.

General principles of the lock-in amplifier

Suppose you have a signal to be detected in the presence of noise and interference. If the frequency of the signal is known, then it can be detected even though it may be much below the level of the noise and interference. The essence of the technique is that the incoming signal (consisting of the wanted signal at a known frequency plus noise and interference at other frequencies) is multiplied by a reference signal at the known frequency and integrated over time. The process relies on a special property of the trigonometric functions:

$$\lim_{T\to\infty} \frac{1}{T}\int_0^T \sin(f_1 t)\sin(f_2 t)\, dt = 0 \text{ if } f_1 \neq f_2$$

and

$$\lim_{T\to\infty} \frac{1}{T}\int_0^T \sin(f_1 t)\sin(f_2 t)\, dt = 0.5 \text{ if } f_1 = f_2.$$

A lock-in amplifier has two inputs. One for the input signal to be measured and one for a reference voltage or frequency f_r. The lock-in will respond only to the component of the input signal with frequency f_r, other frequency components in the input signal will not contribute to the output.

A lock-in will also have some means for adjusting the relative phase between the input and reference signals, although in many modern lock-ins this is done automatically. In addition, there is usually some means of adjusting the time over which the integration is performed; on the lock-in controls this will usually be referred to as the time constant of the measurement.

Theoretical modelling of specular reflectivity

Complete the python notebook SpecularDiffuseReflectivity_FresnelEquationInvestigation-SV.ipynb, then answer the following questions.

Figure 3 shows how you can expect R_p *and* R_s to vary with angle of incidence, θ_i off a glass surface.

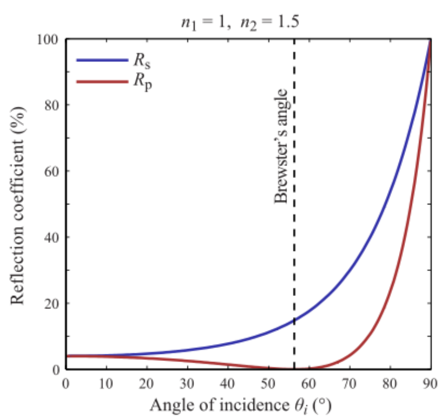

Figure 3: Reflectivity coefficients R_p and R_s (as a %) plotted against θ_i Taken from [2].

- Comment on how your theoretical graph of R_p *and* R_s as a function of θ_i for glass compares.
- At what angles of incidence does $R_p = R_s$?
- For glass, at what angle of incidence does $R_p = 0$?
- As refractive index of the reflective surface varies, how do the graphs of R_p *and* R_s as a function of θ_i vary?

Experimental procedure

The basic set up of this experiment is shown in Figure 4.

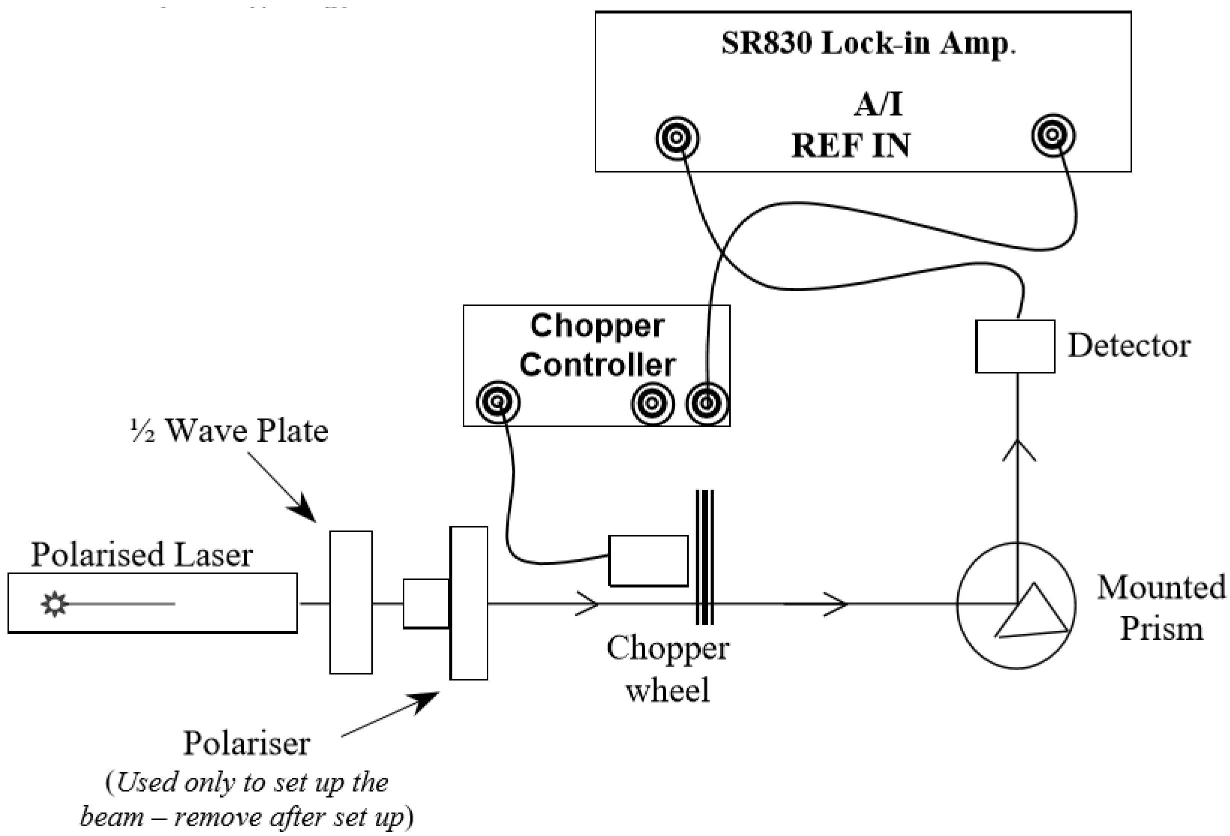

Figure 4: Set up of experimental apparatus.

The experiment involves shining a laser onto a surface (the mounted prism) at varying angle of incidence. The reflected intensity is measured by an optical detector, whose output is fed into a lock-in amplifier. Since a lock-in amplifier will only respond to AC signals, it is necessary to make the light intensity vary. In optical experiments, this is commonly done by passing the beam through a mechanical chopper! The reference frequency is picked up from the chopper vanes by a second source and detector, usually mounted in the chopper wheel housing. In our equipment, it is mounted at the bottom of the chopper wheel.

Since we will only measure light which fluctuates at the chopping frequency, the experiment can be carried out in a lighted laboratory. However, we have found that when the reflected light is of low intensity, the room lighting can cause noise. It is probably best to reduce the ambient lighting when doing the measurements.

The laser used in this experiment is polarised. It is set up passing through a rotating ½ wave plate which can rotate the plane of polarisation of the emitted beam. For setting up the orientation of polarisation of the beam you have a mounted polariser which is arranged so that when the scale is set to $0°$ it passes vertically polarised light (and stops horizontally polarised light). For the initial part of the experiment you will use horizontally polarised light.

The lock-in amplifier used in this experiment is a dual-channel instrument; it can display the magnitude, R, and phase (θ) of the signal simultaneously. In this experiment, you'll just be using it to measure the magnitude of the signal, R. The phase depends on the position where the laser beam passes through the chopper blade and is irrelevant.

Let's begin!

1. Turn the laser on and allow it to stabilize.

Setting up the beam

To achieve horizontally polarized light;

2. Set the polariser to $0°$ and place it in the path of the laser.
3. Rotate the ½ wave plate until the light is extinguished (or at least at minimum intensity).
4. Remove the polariser from the path of the laser beam.
5. Mount the prism on the rotating table with a specular (shiny) face along a central diameter of the table, as shown in Figure 5, and clamp it.

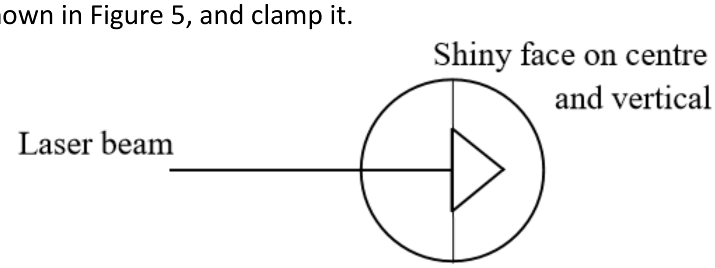

Figure 5: Position of the prism on the rotating table.

6. Put the pointer of the table scale on zero and, after loosening the hand screw just underneath the table, adjust the prism so that the laser beam is reflected on itself. It may be necessary to adjust the tilt of the table too.
7. Check that the detector receives the reflected beam when it is positioned at twice the setting of the pointer. If not, repeat step 6.
8. Tighten the hand screws to secure the position and tilt of the table when you are satisfied with beam-detector alignment.

Setting up the lock-in amplifier

Using Figure 4 as a guide,

9. Connect the detector to the A/I input of the lock-in amplifier.
10. Connect the trigger signal from the chopper control to the reference input of the lock-in.
11. Set the following controls on the lock-in to the following values (working from left to right on the lock-in's front panel):
    a. **Time Constant:** 1s, 6dB, sync off.
    b. **Signal Input:** A, AC, Ground.
    c. **Sensitivity:** 200mV to start.
    d. **Reserve:** Normal.
    e. **Filter:** both line and 2xline on.
    f. **Channel 1:** R, display.
    g. **Channel 2:** θ, display.
    h. **Reference:** Pos Edge.

    The settings are controlled by push buttons and the particular setting for a control is usually indicated by a small light.

12. Set the chopper to around 500Hz.
13. Set the angle of incidence to 10° and position the detector to receive the reflected beam.
14. Reduce ambient lighting ready for taking measurements, and use your desk lamp instead.

Measurement of R_p

15. Obtain a set of readings of voltage for as wide a range of θ_i as you can manage. The voltage readings are proportional to the intensity of the reflected beam being detected. Values from a minimum incidence angle of 10° to a maximum of 80° should be attainable.
16. Since $n \approx 1.5$ for glass, $\theta_B \approx 57°$ (see Equation (5)). Take readings at 1° intervals from $\theta_i = 55° to\ 59°$.
17. Determine the angle at which the reflected light has a minimum intensity as accurately as you can.

Note: You may need to adjust the sensitivity setting for each measurement. The easiest way to find the correct sensitivity setting for the lock-in is to press the **GAIN** button in the **AUTO** group of controls. If the reading fluctuates, you can increase the time constant setting, however you need to wait for 3 time constants before the reading settles. However, the automatic gain adjustment feature does not work if the time constant is set to more than 1s.

18. Record your results in table form, along the lines of Table 1 .

$\boldsymbol{\theta_i}$ **(deg)**	$\Delta\boldsymbol{\theta_i}$(deg)	$\boldsymbol{V_{\theta_i}}$ **(mV)**	$\Delta\boldsymbol{V_{\theta_i}}$ **(mV)**
10			
…			

Table 1: Experimental measurements of the intensity of in-plane-polarised, reflected light.

19. At the end of the run, remove the prism and place the detector at the $180°$ mark. This will allow you to obtain a voltage V_{90}, corresponding to the intensity of the original laser beam.

Measurement of R_s

20. After completing the measurements for horizontal polarization, rotate the ½ wave plate by $45°$ and obtain voltage readings for the vertical polarization at $\theta_i = 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°\ and\ 90°$. (There is no Brewster angle for this polarization of light.)

Analysis of specular reflectivity measurements

Complete the python notebook SpecularDiffuseReflectivity_SpecularReflectivityAnalysis-SV.ipynb to graph and analyse your experimental measurement from Measurement of $R_p$and Measurement of R_s.Then answer the following questions:

- What was your experimental estimate of the refractive index of your prism?
- Compare your experimental estimates of $R_p\ and\ R_s$ with the theoretical predictions that you plotted on the same graph.

Diffuse reflection

1. Adjust the ½ wave plate again by $45°$ to return the beam to horizontal polarization.
2. Replace the specular glass face with the **glossiest** painted surface and set $\theta_i = \theta_r$.
3. Measure reflected intensity as a function of θ_i as you did in Measurement of R_p, recording your results in table form like Table 1.
4. Repeat steps 2-3 but this time using one of the **matte** painted surfaces.

Analysis of diffuse reflectivity measurements

Graph your results by completing the python notebook SpecularDiffuseReflectivity_DiffusePlot-SV.ipynb.

- Did you see evidence of a Brewster angle in your graph?
- If so, is it the same for glass?
- Is there any other notable similarities or differences between R_p off the painted surfaces and the smooth glass surface from section Measurement of R_p?
- Discuss the difference between the R_p measurements for the glossy finish and the matte finish.

Further diffuse investigations

In collaboration with your lab partner, design an experiment to investigate some aspect of diffuse reflectivity further. You could study;

- The angular distribution of the diffusely scattered light.
- Vertical polarization.
- The de-polarisation of light. For example, suppose the input beam is horizontally polarized, is the diffusely reflected beam also entirely horizontally polarized?
- Diffuse reflection off other surfaces, such as grades of paper.
- An idea you and your lab partner think up yourself.

Document your experimental set up, method, the measurements you'll make, any calculations or graphs that you'll perform. If you have time, carry out the experiment.

Bibliography

[1] A. Marsh, "Light reflectance," Edmund Optics, 9 November 2010. [Online]. Available: http://performativedesign.com/definition/light-reflectance/. [Accessed 18 August 2017].

[2] W. contributors, "Fresnel Equations," Wikipedia, The Free Encyclopedia, 21 July 2017. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Fresnel_equations&oldid=791685545. [Accessed 18 August 2017].