A COMMENTED EXAMPLE OF A GOOD LAB WORK REPORT

Why this document?

This document summarizes with the help of an example how a good lab-work report should be written and formatted.

In black on white the actual text that should be handed to the teacher.

In grey (or red) on grey some explanations and comments.

Please read this carefully! In a good report **ALL** points need to be respected. So, if you start reading and you find a number of things that you naturally do when writing a lab work report, do not stop reading! Go through the whole document to *check that you know everything* that is explained here.

The experimental data were acquired by students in 2016 and can be found on the first tab of the Excel file 'Data and analysis.xlsx'.

The very short version of the practice work description would be:

"Measure the dependency of the intensity reflection coefficient *R* of a dielectric interface as a function of the angle of incidence θ_i when using TM (transverse magnetic) polarization and conclude on the refractive index of the used glass.
You may use:
- A laser diode module emitting a collimated monochromatic beam of light
- A rotation stage
- A glass prism
- A photodiode module
- A voltmeter
- Two polarizers."

And a second task:

"Measure the Brewster angle and conclude on the refractive index of the used glass and on the minimum deviation that the light beam undergoes when being transmitted by a prism having an angle of 60° (±15')."

First remark: The shorter the lab work description, the more detailed should be your report, as it then needs to include: (i) an explanation of the measurement protocol and (ii) a discussion of the reasons why you chose the realized measurement protocol.

Leave a margin of at least 3 cm, so the teacher can write the points and remarks

Like: POESII M1 S1 Lab work

Name 1

Course reference

Name 2

Leave some space for the teacher to write a short comment (and/or the mark)

Date

Lab work 1: Verifying the Fresnel Formula in TM polarization

If the lab work experiments are numbered, mention both number and title

Introduction

If the title is well chosen, this explains somehow the title.

In this lab work we verified experimentally that the Fresnel formula for TM polarization is correct by measuring the intensity reflected from a glass surface, in particular at Brewster angle. Finally, the measurements enable us to deduce the refractive index of the used glass.

Theoretical aspects

Define the used notations and sum up useful theory.

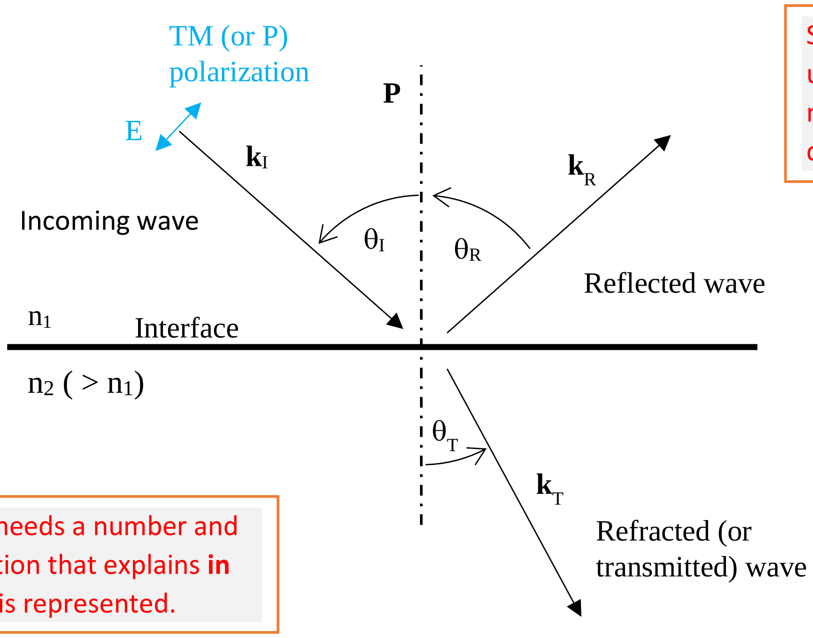
Reflection from a dielectric interface

As can be concluded from Maxwell's equations [1], electromagnetic waves are transversal waves meaning that at any time the electric field vector ***E*** the Magnetic field vector ***H*** and the propagation direction ***k*** are perpendicular to one another. If during the propagation the electric field vector vibrates in a fixed plane (that contains ***k***) one says the wave is linearly polarized.

When the wave encounters a dielectric interface at an oblique angle, one defines the 'plane of incidence' as the plane containing the normal vector **P** to the interface and the wave vector $\mathbf{k}_I$ of the incoming wave (see Figure 1). The reflected and refracted waves are also contained in the plane of incidence. The 'angle of incidence' θ_I is the angle between the normal to the interface **P** and the vector $\mathbf{k}_I$ of the incident wave.

Each figure needs to be called out in the text.

Schematics are very useful to define the notations (angles, distances and the like).



Each figure needs a number and a figure caption that explains **in detail** what is represented.

*Figure 1: Drawing of the plane of incidence defining the angle of incidence θ_I and the angle of the transmitted (refracted) ray θ_T. both measured with respect to the normal **P** to the dielectric interface between medium 1 (with refractive index n_1) and medium 2 (with refractive index n_2). In the drawing $n_2 > n_1$. TM (transverse magnetic) polarization is when the electric field vector E is comprised in the plane of incidence. This polarization is also called P-polarization.*

Put page numbers to avoid problems when pages separate.

If the wave is linearly polarized with the E-field vibrating in the plane of incidence the polarization is named TM-polarization, for transverse magnetic, or P-polarization (for parallel). The Fresnel formulas are derived from the boundary conditions of electric and magnetic fields at dielectric interfaces [2], i.e. the fact that the components of E and H that are parallel to the interface are continuous at the interface.

This (as well as [1] before) are citations of literature. Citations are needed (at least) **in every sentence where a statement is made** that is not trivial and not a conclusion from preceding text.
In science, the references of the cited literature are given at the end of the document in the bibliography section and the numbering is in the order of first appearance in the text.
Numbering and formatting of the literature references in the bibliography section is often done by specialized software. For example: Mendeley, Zotero, Endnote (must pay), Bibtex.
Citations are used to increase the confidence of the reader in your text. Thus, do not use: 'personal communication', 'my.unknown.website.tv' or other low-confidence references.

For TM-polarization, $\vec{H} = \dfrac{\vec{B}}{\mu}$ is parallel to the interface for all three waves and we get [3]:

$$\frac{\left|\vec{B}_{0,I}\right|}{\mu_I} + \frac{\left|\vec{B}_{0,R}\right|}{\mu_R} = \frac{\left|\vec{B}_{0,T}\right|}{\mu_T} \tag{1}$$

$\vec{E}$ is in the plane of incidence and using the components that parallel to the interface we get:

$$\left|\vec{E}_{0,I}\right|\cos\theta_I - \left|\vec{E}_{0,R}\right|\cos\theta_R = \left|\vec{E}_{0,T}\right|\cos\theta_T \tag{2}$$

We also have $\left|\vec{B}_0\right| = \left|\vec{E}_0\right| n$, where *n* is the refractive index of the medium in which B and E are propagating and $\mu_I = \mu_R = \mu_T \approx 1$ for non-magnetic media. So we finally get, after a sign correction [3], the reflection coefficient for the amplitude of the electric field:

$$r_{TM} = \frac{\left|\vec{E}_{0,R}\right|}{\left|\vec{E}_{0,I}\right|} = \frac{n_I \cos\theta_T - n_T \cos\theta_I}{n_I \cos\theta_T + n_T \cos\theta_I} \tag{3}$$

Where θ_T is calculated from n_I, n_T and θ_I using the refraction law $n_I \sin\theta_I = n_T \sin\theta_T$.

Long but also 'simple and important' formulas will be formatted in a separate line labelled with an equation number

The reflection coefficient R for the intensity of the electric field is simply given by:

$$R_{TM} = (r_{TM})^2 \tag{4}$$

In the theoretical part, give short developments of the important relationships that are needed afterwards. It shows that you understand the scientific context of the lab work.

The Brewster angle $\theta_{I,B}$ is the angle of incidence for which no TM polarized light is reflected. In this case the reflected and the refracted ray are perpendicular to each other: $\theta_{I,B} + \theta_{T,B} = \pi/2$.

Thus from (3) and (4) we get with $R_{TM}(\theta_{I,B}) = 0$:

$$n_T \cos\theta_{I,B} = n_I \cos\theta_{T,B} = n_I \cos\left(\frac{\pi}{2} - \theta_{I,B}\right) = n_I \sin\theta_{I,B} \tag{5}$$

Finally, the Brewster angle $\theta_{I,B}$, or simply θ_B, is obtained from:

$$\frac{\sin\theta_{I,B}}{\cos\theta_{I,B}} = \tan\theta_B = \frac{n_T}{n_I} \tag{6}$$

Deviation of a ray in a prism

Light rays transmitted by prisms are deviated by refraction at the input side and at the output side. The angle δ between input and output side links the internal angles ε that are measured with respect to the surface normal on each side of the prism (Figure 2): $\varepsilon_1 + \varepsilon_2 + (180° - \delta) = 180°$. The deviation angle D is obtained as $D = \theta_I - \delta + \theta_T$.

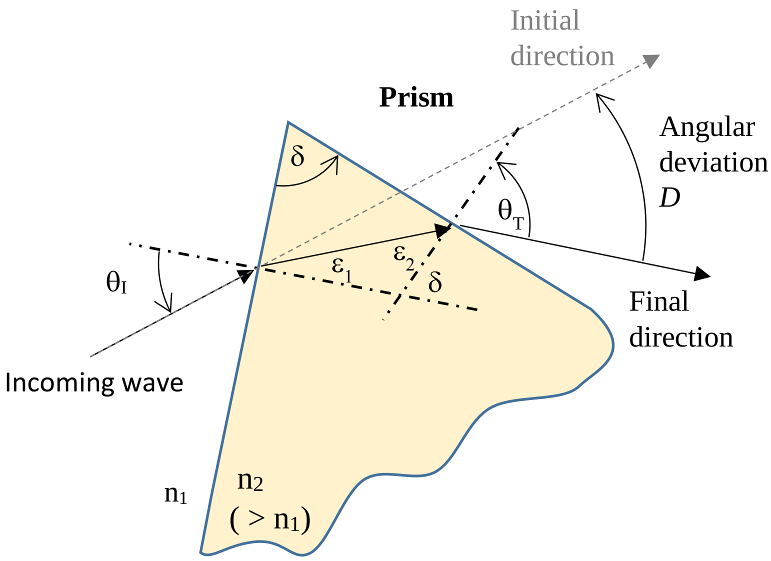


Figure 2: Drawing of the plane of incidence for a ray transmitted through a prism. D is the deviation angle caused by the prism.

The minimum angular deviation D_m of the ray is obtained when the situation is symmetric [4]: $\varepsilon_1 = \varepsilon_2 = \varepsilon$ and $\theta_I = \theta_T = \theta$. So, $\varepsilon = \delta/2$ and $\theta = (D_m + \delta)/2$ and the refraction law then yields the expression for the minimum angular deviation as function of the refractive indices and δ:

$$D_m = 2\arcsin\left(\frac{n_2}{n_1}\sin\left(\frac{\delta}{2}\right)\right) - \delta \tag{7}$$

Experimental protocol

If it was not given, develop the experimental protocol here. If it was given in the lab work description, make a short summary that shows that you understood why this protocol is used and what the critical points are.

We set up the provided elements as shown in Figure 3.

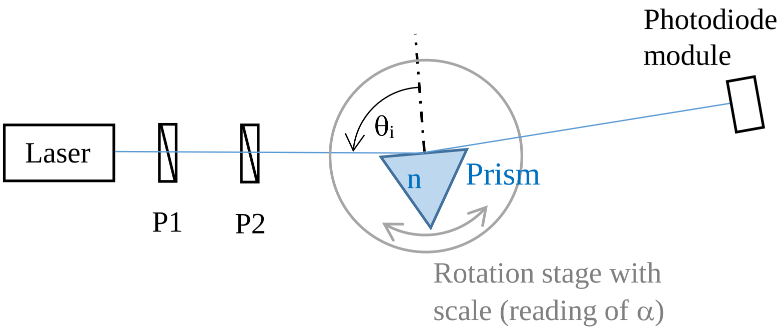


Figure 3: Schematic of the measurement setup. P1 and P2 are polarizers. The prism has refractive index n. Angle readings of the rotation stage are noted α.

Working principle:

The laser diode sends the beam through both polarizers onto the first surface of the prism on the rotation stage. The power of the beam reflected by the prism is measured using the photodiode. The second polarizer defines the polarization direction that is incident onto the prism surface and the angle of incidence is obtained from the readings of the rotation stage.

Practical aspects:

Saturation of the photodiode: Power adjustment is needed to avoid saturation of the photodiode module. The first polarizer is used to adjust the power of the beam that is incident on the prism. When both polarizers are crossed the incident power is zero, when they are parallel incident power is at its maximum.

Power measurement: The photodiode is meant to measure the power of the beam, thus the whole beam has to completely fit onto the sensitive area of the photo-diode. As the laser diode module provides a slightly diverging beam, the distance between the photodiodes and the laser source has to be sufficiently small. Additionally the position of the photodiode, which is moved at each angle of incidence to measure the power of the reflected beam, has to be precisely adjusted before each measurement to make sure no power is lost on the insensitive part of the photodiode.

Measuring high angle of incidence values: At high angles of incidence (grazing incidence) the alignment of the prism with respect to the incident beam becomes important. The full beam has to be reflected by the prism surface. The highest angle that was measured was determined by the onset of significant scattering.

Discussing these practical aspects shows that you really understood all strengths and weaknesses of your setup and that you tried your best to get good data.

Reading the angle of incidence: The angle of incidence is obtained by two readings of the rotation stage. Once the prism was positioned at the right place (rotation about the prism surface and possibility to measure large incidence angles), the angle reading for perpendicular incidence α_0 has been determined by turning the rotation stage until the reflection from the prism surface goes back to the laser. For any other position of the rotation stage α we then obtain the angle of incidence by subtraction: $\theta_i = \alpha - \alpha_0$.

Correcting for background-light: The measurements were taken with some background light present in the room. In order to remove the part of the signal coming from background light it was thus necessary to take for each angle position a reading with the laser passing through the setup and another one with the laser blocked (thus only background light reaching the detector).

Finding TM-polarization and measuring Brewster angle: Before starting the quantitative reflectivity measurements we need to make sure that TM polarization is incident on the prism. TM polarization is the only polarization where the Brewster angle can be observed. In order to find the good settings we used only one polarizer and adjusted the incidence angle and the polarizer angle until a minimum of reflected power was obtained. For this measurement the reflected power was appreciated by our eyes. The photodiode was only used for the quantitative intensity measurements.

Incident light power: The reflectivity being defined as the ratio between reflected and incident power, we also need to measure the incident light power. This was done after setting the right angles for the polarizers and before positioning the prism (without prism). In fact, the measurement of the incident light allowed us to adjust the angle of the first polarizer in order to avoid saturation of the photodiode module during this measurement. As R < 1 for all angles of incidence, no saturation can appear during the whole measurement.

Results

Brewster angle:

As described in the experimental protocol the measurement of Brewster's angle is used to find TM-polarization. We thus analyze this measurement first.

NO result without uncertainty!
Simple uncertainty calculation (like the first one) do not necessarily need to be detailed.
Intermediate steps are allowed if there are less than 3.
(my personal limit).

The obtained angle readings were:

α_0 = 88°15' (±5')   and α_B = 144°25' (±5')

Then, using $\theta_B = \alpha_B - \alpha_0$

and $\Delta\theta_B = \sqrt{\left(\frac{\partial\theta_B}{\partial\alpha}\cdot\Delta\alpha\right)^2 + \left(\frac{\partial\theta_B}{\partial\alpha_0}\cdot\Delta\alpha_0\right)^2} = \sqrt{(1\cdot\Delta\alpha)^2 + ((-1)\cdot\Delta\alpha_0)^2} = \sqrt{(\Delta\alpha)^2 + (\Delta\alpha_0)^2}$ = 7.1',

we obtain the experimental value of $\theta_{B,exp}$ **= 56°10' (± 8') = 56.17 (± 0.12)°**. The relative uncertainty is thus only 0.22%. (As long as we consider only the reading uncertainties of the α-angles.)

Refractive index and angular deviation by the prism:

Using Equations (6) and (7) we can calculate the refractive index *n* of the prism and the minimum angular deviation D_m it causes:

Using $n = \tan(\theta_B)$ and $\Delta n = \sqrt{\left(\frac{1}{\cos^2\theta_B}\cdot\Delta\theta_B\right)^2} = \frac{\Delta\theta_B}{\cos^2\theta_B}$ [5],

we obtain n_{exp} = 1.4921 (± 0.0068). The relative uncertainty is 0.46% and the absolute value is reasonable for a typical glass at 635 nm, which is the wavelength of the laser diode. For example BK7 glass would have n = 1.5150 at this wavelength and fused silica has n = 1.4570 [6]. Considering the price of fused silica it is more probable that the prism is made of BK7. The relative deviation of our experimental value from the BK7 value is approximately $(n_{exp} - n_{BK7})/n_{BK7}$ = -1.5%. This is approximately 3 times the relative uncertainty based on the reading precision of the angles on the scale of the rotary stage. In order to explain this difference we propose the following possibilities:

> **Wherever possible the results need to be compared to reference data!**
> If the theoretical value of the measurement is known the deviation of the measurement result from the reference value has to be discussed.
> In any case, a general discussion of possible errors is expected.
> This discussion is an important input for the teacher to appreciate your knowledge in the domain of the lab work.

- Our reading precision was worse than we thought (not very probable).
- The prism is made from a glass with smaller refractive index than BK7 (not very probable).
- The measurement is limited by our appreciation when the intensity minimum was reached (which is the most probable explanation for this deviation from the BK7-value.)

(However, the analysis of the R(θ_I)-curve in the next paragraph shows that the Brewster angle measurement is less precise than what we can conclude here.)

Using Equation (7) we obtain the expression below for the uncertainty in D_m:

$$\Delta D_m = \sqrt{\frac{\left(2\sin\left(\frac{\delta}{2}\right)\Delta n\right)^2}{1-n^2\sin^2\left(\frac{\delta}{2}\right)} + \left(\frac{n\cos\left(\frac{\delta}{2}\right)}{\sqrt{1-n^2\sin^2\left(\frac{\delta}{2}\right)}}-1\right)^2(\Delta\delta)^2}\ ,$$

And the expected minimum deviation is then $\mathbf{D_m}$ **= 36.50 (± 0.64)°**. (Relative uncertainty of 1.8%.)

> Best mention absolute **and relative** uncertainty, as the second gives a quick impression of the precision of the value.

Fresnel formula:

The original measurement data is given in the tab ‘Measurements’ of the attached Excel spreadsheet named ‘Data and analysis.xlsx’. Figure 4 shows graphs of the measured reflectivity as a function of the angle of incidence and compares them to the theoretical dependency given by Equations (3) and (4).

The reflectivity values *R* are obtained by dividing the reflected power P_R by the incident power P_I (power without prism). The respective powers are obtained by subtracting the background-voltage from the ‘signal+backgroung’-voltage. As for the Brewster angle measurement, the angle of incidence is obtained by subtracting the reading for perpendicular incidence from the reading for the particular situation.

> Explain the treatment of the experimental data (even if it’s very simple).
> ‘Strange’ formulations are allowed (if I make the marks) as long as they are understandable.

The uncertainty for the angle of incidence (±0.12°) is a consequence of the reading uncertainty of 5ʻ. The uncertainty for $R = P_R/P_I$ is calculated using $\Delta R = \sqrt{\frac{\Delta P_R^2}{P_I^2} + \frac{P_R^2}{P_I^4}\Delta P_I^2}$ rather than $\Delta R = R\sqrt{\left(\frac{\Delta P_R}{P_R}\right)^2 + \left(\frac{\Delta P_I}{P_I}\right)^2}$ because some readings for the reflected power P_R were zero. The uncertainty for the power values (voltages) was supposed to be 0.01 V as we are quite sure to have measured the full beam in each position and no fluctuations were observed. The resulting uncertainties are very small (±0.12° for the angle of incidence and less than ±0.13% for R) and are not visible on the graphs.

Explain the uncertainty calculations, even if at the end uncertainties are negligible.

If figures have more than one part, label with (a) etc.

In the caption refer to the labels.

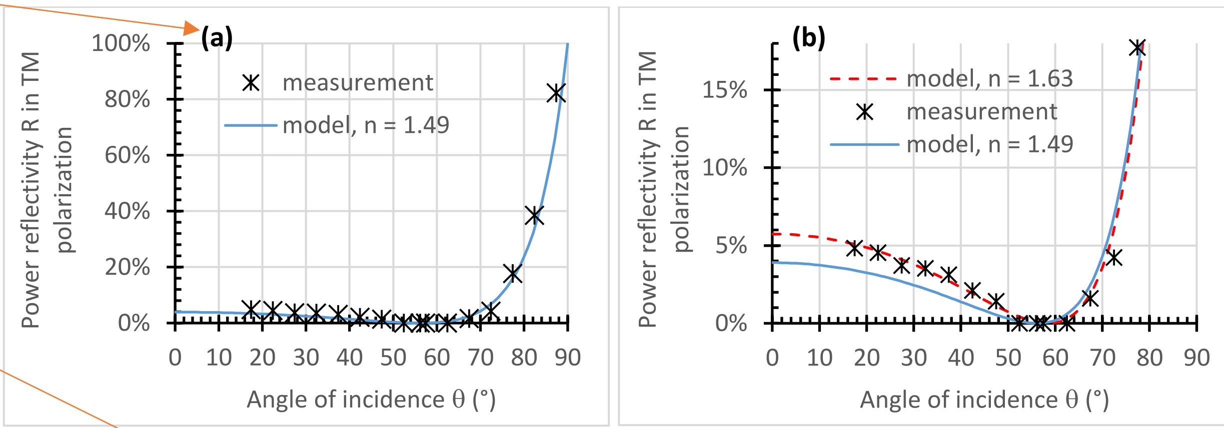


Figure 4: (a) Full scale view of the measurements and the model using the refractive index deduced from the Brewster angle measurement (n=1.49). (b) Zoomed view on the most interesting part of the curve. Comparison of the measurement with the model curves assuming two different refractive indices. Uncertainties deduced from the reading precision are negligible (see text).

Graphs are a very important part of a report or a publication.
For each axes mention 'physical quantity' (in words and symbol) and unity (in parentheses). Put a sufficient number of tick marks and at least three tick labels. Everything should be large enough to be read after printing the report. A legend is needed if there is more than one data set, a graph title is not needed (it has a figure caption and axes titles). Everything should be readable without magnifying glasses when printed. Measurements are represented by MARKERS (points) and should have error bars, model curves are represented by CURVES. Model curves are smooth (put enough x values in the table you plot).

In Figure 4(a) we observe that the model and the experimental data agree quite well. Here the model was calculated using the refractive index deduced from the Brewster angle measurement (n = 1.49). Zooming in on the R-axis we get a more detailed view in Figure 4(b). In fact all points for $\theta_I < \theta_B$ are above the model curve and 3 out of 4 points for $\theta_I > \theta_B$ are below the model curve. We thus suspect a systematic error and try to fit the model to the experimental data by varying the refractive index of the prism. Increasing the refractive index approaches model curve and experimental data on both sides of the minimum. By manual adjustment for $\theta_I < \theta_B$ a good agreement was found for n = 1.63 which is still a reasonable value for certain glass types [7] (see red dashed line in Figure 4(b)). Using QTI-plot [8] for a least-square fit on the same points gives $n_{50°} = 1.627$ (± 0.011). (If on uses all points with $\theta_i < 80°$ one obtains $n_{80°} = 1.611$ (± 0.035) and excluding one more point at $\theta_i = 77.4°$ yields $n_{75°} = 1.644$ (± 0.021).) Thus relative uncertainties for n are in the 1-2% range when using nonlinear curve fitting.

It is usual to repeat the things that are written in the figure caption also the body of the text (and partially also the other way round).

Deducing the refractive index from more than 10 measurement should be more precise than doing it from the Brewster angle measurement alone, so the possibility to fit our experimental data using n = 1.63 probably indicates that the real uncertainty in the Brewster angle measurement was much larger than the value deduced from the angle-reading precision (± 0.12°). For n = 1.63 the Brewster angle would be 58.47°, thus 2.3° more than the measured Brewster angle. This difference has to be compared to the angle range where no reflected intensity was detected during the R(θ) measurements (from 52° to 62°, thus in an interval of 10°) and the uncertainty deduced from the angle-reading precision (± 0.12°). Considering the photodiode module to be linear over the full range of used light powers, we can thus conclude that the refractive index of the prism is 1.63 and that our Brewster angle measurement deviated by approximately 2.3° (or -3.9%) from the real Brewster angle. However we did not check the linearity of the photodiode module which is important to this analysis. If the photodiode module slightly deviated from linearity towards saturation, the real value for the direct light measurement (without the prism) would be a bit higher and thus all real reflectivity values would be lower, which in turn would lead to a smaller refractive index deduced from the R(θ)-measurements. But, due to the observed asymmetry in the deviations of the experimental data from the model curve, a problem with the detector response is not very probable as it would induce a symmetric deviation.

Make detailed discussion of your measurement results. This part shows the background you have in the field of the work and the way you think.
It in fact allows to distinguish a physicist from a technician. (A bit mean this sentence, isn't it?)

Conclusion

We saw during this lab practice that using relative simple means we can determine the refractive index of a piece of glass having at least one polished side by measuring its reflectivity as a function of the angle of incidence. Measuring only the Brewster angle however seems just to give a first estimate for the refractive index value. If the piece of glass is a prism it would also be possible to measure the minimum deviation angle in order to deduce the refractive index, but we did not check this method.

In France usually a 'conclusion' section is expected in lab work reports. In scientific papers, which are somehow similar to lab practice reports, too. Mostly this comes out to write a short summary of the work.

Bibliography

Cite your sources here. Books, course hand-outs, web pages, etc.
** Attention, for some entries I put fake references, but they contain the (fake) information that should be mentioned. **

[1] Course Handout of "Theoretical electro-dynamics", University of Göttingen, 1992. (Or better, a well-known book on electrodynamics)

[2] B. E. A. Saleh and M. C. Teich "Section 6.2: Reflection and refraction" in "Fundamentals of Photonics" (2nd Edition, John Wiley & Sons, ISBN: 0-471-83965-5) p. 204 (1991). (Do not cite a book without giving a chapter or page number, best both)

[3] E. Hecht "Optics" (2nd Edition, Addison-Wesley, ISBN: ?-???-?????-?) p. 94-96 (1987).

[4] https://en.wikipedia.org/wiki/Minimum_deviation (last accessed in February 2016).

[5] Bronstein, Semendjajew "Taschenbuch der Mathematik" (24th Edition, Verlag Harri Deutsch, ISBN: 3-87144-492-8) p. 266 (1989).

[6] http://refractiveindex.info (last accessed in February 2016).

[7] Scott glass catalog map (pseudo reference)

[8] Unofficial QTI plot website: https://intranet.cells.es/Members/cpascual/docs/unofficial-qtiplot-packages-for-windows

Length of a lab work report:

This report without the comments is approximately 6.5 printed pages long. *If a short version is asked for*, you should put with highest priority the ‘results’ section which is about 2 pages long. (Remember that the ‘results’ section always includes a *critical discussion* of the results.) If there is space enough, the comments on the measurement protocol are also useful.

Sending the report by email:

If you send the report by email, the filename should include your name(s) and number and abbreviation of the lab practice it corresponds to.

F. Wagner, march 2016