



UNDERGRADUATE SENIOR PROJECT

LASER POLARIMETER FOR MEASUREMENT OF OPTICAL ACTIVITY

Natcha Nuchsirikulaphong

Advisor

Asst.Prof.Dr. Ratchapak Chitaree

Applied Optics Research Group, Department of Physics,
Faculty of Science, Mahidol University
May, 2020

Abstract

Optical activity is the ability of the material to rotate the plane of polarization. Many matters in nature have this property. Generally, we can check this ability of substance by using the polarimeter. In principle, the polarimeter is an instrument what measures the angle of rotation by passing polarized light through the substance. For the application, this process is used to measure the concentration of sugar in the syrup and can be applied for the detection of specific pathogens in medical purpose. In this project, we will create and develop the polarimeter from the optical instrument in a laboratory. Sugar crystal, the matter which has the property of optical activity will be used to confirm the results compare with the commercial polarimeter.

Keywords : Optical activity, polarimeter

Acknowledgments

First of all, I would like to thank Asst.Prof.Dr. Ratchapak Chitaree for many suggestions, supporting and, your kind of working in the Applied Optics field. Then I would like to thank all the graduate students in Applied Optics and Physics Education Laboratory for always encouraging and many recommendations to me. I would like to thanks the Department of Physics, Faculty of Science, Mahidol University. Finally, I would like to thank my friends and my family so much for their helping, supporting, and believe in me.

Contents

	pages
1. Introduction	1
1.1 Motivation	1
1.2 Contributions by the Research	1
1.3 Overview of the Report	1
2. Background knowledge	2
2.1 Optical activity	2
2.2 Polarization	2
2.3 Polarized light	3
2.3.1 Linearly polarized light	3
2.3.2 Circularly polarized light	3
2.3.3 Elliptically polarized light	4
2.4 Stokes parameters	6
2.5 Poincare sphere	8
2.6 Degree of polarization (DOP)	8
2.7 Ellipticity	9
3. Methodology	10
4. Result and Discussion	11
5. Conclusion	12
References	13

List of figures

	pages
1. Optical activity	2
2. Polarized light	2
3. Linear polarization	3
4. Circular polarization	4
5. Show the ellipse obtained by drawing the graph in the equation (9)	5
6. Elliptical polarization	6
7. Common state of polarization of light	7
8. Poincare sphere	8
9. The process of program	10
10. Process of creating polarimeter	10
11. Linear Polarized(horizontal)	11
12. Linear Polarized(vertical)	11
13. Linearly Polarized (45°)	12
14. Linearly Polarized (-45°)	12
15. Right-hand circularly polarized	13
16. Left-hand circularly polarized	13
17. Ellipse	14
18. The example of information from checking code	14-15

Chapter 1

Introduction

This report is the research explanation of the bachelor's degree student in the faculty of Science, Department of Physics, Mahidol University who was in the consultant of Asst.Prof.Dr. Ratchapak Chitaree

1.1 Motivation

Many materials in nature have an optical activity property. Optical activity is the ability of the material to rotate the plane of polarization when the light passes through it. For instance, protein, nucleic acid DNA and RNA, chlorophyll, hemoglobin, sugar and etc. also have the optical activity. Generally, for checking this ability of substance the polarimeter will be used. Polarimeter was used to measure the angle of rotation of the light. For this application it can be applied for the detection of specific pathogens in medical purposes. Therefore, it is interesting to creating and developing the polarimeter to be able to measure and show the reliable results in cheaper price.

1.2 Contributions by the Research

This work focuses on creating and developing polarimeter. So, the most of work is about writing code in Matlab for calculation and show the result in the Poincare sphere and Stoke parameters. Besides this, we also show the result in three other values. The first value is an azimuth angle that was described as the angle change caused by the rotation plane of polarization. Then the second value is the degree of polarization (DOP) which indicates the polarized light. The last value is the ellipticity, which is the ratio between the length of the minor axis and the major axis of the ellipse that is used to specify the polarization of light more clearly. Then we will check coding by using sugar solution with different concentrations.

1.3 Overview of the Report

This report is divided into five chapters. The first chapter is about the introduction and motivation of this research. The second chapter is about background knowledge about optical activity, polarized light, polarization, Poincare sphere, and Stokes parameters for this study. For the method and instrument of this research will be presented in the third chapter. The result and discussion will be presented in the forth chapter. Finally, the conclusions of this work will be described in the chapter five.

Chapter 2

Background knowledge

2.1 Optical activity

Optical activity is the ability of material to rotate the plane of polarization. It happens when the polarized light pass through the material. This phenomenon can be described by changing the angle of polarized light.

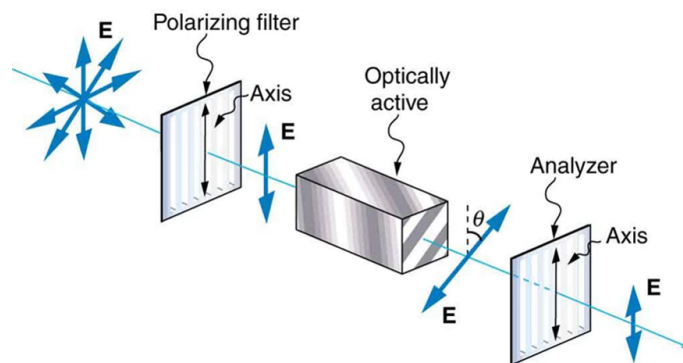


Figure 1: Optical activity

(From: <https://www.fiberoptics4sale.com/blogs/wave-optics/103704710-what-are-optically-active-materials>)

2.2 Polarization

Polarization is the process that transforms unpolarized light into polarized light. It can be created by giving the unpolarized light travel through the polarizer. The polarizer has an application to block the light and give the resultant vector in a single plane of light. So the light that comes out is polarized light.

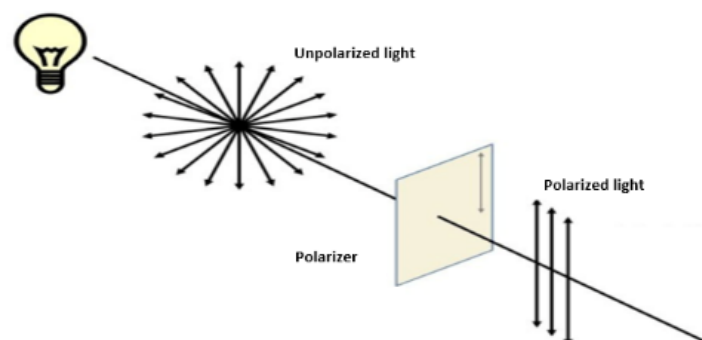


Figure 2: Polarized light

(From: <https://chsopensource.org/polarized-light-photography>)

2.3 Polarized light

2.3.1 Linearly polarized light

Light consists of the magnetic field and electric field which are perpendicular. But in general, optical analysis is preferable using the electric field. Because of the effect of the electric field on particle, such as electron, it has more effect than the magnetic field.

Linearly polarized light can be expressed by the resultant vector. The resultant vector occurs from the conclusion of a vector in the x-axis and y-axis that travel along the z-axis. While both vectors will have the same phase or different phase equal to π .

For the equation of linear polarizing light in the x-axis can be shown as follows.

$$\vec{E}_x = E_x^0 \sin[\omega t - kz - \phi_0] \hat{i} \quad (1)$$

And for the equation of linear polarizing light in the y-axis can be shown as follows.

$$\vec{E}_y = E_y^0 \sin[\omega t - kz - \phi_0] \hat{j} \quad (2)$$

So the resultant vector can be represented by the equation (3).

$$\begin{aligned} \vec{E}_0 &= \vec{E}_x + \vec{E}_y \\ &= (\vec{E}_x \hat{i} + \vec{E}_y \hat{j}) \sin[\omega t - kz - \phi_0] \end{aligned} \quad (3)$$

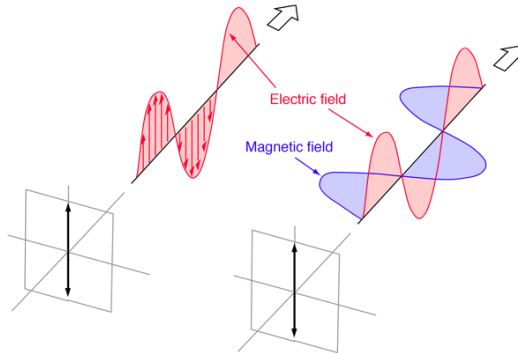


Figure 3: Linear polarization

(From: <http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html>)

2.3.2 Circularly polarized light

In the case of circularly polarized light will consider in the same amplitude but in a different phase. Where the phase difference is equal to $\pi/2$ and $-\pi/2$. The resultant vector can be represented in two case.

The first case is right circular polarized light(rcp). The phase difference between the components in the x and y axis is equal to $\pi/2$. For the resultant vector is sweeping in clockwise direction. The equation of right circular polarized light(rcp) can be shown as follows.

$$\begin{aligned}
\vec{E}_{\text{rcp}} &= E^0(\sin[\omega t - kz + \phi_0]\hat{i} + \sin[\omega t - kz + \phi_0 + \frac{\pi}{2}]\hat{j}) \\
&= E^0(\sin[\omega t - kz + \phi_0]\hat{i} + \cos[\omega t - kz + \phi_0]\hat{j})
\end{aligned} \tag{4}$$

The second case is left circular polarized light(lcp). The phase difference between the components in the x and y axis is equal to $-\pi/2$. For the resultant vector is sweeping in counter clockwise direction. The equation of left circular polarized light(lcp) can be shown as follows.

$$\begin{aligned}
\vec{E}_{\text{lcp}} &= E^0(\sin[\omega t - kz + \phi_0]\hat{i} + \sin[\omega t - kz + \phi_0 - \frac{\pi}{2}]\hat{j}) \\
&= E^0(\sin[\omega t - kz + \phi_0]\hat{i} - \cos[\omega t - kz + \phi_0]\hat{j})
\end{aligned} \tag{5}$$

Furthermore, the sum of rcp and lcp will give the result in linearly polarized light.

$$\frac{\vec{E}_{\text{rcp}} + \vec{E}_{\text{lcp}}}{2} = E^0(\sin \omega t - kz + \phi_0)\hat{i} \tag{6}$$

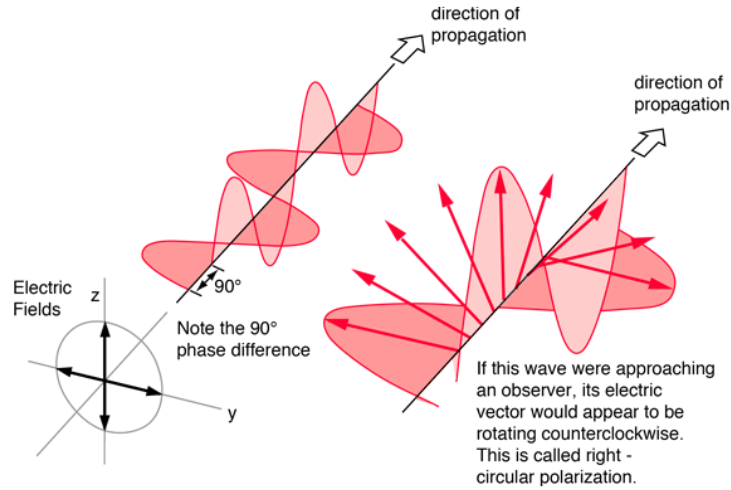


Figure 4: Circular polarization

(From: <http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html>)

2.3.3 Elliptically polarized light

In this case, the status of light in general is an elliptically polarized. The components in the x and y axis can be shown as follows.

$$\vec{E}_x = E_x^0 \sin[\omega t - kz]\hat{i} \tag{7}$$

$$\vec{E}_y = E_y^0 \sin[\omega t - kz + \Delta]\hat{j} \tag{8}$$

Noticed that the amplitude of the component in x-axis and y-axis is not necessary to be equal. For the phase difference between both component is equal to Δ . From equations (7) and (8) can be arranged in the form of an ellipse equation as follows.

$$\left(\frac{E_y}{E_y^0}\right)^2 + \left(\frac{E_x}{E_x^0}\right)^2 - 2\frac{E_y}{E_y^0}\frac{E_x}{E_x^0}\cos\Delta = \sin^2\Delta \quad (9)$$

The equation (9) is an ellipse equation in E_x and E_y axis. The major axis did the alpha angle with the x-axis.

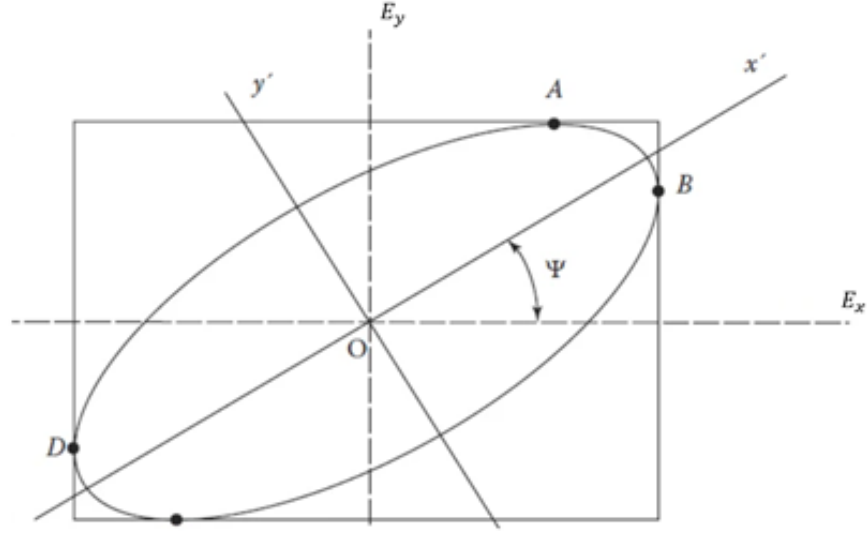


Figure 5: Show the ellipse obtained by drawing the graph in the equation (9)
(From: <https://www.fiberoptics4sale.com/blogs/wave-optics/102492742-stokes-polarization-parameters>)

$$\tan 2\alpha = \frac{2E_x^0 E_y^0 \cos \Delta}{(E_x^0)^2 - (E_y^0)^2} \quad (10)$$

For the equation (10), it use to find the value of α (azimuth). If $\alpha = 0$, the major axis and minor axis are parallel to E_x , E_y respectively. The equation (10) can be rewritten in equation (11).

$$\tan 2\alpha = \frac{2E_x^0 E_y^0 \cos \Delta}{(E_x^0)^2 - (E_y^0)^2} = 0 \quad (11)$$

So when $\Delta = \pm\pi/2, \pm3\pi/2, \dots$ and $E_y^0 = E_x^0 = E_0$, the equation (9) can be arranged in form of circle equation according to equation (12).

$$E_y^2 + E_x^2 = E_0^2 \quad (12)$$

If $\Delta = n\pi$, when n are even number the equation (9) can be rewritten as follows.

$$\left(\frac{E_y}{E_y^0}\right)^2 + \left(\frac{E_x}{E_x^0}\right)^2 - 2\frac{E_y}{E_y^0}\frac{E_x}{E_x^0}\cos\Delta = 0 \quad (13)$$

$$\frac{E_y}{E_y^0} = \frac{E_x}{E_x^0} \quad (14)$$

$$E_y = \frac{E_x}{E_x^0}E_y^0 \quad (15)$$

The equation (15) is linear equation that have slope equal to $\frac{E_y^0}{E_x^0}$. In the same way, if n are odd number the equation (9) can be rewritten to equation (16) that have slope equal to $-\frac{E_y^0}{E_x^0}$.

$$E_y = -\frac{E_x}{E_x^0}E_y^0 \quad (16)$$

The sweeping of the resultant vector of an ellipse polarized light in different directions depending on the phase difference as well as the circularly polarized light. In conclusion, an ellipse polarization is a general state of polarization. While the status of circularly polarization and linearly polarization are special case polarized status.

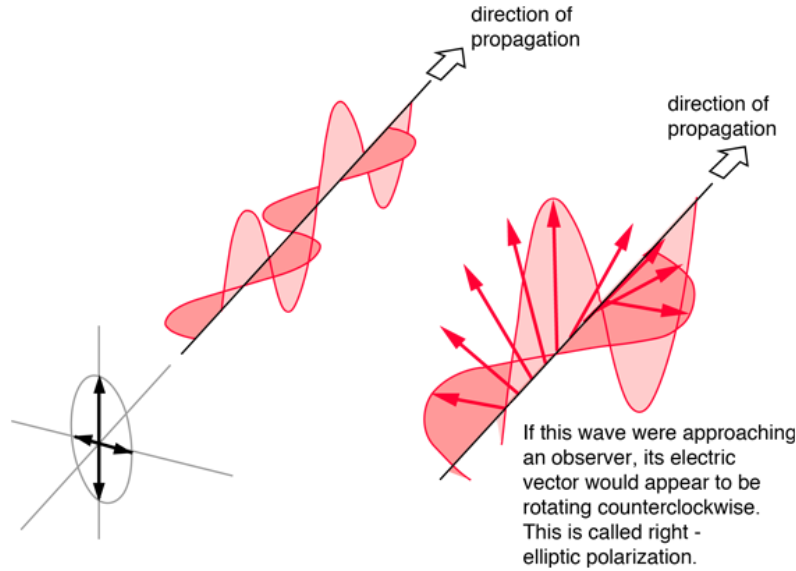


Figure 6: Poincare Sphere
(From:<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html>)

2.4 Stokes parameter

Stokes parameters were defined by George Gabriel Stokes in 1852. They were a set of values that consists of a four-component vector. That use to describes the state of polarized light.

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

Moreover, we can describe Stokes vector in terms of an electric field as in the equation (17).

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} E_{0x}^2 + E_{0y}^2 \\ E_{0x}^2 - E_{0y}^2 \\ 2E_{0x}E_{0y} \cos \delta \\ 2E_{0x}E_{0y} \sin \delta \end{pmatrix} \quad (17)$$

But in the experiment, we couldn't measure the electric field directly. Therefore, we will measure in form of the intensity of light instead. In which the intensity of light is related to the stoke vector as in the equation (18).

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} \text{intensity} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ I_{\text{rcp}} - I_{\text{lcp}} \end{pmatrix} \quad (18)$$

The examples of a common state of polarization are shown below.

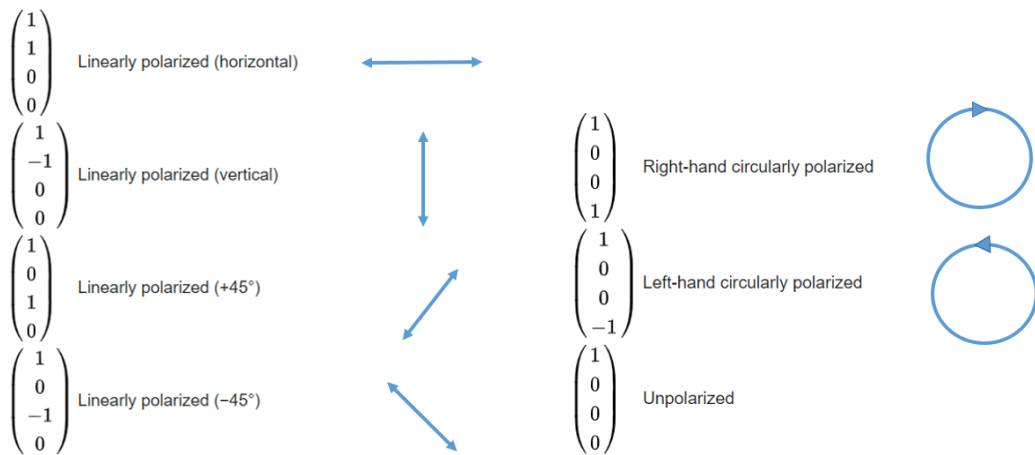


Figure 7: Common state of polarization of light
(From: https://en.wikipedia.org/wiki/Stokes_parameters)

2.5 Poincare Sphere

Poincare Sphere is another example showing the polarization status of light. Which every point on the sphere can be used to indicate the status of a polarized light. For example, at the north polar and the south polar would be represented to the right circular polarized (rcp) and left circular polarized (lcp) respectively. For the points around the equator of the sphere, it is used to represent linear polarization. The rest of the points on the sphere are used instead of elliptical polarization.

The coordinates on the Poincare sphere depend on the stoke parameter [S_1 , S_2 , S_3]. Generally, the point on the surface of Poincare sphere is due to the radius of the sphere of one unit size. And can be determined with χ and ϕ values.

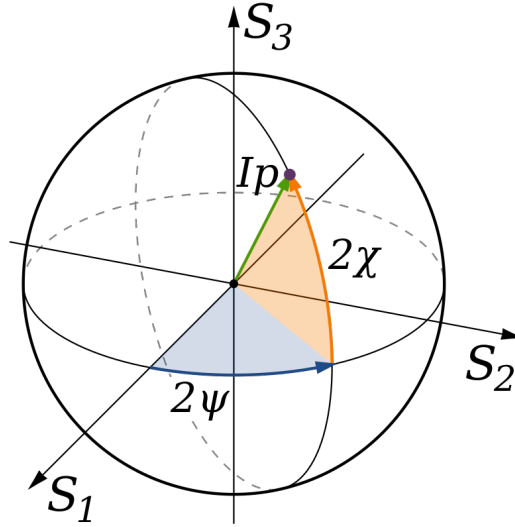


Figure 8: Poincare Sphere
(From: [https://en.wikipedia.org/wiki/Polarization\(waves\)\)](https://en.wikipedia.org/wiki/Polarization(waves))))

Where the χ and ϕ related to stoke parameter and can be found from the equation (19) and (20).

$$2\chi = \arctan \frac{S_3}{\sqrt{S_1^2 + S_2^2}} \quad (19)$$

$$2\phi = \arctan \frac{S_2}{S_1} \quad (20)$$

2.6 Degree of polarization (DOP)

Degree of polarization (DOP) is the quantity that represents the polarization of light. We can calculate value of DOP from equation (21).

$$\text{DOP} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \quad (21)$$

While $\text{DOP} = 1 \rightarrow$ Completely polarized light

$\text{DOP} = 0 \rightarrow$ Unpolarized light

$0 < \text{DOP} < 1 \rightarrow$ Partially polarized

2.7 Ellipticity

Generally, ellipticity is proportional between the length of the minor axis and major axis of ellipse. In this case, the ellipticity will be used to indicate the polarization of light more clearly. We can calculate the value of ellipticity from equation (22).

$$e = \tan \frac{1}{2} \left(\frac{S_3}{\sqrt{S_1^2 + S_2^2 + S_3^2}} \right) \quad (22)$$

For each type of polarized light has a different ellipticity.

$e = 0 \rightarrow$ Linearly polarized light

$e = 1 \rightarrow$ Circularly polarized light

$0 < e < 1 \rightarrow$ Elliptically polarized light

Chapter 3

Methodology

In this work, the Matlab code used to generate the program for the analysis part of the polarimeter what I plan to create. The overall process of this program; the first step is enter the light intensity that obtained from the polarizer in each degree. For the second step, the program will calculate the intensity value and show the result in various form which are the Poincare sphere, the Stokes parameters, state of light, graph, the Degree of polarization(DOP) and the ellipticity.

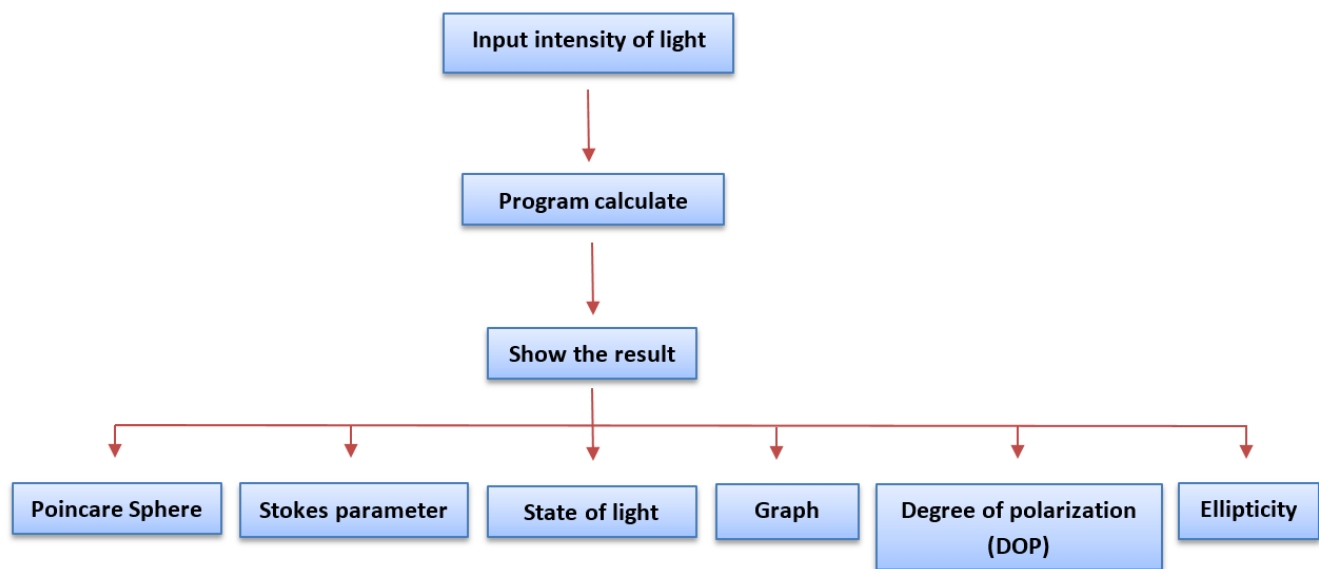


Figure 9: The process of program

Devices that used for creating the polarimeter include laser, polarizer, a quarter-wave plate, Photodetector, Arduino board, and computer. The principle of this process is shooting a laser through the polarizer to create linearly polarized light (or shooting laser through the polarizer and quarter-wave plate to create circularly polarized light). After the laser travels through the substance it will be detected by a photodetector and the collected values will be operated by program. The signal will connect to the computer by the Arduino board and show the result that we want.

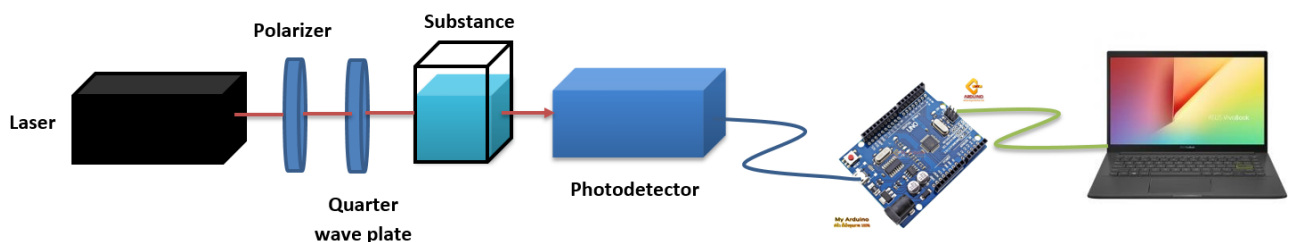


Figure 10: Process of creating polarimeter

Chapter 4

Result

From the program the result that we get after calculate were shown in form of Poincare sphere, Stokes parameter, State of light, graph, Degree of polarization(DOP) and ellipticity.

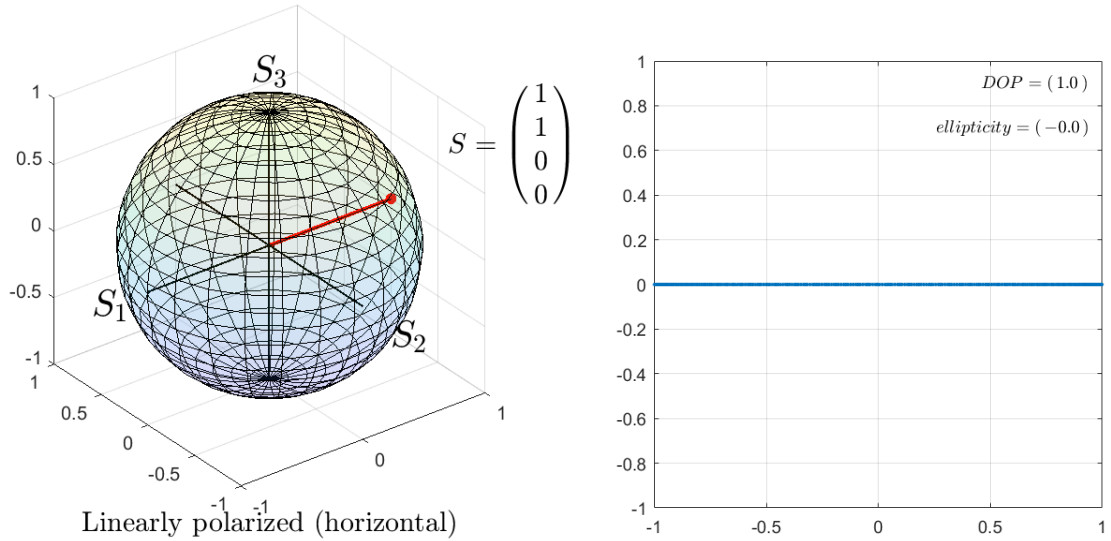


Figure 11: Lineraly Polarized (horizontal)

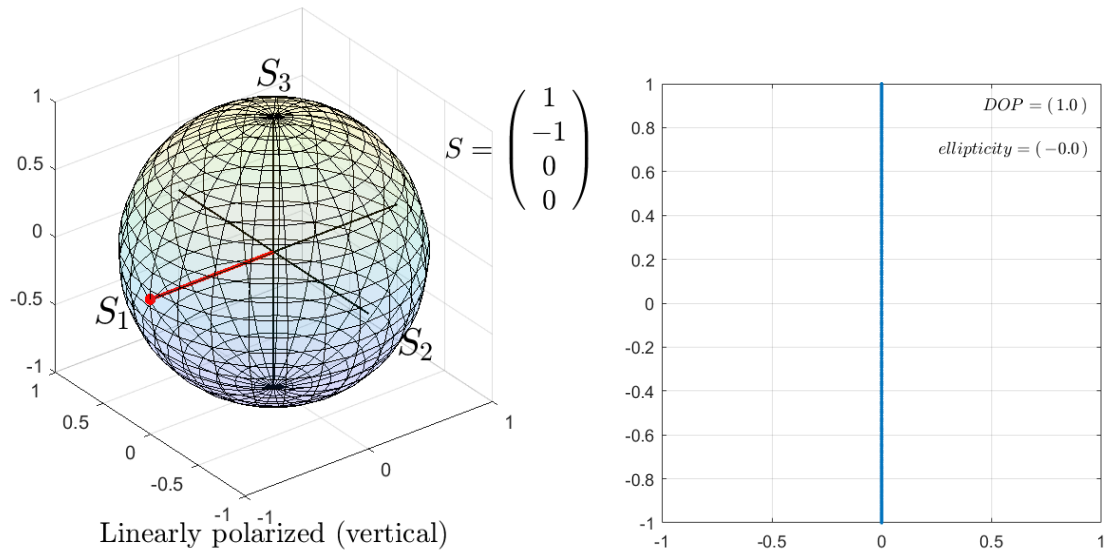
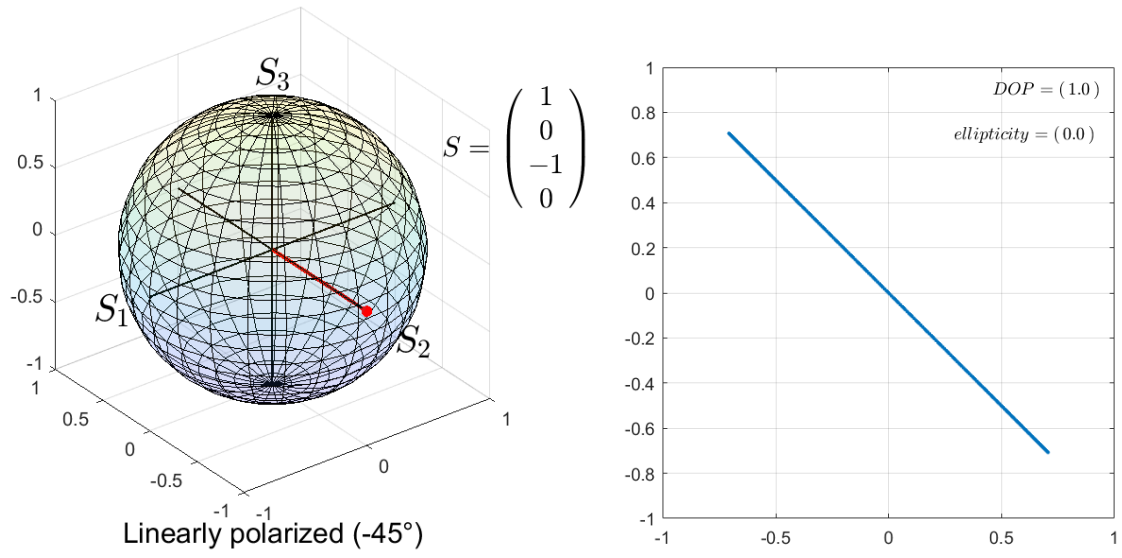
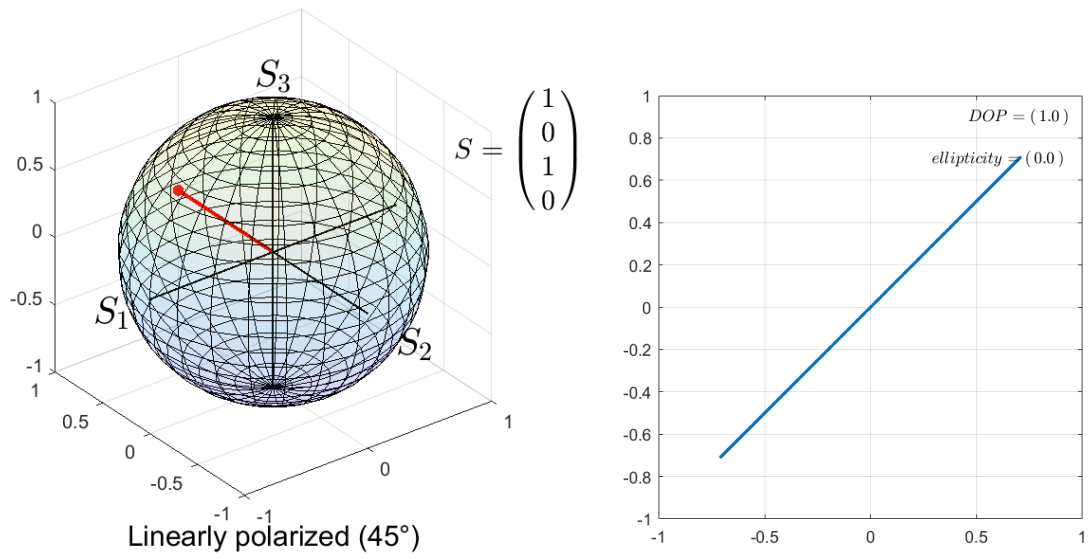


Figure 12: Lineraly Polarized (vertical)

Figure 13: Linearly Polarized (-45°)Figure 14: Linearly Polarized (45°)

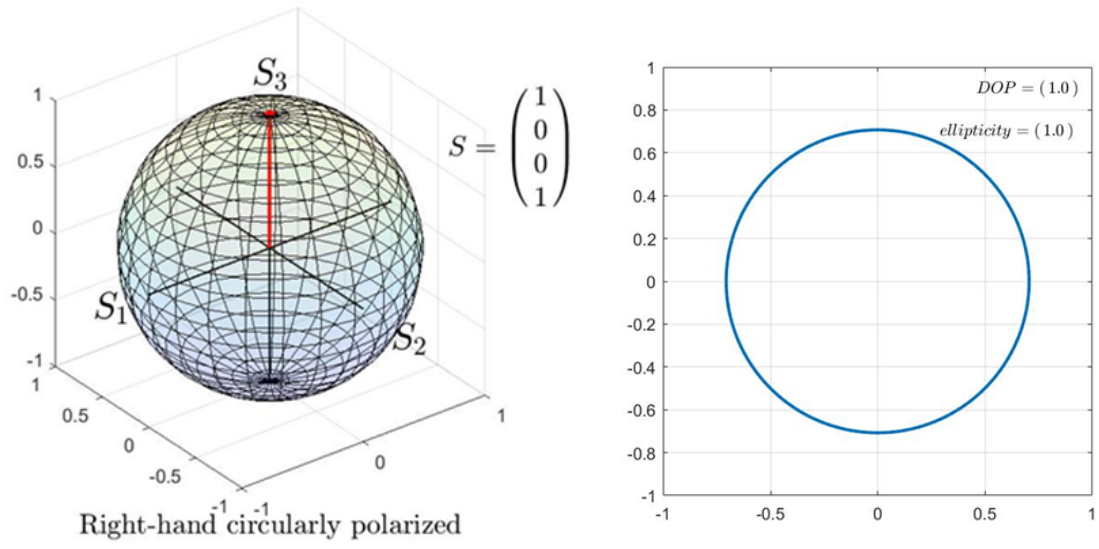


Figure 15: Right-hand circularly polarized

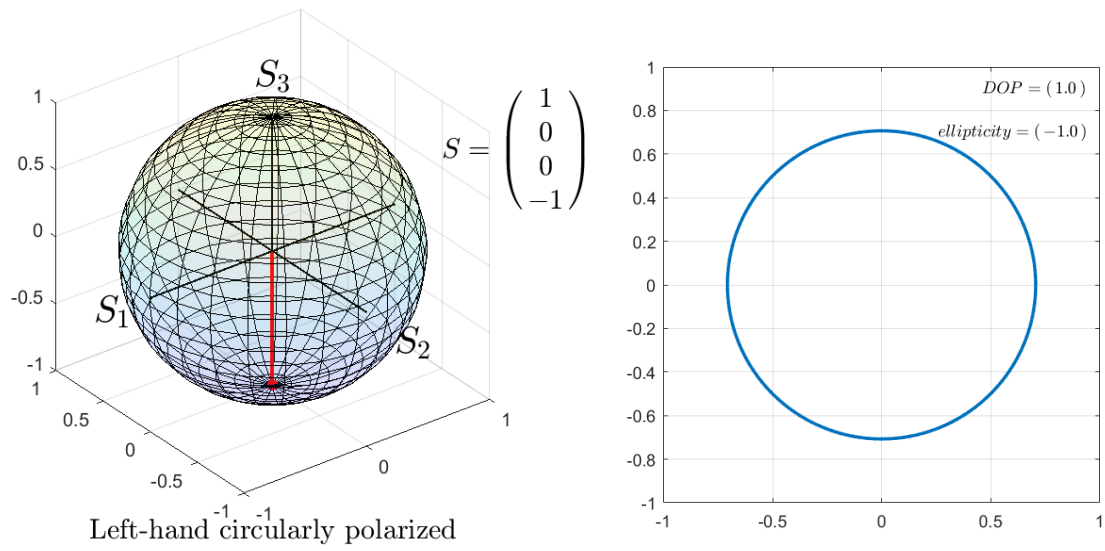


Figure 16: Left-hand circularly polarized

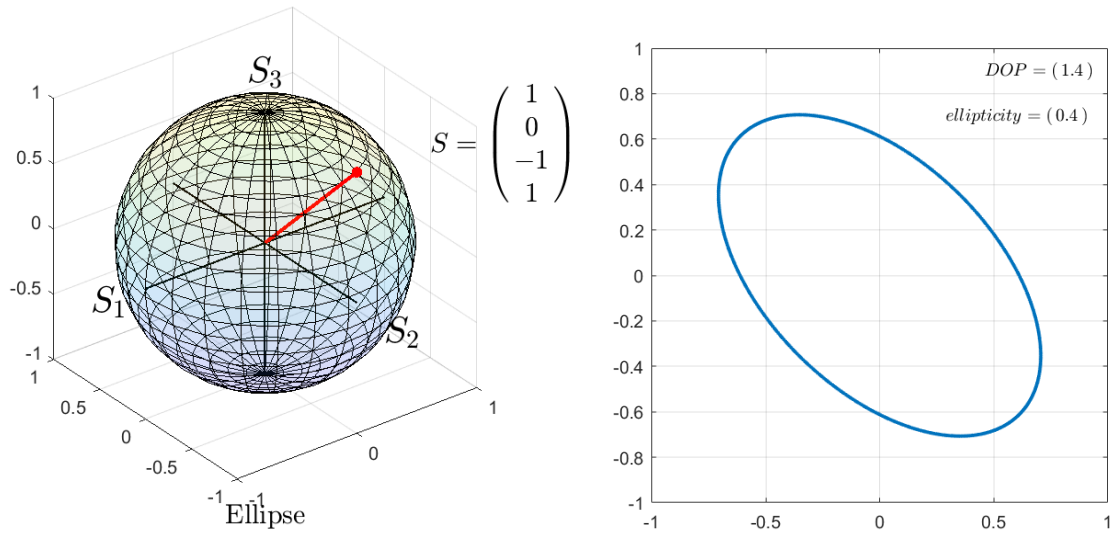


Figure 17: Ellipse

In summary, the program can be used and give the reasonable results by input the stoke parameters of known cases as shown in fig. 11-17. Even so the validity of the program has been checked by random the intensity that passes through the polarizer in each degree. However some random values stay under some conditions that will make the answer incorrect. For example, if the value of I_{lcp} exists the value I_{rcp} should be 0. In the other hand, if the value of I_{rcp} exists the value of I_{lcp} should be 0. The table below is an example of information from checking code.

S_0	S_1	S_2	S_3	state of light	I0	I90	I45	I135	Ircp	Ilcp
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	0	1
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	0	2
1	0	0	1	Right-hand circularly polarized	1	1	0	0	1	0
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	1	2
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	1	3
1	0	0	1	Right-hand circularly polarized	1	1	0	0	2	0
1	0	0	1	Right-hand circularly polarized	1	1	0	0	2	1
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	2	3
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	2	4
1	0	0	1	Right-hand circularly polarized	1	1	0	0	3	1
1	0	0	1	Right-hand circularly polarized	1	1	0	0	3	2
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	3	4
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	3	5
1	0	0	1	Right-hand circularly polarized	1	1	0	0	4	2
1	0	0	1	Right-hand circularly polarized	1	1	0	0	4	3
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	4	5
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	4	6
1	0	0	1	Right-hand circularly polarized	1	1	0	0	5	3
1	0	0	1	Right-hand circularly polarized	1	1	0	0	5	4
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	5	6
1	0	0	-1	Left-hand circularly polarized	1	1	0	0	5	7

1	-1	0	1	Ellipse	1	3	6	6	8	5
1	-1	0	1	Ellipse	1	3	6	6	8	6
1	-1	0	0	Linearly polarized (vertical)	1	3	6	6	8	7
1	-1	0	0	Linearly polarized (vertical)	1	3	6	6	8	9
1	-1	0	-1	Ellipse	1	3	6	6	8	10
1	-1	0	1	Ellipse	1	3	6	6	9	6
1	-1	0	1	Ellipse	1	3	6	6	9	7
1	-1	0	0	Linearly polarized (vertical)	1	3	6	6	9	8
1	-1	0	0	Linearly polarized (vertical)	1	3	6	6	9	10
1	-1	0	1	Ellipse	1	3	6	6	10	7
1	-1	0	1	Ellipse	1	3	6	6	10	8
1	-1	0	0	Linearly polarized (vertical)	1	3	6	6	10	9
1	-1	0	0	Linearly polarized (vertical)	1	3	6	7	0	1
1	-1	0	-1	Ellipse	1	3	6	7	0	2
1	-1	0	-1	Ellipse	1	3	6	7	0	3
1	-1	0	0	Linearly polarized (vertical)	1	3	6	7	1	0
1	-1	0	0	Linearly polarized (vertical)	1	3	6	7	1	2
1	-1	0	-1	Ellipse	1	3	6	7	1	3
1	-1	0	-1	Ellipse	1	3	6	7	1	4
1	-1	0	1	Ellipse	1	3	6	7	2	0
1	-1	0	0	Linearly polarized (vertical)	1	3	6	7	2	1
1	-1	0	0	Linearly polarized (vertical)	1	3	6	7	2	3

Figure 18: The example of information from checking code

Chapter 5

Conclusion

This final chapter concludes the whole study in this work. For the reason that I am interested in this project because the polarimeter that has been sold in the market are quite expensive. Moreover, the operation is quite difficult due to the installation of the device need to have precision. So I would like to create and develop the polarimeter to be easier for using, cheaper and give the reliable result.

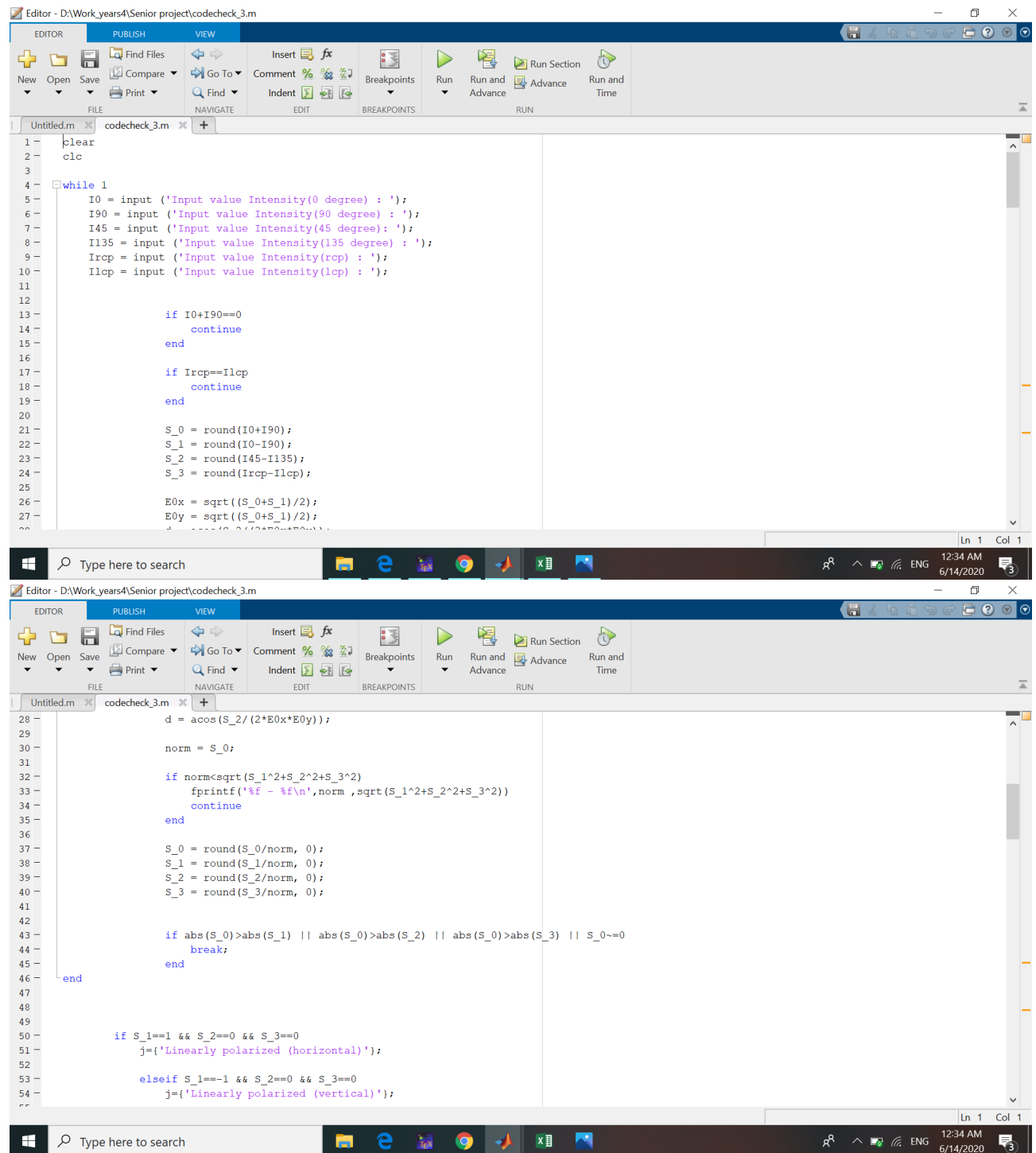
In my plan, the validity of the program can be checked by using the commercial polarimeter in the laboratory for data comparison. Then I will design and create my own polarimeter. However, because of the problem of instrument in the laboratory. It is impossible to store data for comparison, as well as the COVID situation that occurs, I don't have tools for do the experiment. I can only writing code to be used as part of analysis of the device and suppose the intensity value to check reliable of the code.

For coding part, it was wrote to have easy function to use. The principle of working is input intensity when the light travel through polarizer in each degree. Then it was calculate and show result of state of light in form of Poincare sphere, Stoke parameter and graph. Moreover, program will calculate DOP and ellipticity too.

References

- [1] Eugene Hecht, OPTIC, fifth edition, 2017
- [2] Ratchapak Chitaree, The analysis of the optical polarization state, 1968
- [3] Stokes polarization parameter, [Online]. Available: <https://www.fiberoptics4sale.com/blogs/wave-optics/102492742-stokes-polarization-parameters>
- [4] Wikipedia, Stokes parameter, [Online]. Available: https://en.wikipedia.org/wiki/Stokes_parameters
- [5] Britannica, Optical activity, [Online]. Available: <https://www.britannica.com/biography/Frederic-Stanley-Kipping>
- [6] Physics classroom, Polarization, [Online]. Available: <https://www.physicsclassroom.com/class/light/Lesson-1/Polarization>
- [7] Edmund optic, Introduction to polarization, [Online]. Available: <https://www.edmundoptics.com/knowledge-center/application-notes/optics/introduction-to-polarization/>
- [8] Wikipwdia, Polarization ellipse, [Online]. Available: https://en.wikipedia.org/wiki/Elliptical_polarization

Appendix



The image displays two screenshots of a MATLAB editor window, showing code for calculating the degree of polarization. The code is organized into two sections, each starting with a 'while 1' loop.

Top Screenshot (Lines 1-27):

```

1 clear
2 clc
3
4 while 1
5     I0 = input('Input value Intensity(0 degree) : ');
6     I90 = input('Input value Intensity(90 degree) : ');
7     I45 = input('Input value Intensity(45 degree) : ');
8     I135 = input('Input value Intensity(135 degree) : ');
9     Ircp = input('Input value Intensity(rcp) : ');
10    Ilcp = input('Input value Intensity(lcp) : ');
11
12
13    if I0+I90==0
14        continue
15    end
16
17    if Ircp==Ilcp
18        continue
19    end
20
21    S_0 = round((I0+I90)/2);
22    S_1 = round((I0-I90)/2);
23    S_2 = round((I45-I135)/2);
24    S_3 = round((Ircp-Ilcp)/2);
25
26    E0x = sqrt((S_0+S_1)/2);
27    E0y = sqrt((S_0-S_1)/2);

```

Bottom Screenshot (Lines 28-54):

```

28    d = acos(S_2/(2*E0x*E0y));
29
30    norm = S_0;
31
32    if norm<sqrt(S_1^2+S_2^2+S_3^2)
33        fprintf('%f - %f\n',norm,sqrt(S_1^2+S_2^2+S_3^2))
34        continue
35    end
36
37    S_0 = round(S_0/norm, 0);
38    S_1 = round(S_1/norm, 0);
39    S_2 = round(S_2/norm, 0);
40    S_3 = round(S_3/norm, 0);
41
42
43    if abs(S_0)>abs(S_1) || abs(S_0)>abs(S_2) || abs(S_0)>abs(S_3) || S_0~=0
44        break;
45    end
46 end
47
48
49
50 if S_1==1 && S_2==0 && S_3==0
51     j='Linearly polarized (horizontal)';
52
53 elseif S_1==-1 && S_2==0 && S_3==0
54     j='Linearly polarized (vertical)';

```

Editor - D:\Work_years4\Senior project\codecheck_3.m

```

56-         elseif S_1==0 && S_2==1 && S_3==0
57-             j=sprintf('Linearly polarized (45%s)', char(176));
58-
59-         elseif S_1==0 && S_2==-1 && S_3==0
60-             j=sprintf('Linearly polarized (-45%s)', char(176));
61-
62-         elseif S_1==0 && S_2==0 && S_3==1
63-             j={'Right-hand circularly polarized'};
64-
65-         elseif S_1==0 && S_2==0 && S_3==-1
66-             j={'Left-hand circularly polarized'};
67-
68-         elseif S_1==0 && S_2==0 && S_3==0
69-             j={'Unpolarized'};
70-
71-         else
72-             j={'Ellipse'};
73-
74-     end
75-     %plotBlochSphere.m
76-     [Xs, Ys, Zs] = sphere(25);
77-     mySphere = surf(Xs, Ys, Zs);
78-     axis equal
79-
80-     text(0, 0, -2.1, j, 'Interpreter', 'latex', ...
81-         'FontSize', 15, 'HorizontalAlignment', 'Center')
82-     hold off

```

script | Ln 47 Col 9

Type here to search | 12:36 AM 6/14/2020

Editor - D:\Work_years4\Senior project\codecheck_3.m

```

85-     %shading interp
86-     mySphere.FaceAlpha = 0.11;
87-
88-     line([-1 1], [0 0], [0 0], 'LineWidth', 1, 'Color', [0 0 0])
89-     line([0 0], [-1 1], [0 0], 'LineWidth', 1, 'Color', [0 0 0])
90-     line([0 0], [0 0], [-1 1], 'LineWidth', 1, 'Color', [0 0 0])
91-
92-
93-     text(0, 0, 1.3, '$S_3$', 'Interpreter', 'latex', ...
94-         'FontSize', 20, 'HorizontalAlignment', 'Center')
95-     text(-1.3, 0, 0, '$S_1$', 'Interpreter', 'latex', ...
96-         'FontSize', 20, 'HorizontalAlignment', 'Center')
97-     text(0, -1.5, 0, '$S_2$', 'Interpreter', 'latex', ...
98-         'FontSize', 20, 'HorizontalAlignment', 'Center')
99-
100-     line([0 S_1], [0 S_2], [0 S_3], 'LineWidth', 2, 'Color', [1 0 0])
101-     hold on
102-     plot3(S_1, S_2, S_3, 'r', 'markersize', 20)
103-
104-     A = sprintf('$$S=\backslash pmatrix{ %d \cr %d \cr %d \cr %d }$$', S_0, S_1, S_2, S_3);
105-
106-     text(1, -1.3, 1, A, 'Interpreter', 'latex', ...
107-         'FontSize', 15, 'HorizontalAlignment', 'Center')
108-
109-     L = 600*(10^(-9)); %Lambda
110-     k = 2*pi/L; % wave number k=2pi/lambda
111-     jj = -pi:pi/360:pi; %time
112-

```

script | Ln 47 Col 9

Type here to search | 12:36 AM 6/14/2020

