EXPERIMENTAL CHARACTERIZATION OF POLARIZED LASERS

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Abstract

The transversal nature of electromagnetic waves gives rise to a characteristic of light called polarization. It is by studying polarization that we can construct optical systems that enable physicists to exploit the wave nature of light. The following work aims to expose a complete process of characterizing the polarization state of a LASER beam. First, a brief framework is constructed on Polarization theory. Then, characterization techniques are presented in a sequential way; building from linear to circular polarization.

1 Introduction

Most sources of light can be characterized as non polarized, de-coherent and transversal electromagnetic waves. This means that light rays - for instance from the sun - are composed of transversal electromagnetic oscillations with random spatial orientations and temporal decoherence. However, in its simplest and purest form, light has a preferred spatial orientation as shown in figure 1. This state of light is referred to as polarized light.

This work aims to explain a complete process of characterizing the polarization of a LASER beam. This is with the objective of reinforcing the basic principles behind polarization through hands-on experimentation. The team creates a empirical argument of how polarized light behaves when subjected to different optical elements.

2 Materials

1. LASER HeNe (633nm, 15mW)
2. 2 Linear Polarizators.
3. 2 Retarder of quarter wavelength.
4. 1 Retarder of half wavelength.
5. Power / Intensity Measurement device.
6. Fixed Optic Mounts.
7. 2 Mirrors.
8. 1 Collimator.
9. 1 Pupil.
10. Security Glases.

3 Theoretical Framework

3.1 ELECTROMAGNETIC WAVES

An electromagnetic wave as shown in figure 1 can be characterized by its amplitude (E_o), frequency (w), phase (ϕ), direction of the wave ($\vec{k}$) but also the direction of displacement ($\vec{P}$). Note that these last vectors are not the same. The former ($\vec{k}$) refers to the direction in which the light ray propagates and the latter refers to the direction of oscillation.

Def. Polarization: The direction of the displacement vector is called the *direction of polarization*. Furthermore the plane on which this vector lives and oscillates is the plane of polarization [2].

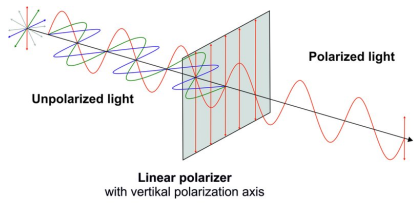

Figure 1: Polarized vs Non Polarized light

On the nature of Circular Polarization

A very interesting state of polarization is circular polarization. When we introduce a phase difference equal to $\pi/2$ between the two perpendicular and constituent [1] components of light, the resulting vector of polarization ($\vec{P}$) propagates in time and space in one of two ways: (i) circular orbits if the components have the same amplitudes or (ii) elliptical orbits if there exists a difference between the components amplitudes. Figure 2 illustrates this state.

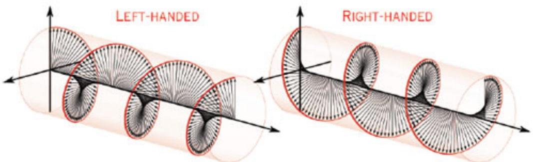

Figure 2: Circular Polarization Illustration (N.A)

One of the biggest misconceptions about this state of polarization is that at any given instant, the polarization state is a circle. Truth is that circular polarization is an emergent illusion that is due to the perpendicular components oscillating out of phase by exactly $pi/2$. This quantity can also be related to the wavelength of the beam. For this case this relation is $\lambda/4$.

3.2 OPTICAL ELEMENTS

The main elements for characterizing the polarization of a beam are presented in this section.

Def. Polarizer: A polarizer is an optical element that only allows one direction of polarization to be transmitted. For instance, a diagonal polarization incident on a vertical polarization will lose its horizontal component and the transmitted wave will be vertical.

Def. Retarder: This type of plate has two different refraction indices on its main perpendicular axis. The axis with a smaller refractive index (n_f) will be the fast axis, the other axis with n_s will be the slow axis. Both refractive indices relate to the thickness (d) of the element by the relation

$$d = \frac{\lambda}{4(n_s - n_f)}. \tag{1}$$

Equation 1 states a retarder is dependent on the wavelength (λ) of the beam that is incident. The other key takeaway is that these elements introduce a difference in phase on the components of the light by allowing one component to move fast and the other slow. We will refer to this difference in phase as ψ when we present the experimental results.

3.3 MALUS LAW

Mauls Law is a straight forward mathematical derivation of the power or intensity of a polarized light ray as the polarizer rotates along the optical axis a given angle θ. The relation

$$I_{tot} = I_{max} * cos(\theta),$$

is a power full tool to determine a certain state of polarization by measuring the intensity experimentally with previous knowledge of the maximum value I_{max}.

3.4 STOKES PARAMETERS

The stokes parameters yield information about the polarization state of a particular beam of light. Furthermore, they can be measured in experiments an hence serve as a practical tool that helps when characterizing optical systems. The parameters are the following:

1. $S_0 = |E_x|^2 + |E_y|^2$
   Total power density
2. $S_1 = |E_x|^2 - |E_y|^2$ Difference between power density transmitted by 2 perpendicular directions of polarization; horizontal and vertical.
3. $S_2 = |E_d|^2 - |E_ad|^2$ Difference between power density transmitted by 2 perpendicular directions of polarization; diagonal and anti-diagonal.

[1]A state of polarization can be mathematically modeled as a vector containing a direction $\hat{x}$ and $\hat{y}$

4. $S_3 = |E_R|^2 - |E_L|^2$ Difference between power density transmitted by 2 perpendicular directions of polarization; circular right and left.

A more elegant way of visualizing such parameters is with a Poincare Sphere (Figure 3). In this phase space, each axes represent a possible polarized state. A vector within this sphere is a possible polarization state for light.

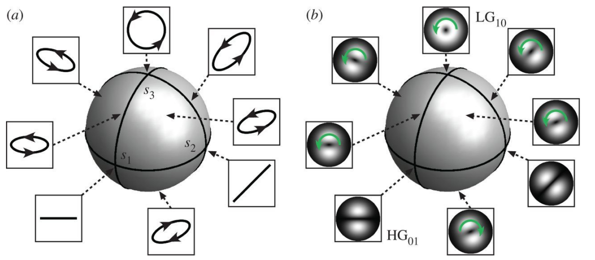

Figure 3: Poincare Sphere [1]

4 Results

4.1 CHARACTERIZATION OF LINEAR POLARIZATION

First, we align the lazer by adjusting the two mirrors in our optical arrangement. This is important in order to ensure a fixed and straight optical path throughout our optical elements.

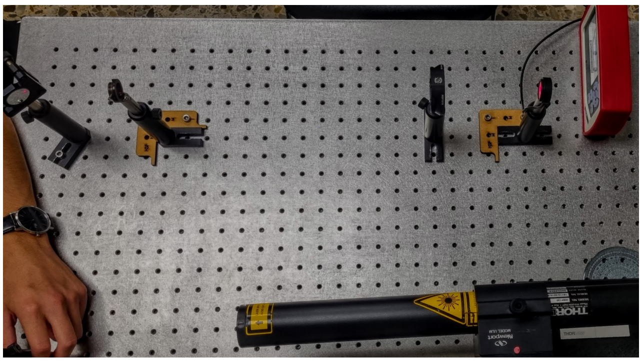

Figure 4: LASER (Bottom Right), aligned mirrors (left side), polarizer (center right) and intensity measurement device (far right).

Once the LASER is aligned, we setup the polarizer and the intensity measurement device. We rotate the polarizer until we obtain a maximum and a minimum value. The values are presented in table 1

	Intensity	Angle
Maximum	10.63 mW	357 *degree*
Minimum	0.02 mW	87 *degree*

Table 1: Measurements of Maxima of the LASER

Because these extrema angles are perpendicular to each other it is possible to conclude that the LASER-beam is linearly polarized. However because the polarizer does not indicate its orientation of polarization, we are not able to determine the polarization of the beam.

To determine the orientation of the polarizer it is necessary to find a source of polarized light with a known linear polarization [2]. For such source, the team used a digital screen to determine that at the 100 degree mark, the polarizer blocks the vertical polarization of the screen (Figure 5).

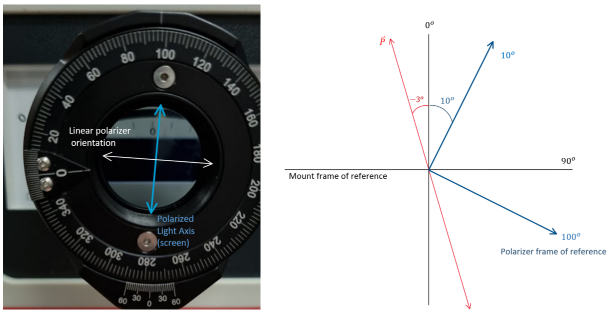

Figure 5: Polarization Diagrams used to determine polarization

This leads us to conclude that the LASER beam in our setup has anti-diagonal polarization ($\vec{P}$) with a -13^o degree shift with respect to the polarizer frame of reference. A diagram illustrating the previous results is presented in figure 5.

[2] An example of such source can be light reflected from a surface at Brewster angle or a digital screen.

4.2 EMPIRICAL PROOF OF MALUS LAW

Rene Descartes once said ”The conquest of nature is to be achieved through number and measure”. In section 8, we exposed that Mauls Law is a simple mathematical derivation that uses basic geometrical considerations about light and leads to a relation between the polarizer, the polarized beam and the intensity or power [3]. In this section, the team aims to test experimentally that this law holds for our arrangement.

To test this law, the team uses the setup exposed in figure 4.We start to vary the angle of the polarizer and take discrete measurements of intensity (Figure 7). After the data is collected, a few considerations are taken into account to calibrate and define the angle 0^o. The results obtained are presented in the figure 6.

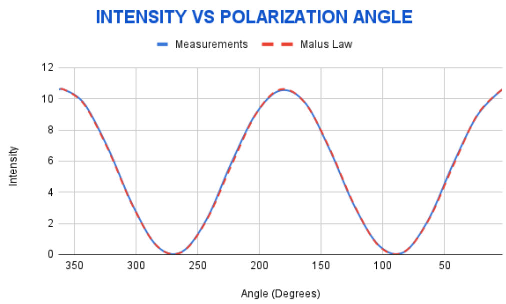

Figure 6: Test of Malus Law

The results leads us to state that Mauls law holds in our experiment. After a carefull study of the difference in values, the team obtained a relative error of 1.04%. The fact that we proved empirically that measurements match the theory lets us use Malus law as a tool in future characterizations with a high certainty.

[3]For practical purposes, we do not differentiate between intensity and power.

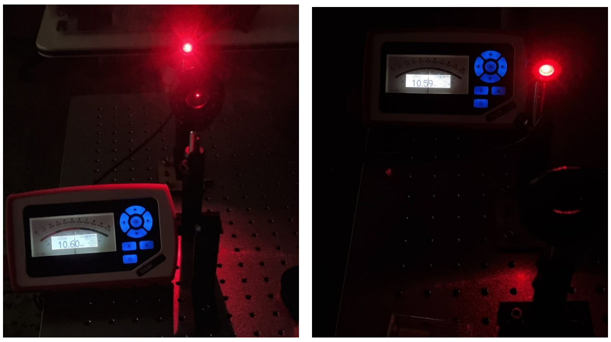

Figure 7: Polarization setup to test Malus Law

4.3 INDUCE A CIRCULAR POLARIZATION

The arrangement presented in figure 8 is made in order to generate and characterize circular polarization.

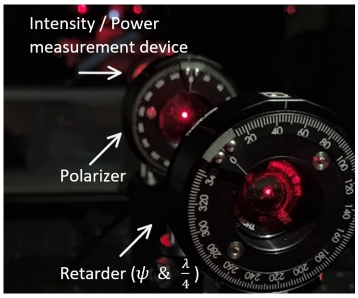

Figure 8: Circular polarization setup

First, the team varied the angle on the retarder until we obtained a value of intensity of $10.57mW$. At this configuration we state that the linear polarized LASER orientation is parallel to the orientation of the fast (or slow) axis of the retarder plate. To verify such statement the team proceeded to vary 90 degrees the angle of the retarder and we obtained another maxima of $10.40mW$. This means that now the LASER polarization is perfectly parallel to the other axis of the retarder. Then, we proceeded to vary the retarder angle -45 degrees to induce circular polarization. We can verify that we obtained this state by varying the polarizer angle. Since its circular polarization, we expect to have minimum variations in intensity as we vary the polarizer orientation since the polarized state is rotating in time in all orientations. To the teams satisfaction, the results of varied between $5.11mW$ and

$5.53mW$. These values correspond to half of the total intensity because at any given angle, the polarizer blocks half of the energy that the circular polarization has.

4.4 INDUCE A PERPENDICULAR POLARIZATION

Just as we have retarders of $\psi = pi/2$, there are retarders that introduce a phase difference of pi or $\lambda/2$ to polarized states. The effect of such elements are that they rotate the state of polarization by 90 degrees.

To induce such polarization, the team took the setup presented in 7 and change the $\lambda/4$ retarder to a $\lambda/2$ retarder. When such element was introduced the intensity measurement was $0.00mW$ this is because the polarizer in front of the retarder was oriented to allow vertical polarization and the retarder induced a horizontal polarization on the incident vertical polarization.

4.5 CHARACTERIZATION OF CIRCULAR POLARIZATION WITH STOKES PARAMETERS

From a practical standpoint, the Stokes parameters narrow down to 4 simple questions: (i) How much intensity or power a given light source has, (ii) How much is it polarized in the horizontal-vertical direction, (iii) How much is it polarized in the diagonal-anti diagonal direction and (vi) How much is it polarized in the circular L-R direction? For this reason, it is of great interest for physicists that try to characterize light in experimental setups to determine.

To determine these parameters for circular popularization states, the team built the following optical system presented in figure 7 once again inserting the $\lambda/4$ retarder. Later, we varied the linear polarizer to obtain the following measurements for each polarization state (Table 2).

	E_1	E_2	Value
S_0	5.27	5.28	10.55
S_1	5.27	5.28	-0.01
S_2	5.46	5.44	0.02
S_3	10.49	0.01	10.48

Table 2: Measurements of Stokes Parameters

Finally, with the same setup we introduced a $\lambda/2$ retarder. After making the same measurements of the stokes parameters we obtained similar results but with the S_3 with a negative value. This result tells us that the circular polarization was inverted due to the $\lambda/2$ retarder. The results are presented in table 3.

	E_1	E_2	Value
S_3	0	10.39	-10.39

Table 3: Measurements of Stokes Parameters with $\lambda/2$ retarder

The mathematical description of this polarized states represent vectors. The optical elements represent matrices - Called Jones matrices. With a simple knowdlege of linear algebra its easy to understend the numerical description of the system presented in figure 9.

The system can be described by the product of the Jones Matrix for quarter waveplate and half wave plate (M). They both act on the **vertical** polarized state $\overrightarrow{E_1}$.

Let Operator Matrix M:

$$M = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix}$$

If:

$$\overrightarrow{E_1} M = \overrightarrow{E_2}$$

Then:

$\begin{pmatrix} 0 \\ 1 \end{pmatrix} \mathrm{M} = \begin{pmatrix} 0 \\ -\mathrm{i} \end{pmatrix} \rightarrow$ **Circular** Polarization Left $\overrightarrow{E_2}$

If we take out the half waveplate retarder, the final polarization will be $\overrightarrow{E_2} = \begin{pmatrix} 0 \\ i \end{pmatrix}$ **Circular** polarization Right.

Figure 9: From vertical to circular polarization

5 Conclusion

Light is a natural phenomena that can be manifested in many different ways. Depending on the state of the light, emergent phenomena like interference and coherence can occur. Furthermore, the practical applications of this phenomena yield excellent promising technologies that can be sized down down to the scale of nanometers. Therefore, it is very important to have characterization tools when dealing with optical systems given the many states of polarization a beam can have.

Thought this work, we exposed the principal characterization techniques when dealing with polarized light. Finally, the team concludes that success-full measurements where obtained. The empirical characterizations exposed reinforced the contents discussed on the optical experimentation course.

Polarization Practice References

[1] Alonso MA Dennis MR. "Swings and roundabouts: optical Poincaré spheres for polarization and Gaussian beams". In: *royalsocietypublishing* (2017).

[2] Bob D Guenther. *Modern optics*. OUP Oxford, 2015.

ON THE INTERFEROMETRY OF LAZER BEAMS

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Abstract

The development of vector calculus in the midst of the XIX century gave rise to very complete models for describing waves. For classical physics, applying these models to the phenomenon known as light became the bedrock of what is now the field of optics. One property of these models is that they allow for two light beams to interact leading to a whole discussion involving phases, frequencies, amplification and total annihilation. In this work, the principal elements used to build a amplitude division interferometer are presented and explained. Furthermore, a brief discussion on the principles of interferometfy is included to serve as a stepping stone towards exposing our results in the last section.

6 Introduction

Quantum electrodynamics provides the most fundamental description of light up to date. However, the classical formulation developed in the early years of this field yields a very elegant, intuitive and simple understanding of light. Furthermore, the mathematical models built around this classical theory are tailor made for the level of the physical experimentation discussed in this work. From this classical standpoint, light can be considered to be a harmonic solution (wave) to the second order, linear and partial differential equation derived from Maxwell's equations [**maxwell1954electricity**]. Because of this considerations, we expect for light to exhibit wave like properties.

One of such properties is interference. By interfering two light beams, it is possible for the emerging beam to sum up constructively, destructively or some state in the middle (Figure 10). The parameter that primarily governs interference is the phase of the wave. However, it is important to keep track of the amplitudes when constructing optical experiments because in order for interference to occur a series of conditions must hold. In the case of the electromagnetic waves, the conditions for interference are that the light source must be monochromatic, coherent and polarized in the same orientation.

This work aims to explain the basic experimental considerations that need surveillance when working with interferometers. This is done by designing and implementing a type of amplitude splitting interferometer known as Mach-Zhender. Later, a series of measurements and modifications are implemented to characterize the phenomena known as interference.

7 Materials

1. LASER HeNe (633nm, 15mW)
2. 2 Linear Polarizators.
3. 2 Beam splitters of cubic type.
4. 1 Retarder of half wavelength.
5. Camara.
6. Fixed Optic Mounts.
7. 4 Mirrors.
8. 1 Collimator.
9. 1 Pupil.
10. Security Glasses.

8 Theoretical Framework

In the early XIX century when Augustin-Jean Fresnel performed Thomas Young experiment, he proved empirically that light behaves like a wave. The results disproved the generally accepted corpuscular theory of light developed by Newton. This lead to the devolpment of a wave theory of light that ended up with Maxwell's equations [**maxwell1954electricity**]. This set of 4 equations, describes how electromagnetic waves behave under any circumstance.

Few mathematical treatment is required to derive a wave equation that all electromagnetic waves must obey. The result

$$\frac{\partial^2 u}{\partial z^2} = \frac{1}{v^2}\frac{\partial^2 u}{\partial t^2}, \tag{2}$$

gives rise to a family of solutions that satisfy the super-position principle [4]. This principle, is the cornerstone that enable mathematics to describe the interaction of two light beams predicted by Young 220 years ago.

8.1 INTERFERENCE

Interference is the phenomena associated to the sum of waves and the interaction of light itself. Thus, the work proceeds to define interference as the vector sum of the amplitudes of two light waves. Figure 10 illustrates the sum of 3 sets of waves. The first row is called constructive interference where the amplitudes magnify each other. The second row is a visualization of destructive interference [5] where a maximum of a wave interferes with a minimum of the other canceling each other out. The last row is a case that is nether total constructive nor destructive interference.

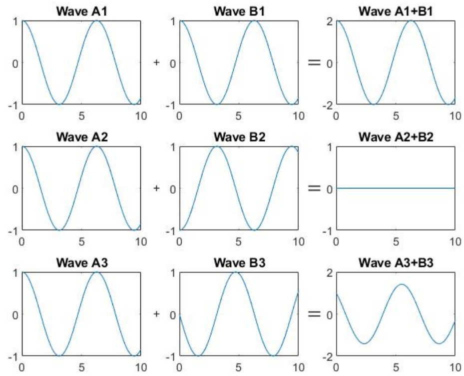

Figure 10: 1) Constructive Interference of A and B, 2) Destructive interference of A and B, 3) Partial constructive interference of A and B.

It is important to mention that a series of characteristics have to hold for a optical system to interfere. To further understand these considerations, consider the vector sum of two light waves: $\vec{E_1} = E_1 exp(i[\vec{k_1}\cdot\vec{r} - wt + \epsilon_1])$ and $\vec{E_2} = E_2 exp(i[(\vec{k_2}\cdot\vec{r} - wt + \epsilon_2])$. The resulting sum, averaged over time [6] is

$$I_{tot} = I_1 + I2 + 2cos(\delta), \tag{3}$$

where $\delta = (\vec{k_2} - \vec{k_1})\cdot\vec{r} + (\epsilon_1 - \epsilon_2)$. Result 3 hints at the fact that w, k, E_i and polarization play a critical role in that collectively create the phenomena of interference. The characteristics are summarized as follows. For electromagnetic waves to interact they must:

- be monochromatic.
- be coherent (temporal coherence).
- share a polarization state.

Figure 11 is an excellent visualization of this result.However in a macroscopic characterization, the important takeaway is that the directional difference between $\vec{k_1}$ and $\vec{k_2}$ controls the number of fringes in displayed in figure 12.

[4]The sum of two solutions to equation 2 is also a solution to the wave equation.

[5]Encountering annihilation in our models is not good for physicists because keep in mind that light is a natural system ruled by conservation laws. Thus, this case brings to question: what happens with that conservation of energy in a case of two light waves? Turns out, energy is simply distributed in a different configuration.

[6]This measurable quantity is calculated by taking a mean value over time of the energy of the field. This leads to the relation $I = \langle E \cdot E\rangle$

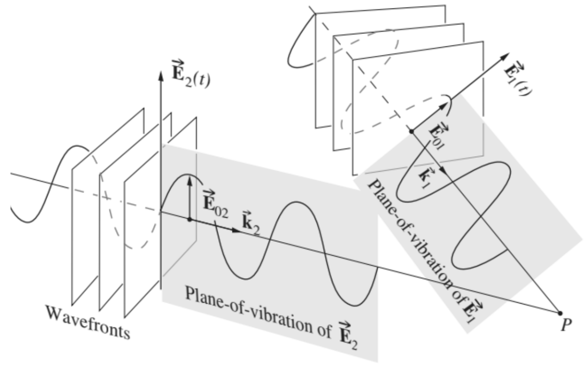

Figure 11: Vector Sum of two electromagnetic waves [**hecht1987optics**]

8.2 TEMPORAL COHERENCE

The measurement of coherence is a comparison between the relative phases of two light waves [2]. As of 2021 every realistic source of light has an associated bandwidth of temporal frequencies. This means that for the case of our LASER is not perfectly monochromatic. The implications of this fact permits us to invoke Heisenberg uncertainty principle

$$\Delta E \Delta t \geq \hbar/2, \tag{4}$$

Where $\hbar$ is Planks constant. The size of this bandwidth is related to ΔE and temporal coherence(τ) is related to Δt. The key take-away is that for more monochromatic beams more temporal coherence they are allowed to have.

The mathematical analysis of such statement can be done with Fourier transforms. It all borrows down to introducing the mutual coherence function (γ)

$$\gamma(\tau) = \frac{\Gamma(\tau)}{\Gamma(0)}, \tag{5}$$

where

$$\Gamma(\tau) = \int_0^\infty E_0(\tau)^2 exp(-iw\tau)dw, \tag{6}$$

relates bandwidth with coherence (τ). Also note the last results is a Fourier transform.

8.3 INTERFEROMETERS

In the most general sense, any interferometer works by either dividing its wavefront or its amplitude. In the case of wavefront division, a point-like source emits a wave and a physical barrier is applied to filter only some selected parts of the wavefront (Figure 12 A). Then, these resulting parts of the wavefront interfere with each other. In the case of amplitude division, a beam splitter (a dielectric) splits an incident beam into two by reflecting some amplitude and transmitting the rest of the amplitude (Figure 12 B). Later it is possible to design a optical system that lets this two beams interfere with each other.

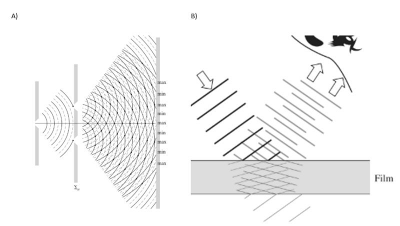

Figure 12: General principles of interferometers [**hecht1987optics**].

Thomas Young´s experiment discussed at the beginning of this section was a interferometer of wavefront division. However, in this work we will be using a type of amplitude division interferometer called Mach Zehnder. This later interferometer splits a beam into two amplitudes in a ratio of 50-50. Then the two beams travel independent paths to later be collimated to create interference.

9 Results

9.1 THE MACH ZEHNDER INTERFEROMETER

The team began by visualizing the layout of the interferometer given the limited space dictated by the dimension of the optical table. Later, the team aligned the LASER along an axis on the table, filtered the light with a spatial filter and collimated the beam with a optical lens. This is done by placing the lens at its focal point along position 1 in figure 13.

We proceeded to build the optical layout for the Mach Zehnder interferometer until we obtained interference patterns. The setup of the Mach-Zehnder interferometer is presented in figure 13. One of the clear advantages of this interferometer is that both interfering beams travel independent paths. This means it is possible to affect one beam of light by changing one of its characteristics and directly study how interference behaves.

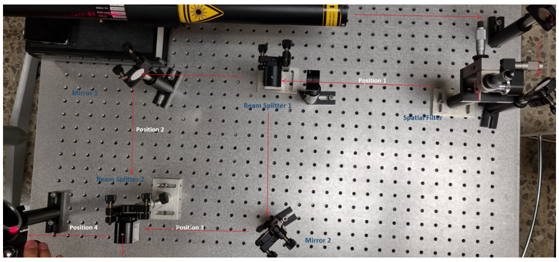

Figure 13: Mach Zehnder experimental layout.

While operating the interferometer the team noted that when the beam splitter is slightly tampered, the fringes wiggle maintaining its spatial orientation like shown in figure 14. This is because the two interfering beams get affected by the tampering in different ways introducing a very strange phase difference. This is one of the big disadvantages of Mach Zehnder: it is very sensible to environmental noise.

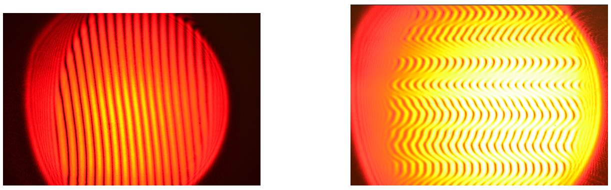

Figure 14: Reference vs Tampered interference patterns observed by the camera.

Later we proceeded to test the interference under different conditions. First, we introduced a flame to one of the paths. When we apply a flame to one of the interferometers arms, the fringes seem to amplify ,deform and loose contrast. This can be explained because light from a flame is not polarized. Hence most of the light does not interfere with the beams and we observe low contrast because we introduced some background light. Deformation can be explained because the density of air is compromised by the flame and this introduces a change in the optical path of one of the beams. This changes the phase of the resulting wave and becomes this visible effect illustrated in figure ??.

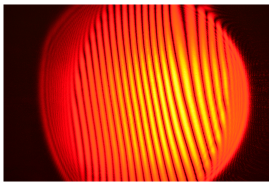

Figure 15: One of the arms is introduced a flame.

Minor alterations on the mirrors drastically affect the system. By moving the orientations [7] of the mirrors in one of the arms we can introduce a variation in the angles between the vectors of propagation $\vec{k_1}$ and $\vec{k_2}$ corresponding to the two interfering beams. This leads to more or less fringes -and their orientation- in the interference patterns.

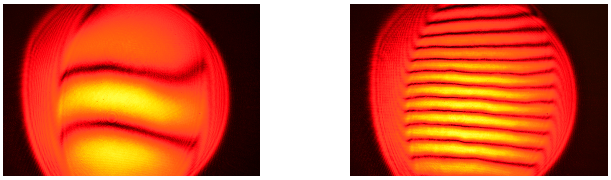

Figure 16: Interference patterns by phase difference observed by the camera.

Another important observation is when the team introduced a intensity filter (0.5 ND) along one of the Mach Zehnder´s arms (Position 2). As shown in figure 17, the contrast of the fringes decreases notably. This is due because the filter absorbs intensity that would otherwise be interfering with the other beam. Therefore, taking as a reference figure 17 A; we can observe a difference in contrast. With the filter configuration, the fringes show a lower contrast.

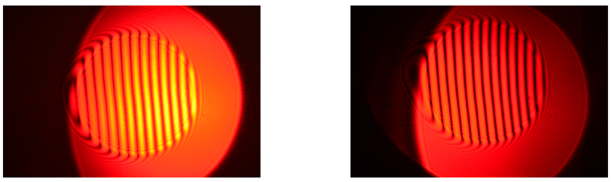

Figure 17: Filtered vs Non Filtered interference patterns observed by the camera.

[7]In the order of millimeters

9.2 POLARIZATION EFFECTS

In section 8 we discussed that a shared state of polarization is needed in order to interference to emerge. To test this statement empirically, we introduced in position 3 (Figure 13) a half wavelength $\lambda/2$ retarder at a 45^o degree angle from its fast axis which in turn matches the orientation of the polarized state of the beam. This inverts the polarization on the beam by 90^o degree. At this point (Figure 18 A), the two beams do not form interference because the polarization states are perpendicular to each other. Then the team adjusted the angle of the $\lambda/2$ retarder to 0^o -I.e not affecting the initial polarization state - we observe the interference pattern once again (Figure 18 B). The team later proceeds to introduce the two perpendicular polarization states until the interference fringes disappear. To recover the interference patterns once again, we first mounted a linear polarizer in position 4. By aligning the polarizer to a 45^o degree angle from the vertical state of the LASER we observed the fringes once again (Figure 18 C)! This is because the interfering vertical and horizontal states can be thought of a superposition of a diagonal and anti diagonal states. In linear algebra this is known as a chance of basis. Thus, the diagonal polarizer in position 4 allows both beams to interfere in its diagonal polarization state and the observation leads to fringes.

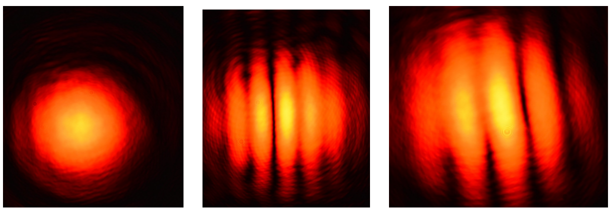

Figure 18: A) No interference because of perpendicular polarization states. B) Interference because 2 parallel polarization states. C) Interference because perpendicular states interfere in a diagonal polarized orientation.

9.3 PHASE RETARDATION BY $\Delta\Lambda$

In the previous subsection the team found that introducing a different air density -due to the presence of a flame- in one of the interferometers arms leads to different interference patterns. This is because a difference in the optical path $\Delta\Lambda$ is introduced and the beams interfere with each other at different phases. To test this phenomena in a more controlled matter, the team proceeded to introduce a glass plate in position 2 (Figure 13). This made one of the beams refract and thus introducing a $\Delta\Lambda$. Figure 19 is a picture of the visible interference affected by the glass (white borders) and the unaffected by the glass on the bottom of the picture.

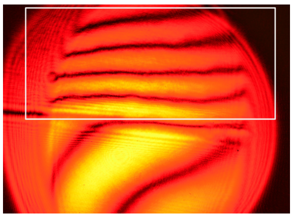

Figure 19: Glass applied to half of a beam in position 2 at an angle.

Two facts are very clear from figure 19: 1) the refraction angle caused by the glass shifts the vector of propagation in one of the beams and thus generates different number of fringes and 2) different orientations.

9.4 INTERFERING WAVE FRONTS

Finally the team set up a configuration to study the interference of two different types of wave-fronts: plane waves and spherical waves. To achieve this, we introduced a lens on position 3 (Figure 13). This focuses the incident plane (or collimated) wavefront generating a spherical wavefront. After this two wave-fronts interfere the following interference pattern emerges [**fig:Wavefronts**]:

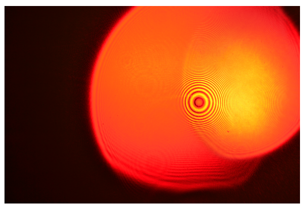

Figure 20: Plane and spherical interfering wave-fronts.

The results are not good quality because of poor collimation techniques. However, during the experiment we observed that an array of concentric circles begins to form when these two wave-fronts interfere.

9.5 ALTERNATIVE INTERFEROMETERS BY PHASE DIVISION

Other configurations involving beam splitters include the Michelson and Sagnac configurations (Figure 21. They have other strong characteristics that can allow physicists to measure different characteristics of the interference phenomena.

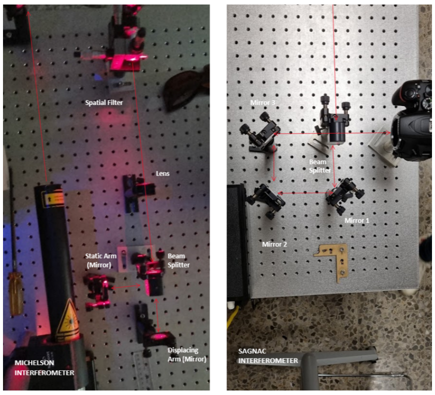

Figure 21: A) Michelson and B) Sagnac interferometer.

We will use this space to answer what I consider 3 pertinent questions about the phenomena of interference.

1. What happens to the energy when we have destructive interference?
2. What is the coherence of our LASER BEAM listed in section 7?

The Sagnac interferometer was used by the team to measure the distribution of energy in the beam. The team built the configuration illustrated in figure 21, later a series of pictures where taken in order to obtain different fringe numbers and registering as matrix digital measurements. The integral of this transversal measurement can be related to the energy as displayed in (Figure 22). Resolving question 1): In regions of destructive interference, energy is in a different configuration state but still conserved due to compensation in regions inside the constructive case.

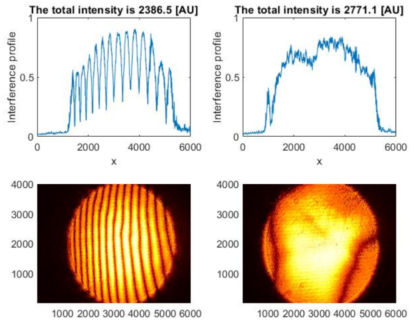

Figure 22: Energy conservation readings match up to value of 92% of energy conservation.

Michelson's interferometer its optimal for experiments involving displacements in mirror. Thus, this configuration will allow the team to perform measurements of the coherence of the LASER. The team began re calibrating the interferometer. Later, we proceeded to move the mirror such that $l_0 -> 0$ and stop when we no longer observe where the interference (Figure 23). The measured value was $x_{I0} = 0.00cm$. Later we varied $l_0 -> \inf$ because the nature of the LASER is not purely monochromatic, the coherence of the beam will hold for a finite range of distance values . We observed a distance where the fringes are no longer distinguishable. That distance is recorded as $x_{IF} = 102.00cm$. E.i the coherence distance (χ) is

$$\chi = x_{IF} - x_{I0} = 102cm, \qquad (7)$$

is related to the temporal coherence discussed in section 8 by introducing the velocity (c)

$$\tau = \chi/c[s]. \qquad (8)$$

Therefore after τ seconds, the LASER light decoheres.

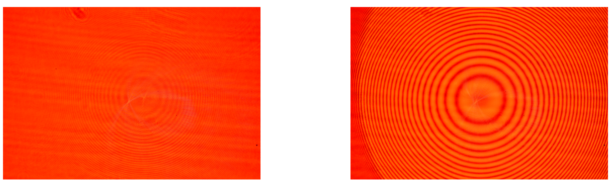

Figure 23: x_{IF} and x_{I0} experimental results (respectively).

10 Conclusion

Throughout this work, we exposed the principal elements to consider when dealing with interferometers. The practice successfully exposes the interaction of optical interference by making optical arrangements with the principal experimental elements like retarders, polarizers, cameras and LASER beams. Furthermore, the key mathematical foundations are mentioned in order to aboard a complete view on the results obtained in experiment.

The results of the experiments presented where very satisfactory because they illustrate what are the main aspects to consider when working with interferometers. The team concludes that it is important to control the collimation of the beams in order to control the number of interference patterns. It is also critical to monitor which elements introduce a change in the optical path because this also can affect the orientation, shape and contrast of the interference. Polarization is another important characteristic to control in the laboratory. Failing to do so can lead to unsuccessful attempts of generating interference.

Finally it is important to select the right interferometer for the experiment being done since every configurations has its own practical advantages.The applications of the interferometers discussed in this work generalize to the following statements 1) Michelson interferometers can have measurement applications with huge resolution values (in the scale of nanometers). 2) Mach Zehnder applications for research because of the wide options for interfering light with different characteristics. 3) Sagnac interferometer is not vulnerable to environmental noise and therefore is ideal for practical applications with few specifics on interference.

Interferometry Practice References

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[2] Bob D Guenther. *Modern optics*. OUP Oxford, 2015.