

Determining the Coherence Length of a Laser Using Michelson Interferometer

Hameedullah Zahin¹, Zaker Hussain Serat², Awsat Rasooli³

¹Department of physics, education Faculty, Urozgan University, Khayro kariz, Tarinkot, Afghanistan

²Department of Physics, Natural Science Faculty, Kabul Education University, Kabul, Afghanistan

³Department of Physics, Natural Science Faculty, Kabul Education University, Kabul, Afghanistan

ABSTRACT: To create interference fringes, it is sufficient to use a beam splitter to divide a laser beam into two beams using and finally superimpose the two beams on the screen to produce a stable interference pattern. By using two different laser sources and superimposing their beams, it is not possible to create an interference pattern in any way. This means that the two superimposed beams must necessarily originate from a single laser beam to achieve a stable interference pattern. Additionally, the coherence length of the beam must be considered. The photons from a coherent light source are coherent within the coherence distance, which in some lasers, can reach up to kilometers.

In the Michelson interferometer, which is based on wave amplitude splitting, the incident beam from a laser is initially split by a beam splitter. Finally, these two split beams are recombined using mirrors at the same beam splitter, pass through it, and then enters a lens that acts as a magnifier. After passing through the lens, the beam produces an interference pattern on the screen.

This paper investigates the use of the Michelson interferometer to measure the coherence length of a laser. By analyzing the fringe visibility as a function of path difference, the coherence length of the laser is determined.

In this experiment, a helium-neon ($He - Ne$) laser with a wavelength of 632.8 nm , a movable mirror at a distance of 7.21m and a fixed mirror at a distance of 0.3m are used, and the coherence length of the mentioned laser was determined to be 13.82m .

KEYWORDS: Michelson interferometer, Helium-Neon laser, Laser coherent length, Temporal coherence, Spatial coherence.

1. INTRODUCTION

Interferometry is one of the most common and accurate optical methods for measuring physical parameters such as wavelength, refractive index, coherence length, aberrations, and etc.

The most renowned and widely used interferometric device is the one invented by Michelson [1,2].

A light beam emitted from a source, after passing through the beam splitter, is divided into two parts. These two parts, after traveling through different optical paths, are reflected by mirrors M_1 and M_2 and recombine with the help of the beam splitter. Consequently, interference can be expected. In this way, an interference pattern is formed [3].

In order to achieve a stable and constant interference pattern, the phase relationship between the interfering waves must remain constant during propagation. Such waves are called coherent waves. Coherence is a property that best distinguishes laser light from other types of light, a feature is the resulting from the nature of the inductive diffusion process [1]. In fact, two waves can only interfere with each other if they are coherent. The distance over which the phase relationship between the two waves remains constant is called the coherence length, and the time required to traverse this distance is called the coherence time.

One of the most prominent examples of coherent waves is laser. Lasers are widely used in scientific research and industrial applications due to their high coherence, monochromaticity, and directional emission. A beam of light emitted from a laser can exhibit almost complete coherence. However, ordinary light sources, such as fluorescent tubes, tungsten filament lamps, and the sun light, are not coherent. While it is possible to produce coherent light from these sources, but the intensity of resulting light is so weak that it is not particularly useful. For scientific purposes, only laser light can generate a coherent and powerful light beam. [4].

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For the wave to be coherent, the following two conditions must be met:

1. The resulting wave must be nearly monochromatic (single- frequency); that is, the frequency spread must have a small linewidth.
2. The wave front must have a specific shape that does not change over time. A wave front is a surface consisted or composed of points with the same phase. A point light source generates a wave whose phase remains constant at equal distance from the source [4].

2. TYPES OF OPTICAL COHERENCE

Optical coherence can generally be classified into two categories: Temporal coherence and spatial coherence. These two forms of coherence describe the correlation of the electromagnetic wave in time and space, respectively, and both play an essential role in the formation of stable interference patterns in optics.

(a) Temporal Coherence

Temporal coherence can be detected with the Michelson interferometer. The first condition for coherence is that the wave must be monochromatic (single frequency). If this condition is met, the coherence is called temporal coherence. Temporal coherence means that the relative phases between two temporal points over a relatively long time interval remain constant. In this way, temporal coherence allows for the prediction of phase and amplitude after a certain time interval between initial and final observations. If this predictive process can be repeated after some time, temporal coherence is said to exist equal magnitude over the prediction intervals [1, 5].

(b) Spatial Coherence

Spatial coherence can be detected using Young's double-slit experiment. When a beam of light passes through two slits, it splits into two beams that superimpose on a screen parallel to the slit plane. If interference fringes are observed on the screen, the beam has spatial coherence; otherwise, it does not. Essentially, Young's double-slit experiment is itself a type of interferometer [4].

A condition for spatial coherence is that the wavefront shape must not change over time. If this condition is satisfied, the resulting light form is called spatial coherence [6]. In other words, a wave is spatially coherent if a constant phase difference exists between any two chosen points on the wave front. The term "constant" implies a sufficient duration for operations on the wave front, such as visual observation or photography. In other words, spatial coherence requires the relative phases between two spatial points to remain constant over a relatively long time interval. In each of these cases, the longer the time interval, the greater the coherence. For a light source to be fully coherent, it must have both temporal and spatial coherence [4].

This paper explores the methodology for determining the coherence length of a laser using a Michelson interferometer. Theoretical principles, experimental setup, and implications of the findings are discussed in detail.

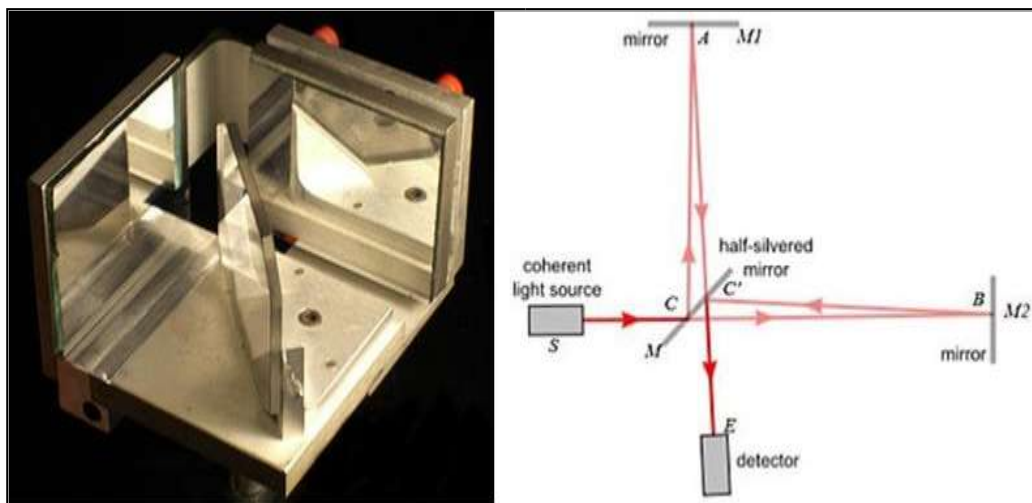


Figure (1): The schematic structure of the Michelson interferometer and its different parts [4].

3. RESEARCH METHODS AND MATERIALS

3.1. Experimental Setup

In this research, a Michelson interferometer was utilized, comprising a coherent laser source, a beam splitter, two mirrors, and a screen to observe interference fringes. The laser used was He-Ne laser with a wavelength of 632.8 nm .

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The Michelson interferometer was used to measure the interference, enabling precise measurement through the phenomenon of interference, including the refractive index of gases, measuring the very small changes in length, determining the wavelength of a transparent objects, etc., using these devices [4,7, 8].

Perhaps the most famous and widely used device for measuring interference is the interferometer invented by Albert Michelson in 1881. The most significant application of the Michelson interferometer is the Michelson-Morley experiment, which validated the hypothesis of special relativity and detection. Its basic design is shown in Figure 2. A light beam 1 originated from the extended source S is split by a glass beam splitter (BS), on which a glass plate coated on its front surface with a thin semi-transparent dielectric or metallic layer. Therefore, the Michelson interferometer operates by amplitudes splitting.

The reflected beam 2 and the transmitted beam 3, with nearly equal amplitudes, are directed to the fully reflecting mirrors M_1 and M_2 , respectively, and there they change their direction.

After returning to the beam splitter, beam 2 is now transmitted, and beam 3 is reflected by the semi-transparent layer. These beams recombine and exit the interferometer as beam 4.

The useful property of this two-beam interferometer is such that all the incident beams to mirrors M_1 and M_2 , are perpendicular or nearly perpendicular. Thus, beam 4 comprises rays that have traversed different optical paths, creating interference [9].

If the light incident perpendicularly on the two mirrors, the optical path difference between the beams associated with mirrors M_1 and M_2 is as following:

$$s = 2d$$

The above relation indicates that if one of the mirrors is displaced by d , the optical path difference changes by $2d$. It should be noted that this equation is true only for the case where M_1 and M_2 mirrors are perpendicular to each other. i.e. forming circular fringes [10, 11].

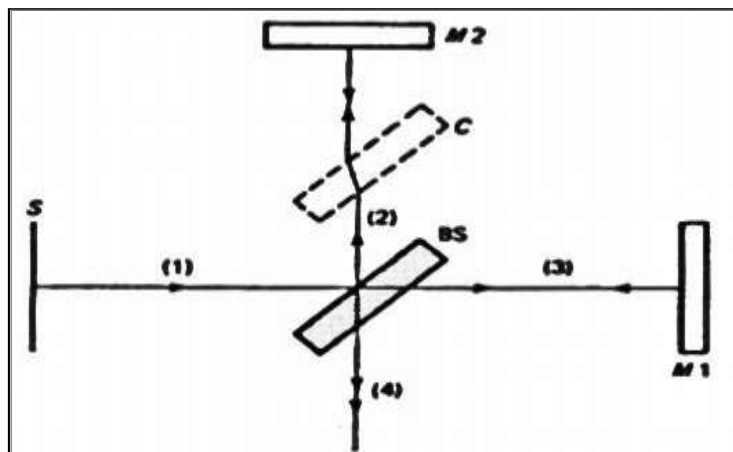


Figure (2) Michelson interferometer [1].

3.2. Experiment Procedures

In this experiment, we want to determine the coherence length of the laser using a Michelson interferometer. The laser used in this experiment is a Helium-Neon laser with a wavelength of 632.8nm . In the Michelson interferometer, we used two fully reflective mirrors positioned at an angle of 90° to each other and a beam splitter is used to split the incident beam into two parts. First, the helium-neon laser beam is aligned horizontally with the surface of the table. The beam splitter is adjusted to allow the light to pass through its center. Mirrors are positioned so that the light strikes their centers. After passing through the beam splitter, the laser beam splits into two, with approximately 50% of the beam transmitted the splitter and 50% of the beam is reflected.

These two beams, after reflecting from mirrors, return and pass through the beam splitter again, then enter to a lens. The lens magnifies the beams, and the combined beam reaches the screen. Due to their different optical path lengths, interference patterns appear on the screen.

As we know, based on interference principles, the distance between the two mirrors must be such that the laser's coherence length allows for interference. In this experiment, one mirror is fixed, and the other is movable. The movable mirror is shifted until the interference pattern disappears from the screen. This maximum distance is considered the laser's coherence length. The

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coherence length is calculated by subtracting the distance from the movable mirror to the beam splitter from the distance from the fixed mirror to the beam splitter and multiplying the result by two. The final value is the coherence length of the helium- neon laser.

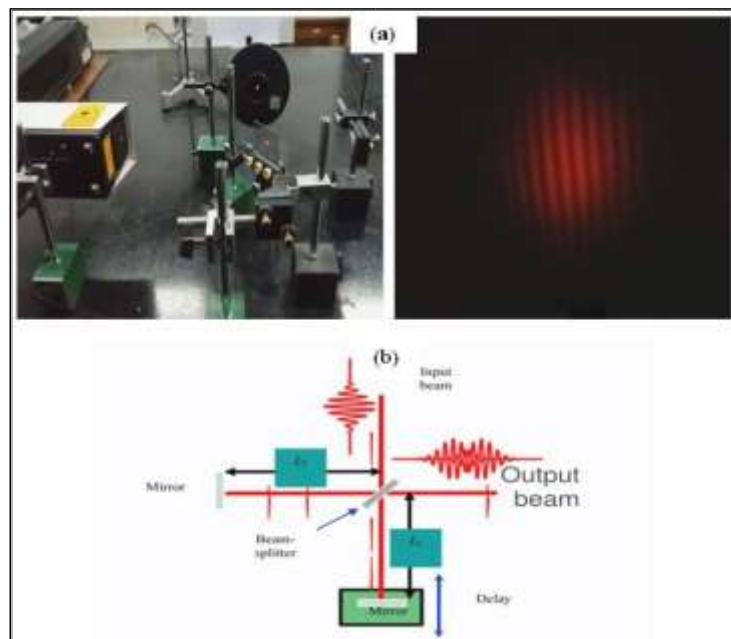


Figure (3): (a) Photograph taken by the authors of the experimental setup to measure the laser coherence length at Iran University of Science and Technology. (b) Schematic diagram, illustrating the Michelson interferometer's functioning for coherence length measurement.

4. RESULTS AND DISCUSSION

From the perspective of an observer, in the position of the detector, it appears that the two reflected beams originate from two coherent sources separated by a distance of $2 \cos d \theta$. Therefore, these two beams will have a phase difference of: $\delta = kd2 \cos \theta$. If the $\delta\pi = 2m$, where m is an integer. Then, the amplitudes of the two waves will be added to each other, and the interference will be constructive. As a result, the intensity of (I) will be maximum (bright fringe). If the phase difference be $\delta\pi = (2m+1)$, then the amplitudes of the two waves will cancel each other, resulting in destructive interference. Therefore, we will have the minimum intensity (dark fringe) [4].

All light sources, even those referred to as monochromatic, have the same line width. If Δy is the frequency bandwidths of the light are studied, the coherence time will be given by:

$$t_c = \frac{1}{\Delta y}$$

Accordingly, the coherence obtained with the help of the relation between wavelength and frequency is equal to:

$$I_c = \frac{\lambda^2}{\Delta y}$$

The coherence length of a laser can be calculated using the following formula:

Coherence length of the laser = (The distance between the moving mirror and the beam splitter - the distance between the fixed mirror and the beam splitter) $\times 2$

$$I_c = (I_1 - I_2) \times 2$$

And The coherence time of the laser is obtained from the following relation:

$$\text{Coherence time} = \frac{\text{Coherence Length}}{\text{Speed of light}} \Rightarrow t_c = \frac{l_c}{c}$$

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Using the experimental data, we got from experiment, the coherence length of the laser is calculated as follows:

$$L_e = (L_1 - L_2) \times 2 = (7.21m - 0.3m) \times 2 = 13.82m$$

Therefore, based on the data we have obtained from experiment, the coherence time of the mentioned laser will be calculated as:

$$t_0 = \frac{L_e}{c} = \frac{13.82m}{3 \times 10^8 \frac{m}{sec}} = 4.6 \times 10^{-8} sec = 0.000000046 sec$$

Table 1: Determination of coherent length and coherence time of He-Ne laser.

Type of laser	Laser wavelength (λ)	Arm of moving mirror (L_1)	Arm of stationary mirror (L_2)	Coherence length (L_e)	Coherence time (t_0)
He-Ne	632.8 nm	7.21 m	0.3m	13.82m	$4.6 \times 10^{-8} s$

5. CONCLUSION

Interferometry is one of the most common and precise optical methods. In order to have a stable and consistent interference pattern, phase relations (phase difference) between interfering waves must remained fixed or constant during the propagation. One of the most prominent examples of coherent waves is the laser beam. After passing through the beam splitter, these two beams, due to their optical path difference, create interference patterns on the display screen as a result of this path difference. This study demonstrates that the Michelson interferometer is an effective tool for measuring the coherence length of a laser. In this paper, we investigated and measured the coherence length of a laser using a Michelson interferometer. The laser used in the experiment, was a He- Ne laser with a wavelength of 632.8nm. The moving mirror was positioned at the distance of 7.21m from the beam splitter, after this distance no interference pattern was observed. And a fixed or stationary mirror at the distance of 0.3m from the splitter. The coherence length of the laser is determined about 13.82m.

According to the conducted research, the coherence length of lasers in advanced systems can extend to several kilometers.

6. ACKNOWLEDGEMENT

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7. CONFLICTS OF INTEREST

All authors declare that they no conflicts of interest to disclose.

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