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Mini Scale Strain Sensor Based on Michelson Interferometer for Structural Health Monitoring

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Abstract

Structural health monitoring (SHM) is critical for ensuring the safety and longevity of infrastructure. Traditional strain sensing techniques often lack the sensitivity and resolution required to detect small-scale deformations, leading to delayed maintenance and increased risks. This study addresses these limitations by utilising a Michelson interferometer laser system to enhance strain sensing in laboratory-scale SHM. The objectives of this research include designing a Michelson interferometer setup integrated with laser and optical components, generating interference fringes, and improving strain sensing sensitivity and resolution. The experimental setup involves a He-Ne laser, a beam splitter, high-precision mirrors, and a photodetector to monitor fringe shifts caused by applied strain. Controlled bending tests were performed on polycarbonate samples. Results indicate a linear relationship between the bending angle and the optical path change, which was measured through fringe shifts, demonstrating the system's high sensitivity and accuracy. For example, at a bending angle of 5°, the optical path change was 0.0436 mm; at 10°, it was 0.0872 mm; and at 15°, it was 0.1308 mm. Sensitivity, indicated by the gradient of the graph of optical path change against bending angle, is high because even small changes in bending angle led to measurable changes in optical path length. Accuracy, reflected in the linear fitting coefficient of the same graph, is also high, as demonstrated by the linear relationship between the bending angle and the optical path change. This study contributes to advancing SHM methodologies by providing a robust, precise, and scalable approach for real-time structural monitoring.

1. Introduction

Structural Health Monitoring (SHM) is a multidisciplinary field that ensures the safety, reliability, and longevity of critical infrastructure such as bridges, buildings, and aircraft. As infrastructure ages, the risk of structural failure due to undetected damage increases, leading to potentially catastrophic consequences. SHM aims to address this by continuously monitoring structural integrity and providing early warnings for maintenance and repair. This proactive approach not only enhances safety but also reduces long-term maintenance costs by preventing major failures [1].

Traditional methods for strain sensing, such as electrical resistance strain gauges and optic sensors, have been widely employed in SHM. However, these methods are often limited by factors such as susceptibility to electromagnetic interference, environmental instability, and insufficient resolution for detecting micro-scale deformations [2]. Additionally, the installation and maintenance of such sensors can be labor-intensive and costly, particularly in challenging environments. These limitations highlight the need for more advanced and precise sensing technologies.

Optical methods, particularly those based on interferometry, have emerged as promising alternatives for SHM applications. Among these, the Michelson interferometer stands out due to its simplicity, high sensitivity, and ability to measure minute changes in optical path length. By leveraging the interference of light waves, the Michelson interferometer can detect even the smallest structural deformations, making it an ideal candidate for strain sensing in SHM [3].

The Michelson interferometer, first developed by Albert Michelson in the late 19th century, has a rich history of applications in physics, astronomy, and metrology. Its ability to measure precise changes in distance has made it a cornerstone in experimental science [4]. In the context of SHM, the Michelson interferometer offers unique advantages, including non-contact measurement, immunity to electromagnetic interference, and the capability to operate in harsh environmental conditions [5].

This study focuses on enhancing the application of the Michelson interferometer for strain sensing in laboratory-scale SHM. By integrating advanced optical components such as a He-Ne laser, high-precision mirrors, and a photodetector, this research aims to improve the sensitivity and resolution of strain measurements. The primary objectives are to design a robust Michelson interferometer setup, validate its performance through controlled experiments, and demonstrate its potential for real-time structural monitoring [6].

2. Methods and Materials

2.1 Block Diagram

Fig. 1 illustrates the experimental setup used in this study is a Michelson interferometer configured for strain sensing. The core components include a He-Ne laser source with a wavelength of 632.8 nm, a beam splitter, two mirrors (one stationary and one movable), a sample, and a detector. The laser beam is directed toward the beam splitter, which divides it into two paths: one reflecting toward the stationary mirror and the other toward the movable mirror. After reflection, the beams recombine at the beam splitter to produce interference fringes, which are detected by the detector. The movable mirror is connected to the sample undergoing strain, allowing changes in the optical path length due to deformation to be observed as shifts in the interference fringes.

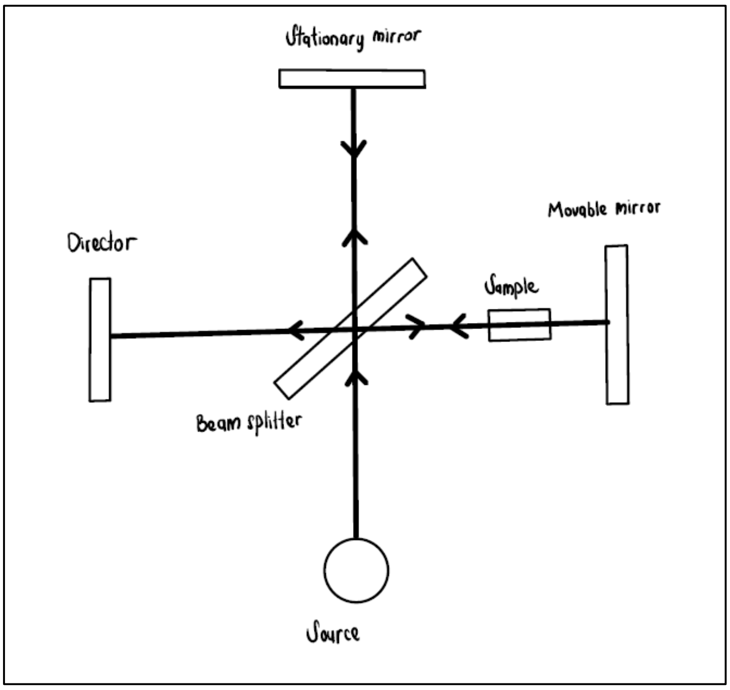

Fig. 1 The experimental schematic diagram of the Michelson Interferometer

The polycarbonate sample, prepared with dimensions of 40 mm in length, was subjected to controlled bending tests. During these tests, strain was applied by incrementally bending the sample at specific angles. The bending process caused changes in the optical path length, which were quantified by analysing fringe shifts. The relationship between the bending angle and the strain was monitored to determine sensitivity and accuracy. The sensitivity was calculated as the gradient of the graph plotting optical path difference against strain.

The experimental setup was aligned to ensure coherent light interaction and minimize noise in the fringe pattern. Data analysis was examined and interpreted to extract quantitative results. This setup provided a robust and precise method for strain detection, enabling a detailed evaluation of the sample's deformation behaviour.

2.2 Fringe Pattern Analysis

The fringe pattern was analysed using interferometric techniques to observe the changes in the optical path difference before and after the bending or deformation of the sample. The sample was subjected to a controlled deformation, and the resulting shift in the fringe pattern was recorded to quantify the strain, which is directly related to the changes in the optical path length.

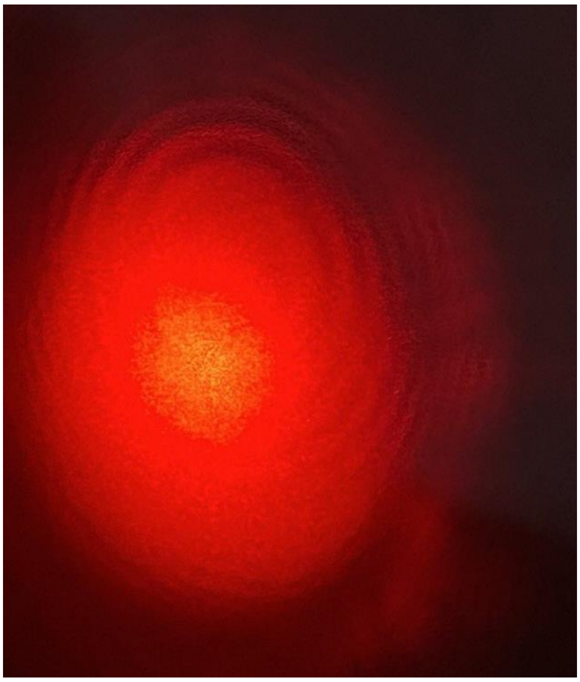

Fig. 2 Output of fringes pattern before bending of sample

Fig. 3 Input of fringes pattern after bending of sample

Before the deformation, the sample was initially positioned in its natural, undeformed state, with no applied force or displacement. The bending angle of the sample was then introduced by applying a specific load or force to the sample in a controlled manner, and the deformation was carefully measured. Using a protractor or angle measurement device, the bending angle was recorded both before and after the deformation process. This data was crucial for evaluating the strain distribution across the sample and correlating the change in the bending angle to the observed changes in the fringe pattern.

2.3 Justification of Material and Bending Increments

The choice of polycarbonate as the sample material was based on its uniform mechanical properties, which ensure consistent deformation under applied strain. Additionally, its widespread availability, cost-effectiveness, and suitability for laboratory-scale experiments made it an ideal candidate for evaluating the performance of the Michelson interferometer system. The bending test was conducted with incremental angles of (0°, 5°, 10°, 15°), which, although relatively large, effectively demonstrated the system's capability to detect fringe shifts corresponding to these deformations. This highlights the practicality and reliability of the method for strain measurement.

2.4 Sensitivity and Future Improvements

While 5° increments were utilized in this study, the system's sensitivity is not restricted to these values. The Michelson interferometer's high sensitivity, derived from the interference of light waves, allows it to detect smaller deformations beyond the chosen increments. This experiment establishes a solid foundation for future work, where smaller bending increments can be explored for more precise measurements. The results reveal a linear relationship between the bending angle and optical path change, confirming the system's high sensitivity. Furthermore, the sensitivity of the setup is quantified by the gradient of the optical path change versus bending angle graph, substantiating the interferometer's ability to detect precise strain changes. These findings validate its robustness and scalability for structural health monitoring applications.

2.5 Materials

The experimental setup utilizes a Michelson interferometer laser system with key components including a laser source, beam splitter, mirrors, and a polycarbonate plastic (40mm x 40mm). Additional tools, such as rulers, g-clamp and protractors, are used for precise measurements, and manual fringe shift analysis is conducted to determine strain values.

2.6 Methods

The experiment begins with assembling and aligning the Michelson interferometer, ensuring proper beam splitting and stable interference patterns. The sample is secured, and incremental bending angles are applied using the g-clamp. Fringe patterns are observed and manually analysed to measure shifts caused by strain. Strain values are calculated based on optical path changes, and results are validated through error and sensitivity analysis to confirm accuracy and reliability.

Fig. 4 Michelson Interferometer setup

Fig. 4 shows the experimental setup includes a He-Ne laser, a 50/50 beam splitter, high-precision mirrors. The laser beam is split into two paths: one reflects off a reference mirror, and the other off a sample subjected to strain. The recombined beams create interference fringes, which are analysed to determine strain. Polycarbonate strips (40 mm x 40 mm) were used as the test material due to their uniform mechanical properties. Controlled bending was applied using a G-clamp to simulate strain, with bending angles of 0°, 5°, 10°, and 15°.

3. Results and Discussion

The Radius of Curvature was calculated using this formula:

$$R = \frac{L}{\theta}$$

The Strain(ε) was calculated using this formula:

$$\varepsilon = \frac{\mathrm{h}}{2\mathrm{R}}$$

The fringe shift was calculated by using this formula:

$$\frac{\Delta}{\mathrm{N}} = \frac{\varepsilon \mathrm{L}}{\lambda}$$

The Optical Path Change was calculated using this formula;

$$\varepsilon = \mathrm{L}$$

Strain values were calculated based on the optical path length changes measured from the fringe shifts. The fringe shifts are observed at different bending angles applied to the polycarbonate plastic. The data shows a linear relationship between bending angles and optical path change, demonstrating the system's sensitivity to strain variations.

Table 1 Theoretical bending strain values

Bending Angle (°)	Radius of Curvature (R) (mm)	Strain (ε) (%)	Fringe Shift (ΔN)	Optical Path Change (ΔL) (mm)
0	∞	0.00000	0.0	0.0000
5	458.19	0.00109	68	0.0436
10	229.19	0.02182	137	0.0872
15	152.79	0.03272	206	0.1308

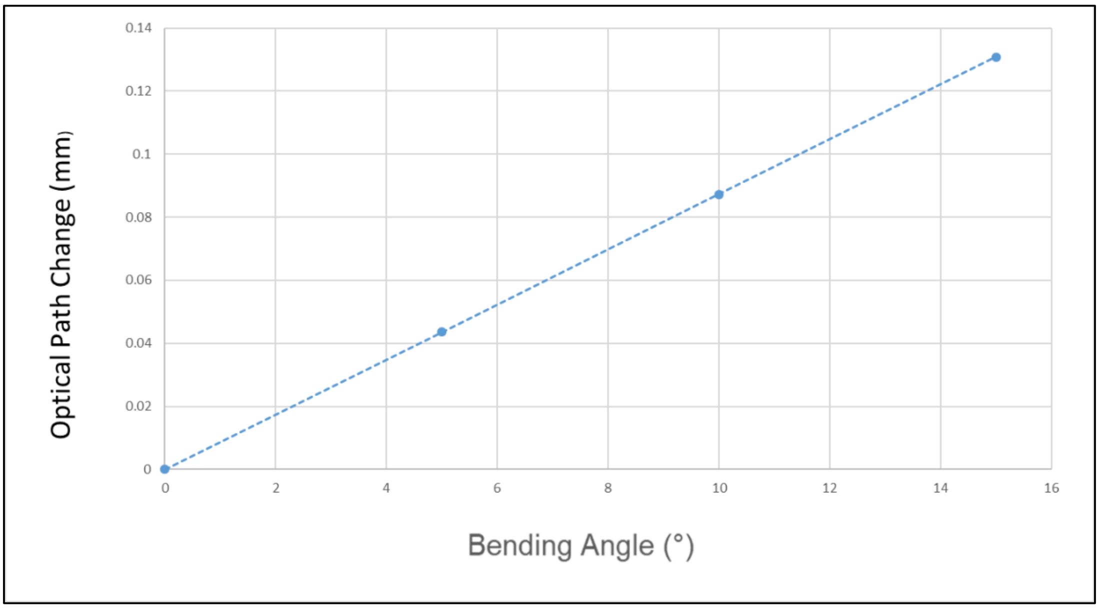

Fig. 5 Optical Path Change against Bending Angle

Fig. 5 shows a positive correlation between the bending angle and optical path change. At 0°, there is no deformation, resulting in 0 mm of path change. However, as the bending angle increases, the optical path change increases non-linearly, indicating a progressive strain effect due to deformation. The observed fringe shifts correspond to changes in optical path length due to strain applied to the polycarbonate plastic. As the bending angle increased, more fringes shifted, indicating greater strain. This confirms that the Michelson interferometer is capable of detecting small deformations accurately.

4. Regression Linear Equation

$$y = 0.00872x + 0.0000$$

where:
•y is the optical path change (mm)
•x is the bending angle (°).

4.1 Fitting Coefficient

$$R^2 = 1.000$$

This indicates a perfect fit, meaning the linear regression line explains 100% of the variability in this data.

5. Conclusion

This study demonstrates the potential of a Michelson interferometer laser system for enhanced strain sensing in structural health monitoring (SHM). The system was validated through controlled bending tests on polycarbonate samples, with bending angles of 0°, 5°, 10°, and 15°. By integrating advanced optical components and performing controlled bending tests on polycarbonate samples, the system achieved high sensitivity and accuracy in detecting strain. The linear relationship between bending angle and optical path change underscores its precision and reliability for laboratory-scale applications. This approach not only advances SHM methodologies but also offers a scalable and cost-effective solution for real-time structural monitoring. Future work can explore finer strain increments and diverse material applications to further refine and validate the system's capabilities. The findings contribute significantly to the fields of optical sensing and infrastructure safety, addressing critical gaps in existing strain detection technologies.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design, data collection, analysis and interpretation of results, draft manuscript preparation:*** *Alwani Athilah Amran and Ahmad Hadi Ali. All authors reviewed the results and approved the final version of the manuscript.*

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