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Development of a Diffraction-Based Micro-Diameter Measurement Instrument

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Abstract: This study presents the development and evaluation of a low-cost, non-contact micro-diameter measurement instrument based on Fraunhofer diffraction for physics education and basic laboratory use. The prototype integrates a 650 nm laser diode, a 16-channel photodiode array, and an ESP32 microcontroller to automate diffraction pattern acquisition and analysis. Repeated measurements were conducted on human hair and banana midrib fibers, with twenty trials for each sample, to examine measurement stability and precision. The system consistently captured diffraction patterns within expected physical ranges. The mean diameter of the human hair sample was 1.99 µm with a standard deviation of 0.12 µm and a coefficient of variation (CV) of 6.03%, indicating high precision. For banana midrib fibers, the mean diameter was 3.22 µm with a standard deviation of 0.37 µm and a CV of 11.49%, which is acceptable for heterogeneous biological materials. Narrow 95% confidence intervals for both samples confirm reliable mean estimation. The results demonstrate that the developed instrument provides stable, repeatable measurements while remaining affordable and simple to operate. This prototype is therefore suitable as an instructional laboratory tool for teaching diffraction concepts and quantitative measurement skills in physics education, as well as for basic research in resource-limited laboratory environments.

Keywords: Diffraction; Micro-Diameter Measurement; Photodiode Array; ESP32

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Introduction

Accurate micro-scale measurement plays a crucial role in physics and materials characterization, particularly in understanding the optical and mechanical properties of small structures (Hecht, 2017; Perry et al., 1974). The physical dimensions of microscopic structures such as the thickness of biological fibers, the diameter of natural materials, or the dimensions of soft tissues often dictate their mechanical, optical, and functional properties. As a result, obtaining reliable micro-diameter measurements is fundamental not only for characterization purposes but also for ensuring reproducibility in experimental studies and maintaining product consistency in industrial applications.

Conventional measurement tools, such as micrometers and calipers, rely on physical contact between the instrument and the sample. While suitable for rigid materials, these tools present challenges when applied to delicate, deformable, or irregular microstructures. Biological materials such as human hair, tissue samples, or plant fibers are particularly sensitive to compressive forces, which may alter their dimensions during measurement, leading to biased or inaccurate results. Contact-based measurement techniques may introduce deformation when applied to soft or biological materials, potentially leading to inaccurate diameter estimation (Levental et al., 2010; Malek et al., 2003).

Digital microscopy provides a non-contact alternative but introduces other limitations, including high equipment cost, the need for periodic calibration, sensitivity to optical alignment, and reliance on image-processing algorithms that require technical expertise. Additionally, accurate micro-diameter estimation from digital images can be complicated by variations in illumination, depth of field, and the orientation of the sample on the imaging plane. Non-contact optical approaches, such as laser diffraction and interferometric techniques, have therefore been widely explored as alternatives for precise fiber diameter measurement (Perry et al., 1974; Jasapara et al., 2003).

Diffraction-based measurement offers a promising, low-cost, and non-contact alternative that bypasses many of these limitations. When a coherent light source, such as a laser, interacts with a thin object, it produces a diffraction pattern whose spatial characteristics are directly related to the object's geometry. Under Fraunhofer conditions, the position of the first-order diffraction minimum can be analytically correlated with the diameter of the object. This makes diffraction especially suitable for measuring fibers, filaments, and other small cylindrical structures without requiring physical contact or high-resolution imaging systems. Early work by Perry, Ineichen, and Eliasson (1974) verified that laser diffraction could be used to determine fiber diameters with high precision. More recently, Nuraeni et al (2019) reaffirmed the suitability of laser diffraction for micro-scale biological fibers in low-cost educational settings, further highlighting its accessibility and practical value. In physics education, laboratory activities are essential for connecting theoretical concepts with experimental evidence, particularly when students engage directly with measurement instruments and data analysis (Hofstein & Lunetta, 2004; Redish, 2003).

Advances in optoelectronics and embedded systems have opened new opportunities to modernize diffraction measurement techniques. Photodiode arrays are capable of capturing intensity profiles with high sensitivity and fast response times, while microcontrollers such as the ESP32 allow real-time data acquisition, processing, and digital display. The integration of these components enables the development of portable, automated, and low-cost instruments capable of analyzing diffraction patterns with minimal operator intervention. Low-cost and accessible laboratory instruments are increasingly important for supporting effective physics learning in schools and universities with limited resources (De Jong et al., 2013; OECD, 2017).

Building upon these technological developments, the present study addresses two central research problems:

(1) how to design and develop a diffraction-based micro-diameter measurement instrument that is low-cost, automated, and suitable for educational laboratories, and

(2) how to evaluate its precision, reliability, and measurement stability when applied to micro-scale biological samples.

Accordingly, this study aims to construct a functional prototype incorporating a 650 nm laser diode, a 16-channel photodiode array, and an ESP32 microcontroller, and to assess its performance through repeated measurements of human hair and banana midrib fibers. By analyzing statistical indicators such as mean diameter, standard deviation, coefficient of variation, and confidence intervals, this research seeks to determine the feasibility of the prototype as an accessible and dependable non-contact measurement instrument for micro-scale applications.

Methods

The prototype developed in this study comprised optical, electronic, and computational subsystems designed to measure micro-scale diameters using Fraunhofer diffraction. A 650 nm red laser diode served as a coherent monochromatic light source and was aligned perpendicular to the fiber sample to generate a stable diffraction pattern. The human hair sample consisted of a single strand obtained from one adult valunteer, while the banana midrib fibers were taken from a single banana plant. All measurements were performed on individual fibers rather than bundled samples to ensure consistency and minimize geometric variation. Human hair and banana midrib fibers were mounted on a custom holder under slight tension to maintain straightness and consistent orientation during illumination.

Diffracted light was detected using a 16-channel linear photodiode array with a fixed spacing of 0.5 mm between adjacent channels. The sensor array was positioned at a distance of 300 ± 1 mm from the sample to satisfy the far-field (Fraunhofer) condition. Each photodiode produced an analog voltage proportional to incident light intensity. An ESP32 microcontroller sequentially sampled all channels using its onboard analog-to-digital converter. A moving average filter was applied to reduce high-frequency noise due to ambient light and electronic fluctuations.

Data acquisition and processing sequence implemented on the ESP32 microcontroller to ensure consistent and repeatable micro-diameter measurements. The algorithm was designed to automate diffraction pattern analysis and minimize operator-dependent variability. First, the ESP32 sequentially scanned the 16-channel photodiode array and digitized the analog voltage signals using its onboard analog-to-digital converter. To reduce the influence of electronic noise and ambient light fluctuations, a moving average filter was applied to the raw intensity data. The filtered intensity profile was then analyzed to identify the channel corresponding to the central diffraction maximum, defined as the channel with the highest recorded intensity. Next, the first-order diffraction minimum was detected as the nearest local minimum in intensity adjacent to the central maximum. The distance between these two features was calculated by multiplying the channel index difference by the known photodiode spacing. This automated processing routine was repeated for each measurement trial and applied consistently to both human hair and banana midrib fiber samples.

The processed intensity profile was analyzed to identify the central diffraction maximum (highest intensity) and the first-order diffraction minimum (nearest local minimum). The linear distance x between these features was obtained by converting the channel index difference into millimeters using the known sensor spacing. The value of x was obtained from the photodiode array by converting the difference in sensor channel indices between the central maximum and the first minimum into a linear distance using the known spacing of 0.5 mm between adjacent photodiodes. This formulation enables accurate diameter estimation without physical contact, making it suitable for fragile and deformable biological samples.

The fiber diameter d was then calculated using the Fraunhofer diffraction relationship:

$$d = \frac{\lambda L}{x} \tag{1}$$

d = fiber diameter
λ = 650 nm (laser wavelength)
L = 300 mm (distance between sample and photodiode array)
x = measured spacing between the centralmaximum and the first minimum

Twenty repeated measurements were performed for each sample to evaluate stability and precision. Statistical parameters including mean diameter, standard deviation (SD), coefficient of variation (CV), standard error of the mean (SEM), and 95% confidence intervals (CI) were computed. The experimental procedure and data processing approach adopted in this study are consistent with laboratory-based learning strategies that emphasize hands-on measurement, automation, and reproducibility in physics education (Sokoloff et al., 2011; Sokoloff & Thornton, 1997).

Results and Discussion

The performance of the diffraction-based micro-diameter measurement instrument was evaluated trhrough repeated measurements of human hair and banana midrib fibers. Twenty measurements were conducted for each sample to assess measurement stability, precision, and reliability. The experimental results obtained form the measurements are sumarized in Table 1 for human hair samples and Tabel 3 for banana midrib fiber samples.

The measurements obtained for the human hair sample produced diameter values ranging from 1.6 µm to 2.7 µm, indicating a relatively narrow data distribution. Repeated values, particularly 1.7 µm and 1.9 µm, were consistently observed across the twenty trials, suggesting stable detection of diffraction minima by the photodiode array system. The calculated mean diameter was 1.99 µm, with a standard deviation of 0.12 µm, a coefficient of variation (CV) of 6.03%, and a standard error of the mean (SEM) of 0.02 µm. The corresponding 95% confidence interval was [1.934–2.046] µm, indicating a small uncertainty range in the estimated mean value. Coefficient of variation values below 10% are commonly regarded as indicators of high precision in repeated optical measurements, particularly in instructional laboratory environments (Hake, 1998; Wieman et al., 2008). The consistent recurrence of similar measurement values across trials indicates reliable identification of the central maximum and first-order diffraction minimum, reflecting stable diffraction signal acquisition. Such sensitivity to small dimensional variations is consistent with earlier laser diffraction studies on fiber measurements (Perry et al., 1974). Despite natural structural variations typically present in human hair, including cuticle irregularities and slight geometric tapering, the observed narrow statistical spread suggests relatively uniform sample geometry or effective averaging of minor irregularities by the diffraction-based measurement approach.

Table 1. Result of Hair Measurements

No.	Measurement	Hair diameter (μm)	No.	Measurement	Hair diameter (μm)
1	1	2.5	11	11	2.2
2	2	1.7	12	12	1.9
3	3	2.7	13	13	1.7
4	4	1.7	14	14	1.7
5	5	2.2	15	15	2.2
6	6	2.5	16	16	1.7
7	7	1.7	17	17	1.9
8	8	2.5	18	18	2.0
9	9	1.7	19	19	1.9
10	10	1.6	20	20	1.9

Table 2. Statistical Summary of Hair Measurements

Parameter	Value
Mean diameter	1.99 μm
Standard deviation (SD)	0.12 μm
Coefficient of variation (CV)	6.03 %
Standard error of mean (SEM)	0.02 μm
95% Confidence interval	[1.934 – 2.046] μm

Table 3. Result of Banana Midrib Fiber Measurements

No.	Measurement	Banana midrib fiber Diameter (μm)
1	1	4.7
2	2	2.9
3	3	3.7
4	4	2.9
5	5	3.1
6	6	2.9
7	7	3.1
8	8	2.9
9	9	2.9
10	10	2.7
11	11	2.5
12	12	3.7
13	13	2.9
14	14	3.4
15	15	3.7
16	16	2.9
17	17	2.7
18	18	3.1
19	19	4.7
20	20	2.9

Table 4. Statistical Summary of Banana Midrib Fiber Measurements

Parameter	Value
Mean diameter	3.22 μm
Standard deviation (SD)	0.37 μm
Coefficient of variation (CV)	11.49 %
Standard error of mean (SEM)	0.08 μm
95% Confidence interval	[3.047 – 3.393] μm

In comparison, the banana midrib fiber measurements exhibited a wider distribution, with diameter values ranging from 2.5 μm to 4.7 μm, as summarized in Table 3. The mean diameter obtained from twenty repeated measurements was 3.22 μm, with a standard deviation of 0.37 μm, a coefficient of variation of 11.49%, and a SEM value of 0.08 μm. The calculated 95% confidence interval [3.047–3.393] μm indicates that the estimated mean diameter remains statistically well constrained despite greater dispersion in individual measurements. Recurrent values around 2.9 μm were observed across several trials, indicating consistent detection of diffraction minima even under structurally variable conditions. The larger variability observed in banana midrib fibers agrees with previous studies reporting that natural plant fibers possess heterogeneous microstructures that influence diffraction responses (Levental et al., 2010; Malek et al., 2003). Variations in cellulose microfibril arrangement and layered cell-wall composition can produce asymmetric diffraction signatures, explaining the broader spread of measured values while maintaining consistent mean estimation.

This study addressed two primary research questions concerning the development and evaluation of a diffraction-based micro-diameter measurement instrument. The first question examined how a low-cost and automated system suitable for educational laboratories could be designed and implemented. The developed prototype integrates a 650 nm laser diode as a coherent light source, a custom fiber holder to maintain sample alignment, a 16-channel photodiode array for detecting diffraction intensity, and an ESP32 microcontroller for automated data acquisition and processing. The experimental configuration shown in Figure 1 ensures proper alignment between the laser source, the fiber sample, and the detector, allowing measurements to be performed under Fraunhofer diffraction conditions. Real-time signal acquisition combined with digital processing and moving-average filtering enables stable identification of diffraction minima without requiring complex imaging systems or expensive optical instrumentation. These design choices demonstrate that diffraction principles can be translated into a practical and accessible measurement system appropriate for instructional laboratories (Hofstein & Lunetta, 2004; de Jong et al., 2013).

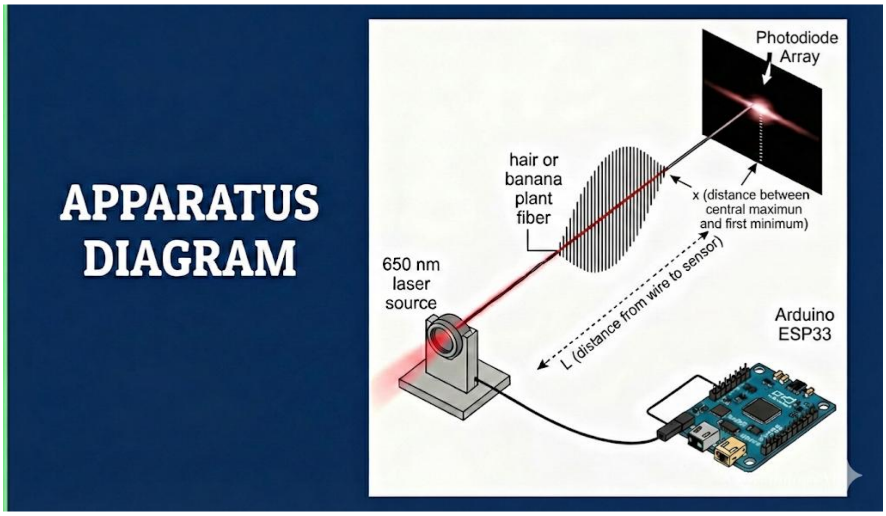

Figure 1. Apparatus Diagram of Human Hair and Banana Midrib Fiber Measurements

The second research question focused on evaluating measurement precision, reliability, and stability when applied to micro-scale biological samples. The measurement results summarized in Tables 1–4 show consistent performance across twenty repeated trials for each sample. For human hair, the obtained standard deviation of 0.12 μm and coefficient of variation of 6.03% indicate high measurement precision, while the narrow confidence interval confirms strong repeatability and minimal uncertainty in the estimated mean diameter. The recurring appearance of similar measurement values demonstrates stable detection of diffraction minima, indicating reliable optical alignment and consistent sensor response. These observations agree with previous findings that laser diffraction techniques are highly sensitive to small variations in fiber thickness (Perry et al., 1974).

In contrast, banana midrib fibers exhibited greater variability, reflected by a coefficient of variation of 11.49%. This behavior is expected because plant fibers possess heterogeneous internal structures composed of cellulose, hemicellulose, and lignin layers that produce irregular cross-sectional geometries. Despite this intrinsic variability, the confidence interval remained relatively narrow, indicating that the developed system reliably estimates average diameters even for structurally complex biological materials. Similar variability patterns have been reported in optical measurements of natural fibers, where dispersion primarily reflects material characteristics rather than measurement limitations (Levental et al., 2010; Malek et al., 2003).

Measurement stability was achieved through controlled experimental conditions and systematic data acquisition. The laser, sample holder, and photodiode array were rigidly mounted to maintain constant geometry, and the detector distance was fixed at 300 ± 1 mm to satisfy Fraunhofer requirements. Samples were mounted under slight tension to prevent positional shifts, while automated signal acquisition and digital filtering minimized environmental noise and operator-dependent errors. Repeating measurements without altering the optical configuration enabled reliable evaluation of repeatability and explains the low statistical dispersion observed in both datasets.

From an instrumentation perspective, the developed prototype achieves a practical balance between accuracy and affordability. Although scanning electron microscopy provides higher spatial resolution and detailed morphological visualization, it requires complex preparation and costly equipment. In comparison, diffraction-based measurement offers rapid, non-contact operation with minimal calibration requirements while maintaining reliable quantitative accuracy. Consequently, the proposed system represents an effective alternative for educational laboratories and basic research environments requiring accessible micro-scale measurement tools (Perry et al., 1974; Jasapara et al., 2003).

Several limitations should be considered. The discrete sampling resolution of the 16-channel photodiode array may reduce sensitivity to very fine diffraction variations, and highly irregular or multilayered samples may generate complex diffraction patterns that challenge simple minima detection. Similar limitations have been reported in previous diffraction-based fiber measurements (Malek et al., 2003; Perry et al., 1974). Nevertheless, the results demonstrate that the prototype successfully bridges theoretical optics and practical instrumentation by enabling stable and repeatable non-contact measurements.

Beyond measurement performance, the system supports laboratory-based learning by allowing students to directly observe diffraction phenomena and perform quantitative analysis. Such hands-on engagement has been shown to enhance conceptual understanding and experimental skills in physics education (Hake, 1998; Finkelstein et al., 2005; Perkins et al., 2006; Wieman et al., 2008; Zacharia et al., 2008; Gunawan et al., 2018). Overall, the findings confirm that diffraction-based measurement remains a robust and practical approach for micro-diameter characterization while providing an accessible platform for both education and basic research applications.

Conclusion

This study successfully designed and developed a low-cost, automated micro-diameter measurement instrument based on Fraunhofer diffraction using a 650 nm laser source, a photodiode array detector, and an ESP32 microcontroller for data acquisition and processing. The experimental implementation demonstrates that the proposed system is suitable for educational laboratory applications due to its simple configuration and automated measurement capability. Performance evaluation through repeated measurements on human hair and banana midrib fibers confirms that the instrument provides stable, repeatable, and reliable measurements. The obtained statistical results indicate good precision, with low measurement dispersion for homogeneous samples and acceptable variability for heterogeneous biological materials. These findings show that the developed prototype is capable of accurately estimating micro-scale diameters and effectively detecting diffraction intensity variations. Overall, the study confirms that a diffraction-based approach can be implemented as an affordable and practical non-contact measurement solution while maintaining sufficient precision and stability for educational and basic research purposes.

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