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Introduction

The phenomenon of diffraction and interference plays a central role in understanding the behavior of light as it interacts with obstacles and openings. In the realm of optics, laser sources such as helium-neon (He-Ne) lasers are renowned for their coherent, monochromatic light, which makes them ideal for experimental investigations into wave phenomena. When a helium-neon laser emitting light at a wavelength of 632.8 nm is directed through a narrow slit, the resulting diffraction pattern reveals the wave nature of light and provides insights into the principles governing wave behavior.

In this article, we explore the problem of determining the width of a diffraction pattern produced when a helium-neon laser beam passes through a single slit of known width. We will delve into the fundamental theory of single-slit diffraction, analyze the relevant equations, and perform detailed calculations. By doing so, we aim to provide a comprehensive understanding suitable for students, educators, and enthusiasts interested in optics and wave physics.

Understanding Single-Slit Diffraction

What Is Diffraction?

Diffraction refers to the bending and spreading of waves when they encounter an obstacle or aperture that is comparable in size to their wavelength. For light waves, this phenomenon manifests as a pattern of bright and dark fringes observed on a screen placed behind the slit.

The Single-Slit Diffraction Pattern

When monochromatic light passes through a single narrow slit, the light waves spread out and interfere with each other, creating a diffraction pattern characterized by:

- A central bright maximum (central fringe) that is the widest.
- Successive dimmer maxima on either side.
- Dark minima (destructive interference points) between maxima.

The pattern's details depend on the slit width, the wavelength of light, and the distance from the slit to the screen.

Fundamental Principles and Equations

Key Variables

Variable	Description	Typical Units
λ	Wavelength of the laser light	meters (m) or nanometers (nm)
a	Width of the slit	meters (m)
L	Distance from the slit to the screen	meters (m)
y	Position of a dark fringe (minimum) from the central maximum	meters (m)

The Diffraction Condition for Minima

The positions of minima in single-slit diffraction are given by:

$$\sin \theta = m \lambda / a$$

where:

- θ is the angle between the central axis and the line passing through the minima.
- m is the order of the minimum ($m = \pm 1, \pm 2, \pm 3, \ldots$).

For small angles (which is typical in such experiments), $\sin \theta \approx \tan \theta \approx y / L$, where y is the position of the minima on the screen.

Relationship Between Fringe Width and Slit Width

The width of the central maximum (or any fringe) on the screen can be calculated using:

$$\text{Width of fringe } (\Delta y) = 2 L \tan \theta$$

For small angles:

$$\Delta y \approx 2 L (\lambda / a)$$

This relation allows us to determine the width of the diffraction pattern given the slit width, wavelength, and distance to the screen.

Given Data and Problem Statement

- Wavelength of helium-neon laser, $\lambda = 632.8$ nm $= 632.8 \times 10^{-9}$ m
- Slit width, $a = 0.30$ mm $= 0.30 \times 10^{-3}$ m
- Distance from slit to screen, $L =$ (assumed or given in problem context, typically 1 m or more)

Note: Since the problem statement does not specify the distance L, we typically assume a standard setup or that the question aims to find the width of the diffraction pattern on a screen placed at a certain distance.

Calculating the Width of the Diffraction Pattern

Step 1: Convert All Units to SI

- $\lambda = 632.8$ nm $= 632.8 \times 10^{-9}$ m
- $a = 0.30$ mm $= 0.30 \times 10^{-3}$ m

Step 2: Determine the Angle for the First Minimum

The first diffraction minimum ($m=1$):

$$\sin \theta = \lambda / a = (632.8 \times 10^{-9}) / (0.30 \times 10^{-3}) \approx 2.1093 \times 10^{-3}$$

Since $\sin \theta$ is very small, $\theta \approx \sin \theta$:

$$\theta \approx 2.1093 \times 10^{-3} \text{ radians}$$

Step 3: Calculate the Position of the First Minimum on the Screen

Assuming the screen is placed at a distance L, the position $y1$ of the first minimum is:

$$y1 \approx L \times \tan \theta \approx L \times \theta$$

Similarly, the full width of the central maximum (from the first minimum on one side to the first on the other side) is:

$$\text{Width of central maximum, } W = 2\, y1 \approx 2\, L \times \theta$$

Step 4: Final Expression for the Width

Putting it all together, the width of the central bright fringe is:

$$W \approx 2\, L \times (\lambda / a)$$

Note: This formula indicates that the width is directly proportional to the distance L and the wavelength λ, and inversely proportional to the slit width a.

Practical Example Calculation

Suppose the screen is placed 1 meter away from the slit (a typical setup):

- L = 1 m

Calculate the width W:

$$W \approx 2 \times 1\text{ m} \times 2.1093 \times 10\text{-}3 \approx 4.2186 \times 10\text{-}3\text{ m}$$

Expressed in millimeters:

$$W \approx 4.22\text{ mm}$$

Interpretation: The central bright fringe spans approximately 4.22 mm on the screen at 1 meter distance.

Additional Considerations

Effect of Increasing Distance

- Increasing the distance L results in a larger diffraction pattern width.
- For precise measurements, controlling the distance is essential.

Wavelength Dependence

- Shorter wavelengths produce narrower diffraction patterns.
- Different laser sources will yield different diffraction pattern widths even with the same slit width.

Slit Width Influence

- Narrower slits produce wider diffraction patterns.
- Conversely, wider slits result in narrower diffraction fringes.

Limitations and Assumptions

- The small angle approximation ($\sin \theta \approx \tan \theta \approx \theta$) holds for small θ, typically less than about 10 degrees.
- The calculation assumes ideal conditions without considering factors like slit imperfections or experimental

errors.

Applications of Single-Slit Diffraction

Understanding single-slit diffraction is fundamental in various scientific and technological fields:

- Optical Instrumentation: Designing spectrometers and diffraction gratings.
- Laser Physics: Characterizing laser beam quality and coherence.
- Communication Technologies: Analyzing beam propagation and diffraction effects.
- Educational Demonstrations: Visualizing wave phenomena in physics education.
- Nanotechnology: Investigating structures at microscopic scales where diffraction limits are relevant.

Conclusion

The analysis of a helium-neon laser passing through a single slit of known width provides a clear illustration of wave diffraction principles. By applying the fundamental diffraction equations and assuming typical experimental conditions, we have shown that the width of the diffraction pattern is directly proportional to the wavelength of light and the distance from the slit to the screen, and inversely proportional to the slit width.

Specifically, with a 632.8 nm wavelength, a slit width of 0.30 mm, and a screen 1 meter away, the central diffraction maximum spans approximately 4.22 mm. This understanding not only enriches our comprehension of wave behavior but also underpins practical applications in optics and photonics technology.

By mastering these concepts, students and professionals can better interpret optical experiments, optimize device designs, and appreciate the wave nature of light that forms the foundation of modern optics.

References

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Frequently Asked Questions

What is the formula used to calculate the diffraction fringe width for a helium-neon laser passing through a single slit?

The fringe width (w) is given by $w = (\lambda \times D) / a$, where λ is the wavelength, D is the distance from the slit to the screen, and a is the slit width.

Given a helium-neon laser wavelength of 632.8 nm and a slit width of 0.30 mm, how does the slit width affect the diffraction pattern?

A narrower slit (smaller a) results in a wider diffraction pattern, increasing the fringe width; conversely, a wider slit produces a narrower pattern.

How can the fringe width be calculated if the distance from the slit to the screen is known?

Use the formula $w = (\lambda \times D) / a$, substituting the given wavelength, slit width, and distance to find the fringe width.

What is the significance of the wavelength 632.8 nm in the context of the helium-neon laser diffraction experiment?

The wavelength 632.8 nm is the specific light emitted by helium-neon lasers, which determines the diffraction pattern's fringe width and overall pattern.

If the distance from the slit to the screen is doubled, how does it affect the diffraction fringe width?

The fringe width doubles, as it is directly proportional to the distance D from the slit to the screen in the diffraction formula.

Additional Resources

Helium-Neon Laser Light (λ = 632.8 nm) Sent Through a Single Slit of Width 0.30 mm: What Is the Resulting Width?

The phenomenon of light diffraction and interference has fascinated scientists and optical engineers for centuries. Among various laser sources, the Helium-Neon (He-Ne) laser is renowned for its coherent, monochromatic light at a wavelength of approximately 632.8 nanometers. When such laser light passes through a narrow slit, it produces characteristic diffraction patterns that can be analyzed to understand the wave nature of light. In this article, we delve into a specific scenario where a He-Ne laser beam with a wavelength of 632.8 nm is incident on a single slit of width 0.30 mm, and we explore what the resulting diffraction pattern looks like, especially focusing on the width of the central bright fringe.

Understanding the Basics: Diffraction and Single-Slit Interference

What is Diffraction?

Diffraction refers to the bending and spreading of waves when they encounter an obstacle or aperture comparable in size to their wavelength. It is a fundamental wave phenomenon that demonstrates the wave nature of light. When a coherent light source like a laser passes through a narrow slit, the wave does not simply travel straight through; instead, it spreads out, producing a diffraction pattern.

Single-Slit Diffraction Pattern

A single slit acts as a new source of secondary wavelets, according to Huygens' principle. The interference of these wavelets creates a characteristic pattern on a screen placed beyond the slit. The pattern consists of a central bright maximum called the central fringe, flanked by alternating dark and bright fringes known as minima and secondary maxima, respectively.

The key features of the single-slit diffraction pattern are:

- The central maximum is the widest and brightest.
- The intensity diminishes for subsequent maxima.
- Dark minima occur at specific angles where destructive interference nullifies the light.

Mathematical Foundations of Diffraction Pattern Width

To analyze the diffraction pattern quantitatively, we rely on the principles of wave interference and the mathematics governing the angles at which minima and maxima occur.

Conditions for Minima in Single-Slit Diffraction

The position of the minima (dark fringes) in the diffraction pattern is given by the equation:

$$ a \sin \theta = m \lambda \quad \text{for} \quad m = \pm 1, \pm 2, \pm 3, \ldots $$

where:
- a = width of the slit
- θ = angle relative to the central maximum
- λ = wavelength of the light
- m = order of the minimum (an integer)

The central maximum is bounded by the first minima on either side, which correspond to $m = \pm 1$.

Calculating the Angular Width of the Central Maximum

The angular width of the central bright fringe, which extends from the first minimum on one side to the first minimum on the other side, is approximately:

$$ \Delta \theta = 2 \theta_1 $$

where θ_1 is the angle corresponding to the first minimum ($m=1$):

$$ \sin \theta_1 = \frac{\lambda}{a} $$

Since for small angles $\sin \theta \approx \theta$ (in radians), this simplifies to:

$$ \theta_1 \approx \frac{\lambda}{a} $$

Thus, the angular width:

$$ \Delta \theta \approx 2 \frac{\lambda}{a} $$

Calculating the Pattern Width on the Screen

From Angular to Linear Width

The physical width W of the central maximum on a screen positioned at a distance D from the slit can be calculated by:

$$ W = 2 D \tan \theta_1 $$

Given the small-angle approximation:

$$ \tan \theta_1 \approx \sin \theta_1 \approx \frac{\lambda}{a} $$

Therefore,

$$ W \approx 2 D \times \frac{\lambda}{a} $$

This formula indicates that the width of the central bright fringe is directly proportional to the wavelength and the distance to the screen, and inversely proportional to the slit width.

Applying the Formula: Numerical Calculation

Let's now carry out a specific calculation based on the provided parameters:

- Wavelength of He-Ne laser, $ \lambda = 632.8 \text{ nm} = 632.8 \times 10^{-9} \text{ m} $
- Slit width, $ a = 0.30 \text{ mm} = 0.30 \times 10^{-3} \text{ m} $

Assuming a typical experimental setup where the screen is placed at $ D = 2 \text{ m} $, we calculate:

$$ W \approx 2 \times 2 \text{ m} \times \frac{632.8 \times 10^{-9} \text{ m}}{0.30 \times 10^{-3} \text{ m}} $$

Simplify numerator and denominator:

$$ W \approx 4 \times \frac{632.8 \times 10^{-9}}{0.30 \times 10^{-3}} $$

$$ W \approx 4 \times \frac{632.8 \times 10^{-9}}{3 \times 10^{-4}} $$

$$ W \approx 4 \times \left(\frac{632.8}{3} \times 10^{-9 + 4} \right) $$

$$ W \approx 4 \times (210.93 \times 10^{-5}) $$

$$ W \approx 4 \times 2.1093 \times 10^{-3} $$

$$ W \approx 8.437 \times 10^{-3} \text{ m} $$

Converting back to millimeters:

$$ W \approx 8.44 \text{ mm} $$

Result: The width of the central bright fringe on the screen is approximately 8.44 millimeters.

Implications and Significance of the Result

The calculated width of approximately 8.44 mm for the central maximum in the diffraction pattern provides critical insights into the wave nature of light and the precision required in optical experiments. Several factors influence this pattern:

1. Wavelength Dependency: The pattern width scales directly with the wavelength. A longer wavelength results in a broader central maximum, illustrating the wave's sensitivity to the light's frequency.

2. Slit Width Influence: The narrower the slit, the wider the diffraction pattern. This inverse relationship underscores the wave-particle duality and the Heisenberg uncertainty principle, which suggests that confining light spatially increases uncertainty in its momentum, leading to broader diffraction.

3. Distance to Screen: The pattern widens proportionally with the distance from the slit to the screen. Longer distances allow more pronounced spread, which is essential for experimental visualization.

4. Practical Applications: Understanding the diffraction pattern width is crucial in designing optical instruments, such as spectrometers, holography systems, and laser communication devices where beam divergence must be minimized.

Real-World Applications and Experimental Considerations

Applications of Single-Slit Diffraction

Single-slit diffraction plays a pivotal role in various scientific and technological applications:
- Optical Testing: Assessing the coherence and wavelength of laser sources.
- Spectroscopy: Understanding spectral line widths and resolving power.
- Material Characterization: Studying surface roughness and nano-scale structures.
- Communication Technologies: Minimizing beam divergence for precise laser targeting.

Experimental Challenges and Considerations

While theoretical calculations provide idealized insights, real-world experiments face challenges such as:
- Alignment Precision: Ensuring the laser beam is incident perpendicularly and aligned with the slit.
- Slit Fabrication: Achieving uniform slit width and smooth edges to prevent extraneous diffraction effects.
- Measurement Accuracy: Precisely measuring distances and fringe widths requires high-resolution screens and measurement tools.
- Environmental Factors: Vibrations, air currents, and ambient light can distort diffraction patterns.

Conclusion: The Significance of Diffraction Pattern Analysis

Analyzing the diffraction pattern of a helium-neon laser passing through a narrow slit reveals the fundamental wave characteristics of light. The calculated central maximum width of approximately 8.44 mm at a 2-meter distance exemplifies the delicate interplay between wavelength, slit width, and observation distance. Such insights are not only academically intriguing but also practically vital in the advancement of optical technologies and experimental physics. As laser applications continue to expand in fields ranging from medicine to telecommunications, understanding diffraction phenomena remains central to optimizing and innovating optical systems.

In essence, the diffraction pattern offers a window into the wave nature of light, bridging theoretical physics and practical engineering—an enduring testament to the wave-particle duality at the heart of quantum

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