LEOK-3 Optics Experiment Kit

Instruction Manual

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COMPANY PROFILE

Lambda Scientific Systems, Inc. specializes in developing and marketing scientific instruments and systems designed and manufactured specifically for experimental education in physics at colleges and universities. Our mission is to become a premier supplier of high-quality, robust, easy-to-use, and affordable scientific instruments and systems to college educators and students for their teaching and learning of both fundamental and modern experiments in physics. Our products focus on comprehensive physics education kits, as well as light sources and opto-mechanic components.

Our physics education kits cover a wide range of experiments in general physics, especially in geometrical optics, physical optics, and fiber optics. Experiments include lens imaging, interferometry, diffraction, holography, polarization, laser physics, quantum optics, and Fourier optics through a series of the most representative apparatus such as Newton’s ring apparatus, Young’s modulus apparatus, Michelson interferometer, Fabry-Perot interferometer, Twyman-Green interferometer, Fourier spectrometer, and laser.

Our fiber optics education kits keep a pace with the advent of fiber optical communication technology by designing experimental systems to teach fundamental optical fiber concepts such as fiber-to-fiber coupling, fiber-to-source coupling, fiber numerical aperture, fiber mode, fiber transmission loss, and fiber sensing. These kits also give students an opportunity to be familiar with modern fiber optic components or apparatus such as Mach-Zehnder interferometer, variable optical attenuator, fiber isolator, fiber splitter, fiber switch, wavelength-division multiplexer, fiber amplifier, and transmitter.

Our light sources include Xenon lamp, Mercury lamp, Sodium lamp, Bromine Tungsten lamp and various lasers.

We also provide a variety of opto-mechanical components such as optical mounts, optical breadboards and translation stages. Our products have been sold worldwide. Lambda Scientific Systems, Inc is committed to providing high quality, cost effective products and on-time delivery.
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1. Introduction

The LEOK-3 Optics Experiment Kit is developed for general physics education at universities and colleges. This kit provides a complete set of optical and mechanical components as well as light sources, which can be conveniently assembled to construct experimental setups. Almost all optics experiments required in general physics education (e.g. geometrical, physical, and modern optics) can be constructed in sequence using these components. Through selecting and assembling the corresponding components into experimental setups, students can enhance their experimental skills and problem solving ability.

LEOK-3 can be used to construct a total of 26 different experiments that can be grouped in six categories:

- Lens Measurements: Understanding and verifying lens equation and optical rays transform.
- Optical Instruments: Understanding the working principle and operation method of common lab optical instruments.
- Interference Phenomena: Understanding interference theory, observing various interference patterns generated by different sources, and learning one precise measurement method based on optical interference.
- Diffraction Phenomena: Understanding diffraction effects, observing various diffraction patterns generated by different apertures.
- Analysis of Polarization: Understanding polarization and verifying polarization of light.
- Fourier Optics and Holography: Understanding principles of advanced optics and their applications.

List of experimental examples

Measuring the focal length of a positive thin lens using auto-collimation
Measuring the focal length of a positive thin lens using displacement method
Measuring the focal length of an eyepiece
Assembling a microscope
Assembling a telescope
Assembling a slide projector
Measuring the nodal locations and focal length of a lens-group
Assembling an erect imaging telescope
Young’s double-slit interference
Interference of Fresnel’s biprism
Interference of double mirrors
Interference of Lloyd’s mirror
Interference of Newton Ring
Fraunhofer diffraction of a single slit
Fraunhofer diffraction of a single circular aperture
Fresnel diffraction of a single slit
Fresnel diffraction of a single circular aperture
Fresnel diffraction of a sharp edge
Analysing polarization status of light beams
Diffraction of a grating
Assembling a Littrow-type grating spectrometer
Recording and reconstructing holograms
Fabricating a holographic grating
Abbe imaging principle and optical spatial filtering
Pseudo-color encoding, theta modulation and color composition
Assembling a Michelson interferometer and measuring the refractive index of air

2. Parts Included in the Kit

2.1 Light Sources

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Specifications</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Pressure Mercury Lamp (LLE-1)</td>
<td>20 W with power supply (100 to 120, or 220 to 240 VAC, 50/60 Hz)</td>
<td>1 piece</td>
</tr>
<tr>
<td>Low Pressure Sodium Lamp (LLE-2)</td>
<td>20 W with power supply (100 to 120, or 220 to 240 VAC, 50/60 Hz)</td>
<td>1 piece</td>
</tr>
<tr>
<td>Bromine Tungsten Lamp (LLC-4)</td>
<td>6 V/15 W with power supply (100 to 120, 220 to 240 VAC, 50/60 Hz)</td>
<td>1 piece</td>
</tr>
<tr>
<td>He-Ne Laser (LLL-2)</td>
<td>1.5 mW with power supply (100 to 120, 220 to 240 VAC, 50/60 Hz)</td>
<td>1 piece</td>
</tr>
<tr>
<td>Small Illuminating Lamp (LLC-6)</td>
<td>3 VDC</td>
<td>1 piece</td>
</tr>
</tbody>
</table>

2.2 Mechanical Hardware

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Specifications</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Axis Stage (LEPO-2)</td>
<td>X translation stage (10 mm travel and 0.01 mm resolution) Z-adjustable (30 mm) with a magnetic base</td>
<td>1 piece</td>
</tr>
<tr>
<td>Z-Adjustable Post Holder (LEPO-3)</td>
<td>Travel 30 mm with a magnetic base</td>
<td>1 piece</td>
</tr>
<tr>
<td>Product Description</td>
<td>Quantity</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic Base (LEPO-4)</strong></td>
<td>3 pieces</td>
<td></td>
</tr>
<tr>
<td>With post holder</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Two-Axis Tilt-able Holder (LEPO-8)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>Φ40 mm for mounting optical components such as lenses,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirrors, gratings, reticle, et al</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Adapter Piece (LEPO-10)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>By using this piece, two lenses can stand closer.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Prism Table (LEPO-12)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>tilt-able in two directions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>White Screen (LEPO-14)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>Uniform diffusing paint</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Iris Diaphragm (LEPO-16)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>0-14 mm adjustable</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Aperture Adjustable Bar Clamp (LEPO-20)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>30-50 mm, with two tilt-able directions, for mounting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tube-type components</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Multi-pinhole Disc Assembly (LEPO-24)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>Φ0.10, 0.15, 0.20, 0.30, 0.50, 0.60, 1.00, 2.00 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Aperture Adjustable Holder (LEPO-6)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>Variable Φ10-50 mm with two directions tilt-able</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lens Holder (LEPO-9)</strong></td>
<td>2 pieces</td>
<td></td>
</tr>
<tr>
<td>Optical diameter: Φ40 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Grating/Prism Table (LEPO-11)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>30° Z-axis rotation, two directions tilt-able</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Plate Holder A (LEPO-13)</strong></td>
<td>2 pieces</td>
<td></td>
</tr>
<tr>
<td>One direction tilt-able</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Object Screen (LEPO-15)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>Symmetrical triangle holes uniform diffusing paint</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Plate Holder B (LEPO-19)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>with two directions tilt-able</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sample Stage (LEPO-21)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td><strong>Single-Side Adjustable Slit (LEPO-28)</strong></td>
<td>1 piece</td>
<td></td>
</tr>
<tr>
<td>Slit width 0–2 mm, slit direction tilt within ±5°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item Description</td>
<td>Image</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------------------------------------------------</td>
<td>----------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Lens Group Holder (LEPO-29)</td>
<td><img src="image1" alt="Image" /></td>
<td>Movable on rail for nodal measurement [1 \text{ piece}]</td>
</tr>
<tr>
<td>Ruler (LEPO-34)</td>
<td><img src="image2" alt="Image" /></td>
<td>Used for experiment of measuring telescope’s magnification (with a tripod) [1 \text{ piece}]</td>
</tr>
<tr>
<td>Newton Ring Assembly (LEPO-38)</td>
<td><img src="image3" alt="Image" /></td>
<td>[1 \text{ piece}]</td>
</tr>
<tr>
<td>Spring Clip (LEPO-40)</td>
<td><img src="image4" alt="Image" /></td>
<td>Used for fastening small white screen and plane samples [1 \text{ piece}]</td>
</tr>
<tr>
<td>Single-sided Rotary Slit (LEPO-42)</td>
<td><img src="image5" alt="Image" /></td>
<td>The slit is variable from 0-5 mm on one side and rotatable [1 \text{ piece}]</td>
</tr>
<tr>
<td>Laser Holder (LEPO-44)</td>
<td><img src="image6" alt="Image" /></td>
<td>Allows attaching a He-Ne laser and other tubular part [1 \text{ piece}]</td>
</tr>
<tr>
<td>45° Glass Holder (LEPO-47)</td>
<td><img src="image7" alt="Image" /></td>
<td>Used for microscope magnification experiment. [1 \text{ piece}]</td>
</tr>
<tr>
<td>Iceland Crystal Rotary Holder (LEPO-50)</td>
<td><img src="image8" alt="Image" /></td>
<td>Used for crystal birefringence experiment. [1 \text{ piece}]</td>
</tr>
<tr>
<td>Erecting prism (LEPO-31)</td>
<td><img src="image9" alt="Image" /></td>
<td>Used for inverting image in two directions [1 \text{ piece}]</td>
</tr>
<tr>
<td>DMM Holder (LEPO-37)</td>
<td><img src="image10" alt="Image" /></td>
<td>* DMM is the abbreviation of Direct Measuring Microscope [1 \text{ piece}]</td>
</tr>
<tr>
<td>Newton Ring Holder (LEPO-39)</td>
<td><img src="image11" alt="Image" /></td>
<td>[1 \text{ piece}]</td>
</tr>
<tr>
<td>Spectral Filter (LEPO-41)</td>
<td><img src="image12" alt="Image" /></td>
<td>Used for Abbe’s image formation and experiment in space filtering. [1 \text{ piece}]</td>
</tr>
<tr>
<td>Biprism Holder (LEPO-43)</td>
<td><img src="image13" alt="Image" /></td>
<td>Can attach a biprism or other optical component to it, and rotate within ± 5°. [1 \text{ piece}]</td>
</tr>
<tr>
<td>Ground Glass Screen (LEPO-45)</td>
<td><img src="image14" alt="Image" /></td>
<td>(\Phi117 \text{ mm}) [1 \text{ piece}]</td>
</tr>
<tr>
<td>Optical Goniometer (LEPO-49)</td>
<td><img src="image15" alt="Image" /></td>
<td>Measuring Brewster angle at accuracy of 0.5°. [1 \text{ piece}]</td>
</tr>
<tr>
<td>Paper Clip (LEPO-51)</td>
<td><img src="image16" alt="Image" /></td>
<td>Used for Abbe’s theory of image formation and experiment of space filtering. [1 \text{ piece}]</td>
</tr>
</tbody>
</table>
### Polaroid Holder (LEPO-52)
Used for polarized light experiment.
- 2 pieces

### Carrier with Holder (LEPO-54-2)
Used with optical rail
- 3 pieces

### X-Adj. Carrier with Holder (LEPO-54-3)
Used with optical rail
- 2 pieces

### X-Z Adj. Carrier with Holder (LEPO-54-4)
Used with optical rail
- 2 pieces

### Optical Rail with Carriers (LEPO-54)
Length 1.0 meter dovetail rail (LEPO-54-1) used with carriers
- 1 piece

### 2.3 Optical Components

- Mounted Lenses: \( f = 4.5, 6.2, 15, 45, 50, 70, 150, 190, 225, 300, -100 \text{ mm}, \) 1 piece each
- Mounted Cemented Lenses: \( f = 29, 105 \text{ mm}, \) 1 piece each
- Mounted Flat Mirrors: \( \Phi 36 \text{ mm}, \) 2 pieces
- Mounted Beam Splitter: \( \Phi 30 \text{ mm}, 5:5 \text{ and } 7:3, \) 1 piece each
- Flaring Grating (at 500 nm): 1200 l/mm, 30 × 30 mm, 1 piece
- Mounted Transmission Grating: 20 l/mm, 1 piece
- Mounted 2-Dimensional Grating: 20 l/mm, 1 piece
- Mounted Waveplates: \( \frac{1}{4}\lambda, \frac{1}{2}\lambda, @632.8 \text{ nm}, \Phi 10 \text{ mm}, \) 1 piece each
- Equilateral Prism: 60°, 1 piece
- Mounted Reticles: 1/5, 1/10 mm, 1 piece each
- Mounted Millimetre Ruler: 30 mm long, 1 piece
- Mounted Double-Wedge Prism (biprism), 1 piece
- Mounted Polarizer: \( \Phi 20 \text{ mm}, \) 2 pieces
- Spherical Mirror: \( f = 300 \text{ mm}, \) 1 piece
- Multiple Slits Plate: groups in 2, 3, 4, 5 slits, 1 piece
- Transmission Character, 1 piece
- Zero Order Filter, 1 piece
- Fresnel Bimirror (LEPO-32): 1 piece
- Modulation Plate, 1 piece
- Small Object for Holography, 1 piece
- Lloyd Mirror (LEPO-33), 1 piece
- Double-slit, 1 piece
- White Screen: 70 × 50 mm, 1 piece
- Projector Slide, 1 piece
### 2.4 Other Parts

<table>
<thead>
<tr>
<th>Description</th>
<th>Part No.</th>
<th>Qty</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holographic Plate</td>
<td>GS-I</td>
<td>1 Box</td>
<td>12 pcs, 9×24 cm each, glass 530 ~ 700 nm, peak @630 nm</td>
</tr>
<tr>
<td>Air Chamber and Pump with Gauge</td>
<td>LEPO-55</td>
<td>1</td>
<td>3 ~ 40 kPa/20 ~ 300 mm Hg used for air index measurement</td>
</tr>
<tr>
<td>Direct Measurement Microscope</td>
<td>LEPO-56</td>
<td>1</td>
<td>20×</td>
</tr>
</tbody>
</table>

### 2.5 Optional Parts

<table>
<thead>
<tr>
<th>Description</th>
<th>Part No.</th>
<th>Qty</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts Holder Stand</td>
<td>LEPO-57</td>
<td>1</td>
<td>each stand can hold 20 parts</td>
</tr>
</tbody>
</table>

* Note: Above parts are subject to change without notice.
3. Experiment Examples

3.1 Measuring the Focal Length of a Positive Thin Lens Using Auto-collimation

Objective:
Understand the principle and method of measuring the focal length of a lens using auto-collimation.

Experimental Setup

![Figure 1-1 Photo of experimental setup](image1)

**Figure 1-1 Photo of experimental setup**

![Figure 1-2 Configuration of components](image2)

**Figure 1-2 Configuration of components**

1: Bromine Tungsten Lamp $S$ (LLC-4)
2: Object Screen $P$ (LEPO-15)
3: Convex Lens $L$ ($f'$=190 mm)
4: Two-axis Tilt Holder (LEPO-8)
5: Flat Mirror $M$
6: Two-axis Tilt Holder (LEPO-8)
7: Optical Rail (LEPO-54)

Principle

Under the condition of paraxial rays, the Gauss equation of thin lens imaging is:

$$
\frac{f'}{s} + \frac{f}{s} = 1
$$

where $s$ is the distance of an object from the thin lens, $s'$ is the distance of a conjugate image of the object from the thin lens, and $f'$ is the focal length of the thin lens. As seen in Figure 1-3, we get:

$$
f = -f' = -\frac{s \cdot s}{s - s'}
$$

![Figure 1-3 Schematic of thin lens imaging](image3)
Here, we use another approach to calculate $f$, i.e., auto-collimation method. As shown in Figure 1-4, an object $P$ is placed on one side of the convex lens. When it is in the focal plane, any ray from the object as refracted by the lens would change into parallel ray. After reflected by the plane mirror and again refracted by the lens, it is converged in focal plane of the lens. The distance between lens and object is the focal length of the lens: $f = s$

![Figure 1-4 Schematic of thin lens auto-collimation](image)

**Experimental Procedures:**

1) Refer to Figure 1-2, align all components in same height along the rail;

2) Move lens $L$ back and forth, till a clear image of the object on $P$ is observed on the back surface of $P$;

3) Adjust axis of mirror $M$, and finely move $L$, till the image is clearest with the same size as the object (so that the object and its image fills up a whole circular region);

4) Write down the locations of $P$ and $L$ as $s_1$ and $s_2$, respectively;

5) Respectively reverse $P$ and $L$ to exchange their front and back surfaces, repeat steps 1-4;

6) Write down new locations of $P$ and $L$ as $s_3$ and $s_4$, respectively;

7) Calculate focal length:

$$f'_1 = s_2 - s_1 \quad f'_2 = s_4 - s_3 \quad f = \frac{f'_1 + f'_2}{2}$$

Note: The point source on the front focal point will be collimated from the lens, and one collimated beam will be focused on back focal point.
3.2 Measuring the Focal Length of a Positive Lens Using Displacement Method

Objective:
Understand the principle and method for measuring the focal length of a lens with displacement approach, and verify “lens equation”

Experimental Setup

Figure 2-1 Photo of experimental setup

Figure 2-2 Configuration of components

1: Bromine Tungsten Lamp S (LLC-4)  
2: Object Screen P (LEPO-15)  
3: Convex Lens L (f’=190 mm)  
4: Two-axis Tilt Holder (LEPO-8)  
5: White Screen H (LEPO-14)  
6: Optical Rail (LEPO-54)

Principle

In the first experiment, we measured the focal length of a thin lens by using an auto-collimation method. Because the center of the lens is not easy to be determined, the measurement error is large. So we take a new method, i.e., displacement method.

If the distance between the object and the screen is at least four times of the focal length and when we move the lens, we can get a clear image twice at different points as shown in Figure 2-3.
Correspondingly, we get the two following equations:

\[ \frac{1}{f} = \frac{1}{s_1} + \frac{1}{s_f} \]  
\[ \frac{1}{f} = \frac{1}{s_2} + \frac{1}{s'_f} \]  

(2-1) \hspace{1cm} (2-2)

Using the conditions: \( D = s_1 + s' = s_2 + s'_2, s_2 = s_1 + d, s'_2 = s'_1 + d \), we can get the formula:

\[ f = \frac{D^2 - d^2}{4D} \]  

(2-3)

This method is more accurate than the previous method.

**Experimental Procedures:**

1) Refer to Figure 2-2, align all components in same height along the optical rail;

2) Move lens \( L \) back and forth, till a clear magnified image of object on \( P \) is observed on screen \( H \). Write down the positions of object \( P \), lens \( L \), and image screen \( H \) as \( D_1, d_1 \) and \( D_2 \), respectively;

3) Fix \( P \) and \( H \), move lens \( L \) far away from \( P \) till a clear magnified image is observed on \( H \), write down position of lens \( L \) as \( d_2 \);

4) Reverse \( P, L, \) and \( H \), repeat steps 1-3, obtain another two locations of lens \( L \) as \( d_3 \) and \( d_4 \);

5) Calculate focal length as:

\[ f_1 = \frac{(D_2 - D_1)^2 - (d_2 - d_1)^2}{4(D_2 - D_1)} \]

\[ f_2 = \frac{(D_2 - D_1)^2 - (d_4 - d_3)^2}{4(D_2 - D_1)} \]

\[ f = \frac{1}{2}(f_1 + f_2) \]

Note: Use “lens equation” to derive the above formula.
3.3 Measuring the Focal Length of an Eyepiece

Objective:
Understand the principle and method for obtaining the focal length an eyepiece lens by measuring the magnification of an image to an object; further verify “lens equation”

Experimental Setup

Figure 3-1 Photo of experimental setup

Figure 3-2 Configuration of components

1: Bromine Tungsten Lamp S (LLC-4) 5: Two-axis Tilt Holder (LEPO-8)
2: Reticle M (1/10 mm) 6: Eyepiece of DMM ME
3: Biprism Holder (LEPO-43) 7: DMM Holder (LEPO-37)
4: To Be Measured Eyepiece Lens Le (f_e=29mm) 8: Optical Rail (LEPO-54)
* Adaptor Piece (LEPO-10) might be used

DMM/ME are the abbreviations of direct measurement microscope and microscope eyepiece, respectively

Principle

Abbe’s method: An image of an object is formed by a lens on a screen. If the lens is fixed and the object is placed to a new position, the image screen needs to move until a focused image is received. If the separation between the two object positions is Δs, and the transverse magnifications of the image are m₁ and m₂, respectively, according to the Gauss equation, we have:

\[
\frac{f}{s_1} + \frac{f}{s_1} = 1 \quad \text{and} \quad \frac{f}{s_2} + \frac{f}{s_2} = 1
\]  

(3-1)

where, \( s_1 \) and \( s_2 \) are the distances of an object from a thin lens, \( s_1' \) and \( s_2' \) are the distances of its conjugate images from the thin lens, as shown in Figure 3-3.
Using the conditions of \( m_1 = y_1/y = s_1'/s_1, \) \( m_2 = y_2/y = s_2'/s_2, \) \( \Delta s = s_1 - s_2, \) and \( f' = -f \)

From equation (3-1), we get

\[
\frac{f}{m_1} (1 + m_1) = s_1, \quad \frac{f}{m_2} (1 + m_2) = s_2
\]

(3-2)

So the focal length of the lens is given by

\[
f = \frac{m_1 m_2}{m_2 - m_1} \Delta s
\]

(3-3)

**Experimental Procedures:**

1) Refer to Figure 3-2, align all components in same height along the rail;

2) Fix reticle plate \( M \) and microscope eyepiece \( ME \), slowly move lens \( Le \) away from \( M \), till a clear magnified image of \( M \) is observed in \( ME \) with no viewing difference with the standard reticle scale of \( ME \);

3) Measure image width (1/10 mm scale) of the reticle \( M \) with the standard reticle in \( ME \), calculate magnification \( m_1 \), write down the locations of \( ME \) and \( Le \) as \( a_1 \) and \( b_1 \), respectively;

4) Move \( ME \) away 30 to 40 mm, then slowly move \( Le \) toward to \( F \), till a clear magnified image of \( M \) is observed again in \( ME \) with no viewing difference with standard reticle scale of \( ME \);

5) Measure this new image width, calculate magnification \( m_2 \), and write down the locations of \( ME \) and \( Le \) as \( a_2 \) and \( b_2 \), respectively;

6) Calculate the focal length of \( ME \) as:

\[
\text{Magnification: } m_i = \frac{\text{image size}}{\text{actual size}}, \quad i = 1, 2;
\]

\[
\text{Distance change of two images: } \Delta s = (a_2 - a_1) + (b_2 - b_1);
\]

\[
\text{Focal length of } ME: \quad f_{ME} = \frac{m_1 m_2}{m_2 - m_1} \Delta s.
\]
3.4 Assembling a Microscope

Objective:
Understand the principle, the construction, and the adjustment of a microscope; measure the system magnification.

Experimental Setup

![Photo of experimental setup](image)

![Configuration of components](image)

1: Bromine Tungsten Lamp $S$ (LLC-4)  
2: Reticule $M_1$ (1/10 mm)  
3: Lens Holder (LEPO-9)  
4: Objective Lens Lo ($f_o = 29$ mm)  
5: Two-axis Tilt Holder (LEPO-8)  
6: Adapter Piece (LEPO-10)  
7: Eyepiece Lens $L_e$ ($f_e = 45$ mm)  
8: Two-axis Tilt Holder (LEPO-8)  
9: 45° Glass Holder (LEPO-47)  
10: Optical Rail (LEPO-54)  
11: Two-axis Stages (LEPO-2)  
12: Two-axis Tilt Holder (LEPO-8)  
13: Millimetre Ruler $M_2$ ($l = 30$ mm)  
Other: Small illuminating lamp (LLC-6)

Principle

As shown in Figure 4-3, the optical system of a microscope employs an objective with a short focal length and a magnifying eyepiece. The magnification is achieved in two stages as shown in Figure 4-3. The microscope objective forms an enlarged image of the object in a position that is suitable for viewing through the eyepiece; the magnification through the objective is given by

$$\frac{y_2}{y_1} = \Delta / f_o$$  \hspace{1cm} (4-1)

Generally speaking, the focal length of the eyepiece $f_e'$ is much less than the distance of the image from the eyepiece $D$, (for normal sight, $D$ is approximate 250 mm), so

$$\frac{y_3}{y_2} \approx \frac{D}{f_e'}$$  \hspace{1cm} (4-2)

Then we get the total magnification:
\[ M = \frac{y_3}{y_1} = \frac{y_3}{y_2} = \frac{D\Delta}{f_o f_e} \]  

(4-3)

Where \( \Delta \) is the distance between the focus of objective and the focus of eyepiece, \( f_o' \) is the focal length of objective and \( f_e' \) is that of eyepiece.

**Experimental Procedures:**

1) Refer to Figures 4-2, align all components in same height along the rail;
2) Fix interval between \( Lo \) and \( Le \) at 180 mm;
3) Move reticle plate \( M_1 \) back and forth, till a clear \( M_1 \) virtual image is observed behind \( Le \);
4) Mount the 45° Glass Holder onto the post of the Eyepiece Lens, set the glass surface at 45° angle with respect to the optical axis; the glass is acting as a beam splitter (BS).
5) Put the millimetre ruler \( M_2 \) beside the Glass Holder (vertical to main optical axis along the rail) and approximate 250 mm distance from the 45° glass; place the Small Illuminating Lamp (LLC-6) closely behind of the millimetre ruler to illuminate the ruler.
6) View behind the Glass by one eye, finely rotate the glass holder to overlap the microscope virtual image from \( M_1 \) and the \( M_2 \) image from the glass reflection; note: if the brightness difference between the two images is too much, try to adjust their illuminating intensities, for example, add ground glass or thin paper sheets in front of LLC-4, or adjust the distance between LLC-6 and Millimetre Ruler.
7) Finely adjust \( M_1 \) to eliminate viewing difference between the two images;
8) Count the scale amount \( a \) in \( M_1 \) image included in the range of 30 mm of image \( M_2 \);
9) Calculate the measured magnification of the assembled microscope and its theoretical magnification:
   
   Measured Magnification: \[ M = \frac{30 \times 10}{a} \]

   Theoretical Magnification: \[ M' = \frac{25\Delta}{f_o f_e'}, \text{ where, } \Delta = D - (f_o' + f_e') \]
3.5 Assembling a Telescope

Objective:
Understand the principle, the construction, and the adjustment of a telescope; measure the system magnification.

Experimental Setup

Figure 5-1 Photo of experimental setup

Figure 5-2 Configuration of components

1: Ruler (LEPO-34)
2: Objective Lens L0 (f_o = 225 mm)
3: Two-axis Tilt Holder (LEPO-8)
4: Eyepiece Lens Le (f_e = 29 mm)
5: Two-axis Tilt Holder (LEPO-8)
6: Optical Rail (LEPO-54)

Principle

As seen in Figure 5-3, the magnifying power of a telescope used for observing objects at infinity is defined as the angular magnification at the pupils because the angles are very small:

$$M = \frac{\tan \omega'}{\tan \omega} = \frac{\omega'}{\omega} = \frac{f_o'}{f_e'}$$  \hspace{1cm} (5-1)

Where $f_o'$ and $f_e'$ are the focal lengths of the objective and eyepiece lenses, respectively, and $\omega'$ and $\omega$ are the object and image angles at the eyepiece and objective lenses, respectively.

Figure 5-3 Schematic of telescope imaging at infinity
As shown in Figure 5-4, when observing an object at quasi-infinity, the power of magnification is:

\[ M = \frac{\tan \omega'}{\tan \omega} = \frac{y_2}{s_2} / \left( y_1 / (s_1 + s_1' + s_2) \right) \]  

(5-2)

Since \( y_2/y_1 = s_1'/s_1 \), therefore,

\[ M = s_1'(s_1 + s_1' + s_2) / s_1 s_2 \]  

(5-3)

![Figure 5-4 Schematic of telescope imaging at quasi-infinity](image)

**Experimental Procedures:**

1) Refer to Figure 5-2, align all components in same height on the optical rail, set the distance between object (a ruler) and eyepiece lens \( Le \) on the experimental table as long as possible;

2) Move objective lens \( Lo \) back and forth, behind \( Le \), use one eye to observe the image of the ruler till it is clear;

3) Use another eye to directly observe the scale lines on the ruler, count how many scale lines (amount \( a \)) in the telescope image are covered by 30 lines on the ruler image directly to the eye;

4) Use a white screen \( H \) (LEPO-14) to find the image of the ruler through \( Lo \), write down the locations of the ruler, \( Lo \), \( H \), and \( Le \) as \( a \), \( b \), \( c \), and \( d \), respectively;

5) Calculate measured magnification of the assembled telescope and compare it with the theoretical value:

- Measured Magnification: \( M = \frac{30}{a} \)
- Theoretical Magnification: \( M = \frac{s_1'(s_1 + s_1' + s_2)}{s_1 s_2} \)

Where \( s_1 = b - a \), \( s_1' = c - b \), \( s_2 = d - c \)
3.6 Assembling a Slide Projector

Objective:
Understand the principle of a slide projector and the function of its condenser, learn how to adjust a projection optical system, and understand illuminating condition for achieving a uniform light field on the screen (Kohler illumination).

Experimental Setup

![Figure 6-1 Photo of experimental setup](image)

![Figure 6-2 Configuration of components](image)

1: Bromine Tungsten Lamp S (LLC-4)
2: Condenser Lens $L_1$ ($f_1$ = 50 mm)
3: Two-axis Tilt Holder (LEPO-8)
4: Projector Slide $P$
5: Plate Holder A (LEPO-13)
6: Projection Lens $L_2$ ($f_2$ = 150 mm)
7: Two-axis Tilt Holder (LEPO-8)
8: White Screen (LEPO-14)
9: Optical Rail (LEPO-54)

* Ground glass on LLC-4 is not used and Adaptor Piece (LEPO-10) might be used

Principle

As shown in Figure 6-3, $L_1$ is a condenser, and $L_2$ is a projection lens. A slide is just behind $L_1$ (we can assume $v_1 = u_2$). If the magnification of a slide projector is $M$, the length of slide projector is $D$, and the focal length of $L_1$ and $L_2$ are $f_1$ and $f_2$, respectively.

By taking $M = v_2 / u_2$, $1 / f_2 = 1 / u_2 + 1 / v_2$, we can get

$$f_2 = \frac{1}{M + 1} v_2$$  \hspace{1cm} (6-1)

By taking $D = u_1 + v_1$, $v_1 = u_2$, $1 / f_1 = 1 / u_1 + 1 / v_1$, we can get

$$f_1 = \frac{v_2}{M} - \frac{1}{D} \left( \frac{v_2}{M} \right)^2$$  \hspace{1cm} (6-2)
Experimental Procedures:

1) Refer to Figure 6-2, align all components in same height on the optical rail, set the distance between $L_2$ and screen $H$ about 0.8 m;

2) Move slide $P$ back and forth, till a clear image (imaged by $L_2$) is observed on $H$;

3) Fix condenser close to $P$, remove $P$, move light source $S$ back and forth, till the image of $S$ formed by $L_1$ is clear on $L_2$ aperture plane;

4) Put back slide $P$ at its previous location, observe the brightness and uniformity of the projected image on the screen;

5) Remove $L_1$, observe the brightness and uniformity of the projected image again, and recognize the function of $L_1$. 

Figure 6-3 Schematic of slide projector imaging
3.7 Measuring the Nodal Locations and Focal Lengths of a Lens-Group

Objective:
Understand the characteristics of nodes of a lens-group, and learn how to measure nodal locations.

Experimental Setup

![Photo of experimental setup](image1)

Figure 7-1 Photo of experimental setup

1: Bromine Tungsten Lamp S (LLC-4)
2: Millimetre Ruler
3: Biprism Holder (LEPO-43)
4: Collimating Lens \( L_0 \) (\( f'_0 = 150 \text{ mm} \))
5: Two-axis Tilt Holder (LEPO-8)

6: Lens Group \( L_1 \) and \( L_2 \) (\( f'_1 = 300 \text{ mm} \), \( f'_2 = 190 \text{ mm} \))
7: Lens Group Holder (LEPO-29)
8: DMM Holder (LEPO-37)
9: Eyepiece of DMM
10: Optical Rail (LEPO-54)

* Others include flat mirror

Principle

As seen in Figure 7-3, there are six cardinal points on the axis of a lens system. \( F \) and \( F' \) are the focal lengths, \( H \) and \( H' \) are the principal points, and dot lines are the surface of the lens system. \( N \) and \( N' \) are the nodal points of the lens system as shown in Figure 7-4. We can get the cardinal points by measuring \( f, f', l, \) and \( l' \), and the thickness \( d \) of the lens system.

![Schematic of lens group](image2)

Figure 7-3 Schematic of lens group
Figure 7-4 Nodal points of lens group

The nodal points are identical to the principal points when the front and rear media of the lens group share the same refractive index. When a light ray enters the front of the lens system and toward the front nodal point, it will exit directly from the rear nodal point at the same angle to the axis as the entrance ray.

For lens systems in air, the nodal points coincide with the principal points and so we can use them to locate the principal planes and find the effective focal length. Let a parallel ray enter the lens system, it will be converged at the effective focal point $F'$ of the lens system as shown in Figure 7-4. When the lens system rotates a small angle through the nodal point $N'$, the beam will still converge on the ray axis and does not have any transverse displacement.

**Experimental Procedures:**

1) Adjust the distance between millimetre ruler and collimating lens $Lo$ to obtain a collimated beam from $Lo$ with the assistance of a flat mirror (self-alignment method);

2) Put in a lens group and eyepiece of DMM, align them to the same height as other optical parts, move microscope eyepiece back and forth to find a clear image of millimetre ruler;

3) Move the lens group back and forth along the rail on the nodal holder, and simultaneously move the microscope eyepiece to follow the clear image. After each movement of the lens group, rotate it around its vertical axis, till the ruler image in the microscope doesn’t have transversal displacement when the lens group rotates. At this moment, the image space node of the lens group is located on the rotation axis of the lens group holder.

4) Replace microscope eyepiece with a white screen, observe the ruler image, write down the locations of the screen and lens group holder on the optical rail as $a$ and $b$, respectively. Also write down the deviation amount $d$ of the central location of the lens group (marked under the lens group tube) from the rotation axis of the holder;

5) Reverse lens-group holder by 180°, repeat steps 3 and 4, obtain another set data of $a'$, $b'$ and $d'$;

6) Data processing: The distances of image space node and object space node from the lens group centre are $d$ and $d'$, respectively, and the focal lengths of the lens group in image space and object space are $f = a - b$ and $f' = a' - b'$, respectively;

7) Make a 1:1 drawing to show the measured lens group and relative positions of the cardinal points of the lens group.
3.8 Assembling an Erect Imaging Telescope

**Objective:**
Understand the principle and function of using double right-angle prisms to erect an image in a telescope system, further adopt skills for adjusting a telescope.

**Experimental Setup**

1: Ruler (LEPO-34)  
2: Objective Lens $L_o \ (f_o = 225 \text{ mm})$  
3: Two-axis Tilt Holder (LEPO-8)  
4: Erecting Prism (LEPO-31)  
5: Eyepiece Lens $L_e \ (f_e = 45 \text{ mm})$  
6: Two-axis Tilt Holder (LEPO-8)  
7: Optical Rail (LEPO-54)  
* Adaptor Piece (LEPO-10) might be used

**Principle**
In the previous experiment example of assembling a telescope, the image is inverted. In the mid 19th century, an Italian named Porro designed a telescope with two prisms set at right angle between the objective lens and the eyepiece. This arrangement not only erects and reverses the image, but also folds the light path, resulting in a shorter and more manageable instrument. The structure of double right-angle prisms (Porro Prism) is shown in Figure 8-3, which can turn the image formed by an objective lens right side up.
**Experimental Procedures:**

1) Refer to Figure 8-2, align all components in same height on the optical rail, set the distance between the ruler and $Le$ on the optical table as far as possible;

2) Assemble a reverse image telescope system using $Lo$ and $Le$, finely focus the object, remember the image direction status;

3) Insert a double right-angle prism at the front of the intermediate image of lens $Lo$, and let their primary cross-sections in horizontal axis and vertical axis, respectively;

4) Adjust the height and location of $Le$, till a clear image of the object is observed, compare this image with the image without prisms (this one should be erect).
3.9 Young’s Double-Slit Interference

Objective:
Observe Young’s double-slit interference phenomena and measure the wavelength of light.

Experimental Setup

Figure 9-1 Photo of experimental setup

1: Sodium Lamp (LLE-2, including Aperture Diaphragm)
2: Lens $L_1$ ($f' = 50$ mm)
3: Two-axis Tilt Holder (LEPO-8)
4: Single-sided Adjustable Slit (LEPO-28)
5: Lens Holder (LEPO-9)
6: Lens $L_2$ ($f' = 150$ mm)
7: Biprism Holder (LEPO-43)
8: Double-slit Plate
9: Adapter Piece (LEPO-10)
10: DMM Holder (LEPO-37)
11: Eyepiece of DMM
12: Optical Rail (LEPO-54)

Principle

To get an interference pattern, the two beams leaving from the slits must have same frequency and a definite phase relation. Generally speaking, most light sources cannot satisfy this condition. In 1801, Thomas Young allowed a single, narrow beam of light to fall on two narrow, closely spaced slits. He placed a viewing screen opposite to the slits. When the light from the two slits struck the screen, a regular pattern with alternative dark and bright rings appeared. When first performed, Young’s experiment offered an important evidence for the wave nature of light. The schematic of Young’s double-slit interference is shown in Figure 9-3.
In this way, the light emitted from $S_2$ and $S_1$ has a definite phase relation because the secondary wave sources from the same wave surface $S_1$ are always coherent. The light path difference ($d$ is the distance between the two slits of the double-slit plate) is:

$$\delta = r_2 - r_1 \approx d \sin \theta \approx d \tan \theta = d \frac{x}{D} \quad (9-1)$$

Where $D$ is the distance between the viewing screen and the slits, $x$ is the vertical distance between the viewing location and the center of the double slits, and $\theta$ is a half of the viewing angle between the lines from the viewing point on the screen to the two slits. If the path difference between a particular point on the screen to the two slits is equivalent to a half of the wavelength (or multiples thereof) of the light, then complete destructive interference will occur at that point, and thus a dark spot will be observed.

$$\delta = d \frac{x}{D} = \pm (2k + 1) \frac{\lambda}{2} \quad \text{(Dark interference fringes)} \quad (9-2)$$

Conversely, if the path difference is equivalent to an integer multiple of the wavelength of the light, then complete constructive interference will occur, and a bright spot will appear on the screen.

$$\delta = d \frac{x}{D} = \pm k \lambda \quad \text{(Bright interference fringes)} \quad (9-3)$$

So the distance between two adjacent dark fringes (or bright fringes) is:

$$\Delta x = \frac{D}{d} \lambda \quad (9-4)$$

In this formula $\Delta x$ and $D$ can be measured, so if we know one of $d$ and $\lambda$, we can calculate the other. In this experiment, if a laser rather than a Sodium lamp is used as the source, the experiment will be easier to conduct and the interference fringes will be observed more obviously.

**Experimental Procedures:**

1) Refer to Figure 9-2, align all components in same height on the rail;

2) Focus the aperture of the light source onto the single slit by a lens, the key to the success of this experiment is to align the slit directions of both single slit and double-slits parallel;

3) Use a direct measurement microscope to observe double-slit interference pattern, equal-interval bright/dark fringe pairs will be observed;

4) Measure the interval $e$ between two adjacent fringes using direct measurement microscope, also measure the distance $L$ between double-slit plate and the microscope;

   Use the known value of double-slit interval $t$ and expression of $e = \frac{L\lambda}{t}$, so that the wavelength $\lambda$ of the illumination light can be obtained.
3.10 Interference of Fresnel’s Biprism

Objective:
Observe Fresnel’s bi-prism interference phenomena and measure the wavelength of light.

Experimental Setup

Figure 10-1 Photo of experimental setup

1: Sodium Lamp (LLE-2, including Aperture Diaphragm)
2: Lens $L_1$ (f' = 50 mm)
3: Two-axis Tilt Holder (LEPO-8)
4: Single-side Adjustable Slit (LEPO-28)
5: Double-wedge Prism (Biprism)
6: Biprism Holder (LEPO-43)
7: DMM Holder (LEPO-37)
8: Eyepiece of DMM
9: Optical Rail (LEPO-54)

Principle

Fresnel’s biprism consists of two equal prisms of small refracting angle, placed together as shown in Figure 10-3. A ray of light from a point source $S$ is divided by refraction into two overlapping rays. The prisms form two virtual images, $S_1$ and $S_2$ of light source $S$. They take the same effect as the two slits in previous Young’s experiment.

![Figure 10-3 Schematic of Fresnel’s biprism interference](image)

So we have the formulae as follows:

$$d \frac{x}{D} = \pm (2k + 1) \frac{\lambda}{2} \quad \text{(Dark interference fringes)} \quad (10-1)$$
\[ \frac{x}{D} = \pm k\lambda \quad \text{(Bright interference fringes)} \quad (10-2) \]

\[ \Delta x = \frac{D}{d} \lambda \quad \text{(10-3)} \]

where \( D \) is the distance between the point source and the viewing screen, \( x \) is the vertical distance between the point source and viewing location on the screen, \( \Delta x \) is the distance between two adjacent dark fringes (or bright fringes), \( d \) is the distance between the two virtual images \( S_1 \) and \( S_2 \). \( d \) cannot be measured directly. But if we put a lens behind the biprism and measure the distance between the images of \( S_1 \) and \( S_2 \) with the eyepiece of a DMM, then \( d \) can be calculated.

**Experimental Procedures:**

1) Refer to Figure 10-2, align all components in same height on the rail;  
2) Focus the aperture of the light source onto the single slit by a lens. The key to the success of this experiment is to align the directions of single slit and the double-edge of biprism parallel;  
3) Use a direct measurement microscope to observe biprism interference pattern, hence, equal-interval bright/dark fringe pairs will be observed;  
4) Measure the fringe interval \( \Delta x \) between two adjacent fringes using a direct measurement microscope, and measure the distance \( D \) between the single slit plate and the microscope;  
5) To obtain the interval \( d \) between the two virtual images generated by the Fresnel’s biprism, put a lens \( L_2 \) (\( f' = 190 \) mm) behind the biprism to image the two virtual images into real images. Move the direct measurement microscope to the real images plane and measure the distance between the two real images as \( d' \), by the use of object-image relationship of lens imaging (lens equation) to obtain \( d \);  
6) Use \( d, \Delta x, D \) and equation (10-3), to calculate the wavelength \( \lambda \) of the illumination light.
3.11 Interference of Fresnel’s Mirrors

Objective:
Observe Fresnel’s double mirror interference phenomena and measure the wavelength of light.

Experimental Setup

![Photo of experimental setup](image1)
![Configuration of components](image2)

<table>
<thead>
<tr>
<th>Number</th>
<th>Component Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sodium Lamp (LLE-2, including Aperture Diaphragm)</td>
</tr>
<tr>
<td>2</td>
<td>Lens $L_1$ ($f' = 50$ mm)</td>
</tr>
<tr>
<td>3</td>
<td>Two-axis Tilt Holder (LEPO-8)</td>
</tr>
<tr>
<td>4</td>
<td>Single-side Adjustable Slit (LEPO-28)</td>
</tr>
<tr>
<td>5</td>
<td>Double Mirrors Assembly (LEPO-32)</td>
</tr>
<tr>
<td>6</td>
<td>Plate Holder A (LEPO-13)</td>
</tr>
<tr>
<td>7</td>
<td>DMM Holder (LEPO-37)</td>
</tr>
<tr>
<td>8</td>
<td>Eyepiece of DMM</td>
</tr>
<tr>
<td>9</td>
<td>Two-Axis Stages (LEPO-2)</td>
</tr>
<tr>
<td>10</td>
<td>Optical Rail (LEPO-54)</td>
</tr>
</tbody>
</table>

Principle

Fresnel’s Mirrors have a structure as shown in Figure 11-3. Two plane mirrors $M_1$ and $M_2$ are orientated with a very small variable angle. Light from point source $S$ is incident on the two mirrors, and the reflection form two virtual images $S_1, S_2$ of light source $S$, which act as coherent sources.

![Schematic of Fresnel’s double mirror interference](image3)
If \( SO = a \), then \( S_1O = S_2O = a \). The distance between \( S_1 \) and \( S_2 \) is

\[
d = 2a \sin \theta
\]  

(11-1)

where \( \theta \) is the angle between the mirrors.

As in Young’s experiment, we get the formulae:

\[
d \frac{x}{D} = \pm (2k + 1) \frac{\lambda}{2} \quad \text{(Dark interference fringes)} 
\]

(11-2)

\[
d \frac{x}{D} = \pm k\lambda \quad \text{(Bright interference fringes)} 
\]

(11-3)

\[
\lambda = \frac{d}{D} \Delta x = \frac{2a \sin \theta}{a \cos \theta + OO} \Delta x \approx \frac{2a\theta}{a + OO'} \Delta x 
\]

(11-4)

**Experimental Procedures:**

1) The key to the success of this experiment is to align the directions of the two mirrors by adjusting the three screws on the back of one mirror, so as to guarantee the normal of two mirrors in one plane, and an appropriate angle between them;

2) To fulfil the above condition, use a small laser beam to illuminate the adjacent area of the two mirrors (half beam on each mirror), and two reflected beam spots can be observed on the far field screen. By fine adjustment of the three screws on the back of one mirror, the input beam and the two reflected beams are in a one plane. The intersection angle \( \theta \) of the two mirrors can be obtained by calculating the ratio of the two beam spots on the screen and the distance between screen and the mirrors (here we align them at about 0.5 degree);

3) Refer to Figure 11-2, align all components in same height on the rail;

4) Focus the light source onto the single slit by a lens, rotate single slit direction and align it parallel to the mirrors’ intersection;

5) Use direct measurement microscope to observe the interference pattern that has equal-interval bright/dark fringe pairs;

6) Measure the fringe interval \( \Delta x \) between two adjacent fringes using the direct measurement microscope and the path length \( D \) from single slit to the microscope via the intersection of the two mirrors;

7) To obtain the interval \( d \) between the two virtual images \( S_1, S_2 \) of the slit light source \( S \), multiply the double angle of two mirrors \( 2\theta \) (measured in above step 2) by the distance \( a \) between the single slit and the mirrors;

8) Use \( d, \Delta x, D \) and equation (11-4) to calculate the wavelength \( \lambda \) of the illumination light.
3.12 Interference of Lloyd’s Mirror

**Objective:**
Observe Lloyd’s mirror interference phenomena and measure the wavelength of light

**Experimental Setup**

**Figure 12-1** Photo of experimental setup

**Figure 12-2** Configuration of components

1: Sodium Lamp (LLE-2, including Aperture Diaphragm)  
2: Lens $L_i$ ($f'=50$ mm)  
3: Two-axis Tilt Holder (LEPO-8)  
4: Single-side Adjustable Slit (LEPO-28)  
5: Lloyd’s Mirror (LEPO-33)  
6: Plate Holder A (LEPO-13)  
7: DMM Holder (LEPO-37)  
8: Eyepiece of DMM  
9: Two-Axis Stages (LEPO-2)  
10: Optical Rail (LEPO-54)

**Principle**
Lloyd’s mirror is simpler to construct than Fresnel’s mirrors. As seen in Figure 12-3, a point source $S_1$ is placed some distance away from a plane mirror $M$ and it is close to the plane of the mirror surface, so that light is reflected at nearly grazing incidence. The coherent sources are the primary source $S_1$ and its virtual image $S_2$ formed by the mirror. The bisector of $S_1$ and $S_2$ then lies in the plane of the mirror surface, as shown in Figure 12-3.

**Figure 12-3** Schematic of Lloyd’s mirror interference
Similar to Fresnel’s mirror experiment, we have the expression:

\[ \lambda = \frac{d}{D} \Delta x \]  \hspace{1cm} (12-1)

Where \( \lambda \) is the wavelength of the light source, \( D \) is the distance between the source and the viewing screen, \( d \) is the distance between the primary point source and its virtual image formed by the mirror, and \( \Delta x \) is the interval between two adjacent dark fringes (or bright fringes) on the screen.

**Experimental Procedures:**

1) Refer to Figure 12-2, align all components in same height on the rail;

2) Focus the aperture of the light source onto the single slit by a lens, mount Lloyd’s mirror approximately vertical;

3) Slowly move the Lloyd’s mirror close to the optical axis from one side, let the input light sweep across the mirror. Behind the mirror, using one eye to observe the direct and the reflected beams, the slit \( S \) and its virtual image \( S' \) (by Lloyd’s mirror) will be observed;

4) Rotate the single slit to align \( S \) and \( S' \) parallel, fix Lloyd’s mirror when the interval of \( S \) and \( S' \) is about 2 mm;

5) Use direct measurement microscope to observe Lloyd’s mirror interference pattern, and equal-interval bright/dark fringe pairs will be observed;

6) Measure the fringe interval \( \Delta x \) between two adjacent dark (or bright) fringes using direct measurement microscope and the distance \( D \) between single slit and microscope;

7) To obtain the interval \( d \) between the two light sources \( S \) and \( S' \), put a lens \( L_2 \) \((f' = 190 \text{ mm})\) behind Lloyd’s mirror to image the two light sources into real images, move the direct measurement microscope to the real image plane and measure the distance between the two real images as \( d' \). Obtain \( d \) by using the lens equation;

8) Use \( d, \Delta x, D \) and equation (12-1) to calculate the wavelength \( \lambda \) of the illumination light.
3.13 Interference of Newton’s Ring

**Objective:**

Observe equal-thickness interference phenomena and calculate the surface curvature by measuring interference fringe separation of Newton’s Ring.

**Experimental Setup**

![Figure 13-1 Photo of experimental setup](image)

![Figure 13-2 Configuration of components](image)

1: Newton Ring Holder (LEPO-39)  
2: Newton Ring Assembly (LEPO-38)  
3: Beam Splitter (5:5)  
4: DMM with Objective  
5: DMM Holder (LEPO-37)  
6: Sodium Lamp (LLE-2)  
7: Plate Holder A (LEPO-13)  
8: Optical Rail (LEPO-54)

**Principle**

The convex surface of a long focal length lens (large radius of curvature) is placed in contact with a plane glass and then they are clamped together. A thin film of air is formed between the spherical surface of the lens and the surface of the plane glass as seen in Figure 13-3. As a result, interference fringes called Newton’s rings can be observed.

![Figure 13-3 Schematic of Newton’s ring apparatus](image)
If \( R \) is the radius of curvature of the convex surface, then the thickness of the thin "air-film" \( h \) is given by

\[
h = R - \sqrt{R^2 - r^2} \approx \frac{r^2}{2R}
\]  

(13-1)

The radius of the \( m_{th} \) dark ring is given by

\[
r_m = \sqrt{mR\lambda} \quad m = 0, \pm 1, \pm 2 \cdots
\]  

(13-2)

Equation (13-2) provides a method to measure the radius of curvature of the convex surface. To reduce measurement error, however, the radii of two rings are actually used to calculate \( R \) as

\[
R = \frac{r_m^2 - r_n^2}{(m - n)\lambda}
\]  

(13-3)

**Experimental Procedures:**

1) Adjust screws of the Newton’s Ring assembly, get proper pressure between the flat glass and the plano-convex lens, and let the contact point around the center;

2) Refer to Figure 13-2, align all components in same height on the rail;

3) Adjust beam splitter, and find interference fringes in the viewing field of the direct measurement microscope;

4) Measure the diameters of the rings using the microscope, such as from 10\(^{th}\) to 15\(^{th}\) rings;

5) Calculate the radius of curvature of the lens by using the radii of any two interference rings \((m_{th} \text{ and } n_{th}, \text{ e.g. } m-n = 5)\), based on equation (13-3), average all results to obtain the radius of curvature.
3.14 Fraunhofer Diffraction of a Single Silt

Objective:
Observe Fraunhofer diffraction phenomena and calculate the width of a single slit

Experimental Setup

Figure 14-1 Photo of experimental setup

Figure 14-2 Configuration of components

1: Sodium Lamp (LLE-2)  
2: A Single-Side Rotary Slit S1 (LEPO-42)  
3: Lens $L_1$ ($f' = 150$ mm)  
4: Two-axis Tilt Holder (LEPO-8)  
5: Single-Side Adjustable Slit S2 (LEPO-28)  
6: Lens $L_2$ ($f' = 300$ mm)  
7: Two-axis Tilt Holder (LEPO-8)  
8: DMM Holder (LEPO-37)  
9: Eyepiece of DMM  
10: Optical Rail (LEPO-54)

Principle

Fraunhofer diffraction is the diffraction of parallel light (the so-called far-field diffraction). It can be simply explained using Huygens’ Principle. As shown in Figure 14-3, a plane wave is incident upon a long, narrow slit and there are an infinite number of secondary sources that emit spherical waves across the aperture. For a particular observation point, each source has a different optical path that introduces a phase relationship between the waves that are emitted across the aperture. The resultant sum becomes an integral over the aperture and a simple relationship between the “angle of diffraction” and the light intensity in the observation plane can be derived.

Figure 14-3 Schematic of Fraunhofer diffraction from single slit
In the observation plane, we may write:

\[ I = I_0 \frac{\sin^2(\beta)}{\beta^2} \]  

(14-1)

where \[ \beta = \frac{2\pi}{\lambda} \frac{a}{2} \sin \theta \] and \( a \) is the slit width.

When \( \beta = n\pi \) where \( n \) is an integer, a minimum diffraction intensity occurs. Then, \( \sin \theta = \frac{\lambda}{a} \) is the condition for the first minima. This relationship can be used to calculate the slit width.

**Experimental Procedures:**

1) Refer to Figure 14-2, align all components in same height on the rail;
2) Put lens \( L_1 \) behind single slit \( S_1 \) at a distance of 150 mm (focal length of \( L_1 \)), the collimated beam illuminates on another single slit \( S_2 \);
3) Put lens \( L_2 \) behind single slit \( S_2 \) to focus the diffracted light;
4) Aim direct measurement microscope to the back focal plane of lens \( L_2 \), where, bright/dark diffraction fringes will be observed;
5) Measure the width of the central fringe \( \Delta x_0 \) using the microscope;
6) Calculate the slit width by \( a = \frac{2\lambda f'}{\Delta x_0} \) at \( \lambda = 589.3 \) nm;
7) Directly measure the slit width using the microscope, and compare this result with the calculated result in step 6.
3.15 Fraunhofer Diffraction of a Single Circular Aperture

Objective:
Observe Fraunhofer diffraction phenomena and calculate the aperture size

Experimental Setup

Figure 15-1 Photo of experimental setup

1: Sodium Lamp (LLE-2)
2: Φ1 mm Aperture
3: Multi-Pinhole Disc (LEPO-24, use 0.2-0.5 mm hole)
4: Lens L₁ (f' = 70 mm)

Figure 15-2 Configuration of components

5: Two-axis Tilt Holder (LEPO-8)
6: DMM Holder (LEPO-37)
7: Eyepiece of DMM
8: Optical Rail (LEPO-54)

Principle

A slit can produce a diffraction pattern with bright and dark fringes parallel to the slit. The size of diffraction patterns produced depends on the shapes of the apertures used. For a circular hole of diameter \( d \), the diffraction pattern consists of a series of concentric dark and bright rings. The pattern of the intensity distribution can be calculated in the same way as for a single slit.

The direction of the first dark ring with respect to optical axis is given by:

\[
\theta \approx \sin \theta = 1.22 \frac{\lambda}{d} \quad (15-1)
\]

where \( d \) is the diameter of the aperture, and \( \theta \) is the angle of observing direction with respect to the incident direction.

Experimental Procedures:

1) Refer to Figure 15-2, align all components in same height on the rail;
2) Select a proper small hole on the disc and put the disc far away from the light source (approx. 600 mm), it approximately satisfies the condition for Fraunhofer diffraction;
3) Put a lens behind the disc to focus the diffracted light;
4) Aim the direct measurement microscope to the back focal plane of the lens, where bright/dark diffraction rings will be observed;
5) Measure Airy disk diameter $d_1$ using the microscope;

6) Calculate aperture diameter by $d = \frac{1.22\lambda f'}{d_1}$ at $\lambda = 589.3$ nm;

7) Directly measure the aperture diameter using the microscope, compare this result with the calculated result in step 6.
3.16 Fresnel Diffraction of a Single Silt

Objective:
Observe Fresnel diffraction phenomena of a single slit

Experimental Setup

Figure 16-1 Photo of experimental setup

1: Laser Holder (LEPO-44)
2: He-Ne Laser (LLL-2)
3: Beam Expander Lens ($f' = 4.5$ mm)
4: Two-axis Tilt Holder (LEPO-8)
5: Single-side Adjustable Slit (LEPO-28)
6: White Screen (LEPO-14)
7: Optical Rail (LEPO-54)

Principle

Diffraction is the bending of light waves around an object in its path and it is a kind of interference caused by the partial obstruction or lateral restriction of a transmitting wave. Because diffraction is an interference effect, it will not occur if the wave is not coherent. Furthermore, diffraction effects become weaker (and ultimately undetectable) as the size of obstruction is made larger and larger than the wavelength of the light.

If a narrow slit with a width of $a$ is illuminated by a plane wave (a laser beam) as shown in Figure 16-3, the intensity distribution observed on a viewing screen at an angle $\theta$ with respect to the incident direction is
\[ I(\theta) = I_0 \frac{\sin^2 \alpha}{\alpha^2}, \quad \alpha = \frac{\pi a}{\lambda} \sin \theta \]  

(16-1)

where \( I_0 \) is the maximum intensity of central fringe of the diffraction pattern.

The intensity minima of a single slit is

\[ \sin \theta = m \frac{\lambda}{a} \quad m = \pm 1, \pm 2, \ldots \]  

(16-2)

**Experimental Procedures:**

1) Refer to Figure 16-2, align all components in the same height on the rail;

2) The distance between beam expander and single-side adjustable slit is about 100 mm and white screen is about 500 mm from the slit;

3) Expand laser beam with a beam expander to obtain a large divergence of the beam;

4) Diffraction pattern can be observed on the screen;

5) Change the slit width from small to large and observe the changes of the diffraction pattern.
3.17 Fresnel Diffraction of a Single Circular Aperture

Objective:
Observe Fresnel diffraction phenomena of a single circular aperture.

Experimental Setup

![Figure 17-1 Photo of experimental setup](image1)

![Figure 17-2 Configuration of components](image2)

1: Laser Holder (LEPO-44)
2: He-Ne Laser (LLL-2)
3: Beam Expander Lens \((f' = 4.5 \text{ mm})\)
4: Two-axis Tilt Holder (LEPO-8)

5: Multi-Pinhole Disk (LEPO-24, use 1.5 mm hole, Including holder)
6: White Screen (LEPO-14)
7: Optical Rail (LEPO-54)

Principle

Diffraction is the bending of light waves around an object in its path and it is a kind of interference caused by the partial obstruction or lateral restriction of a transmitting wave. Because diffraction is an interference effect, it will not occur if the wave is not coherent. Furthermore, diffraction effects become weaker (and ultimately undetectable) as the size of obstruction is made larger and larger than the wavelength of the light.

![Figure 17-3 Schematic of Fresnel diffraction from single aperture](image3)

For a circular hole of diameter \(d\), the diffraction pattern consists of concentric dark and bright rings seen in Figure 17-3. The intensity distribution can be calculated in the same way as for a single slit.

The condition for observing first-order minimum of intensity is:
\[
\sin \theta = 1.22 \frac{\lambda}{d}
\] 

(17-1)

where \( \theta \) is the angle of observing direction with respect to the incident direction.

**Experimental Procedures:**

1) Refer to Figure 17-2, align all components in same height on the rail;
2) Expand laser beam using beam expander to obtain a large divergence of the beam;
3) Diffraction pattern can be observed on the screen;
4) Move the screen slowly away from the hole, the central portion of the diffraction pattern will change from bright to dark alternatively.
3.18 Fresnel Diffraction of a Sharp Edge

Objective:
Observe Fresnel diffraction phenomena at a sharp edge

Experimental Setup

Figure 18-1 Photo of experimental setup

Figure 18-2 Configuration of components

1: Laser Holder (LEPO-44)
2: He-Ne Laser (LLL-2)
3: Beam Expander Lens ($f' = 4.5$ mm)
4: Two-axis Tilt Holder (LEPO-8)
5: Razor Blade (not provided)
6: Plate Holder B (LEPO-19)
7: White Screen (LEPO-14)
8: Optical Rail (LEPO-54)

Principle
The theory of Fresnel diffraction at a straight edge is complicated than the diffraction mentioned above. It will not be addressed here. If you are interested in exploring it further, you can refer to corresponding textbooks.

Experimental Procedures:
1) Refer to Figure 18-2, align all components in same height on the rail;
2) Expand laser beam using a beam expander to obtain a large divergence of the beam;
3) Diffraction pattern can be observed on the screen;
4) Observe and analyze the diffraction pattern with comparison to the theoretical prediction.
3.19 Analysing Polarization Status of Light Beams

Objective:
Observe polarization phenomena, analyze polarization status of an input beam, generate the desired polarization status, and determine the axis direction of a polarizer

Experimental Setup

![Figure 19-1 Photo of experimental setup](image)

![Figure 19-2 Configuration of components](image)

1: Bromine Tungsten Lamp (LLC-4)
2: Lens (f' =150 mm)
3: Two-axis Tilt Holder (LEPO-8)
4: Single-side Adjustable Slit (LEPO-28)
5: Optical Goniometer (LEPO-49)
6: Lloyd Mirror
7: Polarizer
8: Polarizer Holder (LEPO-52)
9: Optical Rail (LEPO-54)

* Others needed: low-pressure sodium lamp (LLE-2), He-Ne laser (LLL-2), quarter-wave plate, iceland crystal rotary holder (LEPO-50), beam expander (f' = 4.5 mm), and two-axis tilt holder (LEPO-8).

Principle

a) Brewster’s Angle

When unpolarized light travels from a transparent medium with a refractive index $n_i$ to another one with a higher refraction index $n_t$, part of the light is refracted into the second medium while the other part of the light is reflected back into the first medium, as shown in Figure 19-3.

![Figure 19-3 Reflection and refraction of light between two media](image)
If the angles of incidence and refraction are $\theta_i$ and $\theta_r$, respectively, the following condition exists, known as Snell's law

$$n_i \sin \theta_i = n_r \sin \theta_r, \quad (19-1)$$

According to Sir David Brewster, at a specific angle of incidence, $\theta_b$, called Brewster’s angle, the reflected ray and the refracted ray are perpendicular to each other, so the sum of the incident angle and the refractive angle is $90^\circ$ as

$$\theta_b + \theta_r = 90^\circ, \text{ namely } \theta_i = 90^\circ - \theta_b \quad (19-2)$$

By substituting equation (19-2) into equation (19-1), we get

$$n_i \sin \theta_b = n_i \sin(90^\circ - \theta_b) = n_i \cos \theta_b$$

$$\tan \theta_b = \frac{n_r}{n_i} \quad (19-3)$$

Then the Brewster’s angle is:

$$\theta_b = \arctan \left( \frac{n_r}{n_i} \right) \quad (19-4)$$

b) Birefringence

Put an iceland spar on a piece of printed paper, and we will see two distinct images of words. One image will remain fixed as the crystal is rotated, and the light ray through the crystal is called "ordinary ray" since it behaves just as a ray through glass. However, the other image will rotate with the crystal, tracing out a small circle around the ordinary image. This light ray is called "extraordinary ray". This is the phenomenon of birefringence.

![Figure 19-4 Schematic of birefringence](image)

c) Malus’s Law

When a light ray passes through a polarizer, then another polarizer, called analyzer, the transmitted light intensity $I(\theta)$ leaving out of the second polarizer, is given by Malus’s Law

$$I(\theta) = I_0 \cos^2 \theta \quad (19-5)$$

Where $I_0$ is light intensity incident on the first polarizer, $\theta$ is the angle of two polarizer axes.
**Experimental Procedures:**

1) Determine the polarization direction of a polarizer: the Tungsten lamp beam is incident on the surface of a glass plate at an angle close to the Brewster’s angle of 57°. Rotate the polarizer, directly observe the reflected beam, when it becomes the darkest, the polarizer axis lays in the plane of incident and reflection beams;

2) Determine the axis of $\frac{1}{2} \lambda$ wave plate: use a He-Ne laser as light source, insert a $\frac{1}{2} \lambda$ wave plate between two orthogonal polarizers with known axis directions, rotate the analyser to find darkest direction by observing on a white viewing card/screen, the angle between the axes of the $\frac{1}{2} \lambda$ wave plate and the polarizer will be a half of the angle rotated by the analyser;

3) Determine the axis of $\frac{1}{4} \lambda$ wave plate: use a He-Ne laser as light source, insert the $\frac{1}{4} \lambda$ wave plate between two orthogonal polarizers with known axis directions, when the angle between polarizer and $\frac{1}{4} \lambda$ wave plate is 45° or 135°, rotate the analyser and output light intensity doesn’t change, therefore the axis of $\frac{1}{4} \lambda$ wave plate will be at 45° or 135° with respect to the polarizer axis;

4) Rotate the analyser to verify Malus’s law;

5) Generate and analyze circular polarization beam and elliptical polarization beam.
3.20 Diffraction of a Grating

Objective:
Observe grating dispersion phenomena, and learn how to make wavelength measurement

Experimental Setup

Figure 20-1 Photo of experimental setup

Figure 20-2 Configuration of components

1: Mercury Lamp with Aperture Hole (LLE-1)
2: Lens \( L_1 \) \((f' = 50 \text{ mm})\)
3: Two-axis Tilt Holder (LEPO-8)
4: Single-side Adjustable Slit (LEPO-28)
5: Lens \( L_2 \) \((f' = 190 \text{ mm})\)
6: Two-axis Tilt Holder (LEPO-8)
7: Grating \((d = 1/20 \text{ mm})\)
8: Plate Holder B (LEPO-19)
9: Lens \( L_3 \) \((f' = 225 \text{ mm})\)
10: Lens Holder (LEPO-9)
11: Eyepiece of DMM with DMM Holder (LEPO-37)
12: Optical Rail (LEPO-54)

*Others needed: Equilateral Prism and Grating/Prism Table (LEPO-11)

Principle

Diffraction grating is a useful optical component in spectral analysis. The principle of a diffraction grating is like that of a single-slit Fraunhofer diffraction. As seen in Figure 20-3, the grating usually consists of thousands of narrow parallel slits. So the interference fringes are very sharp and narrow, and light beams with different wavelengths will propagate in different directions.

Figure 20-3 Schematic of grating diffraction
According to the grating equation, the condition for maximum intensity of each order is given by

$$d \sin \theta = k\lambda \quad (k=0, \pm 1, \pm 2\ldots)$$

(20-1)

Because $\theta$ is very small, we get

$$d \frac{x_k}{f} = k\lambda \quad (k=0, \pm 1, \pm 2\ldots)$$

(20-2)

where $d$ is the grating period, $x_k$ is the distance of between the $k$th order to the zero-th order of the spectral lines on the focal plane of lens $L_2$, $f$ is the focal length of lens $L_2$, and $\lambda$ is the wavelength of the light.

**Experimental Procedures:**

1) Refer to Figure 20-2, align all components in same height on the rail;
2) Orientate adjustable slit in vertical direction, let grating lines parallel to the slit;
3) Reduce slit width, move microscope eyepiece back and forth to get clear Mercury spectrum lines, eliminate viewing difference between the spectrum lines and reticle scale line in the eyepiece;
4) Use microscope eyepiece to measure the first order locations $x_1$ of Mercury spectrum lines at these colours: two yellow lines, one green line and one blue line, record them as $x_{1Y}$, $x_{1Y}'$, $x_{1G}$, $x_{1B}$;
5) Calculate the wavelengths of four spectrum lines using equation (20-2).
3.21 Grating Monochromator

Objective:

Understand the principle of a grating monochromator, and learn how to assemble a Littrow-type grating spectrometer.

Experimental Setup

Figure 21-1 Photo of experimental setup

Figure 21-2 Configuration of components

1: Mercury Lamp with Aperture Hole (LLE-1) 8a: Prism Table (LEPO-12)
2: Lens $L_1$ ($f' = 50$ mm) 9: Optical Rail (LEPO-54)
3: Two-axis Tilt Holder (LEPO-8) 10: Two-Axis Stages (LEPO-2)
4: Single-side Adjustable Slit (LEPO-28) 11: Grating Table (LEPO-11)
5: Flat Mirror $M_2$ 12: Flare grating $G$ (1200 lines/mm)
6: Two-axis Tilt Holder (LEPO-8) 14: Single-side Rotary Adjustable Slit (LEPO-42)
7: Adapter Piece (LEPO-10) 15: Two-Axis Stages (LEPO-2)
8: Spherical Mirror $M_1$ ($f' = 302$ mm)

*Others needed: Plate Holder A (LEPO-13) and White Screen (LEPO-14)

Principle

Using the characteristics of a blazed grating, we can get the spectral lines of a light source. The principle of a blazed grating is almost the same as the last experiment, as shown in Figure 21-3.

Figure 21-3 Schematic of blazed grating diffraction
The blazed wavelength of the $k_{th}$ order is given by:

$$2d \sin \theta_b = k \lambda_{sb} \quad k=1, 2, 3... \quad (21-1)$$

The structure of a grating monochromator is shown below in Figure 21-4.

![Figure 21-4 Schematic of grating monochromator](image)

**Experimental Procedures:**

Note: This experiment is recommended to be carried out in a less bright environment.

1) Refer to Figure 21-2, align all component in same height on the optical rail and let the primary plane of the system parallel to the table;

2) Focus the light source on the adjustable slit (slit width > 0.5 mm) using a lens;

3) Set each component according to Figure 21-2, check the light field on $M_2$, $M_1$ and $G$, make sure no part of the light path is blocked and the central portions of these components are illuminated;

4) Let the incident beam on $M_1$ and the output beam from $M_1$ have a minimum intersection angle (approximately Littrow-style);

5) Use a white screen to find the optimal focusing position of the output spectrum, then replace the white screen with an adjustable slit at about 0.05 mm width;

6) Rotate the grating, spectral lines of the Mercury lamp will exit from the slit sequentially.
3.22 Recording and Reconstructing Holograms

Objective:
Understand the principle of holography; learn to record and reconstruct holograms

Experimental Setup

Figure 22-1 Photo of experimental setup

1: He-Ne Laser (LLL-2)  
2: Laser Holder (LEPO-44)  
3: Beam Splitter (7:3)  
4: Plate Holder A (LEPO-13)  
5: Two-axis Tilt Holder (LEPO-8)  
6: Flat Mirror $M_1$  
7: Optical Rail (LEPO-54)  
8: Two-axis Stages (LEPO-2)  
9: Beam Expander Lens $L_1$ ($f' = 4.5$ mm)  
10: Two-axis Tilt Holder (LEPO-8)  
11: Plate Holder B (LEPO-19)  
12: Holographic Plate  
13: Magnetic Base (LEPO-4)  
14: Object  
15: Sample Stage (LEPO-21)  
16: Z-adjustable Post Holder (LEPO-3)  
17: Magnetic Base (LEPO-4)  
18: Beam Expander Lens $L_2$ ($f' = 6.2$ mm)  
19: Lens Holder (LEPO-9)  
20: Magnetic Base (LEPO-4)  
21: Flat Mirror $M_2$  
22: Lens Holder (LEPO-9)

Principle

Light is a transverse electromagnetic wave, so a ray of monochromatic light can be written as

$$x = A \cos(\omega t + \varphi - \frac{2\pi}{\lambda} r)$$  \hspace{1cm} (22-1)

where $A$ is the amplitude, $\omega$ is the circular frequency, $\lambda$ is the wavelength, and $\varphi$ is the initial phase.

Generally speaking, a camera can only record the amplitude of the light reflected from an object. So the photo taken by a camera is a planar picture. By contrast, holography can record both the phase and amplitude of the light, thus the image is three-dimensional. Even if a hologram is broken or cut up, each small portion still contains the information of the whole object.
There are two steps in making a hologram. The first step is to record all the information of the light reflected from the object on a holographic plate. The second step is to illuminate the hologram and reconstruct the light wave reflected by the object.

In fact, holography is a process of interference. As shown in Figure 22-3, a laser beam is split into two beams: one beam, called the reference beam, is directed toward a holographic plate; another beam, called the object beam, is reflected off an object. The object beam contains such information as location, size, shape and texture of the object. Then the two beams produce an interference pattern on the holographic plate, which is recorded in the light sensitive emulsion. As a result, the holograms of the object are obtained. To reconstruct a hologram, a laser beam is used to illuminate on the holographic plate at the same direction as the reference beam. Then the three-dimensional image of the object can be observed.

**Experimental Procedures:**

Note: The hologram recording experiment is recommended to be carried out on a vibration isolated optical table.

1) Refer to Figure 22-2, align all components in same height on the rail, let the primary plane of the system parallel to the table, remove $L_1$ and $L_2$ from optical path first;
2) Set approximately equal optical path length for object beam and reference beam, and let their intersection angle about 30° to 40°;
3) Adjust $M_1$, let object beam illuminate on the central portion of the object;
4) Adjust $M_2$, let reference beam illuminate on the central portion of the holographic plate (use a paper plate of a similar size for setup);
5) Insert $L_1$ and $L_2$ back to the optical path, adjust them so that the object beam and reference beam are still at their original centers.
6) Move $L_2$ back and forth to change the illuminating intensity of the reference beam; let the intensity ratio between reference beam and object beam about 5:1 to 10:1;
7) Fix all components, turn off indoors light, replace the paper plate with a holographic plate and expose the holographic plate with He-Ne laser for 10 to 15 seconds;
8) Develop and fix the hologram;
9) Put back the hologram at its original location, remove object and block object beam, observe the reconstructed object.
3.23 Making Holographic Gratings

Objective:
Understand the principle of holographic gratings, and learn how to fabricate holographic gratings

Experimental Setup

![Photo of experimental setup](image)

![Configuration of components](image)

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>He-Ne Laser (LLL-2)</td>
</tr>
<tr>
<td>2</td>
<td>Laser Holder (LEPO-44)</td>
</tr>
<tr>
<td>3</td>
<td>Two-axis Tilt Holder (LEPO-8)</td>
</tr>
<tr>
<td>4</td>
<td>Beam Expander Lens (L_1) ((f' = 4.5) mm)</td>
</tr>
<tr>
<td>5</td>
<td>Two-axis Tilt Holder (LEPO-8)</td>
</tr>
<tr>
<td>6</td>
<td>Collimating Lens (L_2) ((f' = 225) mm)</td>
</tr>
<tr>
<td>7</td>
<td>Beam Splitter (5:5)</td>
</tr>
<tr>
<td>8</td>
<td>Lens Holder (LEPO-9))</td>
</tr>
<tr>
<td>9</td>
<td>Holographic Plate</td>
</tr>
<tr>
<td>10</td>
<td>Plate Holder A (LEPO-13)</td>
</tr>
<tr>
<td>11</td>
<td>Optical Rail (LEPO-54)</td>
</tr>
<tr>
<td>12</td>
<td>Lens Holder (LEPO-9)</td>
</tr>
<tr>
<td>13</td>
<td>Flat Mirror (M)</td>
</tr>
<tr>
<td>14</td>
<td>Two-Axis Stages (LEPO-2)</td>
</tr>
</tbody>
</table>

Principle

A holographic grating can be made by exposing a fine-grained light-sensitive emulsion plate to the interference pattern produced by two rays of coherent light. There are several methods for making a holographic grating: Young’s double-slit interference, Fresnel’s mirror interference, Lloyd’s mirror interference, and Mach-Zehnder interference. The last three methods have a similar principle. As shown in Figure 23-3, when two beams of coherent light hit a holographic plate symmetrically, we get

![Schematic of holographic grating fabrication](image)
\[ 2d \sin \frac{\theta}{2} = \lambda \quad (23-1) \]

where \( \theta \) is the angle of the two incident beams, \( \lambda \) is the wavelength of the light, and \( d \) is the grating period.

**Experimental Procedures:**

1) Refer to Figure 23-2, align all components in same height on the rail;
2) Use \( L_1 \) and \( L_2 \) to construct a beam expanding system, to obtain a collimated beam with a larger aperture;
3) Use expression (23-1) to calculate the intersection angle of the two beams according to the desired grating period;
4) Adjust the optical path to fulfil the required angle;
5) Expose the holographic plate for 2 to 3 seconds;
6) Develop and fix the holographic grating;
7) Observe interference fringes under a microscope, measure fringes spacing, compare the recorded result and the designed value.
3.24 Abbe Imaging Principle and Optical Spatial Filtering

Objective:
Understand the basic principle of Fourier optics, and the concepts of optical frequency spectrum and spatial filtering

Experimental Setup

![Photo of experimental setup](image1)

![Configuration of components](image2)

1: He-Ne Laser (LLL-2)
2: Laser Holder (LEPO-44)
3: Beam Expander Lens \( L_1 \) (\( f' = 6.2 \text{ mm or 15 mm} \))
4: Two-axis Tilt Holder (LEPO-8)
5: Collimating Lens \( L_2 \) (\( f' = 190 \text{ mm} \))
6: Two-axis Tilt Holder (LEPO-8)
7: Grating (20 lines/mm)
8: Plate Holder A (LEPO-13)
9: Fourier Transform Lens \( L_3 \) (\( f' = 225 \text{ mm} \))
10: Lens Holder (LEPO-9)
11: White Screen (LEPO-14)
12: Optical Rail (LEPO-54)
13: Adjustable Slit (LEPO-42) (not shown)

Principle

Abbe’s theory assumes that the object to be imaged can be decomposed into a number of elemental gratings - each grating diffracts light at an angle that is a function of the grating period and the groove orientation. The diffracted beams are plane waves that can be focused by a lens to form diffraction patterns in the back focal plane of the lens, as seen in Figure 24-3. These diffraction patterns in turn act as sources of waves that propagate from the focal plane to the image plane where the image is produced. To say in a simple way, it can be considered as two steps: first step is to resolve the information, second is to synthesize the information.

![Schematic of Abbe’s imaging](image3)
Experimental Procedures:

1) Refer to Figure 24-2, align all components in same height along the rail;
2) Use $L_1$ and $L_2$ to construct a beam expanding system, to obtain a collimated beam with a larger aperture and illuminate on the transmission grating (1-D grating) whose grating grooves are in vertical direction;
3) Put a screen $P$ away from the grating about 2 meters, move the transform lens $L_3$ back and forth to form a clear grating image on the screen;
4) Insert an adjustable slit at the back focal plane of $L_3$, block all higher-order spectra except the zero-th order, check whether there are still grating lines in the image;
5) Adjust the slit width so that the zero-th order and the first order spectra pass through, observe the grating image, then remove slit, observe grating image again, compare the two cases;
6) Replace the transmission grating (1-D grating) with a 2-D grating, put a adjustable slit on the Fourier plane and set slit direction in vertical direction to pass the spectrum on Y axis, observe the direction of the grating lines on the image screen;
7) Rotate slit direction by $90^\circ$ to let the X axis spectrum pass, observe the direction of the grating lines on the image screen;
8) Further rotate slit direction by $45^\circ$, observe the direction of grating lines direction on the image screen;
9) Put an iris diaphragm on the Fourier plane, reduce its aperture slowly, till only the zero-th order passes through, observe the image on screen;
3.25 Pseudo-Color Encoding, Theta Modulation and Color Composition

Objective:
Understand the concept of optical spatial filtering, learn the methods for pseudo-color encoding and color composition

Experimental Setup

Figure 25-1 Photo of experimental setup

1: Bromine Tungsten Lamp S (LLC-4)
2: Collimating Lens \( L_1 \) \( (f' = 190\ mm) \)
3: Two-axis Tilt Holder (LEPO-8)
4: Theta (\( \theta \)) Modulation Plate
5: Plate Holder A (LEPO-13)
6: Fourier Transform Lens \( L_2 \) \( (f' = 150\ mm) \)

7: Two-axis Tilt Holder (LEPO-8)
8: Plain White Paper
9: Paper Clip (LEPO-51)
10: White Screen (LEPO-14)
11: Optical Rail (LEPO-54)

Principle
Theta modulation is an application of Abbe’s imaging, so the theory of theta modulation is almost the same as that of Abbe’s imaging (refer to the principle in previous experiment). The object used is a special grating that is composed of three groups of grating reticles. The angle among them is 120° and they represent sky, sun and ground, respectively. Fourier spectrum of such a grating is shown in the middle of Figure 25-3.

Figure 25-3 Schematic of Theta modulation plate
We can use the filter to select the spectrum we want. We can get ‘the blue sky’, ‘the red sun’ and ‘the yellow ground’. It is also called pseudo-color encoding.

Experimental Procedures:

Note: This experiment example is recommended to be carried out in a less bright environment.

1) Refer to Figure 25-2, align all components in same height on the optical rail;

2) Place the Bromine-Tungsten lamp at the front focal point of lens $L_1$ to generate a collimated beam and illuminate onto a $\theta$-modulation plate. Remove the frosted glass as the source and use the filament as the source;

3) Place screen $P$ away from the $\theta$-modulation plate about 0.7~0.8 m, place the transform lens $L_2$ between the $\theta$-plate and the screen, then move $L_2$ back and forth to form a clear $\theta$-modulation plate image on the screen. Slide the frosted glass over to help determine a clear image, once a clear image is found, remove the frosted glass again;

4) Insert the paper clip (LEPO-51) with a filter (can be made by a plain white paper) at the back focal plane of $L_2$ (Fourier plane). An image similar to the middle image shown in Figure 25-3 should be observed, otherwise move slightly to bring into focus;

5) Using a very sharp pin, pierce holes in the filter. Only use the first order spectrum (zero-th order will produce the complete image). As each hole is made, observe the associated image on the screen. Once the Fourier spectrum with the corresponding images is determined, replace the filter with a new one;

6) Using the pin more carefully now, pierce holes at the relevant places on the tiny spectra, i.e. filtering single colors through to observe the sky as blue, the sun as red and the ground as yellow (or your own selection of colors).
3.26 Assembling a Michelson Interferometer and Measuring the Refractive Index of Air

Objective:
Learn how to assemble a Michelson interferometer and measure the refractive index of air

Experimental Setup

Figure 26-1 Photo of experimental setup

Figure 26-2 Configuration of components

1: He-Ne Laser L (LLL-2)
2: Laser Holder (LEPO-44)
3: Two-axis Tilt Holder (LEPO-8)
4: Beam Expander Lens $L_1$ ($f^\prime$=4.5 mm)
5: Beam Splitter $BS$ (5:5)
6: Magnetic Base (LEPO-4)
7: White Screen $H$ (LEPO-14) or Ground Glass Screen (LEPO-45)
8: Plate Holder A (LEPO-13)
9: Air Chamber with Pump $AR$
10: Aperture Adjustable Bar Clamp (LEPO-20)
11: Two-axis Tilt Holder (LEPO-8)
12: Flat Mirror $M_1$
13: Two-Axis Stages (LEPO-2)
14: Flat Mirror $M_2$
15: Lens Holder (LEPO-9)
16: Optical Rail (LEPO-54)

Principle

Figure 26-3 shows a schematic of a Michelson interferometer. A beam of light from the light source $S$ strikes the beam-splitter $BS$, which reflects 50% of the incident light and transmits the other 50%. The incident beam is therefore split into two beams; one beam is transmitted toward the mirror $M_1$, the other is reflected toward the mirror $M_2$. The light reflected from $M_1$ transmits through the beam-splitter to the observer’s eye $E$, and the other light reflected from $M_2$ is reflected by the beam-splitter $BS$ to the observer’s eye $E$.

Since the beams are from the same light source, their phases are highly correlated. When a lens is placed between light source and beam-splitter, the light ray spreads out, and an interference pattern of dark and bright rings, called interference fringes, can be seen by observer.
If we place an air chamber in the light path between beam splitter and mirror $M_2$, and change the density of the air (by deflating or pumping the air in the air chamber), then the distance of light path will change by $\delta$. It will generate a certain number of interference fringes.

$$\delta = 2\Delta n l = N\lambda, \quad \text{so} \quad \Delta n = N\lambda / 2l$$  (26-1)

Where $l$ is length of the air chamber $\lambda$ is the wavelength of the light source, and $N$ is the number of fringes counted. The refractive index of air $n$ is dependent upon both temperature and pressure. If $n$ is near unity, then $n-1$ is directly proportional to the density of the gas, $\rho$. For an ideal gas, we get:

$$\frac{\rho}{\rho_0} = \frac{n-1}{n_0-1}$$  (26-2)

Therefore,

$$\frac{\rho}{\rho_0} = \frac{PT_0}{P_0T}$$  (26-3)

where $T$ is the absolute temperature, $P$ is the ambient pressure. So we get

$$\frac{PT_0}{P_0T} = \frac{n-1}{n_0-1}$$  (26-4)

When temperature is constant, then

$$\Delta n = \frac{(n_0-1)T_0}{P_0T} \Delta P$$  (26-5)

Because $\Delta n = N\lambda / 2l$, we have

$$\frac{(n_0-1)T_0}{P_0T} \Delta P = N\lambda / 2l$$  (26-6)

Thus
\[ n = 1 + \frac{N\lambda}{2l} \times \frac{P}{\Delta P} \]  \hspace{1cm} (26-7)

Note: the standard atmospheric pressure is 101.3 kPa or 760 mm Hg.

**Experimental Procedures:**

1) Refer to Figure 26-2, align all components in same height on the rail;

2) Adjust the output of the He-Ne laser parallel along the optical rail (beam expander lens should not be inserted at this moment);

3) Put in a beam splitter BS at an angle of 45° with respect to beam axis, and adjust its tilt to make the two beams (transmission and reflection) parallel to table;

4) Adjust the tilt of mirrors \( M_1 \) and \( M_2 \) to make the reflected beams coincide with their incident paths, and the two beam spots on the screen \( H \) overlap together;

5) Insert a beam expander \( L_1 \), finely adjust beam splitter, \( M_1 \) and \( M_2 \), till concentric interference rings can be observed on the screen \( H \);

6) Insert an air chamber between beam splitter and \( M_1 \), adjust it parallel to optical path, pump air into the air chamber till a maximum permit pressure (e.g. 40 kPa or 300 mm Hg) is reached and write as \( \Delta P \);

7) Slowly release the air valve, count the number of interference rings changed in the center till air pressure falls to zero;

8) Repeat steps 6 and 7 several times to obtain averaged data;

9) Calculate the refractive index of air using equation (26-7).
4. Laser safety and lab requirements:
Follow the corresponding laser safety guidelines based on AS/NZS 2211.1:1997 and other lab instructions about optical components etc.

Appendix: User Instructions of Silver Salt Plates
Silver salt plate is a common holographic recording medium with high sensitivity, broad spectral response range, and wide adaptability. The micro particles of a silver salt plate make it suitable for recording a variety of holograms. The drawbacks of silver salt plates are low diffraction efficiency and low signal-to-noise ratio, together with tedious post-exposure processing procedures.

1. Specifications:
- Wavelength: 632.8 nm
- Contrast Ratio: >4
- Sensitivity: >30 μJ/cm²
- Thickness: ~ 7 μm
- Resolution: >3000 line pairs/mm
- Cross Sectional Size: 90×240 mm
- Storage: > 1 yr under low temperature environment of 0°C to 7°C such as in a refrigerator
- Safety Lamp: Dark green lamp in a darkroom

2. Handling and Processing Procedures

1.1 Cutting of an unexposed silver salt plate
Before cutting a silver salt plate, place the container under room temperature for about 4 hours and then open the container in a darkroom under the aid of a dark green safety lamp. Put the film side of a silver salt plate down onto two plastic sticks and then cut the glass substrate side from the top with a glass cutting knife into desired sizes. Knock the silver salt plate near the cutting trace on the substrate side gently with the handle of the glass cutting knife and then break the plate into two pieces with fingers. Wrap unused silver salt plates up with the black paper and put back to the container.

Note: Wear gloves during this process to avoid finger print on silver salt plates.

1.2 Exposure of a silver salt plate
The typical size of micro particles with a silver salt plate is in the range of 0.03 to 0.09 μm. The smaller size of micro particles the lower photo sensitivity and higher resolution. For this reason, the exposure time of silver salt plate is longer than that in conventional photography. In addition, the exposure time of a silver salt plate depends on factors such as the laser power and the reflectivity of an object. In practice, one had better use a small stripe of silver salt plate and expose different locations of the stripe with different exposure time durations to determine an optimal exposure time after post-exposure processes.

When putting a silver salt plate on a plate holder, make sure that the film side of the plate faces towards the object under recording. Typically, the film side of a silver salt plate is stickier than
the glass substrate side when touched with moist fingers. Alternatively, the film side of a silver salt plate can be determined under a dark green lamp in a darkroom. The side with higher light reflection is the film side.

1.3 Preparation of developing and fixing solutions

The user can acquire developing and fixing solutions through the following two approaches:

Approach 1: acquire Kodak D-19 Developer Powder and Kodak Fixer (for black and white film and paper) Powder from photographic supplies stores, makes solutions following their instructions.

Approach 2: use formulas to make solutions. The following apparatus and chemicals are needed:

A balance with a precision of 0.01 g; two 1-liter beakers; several glass bottles; a thermometer with a reading scale up to 100 °C; an electric furnace, and distilled water.

The most common chemical used for developing silver salt plates is D-19 from Kodak and the fixing chemical is F-5. Use analytical reagent during the post-exposure process.

**Formula of D-19 developing solution**

<table>
<thead>
<tr>
<th>Description</th>
<th>Dose</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled Water</td>
<td>500 ml at 50°C</td>
<td></td>
</tr>
<tr>
<td>Metol</td>
<td>2 g</td>
<td>Developer for forming soft image</td>
</tr>
<tr>
<td>Anhydrous Sodium Sulfite</td>
<td>90 g</td>
<td>Antioxidant protector</td>
</tr>
<tr>
<td>Hydroquinone</td>
<td>8 g</td>
<td>Developer for forming hard image</td>
</tr>
<tr>
<td>Anhydrous Sodium Carbonate</td>
<td>48 g</td>
<td>Accelerator</td>
</tr>
<tr>
<td>Potassium Bromide</td>
<td>5 g</td>
<td>Suppressant inhibitor</td>
</tr>
<tr>
<td>Add more distilled water to reach 1000 ml</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Formula of F-5 fixing solution**

<table>
<thead>
<tr>
<th>Description</th>
<th>Dose</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled Water</td>
<td>800 ml at 50°C</td>
<td></td>
</tr>
<tr>
<td>Sodium Thiosulfate</td>
<td>240 g</td>
<td>Fixer to dissolve unexposed Silver Bromide</td>
</tr>
<tr>
<td>Anhydrous Sodium Sulfite</td>
<td>15 g</td>
<td>Protector of Sodium Thiosulfate in acid</td>
</tr>
<tr>
<td>Acetic Acid</td>
<td>13.5 g</td>
<td>Developing stopper by neutralizing developer</td>
</tr>
<tr>
<td>Boric Acid</td>
<td>7.5 g</td>
<td>Hardening agent to harden film subtitles</td>
</tr>
<tr>
<td>Potassium Alum</td>
<td>15 g</td>
<td>Suppressant inhibitor</td>
</tr>
<tr>
<td>Add more distilled water to reach 1000 ml</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All the chemicals listed in the formulae should be weighed using the balance and poured in sequence into the beaker containing distilled water at a temperature of approximately 50 °C. After pouring one chemical into the solution, wait until the chemical is fully dissolved in the
solution before pouring the next chemical into the solution. After all the chemicals are poured and dissolved, add more distilled water to reach 1000 ml.

**Note:** 1. Some chemicals used in the developing and fixing processes may be toxic. Some gases given off during the processes are also toxic. Make sure that the processing darkroom is equipped with good ventilation.
2. Some chemicals used in the developing and fixing processes are also corrosive. Make sure to wear rubber gloves to protect hands from contacting these corrosive chemicals.

**Development:**

Under the aid of a green safety lamp, immerse the silver slat plate into the D-19 developing solution with the film side facing down, and keep stirring the solution for about 2 minutes. Take the silver salt plate from the developing solution and wash it with water for 30 seconds. During this process, the temperature of the developing solution should be maintained at 20°C.

**Stopping Development:**

The objective of development stopping is to stop the development of the photosensitive layer of a silver salt plate. Hence, excessive developing liquid can be avoided so that the fixing solution will not be diluted. Soak the developed silver salt plate in the inhibitor solution for 30 seconds and then wash it with water for another 30 seconds.

**Fixing:**

Soak the silver salt plate in the fixing solution for 3 to 5 minutes and keep stirring the fixing solution. During this process, the photosensitive layer of the silver salt plate will gradually become transparent. Keep the fixing process even after the plate becomes totally transparent. The total fixing time duration is approximately twice of that from the initial immersion to the moment when the plate becomes totally transparent.

**Washing:**

Wash the fixed silver salt plate with running water for about 5 minutes. If multiple plates are washed, make sure each plate is fully washed. Also make sure the temperature of the running water does not exceed 25 °C as otherwise the film may come off and be washed away.

**Removal of Sensitizer:**

Soak the silver salt plate in methanol or ethanol solution for 3 minutes

**Drying:**

Let the silver salt plate dry naturally. If the step of sensitizer removal is skipped, then the silver salt plate should be washed with distilled water rather than tap water. Otherwise, the silver salt plate may be contaminated by impurities from tap water.

1.4 **Bleaching of silver salt holographic plate**
The hologram of a silver salt plate obtained after exposing, developing, and fixing processes is an amplitude hologram. Affected by factors such as the size of photosensitive particles, the intensity ratio between object and reference light, and post-exposure processing procedures, the interference contrast of an amplitude hologram is low yielding diffraction efficiency of about 7%. The diffraction efficiency can be enhanced by bleaching the hologram to reduce metal silver to transparent silver salt. This results in the variation of refractive index in the exposed area of the silver salt plate so that an amplitude hologram is converted into a phase hologram. The diffraction efficiency of a phase hologram can reach 30% ~ 40%.

### Bleaching Formula 1

<table>
<thead>
<tr>
<th>Reagent</th>
<th>Dose</th>
<th>concentrated Sulfuric Acid</th>
<th>Potassium Bromide</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium Bichromate</td>
<td>20 g</td>
<td>14 ml</td>
<td>92 g</td>
<td>1000 ml</td>
</tr>
</tbody>
</table>

### Bleaching Formula 2

<table>
<thead>
<tr>
<th>Reagent</th>
<th>Dose</th>
<th>Potassium Bromide</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercuric Chloride</td>
<td>18 g</td>
<td>8 g</td>
<td>800 ml</td>
</tr>
</tbody>
</table>

After the fixing process, ambient light can be turned on to start the bleaching process. Soak the silver salt plate in the bleaching solution and keep swinging the plate in the solution while monitoring the color change of the plate. Take the plate out of the bleaching solution when the black color of the plate dissolves away in the solution. Wash the plate with water and let it dry naturally.