EXERCISE 84	DETERMINATION OF A WAVELENGTH USING A DIFFRACTION GRATING

Exercise Objective: Determination of the emission wavelength of a laser or other monochromatic light source, determination of the diffraction grating constant.
Topics: Diffraction of light, diffraction grating, measurement of light wavelength.

1. Introduction

In geometric optics, the fundamental property of light is its rectilinear propagation in media with a uniform refractive index. This is where the concept of a light ray is defined. Illuminating an opaque screen with a small aperture will result in a narrow beam of light. Reducing the aperture diameter will result in a narrowing of the light ray only to a certain point. Further reduction of the aperture diameter will result in a widening of the light beam.

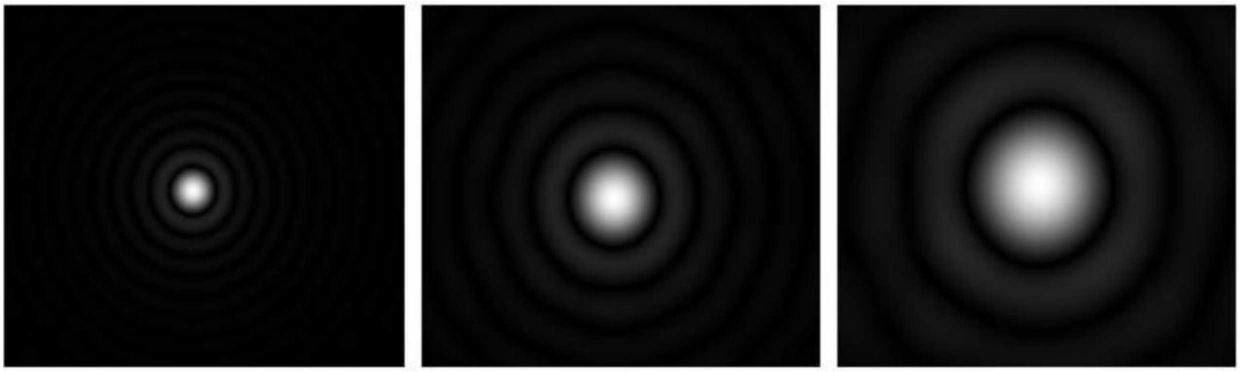

Fig. 1. Light intensity distributions observed on the screen for three circular holes with decreasing diameters.

This effect is a result of the phenomenon of light diffraction, which involves the bending of light rays encountering obstacles. This deviation from the rectilinear propagation of light is related to its wave nature. According to Huygens' principle, each point in space reached by an incident wave can be treated as a new source of a spherical wave. Such elementary waves meet and interfere, thus creating a new light wave.

The wave nature of light was confirmed by Thomas Young. In his experiment (Fig. 2), he directed sunlight at an opaque diaphragm P_1 with a small hole S_0 in the center. According to Huygens' principle, the pinhole acts as a source of an elementary spherical wave. This wave, impinging on holes S_1 and S_2 in diaphragm P_2, again generates two spherical waves. On screen E, we observe a series of alternating light and dark stripes (Fig. 3).

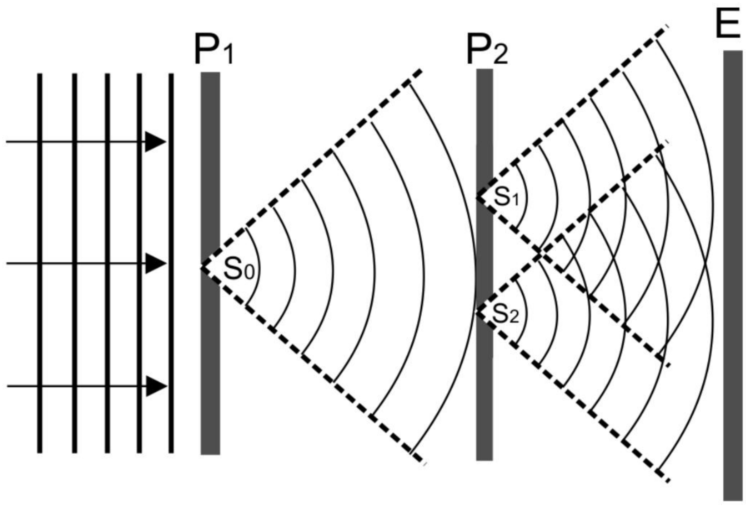

Fig. 2. Young's experiment

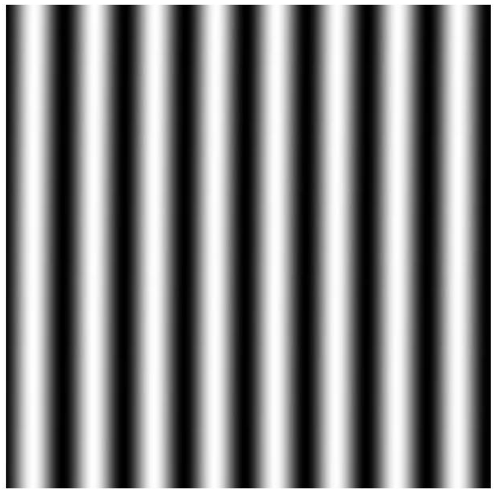

Fig. 3. The image observed in Young's experiment for an opaque diaphragm with two slits.

A diffraction grating is essentially a replica of the double-slot experiment. The fundamental difference is that instead of two, it contains a large number (from several dozen to several thousand) of identical, equidistant slits. Therefore, significantly more light passes through the diffraction grating than through the two slits in Young's experiment.

Suppose a plane light wave is incident perpendicularly on the diffraction grating from the left, as shown in Fig. 4.

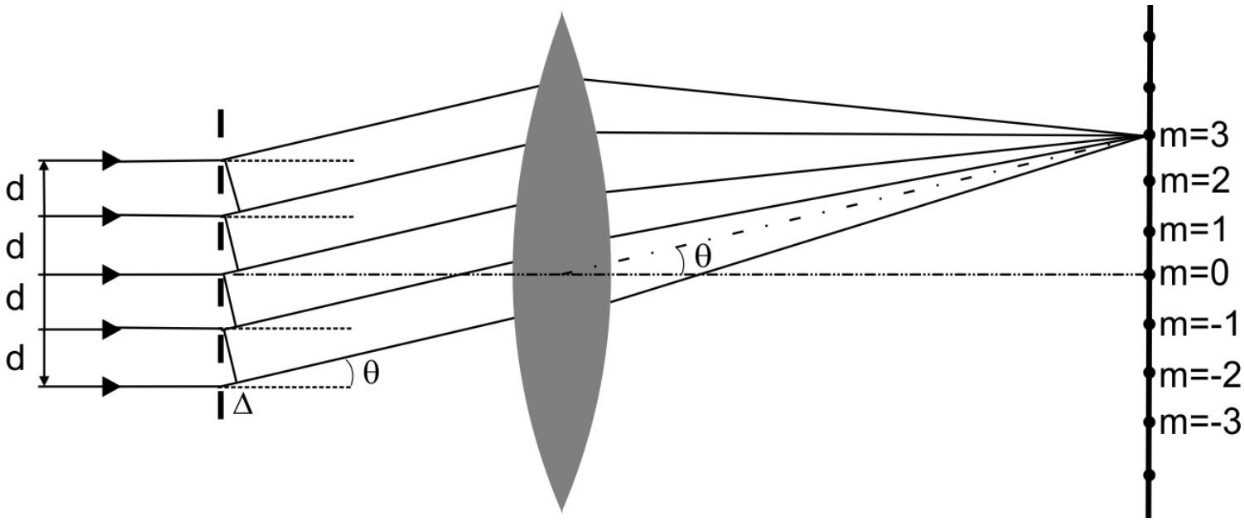

Fig. 4. Diffraction grating scheme.

We remember that each point on the grating's slits is the source of an elementary spherical wave. Let's choose one specific direction from among many, the rays diffracted at an angle θ to the initial ray path. If *d* is the distance between the slits, then the difference *Δ* in the paths traveled between two rays diffracted at adjacent slits (from their slit to the common wavefront behind the grating) is expressed, similarly to Young's experiment, by the equation:

$$\Delta = d \sin \theta \qquad (1)$$

Waves passing through the slits have the same phase of oscillation in them, so they will be amplified in those directions in which the condition for interference amplification of the light intensity is met:

$$\Delta = m\lambda \qquad (2)$$

where $m = 0, \pm 1, \pm 2, \pm 3...$ – the order of the diffraction spectrum, λ – wavelength.

Therefore, the directions of interference amplification of light intensity (maxima) are defined by the diffraction grating equation:

$$\sin\theta_m = m\,\frac{\lambda}{d}\,. \qquad (3)$$

This assumes that the screen on which the rays interfere is very far away. In practice, the diffracted rays are passed through the objective lens (Ob). All mutually parallel, diffracted rays then meet and interfere in the focal plane of the objective lens. This method of interference is more convenient, and the diffraction spectrum (diffraction pattern) of the grating is much clearer.

Diffraction gratings play a very important role in many instruments used in science and technology. Gratings are particularly often used to obtain monochromatic light or for light dispersion and spectral analysis. Therefore, there is a practical need to produce very high-quality diffraction gratings.

Diffraction gratings are divided into transmission and reflection gratings. Transmission gratings allow light to pass through them. They can be obtained by cutting scratches on glass plates or in thin, opaque layers (usually metallic) applied to glass plates. This method can produce gratings with a constant d of several micrometers, meaning from several to several hundred lines per millimeter. Other methods for obtaining transmission gratings include photographic or holographic methods. In these methods, images of light and dark drawn lines or light and dark, equidistant interference stripes are recorded on special photographic plates with very high resolving power. This method can produce diffraction gratings with a very high line density, up to 4000 lines/mm.

In reflection gratings, light does not pass through the grating but reflects off a periodic structure cut into the metal or glass surface, producing the same effect as when passing through a transmission grating (this effect is visible when observing light reflected from, for example, an optical disc – CD).

Transmission diffraction gratings are divided into amplitude and phase gratings.

An amplitude grating is a grating with alternately opaque (dark) and transparent (slit) lines.

A phase grating is transparent to light throughout its entire area. The equivalents of the alternating transparent and opaque lines of the amplitude grating are lines of periodically varying thickness of the transparent medium, periodically changing the phase of the passing light wave.

Due to the fact that diffraction gratings are mainly used to diffract light, an important parameter of diffraction gratings is their diffraction efficiency η, which is defined as the ratio of the intensity of light diffracted in the first diffraction order I_1 to the total intensity of light incident on the grating I_0.

$$\eta = \frac{I_1}{I_0}\,. \qquad (4)$$

The efficiency of amplitude gratings does not exceed 10%, while the efficiency of phase gratings can reach several dozen percent. Therefore, phase gratings are better suited for many applications than amplitude gratings.

The ability of a diffraction grating to split polychromatic light into monochromatic beams is called angular dispersion:

$$\frac{\Delta\theta}{\Delta\lambda} = \frac{m}{d\cos\theta}. \qquad (5)$$

The measure of the ability to separate two closely spaced spectral lines is the chromatic resolving power:

$$R = \frac{\lambda}{\Delta\lambda} = m\,N. \qquad (6)$$

This relationship allows us to determine the smallest difference in wavelength Δλ of two spectral lines that can be separated in the m-th diffraction order using a grating with N slits.

2 Measurement principle and measurement system

Measurements of the diffraction grating constant and wavelength of light are performed on an optical bench containing, in sequence, a monochromatic light source, a slit, a transmission diffraction grating, and a screen with a millimeter scale. After passing through the slit, light strikes the diffraction grating and is diffracted by it. The screen, placed at a distance L_1 from the grating, shows an undiffracted beam (zero-order) and beams of subsequent orders, diffracted at angles θ_m.

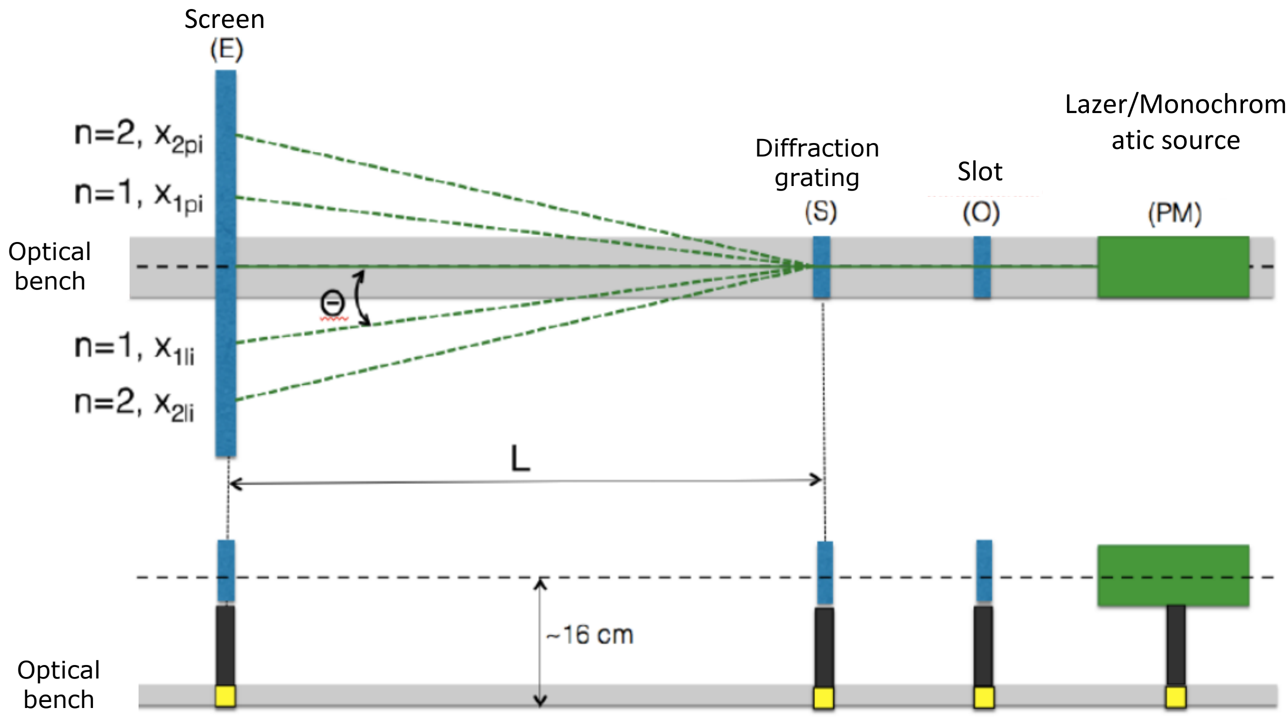

Fig. 5. Measurement system scheme.

3. Tasks to complete

A) Measurements:

Before starting measurements, configure the output position of the monochromatic source/laser so that the light beam propagates along the optical bench. (A detailed description of the procedure can be found in the operating instructions for the measurement station.)

1. **Determining the emission wavelength of a laser or other monochromatic light source**
   Using a diffraction grating with a known grating constant d, read the positions of the diffraction lines on the screen to the left and right of the zero diffraction order. Read the readings for diffraction orders n = 1, 2, 3, 4, and 5. Repeat the measurements for several distances between the diffraction grating and the screen L_i.
2. **Determining the diffraction grating constant**
   For a fixed wavelength of the monochromatic light source, read the position of the first diffraction order to the left and right of the zero diffraction order. Repeat the measurements for several distances between the diffraction grating and the screen L_i.

B) Processing the results:

Place the experimental results in the appropriate tables.

1. **Determine the emission wavelength of the laser or other monochromatic light source**

For each diffraction order n=1, 2, 3, 4, and 5 and the diffraction grating-to-screen distance L_i, calculate the average value of the distance of the diffraction line from the zeroth diffraction order. Calculate the corresponding sines of the diffraction angle $\sin\theta_i$. Based on the diffraction grating equation, calculate the wavelength of light incident on the diffraction grating and its uncertainty.

2. **Determine the diffraction grating constant**
   For each diffraction grating-to-screen distance L_i, calculate the average value of the distance of the diffraction line n=1 from the zeroth diffraction order. Calculate the corresponding sines of the diffraction angle $\sin\theta_i$. Based on the diffraction grating equation, calculate the diffraction grating constant and its uncertainty.

4 Questions:

1. What is the phenomenon of light diffraction? Give examples.
2. Write down the equation for a diffraction grating and discuss the physical quantities involved.
3. What is diffraction efficiency?
4. Name the types of diffraction gratings and discuss their differences.
5. Calculate the diffraction grating constant if, for a laser beam with a wavelength of λ=532 nm, the position of the second diffraction order relative to the undiffracted beam is 20 mm. The screen is placed 10 cm from the diffraction grating.

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