Determination of the wavelength of the monochromatic light using a semiconductor laser

Introduction

The aim of the exercise is determination of the size of slit, wire diameter and the wavelength of the monochromatic light using a semiconductor laser.

The word “laser” is an acronym for “light amplification by the stimulated emission of radiation,” you should not be surprised that stimulated emission is the key to laser operation.

Consider an isolated atom that can exist either in its state of lowest energy (its ground state), whose energy is E_1, or in a state of higher energy (an excited state), whose energy is E_2. Here are three processes by which the atom can move from one of these states to the other:

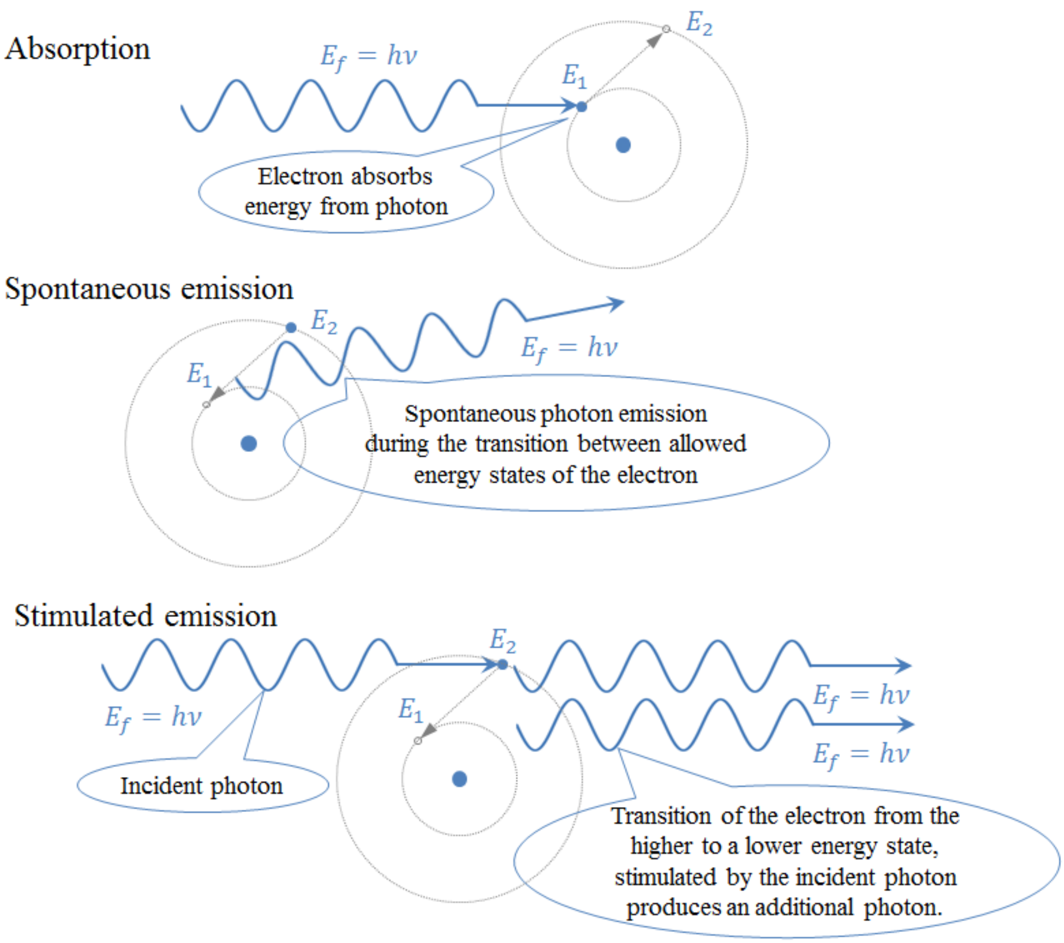

Fig. 4.1 The interaction of radiation and matter in the process of absorption, spontaneous emission, and stimulated emission.

If an atom is placed in an electromagnetic field that is alternating at frequency ν, the atom can absorb an amount of energy $h\nu$ from that field and move to the higher-energy state. The atom can also absorb the energy from the incident photon (see Fig. 4.1). From the principle of conservation of energy we have $h\nu = E_2 - E_1$. The process is called absorption.

If the atom is in its excited state and no external radiation is present, after a time, the atom will go back to its ground state, emitting a photon of energy $h\nu$ in the process called spontaneous emission; - spontaneous because the event is random and set by chance.

If the atom is again in its excited state, but this time radiation with a frequency ν is present, a photon of energy $h\nu$ can stimulate the atom to move to its ground state, during which the atom emits an additional photon, whose energy is also $h\nu$. The process is called stimulated emission; - stimulated because the event is triggered by the external photon. The emitted photon is in every way identical to the stimulating photon. Thus, the waves associated with the photons have the same energy, phase, polarization, and direction of travel.

In the case of laser light, it is necessary to provide an appropriate amount of stimulated emissions that will create a laser beam. This is done in the gain medium - a material of controlled purity, size, concentration, and shape, which amplifies the beam. This material can be of any state: gas, liquid or solid. The gain medium absorbs pump energy, which raises some electrons into excited quantum states. Particles can interact with light by either absorbing or emitting photons. Emission can be spontaneous or stimulated. In the latter case, the photon is emitted in the same direction as the light that is passing by. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, population inversion is achieved and the amount of stimulated emission due to light that passes through is larger than the amount of absorption. Hence, the light is amplified. By itself, this makes an optical amplifier. When an optical amplifier is placed inside a resonant optical cavity, one obtains a laser oscillator. The resonator typically consists of two mirrors between which a coherent beam of light travels in both directions passing through the gain medium repeatedly before it is emitted from the output aperture.

Semiconductor laser, also called a laser diode, is a multilayer structure of n and p type semiconductors. The passage of the electron to the conduction band takes place thanks to the power supply (pumping). Sufficiently large current may cause a population inversion which allow to trigger a laser action. The external walls of the gain medium form the Fabry-Perot resonators.

The wavelength of laser light can be determined using a diffraction grating. The diffraction grating consists of a set of slits with a gap d. We assume that we are dealing with a monochromatic light of wavelength λ propagating in the direction perpendicular to the plane of the diffraction grating. Each slit in the grating acts as a quasi point-source from which light propagates in all directions (although this is typically limited to a hemisphere). After light interacts with the grating, the diffracted light is composed of the sum of interfering wave components emanating from each slit in the grating. At any given point in space through which diffracted light may pass, the path length to each slit in the grating varies. Since path length varies, so do the phases of the waves. Thus, they add or subtract from each other to create peaks and valleys through additive and destructive interference. When the path difference between the light from adjacent slits is equal to half the wavelength, $\lambda/2$, the waves are out of phase, and thus cancel each other being the points of minimum intensity. Similarly, when the path difference is λ, the phases add together and maxima occur. The maxima occur at angles α_n, which satisfy the relationship

$$sin(\alpha_n) = \frac{n\lambda}{d}, \tag{4.1}$$

where α_n is the angle between the diffracted ray and the grating's normal vector, d is the distance from the center of one slit to the center of the adjacent slit, and n is an integer presenting the propagation-mode of interest (see the inset in the Fig. 4.2).

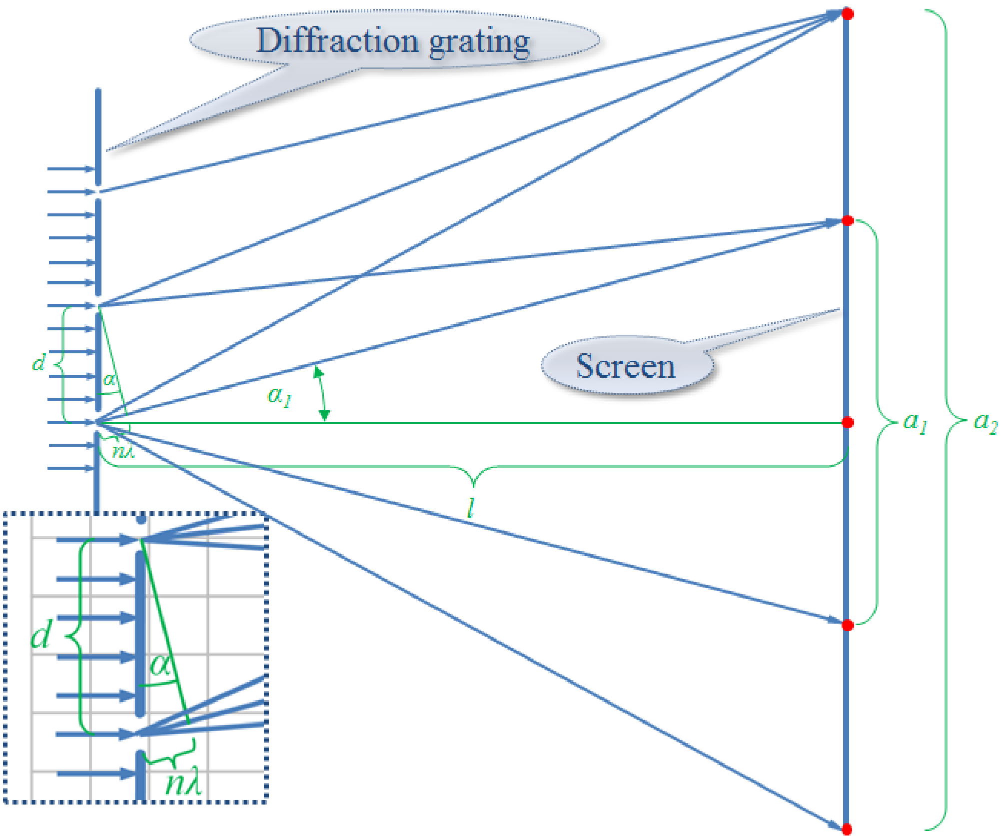

Fig. 4.2 An example of deflection of a laser beam on the diffraction grating slits.

The figure (4.2) shows that for the first mode the following relationship is met:

$$sin(\alpha_1) = \frac{\frac{1}{2}a_1}{\sqrt{\left(\frac{1}{2}a_1\right)^2 + l^2}}. \tag{4.2}$$

where a_1 is the distance between the first interference maxima, l is the distance between the slit and the screen.

In general, this formula has the form:

$$sin(\alpha_n) = \frac{\frac{1}{2}a_n}{\sqrt{\left(\frac{1}{2}a_n\right)^2 + l^2}}. \tag{4.3}$$

Comparing the right sides of equations 4.1 and 4.3 we have:

$$\frac{n\lambda}{d} = \frac{\frac{1}{2}a_n}{\sqrt{\left(\frac{1}{2}a_n\right)^2 + l^2}}, \tag{4.4}$$

from where

$$\lambda = \frac{d}{n}\frac{\frac{1}{2}a_n}{\sqrt{\left(\frac{1}{2}a_n\right)^2 + l^2}}, \tag{4.5}$$

or, after little transformations:

$$\lambda = \frac{d}{n}\sqrt{\frac{1}{1+\frac{4l^2}{(a_n)^2}}}. \tag{4.6}$$

For a single slit, the image obtained on the screen is similar to the image for the diffraction grating, with the difference that the distances between the interference maxima (a_n) are small compared to the distance l. In this case, the following approximation can be accepted

$$\sqrt{\left(\frac{1}{2}a_n\right)^2 + l^2} \cong l. \tag{4.7}$$

Equation 4.4, after taking into account that for the slit $a_n \ll l$ and that instead of the diffraction grating constant (d) we now have the slit width (D), takes the following form:

$$\frac{n\lambda}{D} = \frac{\frac{1}{2}a_n}{l}, \tag{4.8}$$

from where the slit width is

$$D = \frac{2n\lambda l}{a_n}, \tag{4.9}$$

where D - slit width,

n - an integer representing the spectrum order (light spot number)

λ - laser light wavelength,

l - the distance between the slit and the screen,

a_n - the distance between the interference maxima of the respective order (n).

The procedure for determining the diameter of the wire is analogous to that used for the width of the slit. For determination the diameter of the wire, the formula 4.9 is also used.

The laboratory set

On the left side of the optical bench a laser is placed. At a distance of about 30 cm from the laser, a diffraction grating is mounted on the optical bench. In the same place, instead of a diffraction grating, you can mount a frame with a single slit or the frame with wires. At the opposite end of the bench there is a screen. The general arrangement of the described parts of the measurement system is shown in Fig. 4.3. When working with the laser, be especially careful not to direct the laser beams towards the eyes.

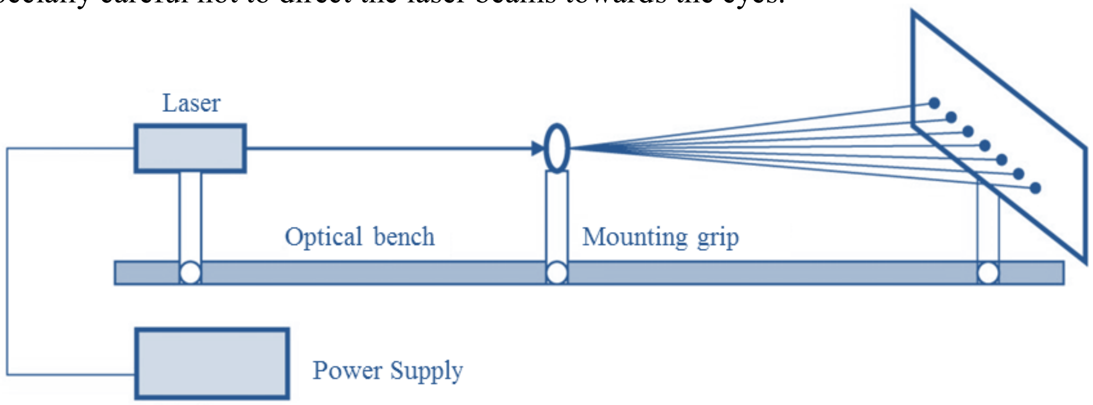

Fig. 4.3 Measuring setup for determination of the wavelength of monochromatic light, the width of the slit and the wire diameter.

Proceeding

1. Determination of the wavelength of the semiconductor laser light.

   a) Mount the diffraction grating on the optical bench at a distance of approx. 30 cm from the laser light source.
   b) After the teacher has checked the system, turn on the laser power supply.
   c) Set the distance from the diffraction grating to the screen so that the third-order light spots are visible (about 1m).
   d) Using the measuring tape or laser meter measure the distance (l) between the diffraction grating and the screen.
   e) Measure distances a_1, a_2, ..., a_6 (see Fig. 4.2) using the millimeter scale on the screen.
   f) Note the value of the diffraction grating constant given by the teacher.
   g) When preparing an exercise report, use formula 4.6 to calculate the wavelength λ.

2. Determination of the slit width.

   a) Mount the slit on the optical bench at a distance of approx. 30 cm from the laser light source.
   b) Set about 1.5 m distance between the slit and the screen.
   c) Point the laser beam exactly at the slit to obtain the most-visible picture of the light spots on the screen.
   d) Measure the distance (l) between the slit and the screen.
   e) Measure distances a_1, a_2, ..., a_6 using the millimeter scale on the screen.
   f) Note the wavelength of the laser light given by the teacher.
   g) When preparing an exercise report, use formula 4.9 to calculate the width of slit (D).

3. Determination of the wire diameter.

The procedure of determining the diameter of the wire is analogous to the determination of the slit width.

Table of measurements and calculation results

DIFFRACTION GRATING				
d (nm)	l (mm)	n	a_n (mm)	λ (nm)
		1		
		2		
		3		
		4		
		5		
		6		
SLIT				
D (nm)	l (mm)	n	a_n (mm)	λ (nm)
		1		
		2		
		3		
		4		
		5		
		6		
WIRE				
D (nm)	l (mm)	n	a_n (mm)	λ (nm)
		1		
		2		
		3		
		4		
		5		
		6		

Processing of the results

1. Perform calculations of the laser wavelength assuming d = $2.0 \cdot 10^{-5}$ m. For the slit width and the wire diameter calculations take the λ = 680 nm for the used laser beam. Save the results in the table.
2. Calculate the uncertainties $U(\lambda)$, $U(D)$ using type A of evaluation, that is:

$$U(\lambda_{śr}) = k \cdot u(\lambda_{śr}) = k \cdot \sqrt{\frac{\sum_{i=1}^{n}(\lambda_i - \lambda_{śr})^2}{n(n-1)}}, \tag{4.6a}$$

$$U(D_{śr}) = k \cdot u(D_{śr}) = k \cdot \sqrt{\frac{\sum_{i=1}^{n}(D_i - D_{śr})^2}{n(n-1)}}, \tag{4.9a}$$

   assuming $k = 2$.
3. Compare the values of the determined physical quantities with the reference ones.

Supplementary literature

1. Andrzej Kubiaczyk, Evaluation of Uncertainty in Measurements, Warsaw University of Technology, http://www.if.pw.edu.pl …