2. SPECTROSCOPY

Tasks:

a) Analyze the spectrum of a white LED light source.

b) Measure the spectrum of a xenon arc lamp.

c) Measure the spectral response and quantum efficiency of a silicon photodetector.

Introduction:

A monochromator is a widely used instrument that allows us to separate the spectrum of an arbitrary light source into the individual spectral components (wavelengths). It is most commonly based on the "Czerny-Turner" configuration presented in Fig. 2.1. The incident light beam (A) enters the monochromator through the input slit (B). After reflecting from the first mirror (C), it hits the diffraction grating (D) where the individual spectral components are separated and reflected into different angles of propagation. By rotating the grating, it is possible to select the desired spectral component and transmit it out of the monochromator through the exit slit (G). Typically, the monochromator is constructed so that the first interference order (m = 1) of the selected spectral component is transmitted out through the exit slit.

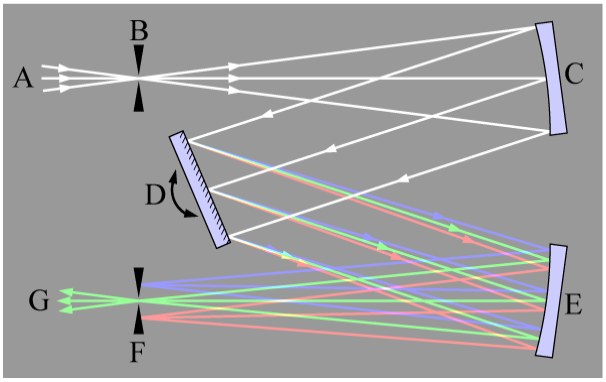

Figure 2.1: Operation principle of a "Czerny-Turner" monochromator.

While using a monochromator it is important to be aware of the effect of interference order overlap. According to the diffraction grating equation (Equation 2.1), the angle of propagation for the first interference order at the wavelength λ is the same as the angle of propagation for the second interference order at the wavelength $\lambda/2$ (for example: 1 × 660 nm = 2 × 330 nm). Therefore, optical filters need to be used during each measurement to filter out the unwanted lower spectral components ($\lambda/2$) and only transmit the desired wavelength λ.

$$\sin\theta_m = \frac{m \cdot \lambda}{P} \tag{2.1}$$

During our measurements, we will use two optical filters. The transmission characteristics of the filters are presented in Fig. 2.2. The first filter SCS245 transmits light from the cut-off wavelength of 220 nm onward, so it will be used in the short-wavelength range. At the wavelength of 440 nm, however, we will need to switch to the second filter SCS425 to avoid interference order overlap (440 nm = 2 × 220 nm). This filter will be used throughout the rest of our measurements.

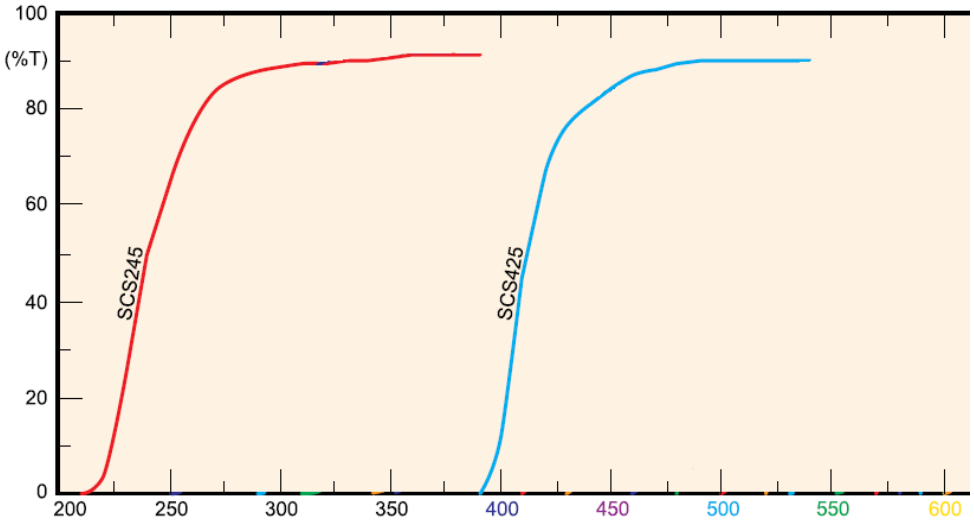

Figure 2.2: Transmission characteristics of filters SCS245 and SCS425.

The wavelength distribution of the optical power $P_{ph}(\lambda)$ emitted by a light source can be determined using a monochromator and a reference photodetector for which the spectral response $SR(\lambda)$ is well known. The spectral response of a photodetector is the ratio of the photo-generated electrical current to the incident optical power at the given wavelength. The spectral response of a silicon photodetector that will be used in our measurements is presented in Fig. 2.3.

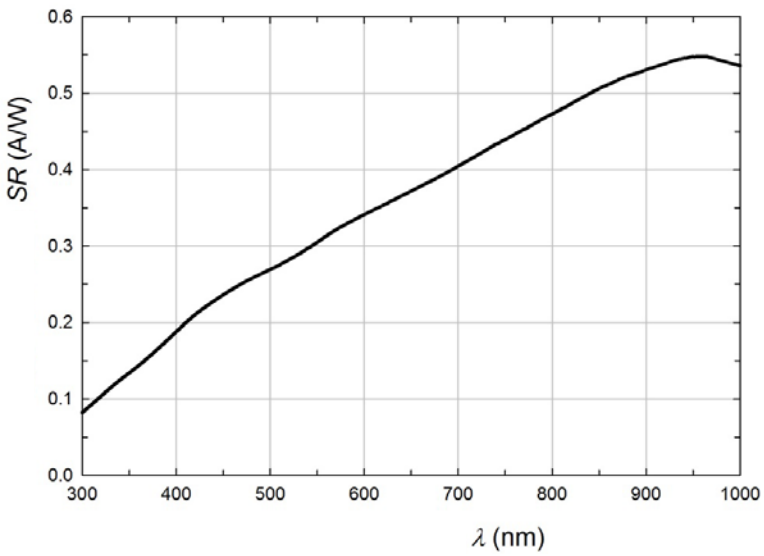

Figure 2.3: Spectral response of a reference silicon photodetector.

The measurements take place at the exit of the monochromator, where all the (monochromatic) light transmitted out of the monochromator is collected using a lens and focused on the photodetector. The transmitted optical power at the selected wavelength can then be calculated from the measured photo-generated electrical current I_{pd} and the known spectral response of the photodetector $SR(\lambda)$, as given by Equation 2.2.

$$P_{ph}(\lambda) = \frac{I_{pd}}{SR(\lambda)} \tag{2.2}$$

In our case, we will measure the photo-generated current of the photodetector indirectly as the voltage output of a transimpedance amplifier (Fig. 2.4). The amplifier puts the photodetector under virtual short-circuit conditions (0 V), and the relation between the input current and the output voltage is given as: $I_{pd} = -K \cdot U_{pd}$

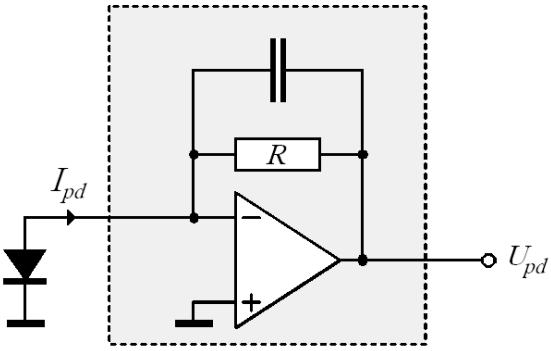

Figure 2.4: Transimpedance amplifier.

However, since the measurements take place at the exit of the monochromator whereas the light source is located at the front, we also need to take into account the transmission characteristics of the monochromator $T_{MC}(\lambda)$, because a significant amount of optical power is lost while propagating through the monochromator. Thus, the output optical power at the exit slit $P_{ph}(\lambda)$ and the input optical power of the light source $P_{ph}^{0}(\lambda)$ are related according to the following equation: $P_{ph}(\lambda) = T_{MC}(\lambda) \cdot P_{ph}^{0}(\lambda)$. Finally, the input optical power of the light source can be calculated from all the mentioned parameters as:

$$P_{ph}^{0}(\lambda) = \frac{P_{ph}(\lambda)}{T_{MC}(\lambda)} = \frac{I_{pd}}{T_{MC}(\lambda) \cdot SR(\lambda)} = \frac{-K \cdot U_{pd}}{T_{MC}(\lambda) \cdot SR(\lambda)} \tag{2.3}$$

Note that thus calculated optical power presents only the part of the emitted light that enters the monochromator, and not the entire optical power emitted by the light source in all directions. However, it reliably gives information about the *spectrum* of the light source, i.e. the optical power distribution over the individual wavelengths. Typically, the spectrum is normalized between 0 and 1.

Regarding the above description of the measurement method we should once again point out that for measuring an unknown light source, we need to use a photodetector with a known spectral response (also called a reference photodetector). On the other hand, if we would like to measure an unknown spectral response of a photodetector, we need to know the optical power emitted by the light source.

For measuring the spectral response of an unknown photodetector, we can use the same method as described above. If we know the optical power $P_{ph}(\lambda)$ that shines upon the photodetector, we can calculate the spectral response from the measured photo-generated electrical current (output voltage of the transimpedance amplifier) from the following equation:

$$SR(\lambda) = \frac{I_{pd}}{P_{ph}(\lambda)} = \frac{-K \cdot U_{pd}}{P_{ph}(\lambda)} \tag{2.4}$$

From the spectral response, we can also calculate the quantum efficiency of the photodetector, which is the ratio of the flux of photo-generated charge carriers (electron-hole pairs) to the flux of the incident photons:

$$QE(\lambda) = \frac{\phi_e(\lambda)}{\phi_{ph}(\lambda)} = SR(\lambda) \cdot \frac{1}{\lambda} \cdot \frac{h \cdot c_0}{q} \tag{2.5}$$

Experimental procedure:

a) Spectrum of a white LED light source

Light-emitting diodes (LED) are semiconductor elements that emit light in a narrow wavelength range around the central wavelength that depends on the energy bandgap of the semiconductor material. White light can be achieved by combining many LEDs of different colors, or by using various phosphorous coatings. In our case, we will analyze the spectrum of a white LED light source that consists of one blue, one green, and one red LED.

Insert the plate with the white LED light source into the slot on the front side of the monochromator. Make sure that the filter **SCS425** is used during the measurement. Rotate the wavelength knob on the front panel so that you can see a light beam at the exit of the monochromator. Focus the light beam onto the surface of the reference photodetector (located on top of the plate with the photodetectors) and connect the photodetector to the transimpedance amplifier. Connect the output of the amplifier to the multimeter (voltage readout). Close the black box that contains the photodetectors, so that any light noise in the room (e.g. ambient lights) will not contribute to the photodetector signal.

- By scanning the wavelength range of **400 – 700 nm**, find the central wavelengths of all three LEDs that comprise the white LED light source. At each central wavelength there is a local maximum of the voltage signal that can be measured using the multimeter.

  λ_M = _____

  λ_Z = _____

  λ_R = _____

- On the plate with the white LED light source, there are three jumpers that can be used to switch on or off each of the three LEDs. Remove individual jumpers and observe how the emitted light changes its color.

- Remove two of the jumpers so that only the **green** LED will emit light. We will determine the spectrum of this LED by measuring the signal of the photodetector in the wavelength range around the central wavelength $\boldsymbol{\lambda_Z}$. The measurement step will be **10 nm**, and the measurements will be performed from the minimal wavelength of $\boldsymbol{\lambda_Z}$ **– 50 nm** to the maximal wavelength of $\boldsymbol{\lambda_Z}$ **+ 50 nm**.

  Enter the wavelengths and the results (voltage on the multimeter) into the 2. and 3. column of the SigmaPlot file *"OPT_Vaja_02a.jnb"*, respectively. Enter the amplification coefficient *K* of the transimpedance amplifier into the 4. column. Finally, open (F10) and run the SigmaPlot transform *"OPT_Vaja_02a.xfm"* which will calculate the normalized spectrum of the LED by taking into the account the measurement results and all the parameters of the measuring system. Print the figure and determine the spectral width of the LED (FWHM – *Full Width at Half Maximum*).

  $\Delta\lambda_{FWHM}$ = _____

b) Spectrum of a xenon arc lamp

As the light source in modern spectroscopy measurements, xenon arc lamps are commonly used since they emit a continuous spectrum in a broad wavelength range including ultraviolet (UV), visible, and infrared (IR) light. In our system, a xenon arc lamp is located at the front side of the monochromator (vertical encasing). To turn on the lamp, a high voltage of 20 kV is required initially to ionize the gases in the lamp and to form the electrical arc. Once the arc is formed, however, the voltage can be dropped significantly. For this purpose, the dedicated power supply unit features a special button "START" that needs to be pressed and held for a couple of seconds to turn on the lamp and achieve stable operating conditions. Once this is achieved, the button can be released. In normal operating conditions, the lamp is powered by a current of 8 A and a voltage of 20 V.

The spectrum of the xenon arc lamp will be measured in a broad wavelength range of **360 – 700 nm** in wavelength increments of **20 nm**. The measurements are performed in the same way as in the case of LED measurement.

Be careful to use the correct optical filters!

In the range from **360 – 430 nm**, the filter **SCS245** must be used.

In the range from **440 – 700 nm**, the filter **SCS425** must be used.

Enter the results (voltage on the multimeter) into the 2. column of the SigmaPlot file *"OPT_Vaja_02bc.jnb"*. Enter the amplification coefficient *K* of the transimpedance amplifier into the 4. column. Finally, open (F10) and run the SigmaPlot transform *"OPT_Vaja_02b.xfm"* which will calculate the normalized spectrum of the xenon arc lamp by taking into the account the measurement results and all the parameters of the measuring system. Print the figure.

c) Spectral response of a silicon photodetector

The spectral response of an unknown photodetector will be measured by taking into the account the spectrum of the light source (xenon arc lamp) that has already been measured in the previous measurements. The spectral response will be measured in the same wavelength range of **360 – 700 nm** in wavelength increments of **20 nm**.

On the plate with the photodetectors, change the position of the jumper so that the unknown (bottom) photodetector will be enabled. Set the position of the photodetector so that the light coming out of the monochromator will be focused in its center. Perform the measurements in the given wavelength range and enter the results (voltage on the multimeter) into the 3. column of the SigmaPlot file *"OPT_Vaja_02bc.jnb"*.

Once again take special care that the correct filters are being used! Finally, open (F10) and run the SigmaPlot transform *"OPT_Vaja_02c.xfm"* which will calculate the spectral response of the photodetector by taking into account the measurement results, the previously measured spectrum of the xenon arc lamp, and all the parameters of the measuring system. The transform will also calculate the quantum efficiency of the photodetector according to the Equation 2.5.

Print the figure (spectral response and quantum efficiency in the same plot). Determine the wavelengths where the spectral response and the quantum efficiency reach their maximal values, and write down these values. Note that the positions of both maxima are not at the same wavelength. Why not?

$\lambda_{S,\,max}$ = _____ SR_{max} = _____

$\lambda_{QE,\,max}$ = _____ QE_{max} = _____