Interference filters

Experiment Objective: explore the principle of interference filters and determine their spectral characteristics.

Tasks:

- to register the transmission spectra of the interference light filters at normal incidence of light and determine: value of the maximum transmission T_{max}, the wavelength of maximum transmission λ_{max}, transmission bandwidth $\delta\lambda$, the contrast factor and reflectance R;
- to analyze the dependence of the maximum bandwidth interference filter on the angle of the incidence light

Optical elements and apparatus:

- ✓ radiation source, incandescent electric lamp (1) with power supply (2);
- ✓ fiber-optic waveguide support (3);
- ✓ Red Tide USB-650 spectrometer (4);
- ✓ fiber-optic waveguide (5) which links holder to the spectrometer;
- ✓ light filter support with protractor (6);
- ✓ set of light filter (7) (C1, C2 and C3);
- ✓ PC with "Spectra Suit" software.

Light filters are devices that change the spectral composition or the energy of the incident light and not change (or almost not change) the shape of its front.

Transmission - is the main characteristic of the light filter ($T = I/I_0$, where I and I_0 are intensity of the transmitted and incident light.

Filters called gray or neutral, if the spectral transmittance in the test spectral range does not depend on wavelength. Light filters not satisfying this condition are called selective.

Selective filters are used either for separating a wide spectral range or to select the narrow spectral region. Light filters of the last type are called narrow-band.

Multiple-beam interference can be used for creation the narrow-band filters. The simplest interference filter is a Fabry - Perot interferometer with a very small gap between the mirrors (from $\lambda/2$ to several wavelengths).

The interference filter consists of a thin plane-parallel layer of a dielectric with a refractive index n, with two reflective layers (with the reflection coefficient R) deposited on the both surfaces of this layer (Fig.1). At the system output an infinite sequence of the decreasing amplitude beam with equal path difference is formed. This beams become to interfere with each other.
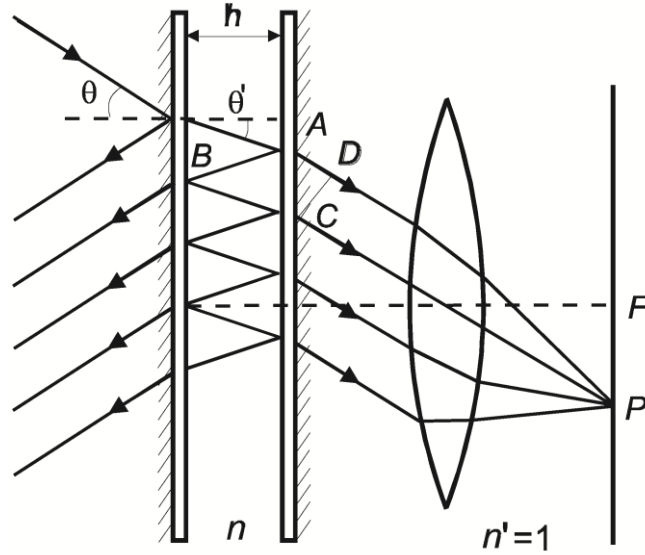
Fig.1. Schematic representation for formation of constant inclination fringes at multiple-beam interference in a Fabry-Perot interferometer.

Light reflection from the two parallel surfaces leads to localized at infinity (or at the focal plane of the lens) fringes formation with equal inclination.

The path difference of two adjacent interfering beams determined by the relation:

$$\Delta = n(ABC) - n'(AO) = 2h\sqrt{n^2 - \sin^2\theta} = 2hn\cos\theta', \qquad (1)$$

where h – thickness of the dielectric layer, θ – angle of light incidence, θ' – angle of refraction, n –refractive index of the dielectric, n' –refractive index of the surrounding medium (assuming $n'=1$).

For the case of no absorption the interferometers transmission is described by Airy's formula:

$$\frac{I}{I_0} = \frac{1}{1 + F\sin^2\delta/2}, \qquad (2)$$

where $F = \frac{4R}{(1-R)^2}$, $\delta = \frac{2\pi}{\lambda}\Delta = \frac{2\pi}{\lambda}2dn\cos\theta'$.

The intensity maxima in the transmitted light will be located where Δ is an integral number of wavelengths:

$$2nh\cos\theta' = m\lambda. \qquad (m = 1, 2, 3,\ldots) \qquad (3)$$

When the condition (3) is satisfied the system is transparent and can be used as a light filter with maximum transmission at $\lambda = \lambda_0$, $\lambda = \lambda_0/2$, $\lambda = \lambda_0/3$ etc. and $m = 1, 2, 3, \ldots$ respectively.

A fragment of the interference filter transmission spectrum for different values of the reflection coefficient R, is shown in Figure 2, where $\lambda_0 = 2nh\cos\theta'$.

The higher the reflectivity of the mirrors, the selective filter, i.e. its transmission decreases rapidly with the retreat of the light wavelength from λ_0, $\lambda_0/2$, $\lambda_0/3$ etc values.

The filter for extracting the first most wavelength bandwidth, is called first order filter ($m = 1$). One of the maxima could be overlap with the desired wavelength value λ_0 by varying h value.

Thus there is a need for suppressing the short transmission maxima at wavelengths $\lambda_0/2$, $\lambda_0/3$ etc. Typically, this is easily accomplished either by special absorptive filters or by absorption material of the filter substrate. The remaining maximum at a sufficiently high mirror layers reflectance R can be very narrow.

Second-order filter ($m = 2$), which selects the wavelength $\lambda_0/2$ requires the suppression of a bandwidth on the long-wavelength side (λ_0) and the short-wavelength bands ($\lambda_0/3$, $\lambda_0/4$, etc. See Fig.2). The higher-order filters can also be created.
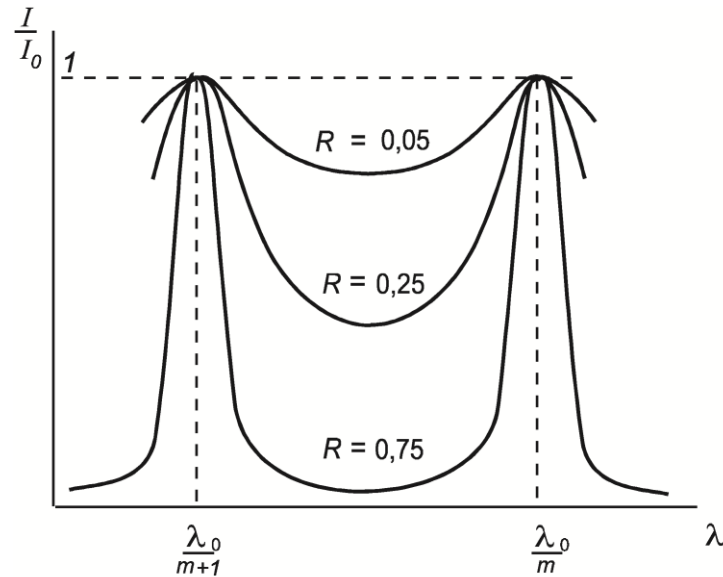

Fig.2. A fragment of the interference filter transmission spectrum.

Thus, the combination of a Fabry-Perot interferometer with a very small optical thickness between the reflective surfaces and the filter, releasing a wide range of the spectrum, has the ability to selectively passes. This optical system is called an interference filter.

The important characteristics of the light filter are:

- value of the maximum transmission T_{max};
- the wavelength of maximum transmission λ_{max};
- transmission bandwidth $\delta\lambda = \lambda_2 - \lambda_1$, where λ_2 and λ_1 are wavelengths when the transmittance decreases twice: $T = T_{max}/2$;
- the contrast factor, which gives a ratio of maximum and minimum transmissions.

An interference filter has a much smaller bandwidth than a conventional absorption filter (colored glass for example) and can be up to several tenths of nanometers in transmission at the maximum of tens of percent.
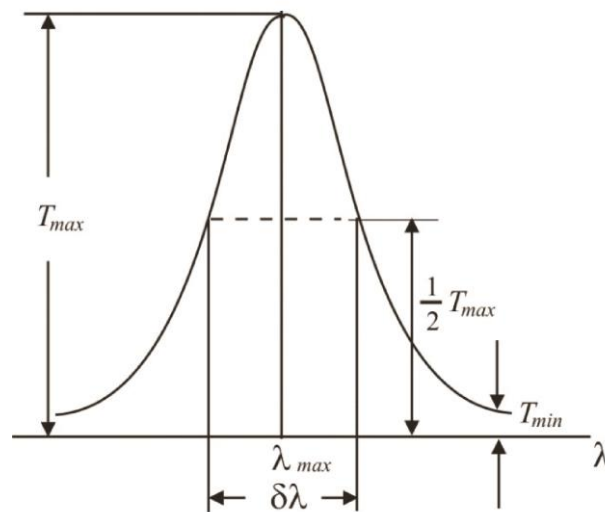

Fig.3. The interference filter transmission spectrum.

The wavelength of maximum transmission λ_{max} can be shifted to lower values by turning the interference filter, increasing the angle of incidence θ (see Fig.1 and Formula 1). However, there is a limitation for such an adjustment which is due to dependence of the reflectance R of multilayer dielectric mirrors on the angle of incidence. Generally the reflectance is maximal for the angle θ, which depends on the filter design.
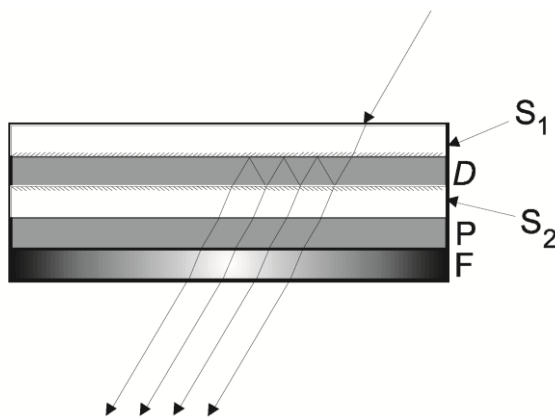
Interference filter is manufactured the following way (Fig.4): on the glass or some other substrate P (which is transparent in the working region of the filter) sequentially by evaporation semitransparent mirror S_2, transparent spacer layer D and second mirror S_1 are applied (S_1 and S_2 may be either metal or dielectric multilayer mirrors). At the end a broadband reflecting or absorbing filter F is applied.

Fig.4. The interference filter structure.

Currently, interference filters are commercially available for the regions of the spectrum from the ultraviolet to the near infrared. Interference filters in the visible region of the spectrum are investigated in this work
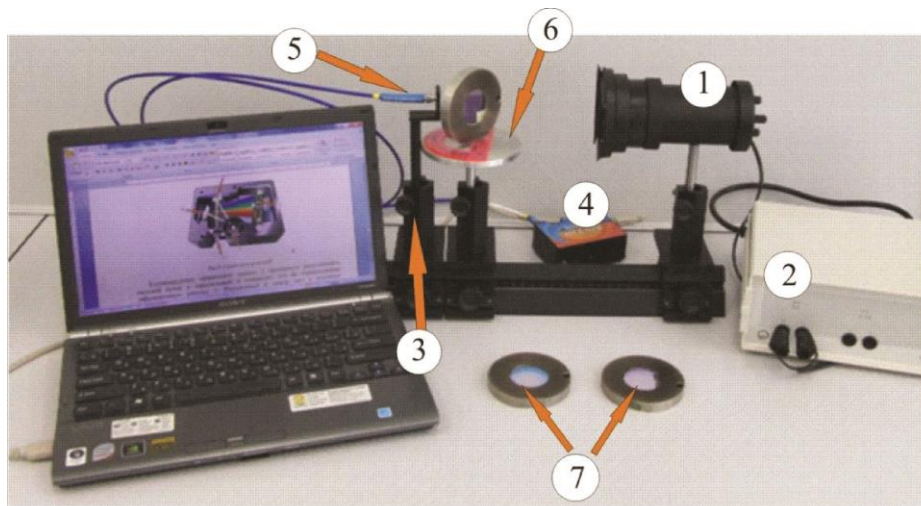
Fig.5. Experimental setup.

Setting the spectrometer and software shell.

Run the SpectraSuite software by doubleclicking on the SpectraSuite icon on the desktop. Connect the spectrometer to the computer via the USB port. Close the auxiliary windows 1 and 2 in the operating window of the program (Fig.6). The detected spectra will be output in the window 3.
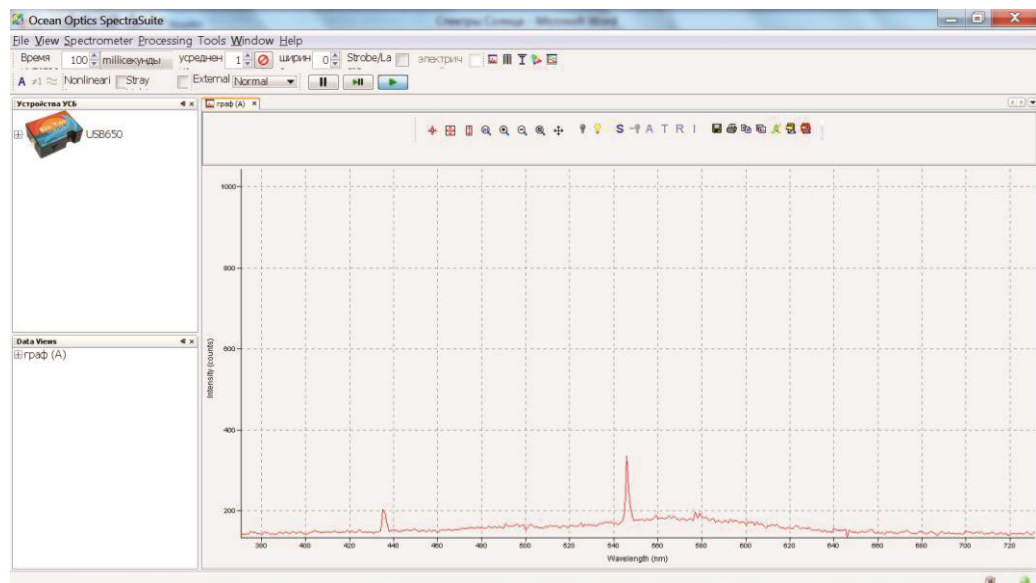

Fig.6. The operating window of the "Spectra Suit" program.

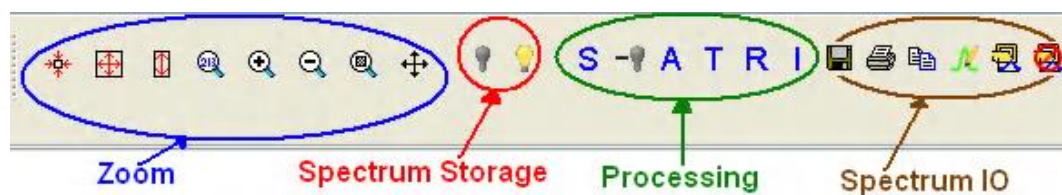The spectra operation buttons are on the panel shown in Figure 7:

Fig.7. Controls and Indicators.

 – Zoom to maximum (350 to 1000 nm).

 – Scale graph to fill window.

 – Scale graph height to fill window. Useful for magnifying small y-axis detail.

 – Set axes ranges manually. Useful if you just want to study a limited waveband.

 and – Zoom in and Zoom out (you can also use the mouse scroll wheel).

 – Zoom to a selected region. Useful for looking at fine detail. By clicking the left mouse button, select a rectangular area on the screen that you want to enlarge.

 – Graph panning.

 – Store Dark Spectrum.

 – Store Reference Spectrum.

 – Scope Mode.

 – Scope Minus Dark Mode.

Depending on the choice of mode it is possible to record the optical density spectra A, transmittance $T = I/I_0$, the reflection coefficient R and the relative luminance I.

The spectra input / output buttons:

 – Save Spectra. Click to save data in either a Grams SPC format, JCAMP format, binary format (which only SpectraSuite can read) or tab-delimited format (can be opened in an Excel spreadsheet).

 – Opens the SpectraSuite Printing dialog box.

 – Copy spectral data to clipboard.

 – Overlay spectral data. Overlays a previously saved spectrum onto the current graph.

 – Delete overlay spectra. Deletes any spectra that have been overlaid on the current graph.

Upon spectrum registration it is important that the recorded signal does not exceed 4000 counts (one count corresponds to the 75 photons ingress on the light-sensitive matrix). So it is necessary to choose the right signal acquisition time, which is set using the "Time" button at the top left of the screen (Figure 8). The range of this parameter is 3 ms to 65 s. The longer the accumulation signal, the greater the signal. Recommended to select this option so that the signal does not exceed 3,500 counts.

Use the "averaging" button to display the average spectrum. The number of the spectra that you want to average given in the appropriate box (Figure 8).
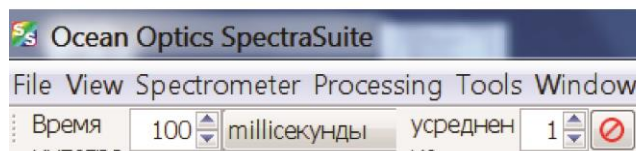

Fig.8. Acquisition Toolbar.

The operation principle of the Red Tide USB-650 spectrometer.

Below is a diagram of how light moves through the optical bench of an Red Tide Spectrometer.

Light enters through the optical fiber on the input slit 1 (Fig. 9). It is a narrow slit made in the opaque plate, and has a fixed width of 25 microns.
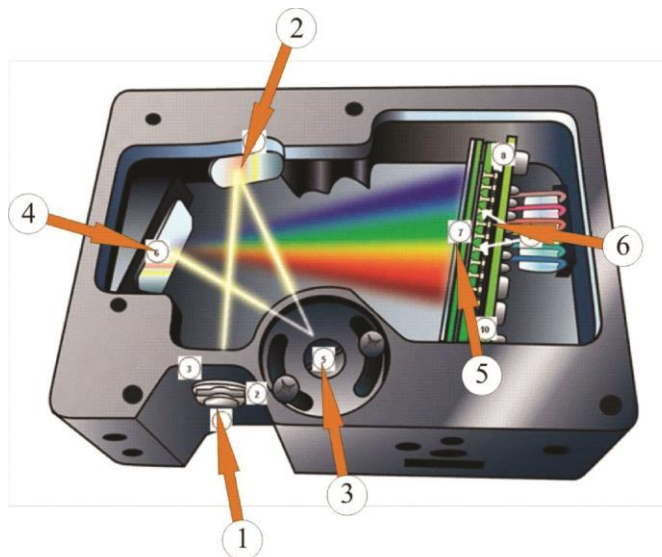
Fig.9. The scheme of the spectrometer.

Collimating spherical mirror (2) converts divergent light beam into a parallel and directs it to a reflective diffraction grating (3). Decomposed light is focused on the detector surface (Silicon Line - CCD detector) (6) by a focusing mirror (4) and a converging lens (5). This detector includes 650 photosensitive elements (pixels), the size of which is 14 x 200 micrometers. One count of the element corresponds to the detection of 75 photons. All elements are aligned along the same straight line so that each pixel corresponds the photosensitive wavelength of a particular light. After analog to digital conversion of electric signals from pixels the digital spectrum is transmitted to the SpectraSuite program.

The transmission spectra registration (dependence of the transmission on the wavelength)

1. Set the light source (1) on the one end of the optical bench and the holder (3) with an optical fiber (5) on the opposite end (Fig.5). Connect the other end of the optical fiber to a spectrometer (4)
2. Turn on the lamp and direct the light from it to the inlet optical fiber. You will see a radiation spectrum that enters the spectrometer. Use the "Time" button to set the acquisition time such that the maximum value was not more than 3500 counts.
3. Register the dark current. To do this, cover with palm the inlet of the optical fiber and press [icon].
4. Register the reference spectrum (spectrum for comparison). To do this, open the inlet of the optical fiber and the press [icon].
5. Go to the registration mode transmission by sequentially pressing **S** and **T** buttons (Fig.7).
6. Press [icon] to select a region of the spectrum from about 450 nm to 900 nm. In this region, the bandwidth filters will be investigated.

Procedure:

Exercise 1. Determination of spectral characteristics of interference light filters (normal incidence).

1. Mount the plate (6) adjacent to the optical fiber holder (Fig.5). Insert interference filter (C1) in a special pin disposed on the base. Filter can be rotated around a vertical axis, the rotation angle measured by a protractor scale located on a stand. Turn the stand so that the bottom of the protractor is perpendicular to the optical bench. Orient the filter so that the light fell on him normally (in this case the angle of incidence is equal to 0°).

2. You will see the transmission spectrum on the display. Move your mouse on the spectrum and right-click. In the appeared window select «Graph Layer Options», then the «Visible Spectrum» in the top line and then «Show visible spectrum layer» - «Clip visible spectrum to trendline».
Note that except the narrow bandwidth in the green region of the spectrum there are bandwidths in the red and blue regions. This is due to the fact that this filter is specially made for educational purposes and has no pass filters.

3. Save the spectrum in a tab-delimited format to analyze it by using other software, e.g., Excel

4. Also save the spectrum as the top layer by pressing [image] .

5. Double click the mouse on the spectrum. You will see the line-cursor. Its position on the wavelength (in nm) and the value of transmittance at this wavelength is shown at the bottom. The line-cursor can be moved around the screen in a two ways: 1) by moving the cursor to the specified point of the spectrum and click the mouse or 2) by typing the wavelength value in the lower window and pressing «Enter». Step-line movement of the cursor is 1 nm.

6. Determine the T_{max}, λ_{max}, $\delta\lambda$, the contrast factor T_{max}/T_{min} and R. To determine the contrast factors, select the lowest transmission value on the left or right of the λ_{max}. The reflection coefficient R can be determined from the value of the contrast factor (see formula Airy):

$$\frac{T_{max}}{T_{min}} = \frac{(1+R)^2}{(1-R)^2}.$$ (4)

7. Determine these characteristics for C2 and C3 filters.

Record the results in the table:

No. light filter	T_{max}, %	λ_{max}/nm	$\delta\lambda$/nm	T_{max}/T_{min}	R
C1					
C2					
C3					

Exercise 2. Analysis of the λ_{max} and $\delta\lambda$ dependence on incidence angle.
1. Consistently register the transmission spectrum of the filter C1 at a different angles of incidence in 5-10° increments. Save the each spectrum as the top layer in the file by pressing . Determine the λ_{max} and $\delta\lambda$ for each angle of the light filter orientation.
2. Record the results in the table:

Angle of incidence $\theta, °$	T_{max}, %	λ_{max}/nm	$\delta\lambda$/nm	T_{max}/ T_{min}	R
C1					
C2					
C3					

3. According to formula (1):
$$\lambda_0^2 = 4h^2 n^2 - 4h^2 \sin^2(\theta). \qquad (5)$$
4. Plot the relationship λ_0^2 from the $\sin^2(\theta)$ and determine the h and n values.