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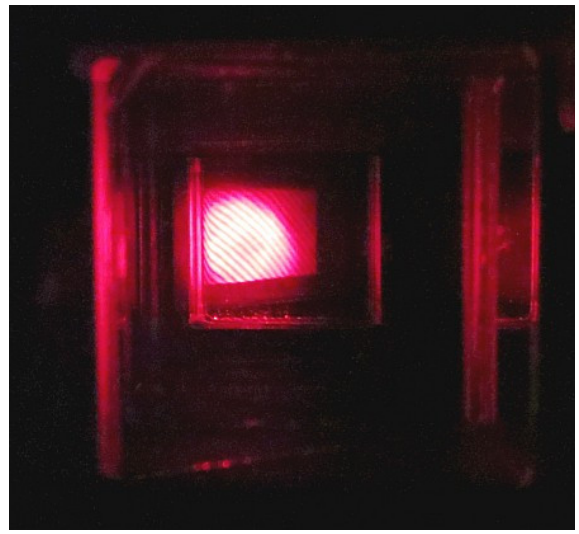
Homemade Fourier Spectrometer

DIY, Electronics for Beginners

Once I read an article about a Fourier spectrometer in Wikipedia , and I wanted to make one myself. This task is not at all simple, but I still managed to make a working model of the spectrometer. Let me warn you right away - this is not an infrared spectrometer, so you can't make particularly interesting measurements with it.

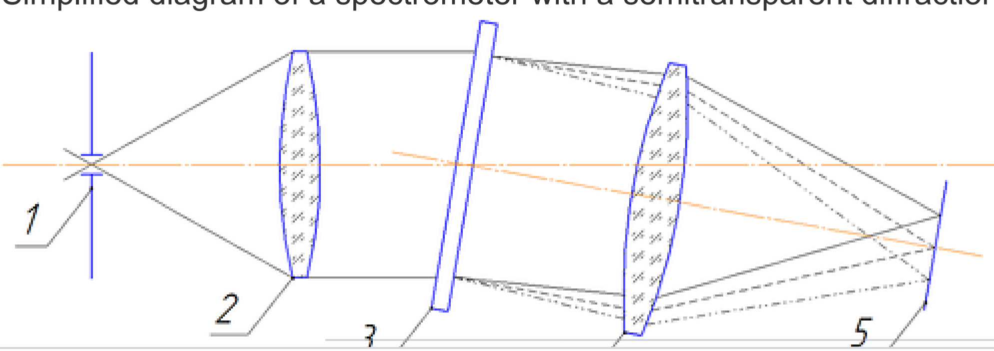


How a Fourier spectrometer works, and how you can make one at home - below (be careful, there are a lot of pictures!).

A bit of theory

Just in case, we will talk about optical range spectrometers.
I will try not to go too deeply into the theory of spectrometer operation, although this topic is very extensive.
The most common types of spectrometers are spectrometers with a dispersing element that is capable of distributing radiation with different wavelengths in space. Examples of such elements are diffraction gratings and prisms.

Simplified diagram of a spectrometer with a semitransparent diffraction grating:



objective, 5 - image plane (plane of the photodetector).

The radiation under study passes through the entrance slit, is transformed by objective 2 into a parallel beam of light, which falls on the diffraction grating. The grating produces a spatial separation of this beam - radiation with different wavelengths begins to spread at different angles. Focusing lens 5 forms an image in plane 5 from parallel beams, which can be recorded by a photodetector (for example, a CCD array).

These types of spectrometers are relatively simple, but they have their drawbacks.
One of the parameters affecting the spectral resolution of the spectrometer is the slit width - the smaller it is, the better the resolution. However, as the slit size decreases, the illumination of the photodetector decreases, which complicates obtaining spectra. Since the light is distributed over the image plane, the illumination of the image decreases.

Prisms, although easy to manufacture and use, are not able to provide high spectral resolution. Another disadvantage is that they can only work in a certain wavelength range determined by the prism material. Ordinary glass is not able to transmit radiation with a wavelength longer than 3-4 μm.

Diffraction gratings are more difficult to manufacture, but provide much better spectral resolution. Reflective diffraction gratings can be used in a wide range of wavelengths - from ultraviolet radiation to far IR. One of the disadvantages of diffraction gratings is that they produce several different orders of spectrum, which can distort the interferogram by overlapping each other. To eliminate them, it is necessary to use light filters that limit the radiation spectrum at the input or output of the spectrometer.

To record the spectrum, multi-element photodetectors are installed in the image plane of the spectrometer, which allow the entire radiation spectrum to be read very quickly. The most common silicon CCD and CMOS arrays are suitable only for the visible spectrum and near IR radiation. To study radiation longer than 1.2 μm, receivers made of other materials are needed, such as germanium, gallium indium arsenide, or even microbolometer arrays. Only a few companies in the world produce such multi-element receivers, they are very expensive and difficult to access.

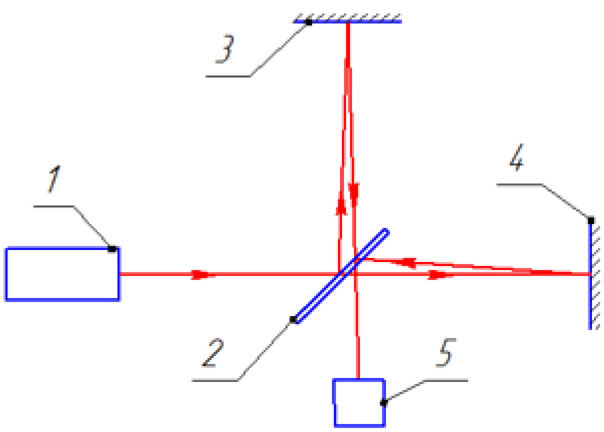
Cheaper single-element photodetectors (photodiodes, bolometers) can also be used to record spectra, but in this case, the image scanning must be mechanical - by moving one of the spectrometer units. This significantly increases the time it takes to obtain a spectrogram and can reduce the accuracy of measuring the absolute values of wavelengths.

Fourier spectrometers use a completely different operating principle - it is based on the phenomenon of interference .

Wikipedia, as it seemed to me, provides the simplest and most understandable description:

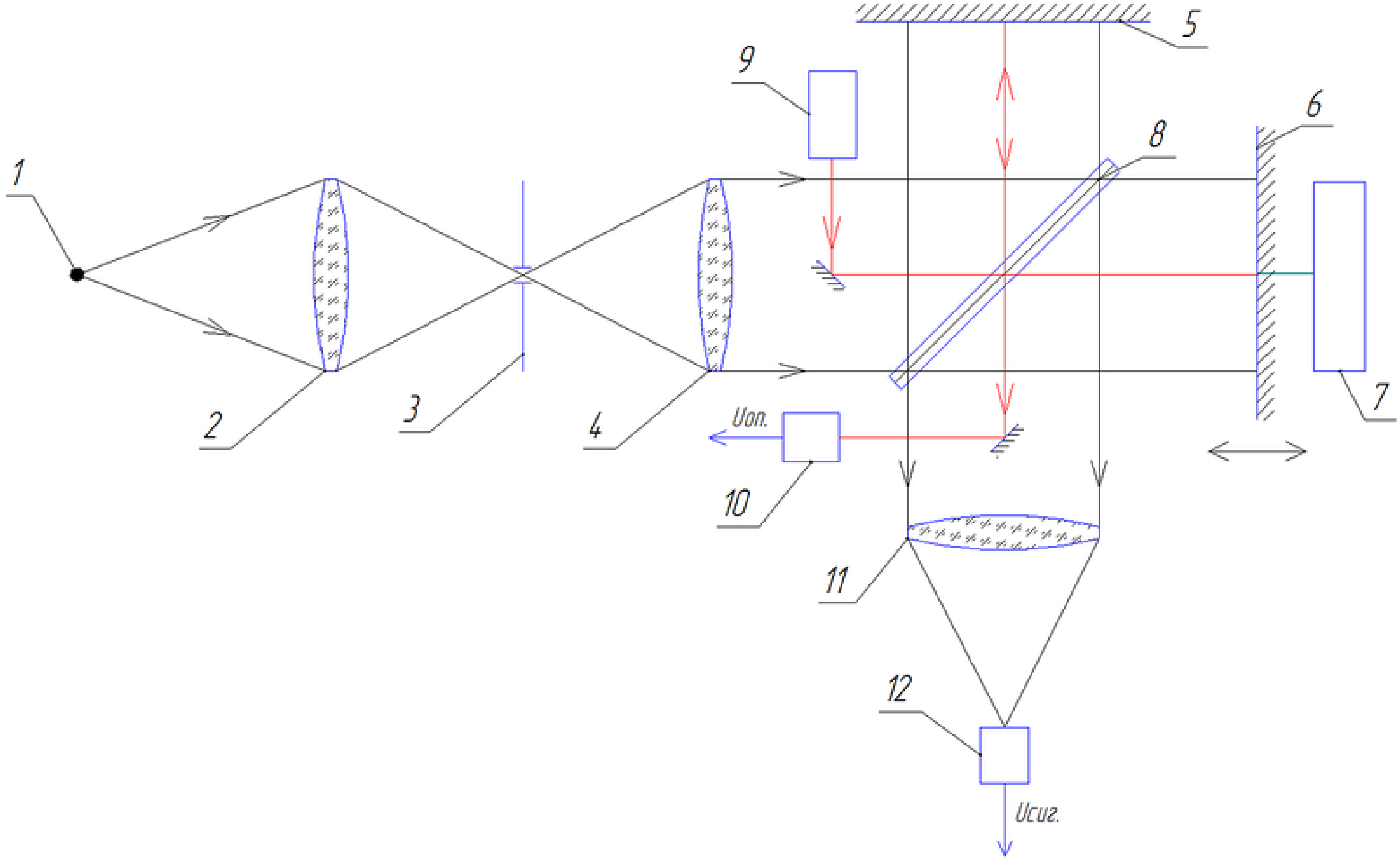
> The main element of the Fourier spectrometer is the Michelson interferometer .
> Let us assume that we have a coherent radiation source with a certain wavelength. When the path difference of two beams arriving at the receiver is equal to λ/2 (i.e. the beams arrived in antiphase), the light intensity registered by the receiver is close to zero. When the right mirror of the Michelson interferometer is moved, the path difference of the beams changes, and the light intensity registered by the receiver also changes. It is obvious that the light intensity is maximum when the path difference of the beams is a multiple of the wavelength. When
>
> the mirror is moved at a constant speed, an electrical signal of a sinusoidal shape will be observed at the output of the receiver. Moreover, the period of the sinusoid depends on the wavelength of the source, and the amplitude on the intensity of the source.
>
> Now imagine that there is an incoherent source at the input. Each wavelength in the spectrum of the light source will produce its own sinusoid at the output of the receiver. Thus, at the output of the receiver we receive a complex signal. When performing the inverse Fourier transform on the received signal, we obtain the spectrum of the input electrical signal, which is also the spectrum of the source radiation (that is, the intensity of the source radiation at different wavelengths).

Radiation interference diagram in a Fourier spectrometer:



In the diagram: 1 — radiation source, 2 — beam-splitting (semi-transparent) plate, 3 — fixed mirror, 4 — movable mirror, 5 — photodetector.

The diagram of a real spectrometer is somewhat more complex: In the diagram: 1 — radiation source, 2,4 — collimating optics, 3 — input diaphragm, 5 — fixed mirror, 6 — movable mirror, 7 — mirror drive, 8 — beam-splitting plate, 9 — reference channel laser, 10 — reference channel photodetector, 11 — focusing optics, 12 — signal photodetector. In order to stabilize the speed of the movable mirror and to ensure "binding" of the spectrometer to absolute wavelength values, a reference channel consisting of a laser and its photodetector (9 and 12 in the diagram) is introduced into the spectrometer. In this case, the laser acts as a wavelength standard. High-quality spectrometers use single-frequency gas lasers for these purposes. As a result, the accuracy of wavelength measurement is very high. Fourier spectrometers have other advantages over classic spectrometers. An important feature of Fourier spectrometers is that even when using a single photodetector, all spectral elements are recorded simultaneously, which provides an energy gain compared to element-by-element mechanical scanning (Falgett gain). Fourier spectrometers do not require the use of optical slits that delay most of the light flux, which provides a large gain in luminosity (Jacquinot gain). Fourier spectrometers do not have the problem of spectral overlapping, as in spectrometers with diffraction gratings, due to which the spectral range of the radiation under study can be very wide, and is determined by the parameters of the photodetector and the beam splitter plate. The resolving power of Fourier spectrometers can be much higher than in traditional spectrometers. It is determined by the difference in the path of the movable mirror Δ. The resolved wave interval is determined by the expression: $\delta\lambda = \lambda^2/\Delta$ However, there is also an important drawback - the high mechanical and optical complexity of the spectrometer. For interference to occur, both mirrors of the interferometer must be very precisely aligned perpendicular to each other. In this case, one of the mirrors must perform longitudinal oscillations, but the perpendicularity must be maintained with the same accuracy. In high-quality spectrometers, in some cases, to compensate for the tilt of the movable mirror during movement, a fixed mirror is tilted using piezoelectric drives. To obtain information about the current tilt, the parameters of the reference beam from the laser are measured.



Practice

I was not at all sure that it was possible to make a Fourier spectrometer at home, without access to the necessary machines (as I already mentioned, mechanics is the most difficult part of the spectrometer). Therefore, the spectrometer was made in stages.

One of the most important parts of the spectrometer is the fixed mirror unit. It is this that will need to be adjusted (smoothly moved) during the assembly process. It was necessary to ensure the ability to tilt the mirror along two axes, and precisely move it in the longitudinal direction (why - below), while the mirror should not tilt.

The basis of the fixed mirror unit was a single-axis table with a micrometer screw. I already had these units, I just needed to connect them together. For a backlash-free connection, I used a simple clamping of the table to the micrometer screw with a spring located inside the base of the table.

Longitudinal movement is provided, then it is a matter of fixing the mirror, which can provide its smooth tilt.

I made it using three adjusting screws removed from a broken theodolite. The metal plate with the glued mirror is pressed by springs to the ends of these screws, and the screws themselves are fixed in a metal corner screwed to
the table.

The design is clear from the photographs:

The mirror adjustment screws and the micrometer screw are visible.

The mirror itself is visible from the front. It is taken from the scanner. An important feature of the mirror is that the mirror coating must be in front of the mirror, and in order for the interference lines not to be crooked, the mirror surface must be of fairly high quality.

Top view:

You can see the springs pressing the table to the micrometer screw and the fastening of the plate with the mirror to the corner.

As you can see from the photographs, the fixed mirror unit is attached to a chipboard. A wooden base for the interferometer is clearly not the best solution, but it was problematic to make it out of metal at home.

Now you can check the possibility of obtaining interference at home - that is, assemble the interferometer. One mirror is already there, so you need to add a second test mirror and a beam splitter. I had a beam-splitting cube, and I used it, although the cube in the interferometer works worse than the beam-splitting plate - its edges give additional reflections of light. The design was as follows: Light should be directed to one of the cube's edges, not facing the mirror, and interference can be observed through the other. After assembly, the mirrors are not positioned too perpendicularly, and therefore primary adjustment is required. I did it using a low-power laser diode connected to a collimating lens of a fairly large diameter. A very small current should be supplied to the laser - such that one can look directly at the crystal. The result is a point source of light.

The laser is installed in front of the interferometer, and its reflections in the mirrors are observed through the cube. For ease of observation, I attached a prism to the cube, directing the radiation coming out of the cube upward. Now, by turning the mirror's adjustment screws, you need to combine the two visible reflections of the laser into one.

Unfortunately, I don't have any photos of this process, and it doesn't look very clear - because of the glare, you can see a lot of glowing dots in the cube. Everything becomes much clearer when you start turning the adjustment screws - some of the dots start moving, and some stay in place.

After the mirrors are set up as described above, it is enough to increase the laser power - and here it is, interference! It looks almost the same as in the photo at the beginning of the article. However, it is dangerous to observe the laser radiation with your eyes, so to see the interference, you need to install some kind of screen after the cube. I used a simple piece of paper through which the interference fringes are visible - the laser's power and coherence are enough to create a sufficiently contrasting image. By turning the mirror adjustment screws, you can change the width of the stripes - it is obvious that it is problematic to observe too narrow stripes. The better the interferometer is adjusted, the wider the stripes. However, as I have already mentioned, the slightest deviations of the mirrors lead to misalignment, and therefore the lines become too narrow and indistinguishable. The sensitivity of the resulting interferometer to deformations and vibrations is enormous - it is enough to press on the base board anywhere, and the lines begin to move. Even steps in the room lead to trembling of the lines.

However, the interference of coherent laser light is not what is needed for the operation of the Fourier spectrometer. Such a spectrometer must work with any light source, including white. The coherence length of white light is about 1 μm.
For LEDs, this value can be larger - several tens of micrometers. The interferometer forms an interference pattern only when the difference in the path of the light rays between each of the mirrors and the beam splitter is less than the coherence length of the radiation. For a laser, even a semiconductor one, it is large - more than a few millimeters, so interference occurs immediately after the mirrors are adjusted. But even from a LED, it is much more difficult to obtain interference - by moving the mirror in the longitudinal direction with a micrometer screw, you need to ensure that the difference in the path of the rays falls into the desired micron range.

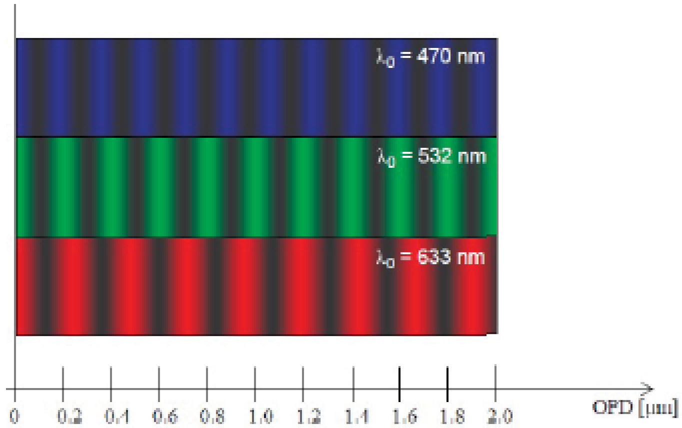
However, as I have already said, when moving, especially quite large (hundreds of microns), due to insufficiently high-quality mechanics of the table, the mirror can rotate a little, which leads to the fact that the conditions for observing interference disappear. Therefore, it is often necessary to reinstall the laser instead of the LED and adjust the mirror alignment with screws.

Finally, after half an hour of trying, when it seemed completely unrealistic, I managed to get interference of light from the LED.

As it turned out a little later, instead of observing interference through a piece of paper at the cube's outlet, it is better to install a matte film in front of the cube - this way you get *an extended light source* . As a result, the interference can be observed directly with your eyes, which significantly simplifies observation.
It turned out like this (you can see the reflection of the cube in the prism):

Then I managed to get interference in white light from an LED flashlight (the matte film is visible in the photo - it is facing the camera with its end and a dim spot of light from the flashlight is visible on it):

If you touch any of the mirrors, the lines begin to move and fade until they disappear completely. The period of the lines depends on the wavelength of the radiation, as shown in the synthesized image found on the Internet:



Now that the interferometer is made, you need to make a movable mirror unit to replace the test one. Initially, I planned to simply glue a small mirror to the speaker and change the position of the mirror

by applying current to it. The design turned out to be as follows: After installation, which required a new adjustment of the fixed mirror, it turned out that the mirror wobbled too much on the speaker diffuser and was slightly skewed when current was applied through the speaker. However, by changing the current through the speaker, it was possible to smoothly move the mirror.

Therefore, I decided to make the design stronger, using a mechanism that is used in some spectrometers - a spring parallelogram. The design is clear from the photo: The

resulting unit turned out to be much stronger than the previous one, although the rigidity of the metal spring plates turned out to be somewhat high.

Then several units were added to the spectrometer:

On the left - a board made of hardboard, with a hole-diaphragm. Protects the spectrometer from external light.

A collimating lens is installed between the hole and the beam-splitting cube, glued to a metal frame:

A special plastic holder is visible on the frame, into which matte film can be inserted (it is in the lower right corner).

A lens for the photodetector is installed. A small mirror on a rotating mount is installed between the lens and the cube. It replaces the prism that was used earlier. The photograph at the beginning of the article was taken through it. When the mirror is rotated to the observation position, it covers the lens, and recording the spectrogram becomes impossible. In this case, it is necessary to stop sending a signal to the speaker of the movable mirror - due to too fast oscillations, the lines are not visible to the eye.

Another single-axis table is visible at the bottom in the center. Initially, a photo sensor was attached to it, but the table did not provide any special advantages, and later I removed it.

I installed a focusing lens from a camera in front:

To simplify the adjustment and testing of the spectrometer, I installed a red photodiode near the diaphragm.

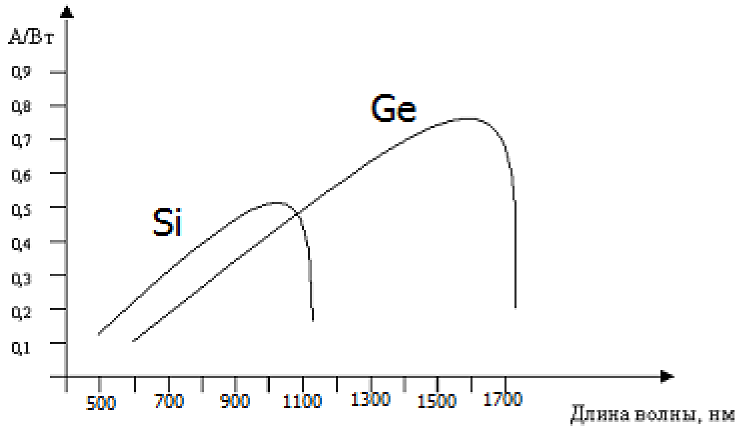
The diode is mounted on a special rotating holder, so that it can be used as a source of test radiation for the spectrometer, the light flow from the lens is blocked. The LED is controlled by a switch installed under the holder.

Now it is worth telling a little more about the photosensors. Initially, it was planned to use only one ordinary silicon photodiode. However, the first attempts to make a high-quality amplifier for the photodiode were a failure, so I decided to use the OPT101 photosensor, which already contains an amplifier with a conversion factor of 1,000,000 (1 μA -> 1V).

This sensor worked quite well, especially after I removed the above-mentioned table and precisely adjusted the sensor in height.

However, the silicon photodiode is capable of receiving radiation only in the wavelength range of 400-1100 nm.
The absorption lines of various substances usually lie further, and another diode is needed to detect them.
There are several types of photodiodes for work in the near IR region. For a simple homemade device, germanium photodiodes are most suitable, capable of receiving radiation in the range of 600 - 1700 nm. These diodes were produced in the USSR, so they are relatively cheap and available.

Photodiode sensitivity:



I managed to get photodiodes FD-3A and FD-9E111. In the spectrometer, I used the second one - it has a slightly higher sensitivity. For this photodiode, I still had to assemble an amplifier. It is made using the TL072 operational amplifier. In order for the amplifier to work, it was necessary to provide it with a voltage of negative polarity. To obtain such voltage, I used a ready-made DC-DC converter with galvanic isolation.

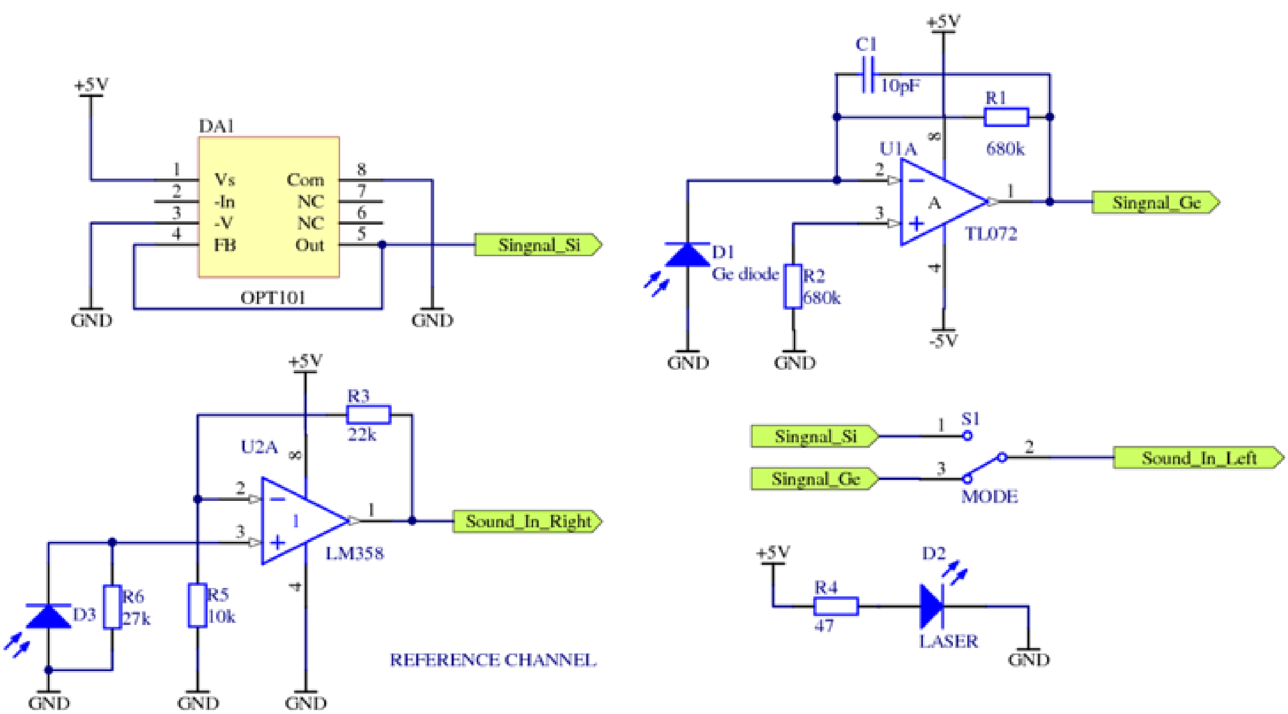
Photo of a photodiode with an amplifier:

The light flow from the interferometer should be focused on both photodiodes. In order to split the light flow from the lens, it would be possible to use a beam splitter plate, but this would weaken the signals from the diodes. Therefore, after the lens, another rotating mirror was installed, with the help of which it is possible to direct the light to the required diode. As a result, such a unit of photosensors was obtained:

In the center of the photo there is a lens, on top of it a laser of the reference channel is fixed. The laser is the same as in the rangefinder , taken from a DVD drive. The laser begins to form high-quality coherent radiation only at a certain current. The radiation power is quite high. Therefore, in order to limit the beam power, I had to cover the laser lens with a light filter. On the right is a sensor on OPT101, below - a germanium photodiode with an amplifier.

In the reference channel for receiving laser radiation, the FD-263 photodiode is used, the signal from which is amplified by the LM358 operational amplifier. In this channel, the signal level is very high, so the gain is 2.

The design is as follows: In the lower left corner of the spectrometer is the reference channel photodiode, its amplifier and a switch for selecting the photodiode used. In the upper left you can see a USB audio card connected to the speaker of the movable mirror. The same audio card is designed to capture the signal from the photodiodes of the main and reference channels. Under the test LED holder there is a small prism directing the laser beam towards the reference channel photodiode. Spectrometer diagram: An example of an oscillogram obtained from the spectrometer (the radiation source is a white LED): The yellow line is the signal fed to the speaker of the movable mirror, the blue line is the signal from OPT101, the red line is the result of the Fourier transform performed by the oscilloscope.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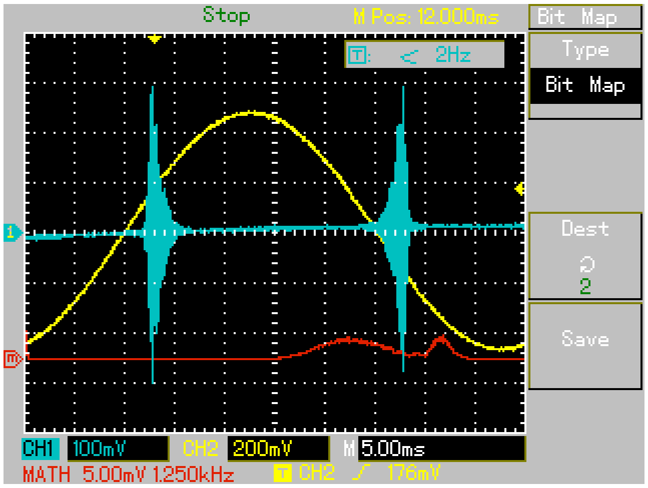


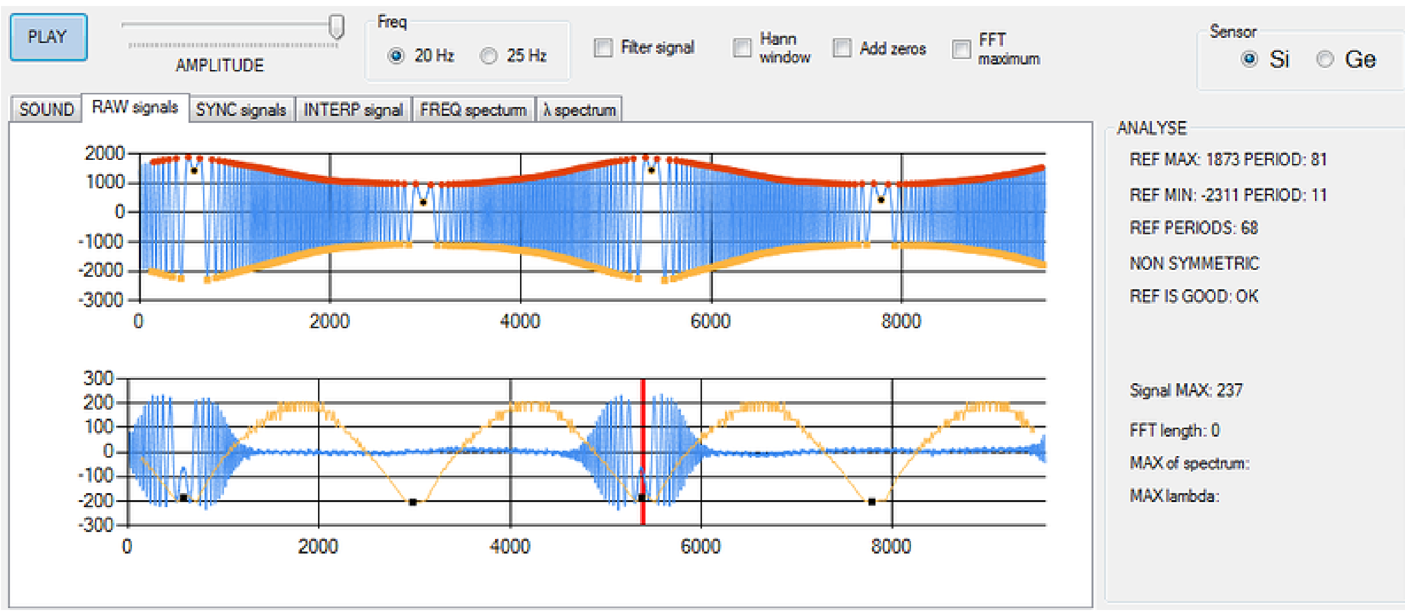
Software part

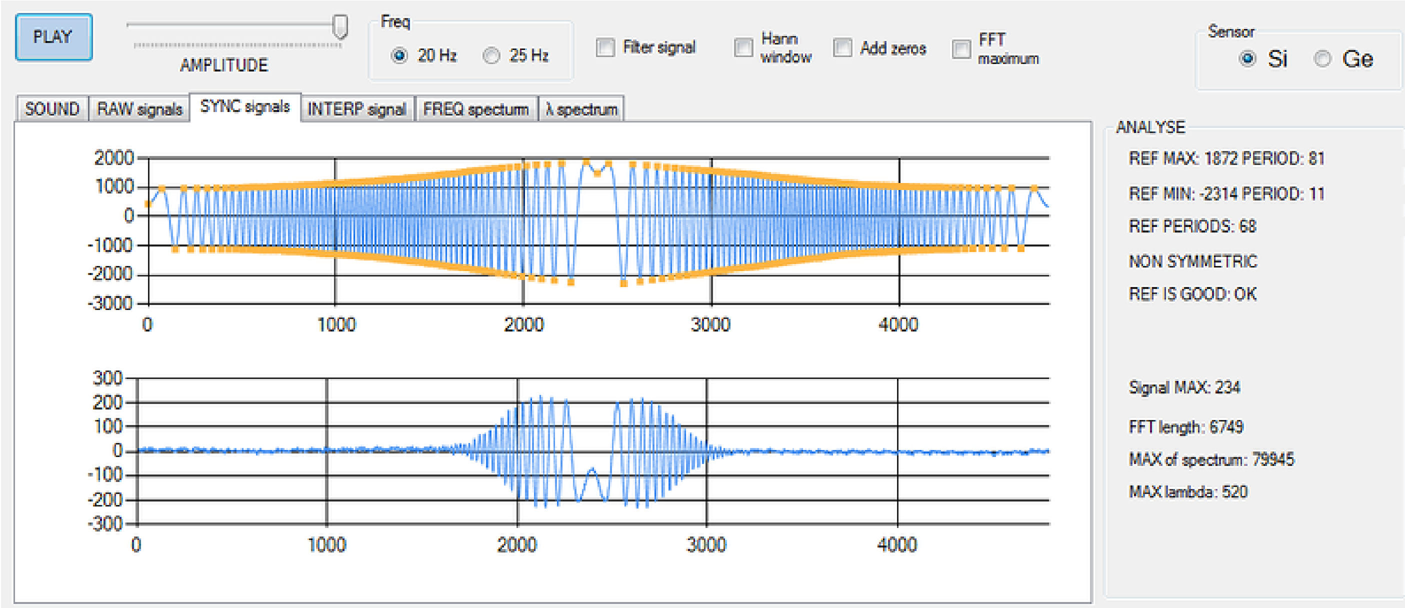
Without software processing, the Fourier spectrometer is impossible — it is on the computer that the inverse Fourier transform is performed, converting the interferogram obtained from the spectrometer into the spectrum of the original signal.
In my case, the special difficulty is that I control the mirror with a sinusoidal signal. Because of this, the mirror also moves according to the sinusoidal law, and this means that its speed is constantly changing. It turns out that the signal from the interferometer output is frequency modulated. Thus, the program must also correct the frequency of the processed signal.

The entire program is written in C#. Work with sound is performed using the NAudio library. The program not only processes the signal from the spectrometer, but also generates a sinusoidal signal with a frequency of 20 Hz to control the movable mirror. Higher frequencies are worse transmitted by the mechanics of the movable mirror.

The signal processing process can be divided into several stages, and the results of signal processing in the program can be viewed on separate tabs.

First, the program receives an array of data from the audio card. This array contains data from the main and reference channels: The reference signal is at the top, and the signal from one of the photodiodes at the interferometer output is at the bottom. A green LED is used as a signal source in this case. Processing the reference signal turned out to be quite difficult. It is necessary to look for local signal minima and maxima (marked with colored dots on the graph), calculate the mirror speed (orange curve), and look for minimum speed points (marked with black dots). The symmetry of the reference signal is important for these points, so they do not always exactly match the actual speed minimum. One of the found speed minima is taken as the interferogram starting point (marked with a red vertical line). Then, one period of mirror oscillation is selected: The number of reference signal oscillation periods per mirror pass (between the two black dots on the screenshot above) is indicated on the right: “REF PERIODS: 68”. As I already mentioned, the resulting interferogram is frequency modulated and needs to be corrected. For the correction, I used the data on the current period of signal oscillations in the reference channel. The correction is performed by interpolating the signal using the cubic spline method. The result is shown below (only half of the interferogram is displayed): The interferogram is obtained, now we can perform the inverse Fourier transform. It is performed using the FFTW library. The result of the transformation: As a result of such a transformation, we obtain the spectrum of the original signal in the frequency domain. In the screenshot, it is recalculated into inverse centimeters (CM^-1), which are often used in spectroscopy. But I am still more accustomed to the scale in wavelengths, so the spectrum has to be recalculated:

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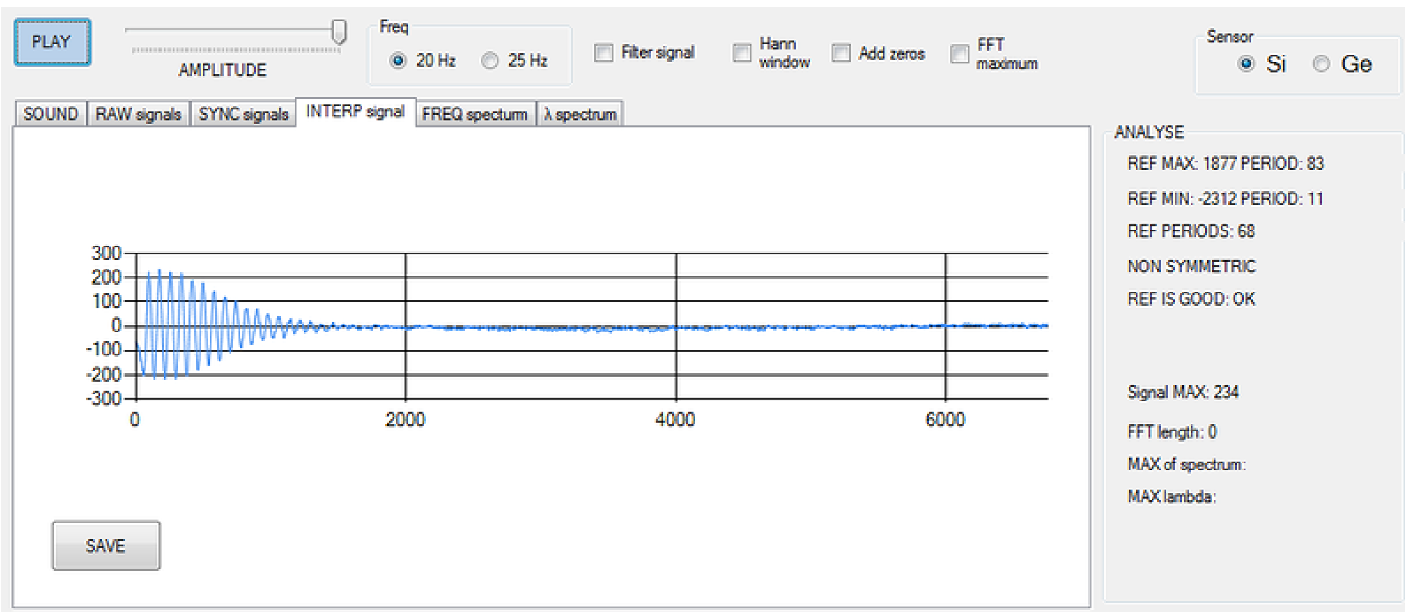
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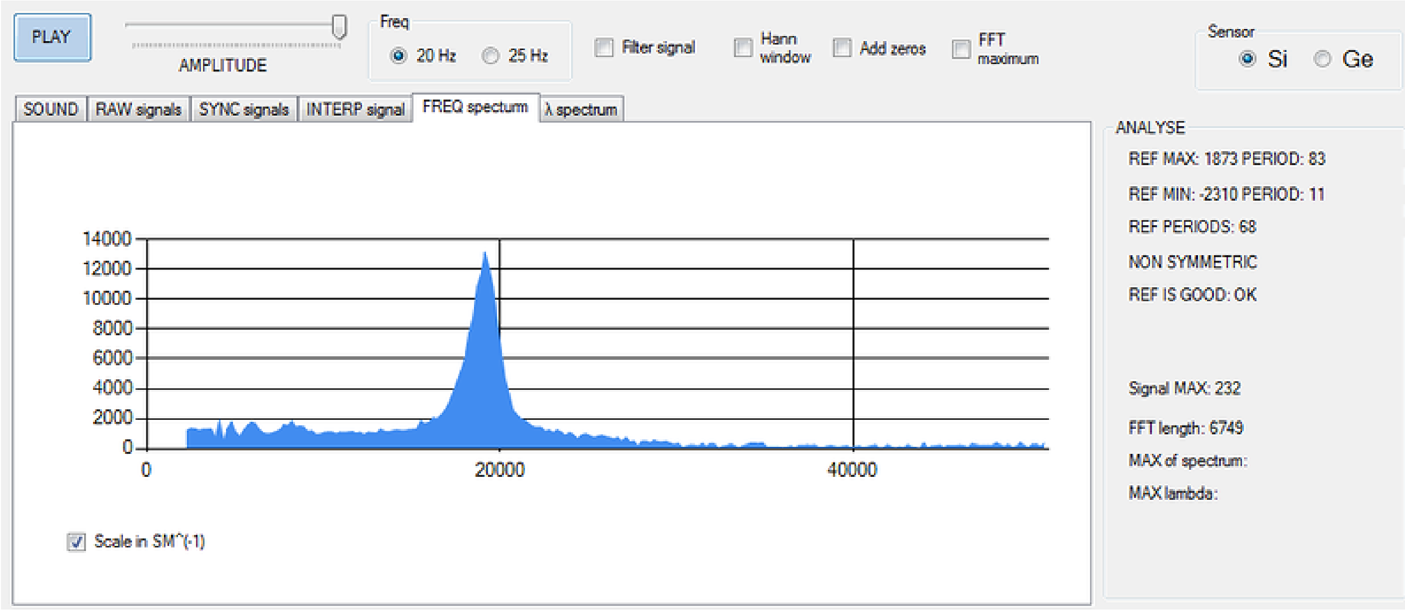
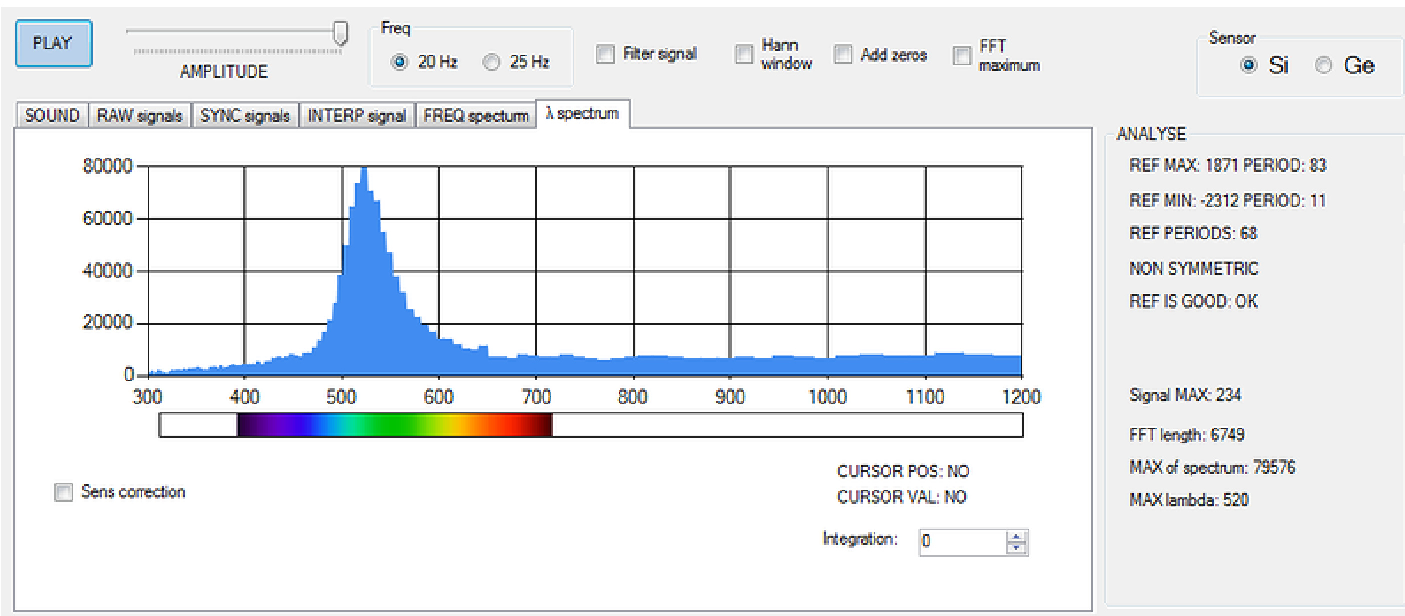
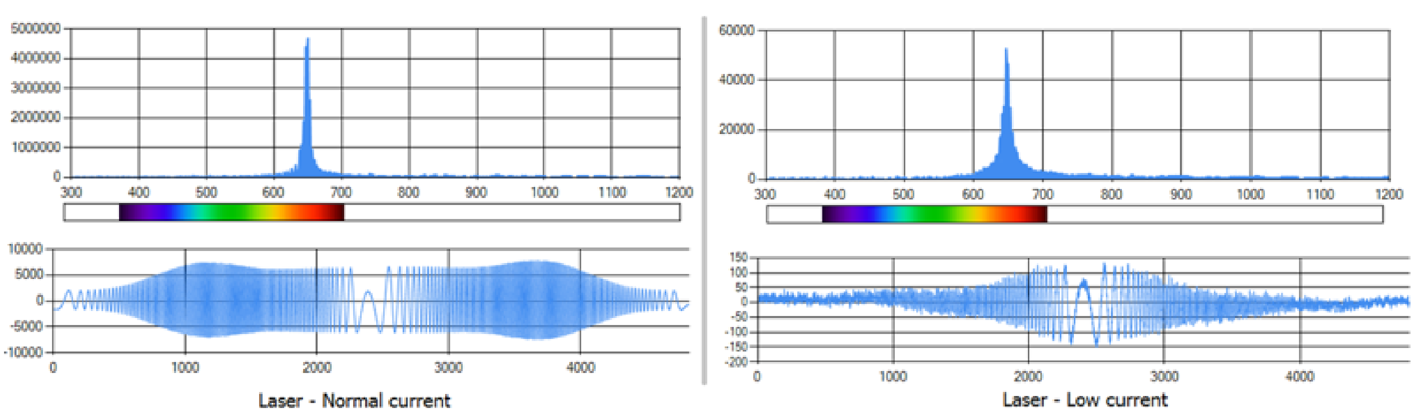


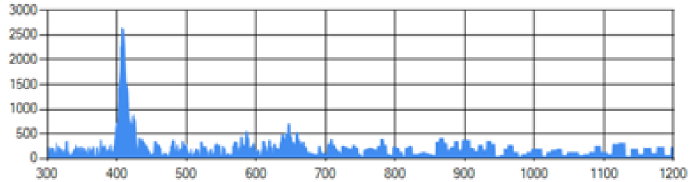


It is evident that the spectrometer resolution decreases with increasing wavelength. The spectrum shape can be slightly improved by adding zeros to the end of the interferogram, which is equivalent to interpolation after the transformation.

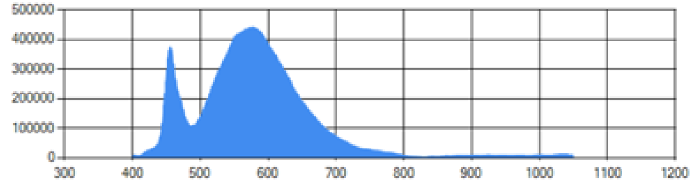
Examples of the obtained spectra

Laser radiation: On the left — the laser is supplied with the nominal current, on the right — a much lower current. As you can see, as the current decreases, the coherence of the laser radiation decreases, and the spectrum width increases. Various LEDs: The following were used as sources: an "ultraviolet" diode, blue, yellow, white diodes, and two IR diodes with different wavelengths. Transmission spectra of some light filters: The emission spectra after interference light filters, removed from the densitometer, are shown. In the lower right corner is the emission spectrum after the IR filter, removed from the camera. It is worth noting that these are not the transmission coefficients of these filters — to measure the transmission curve of a light filter, you need to take into account the shape of the spectrum of the light source — in my case, it is an incandescent lamp. The spectrometer had certain problems with such a lamp — as it turned out, the spectra of broadband light sources are somehow clumsy. I was never able to figure out what this is connected with. The problem may be related to the nonlinear motion of the mirror, or to the dispersion of radiation in the cube, or to poor correction of the uneven spectral sensitivity of the photodiode. And here is the resulting spectrum of the lamp radiation: The teeth on the spectrum on the right are a feature of the algorithm that compensates for the uneven spectral sensitivity of the photodiode. Ideally, the spectrum should look like this: When testing the spectrometer, you cannot help but look at the spectrum of a fluorescent lamp - it has a characteristic "striped" shape. However, when recording the spectrum of a regular 220V lamp with a Fourier spectrometer, a problem arises - the lamp flickers. Nevertheless, the Fourier transform allows you to isolate higher-frequency oscillations (units of kHz) given by interference from low-frequency (100 Hz) given by the network: The spectrum of a fluorescent lamp, obtained by an industrial spectrometer: All spectra above were obtained using a silicon photodiode. Now I will give the spectra obtained with a germanium photodiode: First comes the spectrum of an incandescent lamp. As you can see, it is not very similar to the spectrum of a real lamp (already given earlier). To the right is the transmission spectrum of a copper sulfate solution. Interestingly, it does not transmit IR radiation. A small peak at 650 nm is associated with the re-reflection of laser radiation from the reference channel to the base. This is how the spectrum was taken: Below is the transmission spectrum of water, to the right of it is a graph of the real transmission spectrum of water. Next come the transmission spectra of acetone, ferric chloride solution, isopropyl alcohol. Finally, I will give the spectra of solar radiation obtained with silicon and germanium photodiodes:

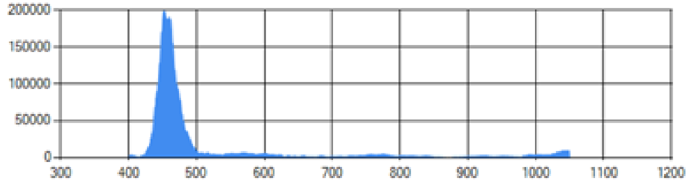




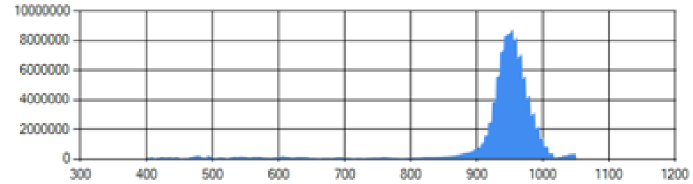
UV LED



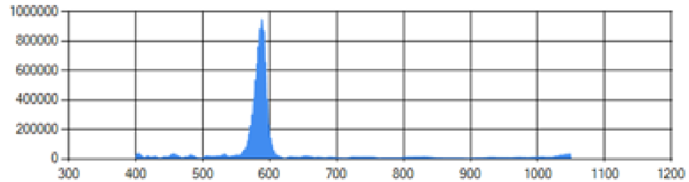
WHITE LED



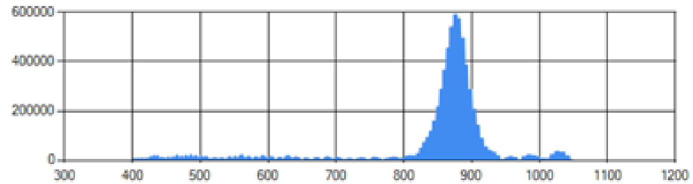
BLUE LED



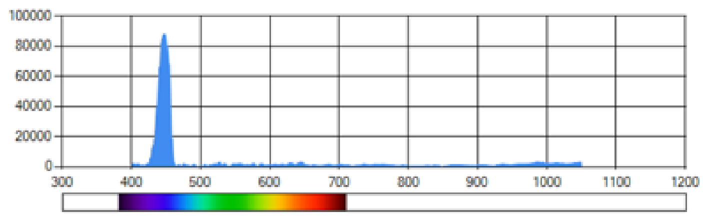
IR LED - 950 nm



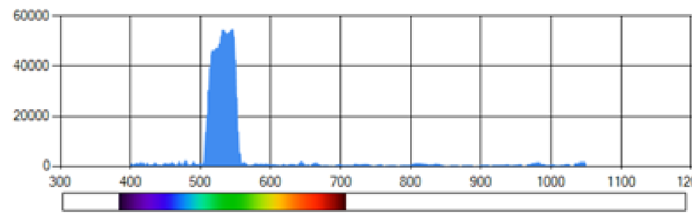
YELLOW LED



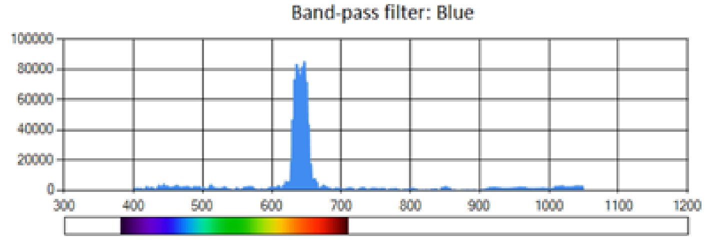
IR LED - 880 nm



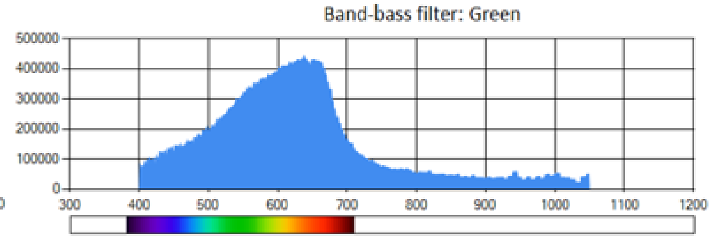
Band-pass filter: Blue



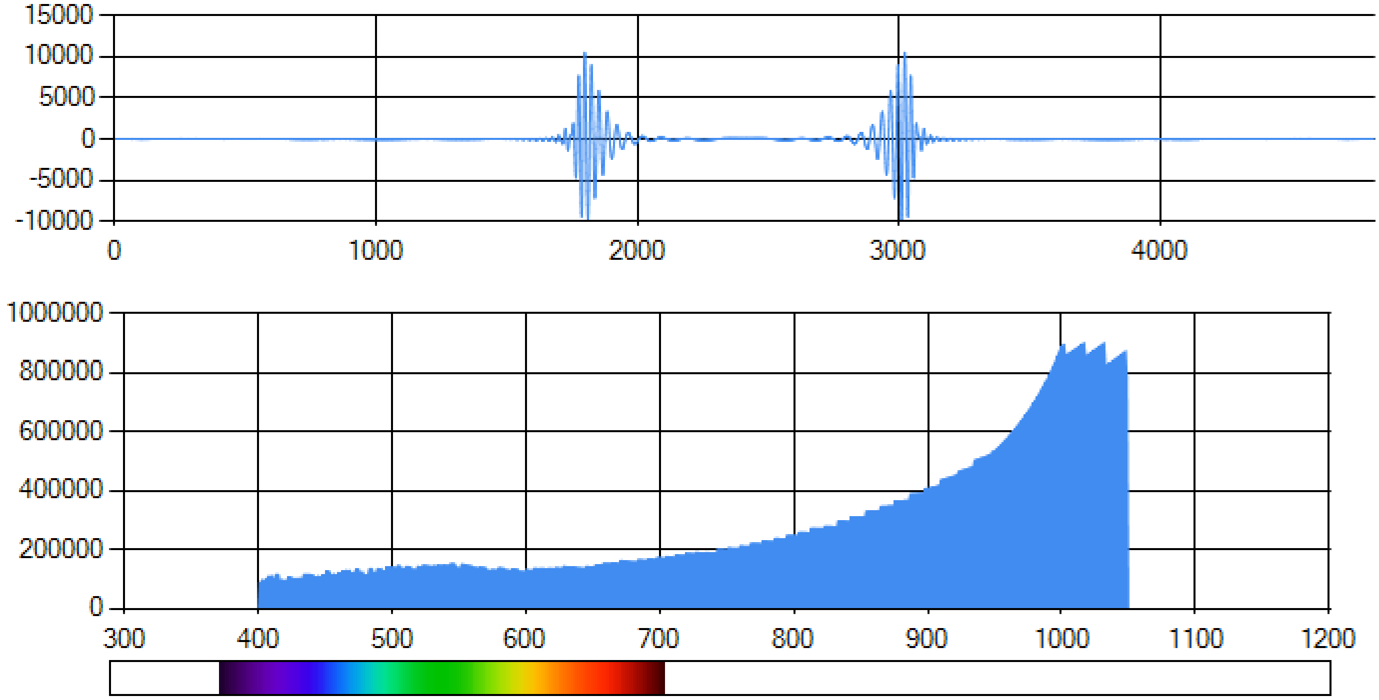
Band-bass filter: Green

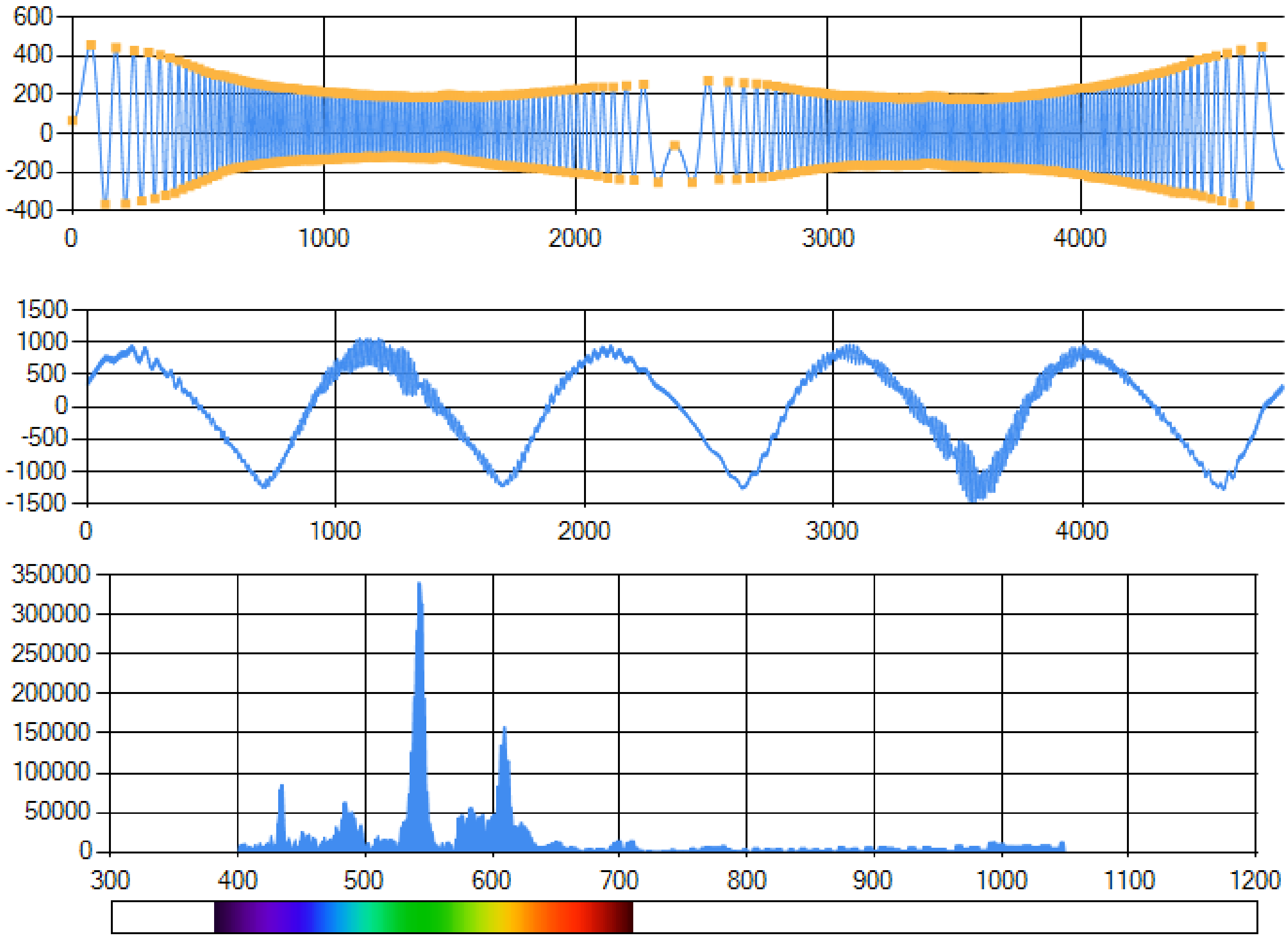


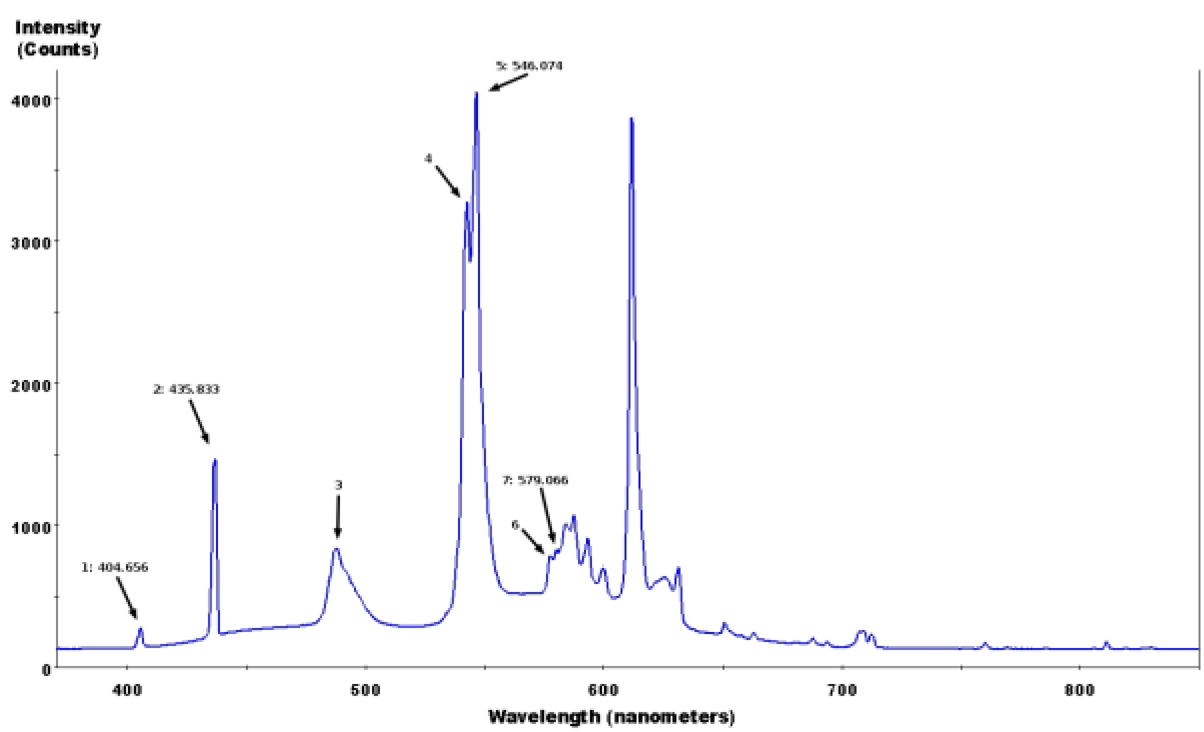
Band-pass filter: Red

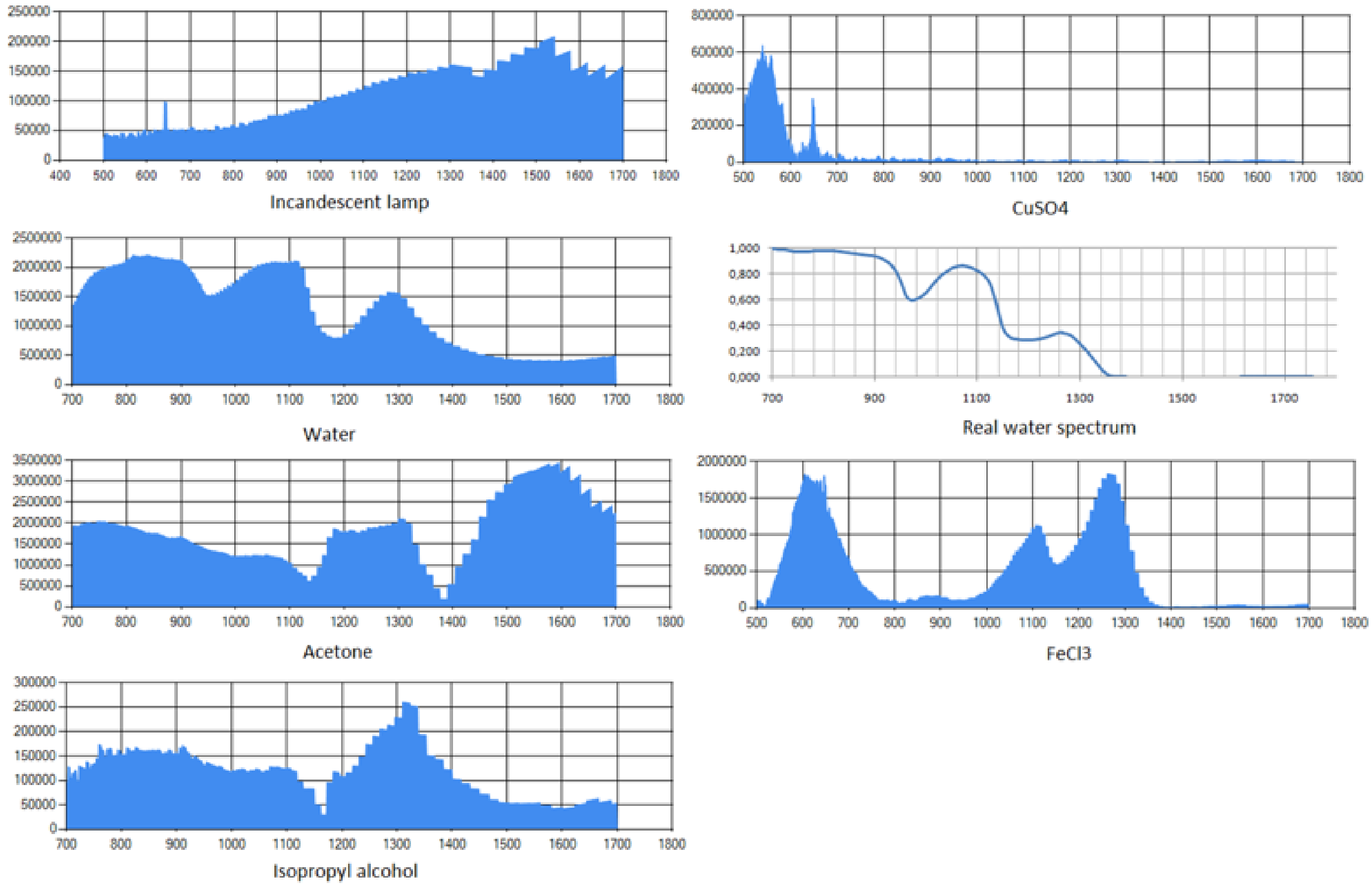


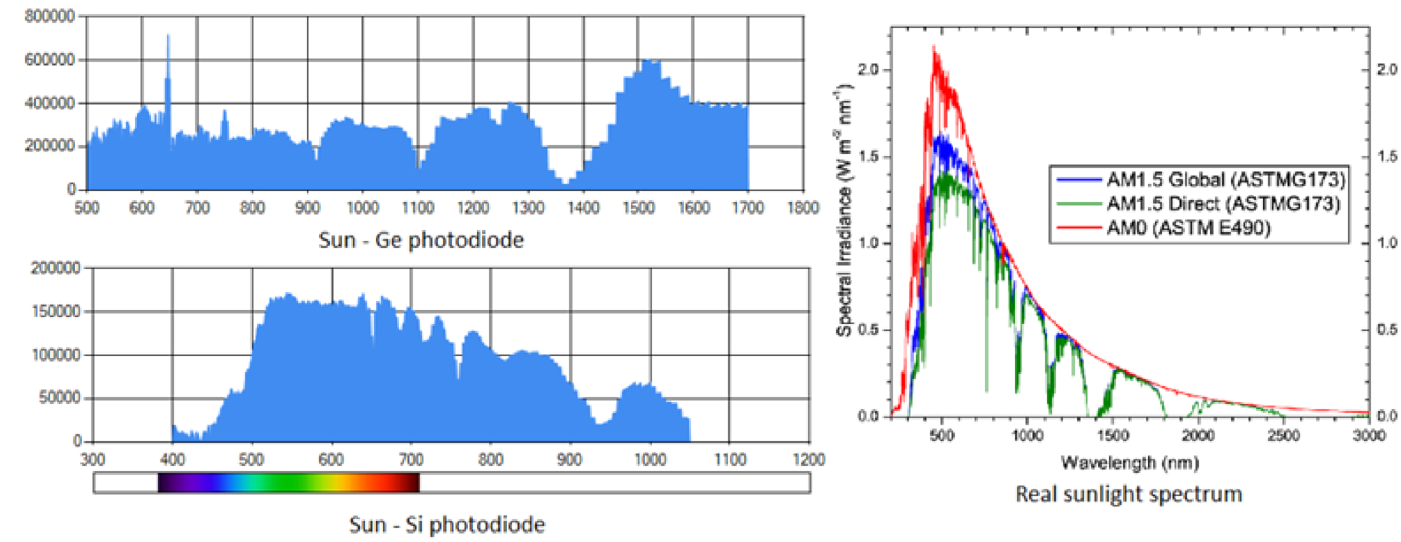
IR cut filter


15000
10000
5000
0
-5000
-10000
0
1000
2000
3000
4000
1000000
800000
600000
400000
200000
0
300
400
500
600
700
800
900
1000
1100
1200


600
400
200
0
-200
-400
0
1000
2000
3000
4000
1500
1000
500
0
-500
-1000
-1500
350000
300000
250000
200000
150000
100000
50000
300
400
500
600
700
800
900
1000
1100
1200


Intensity
(Counts)
4000
3000
2000
1000
0
5: 546.074
4
2: 435.833
3
7: 579.066
6
1: 404.656
400
500
600
700
800
Wavelength (nanometers)


Incandescent lamp
CuSO4
Water
Real water spectrum
Acetone
FeCl3
Isopropyl alcohol



The uneven shape of the spectrum is due to the absorption of solar radiation by substances contained in the atmosphere. On the right is the real shape of the spectrum. The shape of the spectrum obtained by the germanium photodiode is noticeably different from the real spectrum, although the absorption lines are in their places.

Thus, despite all the problems, I still managed to obtain white light interference at home and make a Fourier spectrometer. As you can see, it is not without its drawbacks - the spectra are somewhat crooked, the resolution is even worse than that of some homemade spectrometers with a diffraction grating (primarily due to the small stroke of the movable mirror). But nevertheless - it works!

Program for processing the interferogram

Tags: Fourier, spectrometer, optics, fft

Hubs: DIY, Electronics for Beginners

303 Karma

0.5 Rating

@iliasam

Microcontroller programmer

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