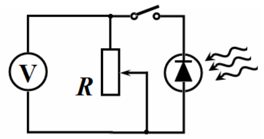
SOLUTION TO THE EXPERIMENTAL COMPETITION

Absorption of light (15,0 балла)

Part 1. Studying a photodetector



1.1 The working measurement circuit is shown in the figure on the right. When the switch is shortened, the multimeter should be switched to the voltage measurement mode, i.e. the voltage across the resistor is measured. When the switch is open, the multimeter should be switched to the ohmmeter mode, the resistance is measured.

1.2 – 1.5 The results of the measurement of the voltage across the resistor as a function of its resistance are shown in Table 1. It also presents the results of calculations of the current using the formula

$$I = \frac{U}{R} \tag{1}$$

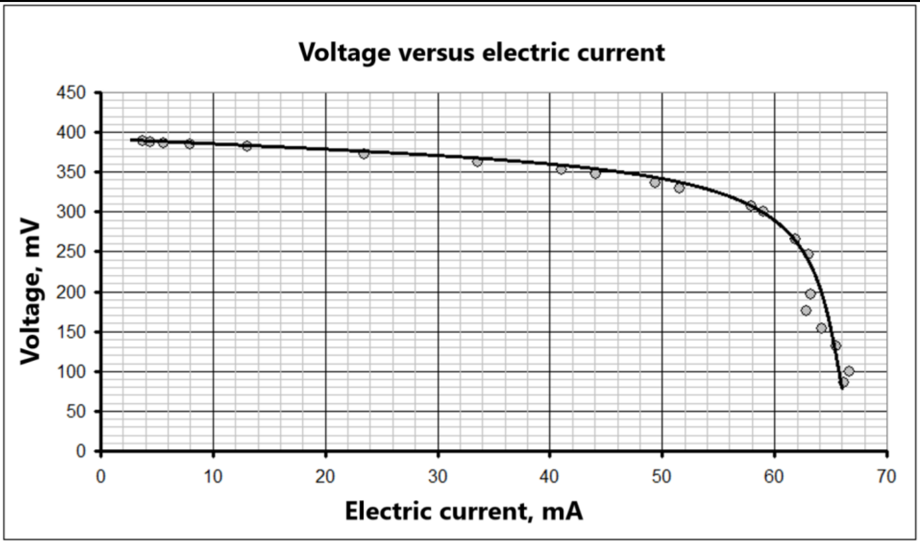
and the heat power generated in the resistor and calculated via the expression

$$P = UI = I^2 R = \frac{U^2}{R} \tag{2}$$

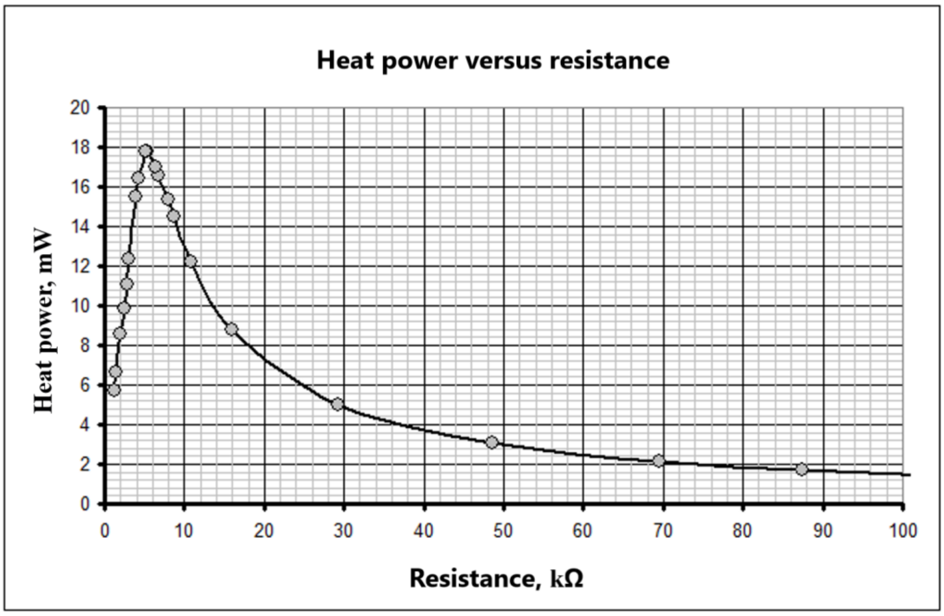
Table 1

R, kΩ	*U, mV*	*I, μA*	*P, μW*
104	389	3,74	1,46
87,4	388	4,44	1,72
69,5	387	5,57	2,15
48,5	385	7,94	3,06
29,3	382	13,04	4,98
15,9	373	23,46	8,75
10,8	363	33,61	12,20
8,6	353	41,05	14,49
7,9	348	44,05	15,33
6,8	336	49,41	16,60
6,4	330	51,56	17,02
5,3	307	57,92	17,78
5,1	301	59,02	17,76
4,3	266	61,86	16,45
3,9	246	63,08	15,52
3,1	196	63,23	12,39
2,8	176	62,86	11,06
2,4	154	64,17	9,88
2	131	65,50	8,58
1,5	100	66,67	6,67
1,3	86	66,15	5,69

The graph of the voltage across the resistor versus its current is shown in the figure below.



The graph of the heat power in the resistor versus its resistance is shown in the figure below.



To determine the position of the maximum, it is necessary to take additional measurements in the range of 0 to 10 kΩ. According to the measurement results, it turns out that the maximum heat power generated in the resistor is reached at

$$R = 5,4k\Omega\,. \tag{3}$$

Part 2. Absorption of laser radiation

2.1 Since the transmittances of the same type of light filters are equal, and the laser radiation is monochromatic, the dependence of the transmitted light intensity on the number of filters has the form of a geometric progression

$$I_n = k^n I_0\,. \tag{4}$$

2.2 The results of measurements of the dependence of the light intensity on the number of filters are given in Table 2. The measurements have been carried out at the resistance of 3.3 kΩ.

Table 2

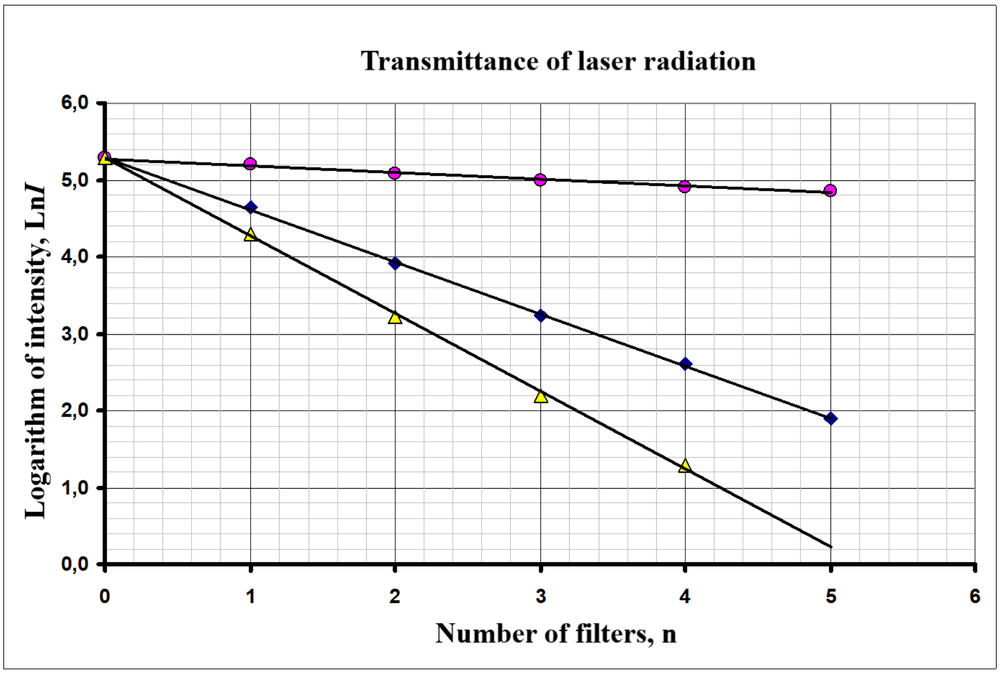
	grey filter	yellow filter	blue filter		grey filter	yellow filter	blue filter
n	*U, mV*	*U, mV*	*U, mV*	*n*	*Ln U*	*Ln U*	*Ln U*
0	196	197	197	0	5,28	5,28	5,28
1	104	180	74	1	4,64	5,19	4,30
2	50	161	24,9	2	3,91	5,08	3,21

3	25,4	148	9	3	3,23	5,00	2,20
4	13,6	135	3,6	4	2,61	4,91	1,28
5	6,6	128		5	1,89	4,85	

To verify formula (4) it is convenient to present it in the semi-log scale as

$$\ln I_n = \ln I_0 - n \ln k \,. \tag{5}$$

At such a scale, the dependence of $\ln I_n$ on the number n of light filters should be linear. The measurements and calculations confirm this conclusion, i.e. formula (4) correctly describes the intensity of the transmitted light. The figure below shows the results obtained.



2.3 As it follows from formula (5), the slope of the dependence is equal to the logarithm of the transmittance

$$a = \ln k \,, \tag{6}$$

therefore, the transmittance is calculated by the formula

$$k = \exp(a) \,, \tag{7}$$

and its error is determined by the expression

$$\Delta k = \exp(a) \cdot \Delta a \,, \tag{8}$$

Table 3 shows the results of calculations (using the least squares method) of the slope coefficients a, their errors Δa, the transmittances k and their errors Δk for all three types of light filters.

Table 3

	grey filter	yellow filter	blue filter
a	-0,678	-0,089	-1,011
Δa	0,014	0,008	0,032
k	0,508	0,915	0,364
Δk	0,007	0,007	0,012

2.4 The transmittance of a pair of filters for the laser monochromatic radiation is equal to the product of the transmittances of each filter:

$$k_{1,2} = k_1 \cdot k_2 \tag{9}$$

Table 4 shows the measured and calculated transmittances for all pairs. As it follows from the data presented, there is a good agreement between these results, i.e. formula (9) is experimentally verified.

Table 4

Pair of filters		measured		calculated
blue + yellow		0,342		0,333
blue + grey		0,187		0,185
yellow + grey		0,460		0,464

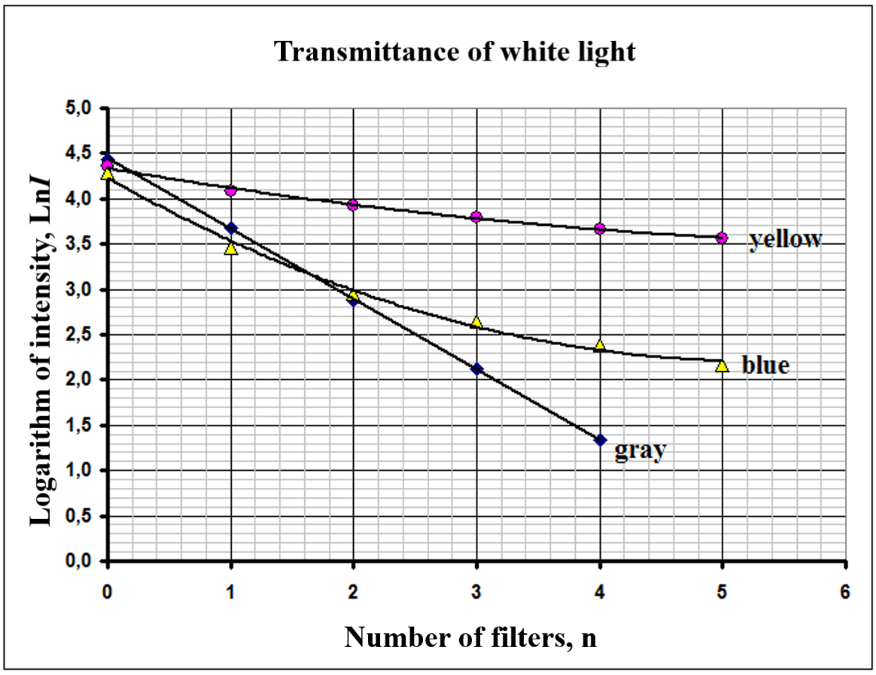
Part 3. Absorption of white light

3.1 The results of measurements of the light intensity transmitted through the filters are shown in Table 5. (the measurements have been made with the resistance of 10.1 kΩ).

Table 5

	grey filter	yellow filter	blue filter		grey filter	yellow filter	blue filter
n	*U, mV*	*U, mV*	*U, mV*	*n*	*Ln U*	*Ln U*	*Ln U*
0	84,8	77,8	72,6	0	4,44	4,35	4,28
1	39,4	59,4	31,7	1	3,67	4,08	3,46
2	17,9	50,8	19,2	2	2,88	3,93	2,95
3	8,4	44,5	14	3	2,13	3,80	2,64
4	3,8	39,2	10,8	4	1,34	3,67	2,38
5		35	8,7	5		3,56	2,16

The graphs of these dependencies are shown in the figure below.



3.2 It can be seen from the graph that formula (5) is correct for grey filters, but not for blue ones. The main reason for the violation of the obtained law is that the transmittance significantly depends on the wavelength of incident light. So, for grey filters, the transmittance varies little in the visible range of wavelength and formula (5) is applicable within the experimental error. For blue filters, though, the transmittance varies noticeably, such that formula (5) turns inapplicable.

3.3 The measured transmittances for the three light filters provided are given in Table 6.

Table 6

grey filter	0,450
blue filter	0,431
yellow filter	0,759

Table 7 shows the measured and calculated transmittances of pairs of light filters. It can be seen that for the white source the transmittance of a pair of filters is not equal to the product of transmittances of each filter, which is prescribed to the dependence of transmittances on the wavelength.

Table 7

Pair of filters		measured		calculated
blue + yellow		0,271		0,327
blue + grey		0,188		0,194
yellow + grey		0,362		0,342

Marking scheme

Part	Content	Total for part	Points
Part 1. Studying a photodetector		**6,0**	
1.1	Switch in the right place	**0,2**	0,2
1.2	Measurements $U(R)$: ***Marked only if data are within 50% from the provided in the official solution:*** - maximumal voltage no more than 350 mV; - maximumal resistance no more than 90 kΩ; - minimal resistamce less than 2 kΩ; - number of points 15 or more *(10-14, 7- 9, less)*; - not less than 5 points in the range of 0-10 kΩ; - monotonically dcreasing dependence; - units stated correctly (kΩ. mV);	**3,5**	 0,2 0,2 0,2 2(*1;0,5;0*) 0,5 0,2 0,1+0,1
1.3	Load characteristic: (***marked only if 1.2 had been marked)*** - formula to calculate electric current; - current calculated for all experimental points; - unit of current stated (μA); - correct qualitative behavior (slow decrease followed by sharp decline); Plotting a graph: - axis named and ticked; - all points correctly drawn; - smooth curve drawn;	**0,9**	 0,1 0,2 0,1 0,2 0,1 0,1 0.1
1.4	Heat power versus resistance: (***marked only if 1.2 had been marked)*** - formula to calculate heat power; - heat power calculated for all experimental points; - correct unit of heat power (μW); - correct qualitative behavior (maximum in the rage of 0-10 kΩ followed by slow decrease); Plotting a graph: - axis named and ticked; - all points correctly drawn; - smooth curve drawn;	**0,9**	 0,1 0,2 0,1 0.2 0,1 0,1 0,1
1.5	Maximum found In the range of 5-6 kΩ (*4-7* kΩ, *out of*)	**0,5**	0,5(*0,3;0)*
Part 2. Absorption of laser radiation		**5,5**	
2.1	Formula $I_n = k^n I_0$	**0,2**	0,2
2.2	Transmittance measurements	**2,6**	

	Marked only if data are within 50% from the provided in the official solution:		
	- Measurements in the range of 0-200 mV;		0,1
	- Initial measurement without filters;		0,1x3=0,3
	- measurements with 5 (4) filters;		0,3x3=0,9
	- decreasing dependence obtained;		0,1x3=0.3
	Linearization		
	- Correct semi-log scale;		0,2
	- logarithns calculated for all points;		0,2
	Plotting a graph **(marked only if measurements had been marked)**::		
	- axis named and ticked;		0,1
	- all points correctly drawn;		0,1
	- straight line drawn;		0.1
	Linear dependence obtained;		0,3
2.3	Formula for the transmittance $k = \exp(a)$	**1,4**	0,1
	Formula for the experimental error $\Delta k = \exp(a) \cdot \Delta a$;		0,1
	Calculations for all points (LSM, averaging);		0,3
	(Calculations for 2 points only);		*0,1*
	Transmittances found:		
	Gray in the range of 0,45-0,55 (*0,4 -0,6; out of*)		0,2*(0,1;0)*
	Yellow in the range of 0,85-0,95 (*0,8-0,98; out of*)		0,2*(0,1;0)*
	Blue in the range of 0,30-0,40 *(0,25-0,45; out of*)		0,2*(0,1;0)*
	Experimntal errors found		0,1x3=0,3
2.4	Measurement of transmittance	**1,3**	
	Gray+yellow in the range of 0,30-0,40 (*0,25-0,45; out of)*		0,2*(0,1;0)*
	Blue+gray in the range of 0,15-0,25 (*0,10-0,30; out of)*		0,2*(0,1;0)*
	Gray +yellow in the range of 0,40-0,50 *(0,35 – 0,55; out of);*		0,2*(0,1;0)*
	Formula $k_{1,2} = k_1 \cdot k_2$;		0,1
	Products found;		0,1x3=0,3
	Experimental results agree with the theory;		0.1x3=0,3
Part 3. Absorption of white light		**3,5**	
3.1	Transmittance measurements	**1,9**	
	Marked only if data are within 50% from the provided in the official solution:		
	- Measurements in the range of 0-100 mV;		0,1
	- Initial measurement without filters;		0,1x3=0,3
	- measurements with 5 (4) filters;		0,2x3=0,6
	- logarithns calculated for all points;		0,3
	Plotting a graph **(marked only if measurements are marked)**:		
	- axis named and ticked;		0,1
	- all points correctly drawn;		0,1
	- smooth curve drawn;		0,1
	Linear dependence for gray filter;		0,1
	Nonlinear dependence for blue filter		0,2
3.2	Theroretical formula not confirmed	**0,3**	0,1
	Reason: transmittance depends on the wavelength		0,2
3.3	Transmittance measurements	**1,3**	
	Gray filter in the range of 0,4-0,5 (0,35-0,55; out of)		0,2*(0,1;0)*
	Blue filter in the range of 0,4-0,5 (0,35-0,55; out of)		0,2*(0,1;0)*
	Yellow filter in the range of 0,7 – 0,8 (0,65 – 0,85; out of)		0,2*(0,1;0)*
	Blue+yellow filters in the range of 0,22-0,3 (0,18 -3,5;out of)		0,2*(0,1;0)*
	Blue+gray filters in the range of 0,14-0,23 (0,1 -0,27;out of)		0,2*(0,1;0)*

	Yellow+gray filters in the range of 0,3 – 0,4 (0,25 – 0,45; out of) Experimental and theoretical transmittances do not coincide		0,2*(0,1;0)* 0,1
	TOTAL	**15**	