

Laboratory work No. KE – 2

## Research of the free-running solid-state Nd:YAG laser

Methodical instructions



**Attention! Laser radiation sources are used during work – it is necessary to familiarize and strictly follow the respective rules of safety**



**It is necessary to use laser safety goggles**

### **Purpose of the experiment**

Investigate the Nd:YAG laser operation in the free-running mode and measure its radiation characteristics.

### **Experiment tasks**

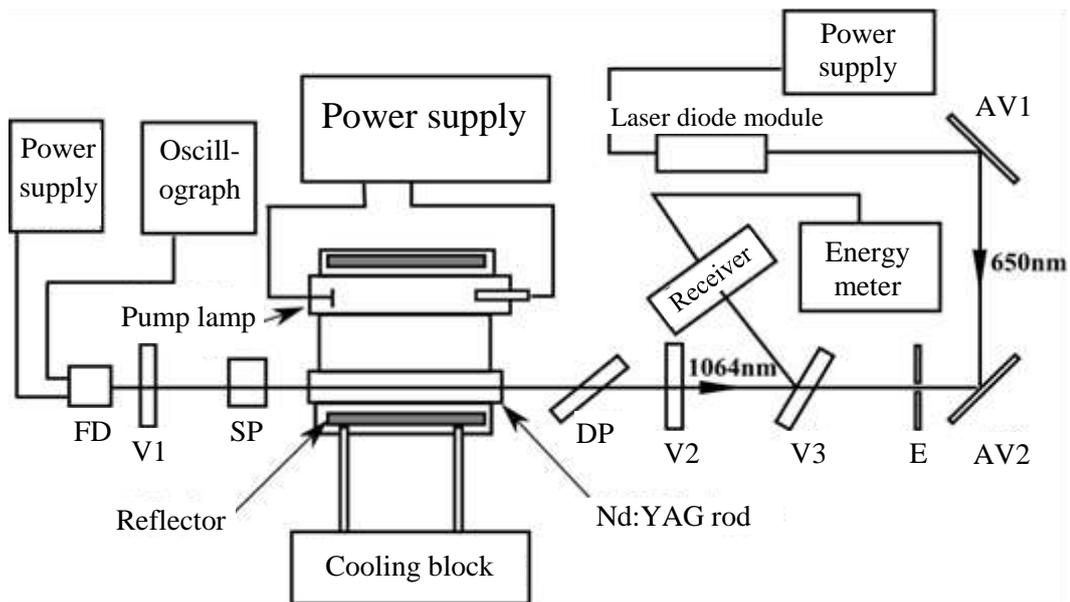
1. Align the Nd:YAG laser with the output coupler which has reflectivity of 84% using the alignment laser diode module.
2. Determine the free-running mode threshold energy.
3. Measure the generated pulse energy dependence on pump energy.
4. Measure the generation threshold dependence on losses in the resonator.
5. Determine the optimal reflectivity coefficient of the output coupler (part 1).
6. Repeat tasks 1-3 using the output coupler with reflectivity of 44%.
7. Repeat tasks 1-3 using the output coupler with reflectivity of 24%.
8. Determine slope efficiencies of the laser.
9. Determine the amount of void losses in the resonator.
10. Determine K coefficient, calculate the weak signal amplification coefficient  $g_0$  and the single-pass amplification coefficient  $G_0$ .
11. Determine optimal reflectivity coefficient of the output coupler (part 2).
12. Estimate pump efficiency.
13. Calculate the threshold inversion and the inversion population depletion coefficient.
14. Determine saturation energy flux.

### **Theoretical topics**

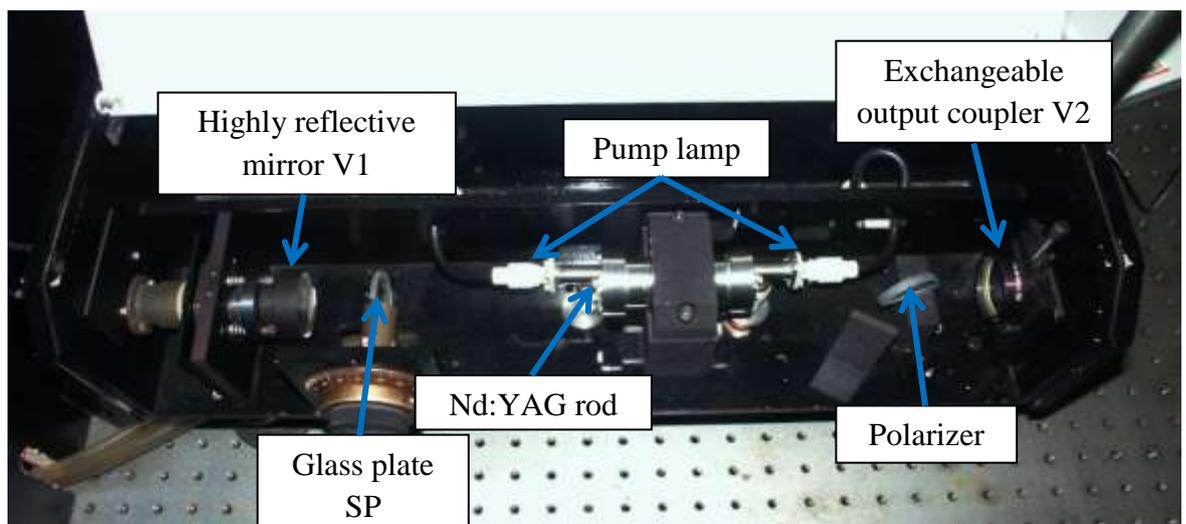
1. Energy level diagram of Nd ions in YAG matrix.
2. How is population inversion implemented in Nd:YAG laser?
3. What is free-running mode?
4. What is laser slope efficiency?
5. Temporal parameters of the free-running mode laser.
6. Factors determining optimal output coupler reflection coefficient.
7. Laser efficient operation coefficient.
8. Pump lamps.

### Equipment and materials

Optical setup of the laser system is depicted in Fig. 1. The laser medium is  $\text{Ø}4 \times 65 \text{ mm}$  size Nd:YAG rod with 1.1%  $\text{Nd}^{+3}$  concentration. The laser rod is pumped with a xenon flash-lamp INP-5/60. The laser resonator consists of a flat highly reflective (99.6%) mirror V1 and a flat output coupler V2. Three different reflectivity output couplers are used: No. 1 - 84%; No. 2 - 44%; No. 3 - 24%. A dielectric polarizer (DP) is placed in the resonator to achieve polarized laser radiation. It is oriented such that the electric field vector of the generated light oscillates in the horizontal plane. For loss tuning a glass plate SP is placed in the resonator. When the plate is rotated around the axis in the horizontal plane, the angle of incidence increases which in turn causes greater light reflection from the plate and increases resonator losses.

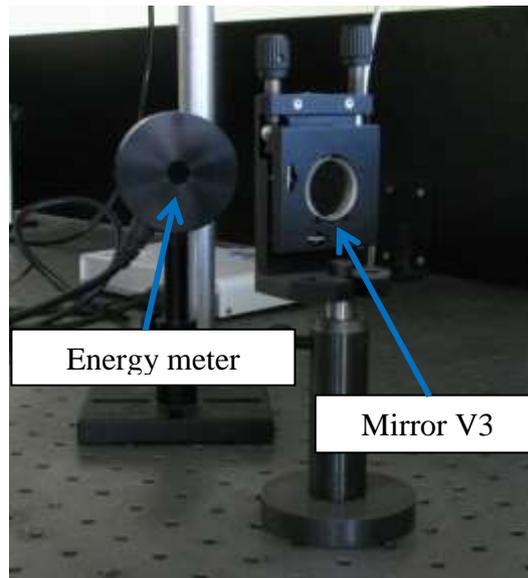


**Fig. 1:** Principal view of the experimental setup.



**Fig. 2:** The free-running mode laser.

The generated laser radiation, after passing the output coupler and reflected from the highly reflective (99.6%) mirror V3, is directed to an energy meter sensor (Fig. 3). The meter measures the generated pulse energy. A part of the pump lamp and the generated laser radiation which leaves through the mirror V1 goes to the photodiode FD - 24 K and is used for estimation of the pump flash and the generated laser pulse parameters and the indication of laser generation. The electric signal form the photodiode is observed on the oscillograph screen.



**Fig. 3:** Mirror V3 and energy meter.

A laser diode module emitting 650 nm wavelength radiation is used for the laser mirror alignment. After reflection from two aluminium mirrors AV1 and AV2, the laser diode module beam is directed to propagate along the axis of the laser resonator. The mirror V3 is transparent for laser diode radiation while the mirrors V1 and V2 are semi-reflective. The alignment of the investigated laser is performed by observing positions of reflections from mirrors on the screen E.

## Preparation of the energy meter for work

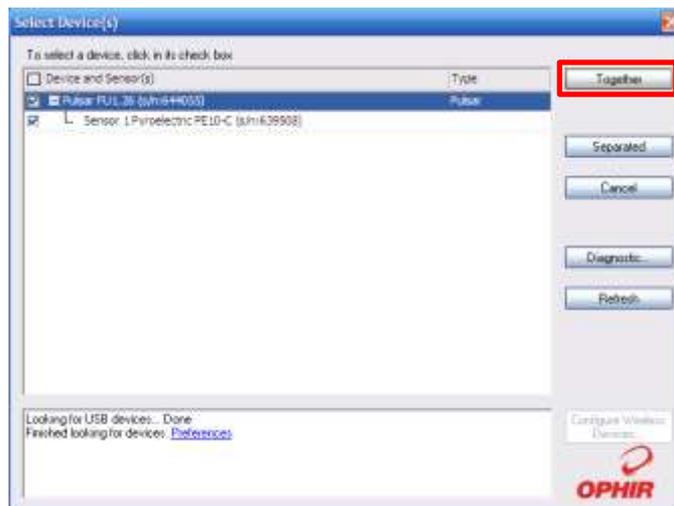
Connect the sensor to the sensor input on the USB interface PULSAR. Connect the PULSAR device to the computer via USB. Connect the 12V power cable to the main line and to the 12VDC input on the device. The POWER/LINK LED lights.



**Fig. 4:** Laser radiation energy meter.

## Software instructions

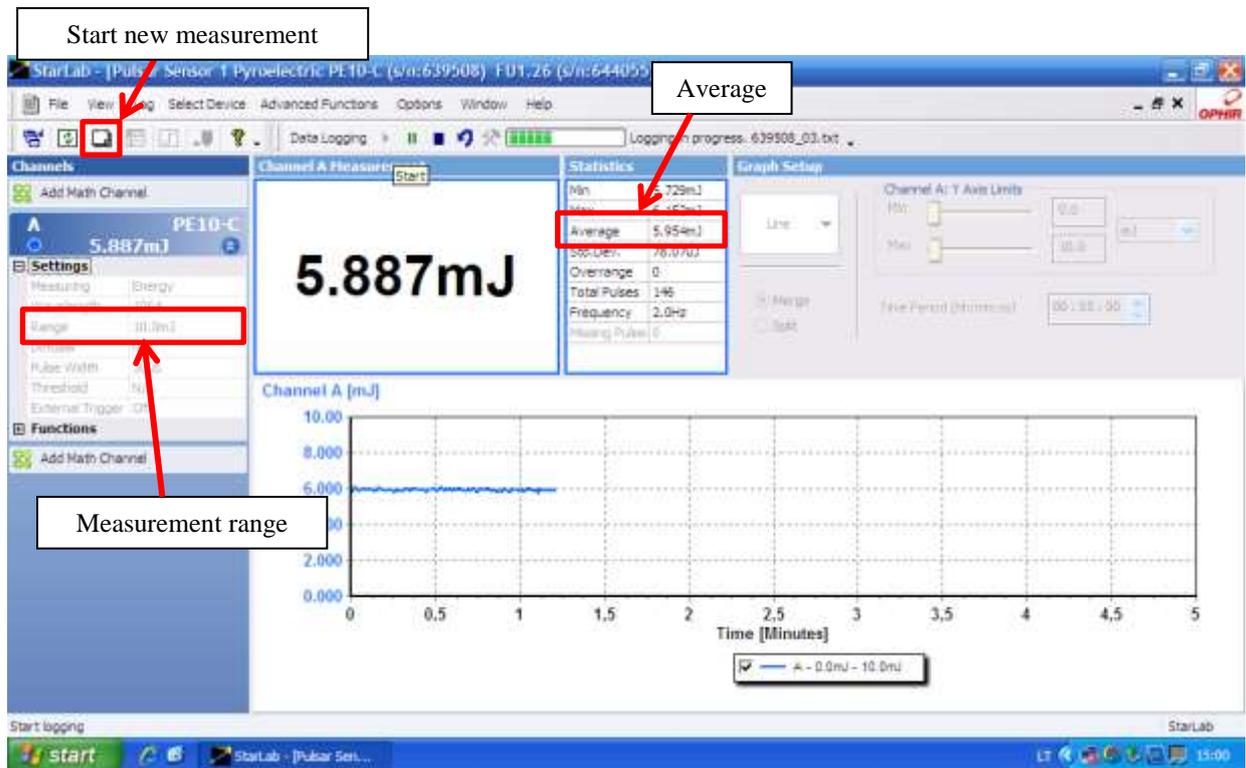
Start the StarLab application by clicking the StarLab icon  on the desktop. The main window and **Select Device(s)** window are opened. Select the device to be used by clicking in the choice box. Then press **Together** or **Separated**.



**Fig. 5:** Energy meter detector selection window.

The application window with **Channels**, **Channel ... Measurement**, **Statistics**, **Data Logging** and **Graph setup** tabs opens. In **Together** mode when more than one device is selected, each device gets a channel, but they appear together in one graphic window. In

**Separated** mode each device gets a separate graphic window. In **Together** mode a user can also create an additional channel to perform mathematical operations with the measured data (press **Add Math Channel**). In the **Settings** tabs a user can select to measure a power or an energy (in this case **Measuring: Energy**), set the wavelength (**Wavelength: 1064 nm**), the range of measurement (**Range**), the pulse duration (in this case set **Pulse Width: 1 ms**). In the numeric display tab (**Channel ... Measurement**) energy meter readings are displayed as numeric value. In the graph display tab the energy meter readings are displayed as a plot. In the graph display settings tab (**Graph Setup**) a user can set various display parameters: time limits, the energy range.



**Fig. 6:** Main StarLab window.

In the statistics tab (**Statistics**) are displayed: **Min** - the minimum measurement taken, **Max** – the maximum measurement taken, **Average** – the average measurement taken, **Std. Dev.** – the standard deviation value, **Overrange** – the number of readings that were over the maximum value for the chosen range, **Total Pulses** – the total number of measurement taken, **Frequency** – the frequency at which the laser is firing and **Missing Pulses** - the number of missed pulses when using the External Trigger. In the registration tab (**Data Logging**) the registration file is configured and data registration is launched/stopped.

The average value (**Average**) should be use for measurements. A new measurement is started by pressing . The measurement range (**Range**) is set during the measurement. The

measured pulse energy cannot be higher than the maximum value for the chosen range or lower than the maximum value for the lower range (Table 1).

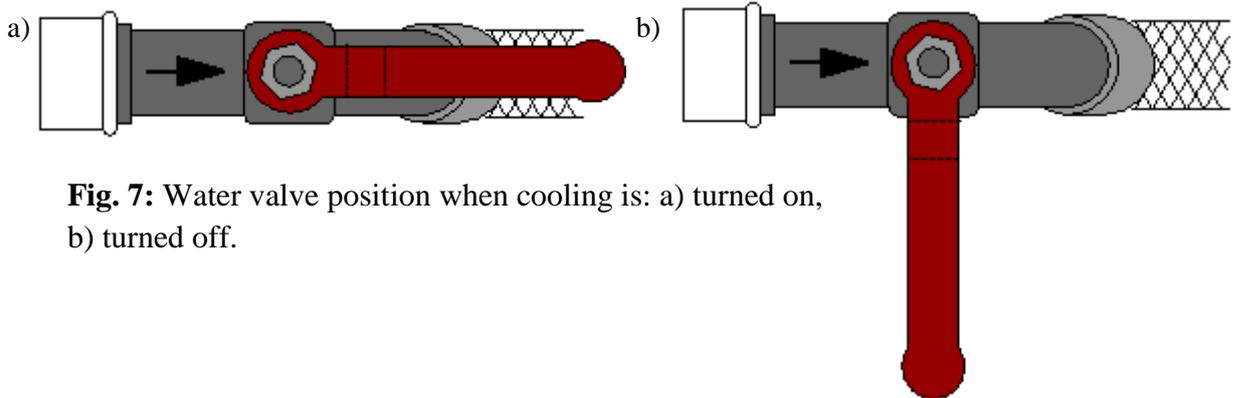
**Table 1.** The measurement range and corresponding pulse energies.

Range	Pulse energy
200 mJ	>15 mJ
20 mJ	15 mJ - 1.5 mJ
2 mJ	<1.5 mJ

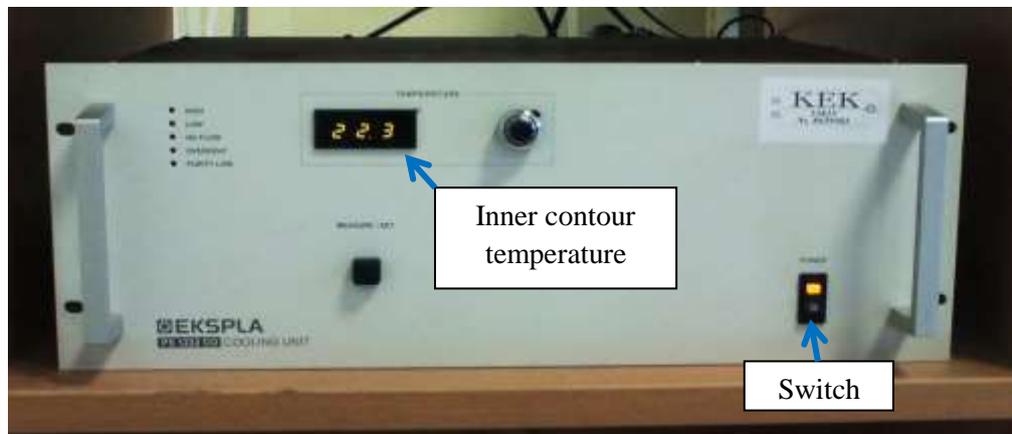
## Experiment procedure

### Preparation of the equipment

- Rotate the water valve which is connected to the laser cooling block (Fig. 7).



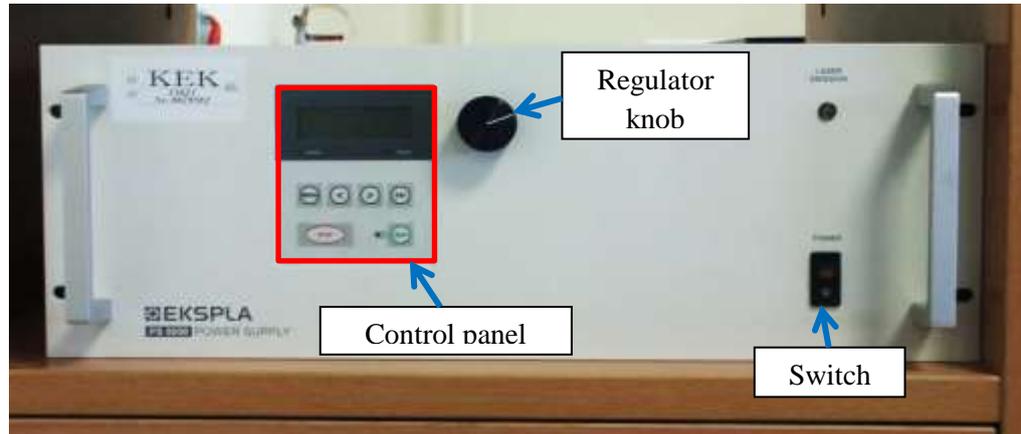
**Fig. 7:** Water valve position when cooling is: a) turned on, b) turned off.



**Fig. 8:** The laser cooling block.

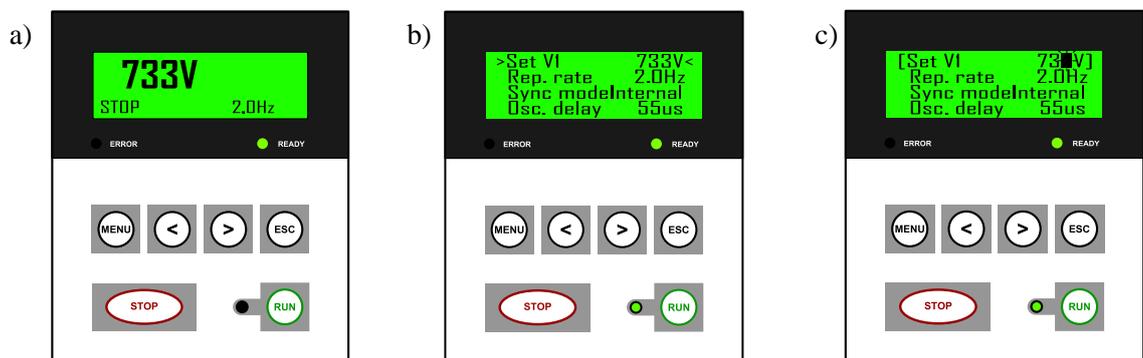
- Make sure that the laser cooling block is connected to electricity. Turn on the cooling block: set the switch on the front side of the block to “POWER” position “I” (Fig. 8).
- Make sure that the water is circulating in the inner contour of the cooling block. Wait for ~1 minute until the pump starts pumping the water through the laser head.
- Connect the socket “Fotodiodo maitinimas 9V” which is on the laser block with the photodiode power supply box. Turn on the photodiode power supply by switching to the position “I”.
- Turn on the oscillograph.
- Connect the socket "Fotodiodo signalas" which is on the laser block with the oscillograph channel 1 input socket.

- Connect the energy meters to USB interface PULSAR-2 which is then connected to the computer. Turn on USB interface power supply.
- Turn on the computer and launch **Starlab**  software.
- Turn on the laser power supply by pressing the “POWER” switch. Indicator lamps “READY” and “LASER EMISSION” on the power supply should turn on (Fig. 9).



**Fig. 9:** Laser power supply.

- To set the voltage for the laser pump lamp, press button “MENU” in the power supply panel (Fig. 10 a) and b)). By turning and pressing the knob select “Set V1” - the lowest value voltage number starts flashing (Fig. 10 c)) - the voltage can be increased or decreased with 1 V accuracy by turning the knob clockwise or counterclockwise. To adjust the voltage with 10 V or 100 V accuracy, use buttons “<” and “>” select tens or hundreds significant digit (the selected digit starts flashing).



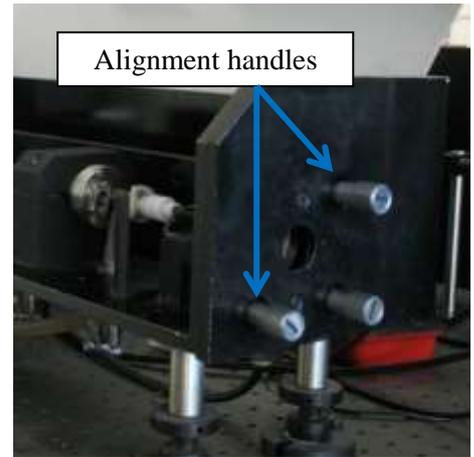
**Fig. 10:** The laser power supply panel: a) when power supply is turned on, b) when MENU is selected, c) when pump voltage adjustment mode is selected.

**IT IS STRICTLY FORBIDDEN TO CHANGE OTHER POWER SUPPLY SETTINGS!!!**

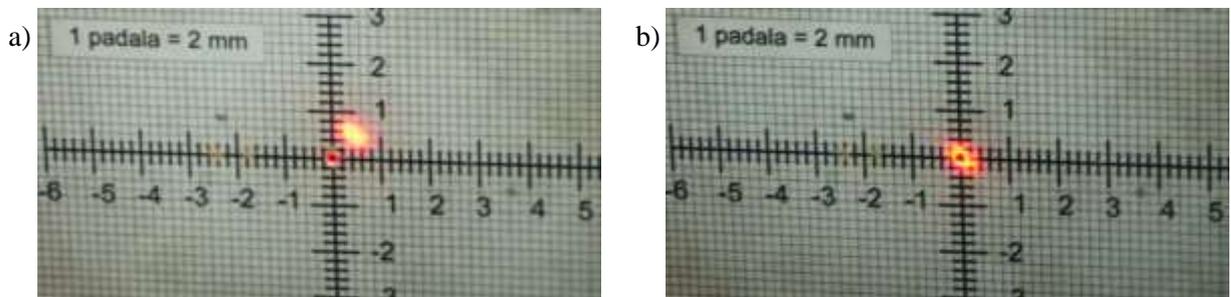
**1. Alignment of the Nd:YAG laser with the 84% reflectivity output coupler using the laser diode module.**

- 1.1. Put the output coupler with 84% reflectivity to the output coupler optical mount.
- 1.2. Turn on the laser diode module.
- 1.3. By using vertical and horizontal optical mount alignment handles (Fig. 11) align the output coupler so that a reflection from it would match the pinhole on the screen E. (Fig. 12).

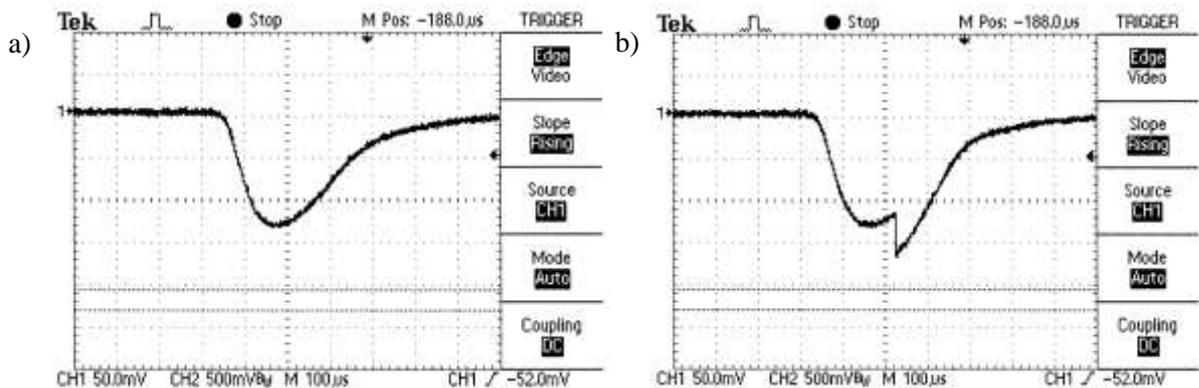
- 1.4. When the “RUN” button is pressed, periodic pump lamp flashing should start. Then the pump voltage should be increased (not exceeding 950 V) until the laser generation starts. Initially, only the pump lamp flash pulse is observed on the oscillograph screen (Fig. 13 a)). When laser generation starts, a short laser pulse adding to the pump pulse and the overall signal looks as depicted in Fig. 13 b).



**Fig. 11:** Laser output coupler alignment handles.



**Fig. 12:** a) the output coupler is not aligned, b) the output coupler is aligned.



**Fig. 13:** Image of the photodiode signal on the oscillograph screen: a) when the laser radiation is not occurring, b) when the laser radiation is occurring.

**2. Estimation of the free-running mode threshold energy.**

- 2.1. When the laser generation is achieved, tune the output coupler such that the short laser pulse would be maximized on the oscillograph screen. Then decrease the pump voltage just above the limit when the laser pulse is still visible on the oscillograph screen and adjust the output coupler again. In such way the lowest pump voltage, for which the laser pulse is still observed on the oscillograph screen, is reached. This is the threshold voltage  $U_{sl}$  of the laser free-running mode.
- 2.2. Calculate the free-running mode threshold energy  $E_{sl}$  (the pump pulse energy is calculated using this formula:  $E_k = \frac{CU^2}{2}$ , here  $C$  – the capacitor battery capacity (in this case  $C = 100 \mu\text{F}$ ),  $U$  – the capacitor voltage which is set with the regulator).

**3. Measurement of the generated pulse energy  $E_L$  dependence on pump energy  $E_K$ .**

- 3.1. Tune the pump voltage by 20 V steps up to 900 V. Using the energy meter measure generated the laser pulse energy. Calculate the pump pulse energy using the aforementioned formula.
- 3.2. Depict measurement results graphically.

**4. Measurement of the generation threshold  $E_{sl}(\varphi)$  dependence on losses in the resonator.**

- 4.1. Losses in the resonator consist of: 1) the output coupler losses, 2) the damper (glass plate) losses which depend on the angle of the plate  $\varphi$  with respect to the resonator axis, 3) losses due to the diffraction and the reflections from laser elements. Losses are tuned with the damper - glass plate SP during the measurement.
- 4.2. While changing the plate rotation angle  $\varphi$  from  $20^\circ$  to  $80^\circ$  (initially by  $10^\circ$  step and from  $50^\circ$  angle by  $5^\circ$  step) and applying the same procedure as in the task 2, measure the threshold energy  $E_{sl}$ . If necessary, adjust the output coupler V2.

**5. Estimation of the optimal output coupler reflectivity coefficient (part 1).**

- 5.1. Set the pump voltage to 700 V.
- 5.2. To estimate the optimal output coupler reflectivity, it is necessary to measure the laser radiation power dependence on the effective reflection coefficient which is tuned by changing the angle of the glass plate  $\varphi$  with respect to the resonator axis.

While changing the plate rotation angle from 20° to 80°:initially by 10° step and from 50° angle by 5° step measure output radiation energy  $E(\varphi)$ .

5.3. Set the pump voltage to 900 V.

5.4. Repeat measurements described in 5.2.

**6. Repeat tasks 1-3 using the output coupler which has 44% reflectivity.**

6.1. Press the “STOP” button to stop the pump lamp power supply. The glass plate SP rotation angle must be set to 0°.

6.2. Repeat tasks 1-3 using the output coupler which has 44% reflectivity.

**7. Repeat tasks 1-3 using the output coupler which has reflectivity of 24 %.**

7.1. Press the “STOP” button to stop the pump lamp power supply. The glass plate SP rotation angle must be set to 0°.

7.2. Repeat tasks 1-3 using the output coupler which has 24% reflectivity.

**8. Estimation of laser slope efficiency.**

8.1. Determine the laser slope efficiency from a linear part of measured  $E_L(E_K)$  curves using the following expression:

$$\eta = \frac{\Delta E_L}{\Delta E_k}, \quad (1)$$

for various reflectivity output couplers.

8.2. Compare slope efficiencies.

**9. Estimation of void losses in the resonator.**

9.1. Using estimated threshold pump energies values for three different output couplers, draw a graph  $-\ln(R_{i\text{sv}}^i \times R_{g+p}) = f(E_{sl})$ , where  $R_{i\text{sv}}^i$  – the reflection coefficient of the  $i$ -th output coupler ( $R_{i\text{sv}}^1 = 0.84$ ;  $R_{i\text{sv}}^2 = 0.44$ ;  $R_{i\text{sv}}^3 = 0.24$ ) and  $R_{g+p}$  – the back mirror reflection coefficient which also takes into account reflection losses when passing the glass plate SP two times. When the glass plate is oriented perpendicular to the resonator axis (a rotation angle is 0°), the coefficient  $R_{g+p}$  is 0.868.  $R_{g+p}$  depends on a rotation angle of the glass plate, therefore pump threshold energies for different output couplers need to be measured when the plate is oriented perpendicular to resonator axis.

9.2. The obtained curve intersection point with y axis (its shows  $-\ln(R_{i\text{sv}}^i \times R_{g+p})$  values) allows estimation of laser inner losses  $-L'$ .

9.3. Using measured threshold pump energies  $E_{sl}(\varphi)$  at various glass plate SP rotation angles  $\varphi$  (task 4 measurements), draw a graph  $-\ln(R_{i\text{sv}}^i \times R_{g+p}(\varphi)) = f(E_{sl})$ . Here  $R_{g+p}(\varphi)$  – the back mirror reflection coefficient at glass plate rotation angle  $\varphi$ .

$R_{g+p}(\varphi)$  values for the glass plate (with the refractive index  $n = 1,44963$ ) used in this laboratory work is presented in Table 2.  $R_{isv}$  in these measurements is 0.84.

**Table 2.**  $R_{g+p}(\varphi)$  at various  $\theta$  and  $\varphi$ .

$\theta^*$ , step	$\varphi$ , °	$R_{g+p}(\varphi)$	$k$
0	0	0.868	1.825
10	20	0.846	1.963
15	30	0.813	2.169
20	40	0.756	2.525
25	50	0.658	3.138
27.5	55	0.587	3.581
30	60	0.499	4.131
32.5	65	0.392	4.800
35	70	0.271	5.556
37.5	75	0.150	6.313
40	80	0.054	6.913

\* - step value on the glass plate SP rotation handle.

9.4. The obtained curve intersection point with y axis (its shows  $-\ln(R_{isv} \times R_{g+p}(\varphi))$  values) allows estimation of laser inner losses  $-L'$ .

9.5. From measured  $L'$  and  $L''$  values, determine average inner laser losses coefficient  $L$ .

### 10. Calculation of $K$ , the weak signal amplification coefficient $g_0$ and the single-pass amplification $G_0$ .

10.1. The coefficient  $K$  is calculated from the inclination of the graph depicting estimated pump threshold energy values for three different output couplers  $-\ln(R_{isv}^i \times R_{g+p}) = f(E_{sl})$  (the task 9) using the expression:

$$2K = \frac{\ln(R_{isv}^1 \times R_{g+p}) - \ln(R_{isv}^2 \times R_{g+p})}{E_{sl}^2 - E_{sl}^1}, \quad (2)$$

here  $E_{sl}^1, E_{sl}^2$  are threshold pump energies at  $R_{isv}^1$  and  $R_{isv}^2$  reflection coefficients.  $K$  is measured in  $J^{-1}$ .

10.2. The weak signal amplification coefficient  $g_0(E_k)$  for various pump energies is calculated using the determined  $K$  values:

$$g_0 l = K \times E_k, \quad (3)$$

here  $E_k$  is the pump energy,  $l$  – the length of the active medium ( $l = 65$  mm).

10.3. The single-pass amplification coefficient  $G_0(E_k)$  for various pump energies is calculated from:

$$G_0(E_k) = e^{g_0 l} . \quad (4)$$

**11. Estimate the optimal output coupler reflectivity coefficient (part 2).**

11.1. With the reference to measurements in the task 5 overall laser radiation energy  $E_v$  can be determined by adding output radiation energy and energy of radiation reflected from the glass plate. During experiments the pulse energy  $E_v$  is determined by multiplying output radiation energy from coefficient  $k$  (it is calculated using Fresnel formulae and presented in Table 2).

11.2. Graphically depict  $E_v = f(R_{isv} \times R_{g+p}(\varphi))$  and determine the optimal output coupler reflection coefficient for both pump energies.

11.3. The optimal output coupler reflection coefficient is calculated using the following formula:

$$R_{1opt} = 1 - \frac{\sqrt{2KE_k L - L}}{1+L} . \quad (5)$$

11.4. Compare calculated optimal reflectivity coefficients.

**12. Estimation of pump efficiency.**

Using the calculated laser slope efficiency  $\eta$ , pump efficiency can be estimated as:

$$\eta_k = \frac{\eta}{\eta_g \eta_s} , \quad (6)$$

here  $\eta_s$  is the efficiency of active medium cross-section utilization (use  $\eta_s = 1$ ) and

$$\eta_g = 2 \frac{1 - R_{isv} \times R_{g+p}}{\sqrt{R_{isv} \times R_{g+p} (L - \ln(R_{isv} \times R_{g+p}))}} , \quad (7)$$

is the feedback efficiency.

**13. Calculate the threshold population inversion  $N_{sl}$  and the population inversion depletion coefficient  $p$ .**

13.1. The population inversion threshold  $N_{sl}$  can be calculated from:

$$N_{sl} = \frac{g_{0s}}{\sigma} , \quad (8)$$

here  $g_{0s}$  is the threshold amplification coefficient,  $\sigma$  - the stimulated emission cross-section which for the Nd:YAG crystal is  $\sigma = 3,5 \times 10^{-19} \text{ cm}^2$ .

13.2. The population inversion depletion coefficient is determined from:

$$p = \frac{N_{sl}}{N}, \quad (9)$$

When the main energy level population  $N = 6 \times 10^{19} \text{ cm}^{-3}$ .

#### **14. Calculation of the saturation energy flux $E_s$ .**

14.1. The saturation energy flux  $E_s$  can be determined in the following way:

$$E_s = \frac{\eta}{\eta_g KA}, \quad (10)$$

here  $A$  is the cross-section of active medium ( $A = 0,125 \text{ cm}^2$ ).

14.2. The obtained value is compared to the value calculated from the following formula:

$$E_s^t = \frac{h\nu}{\sigma}, \quad (11)$$

where  $h\nu = 1,86 \times 10^{-19} \text{ J}$  and  $\sigma = 3,5 \times 10^{-19} \text{ cm}^2$ .

#### **15. Equipment turning off procedure.**

- 15.1. Press "STOP" to turn off the pump lamp power supply.
- 15.2. Press "ESC" to exit the device menu.
- 15.3. Turn off the laser power supply: set the switch "POWER" at the front side of the cooling block to "O" (Fig. 4).
- 15.4. Wait for a few minutes and then turn off the laser cooling block: at the front side of the cooling block to „O“.
- 15.5. Rotate the water valve connected to the outer contour of the laser cooling block (Fig. 3 b)).
- 15.6. Turn off the laser diode module.
- 15.7. Turn off **Starlab** software and the computer.
- 15.8. Disconnect the energy meter power cord.

#### **Literature:**

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