VILNIUS UNIVERSITY
FACULTY OF PHYSICS
STUDIES OF LASERS LABORATORY

Laboratory work **No. NO – 1**

Second optical harmonic generation

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 googles

Vilnius 2018

Purpose of the experiment

Investigate the laser second harmonic generation phenomenon in crystals.

Experiment tasks

1. Construct and align the experimental setup for the second harmonic generation.
2. Measure the pump laser radiation energy characteristics.
3. Measure the second harmonic radiation energy dependence on the crystal orientation close to the phase-matching angle.
4. Measure the second harmonic radiation energy dependence on the incident laser pulse energy for KDP and $LiNbO_3$ crystals.
5. Measure laser radiation energy characteristics when a lens is additionally used.
6. Measure the second harmonic radiation energy dependence on incident laser pulse energy for KDP crystal when a lens is additionally used.
7. Theoretically calculate the second harmonic phase-matching angle and the angular bandwidth and compare it with values extracted from the measurement data.
8. Theoretically calculate the radiation conversion coefficients for KDP ir $LiNbO_3$ crystals and compare them with values extracted from the measurement data.

Theoretical topics

1. In which media is efficient second harmonic generation possible?
2. How are scalar and vector phase-matching implemented?
3. Differences between type I and type II phase-matching.
4. Factors determining second harmonic generation efficiency.
5. Angular, temperature and spectral phase-matching bandwidths.
6. Principles of the quasi-phase matching. Advantages and disadvantages.
7. Methods for production of periodically poled crystals.
8. Periodically poled lithium niobate (PPLN) formations.

Equipment and materials

A mode-locked Nd:YAG laser PL2201 (wavelength is 1064 nm, pulse duration at FWHM is ~30 ps), KDP and $LiNbO_3$ crystals, mirrors, $\lambda/2$ waveplates, polarizers, a beamsplitter, a lens (focal length *f*=500mm), a two channel energy meter, an optical filter (a second harmonic transmittance T=62%), a rotational stage (coarse rotation (up to 360°) and fine rotation (1 micrometer step = 27,3”)), the translation stage at which a screen with vertical slit (width: ~500 μm) is fastened. The coarse rotation of the rotation stage set manually when the tightening screw is loosened. When the rotation stage micrometer is rotated, the screw cannot reach limiting values.

Experiment procedure

The investigation for each task is performed by constructing the experimental setup according to the provided setups.

Attention! Before beginning it is necessary to familiarize with descriptions of the used equipment and work safety features.

Energy meter preparation for work

Connect the sensor to the sensor input on the USB interface PULSAR-2. Connect the PULSAR-2 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.

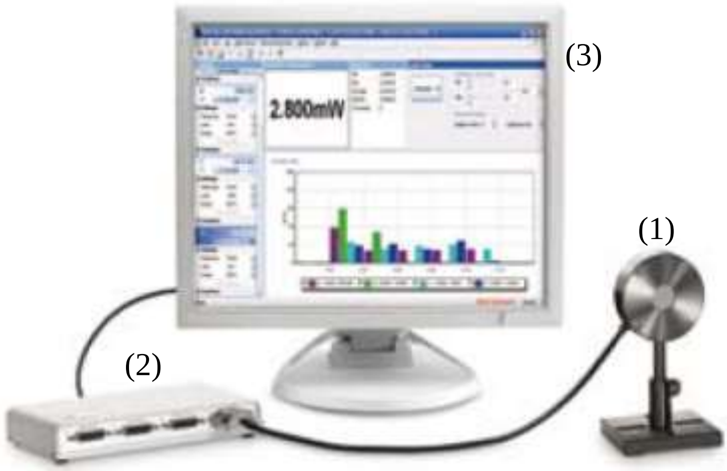


Fig. 1: USB interface PULSAR-2 and energy meter detector.

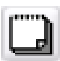
Software instructions

The software is started by double-clicking the **StarLab** icon in the desktop.  Then the main window and **Select Device(s)** window are opened. Then one needs to tick the devices that will be used and then click **Separated**.

Fig. 2: 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 the user can select to measure the power or the energy (in this case **Measuring: Energy**), set the wavelength (**Wavelength: 1064 nm or 532 nm**), the range of the measurement (**Range**), the pulse duration (in this case set **Pulse Width: 1 µs**). 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.

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. The 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

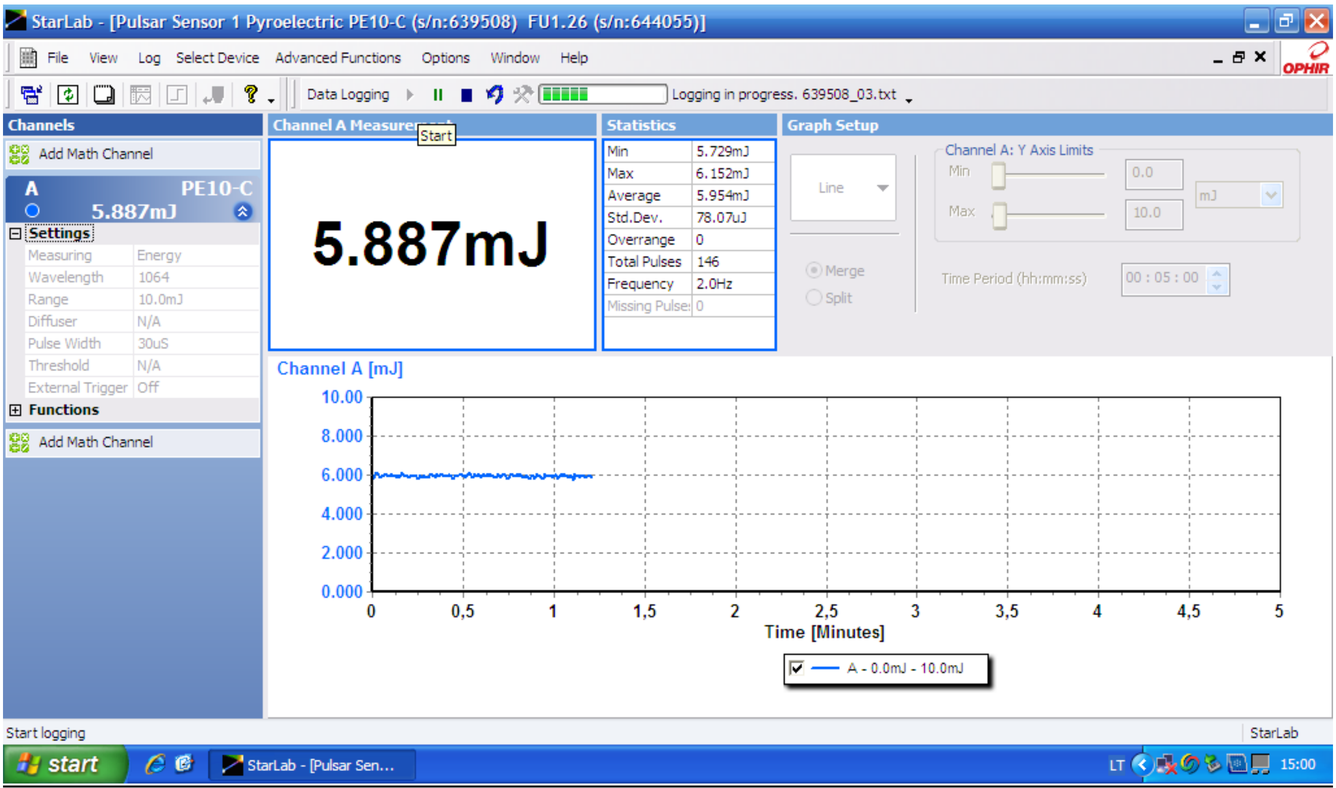


Fig. 3: Main **StarLab** window.

Intructions for turning the laser on/off

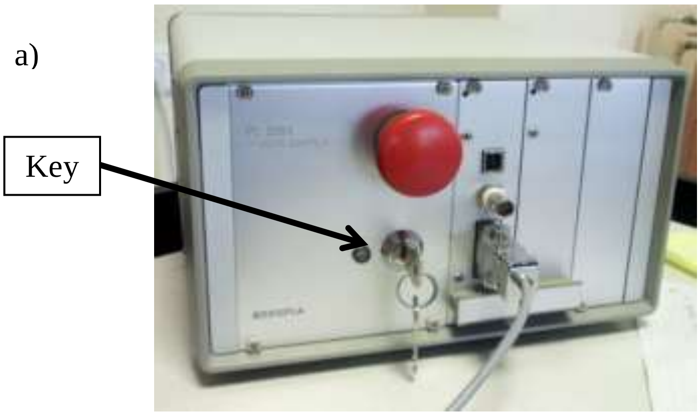
Turning on the laser:

1. Turn on the laser power supply unit: on the rear power supply unit side set the switch to position I. An indicator light **KeySwOff** must appear in the control panel. (Fig. 4).

Fig. 4: a) Laser power supply unit rear side; b) control panel.

2. Turn the key on the front side of the power supply unit clockwise. An indicator light **EMISSION** must turn on in the control panel. (Fig. 5).

a)



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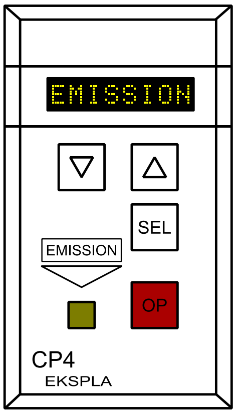
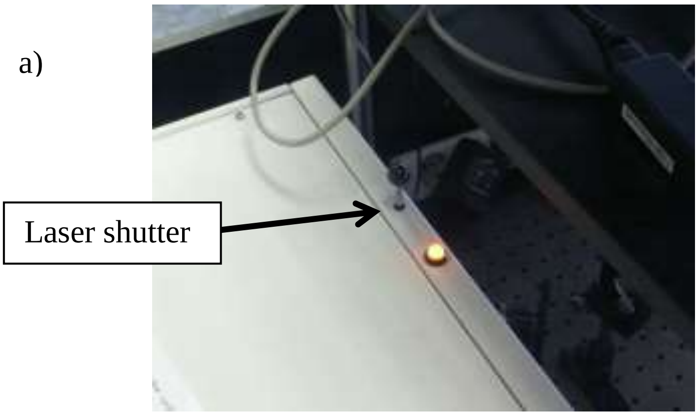


Fig. 5: a) Laser power supply unit front side; b) control panel.

3. Press OP on the laser control panel (Fig. 5 b). When the laser is turned on, an indicator light which is above the radiation output area must turn on (Fig. 6 a) and in the control panel screen **◄ON H52** (the numbers might be different) must appear (Fig. 6 b). Pull the laser shutter upwards – the laser radiation is free to come out of the laser.

a)



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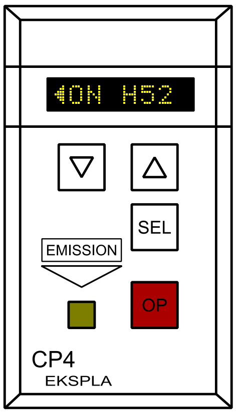
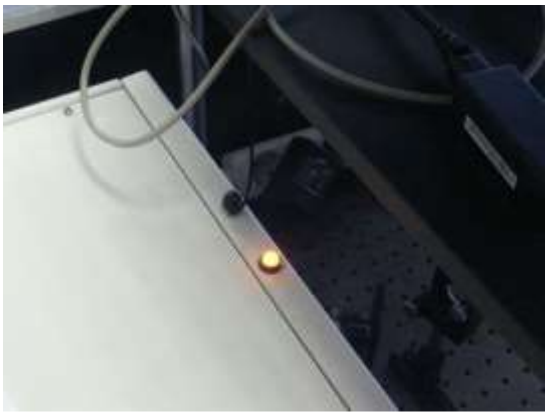


Fig. 6: a) Laser shutter is opened; b) laser control panel when laser is generating.

a)



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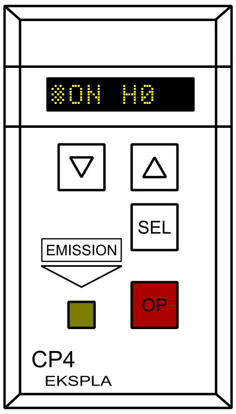


Fig. 7: a) Laser shutter is closed, b) laser control panel when laser generation is stopped.

The laser generation can be stopped by closing the shutter (Fig. 7 a) and pressing OP button again. In laser control panel screen ░**ON H0** must appear (Fig. 7 b).

Turning off the laser:

1. Close the laser shutter.
2. Press the OP button in the laser control panel; **ON H0** must appear in the laser control panel screen.
3. Press the ▽ button in the laser control panel; **standby** must appear in the laser control panel screen.
4. Press the ▽ button in the laser control panel; **sleep** must appear in the laser control panel screen.
5. Turn the key on the front side of the power supply unit counterclockwise.
6. Turn off laser power supply: set the switch on the rear side of the power supply to O.

<u>Measurement procedure</u>

1. Construction and alignment of the second harmonic generation experimental setup.

– Turn on the laser.

– Place and fasten with screws the alignment mirrors DV1 and DV2.

– By aligning mirrors DV1 and DV2 direct the laser beam to propagate along the optical table surface at 130 mm – 140 mm height.

– Align the optical radiation attenuator which consists of the $\lambda/2$ waveplate FP1 and the polarizer P1. The laser beam must propagate through the centers of the optical elements. Leave some space between alignment mirrors and the $\lambda/2$ waveplate for the lens L500. The intensity of radiation is adjusted by rotating the $\lambda/2$ waveplate around its horizontal axis.

– For the generation of the second harmonic laser radiation which polarization is perpendicular to the surface of the optical table will be used. For the adjustment of the laser radiation polarization the $\lambda/2$ waveplate FP2 which is placed after the polarizer P1 will be used. The beam polarization is checked using the second polarizer P2 which is placed after the $\lambda/2$ waveplate FP2. The radiation with polarization perpendicular to the surface of optical table is reflected from the surface of the polarizer. By rotating the $\lambda/2$ waveplate FP2 around its axis and measuring the incident light energy after the polarizer P2, set the beam polarization perpendicular to the surface of the optical table. Then remove the polarizer P2.

– Place and fasten the beamsplitter PD1. The beam needs to be reflected by 45° angle with respect to a normal of the beamsplitter's surface.

– Measure the energy of incident laser light which has passed the beamsplitter dependence on the energy of the reflected radiation for at least 10 different energy values.

2. ***Measurement of the incident laser light characteristics.***

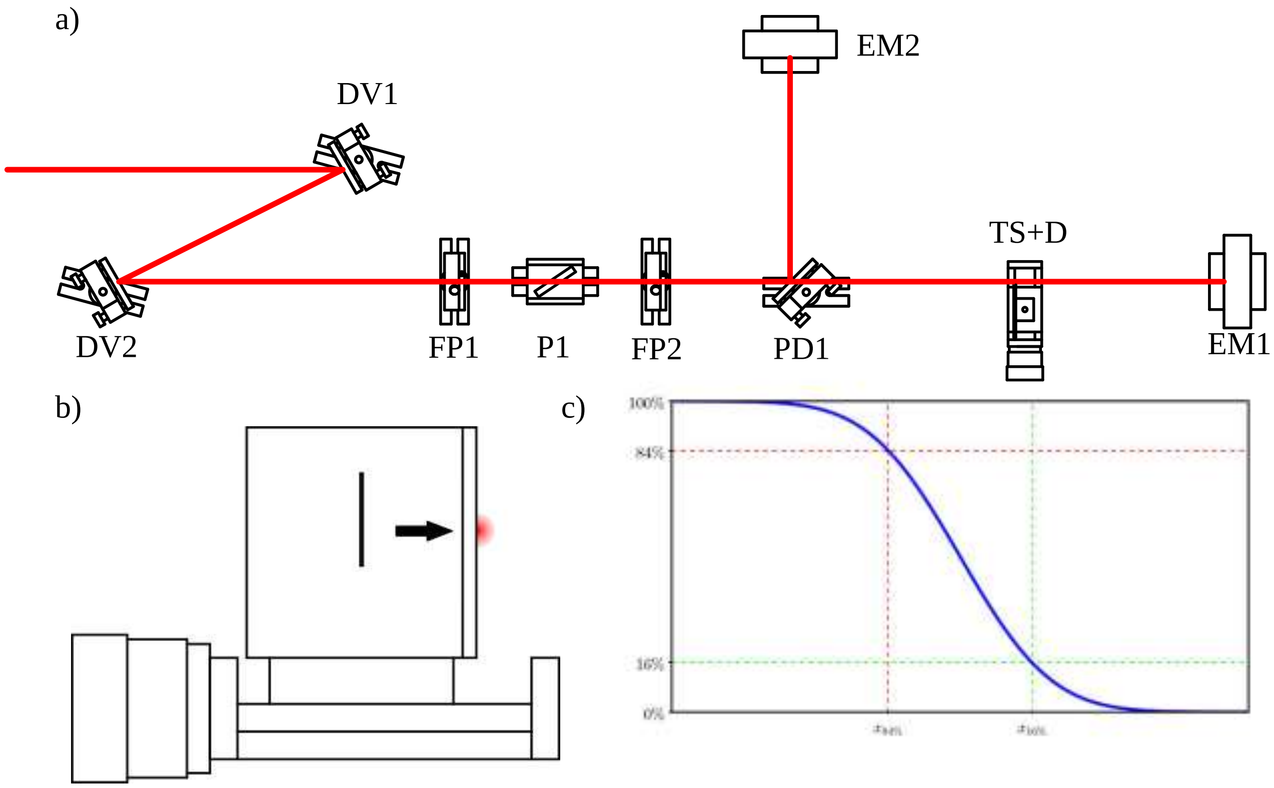


Fig. 8: Measurement of the beam radius. a) experimental setup, b) during the measurement the position of the knife's edge adjusted perpendicularly to the beam propagation direction, c) dependence of the passing radiation intensity on the position of the knife's edge.

– Measure the beam radius with the translation stage TS using the knife-edge method (at least at 20 different transversal translation stage positions). Depict results graphically and determine positions of 84% and 16% of the beam power. Calculate the beam radius at $1/e^2$ level:

$$w_{1/e^2} = x_{84\%} - x_{16\%}\ . \tag{1}$$

3. ***Measurement of the second harmonic radiation energy dependence on crystal orientation close to the phase-matching angle.***

– Replace the translation stage with the rotation stage PS.

– Place the nonlinear KDP crystal onto the rotation stage PS. The laser beam must pass the center of the nonlinear crystal.

– Place the filter F and the energy meter EM1 after the nonlinear crystal. The generated second harmonic beam must hit the center of the energy meter's sensor element. While rotating the nonlinear crystal around its vertical axis, determine the position where the maximum energy of the second harmonic radiation is generated. By adjusting the $\lambda/2$ waveplate FP1, set the energy efficiency $\eta_{e-e} = E_{2H}/E_{1H}$ less than 5%. Place the vertical diaphragm D (500 μm) fastened on the translation stage TS between the filter and the energy meter. The diaphragm hole must be in the center of the beam. If necessary, adjust the translation stage position to achieve this. The distance between the nonlinear crystal and the diaphragm needs to be more than 200 mm.

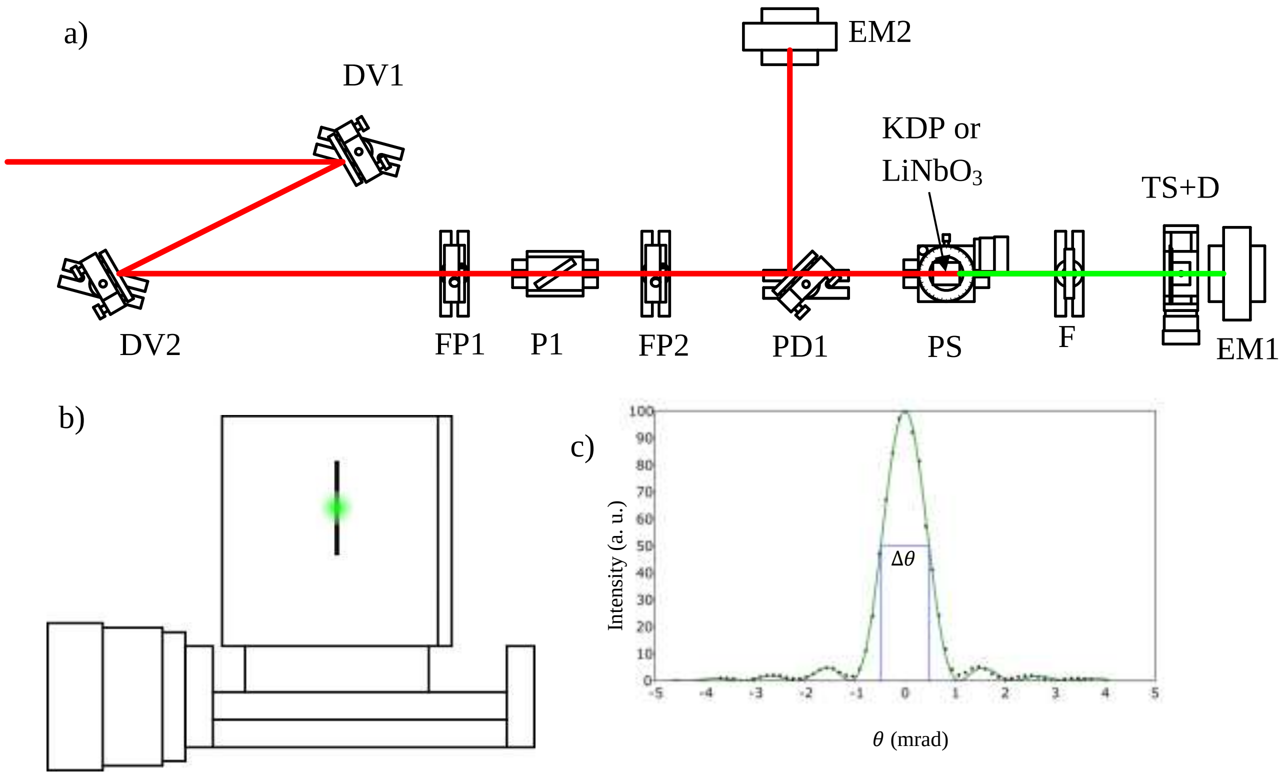


Fig. 9: Measurement of the second harmonic radiation energy dependence on crystal orientation close to the phase-matching angle. a) experimental setup, b) beam position with respect to the diaphragm hole, c) second harmonic intensity dependence on crystal rotation angle.

- While rotating the nonlinear KDP crystal around its vertical axis, measure the second harmonic radiation energy dependence on the crystal orientation (at least 30 points). Fit graphically depicted dependence with the following function:

$$I(\theta) = I_0 \frac{(\sin(\beta(\theta-\theta_0)))^2}{(\beta(\theta-\theta_0))^2}, \tag{2}$$

where I_0 is the maximum intensity, θ_0 – the peak position (angle), β – the constant which depends on refractive indices n_{o1}, n_{o2}, n_{e2}. Determine the full angular width at the half maximum intensity $\Delta\theta$.

- Replace KDP with the $LiNbO_3$ crystal. While rotating the crystal around its vertical axis, determine the position where the second harmonic radiation energy is maximum. By adjusting the $\lambda/2$ waveplate FP1, set energy efficiency $\eta_{e-e} = E_{2H}/E_{1H}$ to be less than 5%. The passing beam must not be obstructed by the crystal aperture and/or the crystal mount.
- Check the diaphragm and the energy meter positions. If necessary adjust them.
- While rotating the nonlinear $LiNbO_3$ crystal around its vertical axis, measure the second

harmonic radiation energy dependence on the crystal orientation (at least 30 angle points). Determine the full angular width at the half maximum intensity $\Delta\theta$.

4. ***Measurement of the second harmonic radiation energy dependence on incident laser radiation power.***

– Remove the diaphragm.
– Place the nonlinear KDP crystal. While rotating the nonlinear crystal around its vertical axis, determine the position when the second harmonic radiation energy is maximum.
– While rotating the $\lambda/2$ waveplate FP1, measure the second harmonic radiation energy dependence on the incident laser radiation energy (at least 20 energy points). When calculating the second harmonic radiation energy, take into account the losses due to presence of the filter.
– Calculate the energy efficiency:

$$\eta_{e-e} = E_{2H}/E_{1H}, \tag{3}$$

dependence on incident laser beam intensity:

$$I = \frac{0.94E_{1H}}{\tau_p \cdot \pi w^2} \text{ (W/cm}^2\text{)}. \tag{4}$$

– Replace KDP with the $LiNbO_3$ crystal. While rotating the nonlinear crystal around its vertical axis, determine the position when the second harmonic radiation energy is maximum. The passing beam must not be obstructed by the crystal aperture and/or the crystal mount.
– While rotating the $\lambda/2$ waveplate FP1, measure the second harmonic radiation energy dependence on the incident laser radiation energy (at least 20 energy points).
– Calculate the energy efficiency dependence on the incident laser beam intensity.

5. ***Measurement of the incident laser light parameters when a lens is additionally used.***

– Place the lens L500 with the focal length *f*=500mm before the $\lambda/2$ waveplate. The laser beam must propagate through centers of optical elements.
– Measure the energy of radiation which has passed the beamsplitter dependence on the energy of the reflected radiation for at least 10 different energy values
– Measure the beam diameter in the focal plane of the lens using the knife-edge method.

6. ***Measurement of the second harmonic radiation energy dependence on incident laser radiation power when a lens is additionally used.***

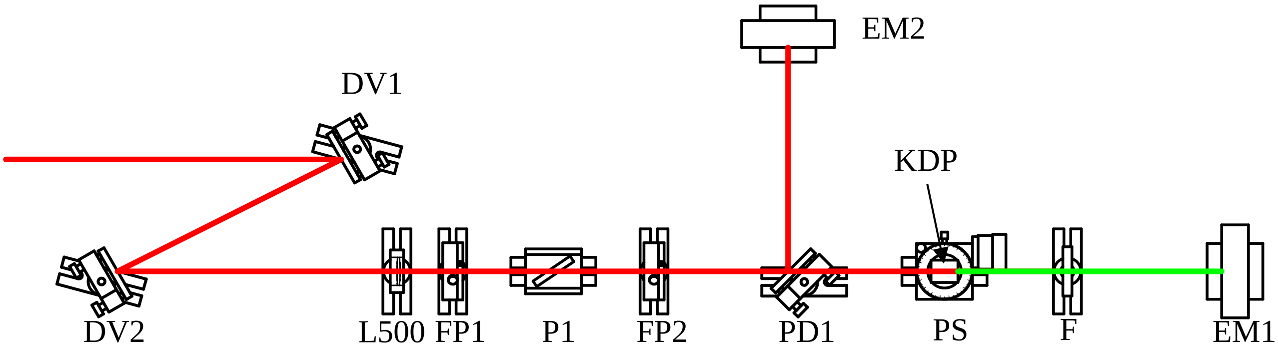


Fig. 10: Measurement of second harmonic radiation energy dependence on fundamental frequency radiation power when a lens is additionally used.

- Place the nonlinear KDP crystal onto the rotation stage. While rotating the nonlinear crystal around its vertical axis, determine the position when the second harmonic radiation energy is maximum.
- While rotating the $\lambda/2$ waveplate FP1, measure the second harmonic radiation energy dependence on incident laser radiation energy (at least 20 energy points).
- Calculate the energy efficiency dependence on the incident laser beam intensity.

7. Theoretical calculation of the second harmonic generation phase-matching angle and the angular bandwidth.

- The second harmonic phase-matching angle Θ_s for type I phase matching is theoretically calculated using the following expression:

$$\sin^2 \Theta_s = \frac{\frac{1}{n_{o1}^2} - \frac{1}{n_{o2}^2}}{\frac{1}{n_{e2}^2} - \frac{1}{n_{o2}^2}}, \tag{5}$$

here refractive indices necessary for calculations are shown in Table 1.

Table 1. Refractive indices for KDP and $LiNbO_3$ crystals at 1064 nm wavelength (n_{o1}, n_{e1}) and 532 nm wavelength (n_{o2} , n_{e2}).

Crystal	n_{o1}	n_{e1}	n_{o2}	n_{e2}
KDP	1.49377	1.45987	1.51254	1.47056
$LiNbO_3$	2.23402	2.15534	2.32509	2.23299

- The angular bandwidth for the second harmonic generation is calculated using this expression:

$$\Delta\Theta = \frac{0.443\lambda_{1H}\left[1+(n_{o2}/n_{e2})^2 \tan^2 \Theta_s\right]}{L \cdot \tan \Theta_s [1-(n_{o2}/n_{e2})^2] n_2^e(\Theta_s)}, \tag{6}$$

where L is the length of the crystal. The refractive index for the phase-matching angle is:

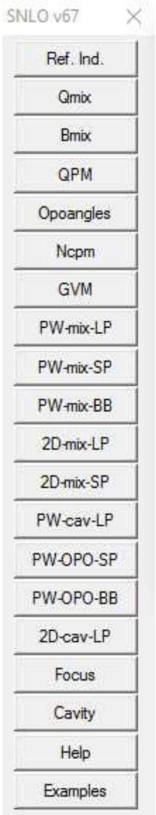
$$n_2^e(\Theta_s) = n_{o2}\sqrt{(1+\tan^2 \Theta_s)/(1+(n_{o2}/n_{e2})^2 \tan^2 \Theta_s)}\ . \tag{7}$$

- Compare calculated values with the measured ones.

8. ***Theoretical calculation of energy conversion efficiencies for KDP and $LiNbO_3$ crystals.***

- For the calculation of the energy conversion efficiency, the **SNLO** software is used (http://www.as-photonics.com/products/snlo).

a)



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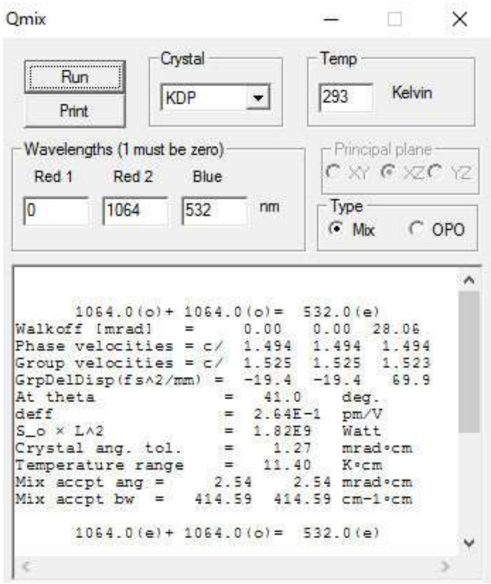

Fig. 11: SNLO software. a) Main menu, b) **Qmix** window.

- When installed, the software is launched by clicking the icon or selecting **SNLO** from the programme list.
- In the opened window for the calculation of nonlinear crystal properties, select the **Qmix** function.
- In opened the **Qmix** window select **KDP** or **LNB_S** (LiNbO3) crystal. In the temperature window **Temp** set 293 K. Select the nonlinear process type **Type**: **Mix**. Type the wavelength **Wavelengths**: **Red 1** – 1064 nm, **Red, Red2** – 0 nm (or vice versa), **Blue** – 532 nm. Click the **Run** button. In the **Qmix** window calculated crystal properties for the specified nonlinear interaction are displayed.
- For the energy conversion efficiency calculation select **2D-mix-LP** function.
- In the **2 dimensional long-pulse mixing** window type: the wavelength **(Wavelengths (nm)**), the refractive index (**Indexes of refraction**) which can be calculated with the **Qmix** function (the phase velocity $v_f = c/n$, where c is the light speed in the vacuum, n – the refractive index), the pulse energy (**Energy/power (J or W)**) which has to be split equally between **Red1** and **Red2** fields (**Blue** must be 0), in the pulse duration field (**Pulse duration (fwhm ns))** type the laser pulse duration. In the beam diameter field (**Beam diam. (fwhm mm)**) type the measured beam diameter at FWHM$d_{FWHM} = 1.18 \cdot w_{1/e^2}$. In the supergaussian beam coefficient (**Supergaussian coeff.**) field type 1. The nonlinear refractive index (**n2...**) and the two-photon absorption coefficients (**beta...**) need to be set to 0. The walk-off should be calculated using **Qmix**. The beam offset field should also be set to 0. Calculations have to be performed for the plane wavefront, so the beam radius of a curvature (**Rad. Curv. (mm/air)**) has to be as big as possible (>10^3). The integration step number **(#of integ/grid points**) should be bigger than (128; 32; 32). In the left crystal size field **Crystal/grid sizes**

(mm)) type the crystal length (for KDP it is 19 mm, $LiNbO_3$ – 17 mm), in other fields type 0. In the effective nonlinear optical coefficient field (**Deff (pm/V)**) type the value calculated from **Qmix**. Since the phase-matching case is being investigated, the phase mismatch (**Delta k (1/mm)**) needs to be set to 0. The distance (**Dist. To image (mm)**) has to be set to the distance between the crystal output plane and the energy meter. The number of time integration steps (**# time steps**) has to be more than 32. Click **Accept** to save parameters.

a) b)

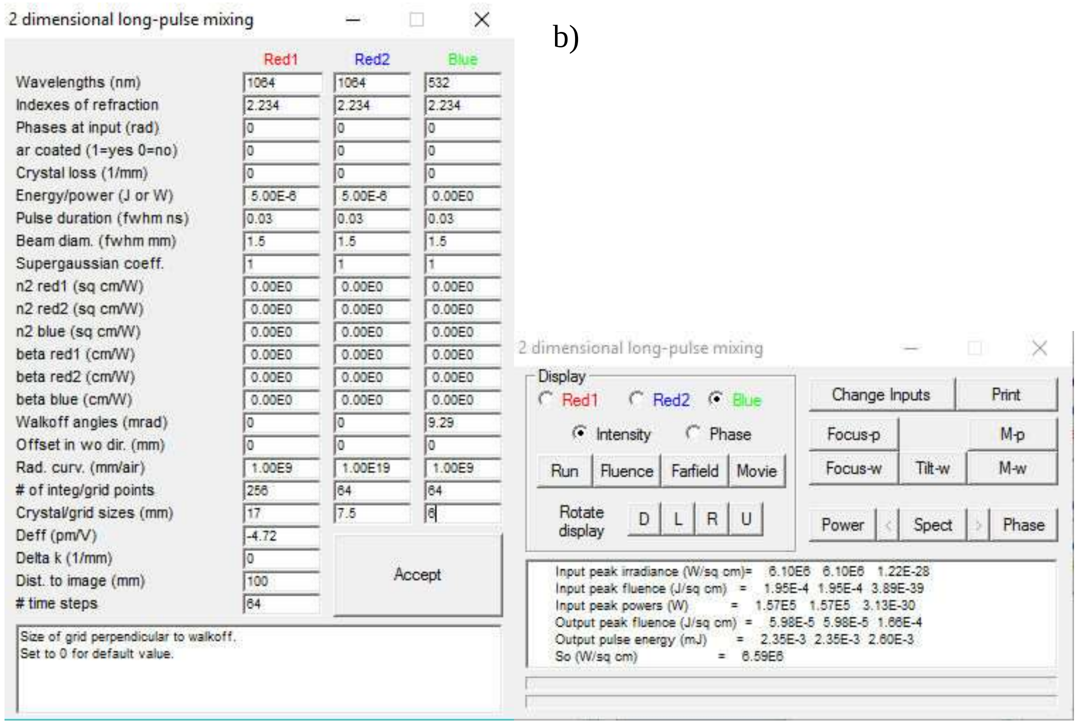

Fig. 12: 2 dimensional long-pulse mixing function. a) the parameters input window, b) **2 dimensional long-pulse mixing** function main window.

- Click **Run** in the opened window to begin the calculation of second harmonic radiation energy parameters. Calculation results are displayed in the same window. To calculate the energy conversion efficiency η_{e-e} use second harmonic pulse energy values (**Output pulse energy (mJ)**).
- Calculate the energy efficiency η_{e-e} dependence on first harmonic radiation energy. Compare calculated and experimental results.