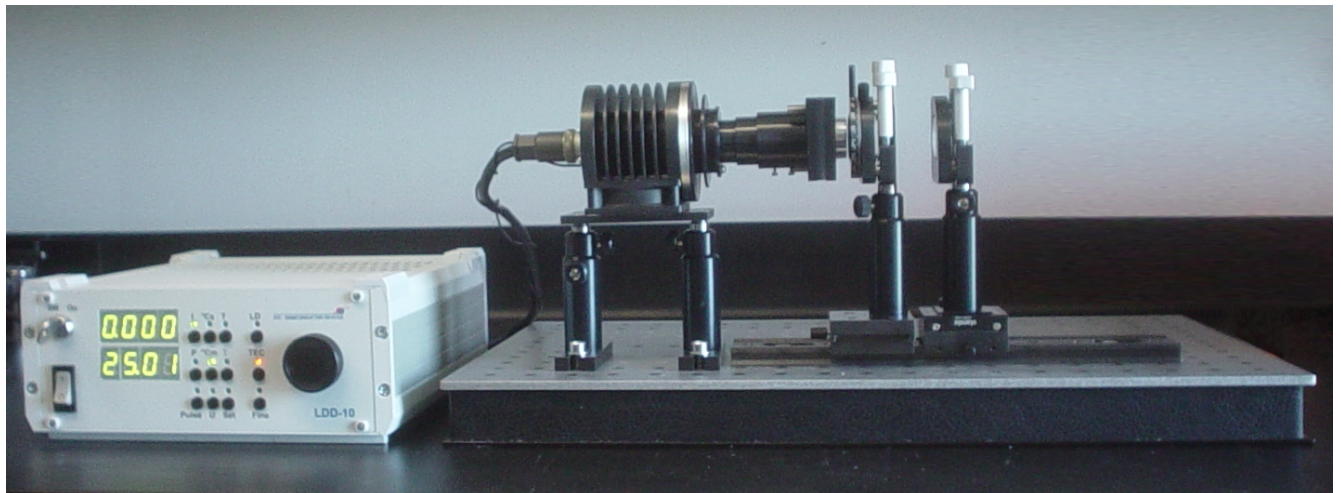


Laser kit for student training



Diode-Pumped Nd:KGd(WO₄)₂ laser

1. Theory

1.1 Background

The principles of laser construction and operation require knowledge on many topics but must include a discussion of:

- Atomic systems (atoms, ions, molecules) exist in discrete energy states only, i.e. they can possess only discrete magnitude of energy;
- Changes in the energy state, so-called *transitions*, are associated with absorption or emission of energy *quantum*, or *photon*.

Energy of transition is described by Bohr's formula $E_2 - E_1 = h\nu_{21}$, where E_1 and E_2 are energy magnitudes of discrete initial (1) and terminal (2) levels, ν_{21} is the frequency of light wave (absorbed or emitted), and h is Plank's constant. It is common in light-matter interaction to consider the medium as an ensemble of a large number of identical atomic systems. Under condition of the thermal equilibrium, described by Boltzmann statistics (Eq. 1), the electron population of the lower energy states (levels) is higher than that of the upper levels, and the medium emits radiation according Plank's law (Eq. 2).

$$n_{1(2)} = n_0 \left(\frac{e^{-E_{1(2)}}}{kT} \right), \quad n_0 = n_1 + n_2, \quad (1)$$

$$\rho(\nu) = \frac{8\pi\nu^2 d\nu}{c^2} \frac{h\nu}{e^{h\nu/kT} - 1}, \quad (2)$$

where $n_{1(2)}$ is population of the initial (terminal) level, k is Boltzmann constant, T is medium temperature, $\rho(\nu)$ is spectral density of emitting energy (energy per wavelength and per volume unity), and c is speed of light.

In order to obtain laser emission it is necessary to push system out of its equilibrium state by introducing external energy (E_1 to E_2 , Fig. 1), for example, by light absorption, in order to get the

population of the upper level higher than that of lower level, in other words, to obtain population inversion. After stopping the pump process, the medium relaxes to initial thermal equilibrium. Common materials return energy to their surroundings by producing heat. A small set of other materials efficiently produces light (E_2 to E_1 , Fig. 1). According to *quantum electrodynamics*, which describes the interaction between an electromagnetic field and matter, the energy, stored by medium after absorption the light, is emitted in the form of *spontaneous* and *stimulated* radiation (photons).

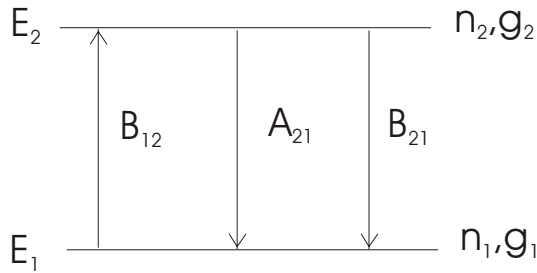


Fig.1. Schematic presentation of atomic system energy levels (with energy E , population n , and degeneracy g) and possible transitions between them.

Spontaneous radiation takes place independent of external electromagnetic radiation. Being emitted by different atoms, spontaneous radiation is characterized by different direction, phase, and polarization, which results in 3D depolarized and non-phased emission of medium. Its probability is described by *radiative Einstein coefficient of spontaneous emission* A_{21} . *Stimulated radiation* takes place only in the presence of external electromagnetic field, which stimulates this transition. Being emitted by different atoms of medium it possess the same characteristics which the external wave has – the same direction, phase, and polarization – and does not differ from the external wave which stimulated it. In other words, the energy of medium is transferred to external wave, or external wave is amplified. Its probability is described by *Einstein coefficient of stimulated emission* B_{21} .

A *laser* - (Light Amplification by Stimulated Emission of Radiation) is device, which is using optimized material and optical design to obtain optimal generation of the stimulated radiation.

Rate equation for scheme in Fig. 1:

$$\frac{\partial n_1}{\partial t} = -\frac{\partial n_2}{\partial t} = B_{21}\rho(\nu)n_2 - B_{12}\rho(\nu)n_1 + A_{21}n_2. \quad (3)$$

For thermal equilibrium:

$$\frac{\partial n_1}{\partial t} = -\frac{\partial n_2}{\partial t} = 0 = B_{21}\rho(\nu)n_2 - B_{12}\rho(\nu)n_1 + A_{21}n_2, \quad (4)$$

using Plank's formula (2):

$$\frac{A_{21}}{B_{21}} = \frac{8\pi\nu^2 h\nu}{c^3}, \quad B_{21} = \frac{g_1 B_{12}}{g_2}. \quad (5)$$

Energy levels of real system are not ideally narrow and resulting in the spectral line of emission possessing some limited width. The shape of line $g(\nu, \nu_0)$ depends on nature of *broadening* of the line. *Homogeneous broadening* takes place, for example, due to collision processes in atomic system (during collision the phase of wave is changing). Thermal broadening is also homogeneous. The shape of homogeneous broadening line is well approximated by *Lorenz* curve. Doppler broadening and broadening due to inhomogeneous distribution of medium parameters are collectively known as *inhomogeneous broadening*. The shape of inhomogeneous broadening line is well approximated by a *Gaussian*.

In a laser where stimulated emission is much stronger than spontaneous emission the rate equation for medium with broadened energy levels (see Fig. 2) can be written in the form:

$$-\frac{\partial[\rho(\nu_s)dv]}{\partial t} = \rho(\nu_s)dv B_{12} h\nu g(\nu_s, \nu_0) \left(\frac{g_2}{g_1} n_1 - n_2 \right). \quad (6)$$

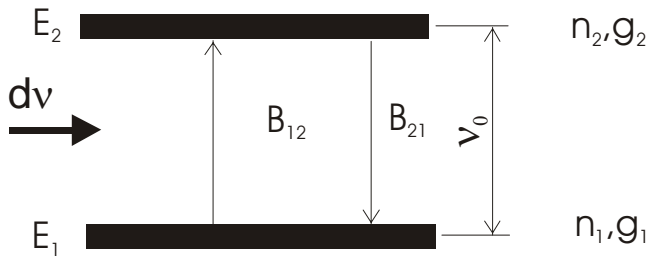


Fig.2. Schematic of 2-level atomic system with broadened energy levels.

After integrating the spectral density of energy will be $\rho(\nu_s) = \rho_0 \exp[-\alpha(\nu_s)x]$, where

$$\alpha(\nu_s) = \left(\frac{g_2}{g_1} n_1 - n_2 \right) \sigma_{21}(\nu_s) \text{ is the absorption coefficient, } \sigma_{21}(\nu_s) = \frac{h\nu_s g(\nu_s, \nu_0) B_{21}}{c} \text{ is the stimulated}$$

emission cross-section for transition $E_2 \rightarrow E_1$.

1.2 Four-level laser systems

An efficient laser medium should ideally possess narrow lines of radiative transitions, or *fluorescence*, high quantum efficiency of transition (number of absorbed photons divided by number of emitted photons), and strong absorption band in the spectral range of optical pumping wavelengths. Some solid-state matrices doped by rare-earth ions, transition element ions, or actinide ions, were found to possess such properties.

Energy levels, or *terms* of ions are usually described in the form of $^{2S+1}L_J$, where L is the orbital quantum number (0,1,2,3,4...→S,P,D,F,G,H...), $2S+1$ is the term multiplicity, or the number of possible orientation of the total spin, and J is the total momentum.

The most favorable laser operation is accomplished with a four-level scheme. In this scheme, a medium is pumped in the energy channel $0 \rightarrow 3$, while the laser channel is $2 \rightarrow 1$ (see Fig. 3). The lower laser energy level 1 should lie higher than the ground state 0 in order to be thermally unpopulated. After the system is excited by pump light with power W_{13} , the inversion of population between laser levels 2 and 1 can easily be achieved during fast thermalization of the electrons from level 3 to level 2 and from level 1 to level 0. In this case the time relaxation from level 3 to level 2 (τ_{32}) and from level 1 to level 0 (τ_{10}) must be faster than that from level 2 to level 1 (τ_{21}).

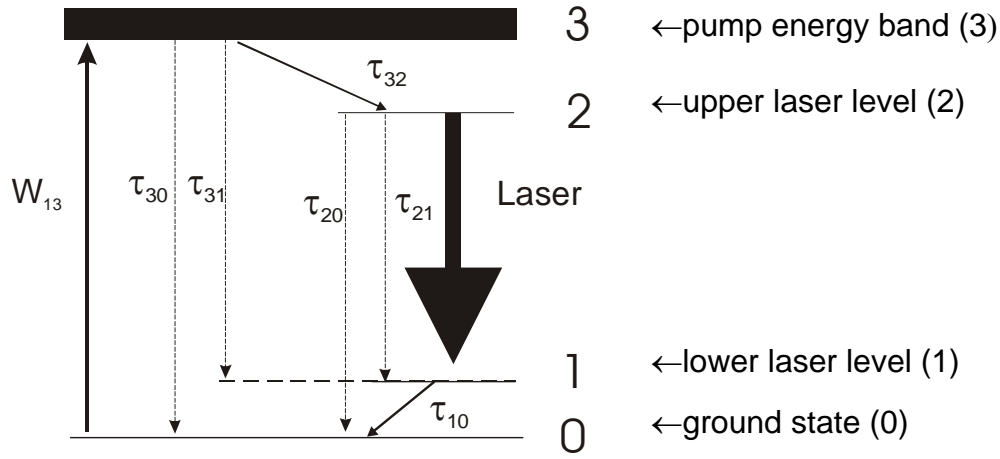


Fig. 3. Schematic of 4-level laser system. Dashed arrows represent energy losses processes with corresponding times of relaxation τ_{30} , τ_{31} , τ_{20} , and τ_{21} .

Quantum efficiency in this case will be:

$$\eta_Q = \left(1 + \frac{\tau_{32}}{\tau_{31}} + \frac{\tau_{32}}{\tau_{30}}\right)^{-1} \leq 1, \quad (7)$$

and rate equations:

$$\begin{aligned} \frac{\partial n_2}{\partial t} &= W_{13} \eta_Q n_0 - \left(n_2 - \frac{g_1}{g_2} n_1\right) c \phi \sigma_{21} - \frac{n_2}{\tau_{21} + \tau_{20}}, \\ \frac{\partial n_1}{\partial t} &= \left(n_2 - \frac{g_1}{g_2} n_1\right) c \phi \sigma_{21} + \frac{n_2}{\tau_{21}} - \frac{n_1}{\tau_{10}}, \\ n &= n_1 + n_2. \end{aligned} \quad (8)$$

Here $\rho(\nu) = h\nu g(\nu) \phi$, $B_{21} \rho(\nu) = c \sigma_{21}(\nu) \phi$, where ϕ is *photon density* (number of photons per volume unit).

The actual energy level scheme for the $\text{Nd}^{+3}:\text{KGd}(\text{WO}_4)_2$ laser medium is shown in Fig. 4.

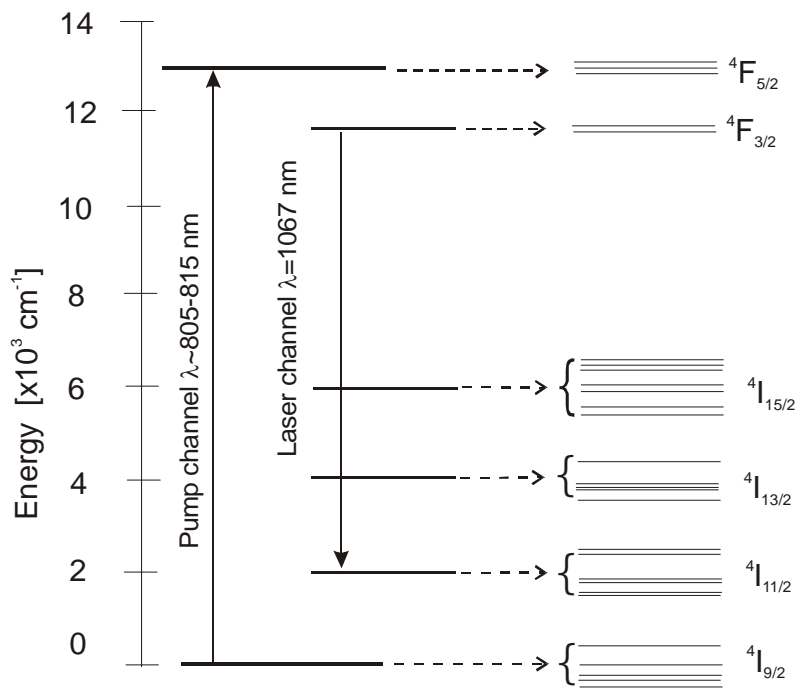


Fig. 4. Energy level scheme of $\text{Nd}^{+3}:\text{KGd}(\text{WO}_4)_2$ laser medium.

1.3. Laser design

Usually the laser consists of an active element (laser medium), a pump unit, a resonator (laser cavity), and some intracavity elements (see Fig. 5). Two mirrors of the resonator reflect the stimulated emission appeared inside the medium to let it pass through medium several times and to get higher amplification of the radiation. Usually one mirror (*rear mirror*) has high reflection (HR) at laser wavelength, while the other mirror possesses some finite magnitude of transmittance T and serves as *output coupler* (OC), i.e. provides the laser radiation to go out of resonator.

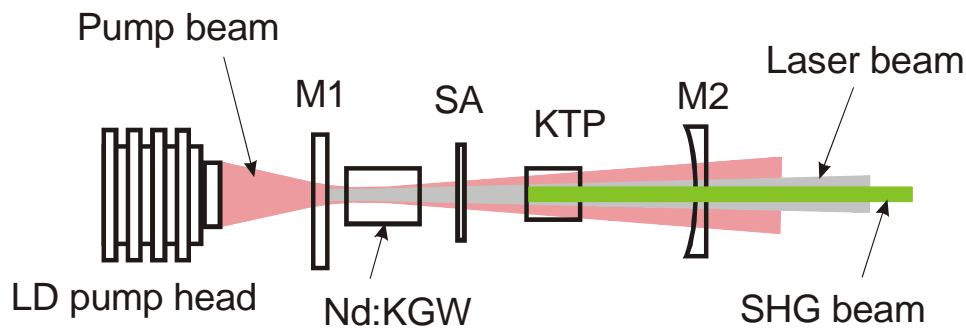


Fig. 5. Schematic of the diode-pumped solid-state laser. M1 - rear mirror, M2 - output coupler, Intracavity elements: SA - saturable absorber, KTP - nonlinear crystal.

1.3.1. Pump module

There are several ways to pump a laser medium – electrical discharge, chemical reaction, free electron beam pumping, and others. Among them the optical pumping by arc lamp and by laser diodes is one of the common methods using in commercial solid-state lasers. In comparison to arc lamp, laser diode (LD) pumping possesses a number of advantages. Since the diode laser emits intense light in a narrow spectral line, and if this line coincides with absorption band of laser medium (see Fig. 6a), the losses of pump energy and thermal loading of the active element will be minimal. Other advantages of laser diode pumping are compactness, high reliability and lifetime, and high efficiency (conversion electric power in light power, see Fig. 6b).

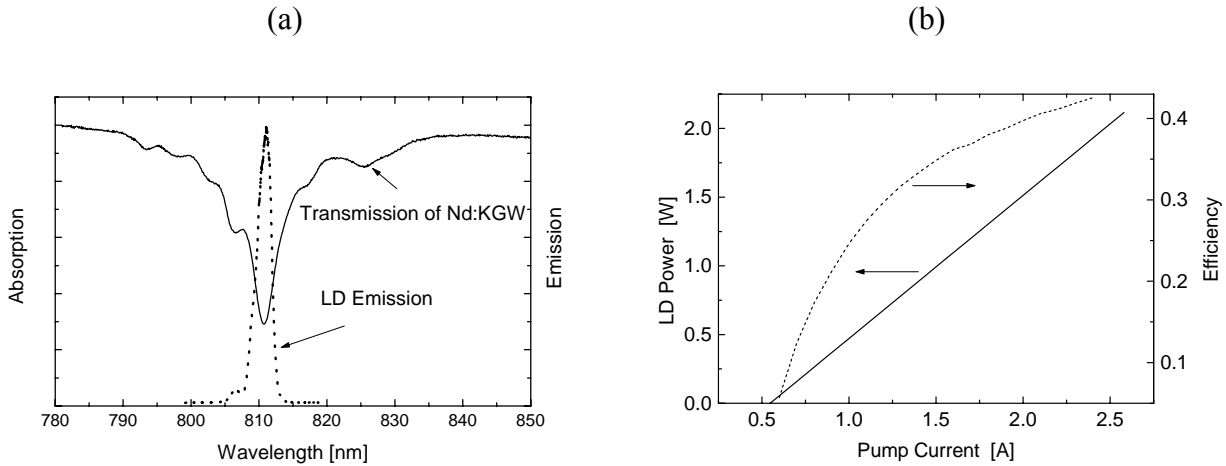


Fig. 6. LDs are an ideal pump source for Nd:KGW active media: (a) the absorption band of Nd:KGW coincides with emission line of commercial LDs, which is very efficient converter of electric power to light power (b).

1.3.2. Optical resonator

Generally, the resonator (laser cavity) consists of two mirrors placed along the common optical axes. By analogy with acoustic waves, optical wavelengths must meet the condition $n\lambda / 2 = \mathcal{L}$. Here \mathcal{L} is resonator length, λ is wavelength, and n is integral number. These waves are called *spectral* or

longitude modes of the resonator. The spatial distribution of electromagnetic fields inside the resonator (*spatial modes*), can be derived from solution of Maxwell equation system using Hermite and Laguerre polynoms. Spatial modes of resonator in orthogonal coordinates are usually labeled as TEM_{mn} , where $m+1$ and $n+1$ are numbers corresponding to quantity of intensity distribution maximums in transversal XY cross-section of the beam ($m \rightarrow X, n \rightarrow Y$). Spatial modes are also called *transversal modes*. Some possible resonator configurations are shown in Fig. 7.

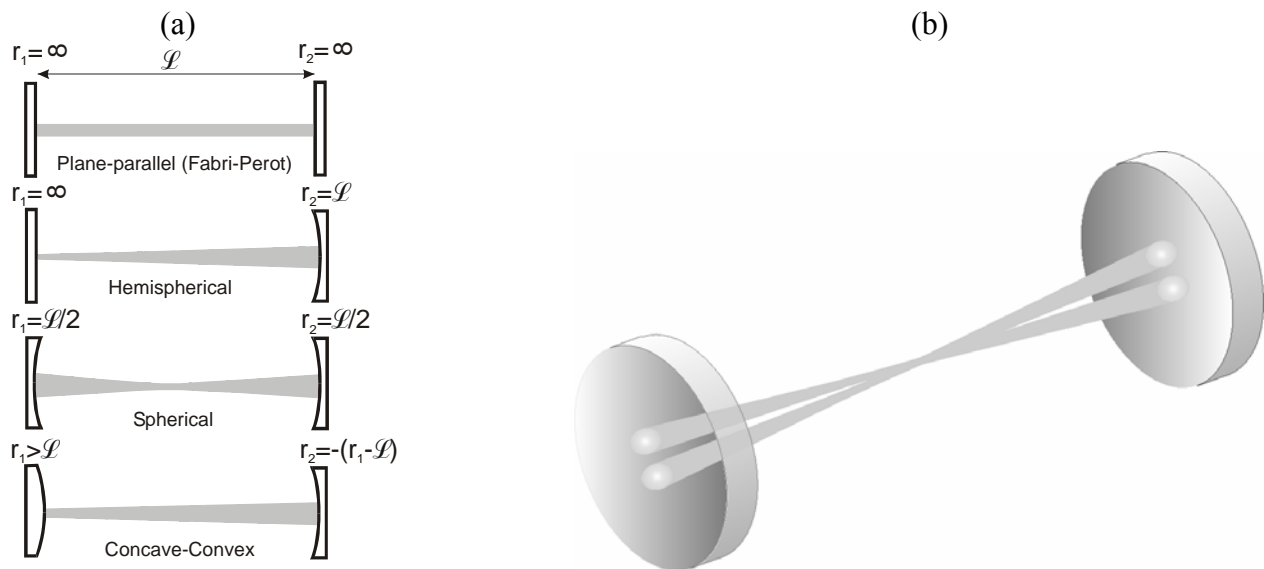


Fig. 7. Different resonator configurations with TEM_{00} fundamental spatial mode (a); TEM_{01} transversal mode in spherical resonator (b). \mathcal{L} is resonator length, r_1 and r_2 are curvature radius of rear mirror and OC, correspondingly.

Fundamental spatial mode TEM_{00} , whose profile is described by a Gaussian function, is the most usable spatial mode in lasers. Parameters of Gaussian beam in the resonator are shown in Fig. 8 and can be defined from formulas (9).

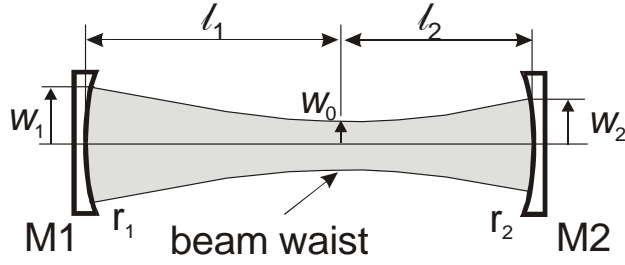


Fig. 8. Longitudinal profile of Gaussian beam in the resonator of length $\mathcal{L}=l_1+l_2$.

$$w_1^4 = \left(\frac{\lambda r_1}{\pi} \right)^2 \frac{r_2 - \mathcal{L}}{r_1 - \mathcal{L}} \left(\frac{\mathcal{L}}{r_1 + r_2 - \mathcal{L}} \right),$$

$$w_2^4 = \left(\frac{\lambda r_2}{\pi} \right)^2 \frac{r_1 - \mathcal{L}}{r_2 - \mathcal{L}} \left(\frac{\mathcal{L}}{r_1 + r_2 - \mathcal{L}} \right),$$

$$w_0^4 = \frac{\mathcal{L}(r_1 - \mathcal{L})(r_2 - \mathcal{L})(r_1 + r_2 - \mathcal{L})}{(r_1 + r_2 - 2\mathcal{L})^2},$$

$$l_1 = \frac{\mathcal{L}(r_2 - \mathcal{L})}{r_1 + r_2 - 2\mathcal{L}} \quad l_2 = \frac{\mathcal{L}(r_1 - \mathcal{L})}{r_1 + r_2 - 2\mathcal{L}}. \quad (9)$$

Under some magnitudes of r_1 , r_2 , and \mathcal{L} formulas (9) do not have physical sense. For these parameters the modes with small losses cannot exist inside the resonator. In this case, the resonator is described as being *unstable*. From a physical point of view, a *stable* resonator is re-focused the beam (after reflecting from mirrors several times) and kept it within the resonator, while a beam in an *unstable* resonator after each reflection becomes more divergent and finally comes out from the resonator.

Criterion of resonator stability is the following $0 < g_1 \cdot g_2 < 1$, where $g_i = 1 - \frac{\mathcal{L}}{r_i}$.

1.3.3. Laser medium in optical resonator

When the laser medium is placed in resonator and its pumping is arranged, the resonator modes, which spectrally coincide with the medium gain spectrum (see Fig. 9), can be amplified yielding the laser emission. Laser operation is a competition inside the resonator between optical *gain* (stimulated

emission) and optical passive *losses* (light outflow from resonator – through output coupler, scattering on the medium defects, etc.). When amplification overcomes the losses a laser will emit light. During the pump power increase, the optical gain raises (gain spectrum for four-level system is close to emission spectrum) while passive losses remains approximately the same. When the gain becomes equal to the optical losses, the pump power is called the *pump threshold*.

One of the important parameter of laser resonator is Q-quality which is defined as

$$Q = 2\pi \left[1 - \exp\left(-\frac{\nu_0}{\nu_c}\right) \right]^{-1} \approx 2\pi\nu_0\tau_c, \text{ where } \tau_c = \frac{2\mathcal{L} \cdot n}{c} (-\ln[R_1R_2] + 2\alpha \cdot \mathcal{L})^{-1} \text{ is the average}$$

photon lifetime in the resonator, and α is absorption coefficient. Another important parameter is passive cavity losses $L = 2\alpha \cdot \mathcal{L} + L_m$, where L_m contains losses other than absorption.

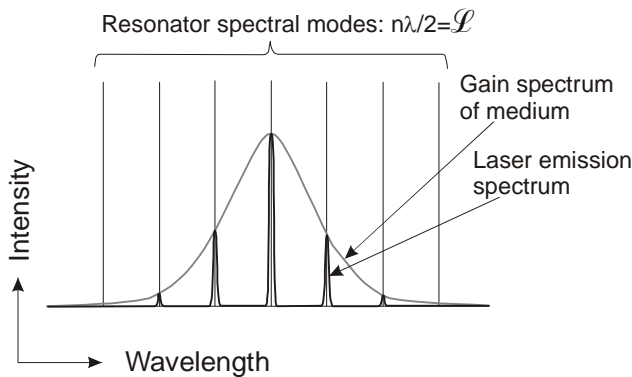
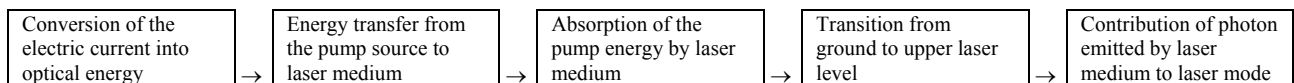


Fig. 9. Schematic of laser resonator spectral modes.

1.3.4. Laser power

Processes, which initiate the energy losses in solid-state laser and methods employed to minimize them, are shown in the following table:



Pump source efficiency, η_{pump}	Efficiency of pump source coupling system, η_T	Correspondence of absorption spectrum of medium to emission spectrum of pump source, η_p	Absorbance of medium at pump wavelength, η_a	Efficiency of upper level population, η_u	Resonator losses, $\eta_c = T/(L+T)$
Using efficient LD instead of lamp	Improvement of pump unit design	Proper choice of pump source	Proper choice of medium (high α or large length)		Pump unit and OC optimization, cavity losses decrease

For steady-state conditions of laser operation, the solution of Eqs. 7-8 can be written as:

$$P_{out} = \eta_{sl} (P_{pump} - P_{th}), \quad (10)$$

where P_{out} is output laser power, P_{pump} is pump power, P_{th} is threshold pump power, and $\eta_{sl} = \eta_p \eta_T \eta_a \eta_u \eta_B \eta_c$ is slope efficiency.

For end-pumping scheme DPSSL shown in Fig. 5:

$$P_{th} = \frac{h\nu_p (L + T)}{2\sigma\tau_f \eta_p \eta_a} \left(\frac{\pi(w_P^2 + w_L^2)}{2} \right), \quad (11)$$

where τ_f is time relaxation from upper laser level, ν_p is pump frequency, w_P is radius of pump beam waist (waist of red beam in Fig. 5), and w_L is radius of laser mode waist (waist of grey beam in Fig. 5).

1.4. Q-switching

Q-switching is a laser design where a special intracavity element (*Q-switch*) is placed inside the laser resonator in order to control the Q-parameter of the resonator by periodically changing the cavity losses. When losses are high, the laser operation is impossible and population of upper laser level is increasing, i.e energy of laser is accumulating. After some time Q-quality is switching to small losses, and energy accumulated by the medium is released in a short laser pulse of high intensity. In *active Q-switch* the process of modulation of losses can be controlled by the operator. There are several types of active Q-switches, for example, electro-optic Q-switches, , where high voltage applied to Pockel's cell

changes the polarization of laser beam, or acousto-optic Q-switches, where the laser beam is diffracted by a refractive index grating induced by a RF field applied to acoustic medium.

Passive Q-switching is based on phenomena of optical bleaching of some materials. Using for modeling of bleaching process 2-level scheme shown in Fig. 1 (see Eqs. (3-5)), for stationary case and high level of pumping ($W_{12}=B_{12}\rho \gg A_{21}$) one can be derived $\frac{n_2}{n_1} \rightarrow 1$, i.e. the number of photons, absorbed by medium, is approximately equal to one of emitted photons. In other words, the medium (in our case Q-switch material) becomes transparent.

A passive Q-switch medium (dye solution, solid-state crystal), or *saturable absorber*, usually possesses some initial absorption at laser wavelength and when placed inside the cavity it introduces resonator losses. When the inversion population achieves the critical magnitude and gain overcomes the losses, laser intensity inside the resonator increases. Increasing the laser intensity results in saturation of the passive Q-switch absorption and following it's bleaching, i.e. to decreasing the resonator losses. After the saturable absorber bleaches, the accumulated energy is totally released in the laser intensity. Consequently, population inversion and, correspondingly, gain are dropped. At this point the saturable absorber restores its absorption, and new cycle of energy accumulation begins. The time scale when laser energy is released in a laser pulse depends on different laser parameters and usually lies in the *nanosecond* range. The typical temporal shape of a laser pulse in low power Q-switched DPSSL is shown in Fig. 10.

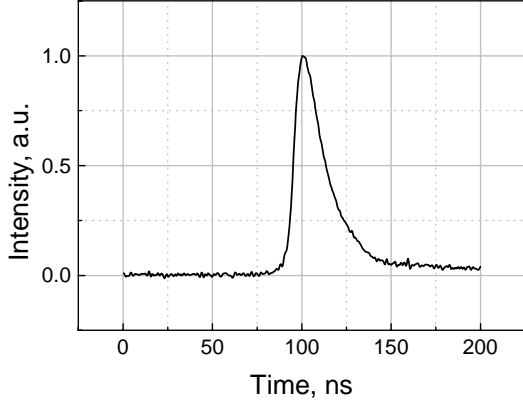


Fig. 9. Output laser pulse profile of diode-pumped Nd:KGW laser.

1.5. Nonlinear optics

In general the interaction between light and dielectric non-magnetic medium causes the medium to be polarized by the electro-magnetic field of the light: the electron shells of the atoms of medium are shifted by electromagnetic field of light, and the atoms obtain an electric dipole moment. Polarization of the medium is described by vector \mathbf{P} , which components are defined according the formula:

$$P_i(t) = \sum_k \chi_{ik}(\mathbf{E}) E_k(t), \quad (12)$$

where χ_{ik} is susceptibility of the medium and \mathbf{E} is the electric field intensity vector of the wave ($E_k(t)$ represents its components), which usually is a plane wave

$$E_k(t) = \frac{1}{2} [E_k \exp(i\varphi) + c.c.], \quad (13)$$

where E_k is electric field wave amplitude, $\varphi = \omega t - \mathbf{k}\mathbf{r}$ is wave phase, $\omega = 2\pi\nu$, ν is wave frequency, \mathbf{k} is wave vector, and \mathbf{r} is coordinate unit vectors, correspondingly; abbreviator c.c. means “complex conjugate”. Formula (12) can be re-written where function $\chi(\mathbf{E})$ is expanded in series of power \mathbf{E} :

$$P_i(t) = \sum_k \chi_{ik} E_k(t) + \sum_k \sum_l \chi_{ikl} E_k(t) E_l(t) + \sum_k \sum_l \sum_m \chi_{iklm} E_k(t) E_l(t) E_m(t) + \dots, \quad (14)$$

where $\chi_{ik} = \chi$, $\chi_{ikl} = \chi^{(2)}$, and $\chi_{iklm} = \chi^{(3)}$, are matrixes of linear, quadratic and third order susceptibilities of the medium, correspondingly. Typical magnitudes for components of the susceptibilities are in range $\chi \sim 1$, $\chi^{(2)} \sim 10^{-11} \text{m/V}$, and $\chi^{(3)} \sim 10^{-21} (\text{m/V})^2$. Therefore, if the intensity of light is low, the second and the third terms of the Eq. (14) will be negligible in comparison to the first one, and interaction can be described in linear consideration. For high intensities of light, common for laser sources, nonlinear polarization should be included in the analysis. Therefore, the first term of the Eq. (13) describes the phenomena of linear optics, while the other two one nonlinear effects.

1.5.1. Second harmonic generation

If we examine Eq. (14) and neglect the $\chi^{(3)}$ processes, the term describing the wave with frequency 2ω will appear in the formula for polarization. It means that incident wave of frequency ω (*fundamental wave*) initiates the polarization wave with doubled frequency. Under some conditions the 2ω -polarization wave can produce light with frequency of 2ω . This phenomenon of re-radiation of light with doubled frequency is called *second harmonic generation (SHG)*. Experimentally, an relatively intense pulse of light, say in the near IR of frequency ω , passes through a medium. On the other side of this medium it is possible to observe both the near IR and some amount of visible light at exactly 2ω frequency. For *collinear* interaction, when fundamental wave and second harmonic are propagated in the same direction (along z-axis), the intensity of the second harmonic $I_{2\omega}$ after distance z is expressed by the following formula:

$$I_{2\omega}(z) = AI_{\omega}^2 \left[\frac{\sin\left(\frac{\Delta k}{2} z\right)}{\frac{\Delta k}{2}} \right]^2, \quad (14)$$

where I_{ω} is intensity of fundamental wave, A is some factor dependent on material properties, $\Delta k = k_{2\omega} - 2k$, $k_{2\omega}$ and k are wave vector projections on z -axis for second harmonic and fundamental waves, correspondingly. Dependence of second harmonic intensity on Δk for a given z is shown in Fig. 10.

The amplitude achieves a maximum if $\Delta k = 0$, or $k_{2\omega} = 2k$, or $n_{\omega} = n_{2\omega}$ (using expression $k = \frac{n\omega}{c}$, where n is refractive index). This condition of efficient second harmonic generation is called *wave* or *phase matching*.

For isotropic, dielectric, and non-absorbed media refractive index is increased by increasing the frequency of light, and phase matching is unrealizable. It is possible only if anisotropy can be induced in the medium by external effect.

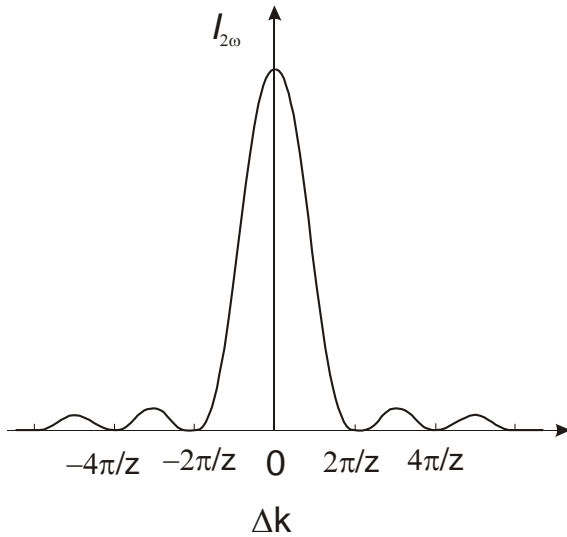


Fig. 10. Dependence of $I_{2\omega}$ on Δk .

In contrast to isotropic media, the light in anisotropic materials, like many crystals, propagates in some directions in the form of two waves – *ordinary* (o) and *extraordinary* (e) with the same frequency, but with different velocities (refraction indices) and with polarizations orthogonal to each other. Refractive index does not depend on direction of wave vector for o-wave but depends on angle between the direction of wave vector and the crystal axis for e-wave. As an example, the dependence of refractive indices for negative ($n_e < n_o$) uniaxial KDP crystal on direction in one of the crystallographic plane (optical axis of the crystal lies in this plane) is shown in Fig. 11. The curves, corresponding to refractive indices for fundamental o-wave and for second harmonic e-wave intersect in four points. Therefore light waves, propagating in a crystal along a direction parallel to lines at angle θ to the crystal

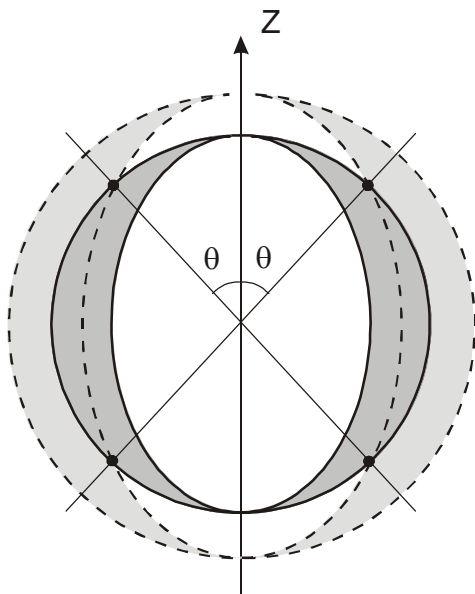


Fig. 11. Indicatrix of refractive index of uniaxial crystal in optical axis plane. Solid lines show index for fundamental wave ω , dashed – for second harmonic 2ω . Circles correspond to indices for o-wave (do not depend on direction of wave vector), ellipses – for e-wave. Z is optical axis; two lines drawn at angle θ to crystal axis represent directions where phase synchronism condition $n_{\omega}^o = n_{2\omega}^e$ (solid dots on curve intersections) is fulfilled.

axis, are in phase matching and the second harmonic generation can be realized. In a 3D picture these directions form the cone with vertex angle 2θ .

The media, typically used for frequency conversion in laser technology, are called nonlinear materials. To get efficient second harmonic generation, the crystal should be properly cut (along the

phase matching direction) and polished. Because of $\chi^{(2)}$ nature of this SHG phenomenon second harmonic intensity will be:

- Noticeable only for high intensity fundamental wave;
- Quadratically dependent on intensity (see Fig 12).

It means that the higher power of fundamental wave applies, the higher efficiency of SHG conversion will be obtained. For low power lasers one of the ways to increase power of second harmonic is to place nonlinear crystal inside the cavity – intensity of fundamental wave inside the resonator is usually much higher than outside.

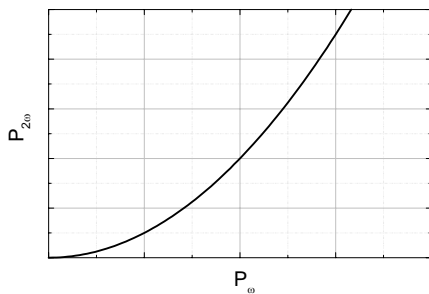


Fig. 12. Quadratic dependence of second harmonic power ($P_{2\omega}$) on fundamental wave power (P_{ω}).

SHG processes can be optimised to be quite efficient (with conversion coefficient more than 80%) and are commonly used in industry. A very common laser is Nd:YAG laser providing nanosecond pulses at 1064 nm. Doubling the frequency using a nonlinear crystal allows the laser to produce intense pulses at 532 nm. This option only costs a few thousand dollars and adds great versatility.

1.5.2. Stimulated Raman Scattering

Stimulated Raman scattering (SRS) is another nonlinear optical process, which can be used to change (shift) the wavelength of laser light. Unlike the second-order nonlinear optical processes, which can take place only in a non-centrosymmetrically oriented medium, the third-order $\chi^{(3)}$ processes can take place in any medium, random or ordered (solid-state media, gases, liquids).

The energy level diagram for vibrational SRS in Raman medium (where $\chi^{(3)} \neq 0$ and Raman scattering is strong enough) is shown in Fig. 13. The energy levels involved are the ground vibrational state ($v=0$) and the first excited vibrational state ($v=1$). The dashed line represents the virtual energy level for of this interaction. When pump (laser) radiation of high intensity passing through long Raman medium stimulated emission of the Stokes wave can occur. Since the medium is considering as Raman medium, pump wave spontaneously scattered on vibration wave of crystal lattice plays a role of “Stokes” wave, and therefore the process can be built up directly from spontaneous emission. In the Stokes process, the energy, which is lost in converting the pump wave to the Stokes wave (with smaller frequency) goes into a vibration of the lattice, or *phonon*.

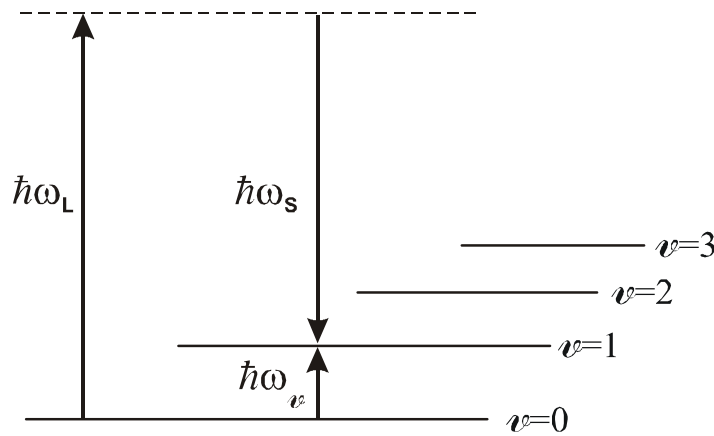


Fig. 13. Energy diagram for Stimulated Raman Scattering (first Stokes).

Since the origin of SRS is spontaneous Raman scattering, to know the frequency of Stokes wave in SRS frequency conversion it is necessary to first know the Raman spectrum of the medium. For $\text{KGd}(\text{WO}_4)_2$ material non-polarized Raman spectrum is shown in Fig. 14.

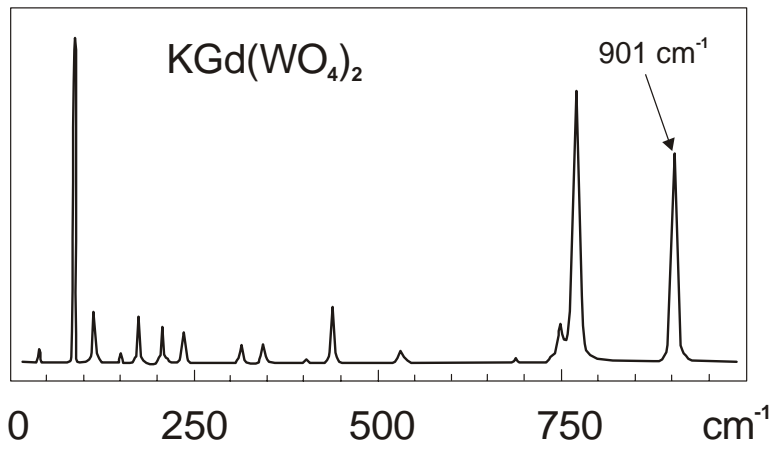


Fig. 14. Non-polarized Raman spectrum of $\text{KGd}(\text{WO}_4)_2$ crystal. One of the most important peaks is at 901 cm^{-1} .

The $\text{KGd}(\text{WO}_4)_2$ crystal is good as laser host material as well as a Raman medium. Therefore this medium can be used for laser operation and SRS frequency conversion simultaneously. The process where the laser emission and its nonlinear conversion originate in the same medium is called *frequency self-conversion*.

The laser kit for student training is based on a Nd:KGW laser, pumped by a high power diode laser. The kit was designed to serve as an experimental tool for student laboratory practices to teach the concepts of laser physics and nonlinear optics and to train students in diode pumped solid-state laser design. Modular design of laser kit allows to train more fast and efficient. The kit manual consists of the kit modules description, short course of fundamental laser physics and nonlinear optics theory and detailed description of 9 laboratory exercises covering the laser physics and nonlinear optics aspects.

The laser kit consists of:

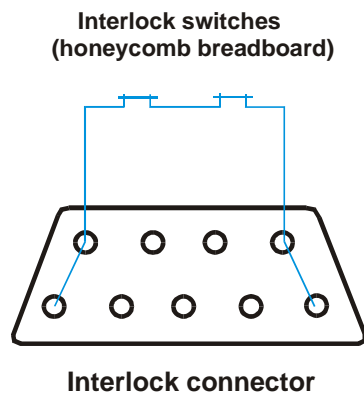
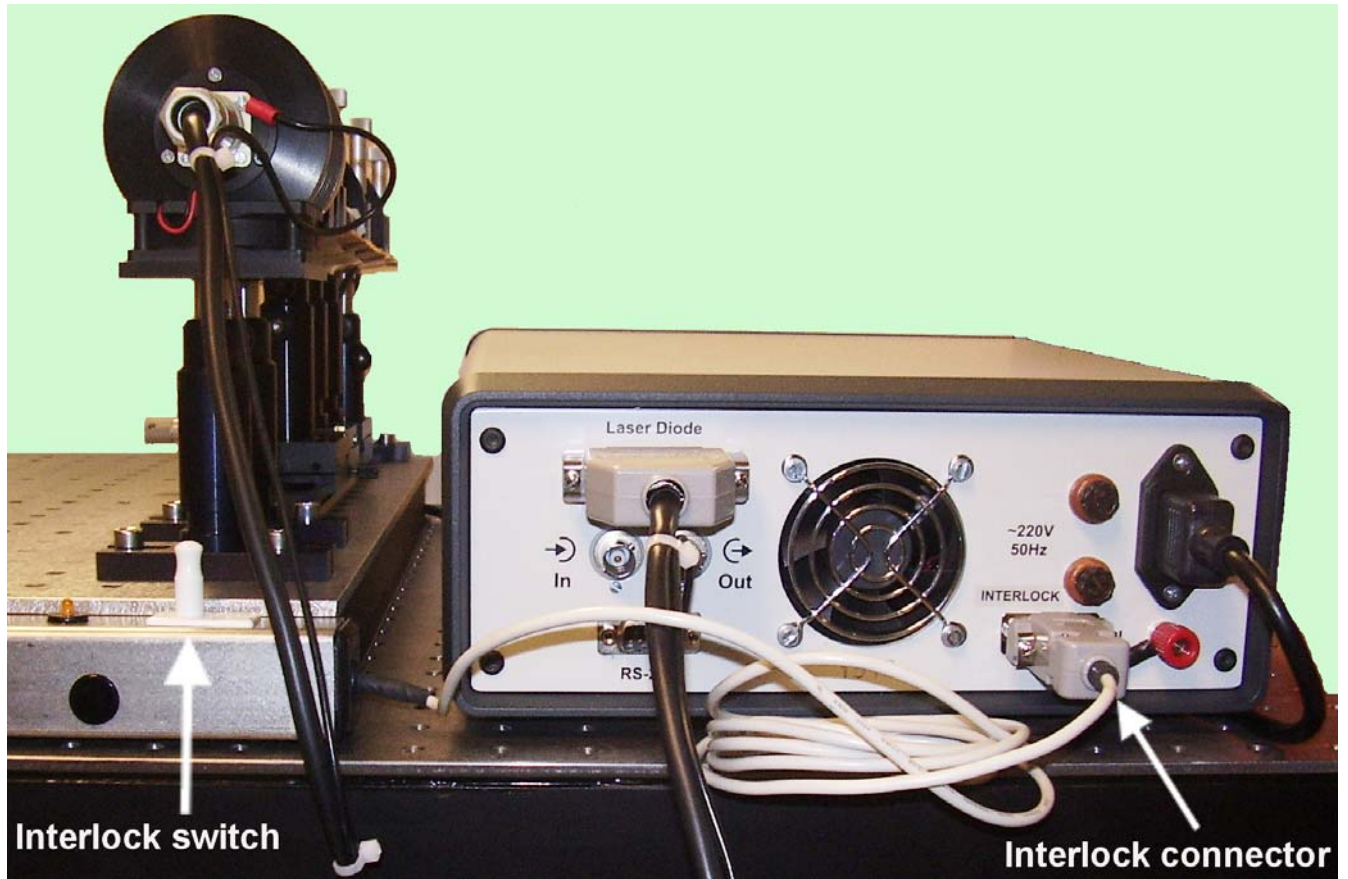
- Pump laser diode with thermoelectric cooler and pump optics attached to microprocessor-controlled power supply.
- Nd:KGW laser crystal in a holder.
- Set of 3 laser curved cavity mirrors.
- Cr:GSGG AR/AR-coated passive Q-switch in a holder.
- KTP nonlinear crystal in a holder.
- Honeycomb breadboard.
- Optical rail.
- Mirror/crystal mounts (2 pieces).
- Safety glasses.
- IR-to-Visible radiation converter (2 pieces).

The laser diode is class IV laser product. In the operator's manual the mention is made of safety hazards while handling high power lasers. The kit includes laser safety eyewear and labels attached on diode laser.

DPSS Laser Specifications

Active Crystal	Potassium Gadolinium Tungstate doped with Nd ³⁺ ions (Nd:KGW)
Type of Pumping	Longitude (end) Diode Pumping
Diode Pump Power at 808 nm, W	0 – 1.6 (tunable)
Laser Cavity Length, mm	Demi-confocal, 75.0 (or 50.0)
Mode of Operation	Continuous Wave (CW) or Pulsed (passive Q-switch)
Output Wavelength, nm - fundamental - Second Harmonic (with intracavity doubling) - 1-st Stokes Raman Scattering (with intracavity Raman conversion at non-linearity of active medium)	1067 533,5 1180
Output Power on CW mode (at 0.95 W pump power for 808 nm), mW - at fundamental - at Second Harmonic	≥ 300 ≥ 15
Output Power on Q-switch mode (at 0.95 W pump power for 808 nm), mW - at fundamental - at Second Harmonic - at 1-st Raman Stokes	≥ 100 ≥ 15 ≥ 0.1
Pulse Repetition Rate (at 0.95 W pump power for 808 nm), kHz	~ 40 (~50*)
Pulse width of fundamental output for Q-switch mode (at 0.95 W pump power for 808 nm), ns	~ 50 (35*)
Electrical consumption	110V/220V, 50-60 Hz, 100 W
Operating temperature	15-30 °C
Storage temperature	-10 to +50 °C
Operating humidity	20 - 90% RH Non-condensing

Laser interlock connection



Caution!

Interlock switch has three operation positions:

(i) – pulled up (released), LD power supply is **ON**

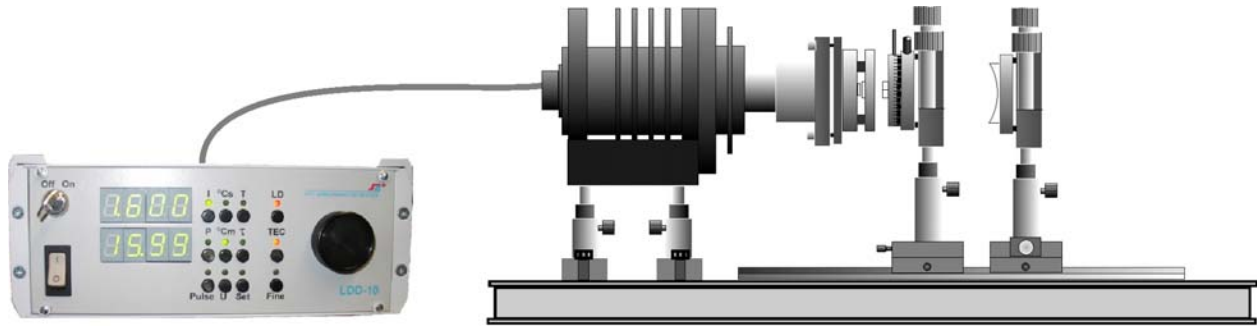
(ii) – intermediate, LD power supply is **OFF**

(iii) – pushed down (not released). LD power supply is **ON**


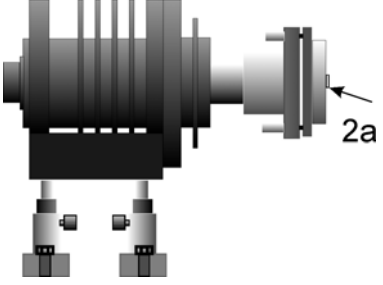
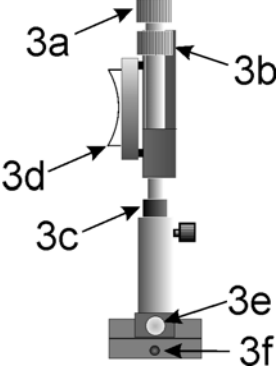
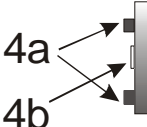
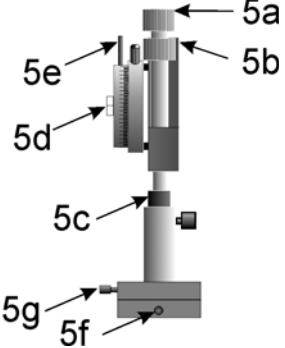
Set (i) uses for installation procedure and for laser operation without the acrylic cover.

Set (ii) uses for laser shut down for normal operation in case of the acrylic cover is removed.




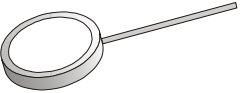





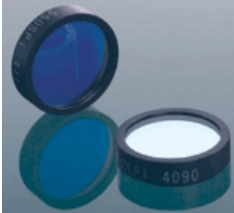
Set (iii) uses for normal operation when acrylic cover is installed, and its flanges pushed down the interlock switches.


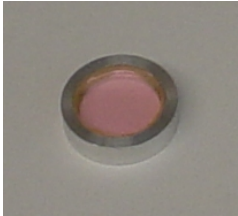

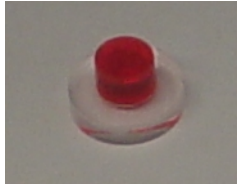
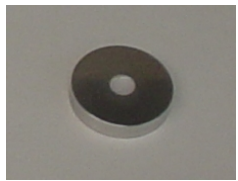


Modules description

<u>MODULE 1: LD POWER SUPPLY</u>	<u>MODULE 2: LD AND LASER CRYSTAL</u>	
 <p> a – Power ON/OFF b – Power key c – Current control potentiometer </p>	 <p>a –Nd:KGW laser crystal</p>	
<u>MODULE 3: OUTPUT COUPLER</u>	<u>MODULE 4: SATURABLE ABSORBER</u>	<u>MODULE 5: KTP CRYSTAL FOR SHG</u>
 <p> a – Vertical alignment of mirror b – Horizontal alignment of mirror c – Post collar d – Output mirror e – Horizontal shift alignment of mirror (perpendicular to optical axis) f – Platform fixed to optical rail </p>	 <p> a – Magnetic ring b – Cr:GSGG crystal </p>	 <p> a – Vertical angular alignment of crystal b – Horizontal angular alignment of crystal c – Post collar d – KTP crystal e – Handle for rotation of crystal f – Platform fixed to optical rail g – Horizontal shift alignment of crystal (perpendicular to optical axis) </p>

Accessories and additional modules

	<p>Honeycomb breadboard for laser kit installation (included)</p>
	<p>Optical rail with metric scale for resonator alignment (included)</p>
	<p>Safety glasses (included)</p>
	<p>Converter of IR emission to visible (included)</p>
	<p>Converter of IR emission to visible (for SRS detection, included)</p>
	<p>Red laser diode module</p>
	<p>Power Meter</p>
	<p>Fast photodiode for measurement of intensity kinetic</p>
	<p>Oscilloscope</p>
	<p>Glass filters</p>

	Spectrometer
	Saturable absorber
	Organic crystal powder for SHG
	Sample for two-photon excited luminescence observation
	Sample for anti-Stokes excited luminescence observation

Module 1: LD power supply

The LD power supply LDD-1C is an electrical current generator with various control options, which provide a stable operation of the Laser Diode at the optimized temperature conditions. For detailed description please read LDD-1C User Manual (included).

Module 2: LD and laser crystal

This module consists of a LD head (808 nm output wavelength) with a thermo-electric cooler for laser diode temperature stabilization, focusing system, and mounted potassium gadolinium tungstate crystal doped with neodymium ions (**2a**) - Nd:KGW ($\varnothing 3\text{mm} \times 10\text{mm}$) as active medium of solid-state laser with laser transition at 1067 nm (attached to the focusing system cylinder). The two parallel crystal facets are optically polished and coated by dielectric coatings. One side is coated with an anti-reflection (AR) thin film (in order to decrease intracavity passive losses). The second facet is coated by multi-layer dielectric film with high reflection in range of 1060-1180 nm, and serves as rear mirror.

See Appendix I for LD parameters.

CAUTION

- *Do not touch any polished surface of crystal by fingers and any others hard materials. It can cause damage of surface optical quality.*

Nd:KGW crystal and pumping LD are pre-aligned, but may require optimization. If original alignment has loosen the following procedures should be fulfilled:

- the crystal housing in module 2 should be rotated in mount around axis to obtain the maximum absorption of the pump beam;
- the crystal housing in module 2 should be shifted along the direction of optical axis to achieve a maximum up-converted intensity (yellowish radiation in pump waist area) at constant pump power.

Module 3: Output coupler

Secure this module to the optical rail as shown. Spherical concave mirror **3d** (curvature radius $r=75$ mm) is mounted in mirror holder. Fine thread screws **3a** and **3b** with allow alignment of the tilt of mirror relatively to optical axis of laser. Micro-screw **3e** allows the mirror to be horizontally adjusted in the direction perpendicular to the optical axis. The mounting platform is fixed to optical rail by screw **3f**. Infrared output of the laser requires the “IR” mirror to be used (see label on the lateral face of mirror). This mirror has transmittance $T=0.05$ at the laser wavelength (1067 nm). Second harmonic generation and stimulated Raman scattering outputs also require special mirrors: “SHG” and “SRS”, respectively. These mirrors have high reflection (HR) at laser frequency and optimal transmittance for second harmonic and Raman output. Post collar **3c** retains the position of the post in post holder providing proper mirror height position in the resonator.

CAUTION

- *Be extremely careful while changing mirrors. Do not touch surface of output coupler by fingers and any others hard materials. It can cause damage of surface optical quality.*

Post collar **3c** serves as regulator of OC position height. Accessories for fine adjustment of output mirror height are not provided for this model. Please avoid unscrewing the post collar to keep proper pre-alignment of the OC height.

Module 4: Saturable absorber

The saturable absorber provided is thin gadolinium scandium gallium garnet crystal plate doped with chromium ions (Cr:GSGG, thickness ~ 1 mm) with initial transmittance at laser wavelength $T_0=95\%$. Both faces are polished and AR-coated in order to decrease intracavity passive losses.

To place the saturable absorber module into the resonator, gently attach it to module 2 using the magnetic ring. Side marked by black point should be faced to module 2. During this procedure avoid any contact between crystals and mechanical parts. Be sure that the crystal mounts do not block the open apertures of laser and saturable absorber crystals.

CAUTION

- *Do not touch surface of crystal by fingers and any others hard materials. It can cause damage of surface optical quality.*
- *Keep the magnetic ring clean so the crystal stays aligned.*

Module 5: KTP crystal

Module 5 is intended to convert fundamental laser frequency to second harmonic. Module 5 is also mounted on the optical rail. Nonlinear Potassium Tytanil Phosphate (KTP) crystal **5d** ($4\times 4\times 4.5$ mm) is cut at proper angle to meet the requirement of phase synchronism. The two parallel sides of the crystal are polished and AR-coated at laser wavelengths in order to decrease intracavity passive losses. The crystal mount possesses two fine thread screws (**5a** and **5b**) for angle alignment of the crystal relative to the resonator axes in horizontal and vertical planes. Handle **5b** allows crystal rotation around the resonator axis. Post collar **5c** keeps the post within the post holder and is to adjust crystal height position in the resonator. Horizontal shift of the crystal along optical axis and in directions perpendicular to it is realized by sliding the holder platform along the optical rail and platform guide. Screws **5g** and **5f** are used to fix the platforms after alignment.

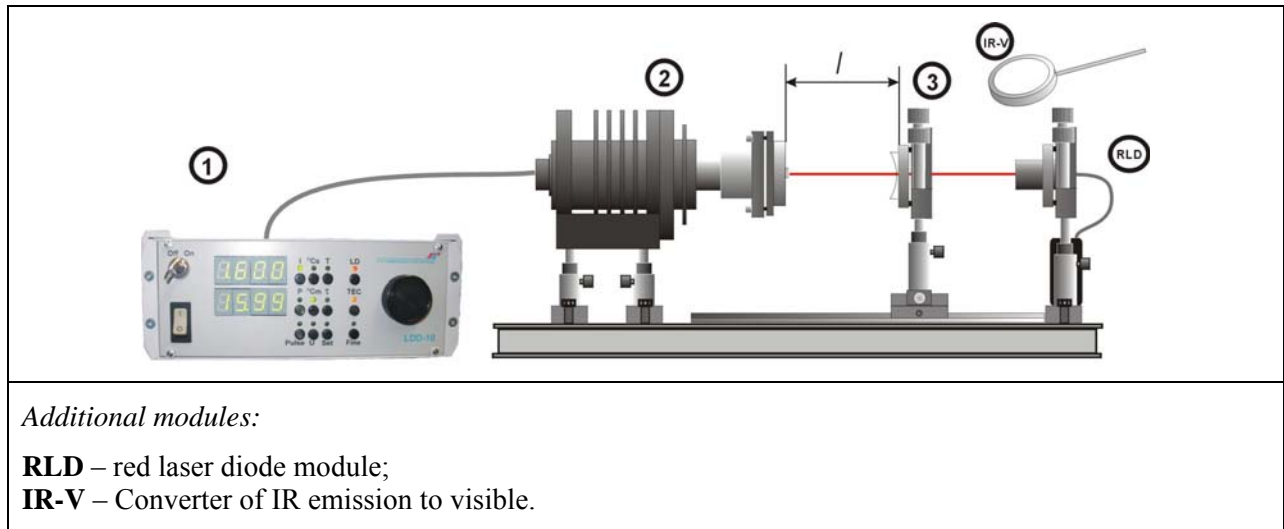
CAUTION

- *Do not touch surface of crystal by fingers and any others hard materials. It can cause damage of surface optical quality.*

Installation and alignment

Please see attached CD with the instruction and movie for an initial laser kit installation. Follow the shown procedure for initial laser kit installation.

The laser kit is usually delivered with all laser modules mounted on the honeycomb board and pre-aligned to be ready for lasing. If the laser alignment has been lost during shipment, try to adjust gently the screws 3a and 3b of the mirror holder in both angular directions while continuously checking the lasing of second harmonic (green) laser beam. If unsuccessful, please use the following alignment procedure.



1. Remove all holders from the optical rail.
2. Align pilot red laser along the optical axis of DPSSL layout. For this purpose direct the laser beam to laser crystal facet of module 2 in such way that it enters to the laser crystal close to the center of crystal aperture. Adjust the red laser direction until reflected beam (from the crystal surface) returns normally. A piece of white paper with a pinhole (~ 1 mm) between red laser and crystal (serving as an aperture) can assist with the alignment.
3. Place the IR output mirror (module 3) onto the rail. The output mirror should be placed at a distance ≈ 60 mm (area of resonator stability) from laser crystal holder (see figure above) by sliding the mirror holder platform along the optical rail.
4. Align the mirror along the optical axis of the DPSSL layout. Superimpose the centers of the red laser beams reflected from both surfaces of the mirror using screws 3a and 3b of mirror holder. If necessary, shift the mirror by micro-screw 3e horizontally in a direction perpendicular to optical axis in such way that red laser beam spot will be in the center of the mirror.
5. Set two interlock switches to the (i) position. Turn on the power supply (module 1) and adjust the pump current to ~ 1.500 A (see the instruction on power supply, page 27).
6. Check the laser output by using the IR-V converter – place the white surface of the converter in the way of the laser output beam. If laser light is present, the IR laser beam will be seen as a green spot on the converter surface.
7. If there is no lasing (no green spot), slightly adjust the screws (3a and 3b) of the mirror holder in both angle directions while continuously checking the IR-V converter for a green spot.
8. Once the laser operation results in a green spot, try to adjust it to higher brightness while keeping the beam shape close to round by adjusting the screws of mirror holder.
9. Laser kit is ready to perform the experiments proposed below. Set the interlock switch to the (ii) position.



Laser Safety.

Caution: Please read this section carefully before practice laser kit!

The Nd:KGW laser student kit is a laser which is designed for laboratory use only. These lasers should be operated in suitable room and under the direct supervision of a person qualified in the safe use of lasers.

- The laser diode in Module 2 (LD and laser crystal module) produces a maximum CW power of 1800 mW at 803-810 nm and is Class 4 laser product.
- Module 2 configured with the Laser Diode and laser crystal installed in output aperture of Laser Diode (absorbing more than 90% of Laser Diode emission) produces a maximum CW power of 180 mW at 803-810 nm. Removal of laser crystal from Module 2 is not recommended and will void all warranties.
- The diode pumped solid-state Nd:KGW laser built on the base of laser student kit produces a maximum CW power of 360 mW or 6 μ J in pulsed mode at 1067 nm.
- The diode pumped solid-state Nd:KGW laser built on the base of laser student kit with intracavity second harmonic generation n produces a maximum CW power of 0.5 mW or average 5 mW in pulsed mode at 534 nm.

The complete assembled laser is therefore a product, which exhibits the power characteristics of a Class 3B laser. The Nd:KGW laser kit can be modified in a number of different ways, therefore the responsible person of this system must ensure that the safety requirements are met.

The manufacturer provides a guarantee for the individual modules, but does not accept any responsibility of damage, which arises from the combination of the modules.

At all times During laboratory alignment, operation, maintains, or service of this laser avoid exposure to laser or collateral radiation exceeding the accessible emission limits listed in "Performance Standards for Laser Products", United States Code of Federal Regulations, 21 CFR 1040 10(d).

The user must observe the laser safety regulations:

- Section 5(A)(1) General Duty Clause of OSH Act
- 29 CFR 1910.95 Occupational Noise Exposure and Appendices
- 29 CFR 1910.133 PPE
- 29 CFR 1910.134 Respiratory Protection

29 CFR 1910.147 Lockout/Tag out
29 CFR 1926.54

Class 3B lasers are potentially hazardous, because a direct beam or a beam reflected by a mirror can enter the unprotected eye (direct viewing into the beam). The following common precautions should be made to prevent direct viewing into the beam and to avoid uncontrolled reflections from mirrors:

- a) The laser should only be operated in a supervised laser area.
- b) Special care should be taken to avoid unintentional reflections from mirrors.
- c) Where possible the laser beam should terminate on a material, which absorbs or scatters the light diffusely after the beam has passed along its intended path. The color and reflection properties of the material should enable the beam to be diffused, so keeping the hazards due to reflection as low as possible (minimum distance of 13 cm between screen and cornea of the eye and a maximum observation time of 10 s)
- d) The use of appropriate protective eyewear at all time is strongly recommended.
- e) The entrances to supervised laser areas should be identified with the laser-warning symbol.

The voltage in the system can be harmful or even lethal. Whenever handling or servicing the laser, always disconnect the power cord to the power supply.

The Laser Diode is sensitive to Electro-Static Discharge. Never handle Laser Diode disconnected from power supply without being properly grounded through the use of properly installed and maintained grounding wrist straps.

<p>Attention: The individuals and the institutions that are operating the laser kit are solely responsible for observing the laser safety rules</p>
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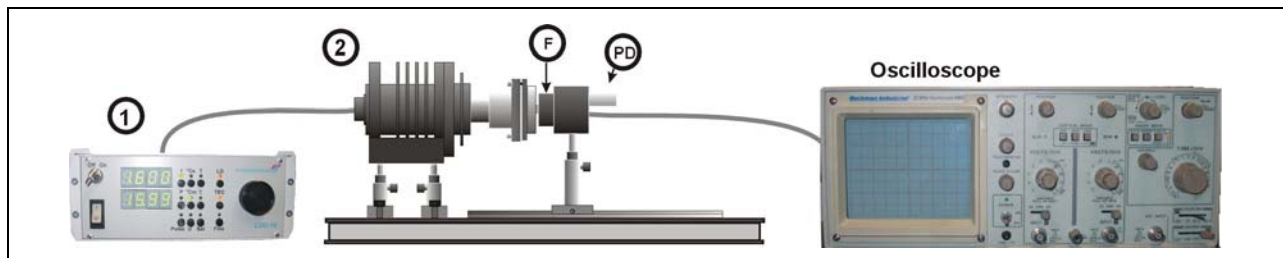
EXPERIMENTS *

Caution: please use laser safety glasses to perform all experiments

Experiment #1: Measurement of the time relaxation of the upper laser level of $\text{Nd}^{3+}:\text{KGd}(\text{WO}_4)_2$

The purpose of this experiment is the measurement of time relaxation (lifetime) from upper laser level ${}^4\text{F}_{3/2}$ of $\text{Nd}^{3+}:\text{KGd}(\text{WO}_4)_2$ laser crystal. Lifetime is the time, which pass before the intensity magnitude of spontaneous emission became e times ($e \approx 2.7$) less than the initial value. For neodymium ion concentration $C_{\text{Nd}} = 3\text{at}\%$ the relaxation time of ${}^4\text{F}_{3/2}$ multiplet is approximately 110 μs .

EXPERIMENT SETUP:



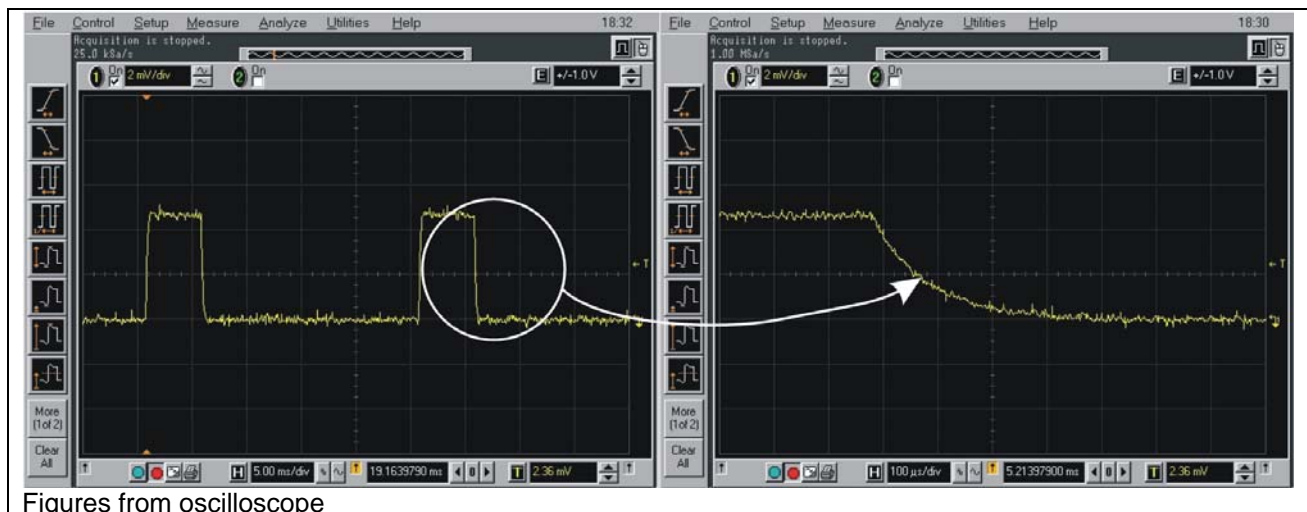
Additional modules:

F – filter for cutting pump emission (FEL0850 (850LP), Thorlab Inc);

PD – fast photodiode for measurement of intensity kinetic;

Oscilloscope.

1. Place filter F (Long Pass FEL0850) to the filter mount attached to the photodiode PD. Slide carefully photodiode rail carrier on the rail to the LD module. Modules F & PD should be as close as possible to the module 2. Do not touch module 2 by the face of PD module, leave a space approximately 0.5 -1.0 mm between the faces of PD and module 2.
2. Switch LD power supply to PULSE mode of operation and set pulse duration to 5 ms value and pulse repetition period to 25 ms (see page 27). In this regime laser operation the crystal will be excited by light pulses with of 5 ms and period of repetition of 25 ms.
3. Increase LD current up to 2.000 A. Obtain on the oscilloscope the picture of the photodiode signal, corresponding to spontaneous emission intensity changes, like the picture shown in the figure below.



Figures from oscilloscope

4. In the falling edge of the spontaneous emission pulse find the intensity level corresponding to $1/e$ (I) from the maximum (I_m). Find the time t between maximum and $1/e$ level of the intensities. This value will correspond to the Nd^{3+} fluorescence lifetime of the ${}^4\text{F}_{3/2}$ energy upper laser level in $\text{Nd:KGd}(\text{WO}_4)_2$ ($\sim 110 \mu\text{s}$)

After finishing the experiment:

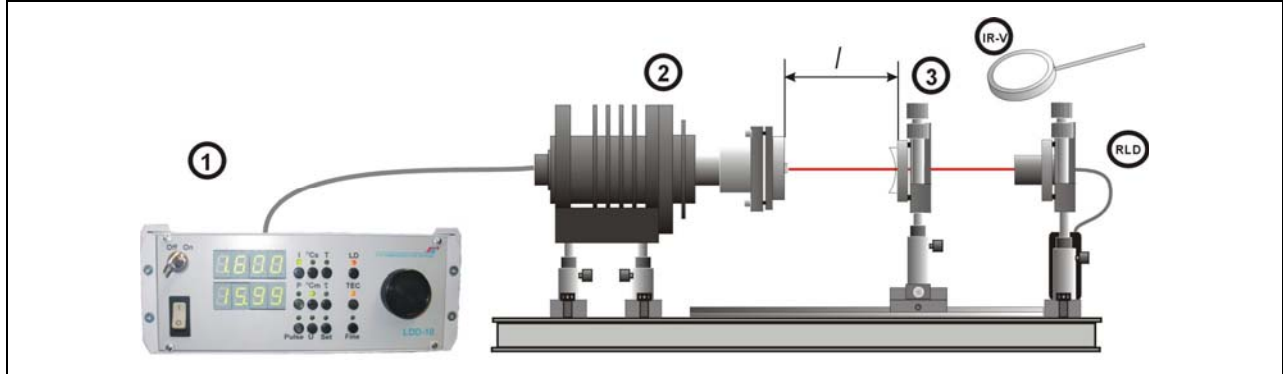
- Decrease the LD pump current to zero (module 1);
- Return power supply from PULSE mode to CW by pushing “PULSE” knob (module 1);
- Turn off power supply (module 1);
- Cover the laser layout with Plexiglas shield to protect optical elements from dust.

* All experiments are executing with interlock switch set at the position (i).

Experiment #2: Obtaining CW laser operation

The purpose of this experiment is to obtain CW laser operation from a $\text{Nd}^{3+}:\text{KGd}(\text{WO}_4)_2$ laser crystal and optimize it to maximum power.

EXPERIMENT SETUP:



Additional modules:

RLD – Red diode laser module;

IR-V – Converter of IR emission to visible.

1. Align RLD module (or He-Ne laser) along the optical axis of DPSSL layout. For this purpose you must direct the laser beam to the laser crystal facet of module 2 in such way that the reflected beam (from the crystal) coincides with the direct beam. White aperture on the RLD face could be served for the alignment. Add the IR output mirror (module 3) to the layout. The output mirror should be placed at a distance $l \approx 64$ mm (section of resonator stability) from laser crystal holder (see setup figure above) by sliding the mirror holder platform along the optical rail.
2. Align the mirror along the optical axis of the DPSSL layout. Superimpose the centers of the RDL module beams reflected from both surfaces of the mirror using screws 3a and 3b of mirror holder. If necessary, shift the mirror by micro-screw 3e horizontally in a direction perpendicular to optical axis in such way that RDL beam spot will be in the center of the mirror.
3. Turn on the power supply (module 1) and adjust the pump current to ~ 1.500 A.
4. Check the laser output by using IR-V converter – place the white surface of the converter in the way of the laser output beam. If laser light is present, the IR laser beam will be seen as a green spot on the converter surface.
5. If the laser is not working properly (no green spot) try to adjust the screws of the mirror holder in both angular directions while continuously checking the IR-V converter for a green spot.
6. Once the laser operation results in a green spot, try to adjust it to higher brightness (e.g. higher laser power) while keeping the beam shape close to round by adjusting the screws of mirror holder.
7. **(Optional)** If the laser power meter is available, maximize the output laser power using the power meter by adjusting the mirror holder screws. Refer to the power meter manual for directions to measure the laser power by the power meter.

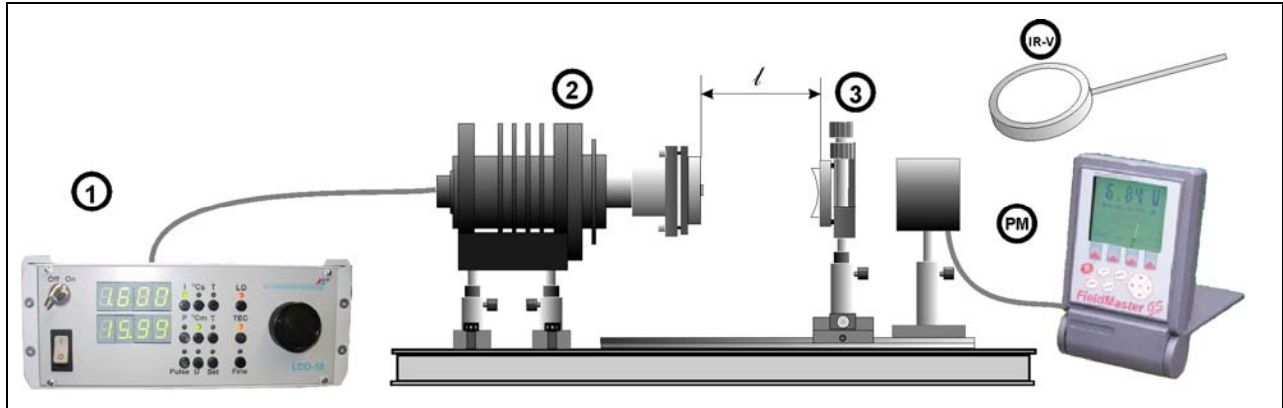
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Turn off RDL module
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

Experiment #3: Single mode laser operation and resonator stability

The aim of this experiment is to obtain the laser operation at single TEM₀₀ transversal mode and to verify the length of the stable resonator.

EXPERIMENT SETUP:



Additional modules:

PM – Power Meter;

IR-V – Converter of IR emission to visible.

1. Align the laser to obtain CW laser operation with IR output coupler, or use the alignment, which was done in previous experiment with $l \approx 64$ mm.
2. Adjust pump current to 1.300 A.
3. Align the output laser spot visualized by IR-V converter to shape close to round (without structure). This output beam corresponds to single TEM₀₀ mode laser operation.
4. Align the output power of the laser to maximum using screws 3a and 3b of output coupler module. Do the alignment gently keeping TEM₀₀ mode operation. Check laser output power at the end of alignment.
5. Repeat the steps 3-5 for $l \approx 30$ mm and $l \approx 68$ mm.
6. During alignment procedure and power measurement pay attention to power output and output beam diameter/mode structure changes.
7. Try to observe laser operation for $l > 68$ mm by gentle sliding of output mirror module along the optical rail keeping the resonator aligned. The area of non-stable resonator will be reached when output power decreased sharply.

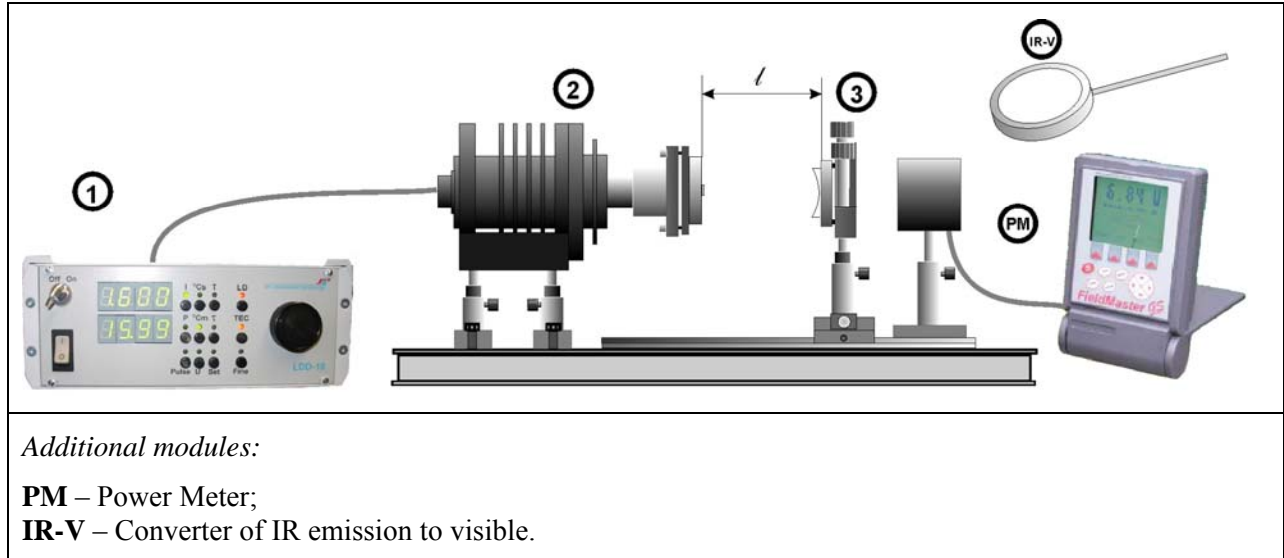
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

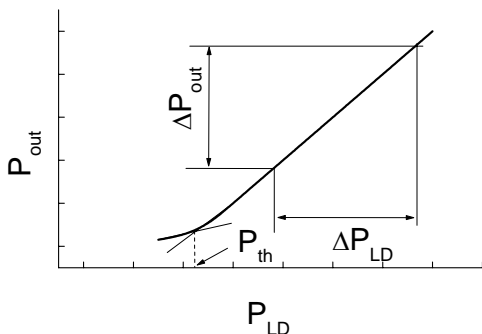
Experiment #4: Measurement of laser threshold and output power at CW laser operation

Once the laser operation appeared and was adjusted to maximum output power for given pump current in the previous experiment, the laser is ready for threshold and power measurements.

EXPERIMENT SETUP:



1. Align the laser to obtain CW laser operation with IR output coupler, or use the alignment, which was done in previous experiments with $l \approx 64$ mm.
2. Adjust pump current to 1.500 A.
3. Align the output power of the laser to maximum using screws 3a and 3b of output coupler keeping the TEM₀₀ mode. Measure the output power for a given pump current using the power meter.
4. Decrease the pump current down by 0.100 A. If necessary, align the output power of the laser to maximum using screws 3a and 3b of output coupler. Measure the output power for given pump current using power meter.
5. Repeat step (4) for currents of 0.600 A.
6. Further decrease the pump current until the laser operation disappears.
7. Use Table 1 of Appendix 1 to recalculate LD power from known magnitudes of pump current.
8. Plot the dependence of the output laser power P_{out} on pump LD power P_{LD} .
9. Calculate the optical laser threshold (P_{th}), efficiency (P_{out} / P_{LD}) and slope efficiency ($\Delta P_{out} / \Delta P_{LD}$) of the laser.



Typical power-power dependence of DPSSL

After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

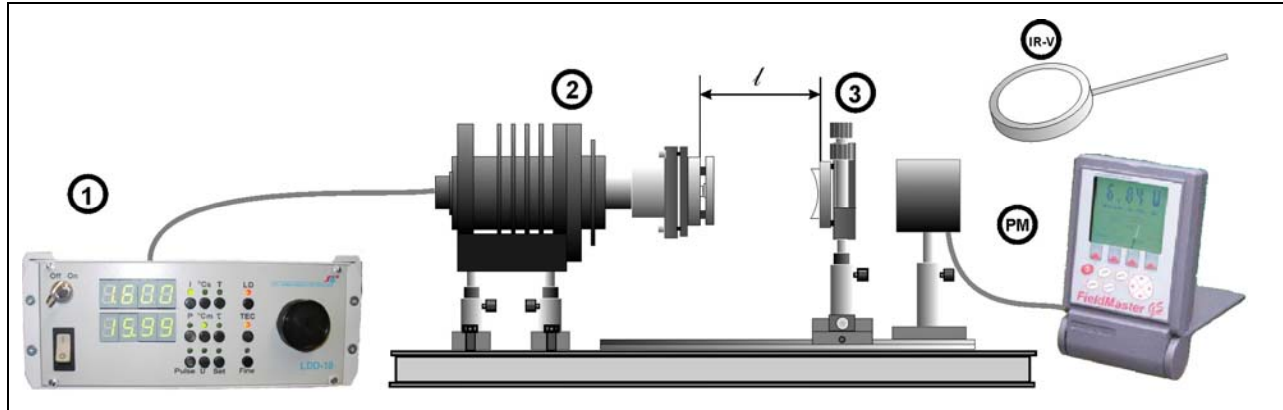
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

Experiment #5: Passive Q-switched regime of laser operation

The aim of this experiment is to obtain pulse laser operation using the passive Q-switching technique.

EXPERIMENT SETUP:



Additional modules:

PM – Power Meter;

IR-V – Converter of IR emission to visible.

1. Align the laser to obtain CW laser operation with IR output coupler, or use the alignment, which was done in previous experiments with $l \approx 64$ mm.
2. Adjust pump current to 1.500 A.
3. Align the output power of the laser to maximum using screws 3a and 3b of output coupler keeping operation at TEM₀₀ mode.
4. Insert module 4 (saturable absorber) into the resonator as shown by gently attaching it to Nd:KGW crystal holder of module 1 using the magnetic ring (see setup layout picture). Rotate the module around optical axis to match black mark on the Cr:GSGG crystal holder with the radial groove on the Nd:KGW crystal holder. During these procedures avoid any contact between the crystals and mechanical parts. Be sure that the crystal mounts do not block the open apertures of laser and saturable absorber crystals. Side marked by black point should be faced to module 2.
5. Align the output power of the laser to maximum using screws 3a and 3b of output coupler. Measure the output power for preset pump current using power meter.
6. Decrease the pump current down to magnitude of 100 mA less than previous. If necessary, align the output power of the laser to maximum using screws 3a and 3b of output coupler. Measure the output power for given pump current using power meter.
7. Repeat step (6) until the pump current is 0.900 A.
8. Use Appendix 1 to recalculate LD power from known magnitudes of pump current.
10. Plot the dependence of the output laser power P_{out} on pump LD power P_{LD} .
11. Define from the obtained data threshold (P_{th}), optical efficiency (P_{out} / P_{LD}) and slope efficiency ($\Delta P_{out} / \Delta P_{LD}$) of the laser.

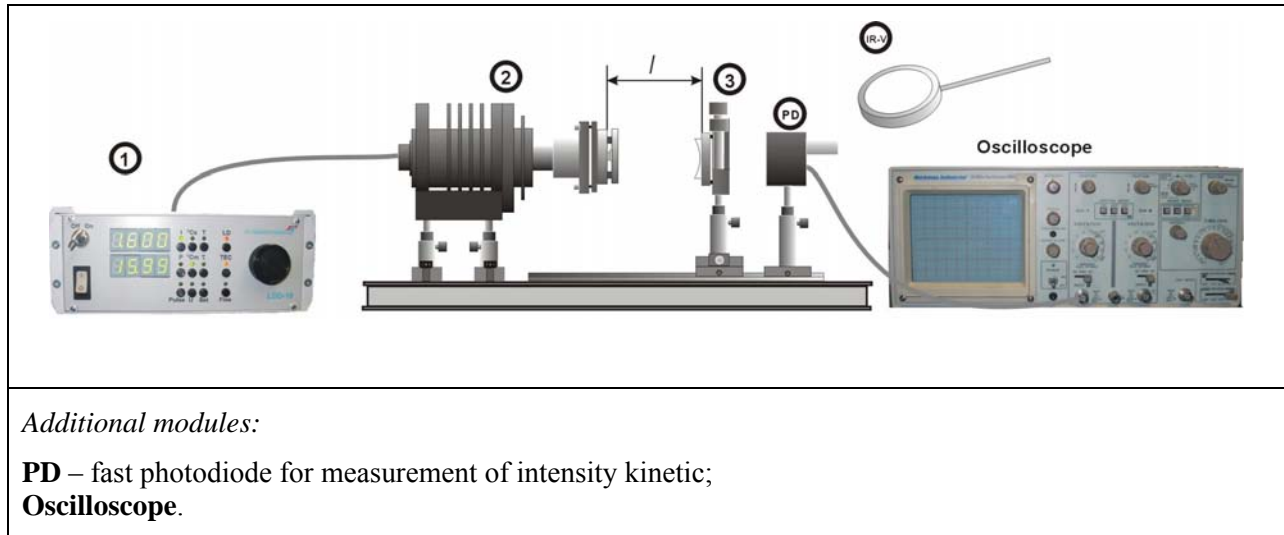
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

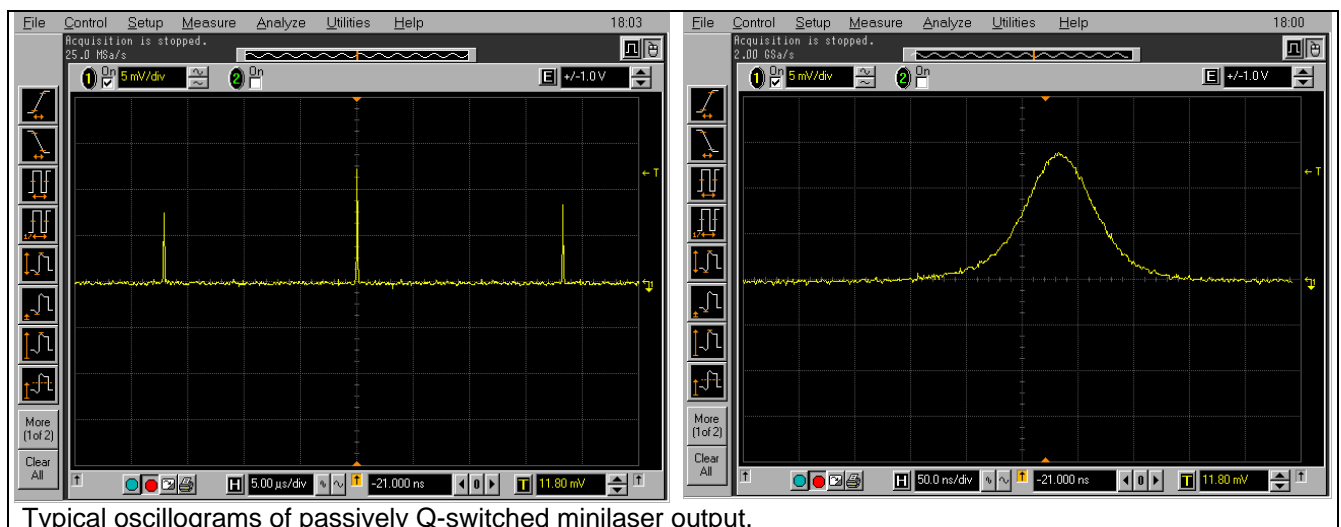
Experiment #6: Passive Q-switched regime of laser operation

The aim of this experiment is to investigate temporal parameters of passive Q-switched laser operation.

EXPERIMENT SETUP:



1. Use the alignment, which was done in experiment 5.
2. Turn on power supply (module 1) and adjust pump current to 1.500 A.
3. Align the output power of the laser to maximum using screws 3a and 3b of output coupler keeping the operation at TEM₀₀ mode.
4. Place the photodiode module connected to oscilloscope in the way of laser beam. **To avoid photodiode damage, place between photodiode and output coupler a piece of white paper (closer to photodiode).**
5. Obtain a reliable picture of laser pulses on oscilloscope (see pictures).
6. Measure the pulse duration at FWHM (full width at half maximum).
7. Measure the pulse repetition rate.
8. Repeat steps 5-7 for different pump powers (pump currents).
9. Use Appendix 1 to recalculate LD power from known magnitudes of pump current.
10. Plot the dependence of the pulse width τ and repetition rate f on pump LD power P_{LD} .



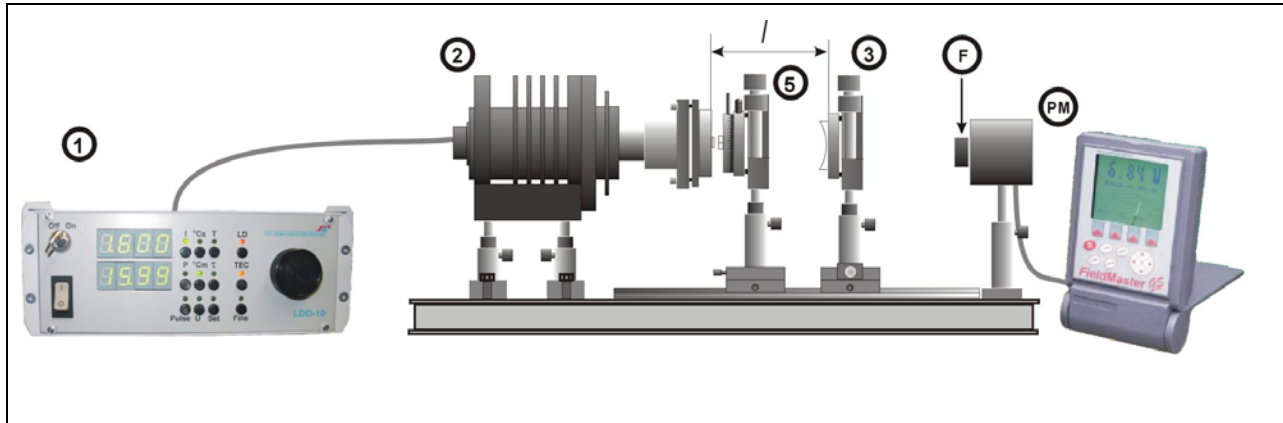
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

Experiment #7: Intracavity CW second harmonic generation

The aim of this experiment is to obtain the intracavity second harmonic generation for CW laser operation and to adjust it to maximum power by achieving the best phase-matching (conversion efficiency).

EXPERIMENT SETUP:

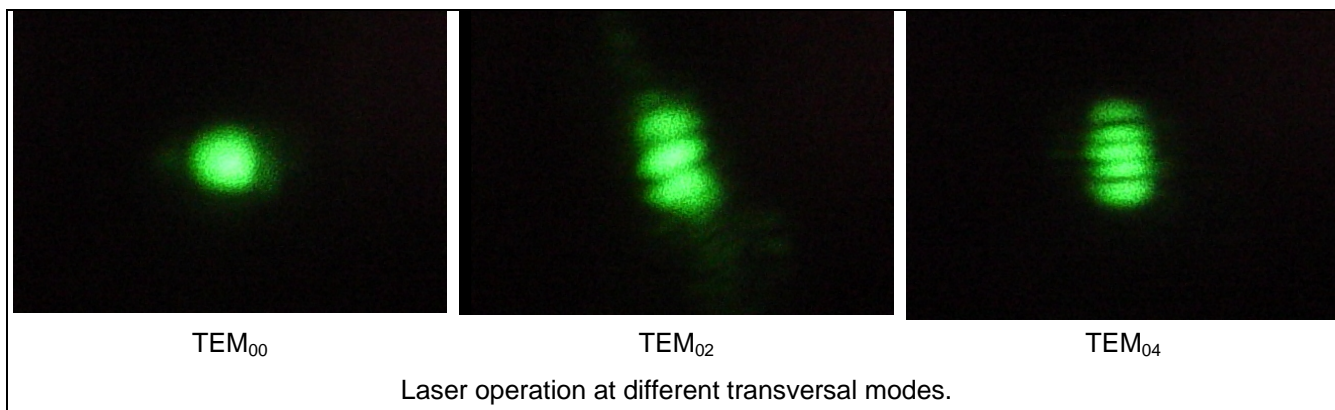


Additional modules:

PM – Power Meter;

F – filter for cutting 1067 nm emission (FES0600 (600SP), Thorlab Inc).

1. Align the laser to obtain CW laser operation with SHG output coupler with $l \approx 64$ mm.
2. Adjust pump current to 1.300 A.
3. Align the output power of the laser to maximum using screws 3a and 3b of output coupler keeping the operation at TEM₀₀ mode.
4. Insert module 5 (nonlinear crystal) into the resonator. Place the module as close to the laser crystal, as possible (see picture) avoiding any contact between crystals and mechanical parts. Be sure that the SHG crystal mount does not block the open apertures of laser and saturable absorber crystals. When the nonlinear crystal is inserted properly, the second harmonic (green light) should appear. If not, align the crystal using angle alignment screws 5a and 5b.
5. When green light appears align the green light output spot to achieve symmetric profile (close to round shape) using screws 3a and 3b of output coupler.
6. Insert glass filter to cut IR (1067 nm) radiation after output coupler.
7. Adjust the intensity of green light (output power) to maximum using screws 5a 5b.
8. Adjust the intensity of green light to maximum by rotating the SHG crystal around the resonator axis (use handle 5e). If during the rotation the green beam shape tends to change, use screws 5a 5b to re-adjust the beam spot back to a round shape.
9. Align the output power of the laser to maximum using screws 3a and 3b of output coupler.
10. Measure and plot the dependence of the output second harmonic power P_{out} on pump LD power P_{LD} .
11. Measure and plot the dependence of the output second harmonic power P_{out} on angle of nonlinear crystal rotation.
12. Re-adjust the laser from single mode TEM₀₀ operation to two-, three-, four- mode operation by using screws 3a and 3b of output coupler module.



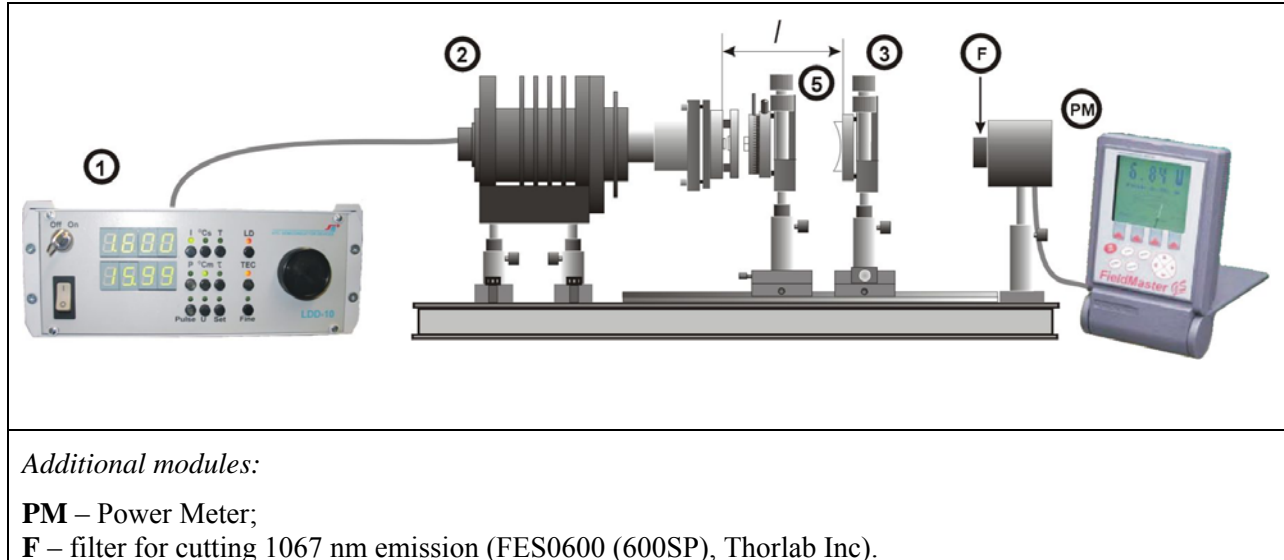
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

Experiment #8: Intracavity second harmonic generation using Q-switched laser operation

The aim of this experiment is to obtain and investigate intracavity second harmonic generation for Q-switched laser operation.

EXPERIMENT SETUP:



1. Align the laser to obtain Q-switched laser operation (see Experiment #5) with SHG output coupler ($l \approx 64$ mm).
2. Adjust pump current to 1.300 A.
3. Align the output power of the laser to maximum using screws 3a and 3b of the output coupler keeping the operation at TEM₀₀ mode.
4. Insert module 5 (nonlinear crystal) into the resonator. Place the module as close to the saturable absorber, as it is possible (see picture) avoiding any contact between crystals and mechanical parts. Be sure that the SHG crystal mount does not block the open apertures of laser and saturable absorber crystals. When nonlinear crystal was inserted properly the second harmonic (green light) should appear. If not, align the crystal using the angle alignment screws 5a and 5b.
5. When green light appears align the green light output spot to a symmetric profile using screws 3a and 3b of output coupler.
6. Insert glass filter to cut IR (1067 nm) radiation after output coupler.
7. Adjust the intensity of green light (output power) to maximum using screws 5a and 5b.
8. Adjust the intensity of green light to maximum by rotating the SHG crystal around the resonator axis (use handle 5e). If during rotation procedure the green beam shape will tend to change use screws 5a 5b to re-adjust the beam spot back to round shape.
9. Align the output power of the laser to maximum using screws 3a and 3b of the output coupler. Measure the output power for given pump currents using the power meter.
10. Plot the dependence of the output second harmonic power P_{out} on pump LD power P_{LD} . Compare this dependence with that obtained in previous experiment.

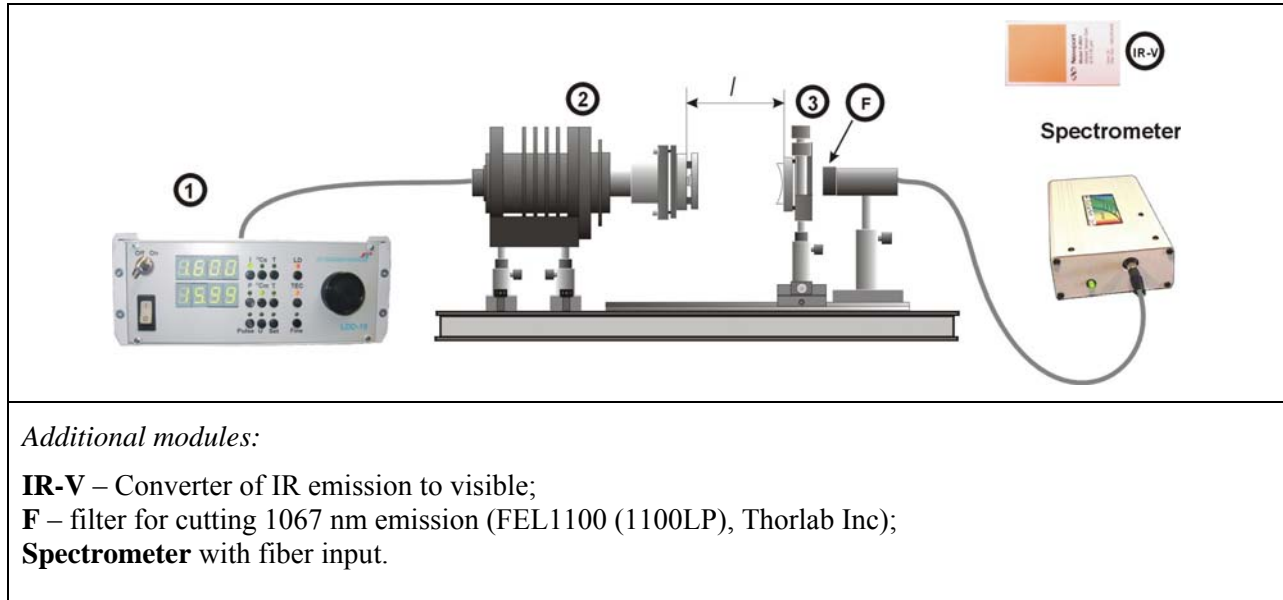
After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

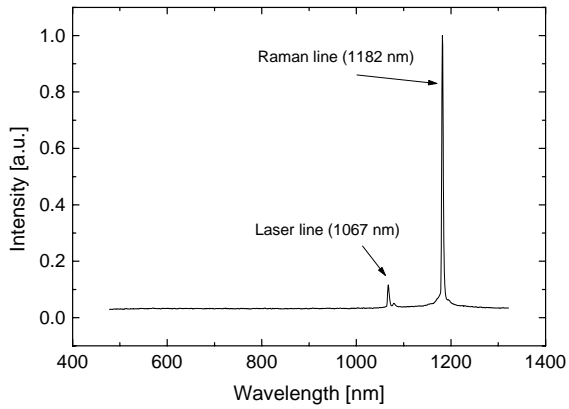
Experiment #9: Intracavity Raman self-conversion using Q-switched laser operation

The aim of this experiment is to obtain and investigate intracavity Raman self-conversion using the same crystal, which is used for laser operation. Since the Stimulated Raman Scattering is the third order of non-linearity, this effect can be obtained only for high laser intensity using Q-switched laser operation.

EXPERIMENT SETUP:



1. Align the laser to obtain Q-switched laser operation (see Experiment #3) with SRS output coupler ($l \approx 34$ mm).
2. Adjust pump current to 1.400 A.
3. Align the output power of the laser to maximum using screws 3a and 3b of output coupler keeping the operation at TEM_{00} mode.
4. Insert glass filter to cut IR (1067 nm) laser radiation after output coupler.
5. Check the SRS output by using IR-V card converter – place the pink rectangular area (sensitive to radiation) of the converter card in the way of the output beam. If SRS light is present, the IR laser beam will be seen as a yellow bright spot on the converter surface.
6. If the laser is not working properly (no bright spot) try to adjust gently the screws of the mirror holder in all directions while continuously checking the IR-V converter for a bright spot.
7. Once the SRS operation results in a yellow spot, try to adjust it to higher power while keeping the beam shape close to round by adjusting the screws (3a and 3b) of mirror holder.
8. Place the laser beam onto the spectrometer fiber.
9. Align the fiber to obtain the first Raman component wavelength (1.18 μm) on the spectrometer.
10. Decrease the pump current down to magnitude when Raman line disappears. This is Raman threshold.



Typical spectrum of output emission of laser operating at laser and Raman wavelengths simultaneously.

After finishing the experiment:

- Decrease the LD pump current to zero (module 1);
- Turn off power supply (module 1);
- Cover the laser layout by Plexiglas shield to protect optical elements from dust.

For questions and comments please contact:

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