Ma 14: Solid State Laser Principles

1. Abstract

The process of *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation (laser) can currently provide electromagnetic radiation with exceptional properties from the infrared over the full visible to the ultraviolet spectral range and in special cases into the x-ray regime. It is particularly the coherence in the phase and direction of laser emission that has allowed for its wide spread usage in industrial, medical and scientific applications, largely surpassing the capabilities of any other light source. Lasers currently allow for the highest precision in the measurement of frequency and time to be achieved, with a relative accuracy in the range of and even below $\Delta\nu/\nu = 10^{-15}$. This is in competition with and can surpass the cesium clock standard based on microwave technology. The directionality of laser emission has allowed for long distance measurements on the order of tens to hundreds of kilometers in monitoring atmospheric distortions for ground based telescopes in astronomy or in determining constituents of the mesosphere in environmental applications. Even distances of hundreds of thousands of kilometers have been measured by determining the distance to the moon with a precision of a few centimeters. On smaller length scales, resolution far below the wavelength of light can be achieved on the order of tens of nanometers in the imaging of macromolecular systems and organelles of cells in biology. The relative motion of atoms in molecules can be observed with a precession on the order of tens of picometers with the temporal resolution offered by femtosecond laser pulses and the recent development of attosecond technology offers the resolution of electron dynamics. With respect to power, the continuous wave power of standard lasers extends into the kilowatt range. A peak power in the Terawatt domain and in special cases to the Petawatt regime can be achieved with pulsed lasers. This allows for standard applications such as high accuracy material machining for medical and industrial applications and provides an easy access to nonlinear optics. On the upper end of this power scale, even the regime of relativistic optics can be explored. This short summary is only a selected list out of a much larger catalogue of capabilities and applications of laser technology that are rooted in the unique coherence of this radiation source. This catalogue is continuously expanding and it provides the motivation to understand the fundamental principles underlying laser technology.

2. Preparation

2.1 Fundamental principles of the laser

While there are different mechanisms for obtaining the coherent emission of light from a medium, light amplification by stimulated emission of radiation or **lasing** is most commonly realized by **pumping** an **active medium** within a **cavity** or **optical resonator**. These three fundamental elements of a laser are employed to obtain a particular set of conditions for the interaction of an optical medium with the light quanta or **photons** of a radiation field. The function behind these three elements becomes clear when considering the type of processes that can take place in the interaction of light with a medium, the probability of these processes and the conditions that are necessary for enhancing one particular type of event. In view of the black body

radiation reported by Wilhelm Wien and its interpretation by Max Planck at the turn of the last century, Albert Einstein was able to formulate the equilibrium state of a quantized radiation field with its source and derive the three basic processes of **absorption**, **spontaneous emission** and **stimulated emission** together with the respective probabilities described by the **Einstein coefficients** B_{nm}, A_{mn} and B_{mn}. Among these three processes, it is only stimulated emission that generates electromagnetic radiation fully equivalent in **frequency**, **phase**, **polarization** and **direction** within the amplification of light. These properties are responsible for the distinctive coherent emission of a laser. Due to this, the elements of a laser are configured to particularly enhance stimulated emission in its competition with absorption and spontaneous emission. These work against coherent amplification by annihilating photons or generating incoherent radiation.
In order to enhance the probability of stimulated emission over an absorption process, the active medium usually provides a **three** or **four level structure** of quantized states that are coupled in a particular manner via **radiative** and **non-radiative** processes (see Fig. 1). The pumping process serves to deposit energy into the active medium, which populates the excited energy levels and brings the system into the state **population inversion** between the two levels that serve for the **lasing transition**. When the population of an excited state level exceeds the population in the energetically lower level, the probability of stimulated emission surpassed the respective rate of absorption. Pumping an active medium for a continuous, steady-state cycling through the three or four levels of the system and indirectly populating the state involved in the stimulated emission process is commonly achieved by **optical pumping** (flash or arc lamps, diodes or other lasers). Alternatively, pumping can also be achieved without radiation through electric discharge (*i.e.* HeNe, Ar^+, and N_2 laser). Coherent emission can also be obtained from other processes such as the luminescence of chemical reactions (*i.e.* HCl laser) or be induced by the acceleration of electrons in their passage through magnetic fields of alternating polarity (wigglers in a free electron laser).
Further considering the competition between spontaneous and stimulated emission, the medium is commonly brought into an optical resonator, which consists of reflective faces that trap the emission in specific modes. The dimensions of the cavity determine the frequencies at which these modes can oscillate. By introducing the resonator, the radiation field is directly coupled back to the active medium. This allows for the number of photons per cavity mode to surpass unity and under these conditions, the probability of stimulated emission exceeds the value for spontaneous emission. For this case, the **threshold for lasing** is meet when the amplification by stimulated emission further compensates the losses within the cavity. When this occurs, the modes of the cavity that are within the bandwidth of the **gain profile** of the medium spontaneously begin to oscillate and the system transfers into the state of lasing. In some cases, the gain of certain laser media is high enough to operate without a cavity (*i.e.* N_2 laser). A **closed cavity** (confinement in all three dimensions) and an **open cavity** (on-axis confinement in one dimension) are principally possible but the exceedingly high number of modes for a reasonable cavity size make closed configurations unpractical for the wavelengths in the ultraviolet, visible and near infrared spectrum. Closed cavities are however used for longer wavelengths in masers (*m*icrowave *a*mplification by *s*timulated *e*mission *r*adiation). Open cavities used for lasers usually consist of two high reflective mirrors, where one of the mirrors shows a slightly lower reflectivity in order to allow for a small percentage of the coherent emission to escape the cavity. The number of nodes along the axis of the resonator defines the **longitudinal modes** of the cavity and their frequencies. While most lasers

are designed to operate with a **Gaussian profile** in the cross-section of the intensity distribution normal to the axis of a cavity, the **transversal mode** of an open cavity can also show nodes (two dimensional **Laguerre polynomials** for cylindrical symmetry). The structure of the transversal electromagnetic mode (denoted by $\mathbf{TEM_{nm}}$) is determined by the curvature of the cavity mirrors and their distance. These are usually adjusted to meet the **stability criterion**, which describes the capability to contain the radiation within the cavity and avoid losses out of the open configuration. Since the geometry varies for different transversal modes, the frequency of the emission from different modes can be shifted from the frequency of the ideal Gaussian TEM_{00} mode.

2.2 General principles of operation: the continuous wave Nd:YAG laser

While the active medium of a laser can range form gases to liquids and solutions of dyes, solid state materials such as crystals or glasses doped with metal ions show many advantages over other media. Next to their specific emission properties, the advantages are generally given by engineering aspects such as their durability, long lifetime, reproducible and stable emission parameters as well as their simple and compact integration into a laser configuration. It is noteworthy, that the first laser realized by Theodore Maiman in 1960 was a solid state ruby laser (aluminium oxide, Al_2O_3 crystal lattice doped with of Cr^{3+} ions). At the time, the laser was often referred to as an “optical maser” since Charles Townes and Arthur Schawlow obtained the first coherent radiation by stimulated emission in the microwave regime with the ammonia maser in 1954.
Within the class of solid state lasers, the **Nd:YAG** laser (a yttrium aluminium granate, $Y_3Al_5O_{12}$ host crystal doped with Nd^{3+} ions) is one of the most wide spread laser media in industrial and scientific applications. The term scheme for this system is shown in Fig. 1. The system has four discrete absorption bands between the sublevels of the $^4I_{9/2}$ and $^4F_{5/2}$ electronic states of the Nd^{3+} ions in the YAG host lattice between 804.4 and 817.3 nm that are relevant for pumping the system. Non-radiative coupling via **lattice phonons** transfers the system to the sublevels of the $^4F_{3/2}$ state from which lasing transitions to the $^4I_{9/2}$, $^4I_{11/2}$, and $^4I_{13/2}$ sublevels occur at 946, 1064 and 1322 nm, respectively. The cycling through these states constitutes a classical four-level laser medium as shown in Fig. 1. The fast non-radiative relaxation processes together with the long lifetime of the $^4F_{3/2}$ state guarantee high **quantum efficiency** in the conversion of the pump energy to laser energy output.

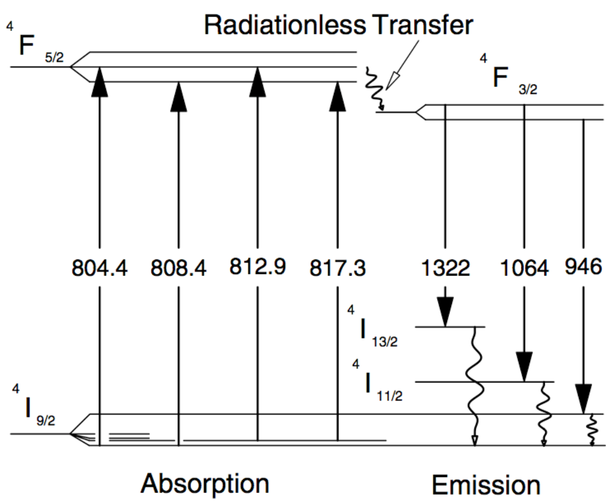


Fig. 1: The term scheme for the Nd:YAG medium with the four-levels relevant for lasing. Taken from [6].

The pumping of the $^4F_{5/2} \leftarrow {}^4I_{9/2}$ transitions in the Nd:YAG medium is generally realized by flash and arc lamps or by diode emission. While flash and arc lamps are economical, their broadband emission is not well matched for pumping the limited spectral range of the narrow absorption bands in Nd:YAG. This leads to a low efficiency for this arrangement. The tunable emission of a *diode laser* (or arrays of laser diodes for higher power) allows for the pumping of the absorption bands in the Nd:YAG medium at approximately 20 times higher efficiency than with flash or arc lamps. Furthermore, using diode lasers for pumping a Nd:YAG medium results in significantly high stability in the laser emission. It allows for compact integration into the laser arrangement due to the limited size of diodes and avoids the extensive cooling mechanisms associated with the inefficient and instable pumping with flash or arc lamps.

Since diode lasers are becoming an integral part of Nd:YAG laser operation, it is important to review the particular aspects of their function relevant for this application. Generally, diode lasers are **pn-junction semiconductor** lasers, which means they are composed of a p-type and n-type semiconductor materials in mechanical contact. For pumping the Nd:YAG medium, p- and n-AlGaAs semiconductor materials are used with an GaAs **active zone** that spatially separates the charge carriers at the boundary of the heterojunction. This acts as an energy barrier for the **Fermi energy level** before voltage is applied as shown in Fig. 2. Significant differences arise between the working principle of a classical laser configuration and this type of a diode laser arrangement. The emission is obtained from electron-hole recombination when a current is driven through the junction by applying voltage. In this process, excess n-zone electrons at higher energies meet hole charges of the p-zone in the active GaAs region as illustrated in Fig. 2. Radiation from this recombination is obtained at wavelengths that correspond to the energetic separation in the band structure. Amplification is achieved parallel to the junction through a cascade of stimulated emission in the electron-hole recombination at elevated electron densities from the injection current into the active zone through the applied voltage. This cascade of stimulated emission is possible since the band structure is not limited to a discrete energy as the isolated eigenstates of metal ions in a host crystal that follow the **Pauli exclusion principle**. This allows for numerous electrons to occupy a band at varying energies to the point of inversion through the current driven into the active zone.

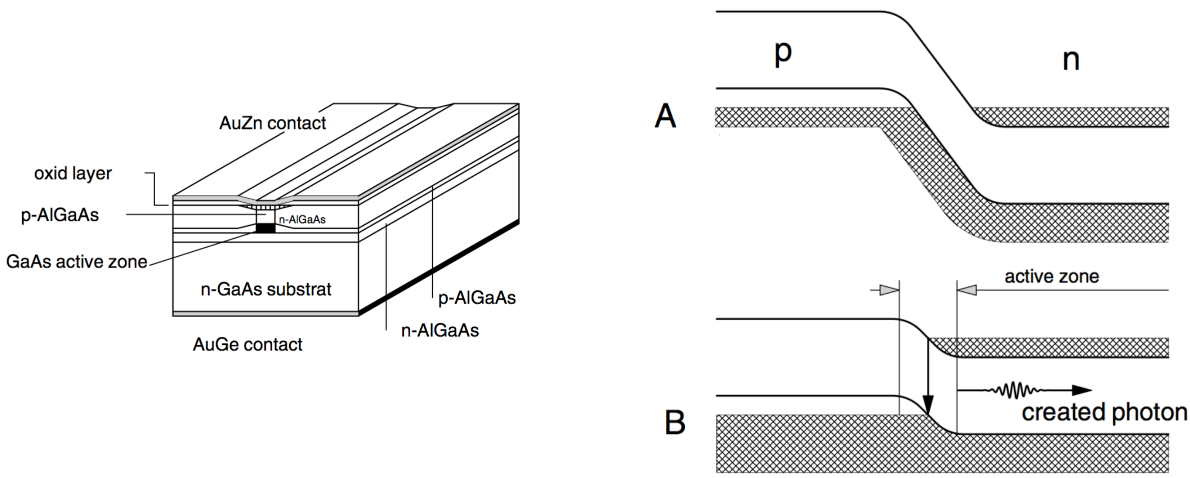


Fig. 2: Schematic of a AlGaAs semiconductor laser (left). Relative energy of the band structure and Fermi level without (A) and with (B) applied voltage as well as the emission from the transition in electron-hole recombination (right). Taken from [6].

Not only the mechanism for obtaining inversion and stimulated emission is changed from a classical lasers arrangement, the guiding of the laser emission in a diode is also fundamentally different. Rather than the free propagation of the coherent radiation within the confinement of the laser cavity, the dimensions of the active zone and the **refractive index** of the materials at the junction act as a **waveguide** in directing the light through the system. Due to this, the laser mode reflects the geometry of the active zone and causes the rectangular like transversal mode profile and high divergence typical for semiconductor lasers. Another important consequence arises form this laser arrangement. The energy of the band structure is dependent on the density of the medium as well as the density of charge carriers in the active zone. This makes the spectrum of the emission obtained from the diode significantly dependent on the temperature and the current in the diode. While the spectral shifting of the emission by temperature and current allows for the practical tunability of laser diode emission, precision temperature and current control is often necessary for stable pumping conditions.
With the diode pump laser described above and the four-level system provided by the Nd:YAG crystal, the full laser operation is realized with a simple cavity composed of two **dielectric mirrors**. The tunability of the diode pump laser offers the possibility to discretely pump one of the four different absorption bands of the Nd:YAG medium. Hereby, the relationship of the pump power to the laser power can be compared for these transitions. The laser can also be switched between the three different lasing transitions by changing the dielectric mirrors for reflecting a particular laser frequency. Furthermore, the distance of the cavity mirrors allows for the divergence and transversal mode properties as well as the general stability criterions to be explored.

2.3 Versatile operation: the pulsed Nd:YAG laser with second harmonic generation

When higher peak power and the respective intensities are desired in the emission or if time resolution is necessary in the application, lasers can easily be transferred into a **pulsed operation**. This is generally realized by **quality-** *i.e.* **Q-switching** or with the technique of **mode locking**. Q-switching is generally realized with opto-electronic devices such as **Pockels cells** or **opto-acoustic modulators**. When brought into the laser cavity, these devices can periodically alternate in blocking and opening the cavity for the radiation. In a Pockels cells, different polarization states are generated with the modulation of the bifringence in crystals such as KTP ($KTiOP_4$ or potassium titanyl phosphate). This is achieved via the **Pockels effect** when strong electric fields act on the crystal in a capacitor with high voltage applied. The induced change in polarization of the light transmitted by the crystal can be discriminated with polarizers for opening and closing the cavity. Opto-acoustic modulators utilize radio frequency (rf) piezo-electric transducers that generate standing acoustic waves in crystals such as quartz. This leads to a temporal transmission grating by modulating the refractive index of the crystal and diffracts radiation out of the cavity during the closing period. The **repetition rate** with which laser pulses are emitted can be controlled by the modulation frequency of the Q-switch. The **pulse duration** obtained from Q-switching a cavity is determined by several conditions. It is easily assumed that the duration of the laser pulse is given by the duration that the Q-switch opens the cavity but the degree of population inversion and the rate of its depletion are the essential parameters for the pulse duration. These are dependent on the pump power and duration for which the Q-switch closes the cavity. Furthermore, the **gain bandwidth** sets the lower limit for the pulse duration, which is largely determined by the bandwidth of the emission of the active medium and the cavity arrangement. The relationship of pulse bandwidth and pulse duration is determined by **Fourier transformation**, which gives the **time-bandwidth product** for a particular **envelope function**. The bandwidth $\Delta\nu$ and pulse duration $\Delta\tau$ are given at "**full width half maximum**" (FWHM) of the profile and for a Gaussian envelope, $\Delta\nu \cdot \Delta\tau = 0.44$ (see Fig. 3).

The Fourier relationship of the frequency and time domain can give a deeper insight to the technique of **mode locking** for realizing pulsed laser emission. **Active mode locking** is achieved with fast opto-acoustic modulators. For the case of **passive mode locking**, high intensity radiation in a cavity can self-modulate by nonlinear optical effects such as **Kerr lensing** or **saturable absorbers** and **colliding pulse mode locking** can also lead to **self-modulation**. In order to understand the mechanism of pulse formation, it is instructive to beginning by viewing only a single longitudinal mode at the frequency ν, which is located at the peak of the gain profile (see Fig. 3). The frequency at which amplitude of the electromagnetic radiation is periodically disturbed can be seen as a **modulation frequency** ν_{mod} of the **carrier frequency** ν in the longitudinal mode. The repeated modulation of a wave in time with a period significantly longer than the cycle of the wave $\tau_{cyc} < \tau_{rep}$ results by principles of Fourier transformation in the generation new frequencies or discrete **coherent sidebands** that are positioned at $\nu \pm \nu_{mod}$. Important to note is the fact that these sidebands are locked in phase with the original carrier frequency. Furthermore, sidebands can also be modulated to further produce frequencies at $\nu \pm n\nu_{mod}$ (n = 1,2,3…). In a continuous wave operation, the longitudinal modes all oscillate independently with a random relative phase to one another. When these modes are modulated, the cascade of sidebands that are generated can coincide in frequency with a neighboring longitudinal mode. The sidebands induce their phase onto the coinciding longitudinal mode and the modes within the gain profile spontaneously lock in phase. In their superposition, phase-locked longitudinal modes interfere coherently and lead to a highly modulated carrier wave in time. This modulated wave in time can be viewed as a train of pulses that occur at the period that corresponds to the repetition rate with $\tau_{rep} = 1 / \nu_{mod}$. This is equivalent to the round-trip time of light at the carrier frequency ν in the cavity. As described by the time-bandwidth product, the duration of the individual pulse structures decrease with an increasing number of modes that are phase locked. This mechanism allows for the coupling of up to 10^6 longitudinal modes in high bandwidth gain media such as Ti:sapphire (sapphire host crystal doped with Ti^{3+}) for laser pulses with a duration down to several femtosecond.

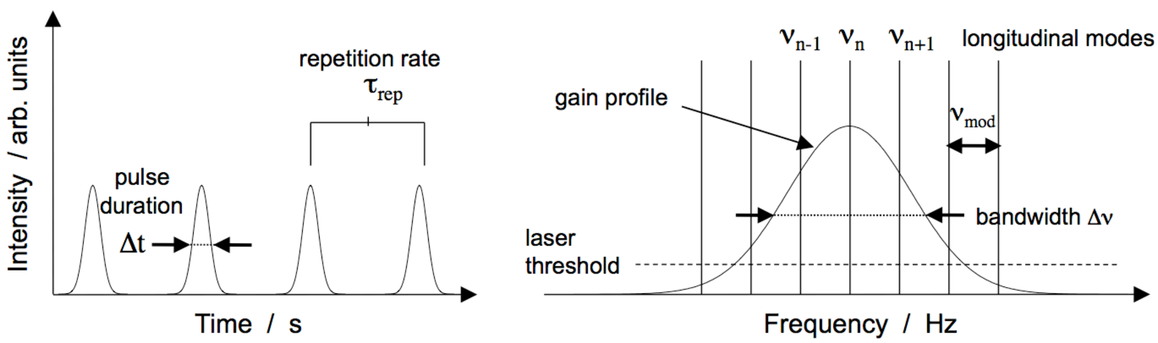


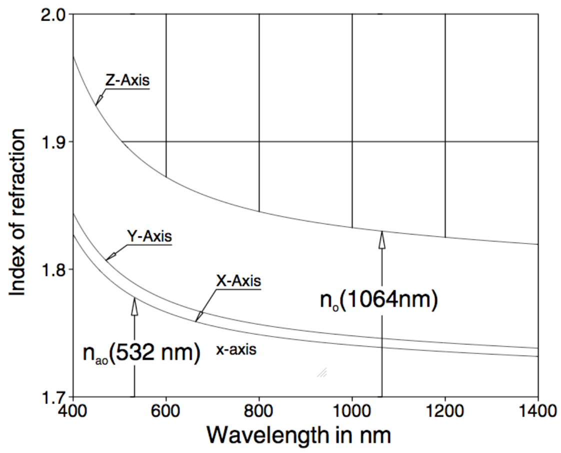
Fig. 3: Schematic for illustrating the principles of mode locking, showing the relationship in the frequency of longitudinal modes, the modulation frequency and the gain bandwidth (right) as well as the respective repetition rate and pulse duration in the time domain (left). Time and frequency domain are related by the time bandwidth product $\Delta\nu \cdot \Delta\tau = 0.44$ for Gaussian profiles and by $\tau_{rep} = 1 / \nu_{mod}$.

For the Nd:YAG laser, the emission at 1064 nm or ν = 2.82 THz has a gain bandwidth of $\Delta\nu$ = 0.12 GHz, which translates via the time-bandwidth product to a minimum pulse duration of $\Delta\tau$ = 8.33 ns for a Gaussian envelope. Commonly, a slower time scale of the rising and falling edge of pulse is obtained form standard Q-switched Nd:YAG lasers. Here, the rising and falling edge of the pulse are determined by the build-up of lasing after opening of the Q-switch and the depletion of inversion in the active medium while the Q-switch is open. This can lead to an asymmetric pulse form in time. The pulses of a Q-switched Nd:YAG laser can commonly range the nanosecond to the lower microsecond regime. The repetition rates can be adjust with the Q-switch and are usually operated in the Hz to kHz range. The **pulse power** is largely determined by the combination of the repetition rate, pump power and duration of the pulse.

An important aspect of pulsed lasers is the high field strength and corresponding intensities that can easily be achieved in the emission. This capability has greatly enhanced the field **nonlinear of optics**. Conversely, the resulting developments in the field of nonlinear optics have allowed for laser technology to advance significantly. A particularly relevant application of nonlinear optics in laser technology is the generation of different frequencies from the laser emission. In many laser applications, specific wavelengths are required and most active media are fixed or limited in the range or bandwidth of their emission. The conversion of a laser frequency via nonlinear processes can be realized in an **intra**- or **extracavity** configuration. In this context, it is advantageous to briefly outline the fundaments of nonlinear processes used for frequency conversion. Generally, nonlinear optical effects are rooted in a displacement of electrons in a dielectric medium or oscillating **polarization** that has a higher order dependency on the amplitude in the electric field of light inducing the effect. This means for the well-known linear effects in optics, the polarization oscillates at the frequency of the inducing electric field of the light. A **nonlinear polarization** can oscillate at **sum** or **difference frequencies** of the inducing field or fields. Since the higher-order **electric susceptibilities** of most dielectric media are very small, a high electric field strength and the respective intensity are required for inducing a significant nonlinear polarization in a medium.

The general formalism of nonlinear optics can be somewhat complex but the process of frequency doubling in **birefringent**, **non-centrosymetric crystals** is an excellent introduction. It is also one of the most commonly applied nonlinear processes in laser technology. **Frequency doubling** or **second harmonic generation** is an energy and impulse conserving process. Hereby, the energy and impulse of two photons at the fundamental frequency ν are converted to twice the energy of a single photon at the second harmonic frequency 2ν with the respective impulse. While the conservation of energy is easily meet by doubling the frequency, the conservation of the impulse is more complicated. This is due to substantial dispersion of the refractive index in an optically dense medium such as a crystal (see Fig. 4). This leads to the innate shift in velocity of light generated at double the frequency with respect to the original fundamental wave. In order to meet the **phase-matching conditions** in the velocity of the fundamental frequency and its conversion to its second harmonic in a medium, the different values for the refractive index in the **ordinary** (*o*) and **extraordinary** (*eo*) **axis** of a bifringent crystal are utilized. By placing the optical axis of the crystal at a specific angle to the polarization of the incoming fundamental beam, the effective refractive index for the different frequencies can be compensated according to $n_\nu = n_{2\nu}$. This allows for the conservation of impulse to be realized in matching the phase of the fundamental and second harmonic frequency in their propagation through the crystal. The angle necessary for achieving this situation can be determined from the

refractive index ellipsoid of a specific material at the position for which the criterion, $n_{2\nu,\,o}(\theta) = n_{\nu\ \ eo}(\theta)$ is satisfied as shown in Fig. 4. Common materials used for this purpose are BBO (β-barium borate), KTP (potassium titanyl phosphate), LBO (lithium triborat) or LiNbO3 (lithium niobate) crystals.
In summary, by introducing a Pockels cell as well as a KTP crystal into the cavity, the Nd:YAG laser allows for comparing the power in continuous and pulsed operation at 1064 nm and the conversion efficiency in second harmonic generation to an emission at 532 nm. A comparison can be made for an intra- as well as an extracavity arrangement. The power relationship of the fundamental and second harmonic can also be determined. Both aspects can also be explored for variations in pump power with the diode laser as well as the repetition rate.



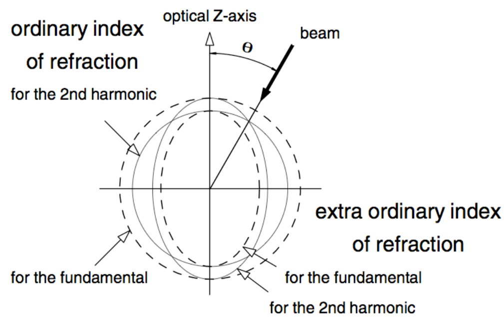


Fig. 4: Dispersion curve for the fundamental and second harmonic of the Nd:YAG laser in KTP (left). Schematic representation of a refractive index ellipsoid for achieving phase-matching in second harmonic generation within a birefringent, nonlinear crystal (right). Taken from [6].

3. Tasks

a) Characterization of the diode pump laser: Using the photodiode and oscilloscope, measure the power of the diode laser emission as a function of the diode current and determine the threshold current for lasing. Further determine the spectral dependency of the diode emission as a function of the diode temperature. This is done by measuring the absorption profile of the Nd:YAG medium indirectly via the transmission of the laser diode emission at a set of fixed values for the diode current. Find the conditions for a constant emission wavelength for pumping the Nd:YAG at 804.4 and 808.4 nm for different values of the diode output power *i.e.* plot the pairs of values for temperature and current of the diode laser giving variable output power for a fixed emission at 804.4 or 808.4 nm. Calibrate the voltage scale measured with the photodiode using the power meter appropriate for high emission power. Assume a linear response of the photodiode to the laser emission and consider the possible offset voltage of the photodiode. The photodiode should generally be used rather than the power meter since it offers the required resolution and sensitivity.

b) Characterization of the Nd:YAG medium: Determine the life time of the $^4F_{3/2}$ state by pulsing the diode laser emission and measuring the fluorescence of the Nd:YAG medium as a function of time via the photodiode and the oscilloscope. Use the TTL trigger output on the laser diode controller for synchronizing the measurement with the repletion rate of the diode emission. Consider that the decay of the emission is not only determined by the lifetime of the $^4F_{3/2}$ state but also the time scale in switching the current and the diode emission on and off. Evaluate the necessity for deconvolution of both effects by measuring the response time of the photodiode.

c) YAG laser operation: Set up the basic components of the Nd:YAG laser (diode pump laser, Nd:YAG medium, and cavity mirrors). Calculate the optimal mirror distance for achieving the stability criterion and bring the system into optimal lasing by maximizing the laser power at 1064 nm using the photodiode and oscilloscope. Adjust the angles and distance of the output mirror and characterize the different TEM_{nm} that can be achieved by imaging the laser mode with the CMOS chip (use gray filters !). Bring the mode aperture (iris) into the cavity and adjust the laser into a TEM_{00} operation. Determine the quantum efficiency (pump power versus laser power) for the 804.4 and 808.4 nm absorption bands of the Nd:YAG medium for different diode pump power values at constant emission wavelength. This can be done in a TEM_{00} mode or in other modes. Also determine the threshold pump power for Nd:YAG lasing. Recalibrate the photodiode with the power meter as performed under task (a).

d) Operating the Nd:YAG in an intracavity second harmonic mode: Insert the KTP crystal into the cavity and replace the output coupler with a mirror for fully reflecting 1064 nm and maximal transmission of 532 nm. Optimize the cavity mirrors and angles of the KTP crystal for optimal power at 532 nm. Measure the efficiency of the 532 nm output at different values of diode power for pumping the 808.4 nm absorption band in the Nd:YAG medium. For different values of the diode pump power, compare the efficiency and the output power with the 1064 nm emission from task (c). The photodiode can be recalibrated at 532 nm with the power meter as done in task (a).

e) Operating the Nd:YAG Laser in a pulsed mode: With the output coupler mirror that allows partial transmission of 1064 nm, insert the Pockels cell into the cavity and adjust the laser into an optimal pulsed operation with the cavity mirrors and the voltage level for the Pockels cell. Characterize the pulse train emitted from the laser at 1064 nm with the oscilloscope for varying diode pump power. Approximate the pulse duration and calculate the pulse energy and pulse power of the 1064 nm emission for varying values in repetition rate and diope pump power. Compare the continuous wave power from task (c) with the pulse power at 1064 nm. The photodiode can be recalibrated as in task (a) considering the repetition rate of the laser.

f) Operating the Nd:YAG laser in a pulsed mode with second harmonic generation: Place the KTP crystal after the output coupler mirror and determine efficiency of the second harmonic generation for an extracavity configuration at different power levels in the pulsed Nd:YAG laser emission at 1064 nm. A lens can be used for focusing the fundamental into the KTP crystal. Compare the pulse power of the 532 nm radiation at different diode pump power levels The relationship of power at the fundamental wavelength of 1064 nm and the power for the second harmonic emission at 532 nm should be determined. Replace the output coupler mirror for 1064 nm emission with the mirror for intracavity second harmonic generation and insert the KTP crystal into the cavity. Adjust the system for optimal operation. Compare the continuous wave power from task (d) with the pulse power at the 532 nm. This should also be performed at different diode pump power and the relationship of pulse power at 1064 nm from task (e) and the power for the second harmonic emission at 532 nm can be determined. Recalibrate the photodiode with the power head as carried out under task (a) considering the repetition rate of the laser.

4. Experimental setup

4.1 Schematic

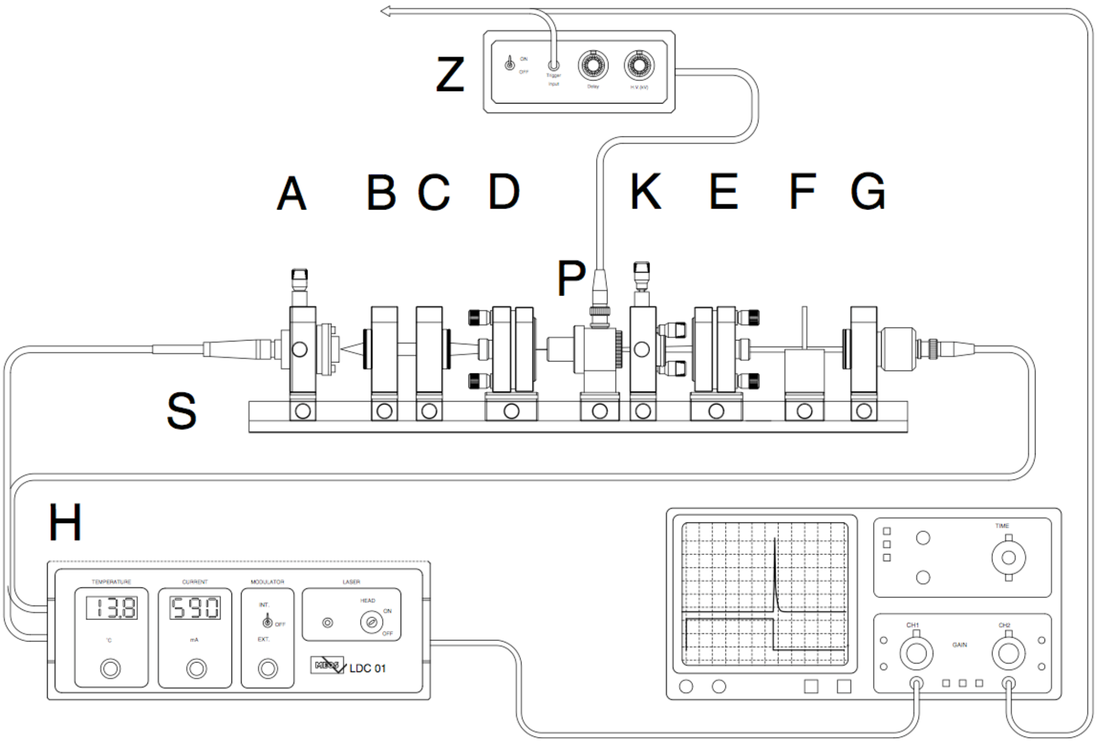


Fig. 5: Experimental setup for a Q-switched Nd:YAG laser with intracavity second harmonic generation.

4.2 Equipment list

	Device	Note to the function
A	diode pump laser	with controller (**H**)
B	lens	collminator for the diode emission
C	lens	for focusing the diode emission
D	end mirror and Nd:YAG medium	coated for 532, 1064 and 1322 nm emission
E	output coupler	individual mirrors for 532, 1064 and 1322 nm
F	filter holder	for high/low pass and gray filters / CMOS chip
G	photodiode	input for the digital oscilloscope
K	KTP crystal	for second harmonic generation to 532 nm
P	Pockels cell	with high-voltage supply (**Z**)
S	slide rail	for optical mounts at variable distances

4.3 Notes on certain procedures

The operation manual of the Nd:YAG laser can be used for specific parameters and settings required for realizing tasks (a) - (f). The manual is available online and in digital form at the experiment [6]. The tasks are designed so that points (a) - (c) are always carried out and a choice in conducting points (d) - (f) can be made. Each group should consult the tutor one week before the experiment concern tasks (d) – (f). Also, the rules and procedures for safe and correct working with lasers and optics should be thoroughly reviewed before conducting the experiment.

5. Notes on the preparation, analysis and discussion

For the general and written preparation before the experiment, the subjects given in bold face in the text of Section 2 should be used as a list of key words relevant to the experiment. In the report, the analysis should be made using the values and plots that are obtained from tasks (a) – (f) in the experiment, whereby the relationship between different laser parameters should be emphasized as well as the comparison in the conditions and laser output of different operational modes. In the discussion, the tendencies and relationships derived in the analysis of experimental data should be evaluated within the theoretical framework of the subjects given by the key words in bold face from Section 2.

6. Literature

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