Ba 14: Solid State Laser Principles I

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 $\Delta v/v = 10^{-15}$. 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 a hundred 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 and a peak power up to the Petawatt domain can be achieved with special 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 much a 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 photons or electromagnetic radiation fully equivalent in **frequency**, **phase**, **polarization** and **direction** in 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-Gaussian** or **Hermite-Gaussian** polynomials for cylindrical or cartesian symmetry, respectively). The structure of the transversal electromagnetic mode (denoted by **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 diode and 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 $^4F_{5/2}$ state from which lasing transitions to the $^4I_{1/2}$, $^4I_{3/2}$, and $^4I_{9/2}$ 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 $^4F_{5/2}$ state guarantee high **slope efficiency** and **quantum yield** in the conversion of the pump energy to laser energy output.

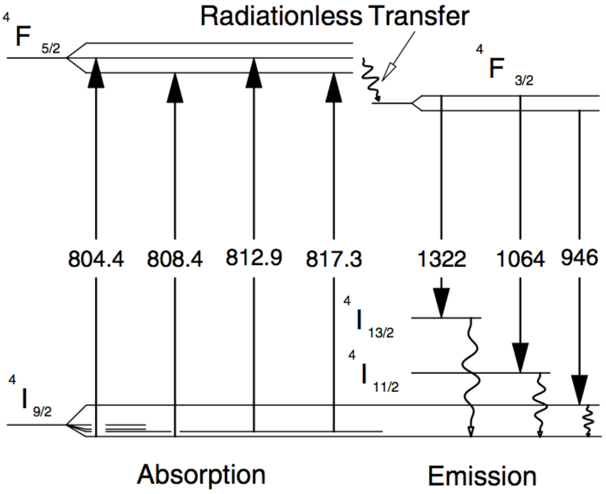

Fig. 1: The term scheme for the Nd:YAG medium with the four-levels relevant for lasing. Taken from [5].

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 the 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, a p- and n-AlGaAs semiconductor material is 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.

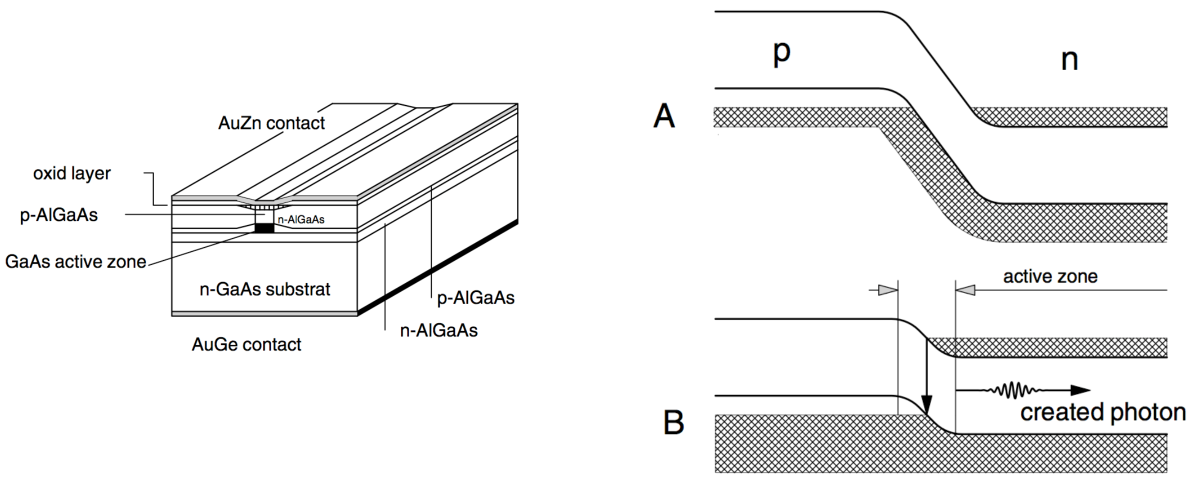

Fig. 2: Schematic of a AlGaAs semiconductor laser (left). Relative energy of the band structure and Fermi level without (A) and with (B) applied voltage as well as the emission from the transition in electron-hole recombination (right). Taken from [5].

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.

3. Tasks

a) Characterization of the diode laser power as function of current using the telescope, photodiode and oscilloscope: Determine the threshold current for lasing as well as the slope efficiency in a plot of the power versus current in the diode laser emission at selected temperatures. The photodiode should generally be used to measure the laser diode emission due to the much higher sensitivity and resolution necessary for characterizing the transition into lasing but the voltage scale measured with the photodiode can be converted into watts using a power meter at high current/power of the diode laser. Plot the values for the threshold current as a function of temperature and discuss the temperature dependency in view of the architecture and mechanism for lasing in a pn-junction semiconductor laser.

<u>Note</u>: the photodiode will saturate at higher power levels giving a nonlinear response. Use neutral density filters to bring the measurements with the photodiode in the range below saturation.

b) Characterization of the diode laser spatial mode using the telescope and CMOS detector: Record the spatial profile of the laser diode emission at different current/power levels of the diode laser below and above lasing. Use neutral density filters to ensure that the CMOS chip is not saturated at higher power levels of the laser diode emission for the complete range of the measurement series. Convert the 8-bit gray-scale (256 gray tones) of the CMOS bitmap image into a 2-D numeric array and characterize the spatial intensity distribution as a function current/power. Discuss the observed behavior of the spatial mode in view of the geometry of a pn-junction semiconductor laser and its waveguide properties versus a standard laser cavity. Further discuss this emission profile in view of possible applications of diode laser.

<u>Note1</u>: avoid saturation of the CMOS detector at higher power levels by using a neutral density filters to bring the full measurement series in the range below saturation.
<u>Note2</u>: A LabView application is available at the experiment for converting the 8-bit gray scale of the bitmap files from the CMOS detector software and analyzing cross-sections and areas.

c) Continuous wave operation of the Nd:YAG laser: Setup the basic components of the Nd:YAG laser given by the diode pump laser, telescope, Nd:YAG medium, and cavity mirrors. Calculate the optimal mirror distance for achieving the stability criterion assuming a hemispherical resonator with a flat end mirror coated on the back face of the active Nd:YAG medium and an output mirror with a radius of curvature at R = 100 mm. Bring the system into optimal lasing by adjusting the mirror angles, translation of the pump diode laser, distances of the telescope mirrors and the position of the medium for maximizing the laser power at 1064 nm using the photodiode and oscilloscope. Next, detect the Nd:YAG spatial mode with the CMOS chip and make fine adjustments to guarantee a TEM_{00} transversal mode by inserting the iris into the cavity as a spatial filter for limiting the angles of the modes. The iris should be adjusted to allow maximum Nd:YAG laser output power for the full range of the diode pump power settings. Once this is achieved, use the photodiode to record the output power of the Nd:YAG laser as a function of diode pump power. From the plot of the data, extract the threshold pump power for lasing as well as the slope efficiency of the Nd:YAG laser. The photodiode should generally be used for this due to the sensitivity and resolution necessary for characterizing the transition into lasing but the voltage scale obtained with the photodiode can be converted into watts with a power meter capable of measuring at high output power of the Nd:YAG laser. From the relationship of the slope efficiency, quantum efficiency and quantum yield, calculate the quantum yield as a function of cavity losses in the range of 0 - 10% with a transmission of 2% at 1064 nm for the output mirror. Since the central wavelength of the diode pump laser is dependent on the temperature of the diode, repeat this procedure for two temperatures that correspond to pumping detuned from the resonances in the Nd:YAG medium at 804.4, 808.4, 812.9 and 817.3 nm (best at diode temperatures of $T < 14°C$) and pumping on resonance to the 808.4 nm transition (see the spectral calibration curve for the temperature dependency of the diode pump laser). Discuss the different slope efficiencies and the consequences of the spectral shifting of the diode pump laser as a function of temperature for efficient and stable Nd:YAG laser operation.

Note1: The photodiode will saturate at high power levels giving a nonlinear response. Use neutral density filters to bring the measurements with the photodiode in the range below saturation. Do not use neutral filters for calibration with the power meter.
Note2: a low-pass edge filter should be used for blocking the residual pump laser emission before the detector for background free characterization of the 1064 nm emission.

4. Experimental Setup

4.1 Schematic

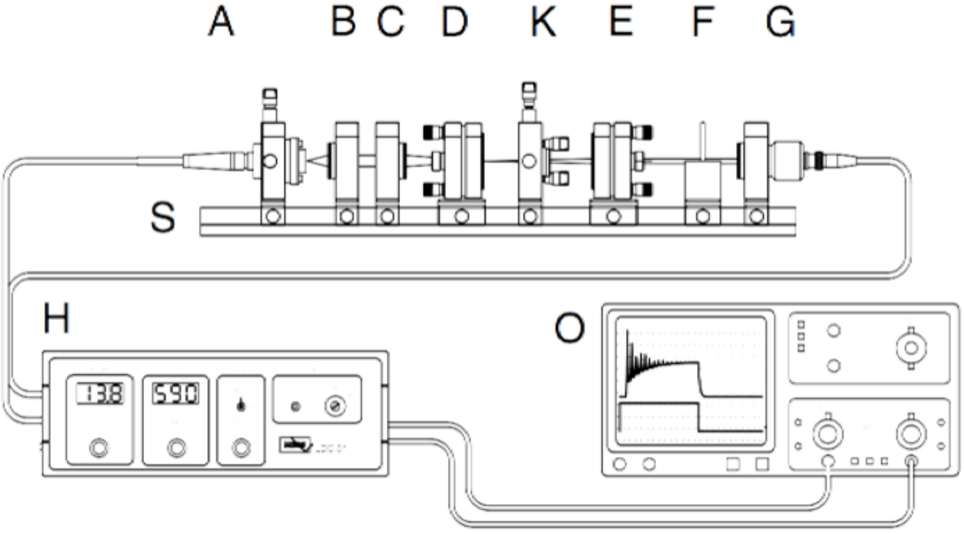

Fig. 5: Experimental setup for the diode-pumped Nd:YAG laser with intracavity spatial filter in a continuous wave mode at the fundamental wavelength of 1064 nm.

4.2 Equipment List

	Device	**Note to the function**
A	diode pump laser	with controller (**H**)
B	telescope lens	collimator for the diode emission
C	telescope lens	focusing of the diode emission
D	end mirror/Nd:YAG medium	coated for 532 and 1064 nm operation
E	output coupler	with mirror for T=2 % @1064 nm
F	filter holder	for high/low pass and neutral filters + CMOS chip
G	photodiode	relative measurements of the laser output power
K	intercavity spatial filter	iris with xy-translation normal to the cavity axis
O	oscilloscope	readout of the photodiode
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) - (c), which is also available in digital form at the experiment [5]. Each group should consult the tutor one week before the experiment concerning supplementary tasks that can be performed *i.e.* life-time measurements of the $^4F_{5/2}$ state of the Nd:YAG laser, *etc*. Importantly, the rules and procedures for safe and correct working with lasers 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) – (c) in the experiment, whereby the relationship between different laser parameters should be emphasized as well as their consequences for the laser operation. 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

[1] W. T. Silfvast, *Laser Fundamentals*, 2nd Edition, Cambridge University Press, Cambridge, 2004.

[2] E. Hecht, *Optics*, 4th Edition, Addison Wesley, San Francisco, 2002.

[3] R. Paschotta, *Encyclopedia of Laser Physics and Technology*, Wiley-VCH, Weinheim, 2008. (open access: http://www.rp-photonics.com/encyclopedia.html)

[4] J. Eichler, H.J. Eichler, *Laser: Bauformen, Strahlführung und Anwendungen*, 3rd Edition, Springer, Berlin, 2003.

[5] R. W. Boyd, *Nonlinear Optics*, 2nd Edition, Academic Press, San Diego, 1995.

[6] K. Dickmann, *Diode laser pumped Nd:YAG Laser*, (operation manual to the Nd:YAG Laser and advanced laboratory experiments), MEOS Cooperation.