Ministry of Higher Education and Scientific Research

Al – Zahraa University for Women

College of Medical and Health Technologies

Theoretical

Classification of lasers

Lecture 3

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Classification of lasers:

Medical applications require different types of lasers. Based on their gain medium, lasers are classified into five main types: Solid-state laser: A solidstate laser is a laser that uses solid as a laser medium. In these lasers, glass or crystalline materials are used. In these lasers, *r*are earth elements such as neodymium, chromium, erbium, thulium, or ytterbium are commonly used as dopants. The most commonly known solid-state lasers are the Ruby and Nd:YAG lasers.

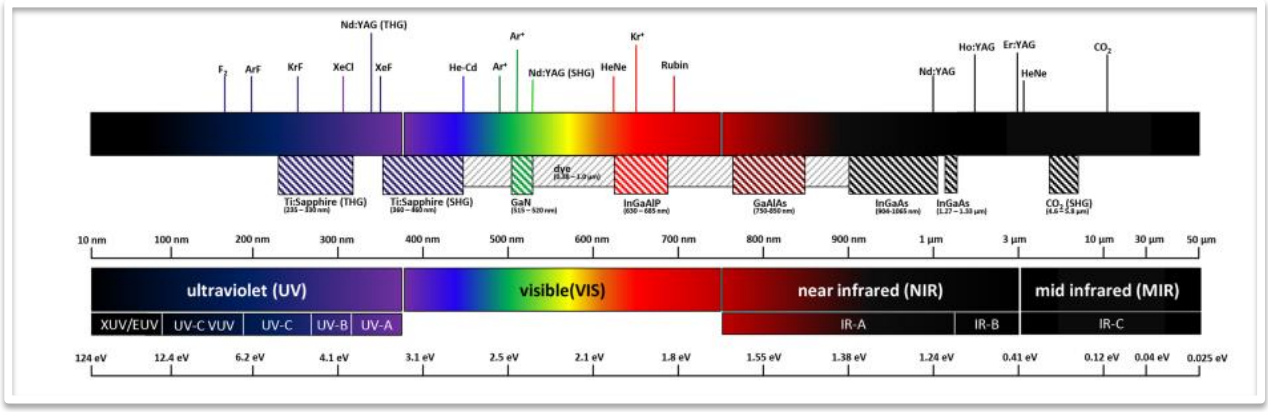
• Gas lasers: A gas laser is a laser in which an electric current is sent through a gas to generate light through a process known as population inversion. Examples of gas lasers include carbon dioxide (CO2) lasers, heliumneon lasers, argon lasers, krypton lasers, and excimer lasers.
• Semiconductor lasers (Laser diodes): Laser diodes, also called diode lasers and semiconductor lasers, are similar to regular diodes in that they have a positively-negatively (PN) charged junction. In semiconductor lasers, a

p-n junction of a semiconductor diode forms the active medium or laser medium. The optical gain is produced within the semiconductor material. The difference is that laser diodes have an intrinsic layer at the PN junction made of materials that create spontaneous emission. The intrinsic layer is polished so that the generated photons are amplified, ultimately converting the electric current into laser light.

- **Liquid lasers (Dye lasers): Liquid lasers use an organic dye in liquid form as their gain medium. They are also known as dye lasers and are used in laser medicine. One of the advantages of dye lasers is that they can generate a**
- **much wider range of wavelengths, making them good candidates to be tunable lasers, meaning that the wavelength can be controlled while in operation.**
- **Fiber lasers: A fiber laser is a special type of solid-state laser that is a category of its own. In fiber lasers, the gain medium is an optical fiber (silica glass) mixed with a rare-earth element. The light guiding properties of the optical fiber are what makes this type of laser so different: the laser beam is straighter and smaller than with other types of lasers, making it more precise. Fiber lasers are also renowned for their small footprint, good electrical efficiency, low maintenance and low operating costs. Examples of fiber lasers used for these applications include ytterbium and erbium-doped fiber lasers.**

The neodymium–YAG laser:

Nowadays, the neodymium-doped yttrium aluminium garnet (Nd:YAG) laser is the most important and well-established solid state laser and is used in a number of different fields of application such as materials processing, metrology and laser medicine. This type of laser source stands out due to its simple, compact and robust setup and its high mean laser power. Depending on the particularly applied type of pumping and excitation, either by flash lamps or laser diodes, its degree of efficiency amounts to approximately 2–5%. Generally, the laser active medium used in such lasers, the neodymium Nd^{3+} ion, can be embedded and operated in different host crystals or glasses. However, the yttrium aluminium garnet ($Y_3Al_5O1_2$, usually abbreviated YAG)

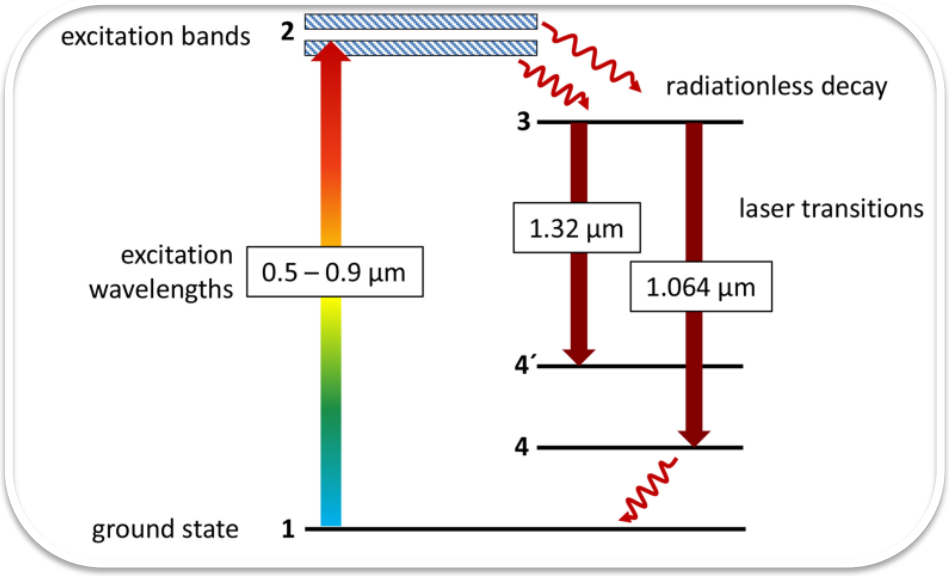


Overview of medical laser systems.

crystal system has turned out to be the most suitable one due to the comparable size of neodymium ions and yttrium ions which are replaced by the actual laser active Nd3+ ions in the course of the doping process during crystal growth. The concentration of these ions within the YAG host crystal typically amounts to about 1.5 volume per cent. At present, Nd:YAG crystals with a maximum length of 150 mm can be produced where crystal rods with a diameter of approximately 3–7 mm and a length of about 90–150 mm are usually used for laser sources. As shown in figure 1.7, Nd:YAG lasers are four-level lasers. Here, the energy levels and the laser transition of Nd:YAG is shown where the Nd3+ ions are found in the ground state initially. As a consequence of absorption of incident pumping light provided by flash lamps or pumping laser diodes, these ions take an excited state in the excitation bands (2) and the upper metastable and longlasting laser level (3) is populated due to fast and radiationless transitions. Light emission at a wavelength of 1064 nm (i.e. near infrared light) then follows from the

population inversion between the transition of the third and fourth level where some commercially available Nd:YAG lasers also generate radiation at a wavelength of 1320 nm (transition of level (3) to (4′)). Subsequent frequency conversion using nonlinear phenomena in suitable media such as potassium titanyl phosphate (KTiOPO4, usually abbreviated KTP) further allows the generation of shorter wavelengths. For the fundamental Nd:YAG wavelength of 1064 nm, visible green laser light at a wavelength of 532 nm is generated by such a frequency conversion of the second harmonic, whereas the third and fourth harmonic feature a wavelength of 355 nm and 266 nm, respectively, In practice, pumping of the laser active transition is usually realised using inert gas (e.g. krypton or xenon) arc discharge flash lamps. Such lamps feature emission bands in the range of 500–900 nm which conform quite well to the

pump levels. Here, the total efficiency amounts to approximately 2%. The use of laser diodes with an emission wavelength of 805–808 nm as pump source allows increasing the efficiency up to approximately 15% at an output power of 10–15 W.



Energy levels and laser transition of the four-level laser gain medium Nd:YAG.

Properties, parameters and characteristics

• Laser active gain medium: YAG-crystal, doped with the actual laser active neodymium ion.

• Emission wavelength: 1064 nm.

• Efficiency factor: typically 1–2% for flash lamp-pumped systems and up to 15% for diode-pumped systems (at 10–15 W).

• Pulsed or continuous wave (cw) operation possible.

• Typical pulse duration: 5–20 ns.

• Guidance by fibres possible.

• Simple, compact and robust setup.

• Penetration depth into tissue: approximately 2–8 µm.

Applications in medicine

• Continuous wave (cw) laser for surgical applications such as cutting and drilling .

• Continuous wave (cw) laser for laser-induced interstitial6 thermotherapy (LITT).

• Long-pulse laser for dermatological applications such as bleaching and dentine sealing .

• Q-switched, pulsed laser for laser-induced shock-wave lithotripsy (LISL) or the removal of tattoos .

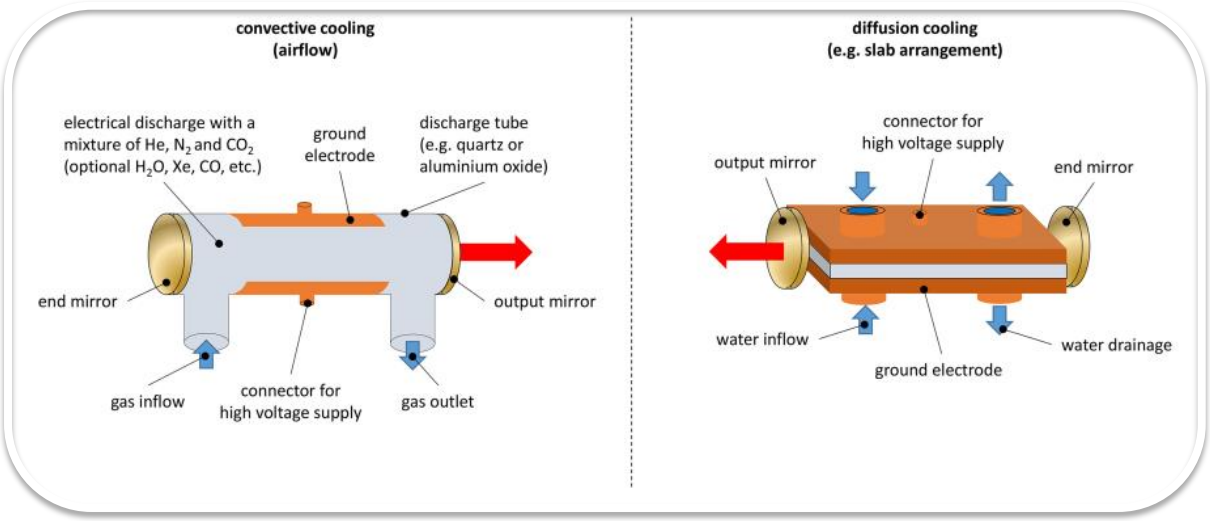
The carbon dioxide laser:

The carbon dioxide (CO2) laser is one of the oldest and most important laser sources in a number of different fields of applications and especially in laser surgery. The gas used for this special type of gas laser is a mixture of helium (82%), nitrogen (13.5%), and carbon dioxide (4.5%) which fills an arc discharge tube One should note that the gases which contribute to the actual laser process are nitrogen and carbon dioxide, whereas helium is added in order to increase the efficiency factor of the laser process. For the generation of laser light, nitrogen molecules are excited by an electric discharge within the tube. The energy is then transferred from the excited nitrogen toCO2 molecules by collisions, resulting in the actual pumping of the gas mixture. Laser emission in the wavelength range from 9 to 11 µm then occurs between two vibrational states of the CO2 molecule as shown in figure 1.18 where the strongest lines are found at 10.6 µm and 9.6 µm. The first one arises in the case of a symmetric linear vibration of the involved carbon and oxygen atoms. In contrast, laser irradiation at a wavelength of 9.6 µm is formed during the transition from the upper level to a symmetric bending vibration of the CO2 molecule. The processes in such CO2 lasers can be further supported by adding hydrogen to the gas mixture, resulting in a faster and increased excitation of electrons to a higher energy level. Due to the comparatively high degree of efficiency, CO2 lasers are even available as battery-driven systems nowadays. However, CO2 laser irradiation is located in the far infrared wavelength range, restricting the possibilities of beam shaping and guidance.

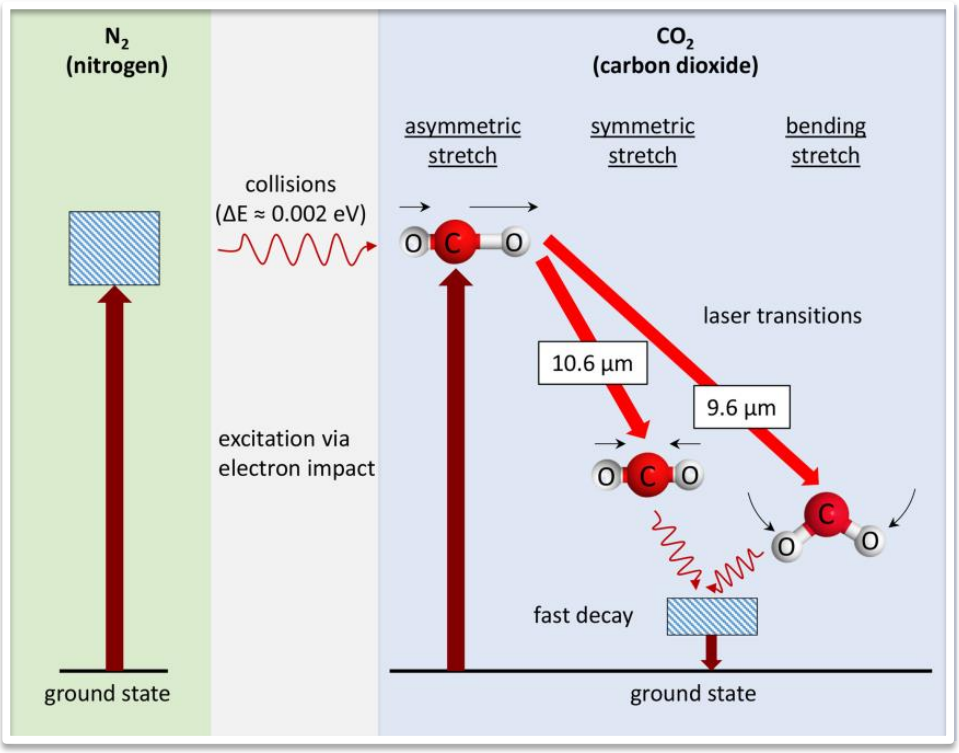
For focussing, refractive components such as lenses made of special IR-transparent materials (e.g. gallium arsenide, GaAs or zinc selenide, ZnSe) are in hand. Beam guidance and transportation is usually performed with the aid of mirror-based jointed arms or hollow-core fibres.

Properties, parameters and characteristics

- **Laser active gain medium: gaseous carbon dioxide.**
- **Gas mixture (typical): CO2:N2:He .**
- **Emission wavelengths: 10.6 µm and 9.6 µm.**



Basic setup of a CO2 laser.



Energy levels of a CO2 laser including the vibrational modes of the CO2 molecule and the laser transitions at 10.6 µm and 9.6 µm.

• Efficiency factor: up to 30%.

• Pulsed or continuous wave (cw) operation possible.

• Simple and robust setup without any hazardous gases.

• Laser power: up to a number of megawatts in cw operation.

• Beam guidance by mirror systems.

• Penetration depth into tissue: some tens of microns (typically 10–30 µm).

Applications in medicine

• Classical laser for cutting soft and hard tissue as well as bones in surgery

• Dermatological applications for the removal of superficial skin alterations such as verrucas.

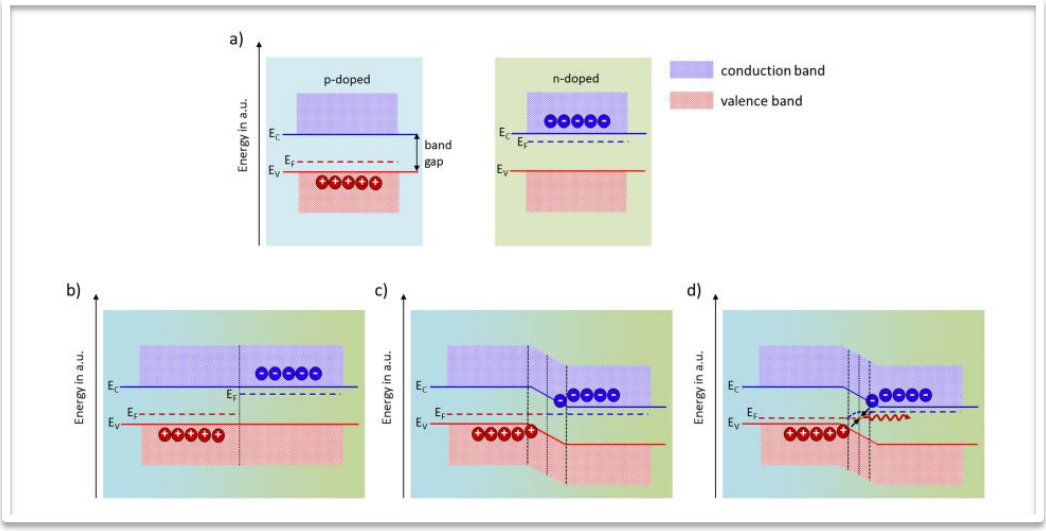
• Laser-based diagnostics, e.g. monitoring of anaesthesia.

• Special applications, e.g. transmyocardial laser revascularisation (TMLR) in cardiology or partial removal of kidney in urology .

The diode laser:

The diode laser, usually also referred to as semiconductor laser, was first presented in 1962. Since that time, it has gained notable importance in a number of fields of application and especially in telecommunications and laser medicine. Its laser active gain medium is a semiconductor which is doped with foreign atoms in order to modify the electrical properties of the basic semiconductor selectively. In the course of this doping process, foreign atoms, the so-called dopants, enter the semiconductor due to diffusion processes and an n-type region and a p-type region are realized within the semiconductor. The first region results in the case of dopants which arecapable of delivering electrons (i.e. an n-doping with donators). In contrast, positively-charged defects, also referred to as holes, are produced within thesemiconductor if the dopant is able to bond free electrons (i.e. a p-doping withacceptors). Since both regions are directly contacted, an intermediate zone, known as the p–n junction, with a valence-conduction band gap is formed and the Fermilevels19 EF are found within this band gap. The Fermi level position is due to the charge distribution 17 For instance, the laser facility Hercules at the Center

for Ultrafast Optical Science (CU-OS) at the University of Michigan provides a laser power of 300 TW at a laser pulse duration of approximately 30 fs. Hercules is thus amongst the most powerful available laser sources. the correction of myopia, hyperopia, or astigmatism by re-shaping the cornea via refractive surgery/cutting of transparent ocular tissue, e.g. for flap preparation. 19 The Fermi level is the energy level where the occupation probability of charge carriers, e.g. electrons, amounts to 50%



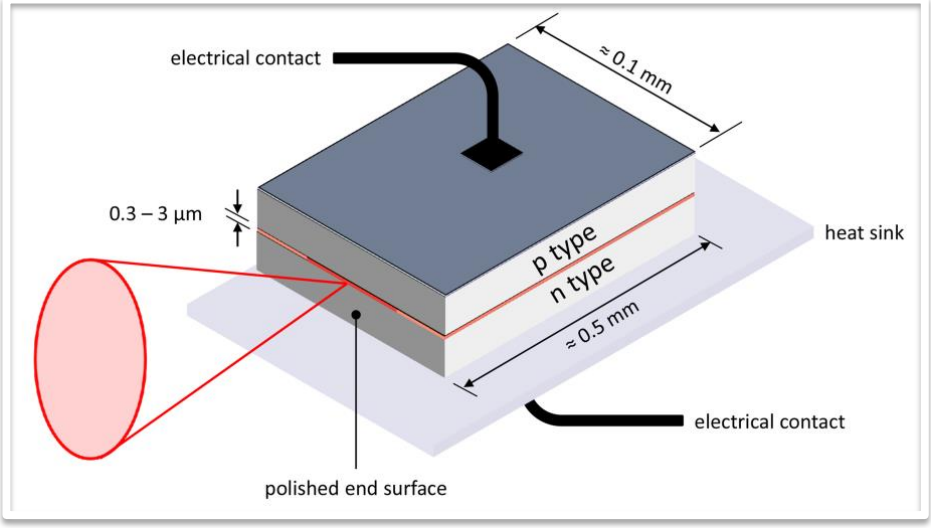
Principle of generation of laser light in a diode laser; for detailed description see text.

When contacting both doped semiconductors with different charge distribution and Fermi level position, respectively, this leads to a difference in the position of both involved Fermi levels. However, this state is not possible in thermodynamic equilibrium and the two energy bands, the conduction and valence band with the energy EC and EV, respectively, are thus shifted until a common Fermi energy level is formed,. As a result the junction becomes free of charge carriers since electrons can diffuse from the n-region into the p-region and positively-charged defects, holes, can diffuse from the p-region to the n-region. When applying a voltage to the semiconductor, the Fermi levels are shifted and the electric-potential barriers are consequently reduced. charge carriers then diffuse into the band gap and electrons and holes recombine. As a result of such recombination, photons are generated by spontaneous emission where the photon energy corresponds to the difference in energy of the energetic states of the involved electrons and holes. Due to the recombination of electrons and holes, photons are then generated by spontaneous emission where the photon energy

corresponds to the difference in energy of the energetic states of theinvolved electrons and holes. When placed in a laser cavity, which is usually given by

the polished end surfaces of the semiconductor crystal emission of laser irradiation can be obtained as follows: electrons can exist in the immediate vicinity of holes without any recombination for a certain time, the so-called

upper-state lifetime or recombination time. Within this short time of approximately one nanosecond, stimulated emission can be initiated by an incident photon, finally resulting in laser operation by light amplification in the p–n junction zone. The output power of a single laser diode is limited to approximately 10–40 W. The combination of a number of such single diodes to diode laser stacks allows the realisation of diode laser systems with high output power of up to a number of kilowatts, which allows even industrial materials processing applications. In comparison to other laser types such as solid state lasers or gas lasers, diode lasers.



Basic setup of a diode laser (adapted from)

feature a number of advantages such as for example a higher degree of efficiency and the possibility to tune the emission wavelength by adjusting the temperature of the semiconductor material20. Moreover, diode lasers are very compact and feature a high duration of life.A selection of semiconductor materials used for diode lasers. In medicine, diode lasers are either used directly as an actively operating tool in diagnostics and therapy or indirectly as targeting laser or pilot laser for the positioning or adjusting of medical equipment. In diagnostics, diode lasers with low output power are employed as light source for the examination of biological tissue, e.g. for the determination of moving particles such as erythrocytes, i.e. redblood cells,

via laser Doppler velocimetry (LDV). The variety of wavelengths ofdiode laser sources, see figure 1.14, and the accompanying variety of depth ofpenetration of laser irradiation into tissue further opens a wide range of therapeutic applications. For instance, tissue reactions such as hyperthermia, coagulation, and vaporisation can be obtained. Moreover, diode lasers are suitable light sources for ophthalmic applications or photodynamic therapy.

Properties, parameters and characteristics

- **Laser active gain medium: doped semiconductors.**
- **Emission wavelengths: typically 350 nm to 11 µm, but up to 50 µm possible.**
- **Extremely high duration of life (theoretically up to 100 years).**
- **Compact and light setup.**

Applications in medicine

- **Light source in diagnostics, e.g. for detection of blood flow velocity via laser Doppler velocimetry (LDV) .**
- **Realisation of tissue reactions such as coagulation, cutting, vaporisation .**
- **Light source for photodynamic therapy (PDT) .**
- **Targeting or pilot laser for medical equipment.**