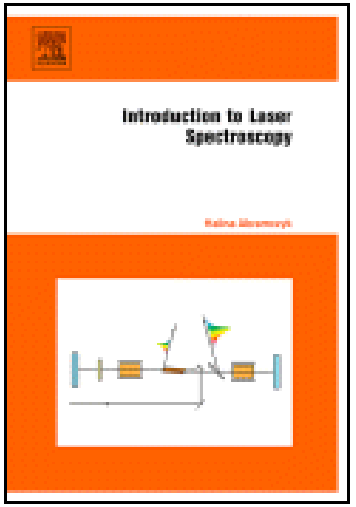


# SPH 618
# Optical and Laser Physics
# University of Nairobi, Kenya
# Lecture 5
# TYPES OF LASERS

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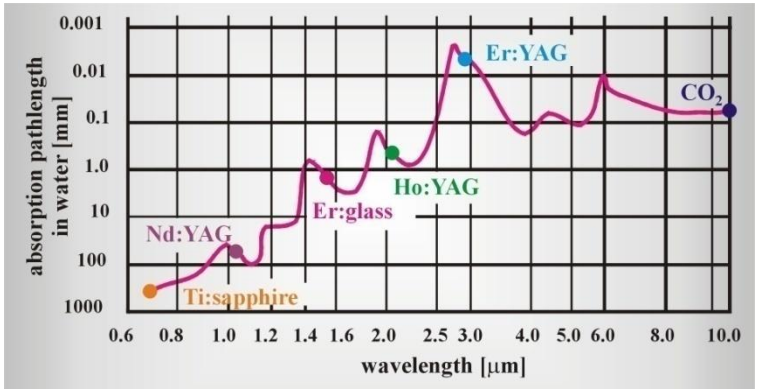
Technical University of Lodz, Lodz, Poland

# Gas lasers, liquid lasers

- Lasers can be classified according to the active medium or the wavelength of the emitted radiation. The most general division based on the first criterion consists of gas lasers, liquid lasers and solid–state lasers. Gas lasers include all lasers in which the gain medium is a gas. The most well–known gas lasers are:
- a) *$CO_2$ laser* (10.6 μm) (near infrared),
- b) *CO laser* (5–6.5 μm) (near infrared),
- c) *$N_2O$ laser* (10.6 μm),
- d) *molecular gas lasers* ($CH_3OH$, $C_2H_2F_2$, $CH_3F$) (40 μm–1 mm) (far infrared),
- e) *chemical lasers* (in which one of the reaction products are: I, HF, HCl, HBr, CO, $CO_2$), near infrared (1.3–11 μm),
- f) *ion argon laser* (a few lines in the range of 476.5 – 514.5 nm) (visible region),
- g) *krypton laser* (503.9–752.5 nm) (visible region),
- h) *helium–neon laser* (632.8 nm) (visible region),
- i) *excimer lasers* such as: ArF, XeCl, KrF emitting radiation at the wavelength of 193, 248, 308 nm (UV),
- j) *nitrogen laser $N_2$* (337 nm) (UV).
- *Liquid lasers* include all lasers in which the gain medium is a liquid. Dye lasers emitting in the visible region belong to the most often used liquid lasers. Output spans the spectrum from the near–UV to the near–IR depending on the dye used.

# Solid state lasers




- *Solid–state lasers* are optically pumped, the gain medium is a solid state material. The most well–known solid–state lasers are:
- *ruby laser* (694.3 nm) (visible region),
- *Nd:YAG* laser with neodymium doped *yttrium–aluminum garnet* matrix, (1064 nm)
- *Titanium–sapphire laser* (670–1070 nm) and other solid–state tunable vibronic lasers,
- rare earth elements other than neodymium (holmium, erbium, thulium) lasers like *Ho:YAG*, *Er:glass*, *Er:YAG*, *Tm:YAG* emitting at about 2 mm depending on a matrix and a doped material used.

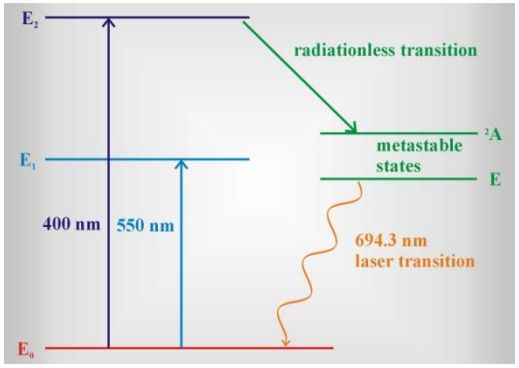
# Semiconductor lasers

- Semiconductor lasers do not belong to the category of solid–state lasers although the gain medium is also a solid. Traditionally, they form separate category because diode lasers are usually electrically pumped and different physical processes are responsible for emission that occurs over a broad spectral range of visible and infrared region.

# Ruby Laser

- Theodore Maiman constructed the world's first laser from a ruby crystal. Since that first ruby laser, researchers have discovered many other materials as the gain medium, but the oldest laser still find some applications. The large energy pulses and the red visible (694.3 nm) light radiation of ruby laser still find the applications in holography and dermatology. The ruby laser is a pulsed laser of low repetition rate. (The repetition rate is the number of pulses that are sent by a laser per 1 second). The pulse duration is on the order of milliseconds, energy of 1 J and the average pulse power on the order of kilowatts. The active medium of a ruby laser is a rod made of a synthetic shapphire ($Al_2O_3$) doped with chromium (0.01–0.5 %) having the same valence number (+3) as the aluminum. The ruby laser can also work in the modelocking regime emitting pulses of 20–30 picosecond duration, energy of 1 mJ and the repetition rate of 20–30 Hz. The electronic transitions in ruby laser are presented in figure

The ruby laser is pumped with a xenon flash lamp. When the chromium $Cr^{+3}$ ions in a ruby crystal absorb photons of visible light at 400 nm or 550 nm, some electrons jump from their ground–state $E_0$ to the excited states $E_1$ or $E_2$. The electron excited to those states almost immediately (ca. 100 ns) dissipate their excess energy to the surrounding crystal lattice. As a result of the radiationless transitions the electrons jump to one of two closely spaced metastable states: $E$ or $^2A$ where they stay for a long time of 3 ms at room temperature. This time is long enough to achieve population inversion. Stimulated emission occurs on the $E \rightarrow E_0$ transition generating the light at a wavelength of 694.3 nm. Because the whole cycle of excitation, relaxation and stimulated emission involves transitions between three energy levels, the ruby laser is known as a *three–level laser*.




Electronic transitions in ruby laser

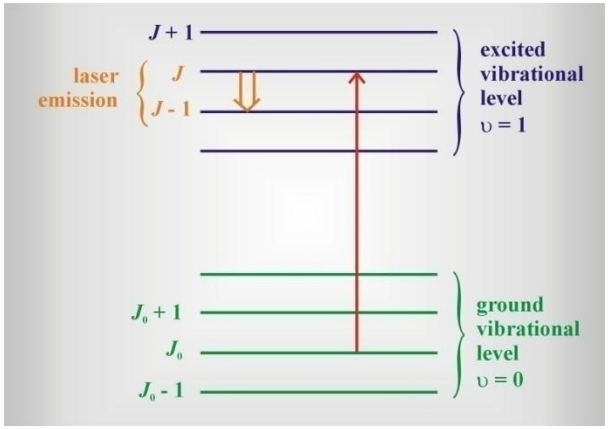
# Ruby Laser

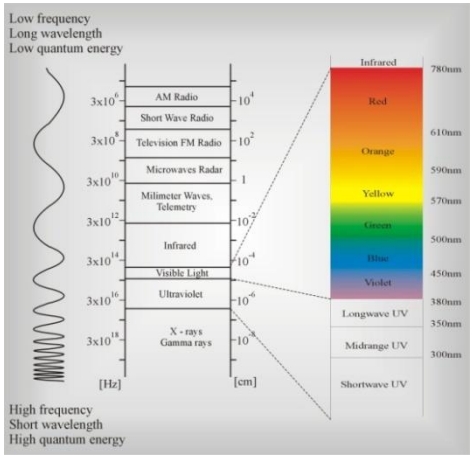
- **APPLICATIONS**

- The ruby lasers find wide applications in holography, plasma diagnostics and dermatology. In dermatological applications the *Q*–switched ruby lasers generating pulses of energy of 2–3 J and the repetition rate of 0.5–1 Hz are utilized. Such an energy is sufficient to remove black, blue and green pigments of skin tattoos as well as stains caused by melanin excess. The laser beam destroys cells containing the pigment by inducing photochemical reactions whereas the surrounding non pigmented areas of skin do not absorb the energy of the light and experience only negligible damage. Then the lymphatic system slowly removes dead cells during the next several months. The ruby laser does not remove red pigments since they do not absorb the red light at 694.3 nm.

# Lasers Operating on Rotational Transitions –FAR INFRARED LASERS

- Lasers emitting light as a result of rotational transitions generate far infrared radiation. Powers of the lasers operating on rotational transitions in commercially available models are comprised in the range from milliwatts to 1 W. *Far infrared lasers* are pumped with radiation at 10 mμ from $CO_2$ or $N_2O$ lasers. The optical pumping causes the molecules are transferred from the rotational state characterized by the rotational quantum number $J_0$ in the ground vibrational state ($\upsilon = 0$) to the rotational state $J$ in the excited vibrational state ($\upsilon > 0$) for a given vibrational mode. The symbol $\upsilon$ indicates the vibrational quantum number. The laser action occurs between the two rotational levels $J \rightarrow J$-1 in the excited vibrational state. The pumping laser should deliver strongly monochromatic radiation in a narrow spectral range to avoid filling neighboring rotational levels lying close to each other.

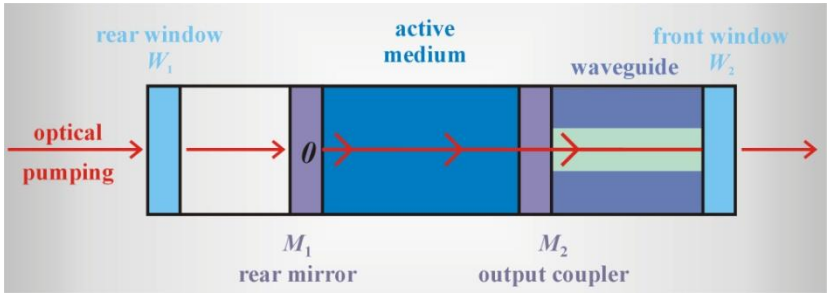


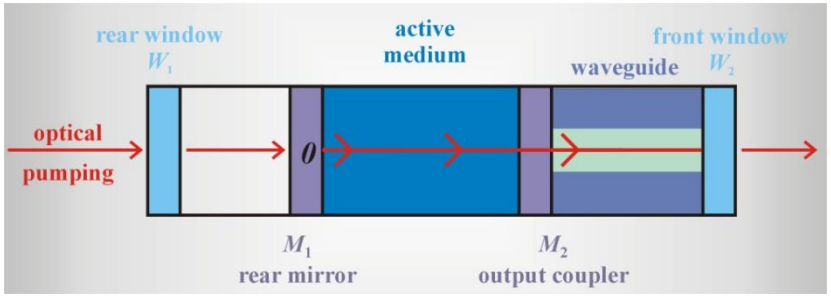




Schematic diagram of quantum transitions in lasers emitting as a result of rotational transitions

# Lasers Operating on Rotational Transitions -FAR INFRARED LASERS

- Active medium in the far infrared lasers are simple organic substances e.g. alcohols and hydrocarbons. In commercial models the optical resonator contains a gas reservoir which can be exchanged and replaced by another one making possible to obtain far infrared radiation from 40 mμ to 2000 mμ. Since the rotational energy depends strongly on molecular mass, so the isotopic substitution may provide additional lines. For example, $CD_3OD$ emit at 41.0 mμ, $CH_3OD$–at 46.7 mμ, $CH_3OH$–at 70.6 mμ.






- Optical resonator of the far infrared laser consists not only of two mirrors, $Z_1$ and $Z_2$, and an active medium, but also a vacuum waveguide, which leads the emitted waves . The vacuum waveguide must be used because air absorption at the wavelength of 30 and 50 mμ would attenuate effectively the light propagation on longer distances. The optical resonator consists of the mirrors $Z_1$ and $Z_2$ between which the laser action occurs as well as the windows $W_1$ and $W_2$ protecting the tube under vacuum from environment influence. The optical elements inside the resonator have to obey several requirements, which sometimes exclude each other:
  - The resonator mirrors $Z_1$ and $Z_2$ have to reflect both the radiation from the range of 10 mm (the pumping radiation) and from the far infrared (the generated radiation). The reflection of the pumping radiation inside the resonator increases the feedback due to the increase of the optical path which is very important taking into account small energies of the rotational transitions.
  - The rear window $W_1$ has to transmit the pumping radiation and is usually made of zinc selenide. There is a hole $O$ of 1–2 mm diameter in the rear mirror $Z_1$ that allows to introduce the radiation at 10 mμ into the cavity.
  - The front window $W_2$ has to transmit the far infrared radiation generated in the resonator. Most of materials are opaque for radiation at wavelengths longer than 50 mm. Only some materials such as silicon, germanium, crystalline quartz, diamond as well as polyethylene can be used in the window $W_2$ as they are transparent for the far infrared light.

# Applications of far IR lasers

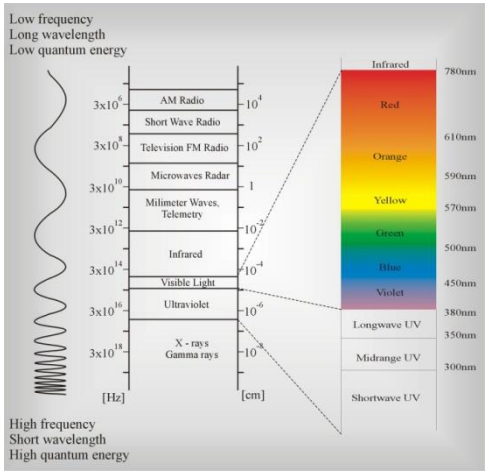
Although commercially available, the far infrared gas lasers are less popular than the gas lasers such as $CO_2$, CO, $N_2O$ that emit shorter wavelengths in the near infrared. This results from technical problems in the far infrared range which are related to propagation in waveguides as well as requirements imposed on optical elements.

# Lasers Operating on Vibrational-Rotational Transitions: CO2 and CO – near IR lasers

The active medium in $CO_2$ laser - carbon dioxide, nitrogen $N_2$ and helium He.

A ratio 1 : 2 : 3 for the $CO_2$ : $N_2$ : He mixture is typical

Pumping - RF (radio frequency) or direct–current electrical discharge in the gas medium

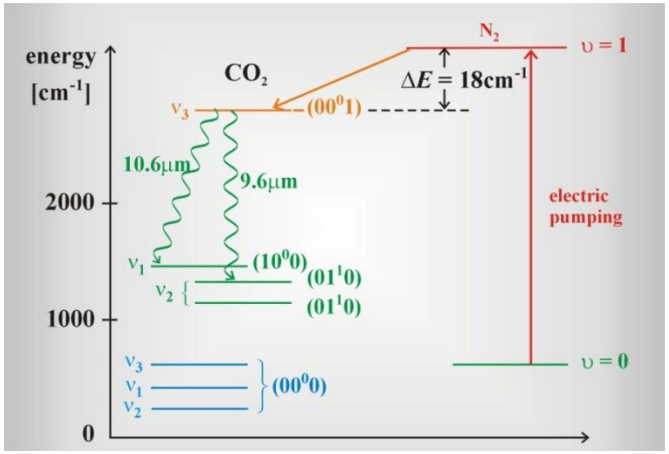


# Mechanism of lasing in $CO_2$ laser

- Electrons produced as a result of ionization excite the stretching mode of $N_2$ molecules promoting them from the ground vibrational state ($\upsilon = 0$) to the first excited vibrational state ($\upsilon = 1$). Nitrogen has a very long–lived first–excited vibrational state that almost exactly matches the upper level of $CO_2$. Therefore, the process of transferring the excess energy via collisions to carbon dioxide is very efficient. The energy of the $N_2$ molecule in the first–excited vibrational state is practically the same as the energy of the first excited vibrational state ($00^01$) of the asymmetric stretching mode $n_3$ of $CO_2$ molecule. Small energy gap ($\Delta E$ = 18 $cm^{-1}$) between the excited levels makes possible the energy transfer from the $N_2$ molecule to the $CO_2$ molecule, return of $N_2$ molecule to the ground vibrational state ($\upsilon = 0$) and the excitation of the mode $n_3$ from the ground vibrational state denoted in fig. as ($00^00$) to the excited vibrational state ($00^01$) in $CO_2$ molecule. The main laser transitions in $CO_2$ occur between the excited states of the mode $n_3$ ($00^01$) and the symmetric stretching mode $n_1$ ($10^00$) (10.6 mμ) or the bending mode $n_2$ ($01^10$) (9.6 mμ). Helium molecules do not take part in the excitation of $CO_2$ molecules directly but they play an important role in heat transfer out of the gas mixture to the tube walls as well as facilitate depopulation of the lower vibrational levels in $CO_2$ contributing in this way to the population inversion maintenance.

$$E = h\nu\left(\upsilon + \frac{1}{2}\right)$$

The numbers in the brackets denote the quantum vibrational numbers of the mode $\nu_1$, the $\nu_2$, and $\nu_3$, respectively. The upper indices define the vibrational level degeneration. For example the symbol ($01^10$) denotes the ground vibrational state for the mode $\nu_1$, the first excited vibrational state for the mode $\nu_2$, which is twice degenerated and the ground vibrational state for the mode $\nu_3$.

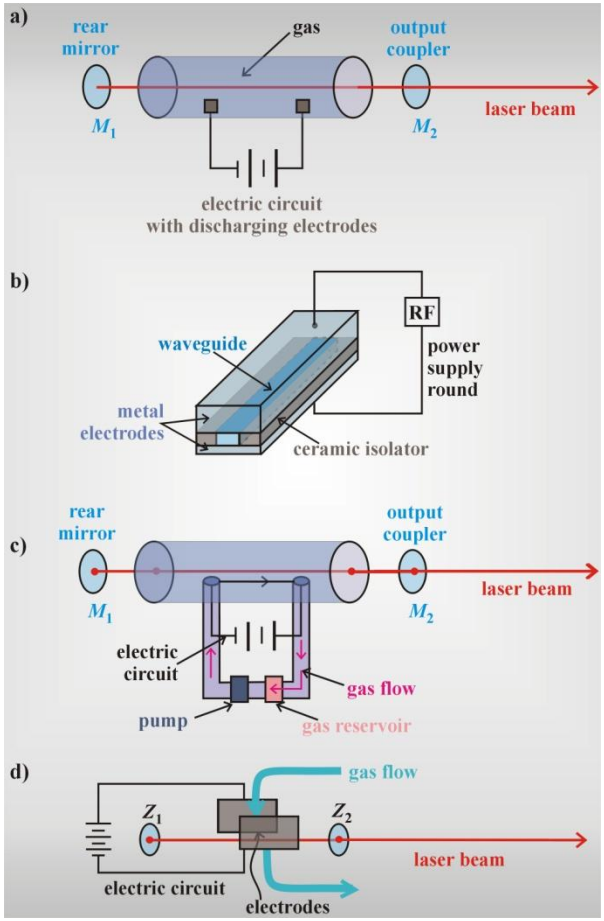



Quantum transitions in $CO_2$ laser

# $CO_2$ lasers

One can distinguish the following types of $CO_2$ lasers:

- *conventional laser with longitudinal direct–current discharge excitation*,
- *waveguide laser with RF excitation*,
- *longitudinal flowing–gas laser*,
- *transverse flowing–gas laser*,
- *transversely excited atmospheric lasers* (*TEA*).



# Applications of near IR lasers

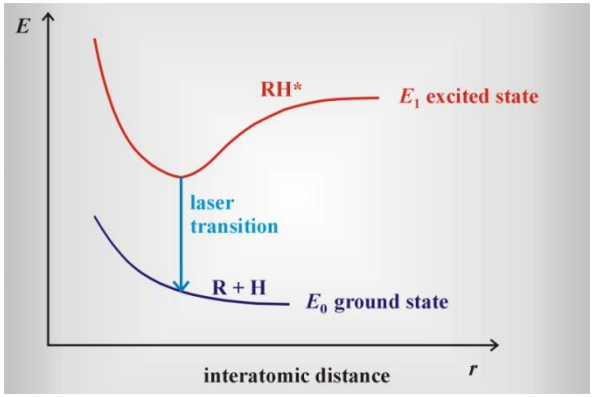
- Although $CO_2$ laser found many applications including surgical procedures, the most popular image is that of a powerful device for cutting, drilling, welding, as well a weapon for defense and security applications with laser beams aboard aircrafts that can destroy ballistic missiles. In 1970 the Air Force built the Airborne Laser Laboratory with a 400 kW gas dynamic carbon dioxide laser housed in a militarized Boeing 707. Now, the defense and security programs replaced carbon dioxide lasers by *chemical lasers*, but they are still a symbol of the most powerful lasers.

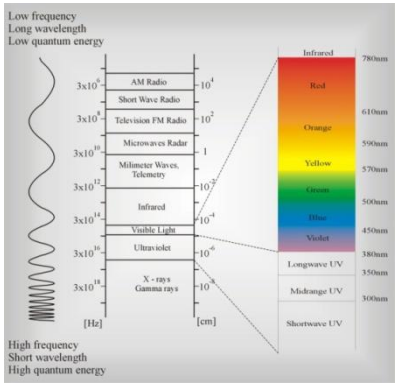
# Chemical Lasers

- *Chemical lasers* emit radiation in the far infrared and infrared regions (1.3-11 mμ)
- Pumping- the energy released during chemical reaction

*Typical chemical lasers*

| Laser | Reaction | Radiation wavelength [μm] |
|---|---|---|
| $CO_2$ | $DF^* + CO_2 \rightarrow CO_2 + DF$ | 10.0–11.0 |
| CO | $CS + O \rightarrow CO^* + S$ | 4.9–5.8 |
| HBr | $H + Br_2 \rightarrow HBr^* + Br$ | 4.0–4.7 |
| DF | $F + D_2 \rightarrow DF^* + D$ | 3.5–4.2 |
| HCl | $H + Cl_2 \rightarrow HCl^* + Cl$ | 3.5–4.1 |
| HF | $F + H_2 \rightarrow HF^* + H$ | 2.6–3.3 |
| I | $O_2^* + I_2 \rightarrow O_2 + 2I^*$ | 1.3 |



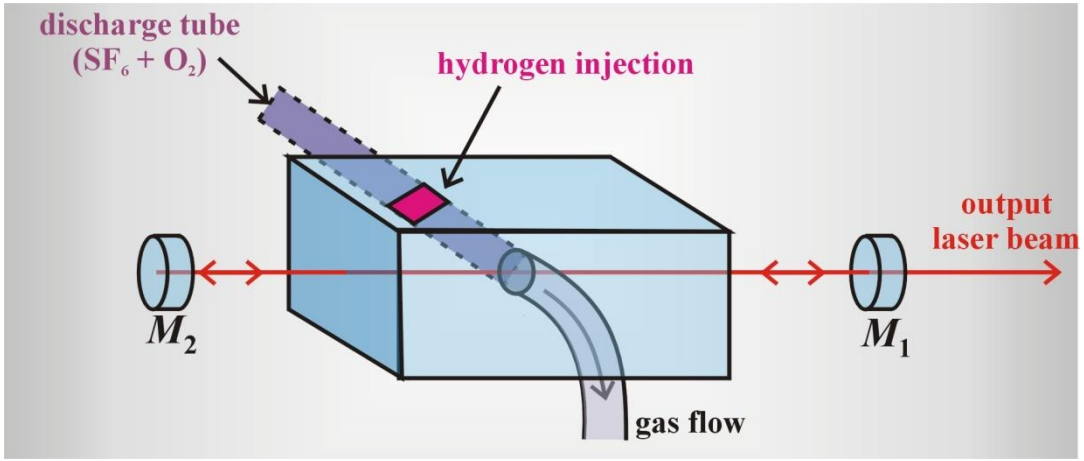



# Chemical Lasers

- In commercially available lasers HF/DF, the hydrogen fluoride is produced by electric discharge in a tube *via* a reaction of sulfur hexafluoride $SF_6$ dissociation. Oxygen is added to react with sulfur. Hydrogen, which is injected to the tube, reacts with fluoride generating the hydrogen fluoride $HF^*$ in vibrationally excited states. Gas flows quickly through the resonator cavity perpendicularly to the axis

- $SF_6 \longrightarrow S+6F$
- $S+O_2 = SO_2$

$$F + H_2 \rightarrow HF^* + H$$



# Application of chemical lasers

There is no other group of lasers where interest is almost entirely dominated by military and defense applications. High–energy laser weapon projects date back to the 1970s. In the seventies the US Navy built a 2.2 MW deuterium–fluoride chemical laser called MIRACL. In eighties the star wars shifted strategic defense to study prospects for space–based laser battle stations and large financial means were invested in development of HF lasers. In nineties the military interest has been shifted to the 1.315 mm oxygen–iodine laser known as COIL. As early as 2005 the Airborne Laser program in US plans to generate a megawatt beam that can destroy ballistic missiles several hundred kilometers away. They plan to mount a chemical oxygen iodine laser on the board of Boening 747.

There is some interest in shifting applications of the chemical oxygen–iodine laser from military to civilian use. A high power COIL emitting at the wavelength of 1.315 mm that can be easily transmitted by standard fused–silica fiber optics may soon be used for general industrial use such as cutting and welding. They show promise to be used as a powerful tool to dismantle obsolete nuclear–weapon production facilities and nuclear–power reactors.

# Solid–State Lasers

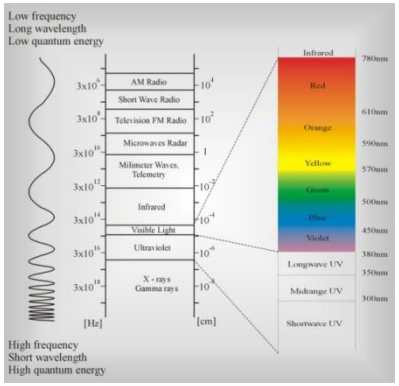
- Pumping – flash lamps, cw lasers, *diode–pumped solid–state lasers* (*DPSSL*)
- active medium - a solid-state host, most often a single crystal, doped with about 1 % of different species, such as neodymium ion or other ions like holmium, erbium or thulium.
- Solid–state lasers can be divided into two broad groups of non–tunable and tunable lasers
- Most solid–state lasers belong to the class of four–levels lasers and they operate on electronic transitions

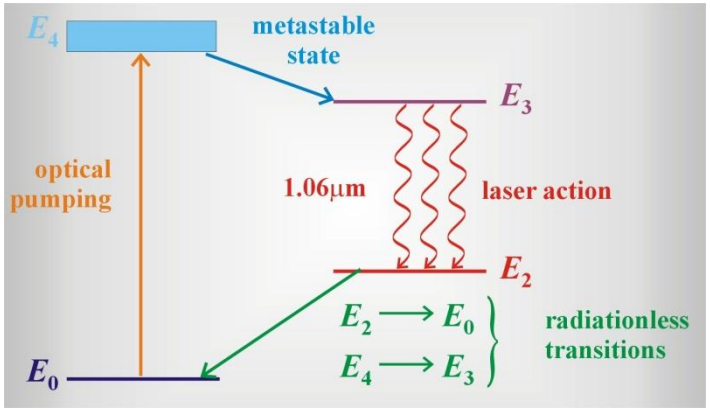
# Neodymium Laser and other Rare Earth Lasers

- active medium - rare earth elements belonging to lanthanide series: neodymium, holmium, erbium and thulium. The neodymium ion can be added as an impurity to crystalline solids or to glasses.
- *Nd:YAG laser,* host - yttrium aluminum garnet $Y_3Al_5O_{12}$ - YAG),
- *Nd:*YLF ($YLiF_4$-yttrium lithium fluoride)
- *Nd:*$YVO_4$ (yttrium orthovanadate).
- *Nd:glass laser*

# Mechanism of lasing in *Nd:YAG laser*

The neodymium ions are pumped optically by a flash lamp or a laser diode from the ground state $E_0$ to the excited state $E_4$ characterized by a short lifetime and not involved directly in a laser transition. Radiationless transitions promote the ion to the metastable state $E_3$ where it stays for longer time of about 100 ms. The population inversion takes place between the states $E_3$ and $E_2$. The laser action between these states produces radiation from the range of near infrared at the wavelength of 1.064 mμ. The lower laser state $E_2$ relaxes quickly to the ground state $E_0$.



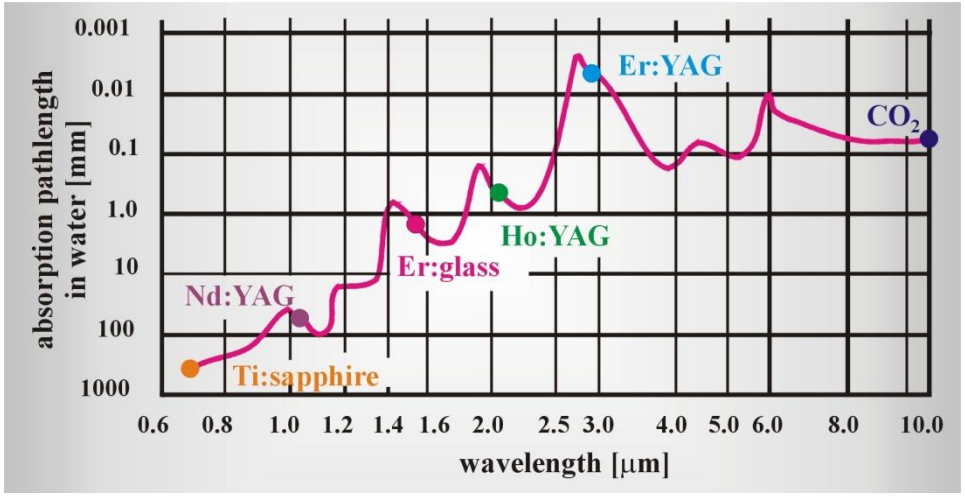



# *Nd:YAG laser*

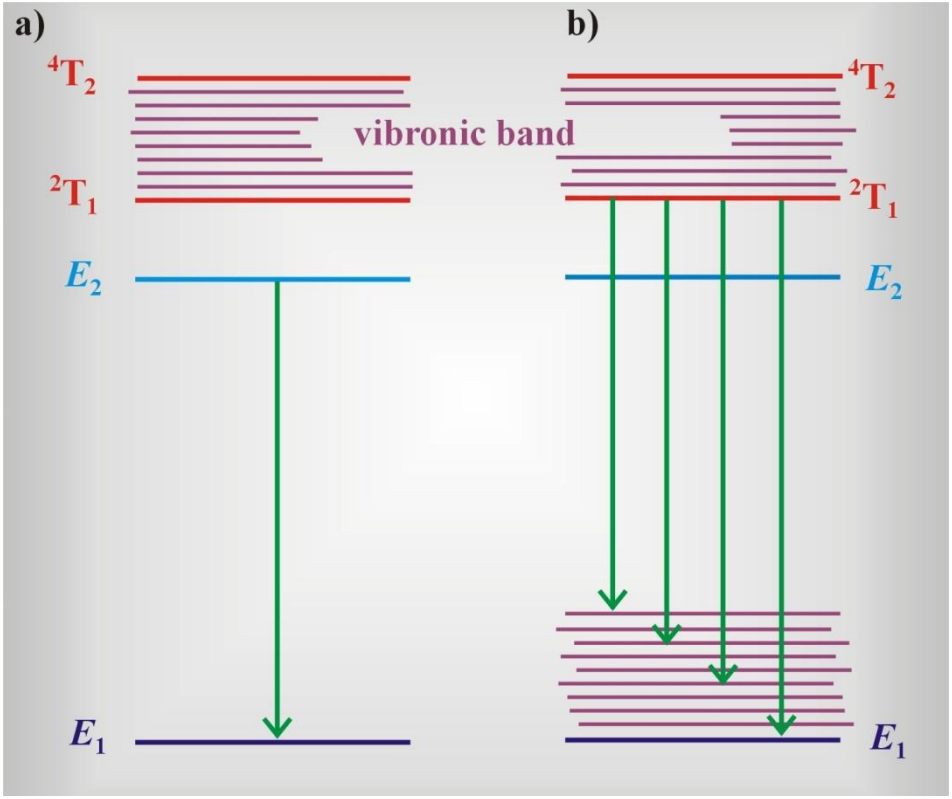
- The neodymium laser can work in the continuous and pulsed regimes. The shortest pulses of tens picoseconds can be achieved in the modelocking regime combined with the *Q*–switching. *Q*–switching without modelocking provides pulses of nanoseconds. The neodymium laser belongs to the group of non–tunable lasers. The typical construction of the lamp–pumped laser resonator is shown in fig.

# *Nd:YAG laser applications*

- There are many industrial applications of Nd:YAG lasers. Metals processing including cutting, welding or marking is almost always associated with Nd:YAG lasers. This kind of applications needs usually large, lamp–pumped lasers. Spectroscopic research or surgical procedures usually need smaller, diode–pumped systems with frequency doubling. The neodymium lasers are utilized to pump another lasers or to pump the regenerative amplifiers. For example, Ti:shappire laser can be pumped by the second harmonic of the neodymium laser (Nd:$YVO_4$, *cw*, 5.5 W, 532 nm). The regenerative amplifier seeded by the Ti:shappire laser (82 MHz, 80 fs, 12 nJ, modelocked) can be pumped with the neodymium lasers (Nd:YLF, 1 kHz, 10 mJ, 250 ns, 527 nm, *Q*–switched). The specifications in brackets illustrate typical commercial parameters. Since the mid–seventies, Nd:YAG lasers have been workhorses in laboratories around the world for pumping dye lasers. The advent of tunable solid–state laser systems and optical parametric oscillators reduced significantly this application.
- The neodymium lasers found many diverse applications in medicine although their applicability is limited by small water absorption, the main component of the human tissue, in the spectral range of 1 mm.

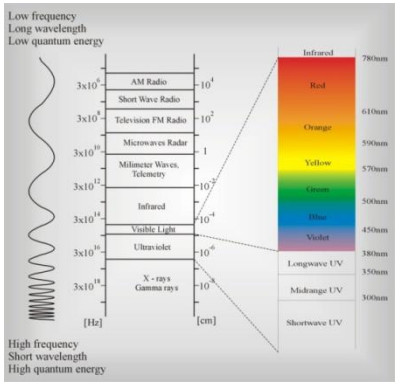


# Tunable Solid–State Lasers (Vibronic Lasers)




Scheme of electronic levels involved in a laser transition in a) non–tunable lasers, b) tunable lasers

# Tunable Solid–State Lasers (Vibronic Lasers)

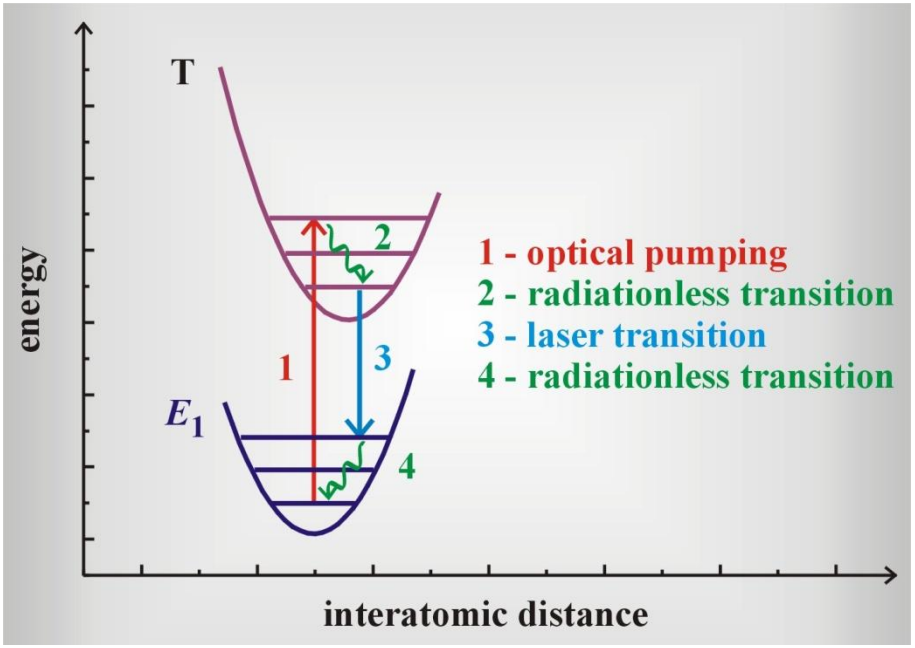



*Solid–state tunable lasers*

| **Active medium** | Operation | Spectral range [nm] |
|---|---|---|
| Alexandrite | continuous | 730 – 810 |
| Ce:YLF | pulsed | 309 – 325 |
| Co:$MgF_2$ | pulsed | 1750 – 2500 |
| Cr:$LiSrAlF_6$ | continuous, pulsed | 760 – 920 |
| Ti:sapphire | continuous, pulsed | 670–1070 |

# Tunable Solid–State Lasers (Vibronic Lasers) –four level system

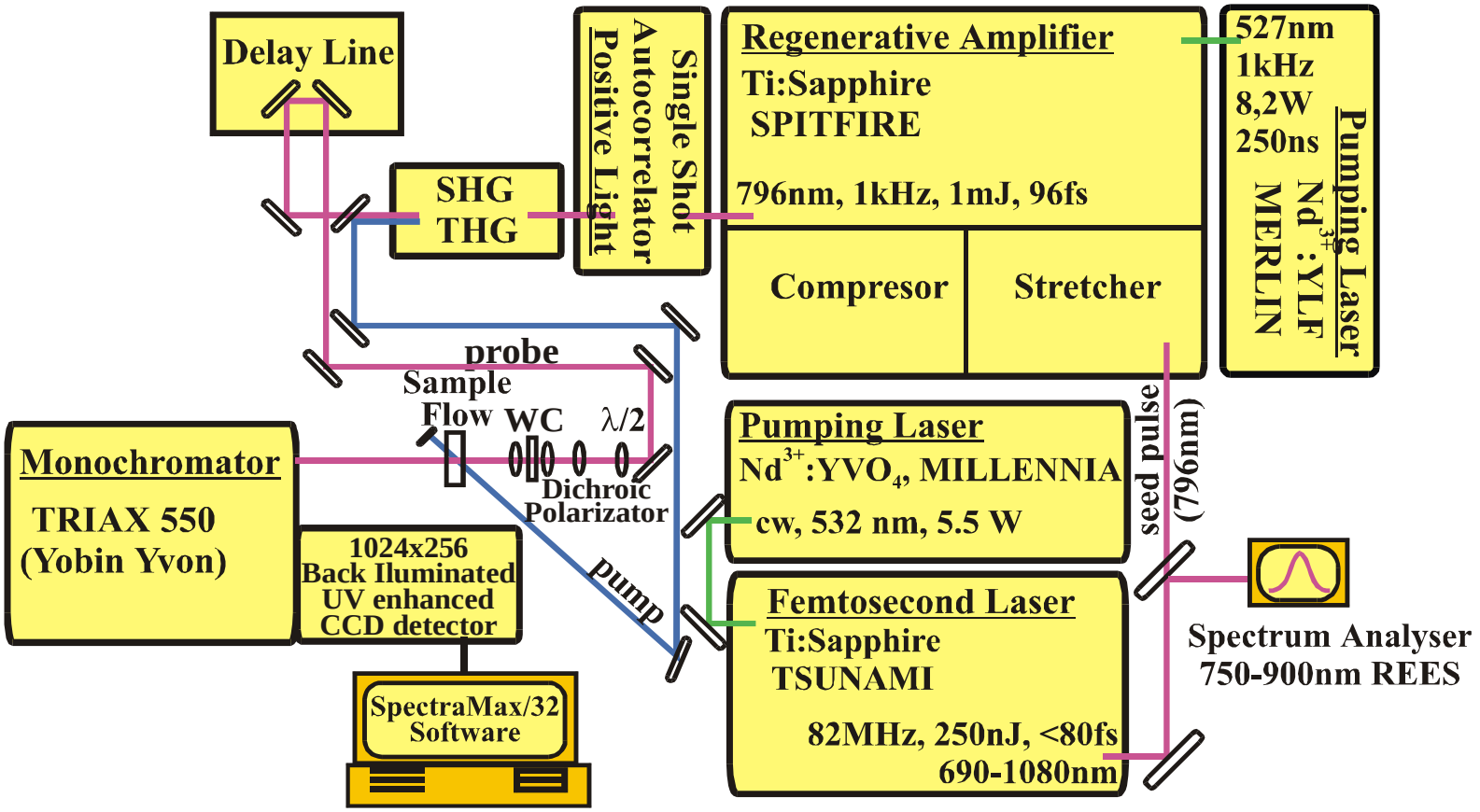
The pumping light (1) transfers the ion from the ground vibrational level ($\upsilon = 0$, $E_1$) of the lower electronic state $E_1$ to the excited vibrational level of the upper electronic state T ($\upsilon > 0$, T). The excited system relaxes quickly in radiationless way (2) to the ground vibrational state ($\upsilon = 0$, T). In the third step the emission (laser action) (3) between the upper electronic state ($\upsilon = 0$, T) and the lower electronic state ($\upsilon > 0$, $E_1$) occurs. The lower state ($\upsilon > 0$, $E_1$) is quickly depopulated by radiationless relaxation to the ground vibrational level of the lower electronic state ($\upsilon = 0$, $E_1$) (4).



# Applications of femtosecond lasers

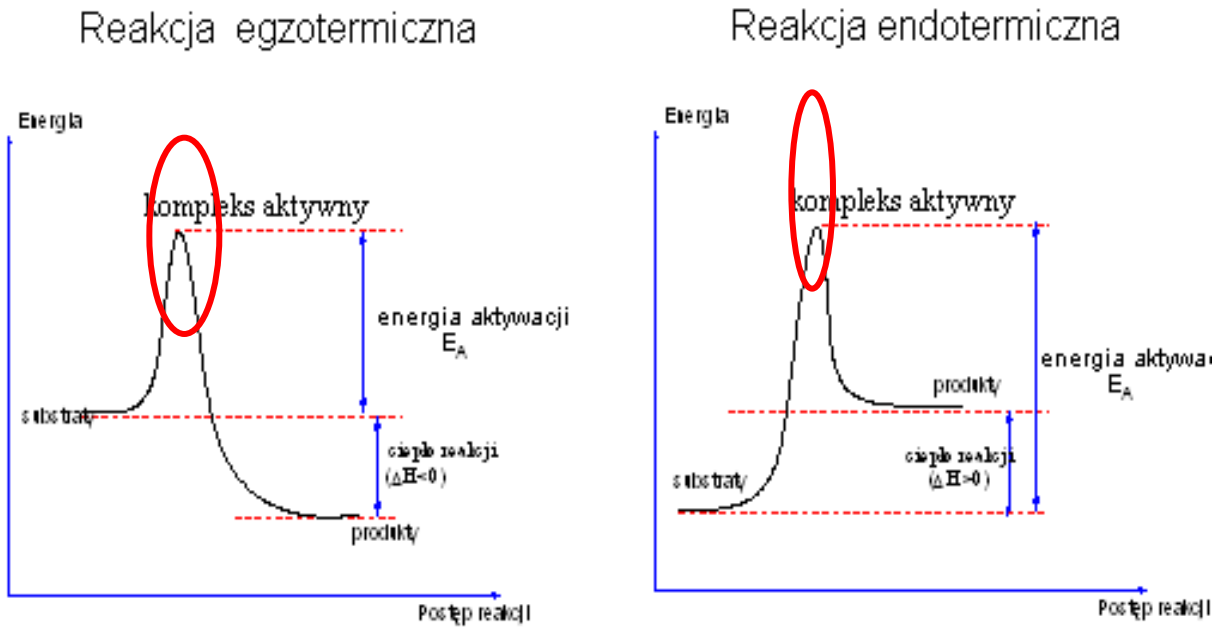
- The development and commercialization of femtosecond lasers has opened up new applications in medicine, particularly in ultrafast surgery. The most fundamental feature of tissue interaction with light is that the heat deposited by the laser diffuses away from the illuminated zone during the pulse duration that may lead to undesirable burning. The transfer of heat generated by a laser beam can be overcome with ultrafast lasers. Femtosecond lasers allow for far more precise cutting than nanosecond lasers and produce much less damage to surrounding tissues than lasers based on photoablation or thermal effects. Femtosecond lasers beam focused on the tissue generates such a high electric fields that atoms are torn apart, producing a plasma. The plasma expands rapidly, creating a bubble in the tissue under surgery and limiting tissue damage to the target area. The shorter the pulse, the smaller energy required for photodisruption and the smaller the size of the interaction area. For example, a 500 fs pulse with the fluence of 1.6 J/cm$^2$ produces a fine cut of only 3 to 13 mm, a 60 ps pulse produces a cavity of 30–120 mm, while a 10 ns pulse creates 300–1200 mm cavity requiring much higher energy and the fluence of 185 J/cm$^2$. So, ultrafast interactions are characterized by negligible heat–affected zones. Later we will describe in more details the main mechanisms responsible for interactions between a tissue and a laser beam including thermal effects, photoablation and plasma disruption. The non-thermal ultrafast interactions opened the way for fine–feature femtosecond laser micromachining. The currently available stents, used when a blood clot or a piece of artheriosclerotic plague lodges in an artery and reduces or totally locks blood flow, have limited usefulness. Femtosecond lasers are the promising tools for stent manufacturing such as cutting the intricate mesh patterns required for making new intracranial stent designs.

# pump-probe femtosecond UV/VIS/NIR absorption

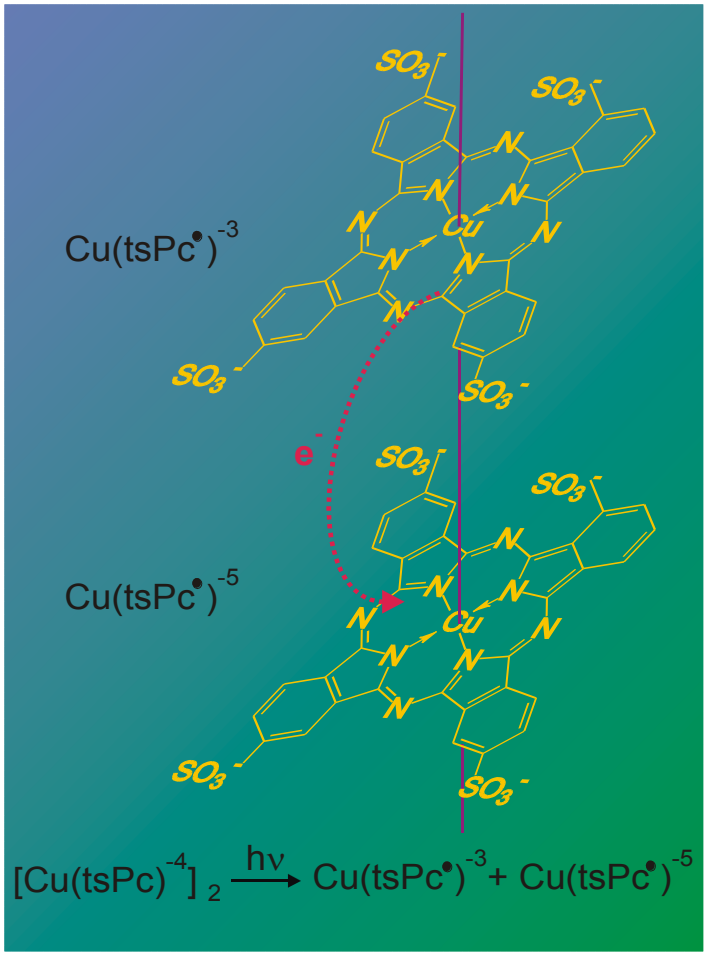


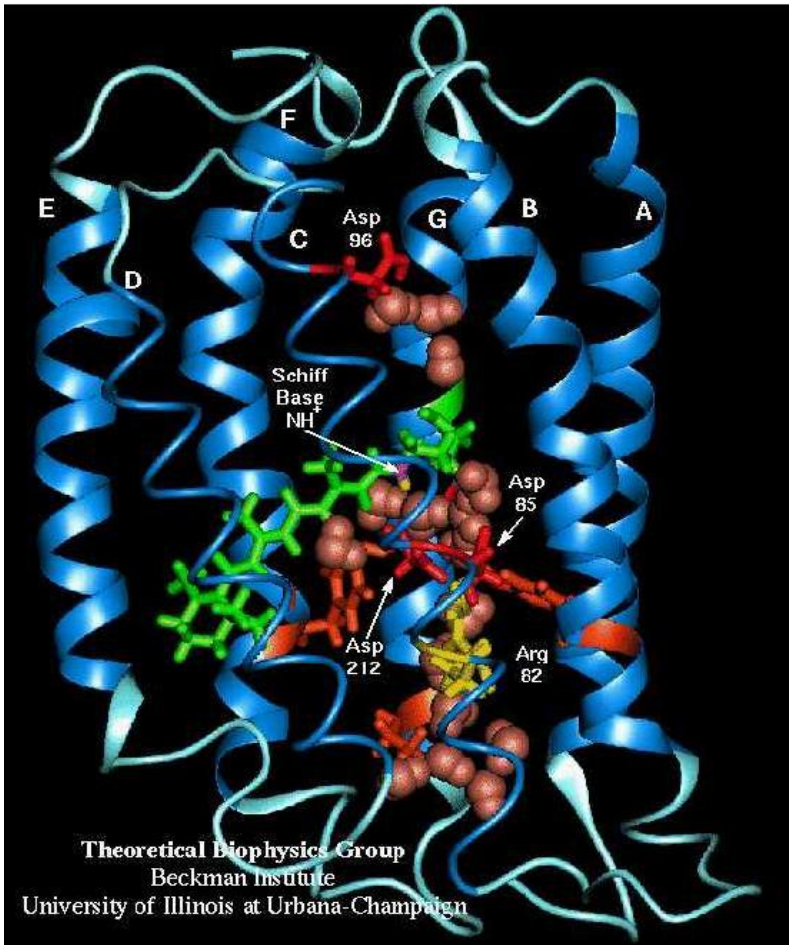
What can we do with something so infinitesimally short?

photographing chemical reactions

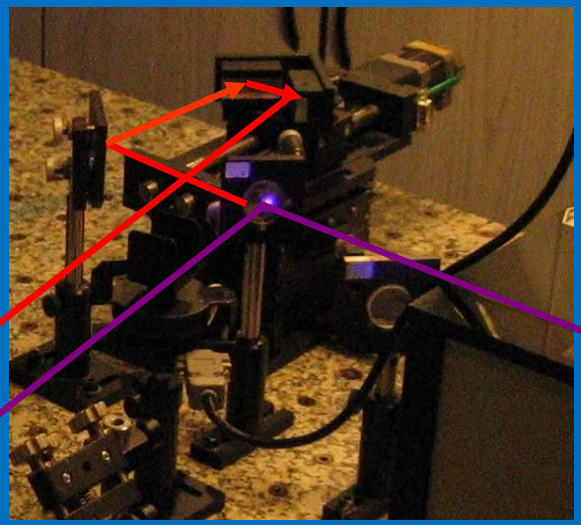


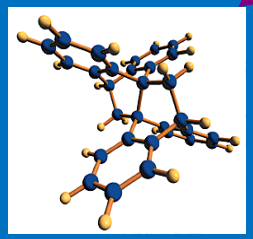
# Ultrafast processes of photosentisitizers in phothodynamic therapy of cancer – metal complexes of phthalocyanines and bacteriorhodopsin



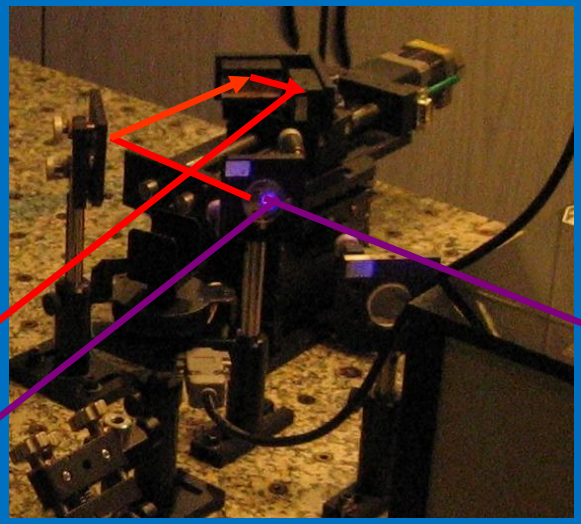



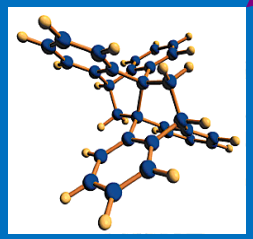
How can we monitor such fast chemical events?
Pump-probe  transient absorption method





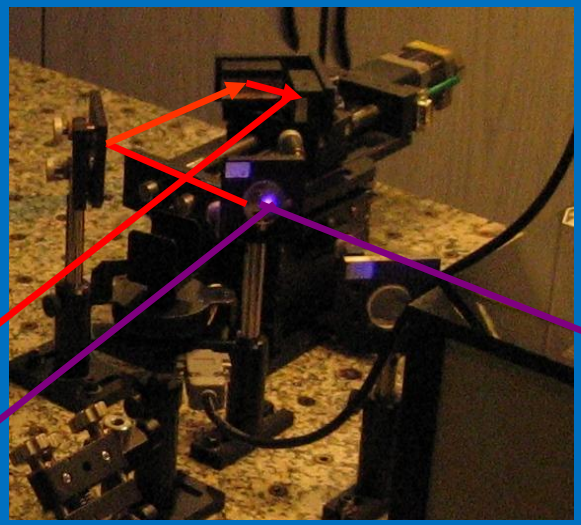
How can we monitor such fast chemical events?
Pump-probe  transient absorption method





I am the first one. I will excited some electrons

# How can we monitor such fast chemical events?
# Pump-probe transient absorption method



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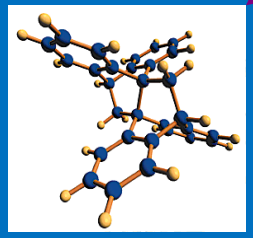

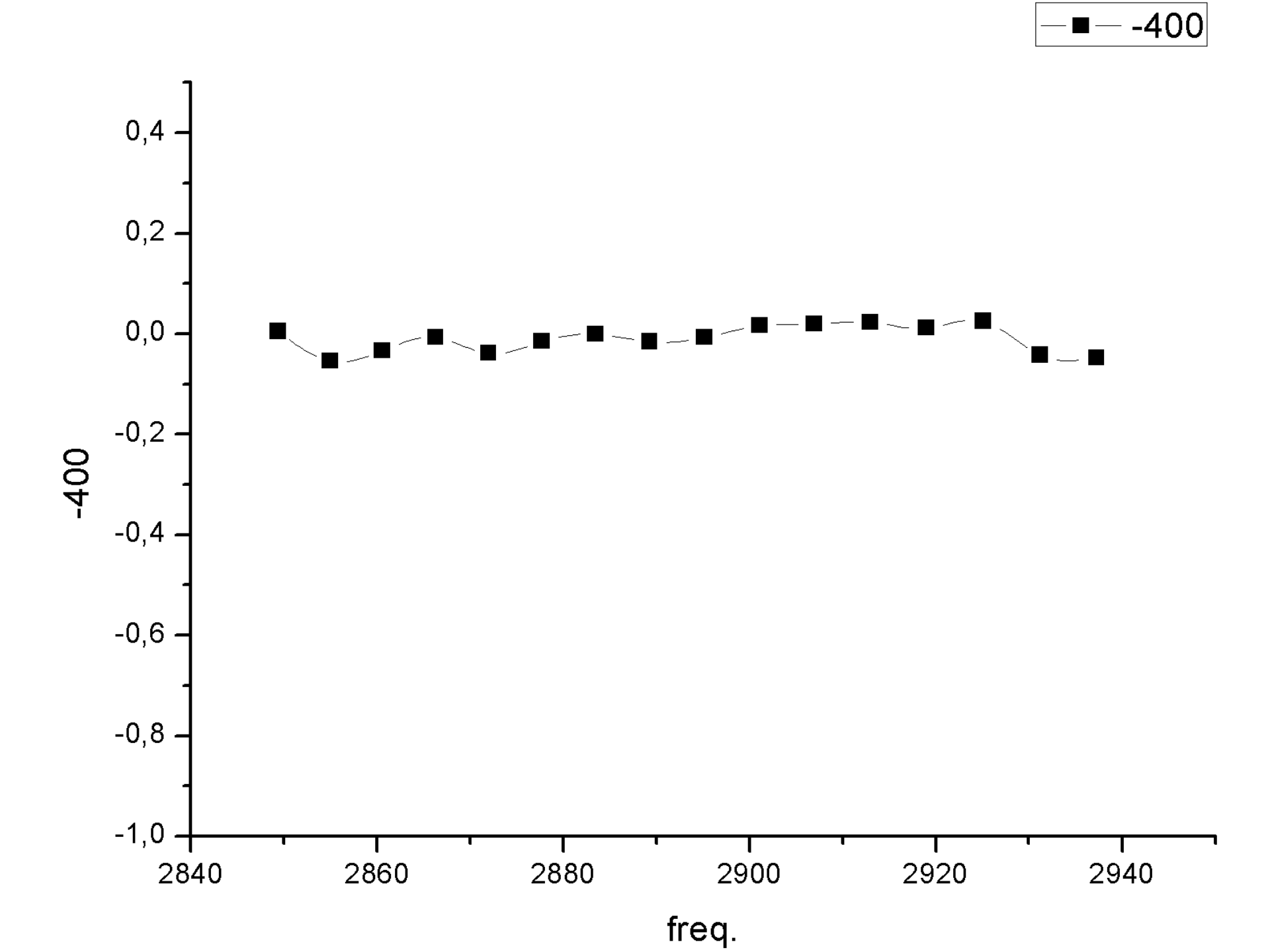
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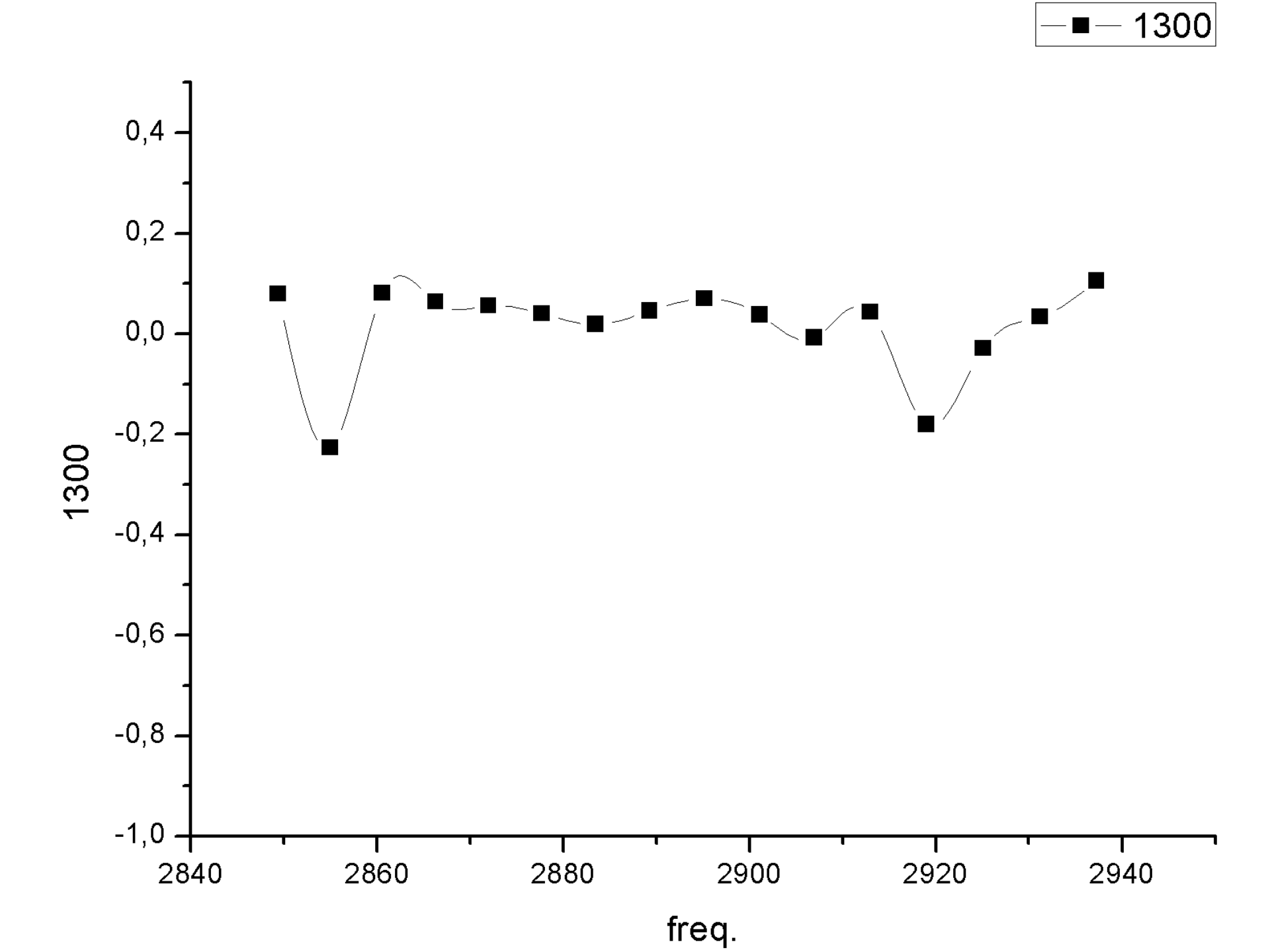
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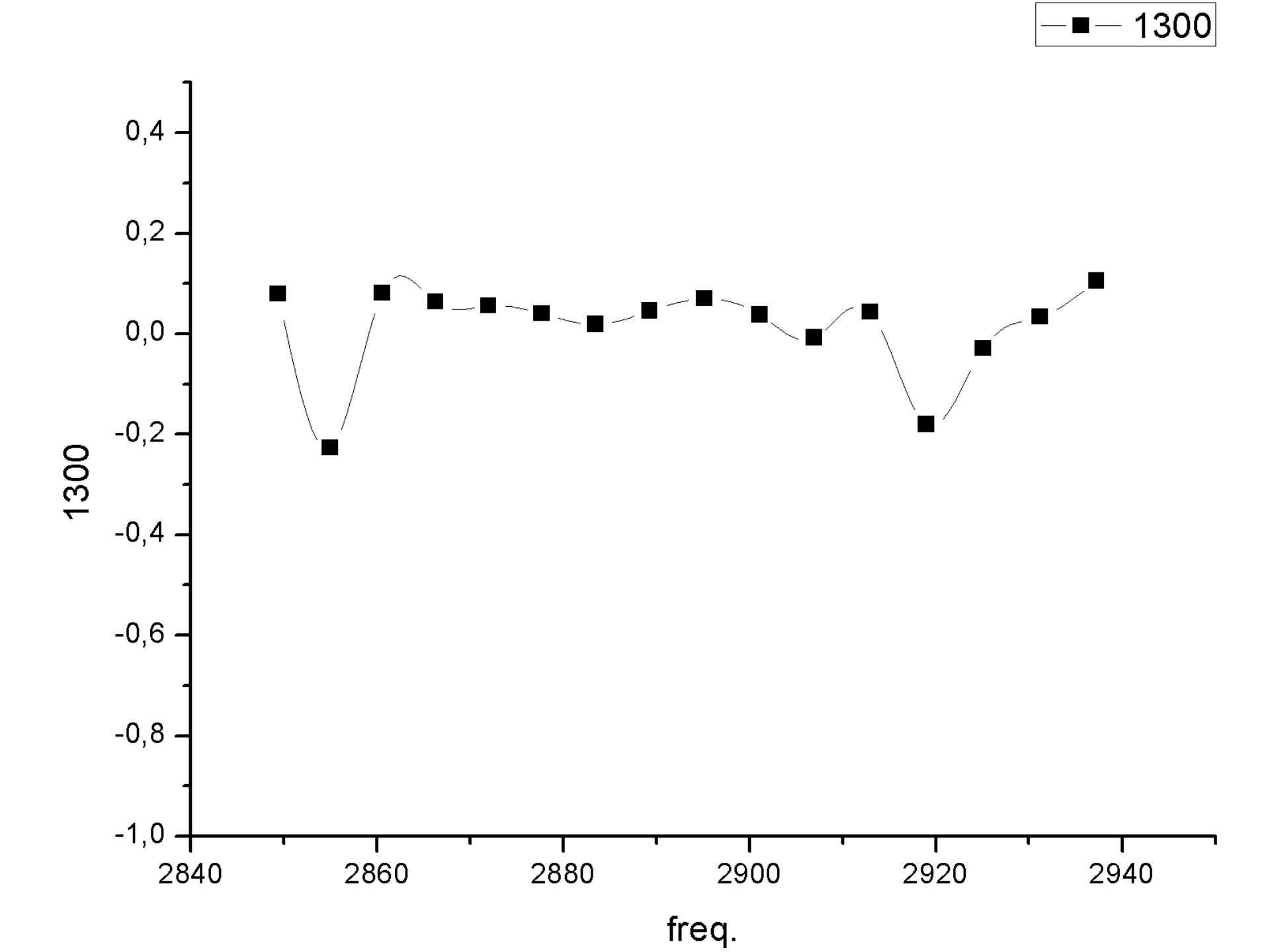
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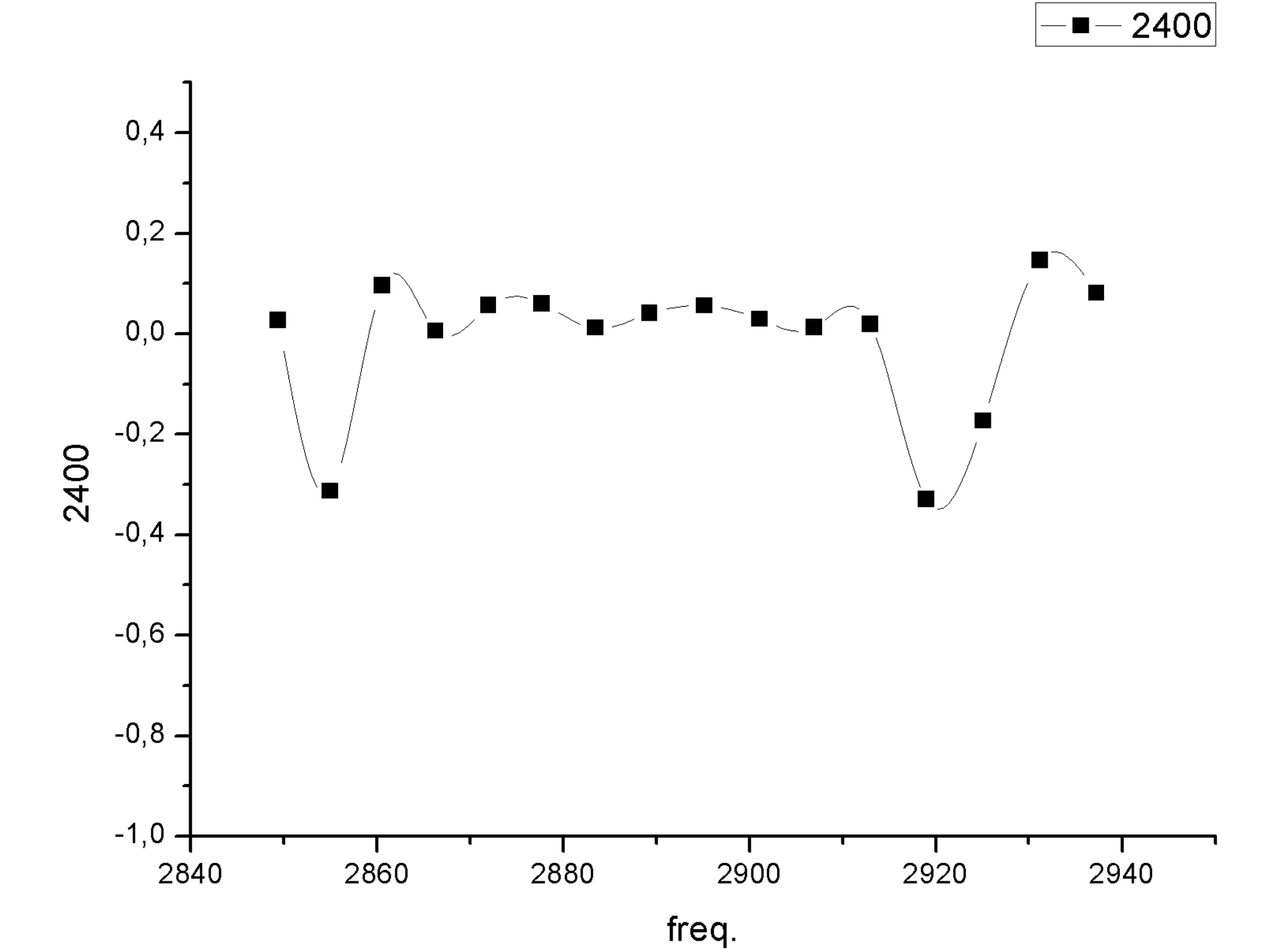
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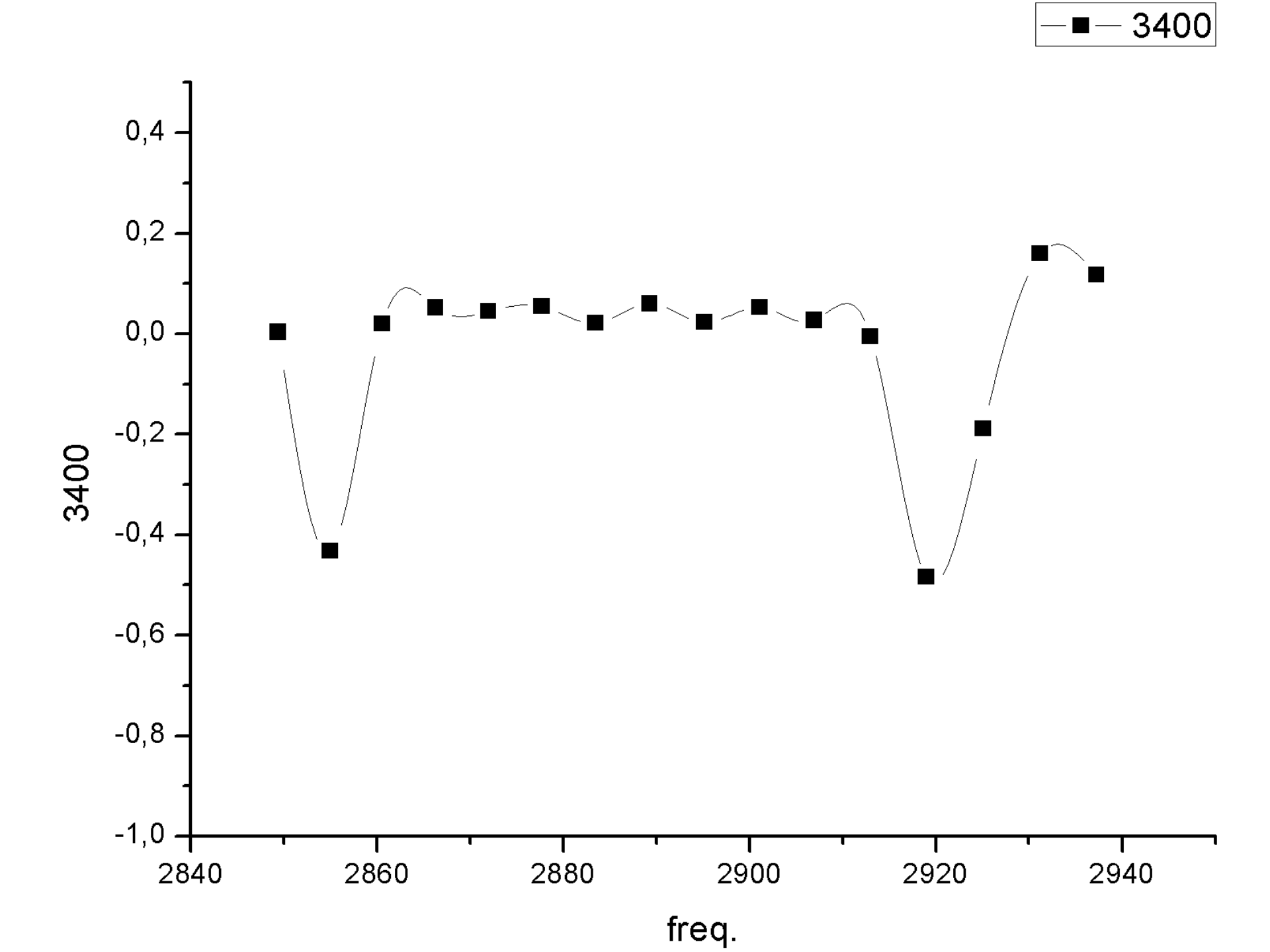
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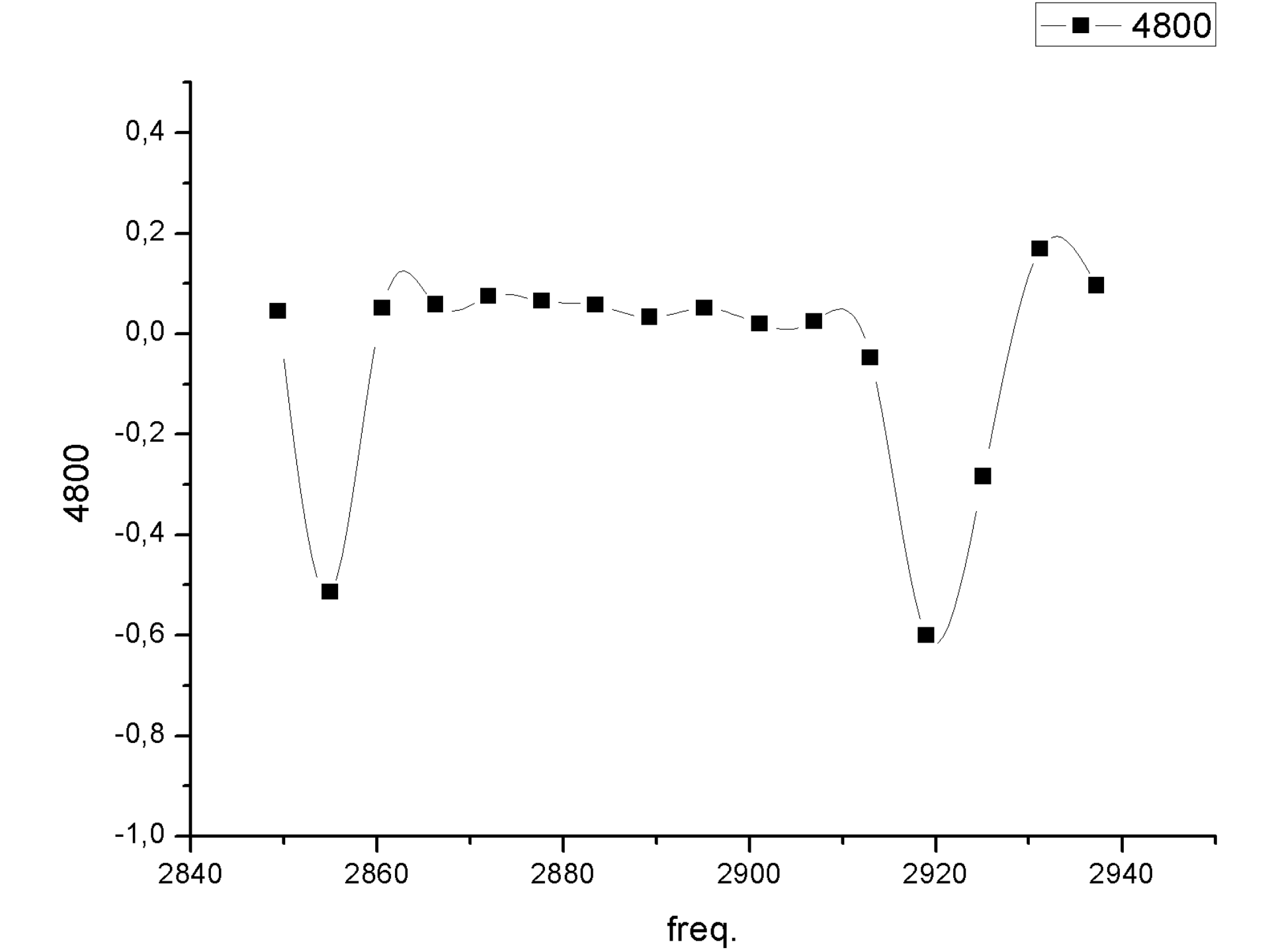
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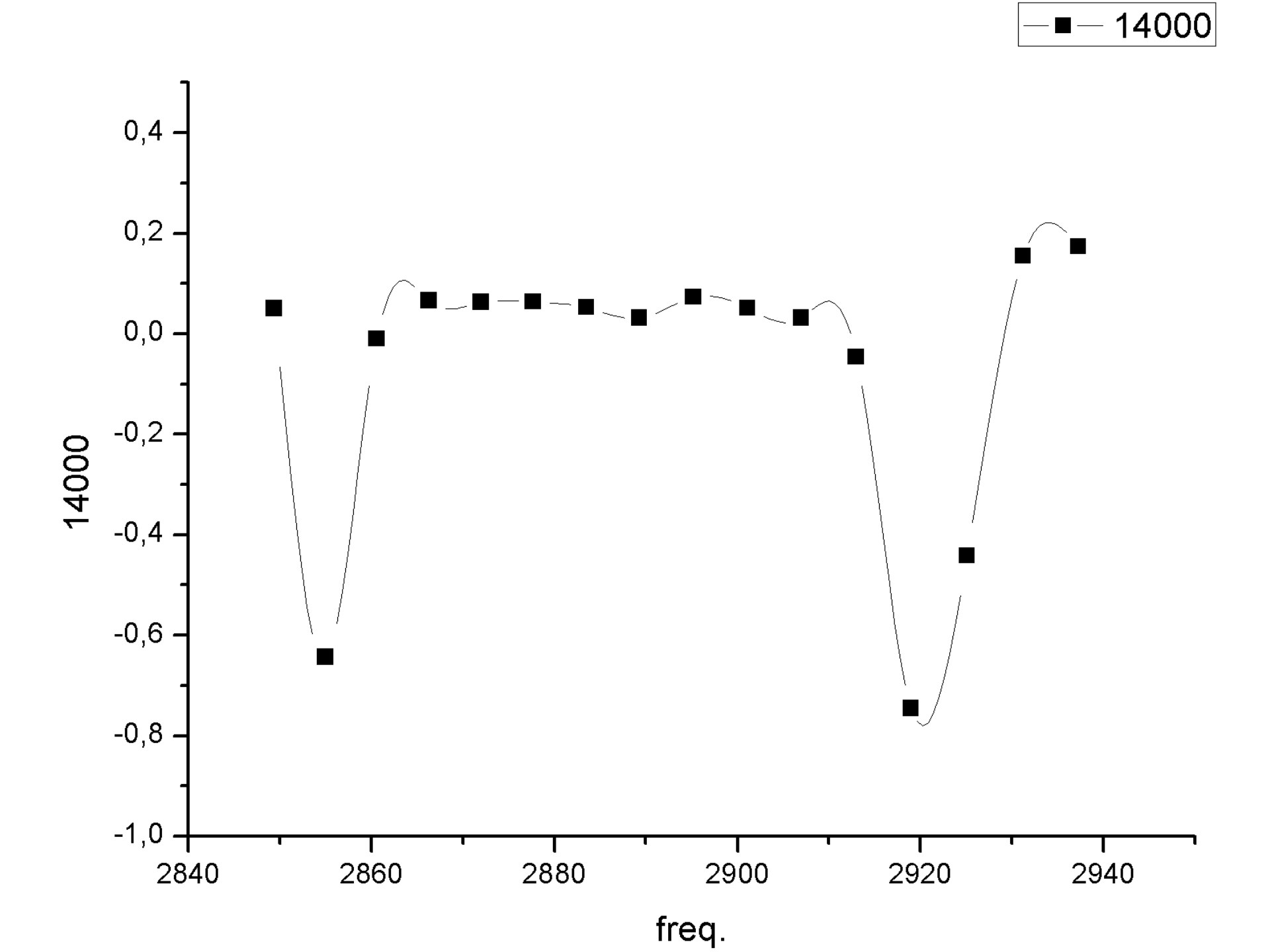
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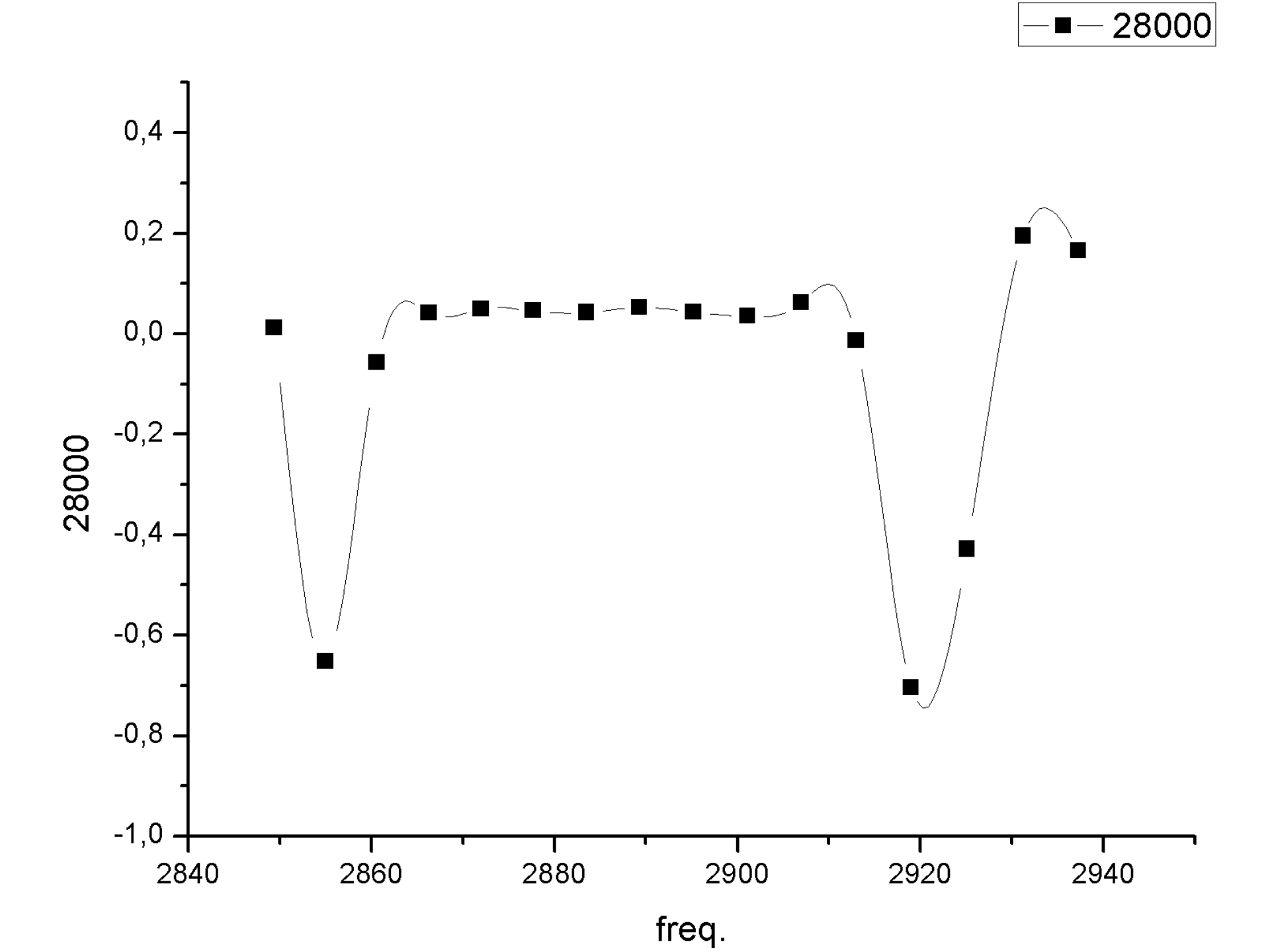
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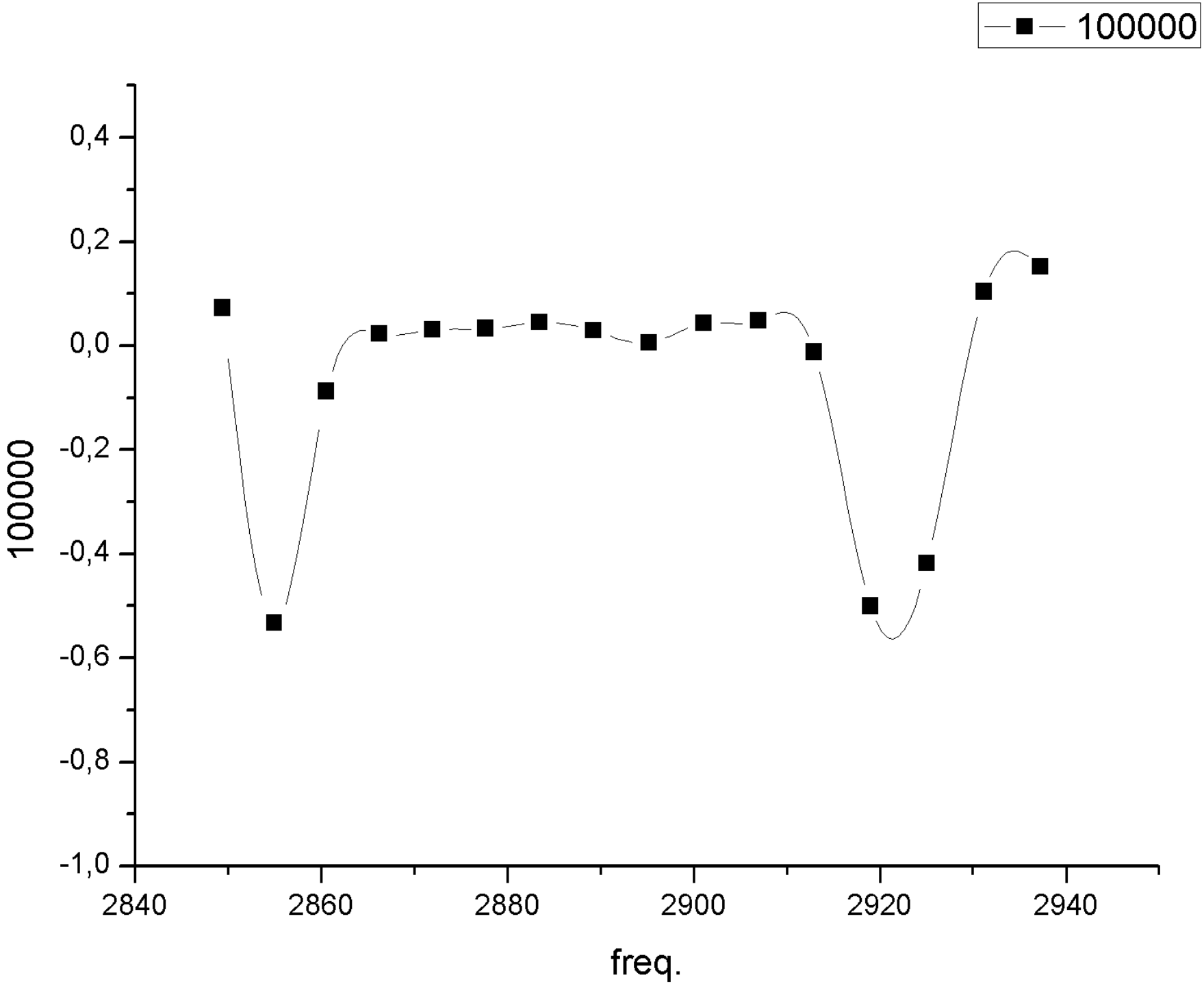
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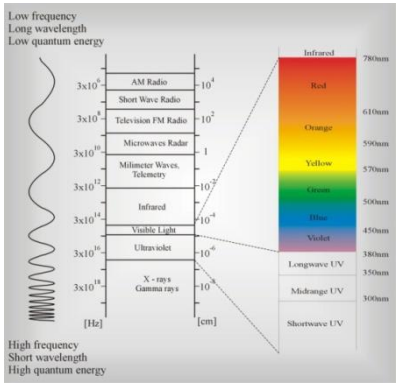
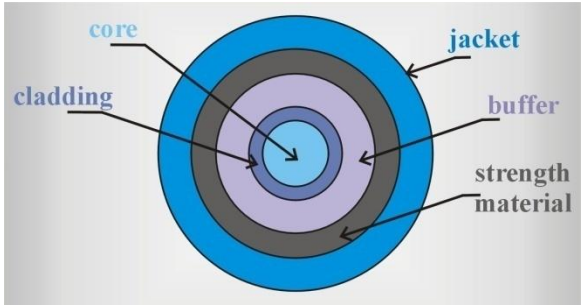
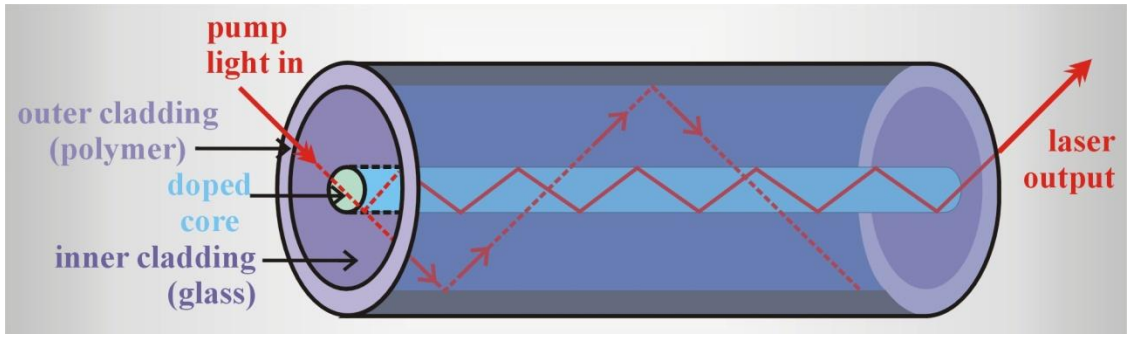


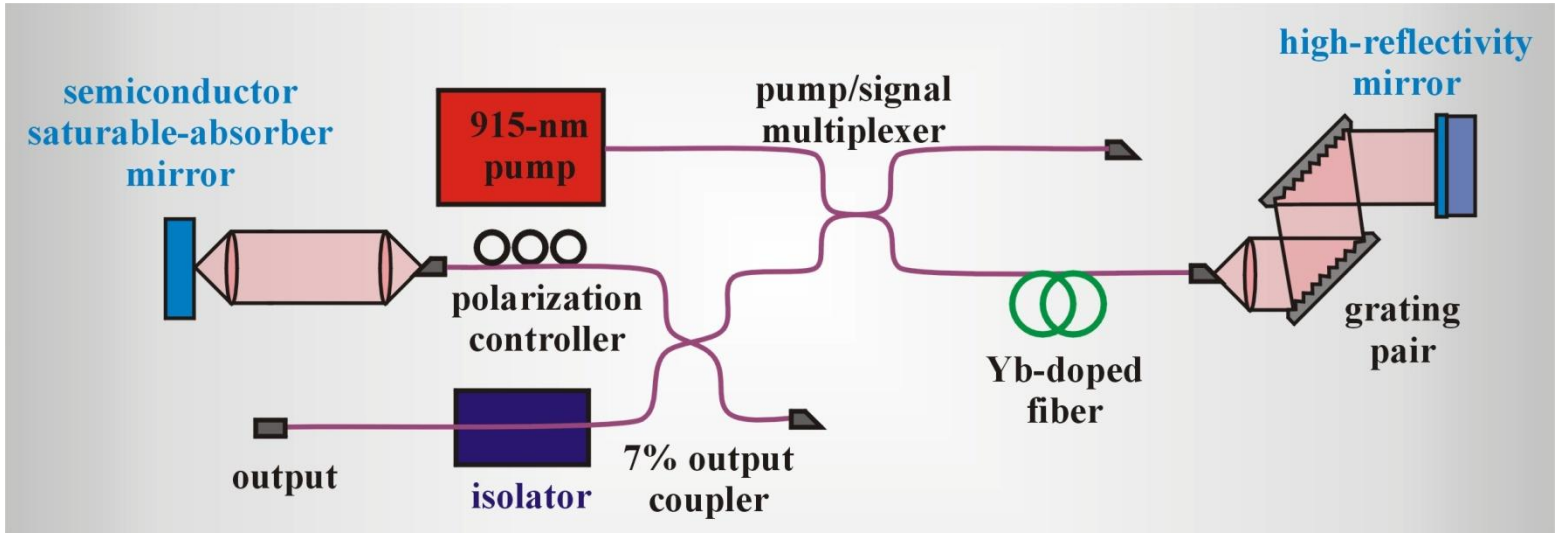

# Fiber Lasers




*A fiber laser* consists of a piece of a fiber cable as a resonator cavity sealed with coated ends that is optically pumped. The cavity length can be tens or even hundred of meters long in contrast to much shorter conventional lasers, but the size of the fiber laser does not create a problem at all as the flexible fiber cable can be rolled up into a small box of a few centimeters. In contrast to conventional lasers based on optical elements that are prone to contamination or misalignment, the fiber lasers cavity is nearly perfectly immune to these drawbacks. The fiber cable used in a fiber laser is modified by doping core with erbium or another earth element (neodymium, erbium, thulium) and adding additional cladding layer. Such a double-cladding consists of an inner cladding (glass) and an outer cladding (polymer). This allows for trapping both of light inside a cavity (core) and the pump light in the inner layer of cladding through total internal reflection. In this fiber configuration, multimode diode pump radiation is injected into a fiber through an end facet, then trapped in the inner cladding, propagating along the fiber and producing a population inversion in the core fiber.



The Yb-doped fiber is pumped with a single diode laser operating at 915 nm and average power of around 130 mW. A semiconductor saturable-absorber mirror, described in chapter 3, passively modelocks the laser. The semiconductor mirror uses an AlGaAs/GaAs distributed Bragg reflector, which usually has a bandwidth of 100 nm. A grating pair compensates for dispersion in the fiber. The laser can be tuned over more than 100 nm from 980 to 1100 nm. The wavelength tuning is achieved by adjusting the angular orientation of the high-reflectivity mirror. The duration of the modelocked pulses varies typically from 1.6 to 2.0 ps across the tuning range. The typical output average power is around 3 mW.



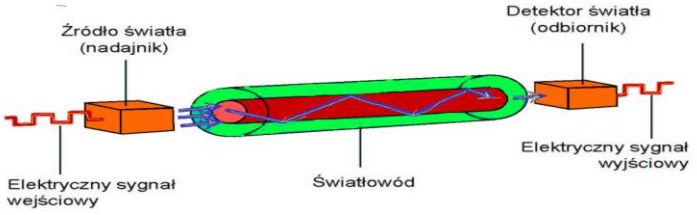

The mode-locked Yb:fiber laser configuration

# Applications of fiber lasers

- Fiber lasers are being developed in laboratories around the world as alternatives to traditional solid-state lasers. For many laser applications, however, average power of watts rather than milliwatts is required. Therefore, the Ti:sapphire laser has remained largely unchallenged as a source of broadly tunable, ultrashort pulses with routinely provided average power up to 2 W from a modelocked oscillator, with pulse duration on the order of 100 fs. The previous generation of high-power fiber systems has never exceeded these limits. However, this situation is changing due to improvements in amplification methods. Continuous wave–2 kW fiber lasers for industrial purposes have recently been developed. Powers as large as 13 W were reported as an output from a modelocked fiber laser emitting 2–5 ps pulses amplified as a result of an induced chirp from the non-linearity and positive dispersion.

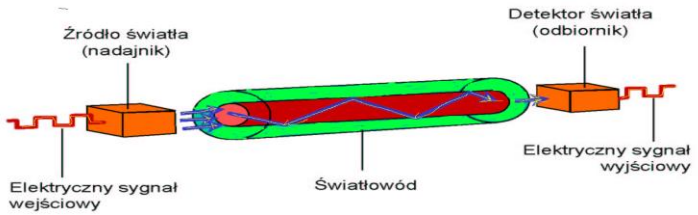
# Applications of fiber lasers

- Rare-earth-doped fibers are well suited to ultrafast applications for several reasons. Their 6-THz amplification bandwidth is broad enough to produce pulses shorter than 100 fs. Now, novel ultrafast fiber lasers are emerging that are capable of delivering average power and pulse duration that may compete with solid-state lasers in certain configurations. Optical communication is a main potential beneficiary of these ultrafast fiber lasers which can be useful in wavelength division multiplexing (WDM). The development of WDM schemes has created a growing market of higher-power devices. In the case of optical amplifiers, the gain must be divided among a large number of channels. Thus, the fiber amplifier power must increase.




| Time frame | WDM Type | Channels | Wavelength | Channel Spacing |
|---|---|---|---|---|
| 1980's | Wideband | 2 | 1310nm, 1550nm | - |
| Early 90's | Narrowband | 2 - 8 | C-band | 200-400 GHz |
| Mid 90's | Dense | 16 - 40 | C-band | 100-200 GHz |
| Late 90's | Dense | 64 – 160 | C-band | 25-50 GHz |
| Current | Dense | 160 – 320 | C/L-Band | 12.5-25 GHz |

# What can we do with so infinitesimally short pulses in real world applications?

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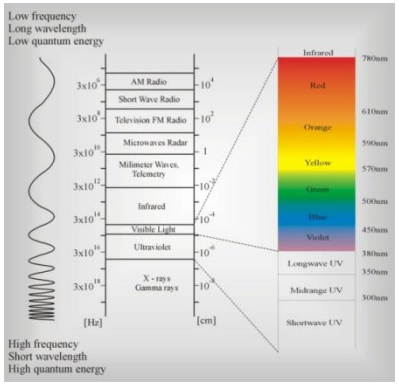
| Current | Dense | 160 – 320 | C/L-Band | 12.5-25 GHz |

- Fast optical networks utilizing the wavelength multiplexing technologies WDM, DWDM, UWDM are one of the greatest beneficient of the modern laser technology in building of complete optical platforms that includes
- optical fibers
- lasers, modulators, reflectometers
- optical amplifiers
- multiplexers and demultiplexers
- switches and teracommutators

# Gas Lasers in Visible Range

In *gas lasers* the gain medium is a gas. Here we will discuss gas lasers operating on electronic transitions like solid–state lasers. Gas lasers are facing stiff competition from solid–state lasers, but they are still powerful tools in many scientific, medical and industrial applications.




- **Helium–Neon Laser (**632.8 nm)
- **Ionic Gas Lasers. Argon Laser (514 nm)and Krypton (**647.1 nm)**Laser**
- **Nitrogen Laser (**337 nm)

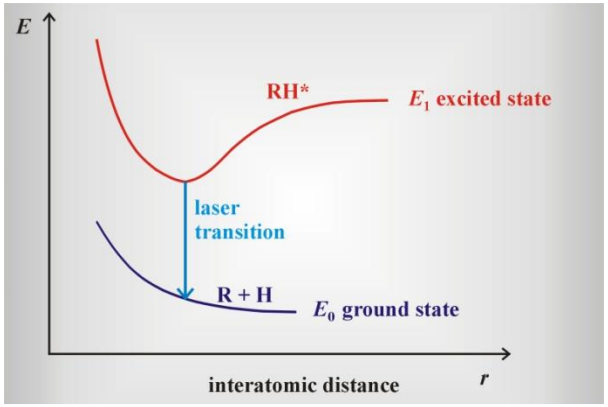
# Helium–Neon Laser. Applications

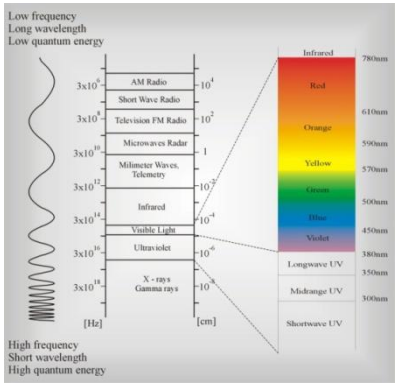
Generally, there are several laser transitions possible, but most HeNe lasers are designed to favor 632.8 nm emission. The transitions in infrared at wavelength of 1523.5 nm and 3392 nm are not usually used in mass production due to higher prices related to special optics in IR. However, they have several specific uses. For example, the 1523.5 nm line is successfully used for testing of silicon–glass optical fibers due to minimal losses in this spectral area. Although laser diodes provide an alternative to helium–neon lasers, they are still used in alignment, interferometry, metrology, medical diagnosis like flow cytometry, holography, in malls to read product codes due to good beam coherence and quality. They are also used to determine position of patient under X irradiation. They serve in industrial alignment to determine straight line with laser beam in buildings, tunnels, sewer pipes construction. The compact laser diodes, however, partially relegated the helium–neon lasers as hand–held barcode readers, but they still dominate industrial code readers because of their low divergence.

# Gas Lasers from Ultraviolet Range

- **Excimer Lasers**

- Excimer lasers, beside nitrogen laser, are the most popular gas lasers generating radiation from the ultraviolet range. Active medium is a mixture of a noble gas, halogen gas and a buffer gas, usually neon. Gas mixture in a typical excimer laser consists of 2–9% of a noble gas, 0.2% of a halogen gas, and 90–98% of a buffer gas which serves as a medium to transport energy. The mixture is confined in a pressure vessel, typically at a pressure of 3500–5000 millibars. The gas mixture is usually excited by means of a fast electric discharge lasting a few tens of nanoseconds.
- Short living, unstable in the ground state, halides of noble gases such as: ArF, KrF, XeF, XeCl are created in the gas mixture
- The excimer medium has a very high gain, and output coupler reflectivity of 10–30% is sufficient to achieve an adequate output. The most often used emission lines of excimer lasers are: 193 nm (ArF), 248 nm (KrF), 308 nm (XeCl) and 351 nm (XeF). The powers of these lasers are from 1 W to 100 W (for KrF and XeCl and even more).



# Excimer Lasers

- One should remember, that the excimer lasers, although often used in laboratories, industry and medicine, contain a toxic active medium. So, the special safety should be kept. In the early days of the excimer laser development the corrosion of the gas vessel due to halogens presence was a serious problem. In all modern lasers this problem was removed by careful selection of materials, such as electrodes made of nickel or bromine, elimination of organic materials such as lubricants, seals or insultors. These technical improvements extended the lifetime between exchanges of laser gas to $10^8$ pulses.

# Applications of excimer lasers

Excimer lasers produce high pulse energies, high average and peak powers. One of the biggest excimer lasers is Aurora in Los Alamos National Laboratory (5 ns, 5 kJ, KrF) used for plans of nuclear fusion control tests. The excimer lasers were used in scientific laboratories to pump dye lasers as well as to generate higher harmonic to reach vacuum ultraviolet range. Excimer lasers are particularly significant in application such as metrology and systems alignment. They are important tools to monitor pollution and ozone concentrations in upper layers of the atmosphere. Excimer lasers emitting in deep ultraviolet currently dominate the lithography industry. They serve to draw patterns, marks, trade codes on ceramics, glass, plastic and metal. Krypton and argon fluoride (KrF and ArF) lasers used in deep-UV microlithography facilitates chip designs generating circuit features smaller than 0.18 mm.

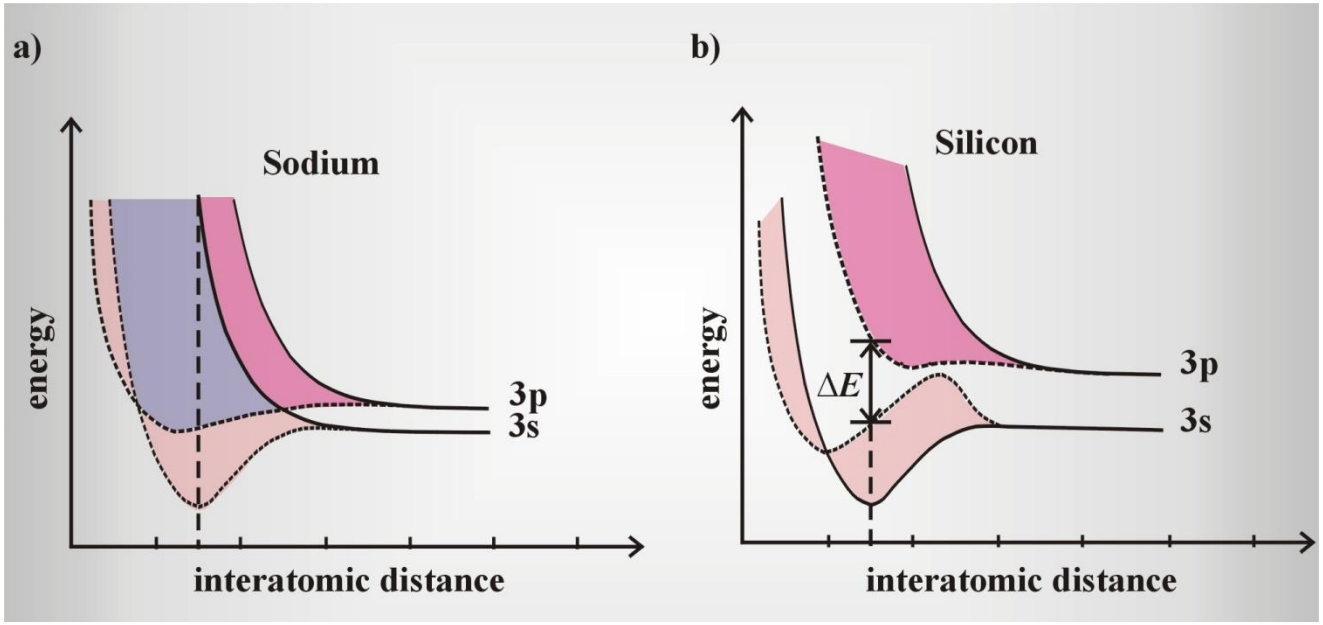
# Nitrogen laser

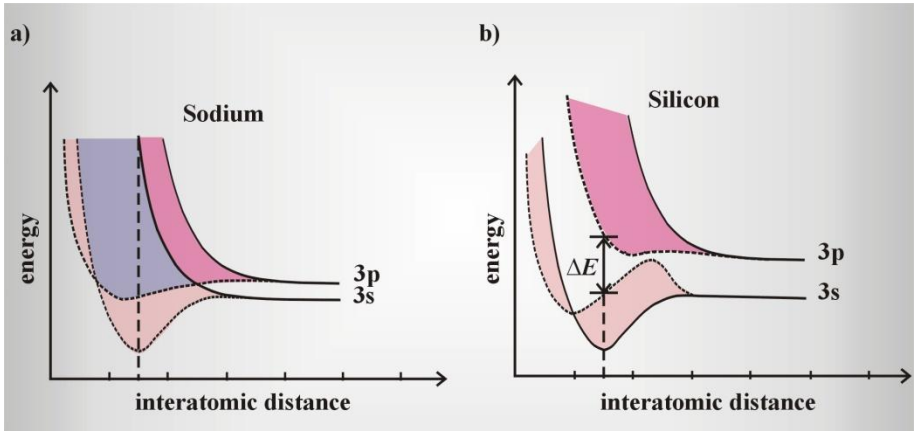
- The nitrogen laser emits radiation at 337 nm. The active medium of nitrogen lasers is a gas nitrogen. The gas is confined within a pressure vessel, usually at total pressure between 101 Pa and 2700 Pa. The nitrogen laser generates pulses of duration between 300 ps (at atmospheric pressure) to 10 ns (at 2700 Pa). The repetition rate changes from 1 to 100 Hz. Low repetition rate lasers use a configuration of sealed-off devices and high repetition rate lasers employ flowing version. The pulse energy changes from microjoules to 10 milijoules. During many years it was used to pump dye lasers and as a source for many other applications requiring UV radiation. The nitrogen laser is well suited to UV laser-induced fluorescence applications in clinical, pharmaceutical, environmental, and process control work.

# Semiconductor Diode Lasers

# Intrinsic Semiconductors. Doped Semiconductors. *n–p* Junction

Every material has characteristic properties related to electric current conductivity. Three main classes can be distinguished: a) metals, b) semiconductors, c) insulators. Atoms in a solid are packed into a dense crystalline arrangement, and electron energy levels are no longer narrow discrete lines. They are significantly broadened due to interactions with condensed environment. However, there is a fundamental difference in the energy gap in metals, *semiconductors* and *insulators*






Let us take for example a metal, e.g. sodium ($^{11}$Na) with the electronic structure: $(1s)^2(2s)^2(2p)^6(3s)^1$. The outer electron level 3s is broadened considerably like the first upper lying electron level 3p, unoccupied for an isolated atom. This results in overlapping between the neighboring levels (fig. 4.22a) and the electron can be found either on the 3s or 3p levels. This area of overlapping levels is called *the conduction band* because the electrons occupying 3s or 3p orbitals are common for all the atoms and can wander freely through the solid from one atom to another.

In semiconductors, e.g. in silicon $^{14}$Si: $(1s)^2(2s)^2(2p)^6(3s)^2(3p)^2$ the outer electron levels are also broadened in a dense crystalline matrix but they do not overlap (fig. 4.22b). The 3s and 3p orbitals broaden into two distinct bands separated by the energy gap $\Delta E$. We say that the four electrons (originally two from 3s and two from 3p) occupying 3s (or more precisely $sp^3$ orbital) are in *the valence band*, while the level 3p (conduction band) remains empty.

A material, in which the energy gap D*E* becomes very large is called an *insulator*. In the *insulators* the energy gap D*E* is on the order of 3 eV or more, which indicates that the collision energy as well as another forms of thermal energy of molecules are insufficient to transport an electron from the valence band to the conduction band. In semiconductors the energy gap D*E* is much smaller (1 eV for silicon) allowing a fraction of electrons to jump to the conduction band at room temperature. At absolute zero temperature, semiconductors become insulators.

# a) intrinsic semiconductor, b) semiconductor of *n*-type, c) semiconductor of *p*-type

- When silicon matrix $^{14}Si$ ($(1s)^2(2s)^2(2p)^6(3s)^2(3p)^2$) is doped with phosphorus $^{15}P$ atoms ($(1s)^2(2s)^2(2p)^6(3s)^2(3p)^3$), which have the energy of the electrons in the 3s ($E_d$) state approximately the same as the energy of the silicon electrons in the conduction band 3p, the phosphorus electron (donor) can easily jump to the conduction band of the silicon (acceptor) (fig. 4.24b). The semiconductors that are doped in such a way get additional excess electrons and they are called the *semiconductors of n-type*. On the other hand, if silicon matrix is doped with aluminum atoms $^{13}Al$ ($(1s)^2(2s)^2(2p)^6(3s)^2(3p)^1$), which have the electron energy ($E_a$) close to the energy of the silicon valence band 3s, the electrons from the silicon jump to the level $E_a$ of aluminum leaving a hole in the valence band of the silicon (fig. 4.24c). Semiconductors that are doped in such a way are called the *semiconductors of p-type*.

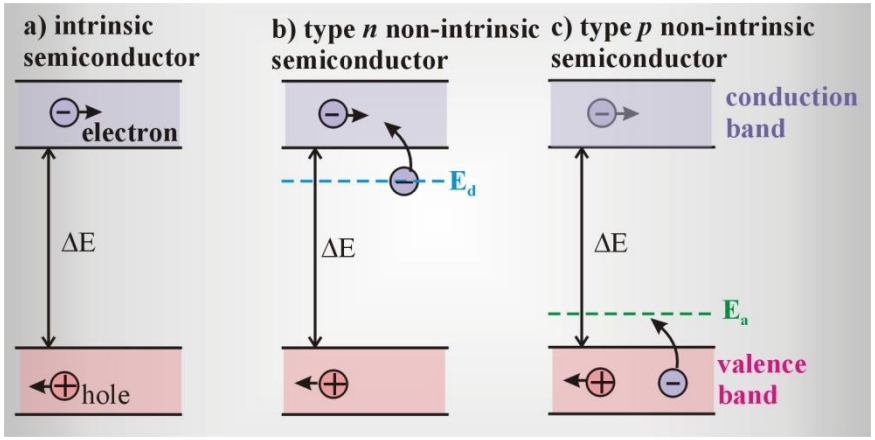



**Fig. 4.24** Scheme of intrinsic and extrinsic semiconductors: a) intrinsic semiconductor, b) extrinsic semiconductor of *n*-type, c) extrinsic semiconductor of *p*-type

# *p-n* junction

- If *n*–type and *p*-type semiconductors are brought together to form a *p-n junction*, holes migrate from the *p*-region to the *n*-region and conduction electrons move in the opposite direction. As a result of this migration an area in the direct neighborhood of the junction becomes depleted of mobile charge carriers (fig. 4.25), with an excess of negative charges on one side and an excess of positive charges on the other side of the semiconductor. Consequently, such a charge distribution induces an internal electric field *E* directed towards *p*-region. This internal field prevents charges from further migration across the junction. The *p-n* junction is called the *photodiode*.
- When the *p-n* junction is irradiated, new electron–hole pairs are generated, which are moved by the internal field *E*. The holes move towards the area *p*, electrons – towards the area *n* causing decrease of the internal voltage potential.

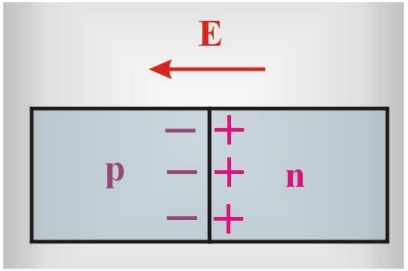
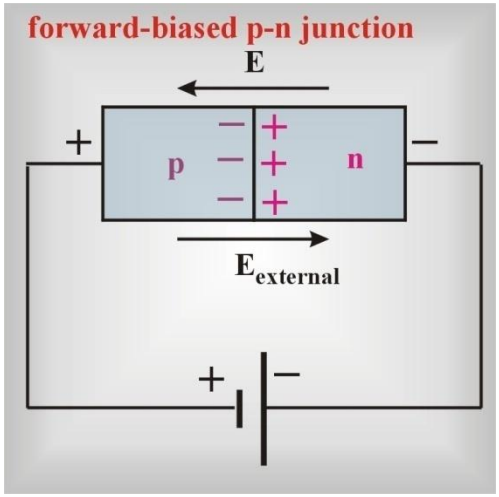
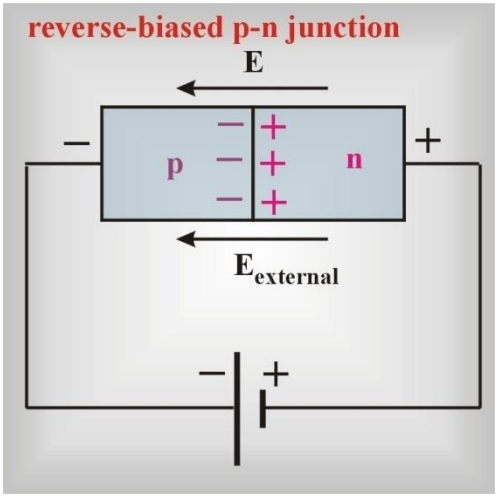



**Fig. 4.25** *p-n* junction

# Forward biased junction and reverse biased junction

Detection on the junction can be improved by applying an external voltage supply. When a negative terminal of the external voltage source becomes connected to the *n* region, and the positive one to the *p* region, the *p-n* junction is said to be *forward biased*. This means that the charge carriers, both holes from the area *p* and electrons from the area *n*, flow towards the junction under the external field $E_{ex}$ (fig. 4.27). The external field $E_{ex}$ is directed just opposite to the internal field *E*. The semiconductor lasers, which will be discussed in the next chapter use the forward biased junction. On the other hand, when *the negative* terminal of the external voltage source is connected to the *p* region, and the positive one to the *n* region, the *p-n* junction is said to be *reverse biased* (fig. 4.28).



# DIODE LASER

- The simplest light-emitting diode (LED) is the forward biased *p*-*n* junction. The external forward biased voltage applied to the *p*-*n* junction force holes from the *p*-region and conduction electrons from the *n*-region towards the junction. The movement of the charge carriers in the opposite directions creates an electric current through the device and recombination of the electrons and the holes at the junction. The energy gained in the recombination can be released as non-selective heat (silicon and germanium semiconductors) or as light (GaAs) at energy of photons equal to the gap D*E* between the valence band and the conduction band. The different patterns of relaxation by means of radiative or radiationless decay depend on the band-gain structure. Semiconductor materials with a *direct band gap* dissipate the recombination energy mostly by light, in contrast to semiconductors with an *indirect band gap* in which the energy is released mostly by heat. Radiative way of energy releasing is observed in materials that belong to the III–V groups of elements as well as in some materials from the II–VI groups. The distinct paths of relaxation originate from the fact that the conduction electrons and the holes experience separate dynamics in various materials. In the direct-band gain semiconductor the momentum of an electron returning from the bottom of the conduction band to the top of the valence band changes very little in contrast to a semiconductor with the indirect band gap, in which this electron transition is accompanied by a significant shift in momentum.
- In principle, a semiconductor laser (also known as a diode laser) can be obtained from a LED in which population inversion is achieved. The diode laser requires much higher current densities than LED to reach laser threshold (fig. 4.29). The population inversion between the conduction and valence bands is achieved by applying a strong forward bias across the device to inject a large number of electrons and holes into the junction. Operating under the conditions of population inversion means that the number of recombination events exceeds considerably the number of electron-hole pair generation.
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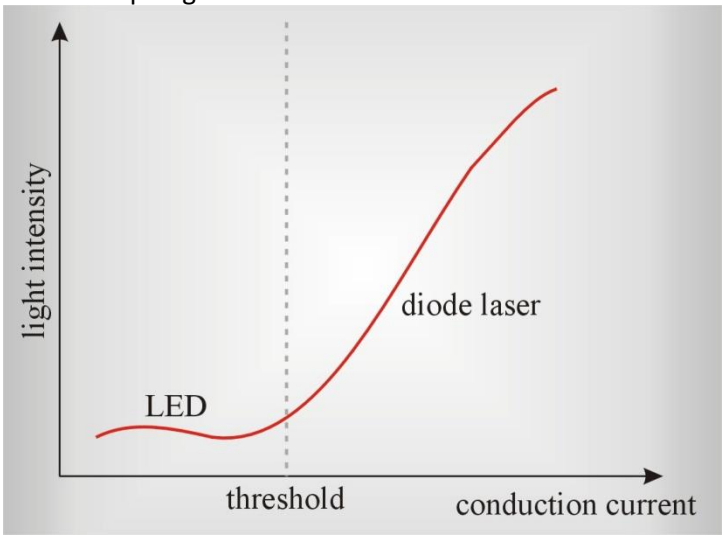



**Fig. 4.29** Scheme illustrating the difference between the light-emitting diode (LED) and the diode laser

# DIODE LASER

- To achieve a greater efficiency some kind of optical feedback is needed like in other lasers that we described so far. Usually, two opposing facets cleaved perpendicularly to the junction play a role of an optical cavity like mirrors in conventional lasers. Therefore, light emitted on the *p*-*n* junction is reflected on the diode edge and turns back to the junction again, additional electrons and holes are produced with electrons jumping from the valence band to the conduction band. The electrons recombine again with the holes under applied forward bias voltage and return to the valence band emitting light of the energy equal to the difference between the valence band and the conduction band D*E*. Moreover, the optical feedback between the parallelly cleaved facets produces a more directional, coherent beam of light from the junction plane in contrast to LED that emits in nearly all directions. The simplest laser diode is presented in fig. 4.30.

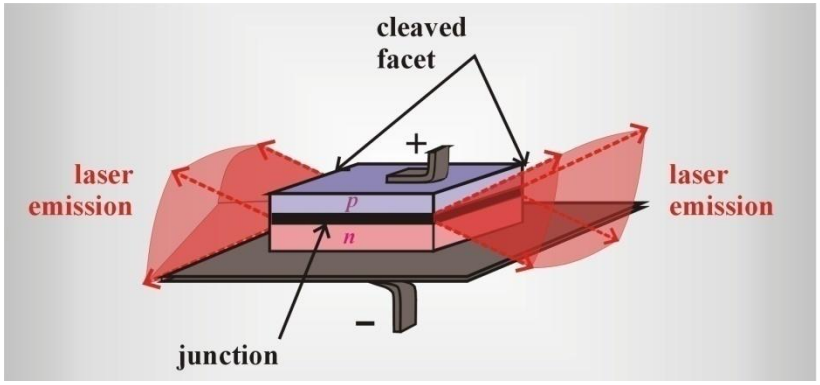
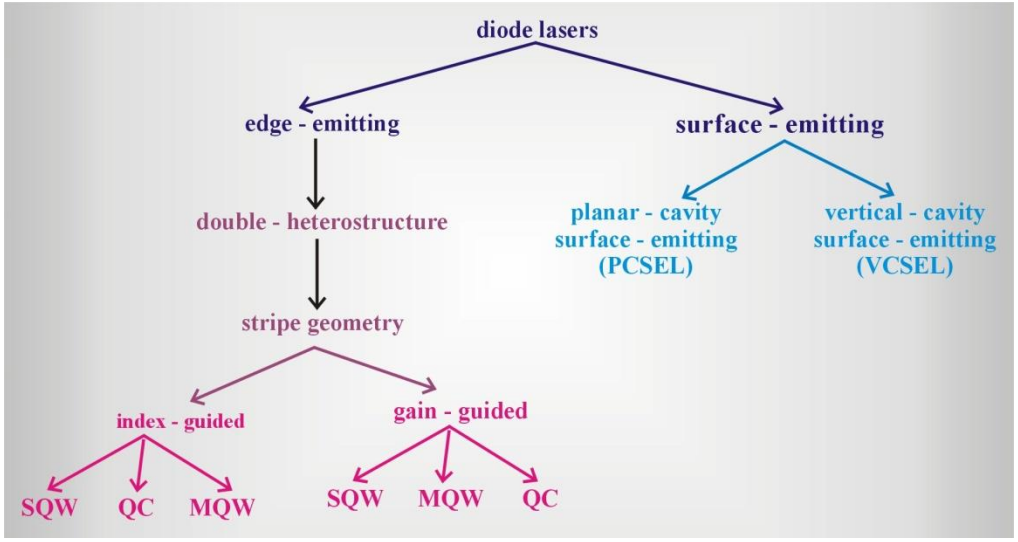



**Fig. 4.30** Laser diode scheme

# DIODE LASER

- The earliest diode lasers presented in fig. 4.30 that were a simple *p-n* junction required extremely high current densities to reach laser threshold. Although the first semiconductor laser was built in 1962, many years elapsed before the technology matured enough to meet the demands of real-world applications. The first diode lasers had to operate only in pulsed regime under cryogenic cooling. Better performance of diode lasers was attained by inserting a few layers of a semiconductor material instead of the simple *p-n* junction described above. The first continuous wave operation at room temperature was achieved in 1970. The *cw* operation becomes possible through the advent in the technology of *double heterostructures*.



# DIODE LASER

- In order to achieve a goal of performance equal to reliability and stability of other lasers, diode lasers required a few important improvements.
- First, they needed to reduce heat while maintaining a population inversion.
- Second, to improve the beam quality and its divergence.
- Third, to provide higher power levels while maintaining a single transverse mode output.
- Forth, to control output wavelength.

# DIODE LASER

- The first goal can be achieved by increasing effectiveness of inversion population at a given current or/and by reducing the current flow into a small region. Double heterostructure architecture, presented in fig. 4.32a, helps to confine charge carriers, enhancing population inversion. A double heterostructure junction consists of a very thin *p*-type layer (approximately 0.2 mm) of a direct-band-gap material having a smaller band-gain than the thicker *p*-type and *n*-type layers above and below it. When a forward biased voltage is applied to this *p*-*p*-*n* junction, holes and electrons are injected from the outer regions into an central active layer, where they become trapped in the potential well created by the wider-band-gain materials. "Carriers confinement" into a small volume increases population inversion, which means higher efficiency, lower threshold current, less heat and more light.
- This effect can be enhanced by adding "current confinement" to the double heterostructure. One way to introduce the current confinement is to use a stripe electrode instead of wide area of the diode's surface. Confining the current into a small region perpendicular to the plane of a junction leads to higher current density, higher concentration of charge carriers inside a diode, higher gain and less heat. A number of techniques can be used to confine the current flow to a small area, but the simplest method is presented in fig. 4.32b. A thin ribbon of positively charged metal is put between two insulator layers such as silicon–dioxide ($SiO_2$) and cover the *p*-*p*-*n* junction instead of a monolithic layer of a metal as in fig. 4. 32a.

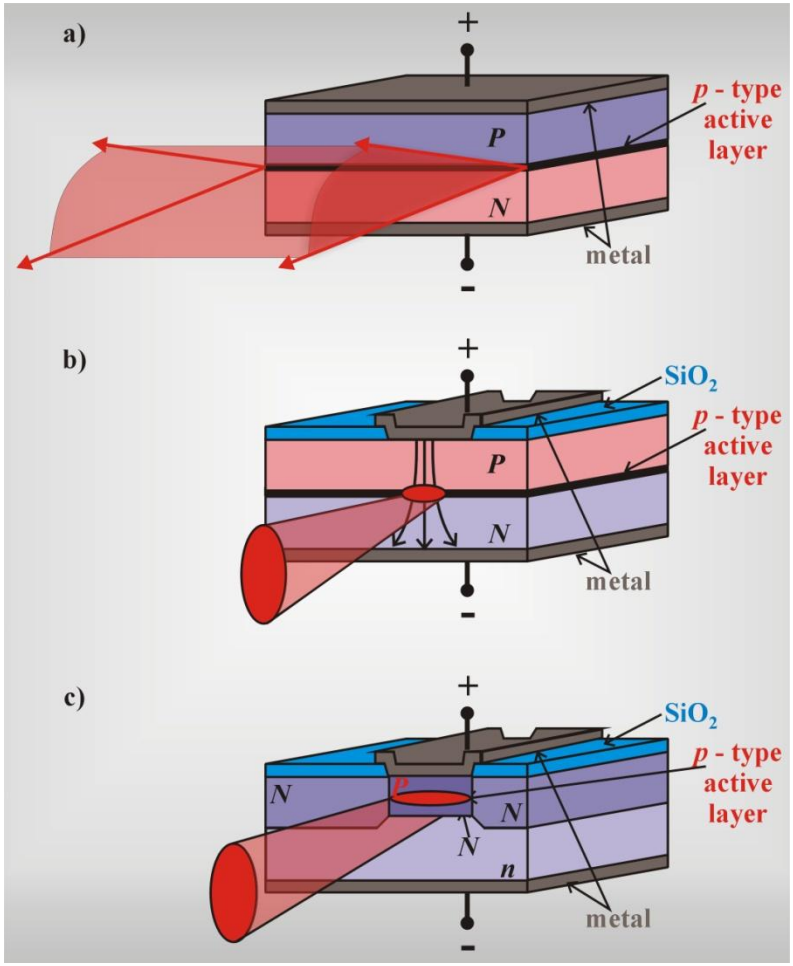
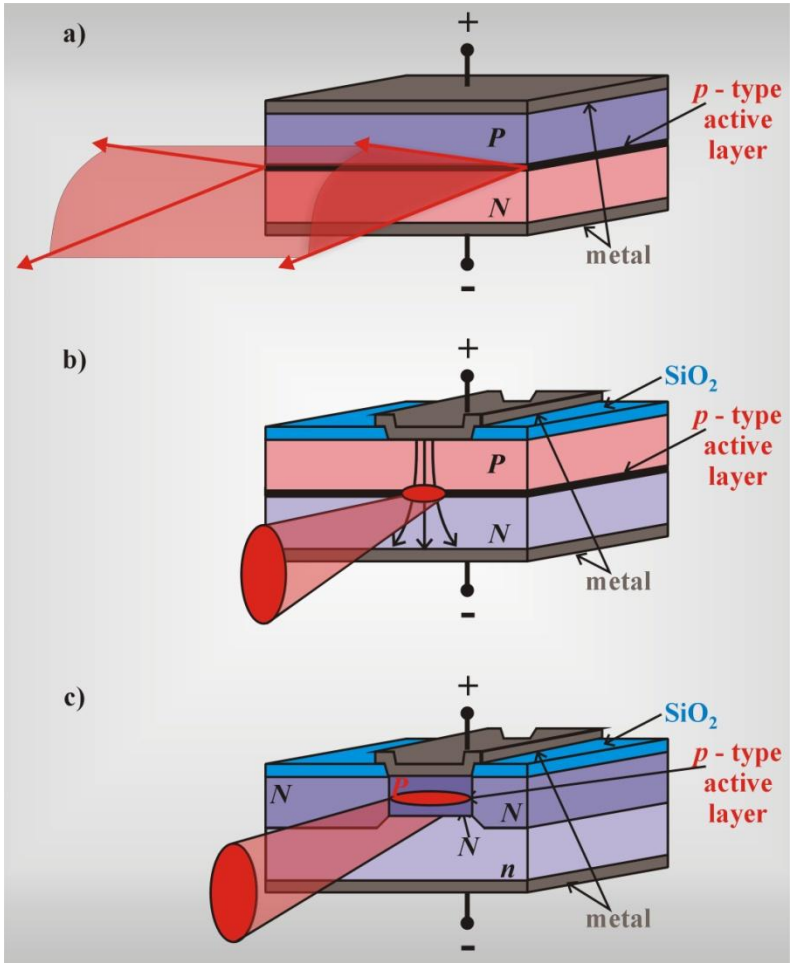



**Fig. 4.32** a) the basic double heterostructure diode; b) gain-guided, striped geometry diode; c) index-guided, striped geometry diode

# DIODE LASER

- The effects of “carriers confinement” and “current confinement” can be additionally enhanced by introducing “photons confinement”. Index-guided technique is commonly applied to trap photons inside the optical cavity to increase the density of the cavity optical power. The principle of index-guided diodes is illustrated in fig. 4.32c. A thin active layer of *p*-type small-band-gain material is surrounded on four sides by the wider-band-gain materials characterized by refraction index lower than that for the active layer. This architecture is a gain-guiding, but additionally it takes advantages of trapping light inside a narrow area through total internal reflection due to higher refractive index inside the cavity. This architecture helps to confine the generated photons into a narrow region, enhancing optical feedback and population inversion.
- One can notice that both the gain-guided diode laser and the index-guided diode laser produce a tighter coherent beam of light from the narrow active area in contrast to the double heterostructure in fig. 4. 32a that emits a broad beam across the entire junction area. The index-guided diodes generate a narrower, more coherent beam than the gain-guided diodes, but the latter can reach higher powers.



# *quantum wells*

- If we reduce the thickness of the *p*-type active layer in the double heterostructure down to 50 nm and less, which is feasible with the development of advanced semiconductor fabrication techniques, additional quantum effects occur in the active layer of the junction. Both the valence and the conduction bands split into discrete sublevels, with energy and momentum of the charge carriers depending on the thickness of the layer. Such double heterostructures with an active layer thicker than 50 nm are called *quantum wells*. When only one thick active layer is employed, the diode laser is called a *single-quantum-well* (*SQW*) in contrast to a *multiple-quantum-well* (*MQW*), where SQW heterostructure layers are stacked. SQW and MQW have both gain-guided and index-guided versions. They have higher gain and lower current threshold and the output beam is much more coherent than in conventional double heterostructure architectures.

# Planar-cavity surface-emitting diode laser (PCSEL); vertical-cavity surface-emitting diode laser (VCSEL)

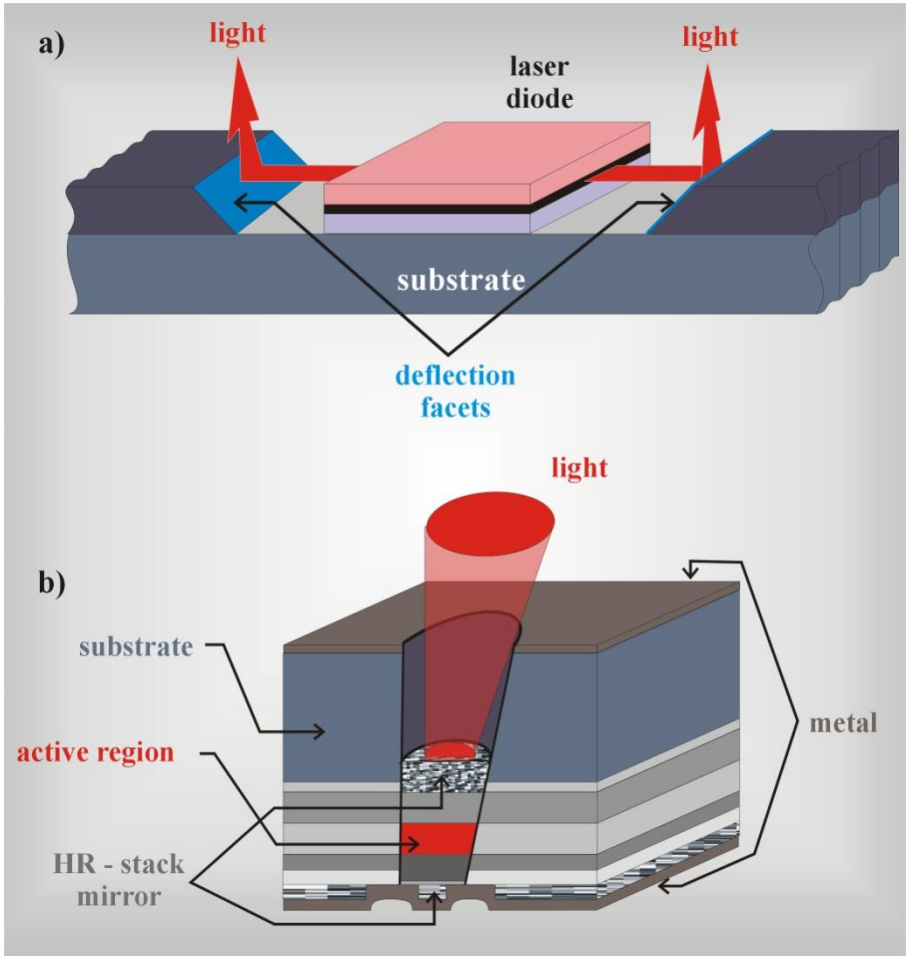



**Fig. 4.33** a) planar-cavity surface-emitting diode laser (PCSEL); b) vertical-cavity surface-emitting diode laser (VCSEL)

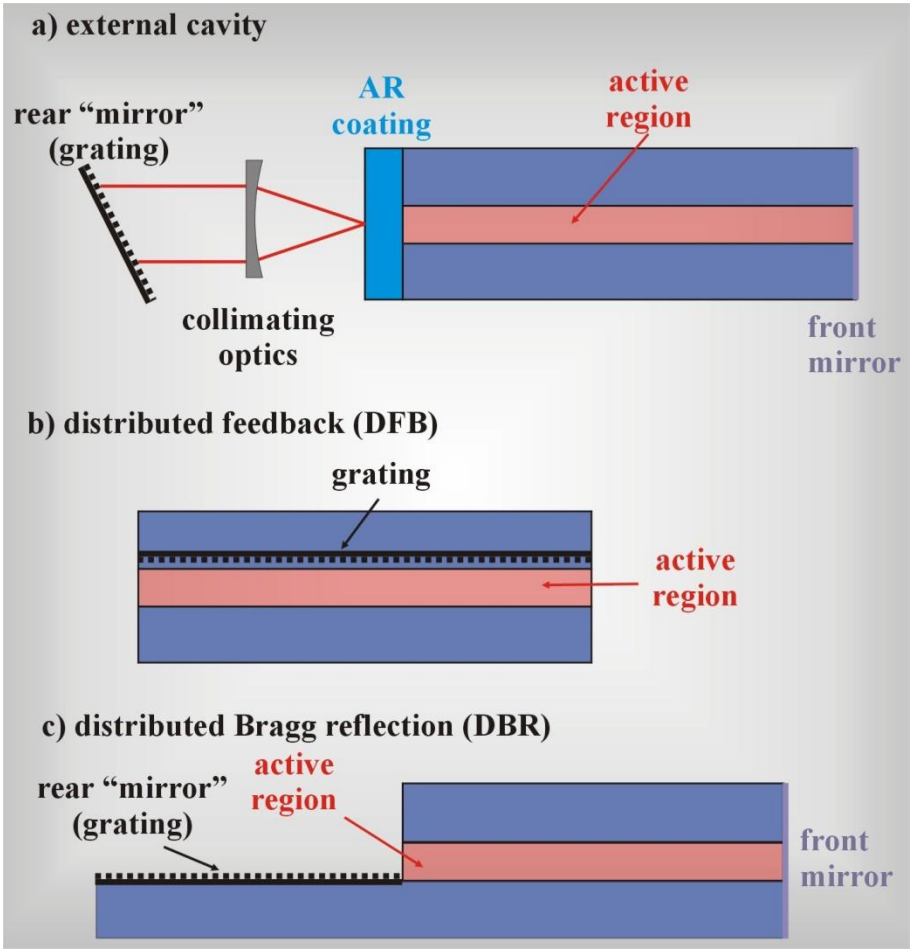
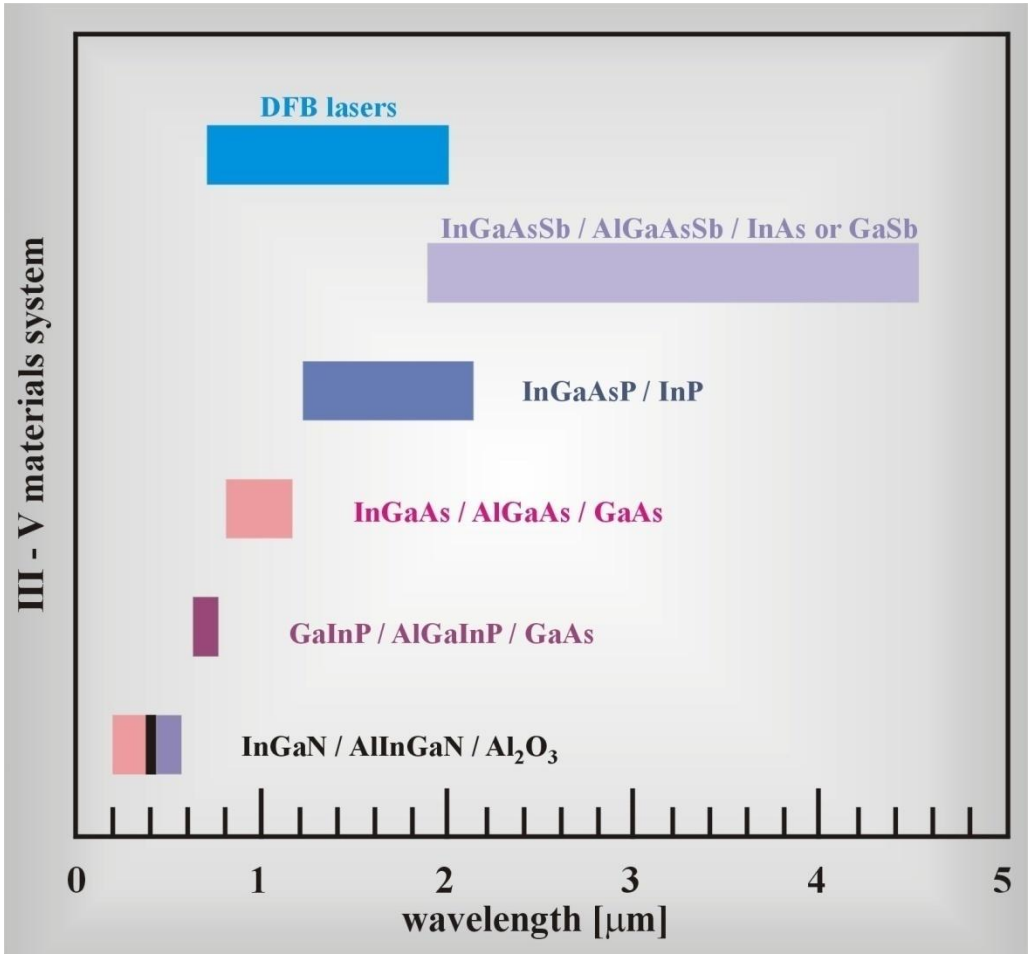
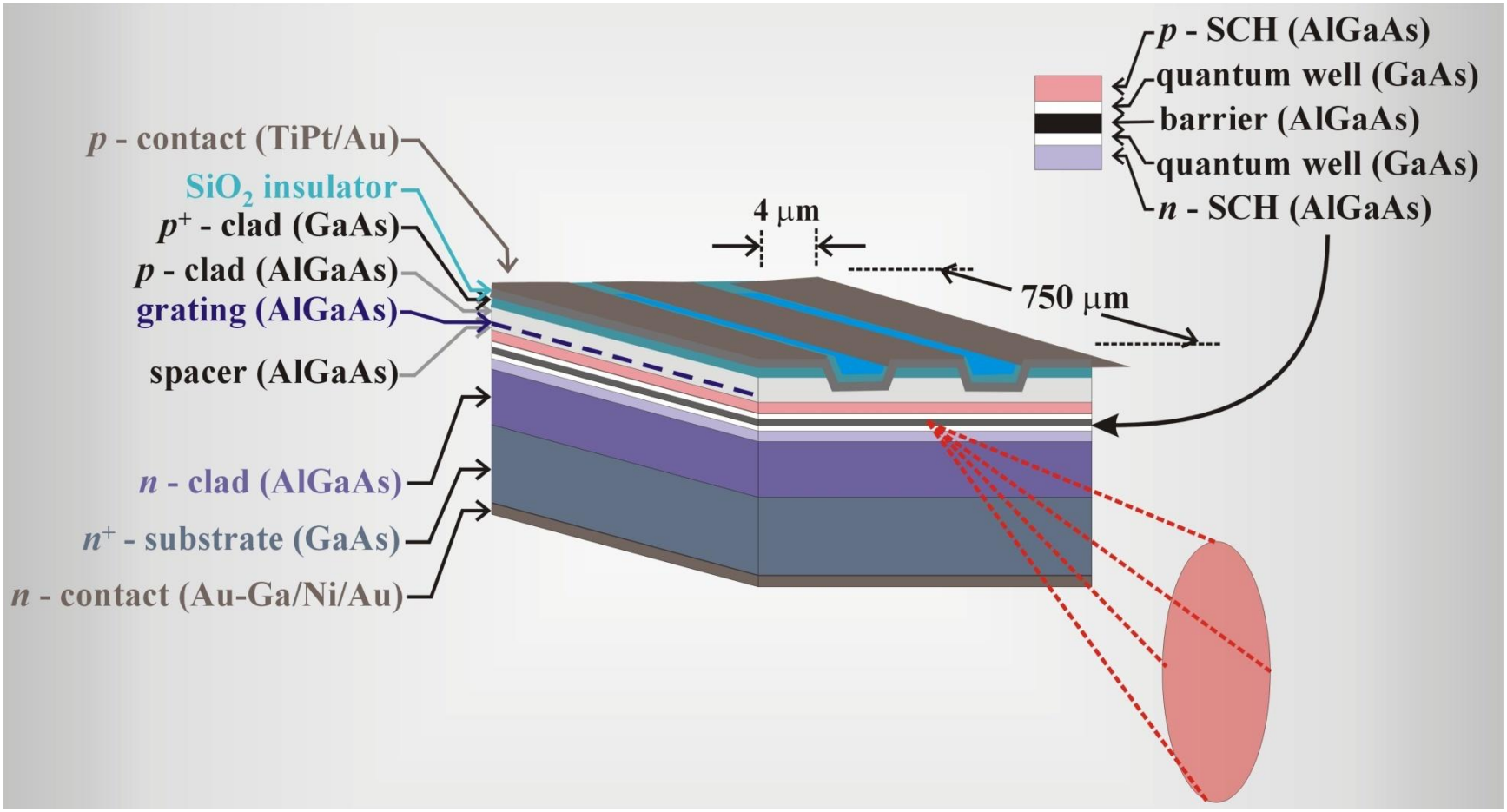



**Fig. 4.34** Configurations used for narrow band light output from laser diodes, a) external cavity; b) distributed-feedback (DFB); c) distributed-Bragg-reflection (DBR)


DFB lasers
InGaAsSb / AlGaAsSb / InAs or GaSb
InGaAsP / InP
InGaAs / AlGaAs / GaAs
GaInP / AlGaInP / GaAs
InGaN / AlInGaN / Al2O3
III - V materials system
0
1
2
3
4
5
wavelength [μm]


p - SCH (AlGaAs)
quantum well (GaAs)
barrier (AlGaAs)
quantum well (GaAs)
n - SCH (AlGaAs)
p - contact (TiPt/Au)
SiO2 insulator
p+ - clad (GaAs)
p - clad (AlGaAs)
grating (AlGaAs)
spacer (AlGaAs)
n - clad (AlGaAs)
n+ - substrate (GaAs)
n - contact (Au-Ga/Ni/Au)
4 μm
750 μm