Practical course experiment 09: Diodelaser

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In this experiment, the power and frequency behaviour of a diode laser is to be investigated by recording the output power and emission spectrum when the temperature and seed current are varied.

1 Important notes

The laserdiode used is categorized into safety class 3R. The following safety instructions must be observed when carrying out the experiment:

1. Never look directly into the laser beam!
2. Take off watches, jewellery etc. on fingers, hands and forearms before starting the experiment to avoid uncontrolled reflections!
3. You must wear laser googles when adjusting the laser beam.
4. Do not supply the laser diode with currents above its maximum limit (in this case 40mA).

2 Introduction

Since their invention 30 years ago, lasers have become one the most important instruments in optical spectroscopy. The most important types are gas, dye, solid-state and semiconductor lasers. Semiconductor lasers are lasers whose amplification is achieved by transitions between the conduction and valence bands in the semiconductor. The p-n junction in a semiconductor diode is particularly suitable for this purpose. Such diode lasers have several properties that make them superior to other types of lasers, namely their compact design, the convenient supply of energy via electric current and their extremely high efficiency. This has also made diode lasers commercially interesting, which in turn has had a very positive impact on their availability and price over the last decade. However, diode lasers also have properties that are unfavourable for spectroscopy, namely low maximum power (only in recent years have diode lasers with high output power been developed), low spectral purity, an unclean beam profile and no continuous tunability. Nevertheless, diode lasers are used today in a wide variety of spectroscopic applications, as the frequency, beam and tuning properties can be significantly improved with suitable optical and electrical control mechanisms. In this experiment, the basic properties common to (almost) all diode lasers are analysed. This is a commercial laser diode available for a few tens of euros without any additional measures to stabilise its frequency.

3 Basics

A laser is a device that generates spatially and temporally coherent light. The coherence results from optical amplification through stimulated emission. The basic principle of the laser is to generate sufficient gain through stimulated emission to overcome the losses. By pumping energy into the amplification medium, a population inversion between two energy levels can be generated.

3.1 Semiconductor

Semiconductors are substances whose electrical conductivity lies between that of conductors and insulators. They are characterised by the fact that, like insulators, their Fermi energy lies in the band gap, but this is narrower than the band gap of an insulator. Electrons can be lifted into the conduction band by thermal or electrical energy, which increases the electrical conductivity. The conductivity can also be greatly increased by doping. Doping is the introduction of foreign atoms into the semiconductor material. A distinction is made between p-doping (impurity atoms are electron acceptors) and n-doping (impurity atoms are electron donors). If an n-doped layer is now brought into contact with a p-doped layer (a diode), a space charge zone is created at the interface due to charge carrier migration (electrons fill the holes), see Figure 1. If further charge carriers are made available (i.e. current flow in the right direction, introduction of electrons on one side, extraction of electrons (and thus creation of holes) on the other side), a constant filling, i.e. a continuous recombination of electrons and holes takes place, which generates photons with the corresponding energy under suitable conditions.

3.2 Optical Resonator

An optical resonator (cavity, Fabri-Perot interferometer, FPI) is an arrangement of mirrors that reflect a circulating beam of light back into itself. Due to the condition that the electric field on the mirrors must have a node, only light with specific, discrete wavelength or frequency values can permanently circulate between the mirrors: The light path travelled between the mirrors must be an integer multiple of the light wavelength. Equivalently, the light

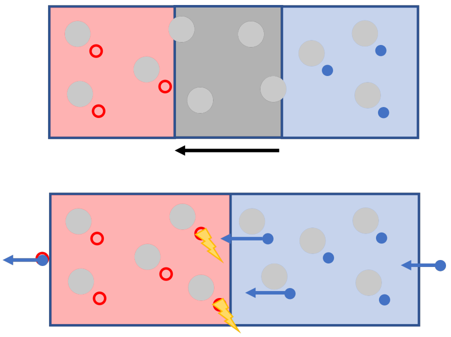

Figure 1: **Semiconductordiode.** Top: p-n transition without external wiring. Bottom: Current flow through and charge carrier recombination in the diode.

frequency must be an integer multiple of a fundamental frequency called the free spectral range (FSR). The following therefore applies:

$$\nu = n\frac{c}{2\eta L} = n \cdot \mathrm{FSR} \tag{1}$$

Here η is the refractive index, L the mirror distance and c the speed of light. The resonator acts as a filter for light irradiated from outside through one of the mirrors, i.e. it selects and transmits only the resonant wavelengths or frequencies.

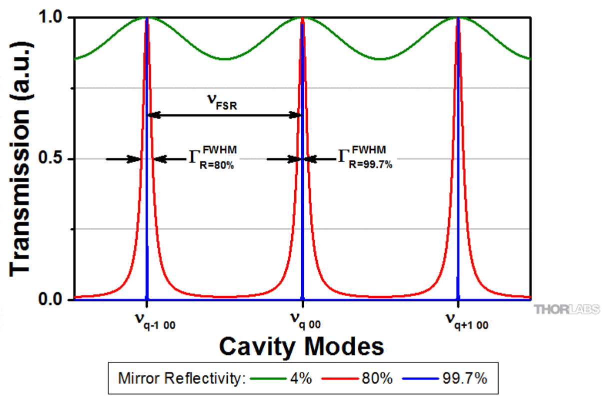

Figure 2: **Transmission spectrum of a FPI.** Transmitted intensity through an FPI with different mirror reflectivity. Graphic taken from [1]

3.3 Laser principle

If an amplifying medium is now placed in an optical resonator that provides enough amplification to compensate for the light losses due to mirror transmission and absorption, laser activity occurs. A light field builds up in the resonator up to a strength at which amplification and losses are just in balance (see Figure 3). The longitudinal laser modes are generated by the resonator.

3.4 Diode laser

A semiconductor laser is normally created by growing a p-doped layer on an n-doped semiconductor substrate (see

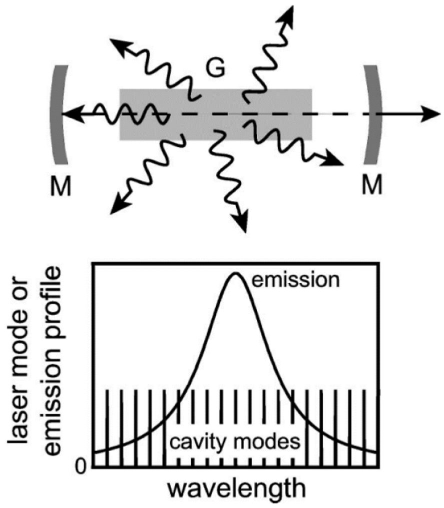

Figure 3: **Laser principle.** Top: Schematic structure of a laser with gain medium and surrounding resonator. Bottom: Laser emission spectrum with indicated gain profile of the laser medium and resonator modes. Graphic taken from [2]

Figure 3). It is operated in the forward direction. The laser light is generated by sending a current (the "injection current") through the active layer of the diode between the n-type and the p-type cladding layer. This creates electrons and holes, which in turn recombine and emit photons. The band gap between the valence band and the conduction band determines the centre frequency of the emitted light, which has a typical line width of a few nm. By adding a dielectric coating to the diode facets, these act as mirrors and an optical cavity is created. Once a threshold current has been exceeded, continuous laser operation can be maintained.

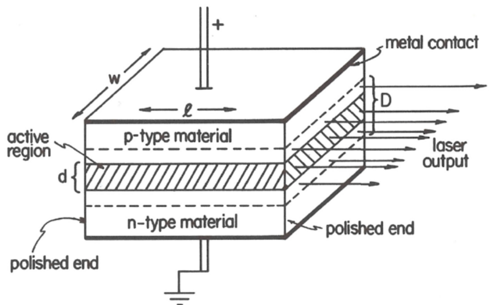

Figure 4: **Internal structure of a diode laser.** Graphic taken from [3]

3.5 Diode laser characteristics

Due to their design and mode of operation, diode lasers have special characteristic properties, including

- **power characteristic** One of the most important characteristics is the behaviour of the generated optical power as a function of the pump current. Treshold behaviour can be observed, i.e. from a certain threshold current I_s, the optical power P increases linearly with the current I, i.e. $\eta = \Delta P/\Delta I$.

- **Differential quantum efficiency** η_d This describes the efficiency of the conversion of electrons to photons (ideally 1 photon with energy hc/λ per electron) and can be determined from the slope of the power curve

$$\eta_d = \eta \frac{e\lambda}{hc} \tag{2}$$

- **gain profile/gain modes** The gain profile defines the wavelength range in which laser operation is possible. All resonator modes can be amplified within this range, whereby they "compete" with each other. If the amplification difference between the resonator modes is large enough, only one of them will "start up" and the laser will then run at "single frequency".

- **frequency tunability** The amplification profile or the amplification modes can be changed with the aid of the pump current and the semiconductor temperature. Both the temperature and the current have an effect on the resonator length as well as on the band gap or the gain profile as a whole. A relative shift in the gain profile compared to the resonator modes leads to so-called "mode jumps", where the laser frequency changes abruptly from one resonator mode to another.

4 Experimental setup and measurements

The experimental setup consists of a laser diode at a wavelength of $\lambda = 670\,\mathrm{nm}$ (Thorlabs HL6756MG), which is mounted in a temperature-stabilised housing (Thorlabs Thorlabs LDM9T) together with the collimator lens. The temperature is measured with a temperature sensor and stabilised to a setpoint via a control circuit. The laser is operated with a current driver. A power meter is available for direct power measurement. The collimated light is directed via two alignment mirrors and then passes through an FPI in which a mirror is mounted on a piezo. This piezo is controlled by a high-voltage amplifier, which in turn receives a triangular voltage from a frequency generator. A photodiode measures the intensity of the light transmitted by the FPI. The signal from the photodiode is recorded with an oscilloscope whose display is synchronised with the triangular voltage. The laser spectrum is repeated several times on the screen, once for each FSR of the FPI that is traversed during the scan.

4.1 Measurement of the power characteristic

In the first measurement, the power curve of the laser diode is to be recorded at three temperatures 20°C, 25°C and 30°C. To do this, the power meter is used to record the output power of the laser diode as a function of the laser current. Select a suitable step size! Determine the threshold current I_s as well as the efficiency η and the differential quantum efficiency η_d using suitable fits for each of

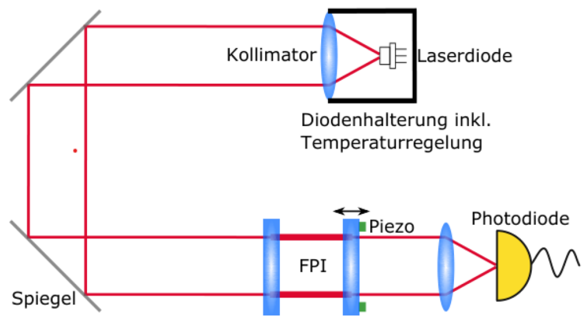

Figure 5: **Experimental setup.**

the three temperatures and analyse their temperature behaviour.

4.2 Measurement of the frequency characteristic

In the second measurement, the dependence of the emission spectrum of the laser diode on current and temperature is analysed. To do this, the transmission signal of the FPI is viewed on the oscilloscope and saved for further analysis. To obtain a calibration of the time axis in frequency, you can assume the FSR of the FPI as $\mathrm{FSR} = 630\,\mathrm{GHz}$. The transmission signal is now recorded for different currents or temperatures. Create a series of measurements for each of the temperatures 20°C, 25°C and 30°C, selecting a suitable step size for the current, starting from the laser threshold! Also create a measurement series for a fixed current approximately in the centre of the lasing range, select a suitable step size for the temperature in the measurement range 20°C - 30°C. Determine the mode spacing or FSR of the laser diode. Determine the frequency tunability in units of GHz/K or GHz/mA with and without taking mode jumps into account.

5 Protocol

The protocol should contain the following elements

- Theory of lasers, optical resonators and diode lasers (figure, most important relationships)

- Experimental setup and components used (briefly)

- Evaluation and discussion of the power characteristics. Does the observed behaviour match the expectations?

- Evaluation and discussion of the frequency characteristics. Which physical processes can explain the observation?

The theory should include the basics and explanations so that all graphs in the protocol can be understood, i.e. it must be clearly explained why laser operation is only possible from a certain pump strength.

6 Preparation

For preparation, other sources must be used in addition to these brief exercise instructions. Refs. [1],[4], [5] and[6] are available online. The preparation is sufficient if the following questions can be answered satisfactorily (i.e. including the most important formulas and with the help of figures):

- Why does a laser diode only start lasing at a certain threshold current?
- Which factors determine the wavelength of the light that a laser emits?
- What is meant by laser modes?
- Which behaviour is called mode hopping? Why do they occur?
- Why does the transmission spectrum of the FPI repeat during the piezo scan?
- Which ratio of the FSR between the FPI and the laser diode is favourable for this experiment?

References

[1] Thorlabs Fabry Perot Interferometer Tutorial Link

[2] Gijs van Soest and Ad Lagendijk. β factor in a random laser. Phys. Rev. E, 65:047601, Mar 2002.

[3] Peter W. Milonni and Joseph H. Eberly. Lasers. Wiley, New York, first edition, 1988

[4] Kamran S. Mobarhan. Test and Characterization of Laser Diode. Link

[5] T.B.M. van Leent. Narrow-linewidth External Cavity Diode Lasers for Atomic Physics. Masters thesis, University of Amsterdam, 2017, Link

[6] Carl E. Wieman and Leo Hollberg. Using diode lasers for atomic physics. Review of Scientific Instruments, 62(1):1–20, 1991, Link