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D PHYS

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Gain characterization of pump DBR VECSEL in the 2-µm range

Semester project

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Abstract

A novel optically-pumped vertical external cavity surface emitting laser (VECSEL) operating in the 2 µm spectral range

In order to gain deeper insights into the impact of VECSEL design (?MENTION WHAT CHANGES IN DESIGN?), it is necessary to measure the characteristic parameters of the VECSEL under various conditions. This involved utilizing an existing setup and control software to measure these parameters at various temperatures and pump powers. To enhance efficiency and save valuable measurement time, the setup was further improved by adding the possibility to control and automate the pump diode power, aswell as further improvement to the stability and detection algorithm of the software.

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Chapter 1

Introduction

Semiconductor lasers present a very cmpact compact, efficient and mass-producable solid state laser. They have many applications in everyday life and science, such as optical communication, data storage, printing, sensing, medical treatment, and pumping solid-state lasers.

A VECSEL (Vertical-External-Cavity Surface-Emitting Laser) is a type of semiconductor laser that emits light perpendicular to the surface of a semiconductor wafer1. Unlike a VCSEL (Vertical-Cavity Surface-Emitting Laser), which has a closed cavity within the wafer, a VECSEL has an external cavity that is formed by one or more optical elements outside the wafer23. This allows for more flexibility in designing the laser parameters, such as wavelength, output power, beam quality and pulse duration23.

Semiconductor lasers are a type of laser that use semiconductor materials as the gain medium. The gain medium is the part of the laser that amplifies the light by stimulated emission, which is the process of emitting photons with the same energy and phase as the incoming photons. Semiconductor lasers use direct band gap semiconductor materials, which have a small energy difference between the conduction band and the valence band. The conduction band is where electrons can move freely, and the valence band is where electrons are bound to atoms. When an electron jumps from the conduction band to the valence band, it releases a photon with an energy equal to the band gap. This photon can then stimulate another electron to jump and emit another photon, creating a chain reaction of amplification. Semiconductor lasers are very compact and efficient, and can be mass-produced and integrated with other electronic devices. They have many applications in everyday life and science, such as optical communication, data storage, printing, sensing, medical treatment, and pumping solid-state lasers.

Semiconductor lasers were first developed in the early 1960s as homogeneous junction lasers, which were pn junction diodes made on a single material1. The first semiconductor laser was demonstrated by Robert N. Hall and coworkers at the General Electric Research and Development Center in Schenectady, New York, in

19622. Around the same time, two other groups also demonstrated semiconductor lasers independently3. However, these early lasers could only operate at very low temperatures and with high currents, limiting their practical applications.

Since then, semiconductor lasers have undergone significant improvements in performance, efficiency, reliability, and diversity. Some of the key developments include heterojunction lasers, which use different materials for the active region and the cladding layers; quantum well lasers, which confine the electrons and holes in thin layers to enhance the optical gain; distributed feedback lasers, which use a periodic structure to provide wavelength-selective feedback; vertical cavity surface emitting lasers (VCSELs), which emit light perpendicular to the surface of the chip; and quantum cascade lasers, which use intersubband transitions in multiple quantum wells to generate mid-infrared or terahertz radiation.

A VECSEL is a type of semiconductor laser that is based on a VCSEL (Vertical Cavity Surface Emitting Laser), but with an external cavity. A VCSEL is a laser diode that emits light perpendicular to the surface of a semiconductor wafer, unlike conventional edge-emitting lasers that emit light from the edges of the wafer12. A VCSEL has a closed cavity within the wafer, which consists of two highly reflective mirrors (called distributed Bragg reflectors) that sandwich a thin layer of active material (called quantum wells) where the light is generated by stimulated emission312.

1.1 Gain saturation

Gain saturation is a phenomenon that occurs when an amplifier device, such as a laser gain medium, cannot maintain a fixed gain for arbitrarily high input powers. This would require adding arbitrary amounts of power to the amplified signal.

For example, a sudden increase in the signal input power of a laser gain medium will reduce the gain only within a certain time because the population in excited laser ions is only reduced with a certain finite rate. This has important consequences for laser dynamics2.

In the steady state (i.e., for long time scales with constant pump power and resonator losses), the gain is where Psat is the saturation power. Note that it has been implicitly assumed that the pump rate is constant, i.e., there are no effects of pump saturation2.

The dynamic behavior of a laser is determined by the interaction of the intracavity light field with the gain medium. Essentially, the intracavity laser power can grow or decay exponentially according to the difference between gain and resonator losses, whereas the rate of change in the gain is determined by stimulated and spontaneous emission (and possibly by other effects such as quenching and energy transfer)3.

In the case of a laser gain medium, the gain does not instantly adjust to the level according to the optical input power because the gain medium stores some amount of energy (excitation energy of the laser-active ions, atoms or molecules), and the stored energy determines the gain. For example, a sudden increase in the signal input power of a laser gain medium will reduce the gain only within a certain time because the population in excited laser ions is only reduced with a certain finite rate. This has important consequences for laser dynamics2.

Gain saturation is a phenomenon that occurs when an amplifier device, such as a laser gain medium, cannot maintain a fixed gain for arbitrarily high input powers. This would require adding arbitrary amounts of power to the amplified signal. Therefore, the gain must be reduced for high input powers; this phenomenon is called gain saturation (or gain compression).

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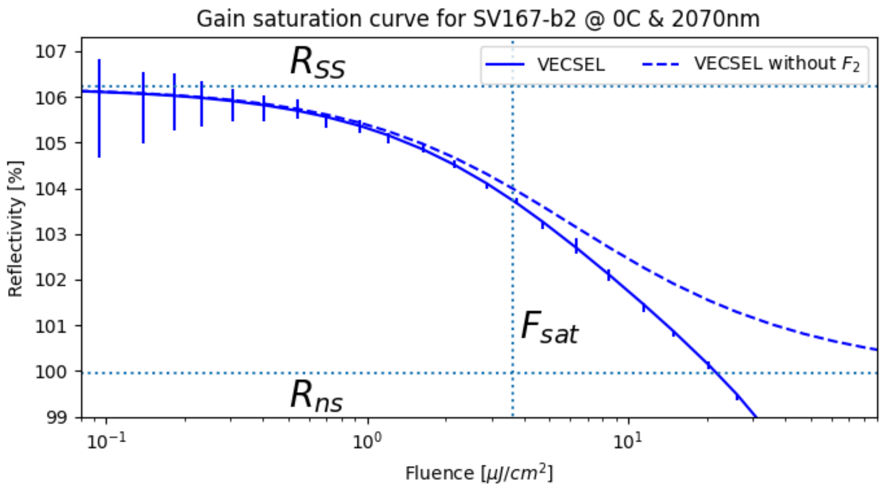

Figure 1.1

1.2 VECSEL Chips

The basic structure of a VECSEl gain chip is shown in Fig. 1.2. The main feature of the structure are as follows:

- Heat spreader: The heat spreader role is in dissipating the heat generated

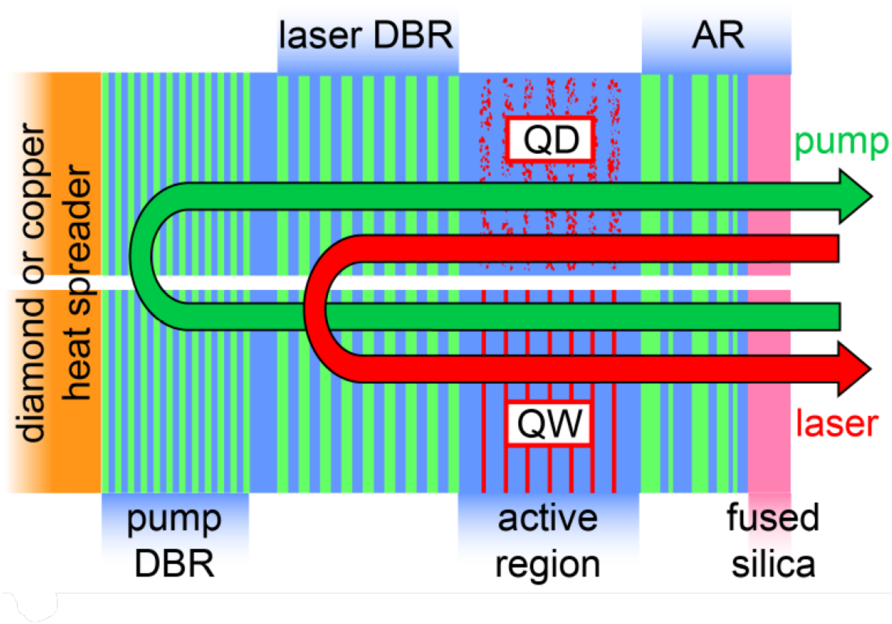

Figure 1.2

during the operation of the VECSEL chip to a Peltier-stabilized copper heat-sink.

- Pump & laser DBR: The purpose of the two bottom mirrors is to reflect the laser light and the pump light. Two advantages: firstly, because of higher absorption, there is a higher optical-to-optical efficiency due to the two passes through the active region, and secondly, there is less absorption in the mirror and in the heat sink, which results also in a higher efficiency and a higher maximum output power. The high reflectivity for two wavelengths is realized by using a superlattice Bragg mirror
- Active region: The purpose of the active region is the conversion of the pump light into the laser light. The gain medium in the active region is often composed of quantum wells or quantum dots.
- Anti-reflection coating: The antireflection section is optimized to reduce the otherwise large reflection from the air/GaAs interface

Below the three different structure of the Vecsel chips used in this work. SEE ETH MAIL

The DBR for the laser wavelength acts as a flat cavity mirror.

Hybrid chip, SV165

This was achieved with a backside-cooled, InGaSb-based VECSEL using a hybrid metal-semiconductor Bragg reflector. We demonstrate the fabrication of such a hybrid metal-semiconductor mirror by combining a copper mirror with 10.5 AlAs0.08Sb0.92/GaSb distributed Bragg reflector (DBR) pairs. Together with a thin 20nm SiO2 diffusion barrier we reach >99.9% reflectivity at 2 um. This allows for a thinner gain chip design compared to the standard DBR requiring 19.5 layer pairs. The structure thickness was reduced from 7.5 um to 4.7 um lowering the thermal resistance of the device from (2.79+-0.16)KW-1 to (2.12+-0.19)KW-1

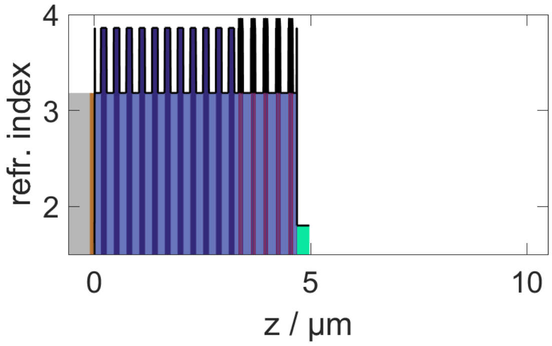

Figure 1.3

No pump DBR chip, SV166

This was achieved with a backside-cooled, InGaSb-based VECSEL using a hybrid metal-semiconductor Bragg reflector. We demonstrate the fabrication of such a hybrid metal-semiconductor mirror by combining a copper mirror with 10.5 AlAs0.08Sb0.92/GaSb distributed Bragg reflector (DBR) pairs. Together with a thin 20nm SiO2 diffusion barrier we reach >99.9% reflectivity at 2 um. This allows for a thinner gain chip design compared to the standard DBR requiring 19.5 layer pairs. The structure thickness was reduced from 7.5 um to 4.7 um lowering the thermal resistance of the device from (2.79+-0.16)KW-1 to (2.12+-0.19)KW-1

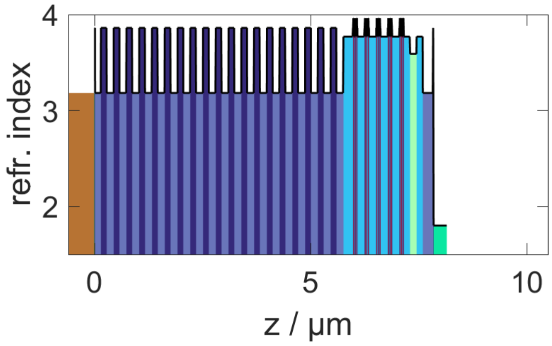

Figure 1.4

Pump DBR chip, SV167

This was achieved with a backside-cooled, InGaSb-based VECSEL using a hybrid metal-semiconductor Bragg reflector. We demonstrate the fabrication of such a hybrid metal-semiconductor mirror by combining a copper mirror with 10.5 AlAs0.08Sb0.92/GaSb dis-

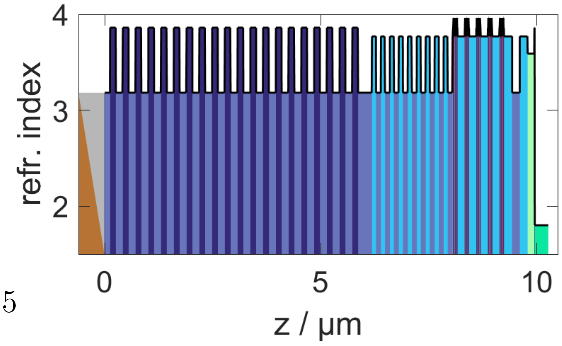

Figure 1.5

tributed Bragg reflector (DBR) pairs. Together with a thin 20nm SiO2 diffusion barrier we reach >99.9% reflectivity at 2 um. This allows for a thinner gain chip design compared to the standard DBR requiring 19.5 layer pairs. The structure thickness was reduced from 7.5 um to 4.7 um lowering the thermal resistance of the device from (2.79+-0.16)KW-1 to (2.12+-0.19)KW-1

1.2.1 VECSEL model

Chapter 2

Methods

In order to accurately determine the characterstic parameters of a VECSEL chip, it is necessary to have an experimental setup that can measure a small change, in the order of 0.1 % in the reflectivity over a dynamic range of about 4 order of magnitde in pulse fluence. A dedicated setup fulfilling these criteria has been constructed and utilized by (INSERT HERE REFERENCES).

For the measurements, a total of 4 different VECSEL chip were used, with three of them having a different structure (further discussed in Section 1.2). We were interested on the impact of different pump powers and the temperatures on the characteristic parameters of the VECSEL across the three different structures. For this we measured the nonlinear reflectivity for each chip for 9 different pump powers in the range from 0 W to 32 W and for three temperatures −10 °C, 0 °C and 10 °C.

The subsequent section provide an overview of the measuerment setup,the structure of the VECSEL chips and the data processing methods.

2.1 Experimental setup

The experimental setup is depectied in Fig. 2.1. The setup is driven by a modelocked Ti:sapphire laser. The laser emits femtosecond pulses at a wavelength of 810 nm, with a repetion rate of 80 MHz and an average output power of 4 W. The laser beam then passes through an optical parametric oscillator (OPO), where the beam undergoes nonlinear frequency conversion resulting in two waves: an idler wave and a signal wave. The OPO idler wave can be tuned from 1.7 µm to 4 µm and has a maximum output power of 650 mW. The idler has been tuned to a specific wavelength of 2071.7 nm and was stabilzied using an integrated automated feedback loop.

To further achieve a wide range of pulse fluences, the laser beam is directed through two wire-grid polarizers. One of the polarizers is placed on a controllable rotation stage to adjust the beam attenuation. The wire-grid polarizers have a broad range of attenuation across different wavelengths and do not alter the beam path during rotation. After the attenuation stage, the beam passes through a beamsplitter, which separates it into two arms: the reference arm and the sample arm.

The reference arm contains a high-reflection mirror, from which a portion of the beam is leaked and collected by a photodiode The reference arm contains a high-reflection mirror from which the leaking signal is collect in a photo diode to monitor the fluence during a measuremnt. The sample in this experiment refers to a VECSEL chip and is placed at the end of the sample arm. Before the beam is incident on the sample, a focusing lens is used to achieve higher fluences on the VECSEL. The VECSEL is probed under a direct incidence angle, and its reflection is collected using the same lens. Both beams are recombined at the beamsplitter and direct to an integrating sphere photodiode to measure the total reflected power.The pump beam enters from the side at a 30° angle and is shown in green.

To differentiate the signals from the two different arms and also measure the photoluminesence (PL) signal of the pumped VECSEL chips, two choppers are used. The two choppers are phase locked and chopper 2 is run at half of the frequency of chopper 1, specifically at 55 Hz. Chopper 2 is placed in the beam path before the attenuator to block the beam during every second cycle of chopper 1. This configuration allows to isolate the PL signal. Whereas chopper 1 is placed such that both arms pass throgh the blades, enabling the passage of light from both or either of the arms.

TODO: The measurement part consists of a non-polarizing beam splitter cube (BS), a lens, a chopper wheel and a photo detector (PD). Instead of detecting A and B simultaneously by two different detectors (like Haiml et al [16]), the signals are separated in time and measured with the same detector system. The separation in time is achieved by a chopper wheel which simultaneously chops both arms and is put close to the 50:50 beamsplitter. The signal is amplified and measured with an analog-to-digital (AD) converter and recorded with a computer. The chopper frequency is typically in the range of 100s of Hertz, and a low-cost 14 bit AD-converter is sufficient to measure photovoltages with 0.01% accuracy (when the photo-current amplifier is set to obtain a full-scale for the reference signal, 14 bits results in 0.006% resolution, averaging over more points can even increase this value). In our measurement system, we lifted the chopper wheel such that the axis of the chopper wheel is a few centimeters above the beam heights, see Fig. 4(a). During one chopper wheel cycle, four different states occur: 1. only reference beam measured, 2. both beams measured, 3. only sample beam measured, and 4. both beams are blocked. The signal in phase 4 corresponds to a background signal from photodiode dark current and environmental background light, which is then discriminated from the measurement signal in phase 1 and 3. In reference [16], a lock-in detection was required to reject the background signal. The lens L1 focuses the incident beam onto the SESAM, typical beam radii are between 5 um and 20 um. We employ a photo detector with a large detection area (typically 7x7 mm) to measure a collimated beam with large beam radius.

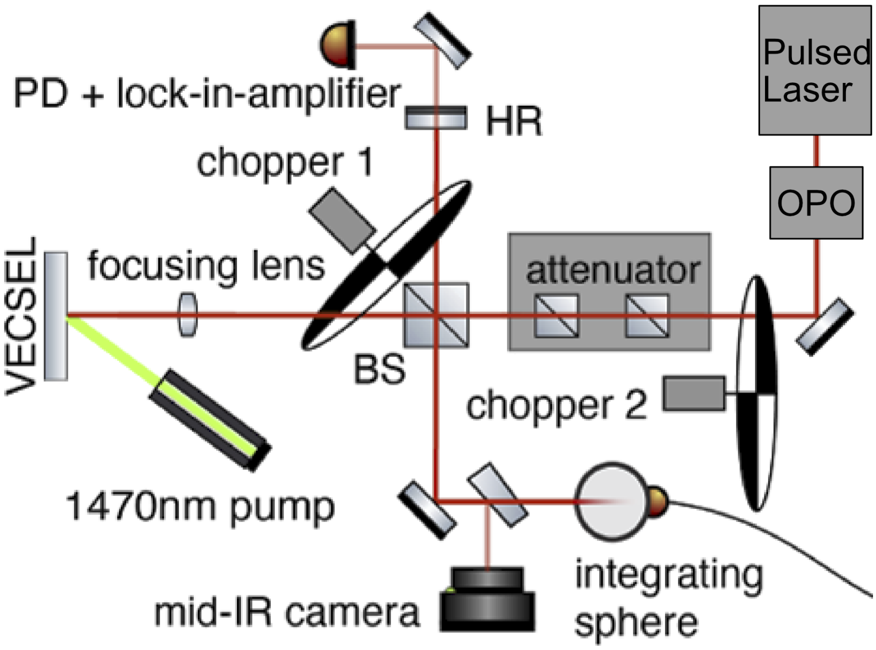

Figure 2.1: Experimental Setup for gain characterization of VECSEL chips. The laser source is a tunable optical paramtertic oscillater pumped by a modelocked Ti:sapphire laser. The beam gets attenuated. The pump beam enters the setup at a 30° angle. Two choppers, phase-locked and operating at different frequencies, are positioned to differentiate signals and measure photoluminescence (PL) emitted by the pumped VECSEL chips. The figure showcases the key components and their relative positions within the experimental setup.

2.1.1 Automation of the pump power

In the original setup, the pump laser diode was controlled over a DC power supply, which can deliver up to 50 A at up to 18 V. The power supply was operated manually in a current control mode. This required after

Due to the choice of emasuring for 9 different pump powers for each temperatue and chip design and one measruement taking about 10 min. All the measuremnt would take a significant amount of time without much downtime between the measurement, since each measurement required to change the pump power and also to manually start the measuerment. Furtunately the power supply had a serial interface, which could be controlled from the software, it was only necessary to build in. This allowed to additionaly set up the current control for the pump power and measure the pump power in one go taking about 90 min.

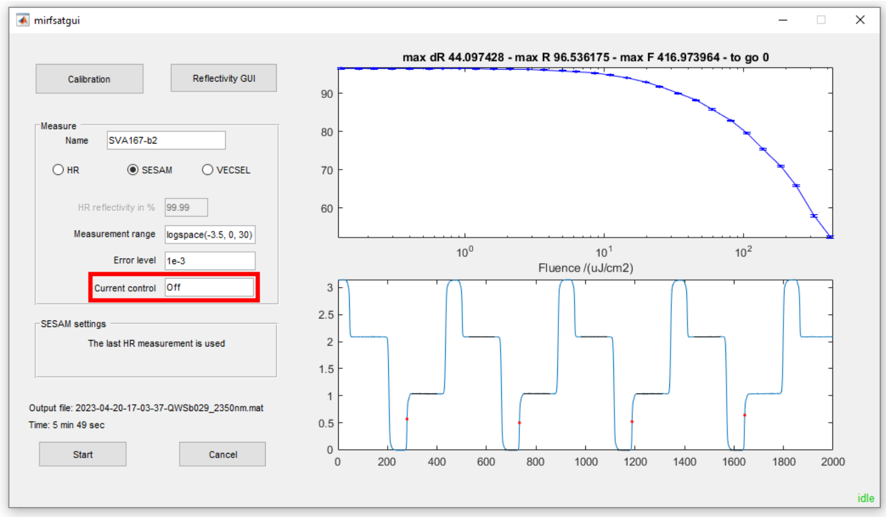

Figure 2.2

2.2 Data processing

The PD signal is amplified by a computer-controlled variable pre-amplifier to use the full range of the AD converter. The absolute gain and the offset have no influence on the measurement accuracy, it is only necessary to provide a linear response. Since the reflectivity R is encoded in only one optical/electrical signal the constraints on the amplifier have become negligible. This is in contrast to the method of Haiml et al., in which the same gain and no offset has to be achieved by both amplifiers [16]. The computer algorithm first detects the rising edges (red dots in Fig. 4(c)) and then takes the mean value of the data points on the flat levels (red lines in Fig. 4(b)). As both beams are blocked in phase 4, we can precisely measure the offset of the photodiode. Level A and B (Fig. 4(b)) are obtained by subtracting the signal level in state 1, and the nonlinear reflectivity is obtained as R = B / A. This is done for 500 periods in succession (takes approximately 5 seconds per fluence) and averaged to minimize detector noise and laser noise. This averaged reflectivity has a standard deviation of 0.01%. The incident fluence can be computed from the level A and the pre-amplifier gain setting. An accuracy of 5% for the fluence measurement is typically good enough, as this will afterwards result in an inaccuracy of 5% for the fitted saturation fluence Fsat.

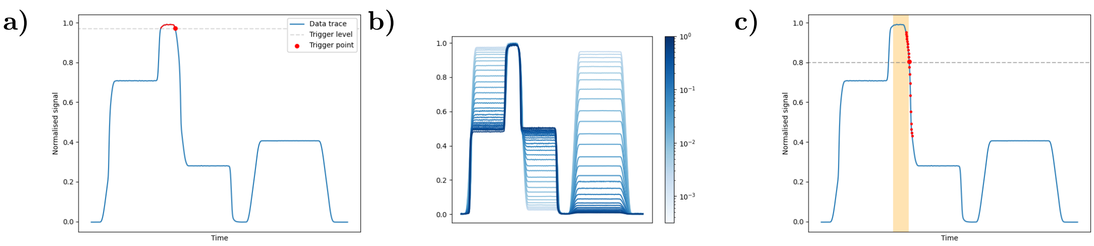

Figure 2.3: Main caption

Chapter 3

Results and Discussion

3.1 Measurement results

3.1.1 Results of SV167-b5

In Fig. 3.1 the result of the $0\,^{\circ}\mathrm{C}$ measurement can be seen.

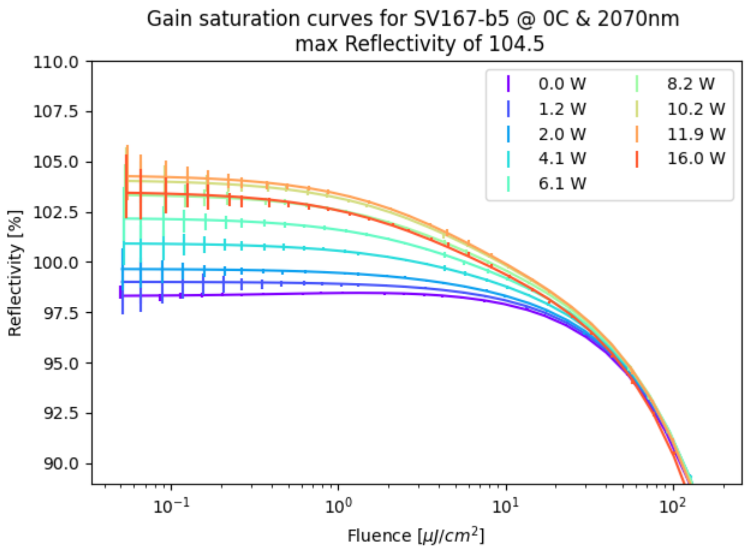
Gain saturation curves for SV167-b5 @ 0C & 2070nm
max Reflectivity of 104.5
Reflectivity [%]
Fluence [μJ/cm²]
0.0 W
1.2 W
2.0 W
4.1 W
6.1 W
8.2 W
10.2 W
11.9 W
16.0 W

Figure 3.1

Chapter 4

Conclusion and Outlook