

## **Optical Gain Experiment Manual**

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## Purpose

The experiment is designed to measure the optical gain and lasing threshold of a semiconductor sample in the ultraviolet and visible light regions based on the Variable Stripe Length Method (VSLM).

## Scope

This manual covers the following statements:

- Giving brief overview about lasing action, optical gain and VSLM for gain measurement.
- Learning how to operate class 4 lasers.
- Operating procedure of optical gain and threshold measurements.

### 1. Background Theory

A laser is an electronic-optical device that produces coherent, monochromatic and directional light. The term "LASER" is an acronym for *Light Amplification by Stimulated Emission of Radiation*. The first working laser was demonstrated in May 1960 by Theodore Maiman at Hughes Research Laboratories.

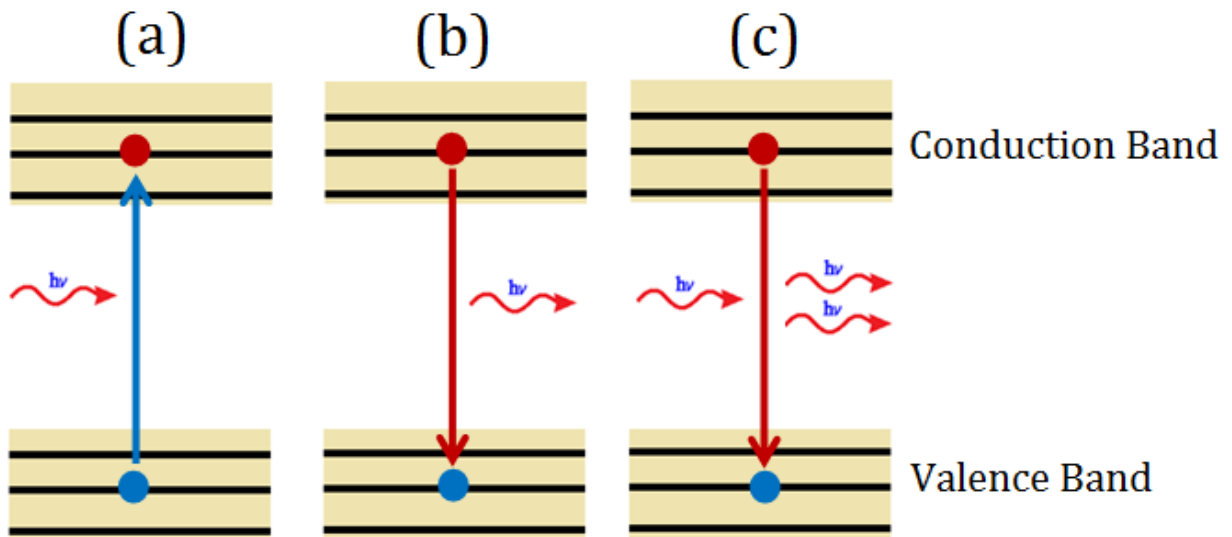
A typical laser consists of:

- Active medium (lasing material)
- Resonator
- Pump source (optical, electrical or both)

The gain medium is a material (gas, liquid or solid) with appropriate optical properties. In its simplest form, a cavity consists of two mirrors arranged such that light is reflected back and forth, each time passing through the gain medium. Typically, one of the two mirrors, the output coupler, is partially transparent to allow to the output laser beam to emit through this mirror. Light of a desired wavelength that passes through the gain medium is amplified (increases in power); the surrounding mirrors ensure that most of the light passes many times through the gain medium [1].

## 1.1 Absorption, Spontaneous Emission and Stimulated Emission

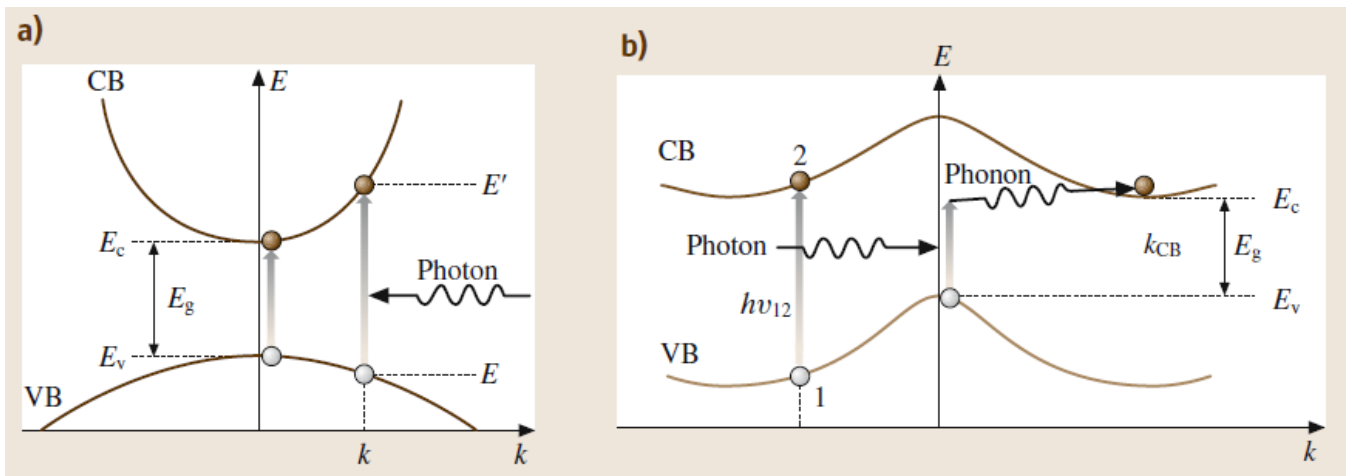
In semiconductors, when an atom is excited by a photon, which has energy equal or higher than the difference between the valence band and conduction band (energy gap), an electron is excited from valence band to conduction band leaving one hole in the conduction band (Absorption) as shown in fig. 1-(a). After a certain time, the excited electron recombines again with the hole and a photon is emitted. If the emitted photon is emitted randomly irrespective of incident photon, the emission process is called spontaneous emission as shown in fig. 1-(b). But, when the emitted photon has the same wavelength, phase and direction as the incident photon, the emission process is called stimulated emission as shown in fig.1-(c).



**Fig. 1:** Light interaction with matter: (a) absorption, (b) spontaneous emission and (c) stimulated emission

## 1.2 Direct and Indirect Semiconductors

From the previous study in physics of semiconductors, there are two types of semiconductors classified according the energy band distribution in wavenumber space, i.e. direct semiconductors such as Si and Ge and indirect band gap semiconductors such as GaAs. Fig. 2-(a) shows the band energy diagram for direct semiconductors, where the maximum of valence band and the minimum of conduction have the same value of wavenumber ( $k$ ). In this case, exciting electrons and electrons-holes recombination are direct process which required only photons. But in indirect semiconductors (fig. 2-(b)), due to the difference in wavenumber value between the maximum of valence band and the minimum of conduction band, the emission process required additional change of crystal momentum (phonon). But photons cannot carry crystal momentum; therefore, the efficiency of emission of indirect band gap semiconductors is much smaller than that of direct band gap semiconductors [2].



**Fig. 2:** Emission process in: (a) direct band gap semiconductors and (b) indirect band gap semiconductors [2]

### 1.3 Optical Gain

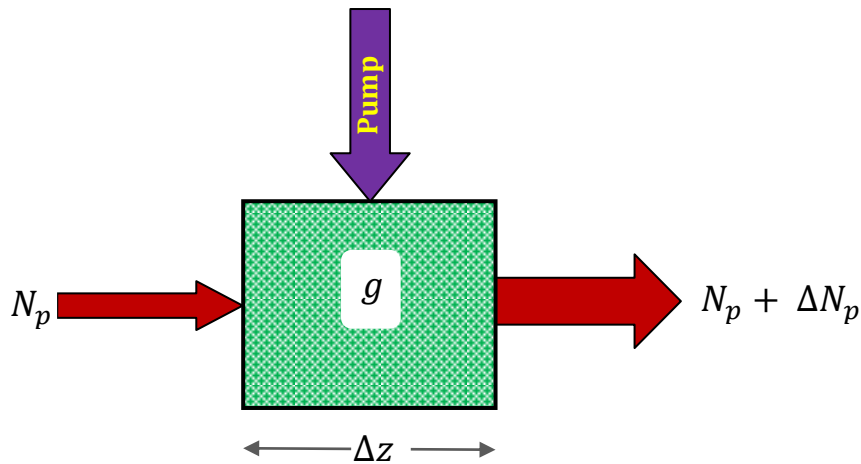
Optical gain is a measure of how well a medium amplifies photons by stimulated emission. If an active region with a gain coefficient  $g$  and small length  $\Delta z$  is considered, the initial photon density  $N_p$  passes through the active region will increase by  $\Delta N_p$  as illustrated in fig. 3.

The total resulting photon density is written as [3]:

$$N_p + \Delta N_p = N_p e^{g\Delta z} \quad (1)$$

For small  $\Delta z$ ,  $e^{g\Delta z} = (1 + g\Delta z)$ . Also,  $\Delta z = v_g \Delta t$ , where  $v_g$  is the group velocity. Then it is possible to write the stimulated emission rate,  $R_{st}$ , in term of gain coefficient as:

$$R_{st} = \frac{\Delta N_p}{\Delta t} = g N_p v_g \quad (2)$$

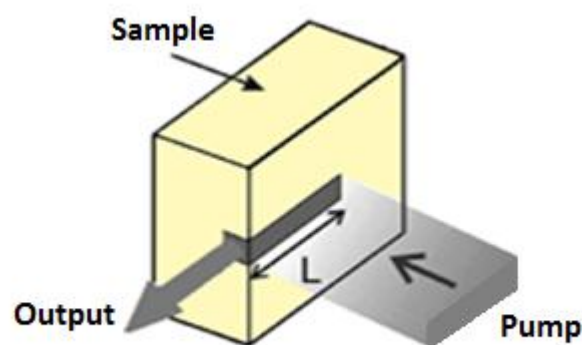


**Fig. 3:** Schematic diagram of gain coefficient definition

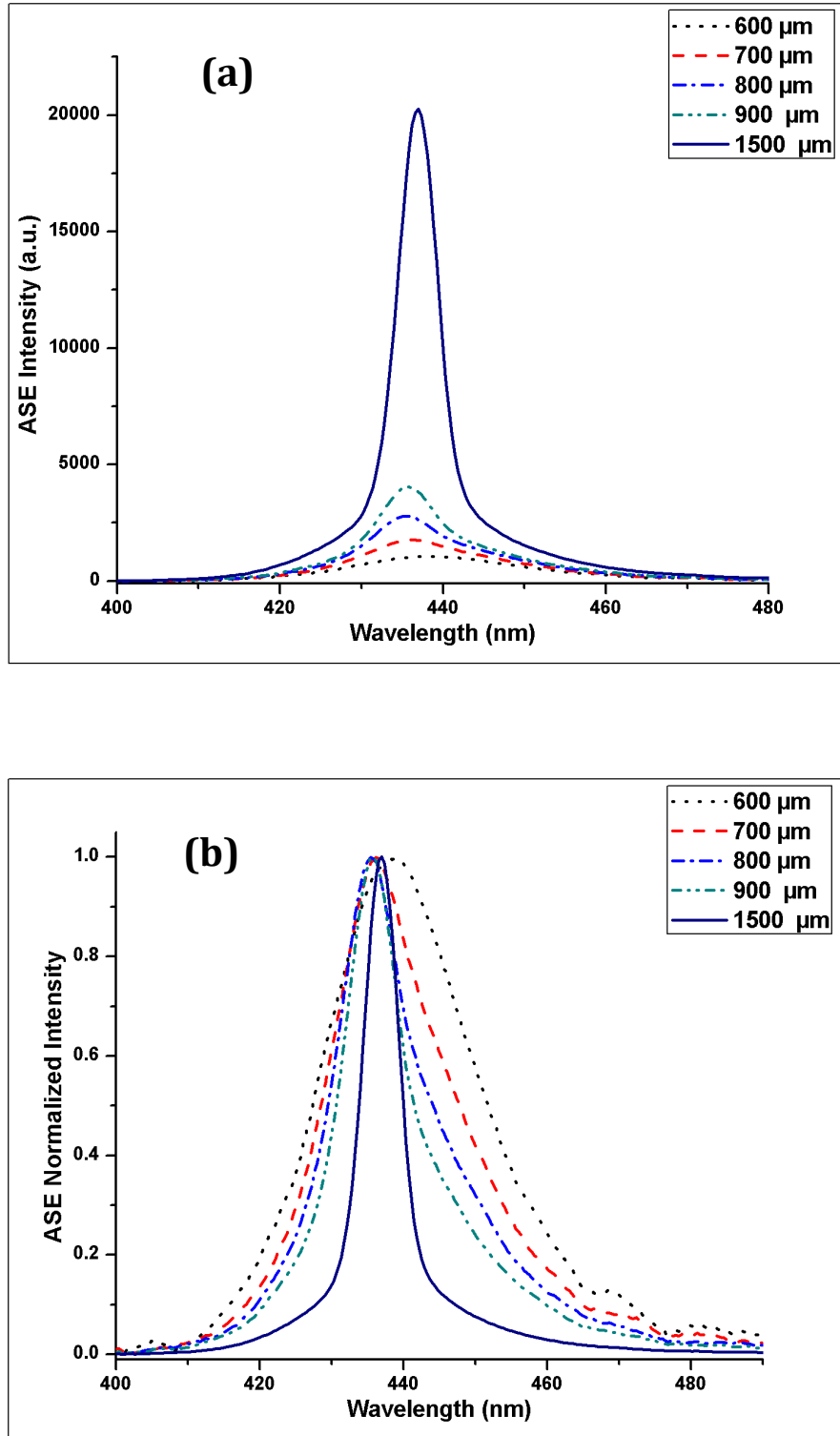
In a laser cavity, to have a resonator mode, the gain of the desired wavelength has to exceed the losses. Therefore, it is important for the people who are working in laser designing and fabrication to investigate the gain of the desired material before designing the laser.

## 1.4 Variable Stripe Length Method (VSLM)

The Variable stripe length Method which has been demonstrated by Shaklee and Leheny in 1971 is a direct measurement of the optical gain. A sample from the active material is pumped by a homogeneous line of a laser beam emitted from high power pulsed laser. The emitted light from the edge of the sample is collected (photo-luminescence spectrum) as shown in fig. 4 [4]. When the length of the stripe is short, the photo-luminescence spectrum is broad. But, by increasing the length of the stripe, the emitted intensity increases super-linearly and the spectrum becomes narrower as shown in fig. 5. The same behaviour is observed by increasing the pump energy at a constant stripe length as shown in fig. 6. The narrowing of photo-luminescence spectrum by increasing the length or the power of the stripe is due to a phenomenon which is called Amplified Spontaneous Emission (ASE). The photons produced by spontaneous emission are not emitted directly but they pass through the gain medium and are amplified many times before emitting from the edge of the sample. Finally the resulting emission has a bandwidth narrower than the bandwidth of spontaneous emission and is showing threshold-like behaviour versus pump energy. The excited region is treated as a one-dimensional optical amplifier.

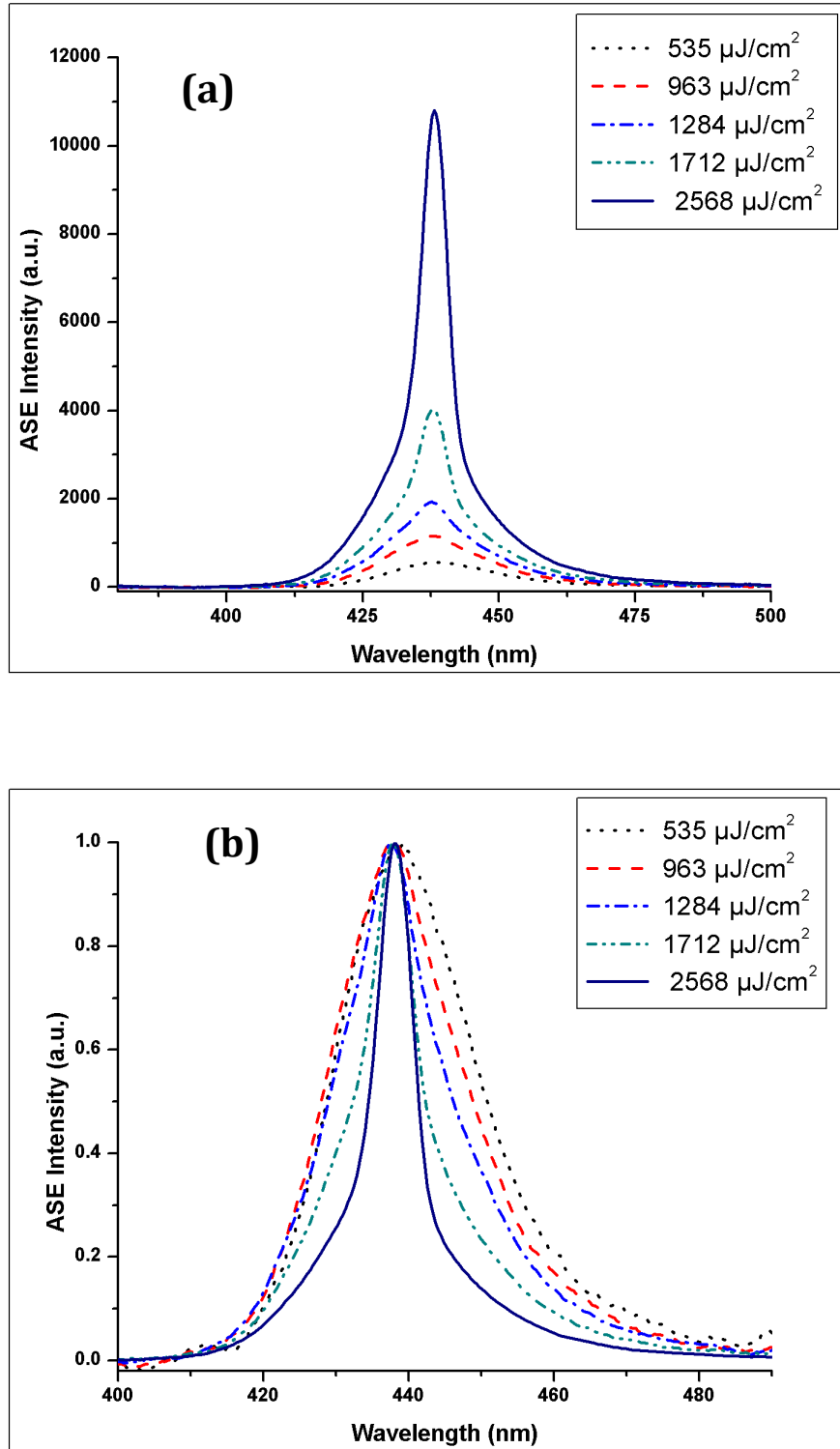


**Fig. 4:** Schematic for VSLM



**Fig. 5:** ASE Intensity vs. wavelength at different stripe lengths from InGaN at  $4.3 \text{ mJ}/\text{cm}^2$ :  
(a) absolute intensity and (b) normalized intensity

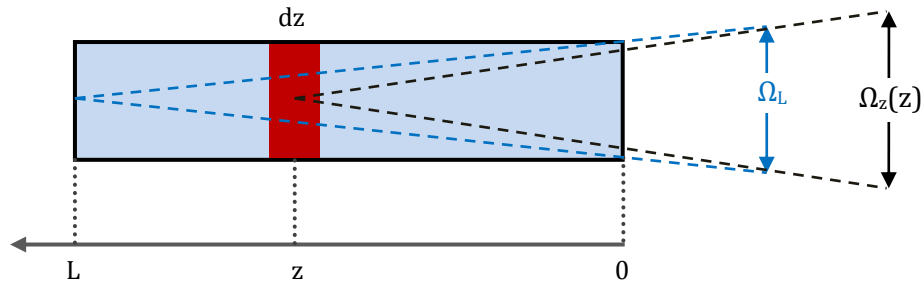




**Fig. 6:** ASE Intensity vs. wavelength at different pump energies and stripe length of 3 mm from InGaN: (a) absolute intensity and (b) normalized intensity

## 1.5 Theoretical Treatment of ASE: One-dimensional Optical Amplifier Model

Let us consider the illuminated stripe as a one-dimensional optical amplifier. i. e. the width of the stripe is very small compared to the length. Therefore, the influence of the stripe width can be neglected. For simple treatment, the one-dimensional Amplifier is considered to have cylindrical shape with length  $l$  and cross sectional area  $s$ . The ASE emission is assumed to be in both  $z$ -directions and the solid angle which is seen from zero position is  $\Omega$  but the solid angle of the differential element  $dz$  is  $\Omega(z)$  (see fig. 7).



**Fig. 7:** ASE along the illuminated stripe

In low saturation regime, the intensity from the differential element  $dz$  which emits from the facet of the amplifier consists of stimulated emission and spontaneous emission and can be written as [5]:

$$\frac{dI}{dz} = (\Gamma g_m - \alpha)I + (S_{sp}N^* \times h\nu) \left( \frac{\Omega(z)}{4\pi} \right), \quad (3)$$

where,  $g_m$  is the material gain,  $\Gamma$  is the confinement factor of the waveguide structure,  $\alpha$  is the propagation loss coefficient,  $S_{sp}$  is the spontaneous emission rate,  $N^*$  is the excited state population density and  $h\nu$  is the energy of the emitted photon.  $\Omega(z) = \Omega$  due to the fact that the ASE emission arises from emitting elements near  $z = 0$ , which receive the largest gain. The gain and the pump intensity are assumed to be constant over the whole pumping length, and then equation (3) can be easily integrated. By using the boundary condition  $I_{ASE}(0) = 0$ , the ASE emission can be written as:

$$I_{ASE}(z) = \frac{J_{sp}(\Omega)}{g} (e^{gz} - 1), \quad (4)$$

where  $J_{sp}(\Omega) = \frac{A_{sp}N^*h\nu\Omega}{4\pi}$  is the spontaneous emission intensity emitted within the solid angle  $\Omega$  and  $g$  is the net modal gain of the material, defined as  $g = \Gamma g_m - \alpha$ . For simplicity, we will consider  $\Gamma = 1$  and  $\alpha = 0$ . The net modal gain of the material gain  $g$  can be calculated from fitting the experimental data to equation (4). Some optical gain values for different semiconductor materials measured with VSLM are given in table 1.

Furthermore, the relation between FWHM and pump energy can be described by eq. 5.

$$FWHM(x) = \frac{A1-A2}{1+(x/x_0)^p} + A2 \quad (5)$$

Where  $x$  is pulse energy,  $A1$  and  $A2$  are the FWHM in the high and low pulse energy limits, respectively,  $x_0$  is the pulse energy at value of FWHM equals  $(A1 + A2)/2$  and  $p$  represents the steepness of the function as illustrated in fig. 15.

| Semiconductor material |          | Optical gain for $10^7$ W/cm <sup>2</sup> and 2 °K (cm <sup>-1</sup> ) | Wavelength of the peak gain (nm) |
|------------------------|----------|--|----------------------------------|
| III-V                  | GaAs     | 2000   | 820                              |
|                        | GaP : N  | 10000  | 540                              |
|                        | GaP : Bi | 175  | 555.4                            |
|                        | GaN      | 1000   | 359                              |
| II-VI                  | CdS      | 200  | 490.5                            |
|                        | CdSe     | 1000   | 684                              |
| I-VII                  | CuCl     | 6400   | 392                              |
| III-VI                 | GaSe     | 10000  | 600                              |

**Table 1:** Optical gain measurements for different semiconductor materials [6]

## 1.6 VSLM Limitations

To deduce the relation between ASE emission and stripe length, the homogeneity of the gain and pump intensity has been assumed, which is not valid always in reality. Therefore, there are some effects which influence the experimental results and give artificial gain values.

### 1.6.1 Gain Saturation Effect

From one-dimensional optical amplifier model, it is expected that the ASE intensity increases with the increase of stripe length. But in reality, the gain is saturated after a certain length, the saturation length, and the experimental results will not follow equation (4). In order to consider the gain saturation effects, the constant material gain  $g_m$  and the population density have to be replaced in equation (3) by the following expressions:

$$g_m(z) = \frac{g_{m0}}{1 + \frac{I(z)}{I_{sat}}} \quad \text{and} \quad N^*(z) = \frac{N_0^*}{1 + \frac{I(z)}{I_{sat}}}, \quad (6)$$

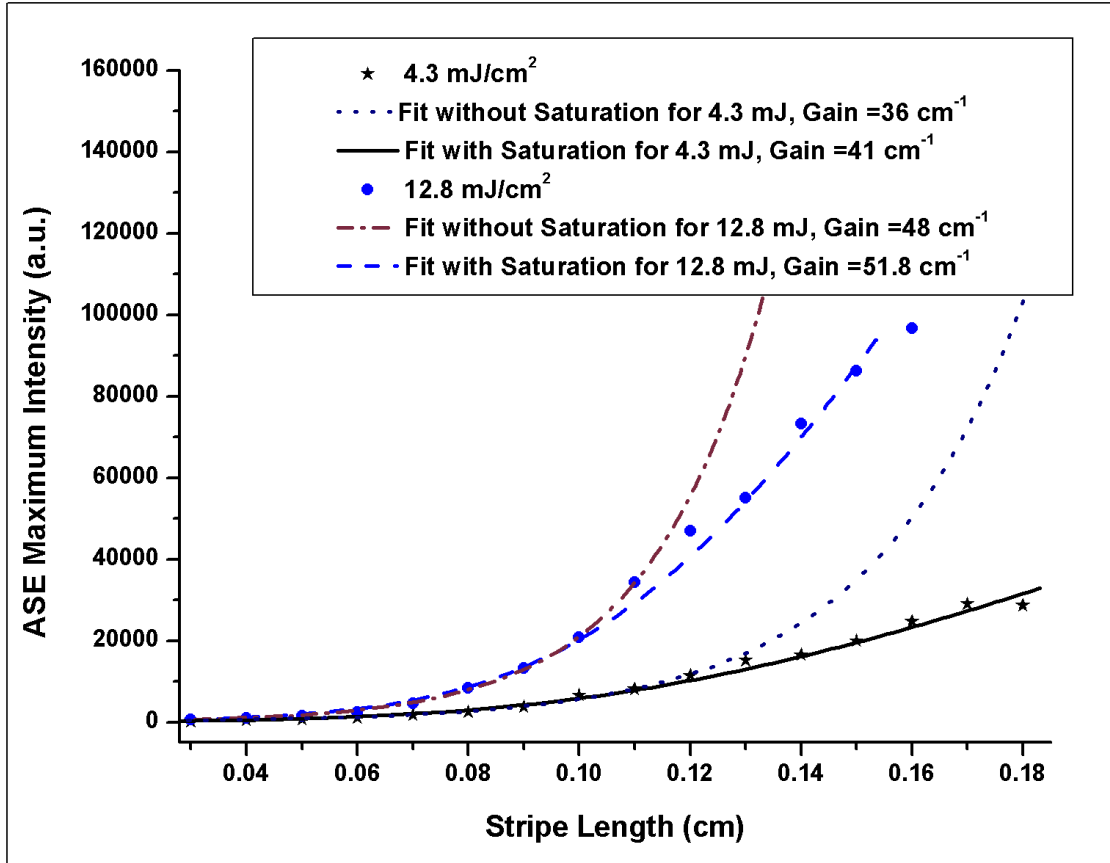
Where  $g_{m0}$  is the small signal gain,  $N_0^*$  is the small signal population density,  $I_{sat}$  is the signal saturation intensity, defined as  $I_{sat} = \frac{h\nu}{\sigma\tau}$  for a four level amplifier, where  $\sigma$  is the emission cross section and  $\tau$  is the radiative life time.

$$\frac{dI}{dz} = \frac{g_{m0}I}{1 + \frac{I(z)}{I_{sat}}} + \left( A_{sp} \frac{N_0^*}{1 + \frac{I(z)}{I_{sat}}} \times h\nu \right) \left( \frac{\Omega(z)}{4\pi} \right) \quad (7)$$

The solution for eq. (6) can be written as [7]:

$$I_{ASE} = \frac{I_{sat}}{1 + C_{sat} \exp(-g_{m0}z)} + \frac{I_{sat}}{1 + C_{sat}}, \quad (8)$$

where  $C_{sat}$  is the saturation constant.

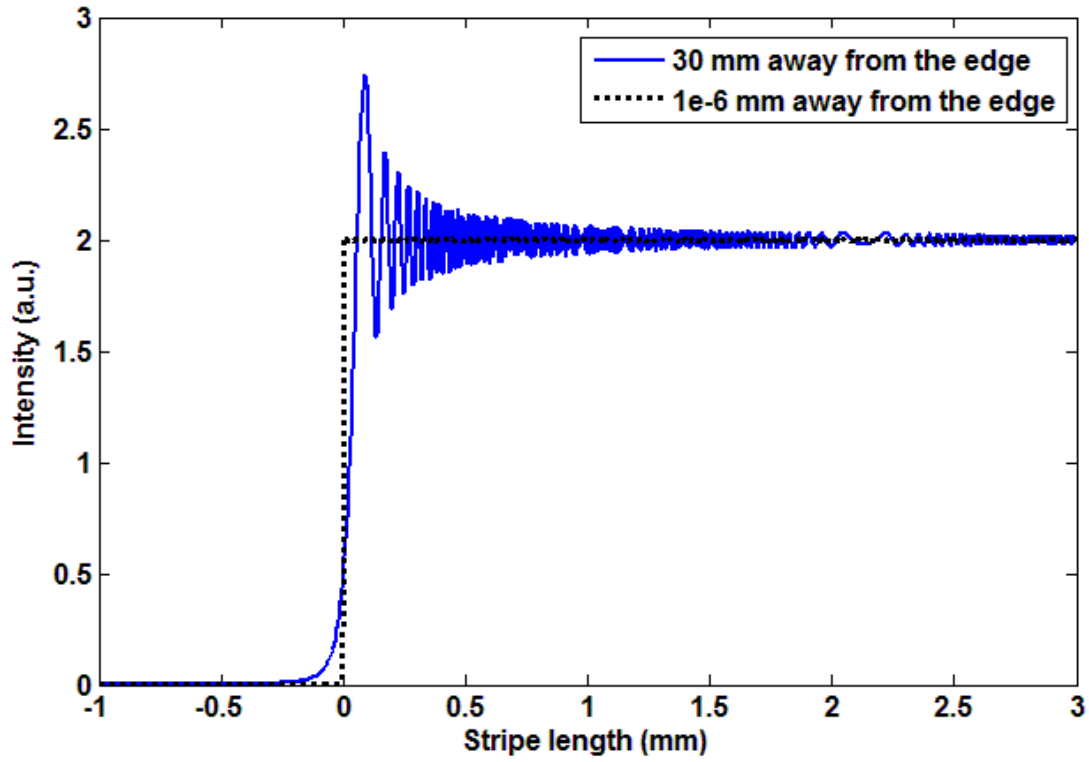


**Fig. 8:** Gain calculation with and without saturation effects for InGaN

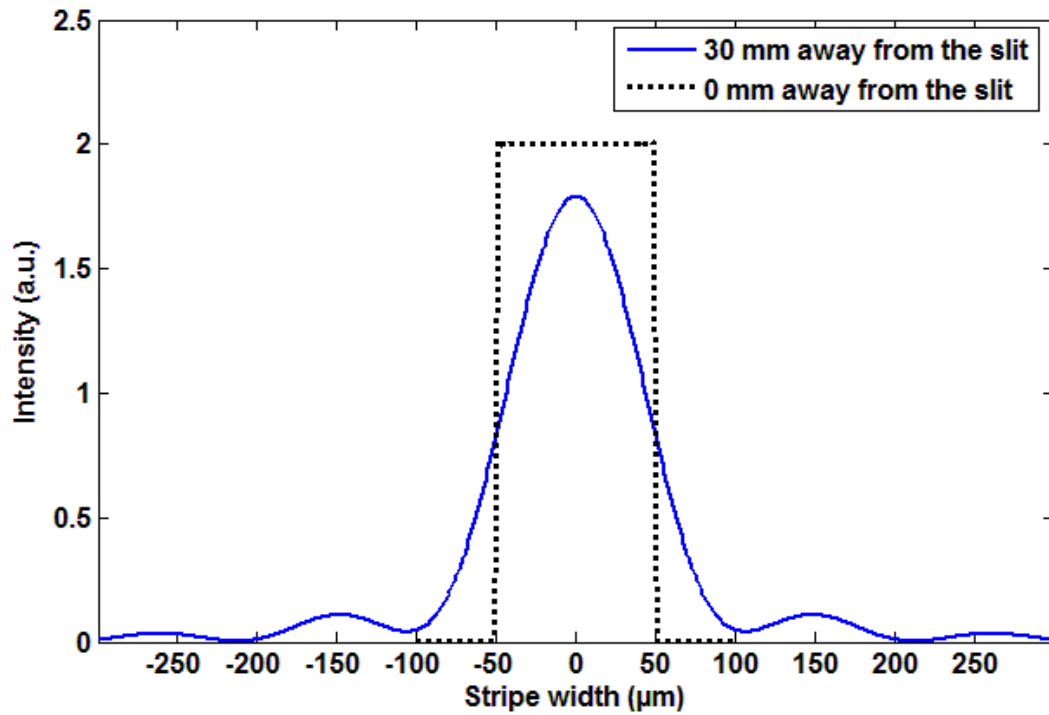
An example for the influence of gain saturation effect for a InGaN sample is given in fig. 8. The data are fitted fit according to equation (4) and (8) for two different energy fluencies.

### 1.6.2 Pump Diffraction Effects

In the gain experiment, there are slit to reshape the profile of laser beam and shutter to control the length of the stripe. Both of them can produce diffraction patterns. Simulation results for diffraction patterns from the slit and the edge of the shutter are shown in fig. 9 and 10. Due to the diffraction effects, the intensity of the laser along the stripe with size of  $(0.1 \times 3) \text{ mm}^2$  is not homogenous when the working distance is 30 mm. To avoid these effects, it is very important to place the sample very near to the slit and the shutter ( $< 1 \text{ mm}$ ).



**Fig. 9:** Simulation results for the diffraction patterns from the edge of the shutter at 30 mm away from the shutter (solid line) and 1  $\mu\text{m}$  away from the shutter (dashed line).



**Fig. 10:** Simulation results for the diffraction patterns from a slit with size of  $(0.1 \times 3) \text{ mm}^2$  at 30 mm away from the slit (solid line) and 0 mm away from the slit (dashed line)

## 2. Laser Safety

The used laser is class 4 laser which has the following definition [8]:

*“Class 4 laser is a laser which has power above 500 milliwatts and can injure you if viewed directly or by viewing both the specular and diffuse reflections of the beam. A danger sign will label this laser. These lasers can also present a fire hazard. Eye and skin protection is required.”*

### 2.1 Laser Hazard

**Eye and skin hazard:** Exposure to the direct beam, specular reflections, or diffuse reflections can damage skin or eye. The pumping laser is working at 355 nm (UV), corneal flash burns and painful condition of the cornea may happen. Furthermore, UV radiation can also cause photokeratitis and cataracts in the eye's lens. Further information about the hazards of laser radiation, you can find in ref. 9.

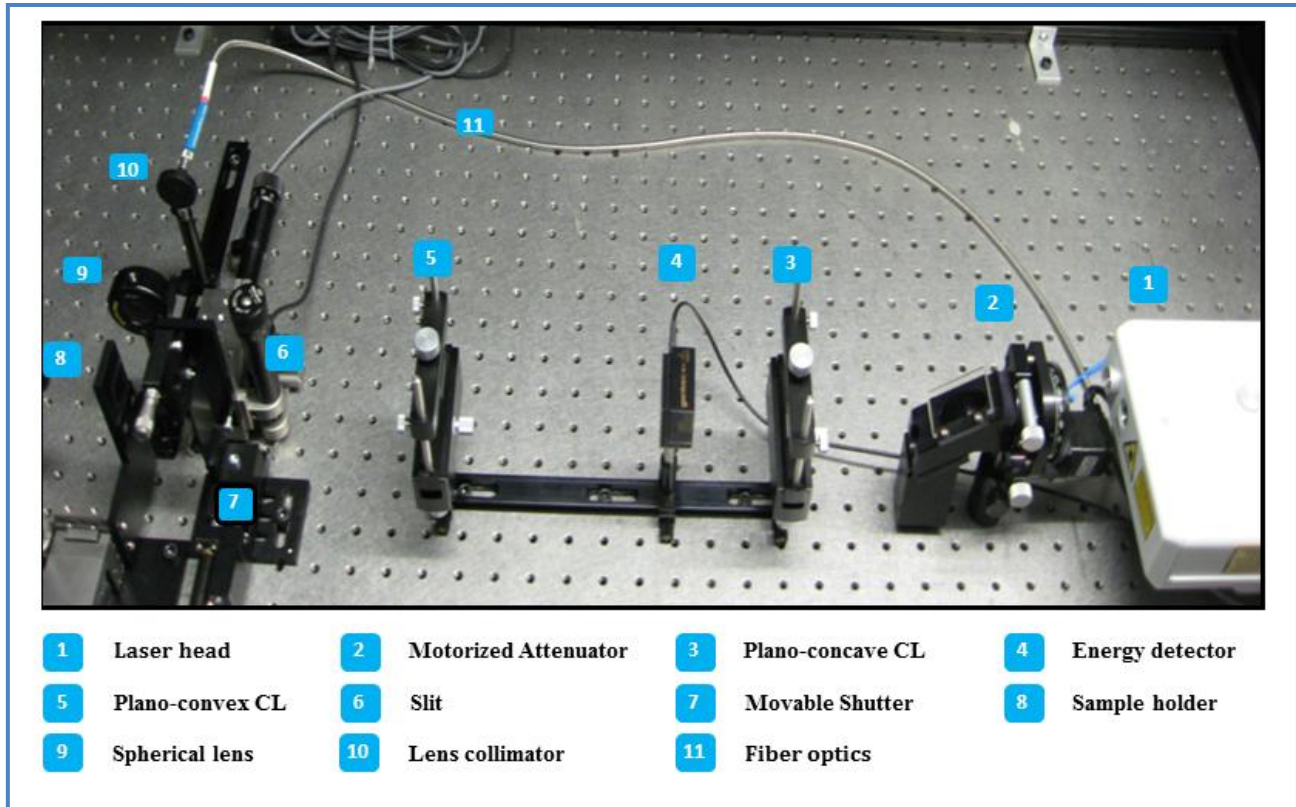
**Fire hazard:** Due to the high power of the laser, it may produce a fire hazard.

### 2.2 General Safety Instructions

- It is not allowed for you to work alone in the lab.
- Make sure that the removal safety label is attached onto the lab door.
- It is not allowed for you to open the lid of the protection box.
- In case that you face problems switch off the laser directly and contact the responsible persons.

### 3. Equipments

The layout of the optical gain measurement setup is shown in fig. 11.



**Fig. 11:** Layout of the optical gain measurement setup

The setup is divided into five main parts:

- **Laser System:**

The used laser is a frequency tripled Nd:YAG which emits light at a wavelength of 355 nm. The profile of the laser beam is Gaussian and has a beam diameter of 3.6 mm and beam divergence of 1.2 mrad. Furthermore, the laser is pulsed using Q-switched configuration with pulse width of 18 ns, repetition rate from 1- 20 Hz and pulse energy from 0- 16 mJ.



- **Laser Beam Attenuator:**

The laser beam attenuator consists of two components: a  $\lambda/2$  wave-plate which is used to polarize the laser beam and beam splitter to separate the s and p (vertical and parallel) components of the incident laser beam. By changing the angle of the  $\lambda/2$  wave-plate using motorized stepper motor, the Laser energy can be varied from 10  $\mu$ J to 16 mJ for both s and p components.

- **Laser Shaping System:**

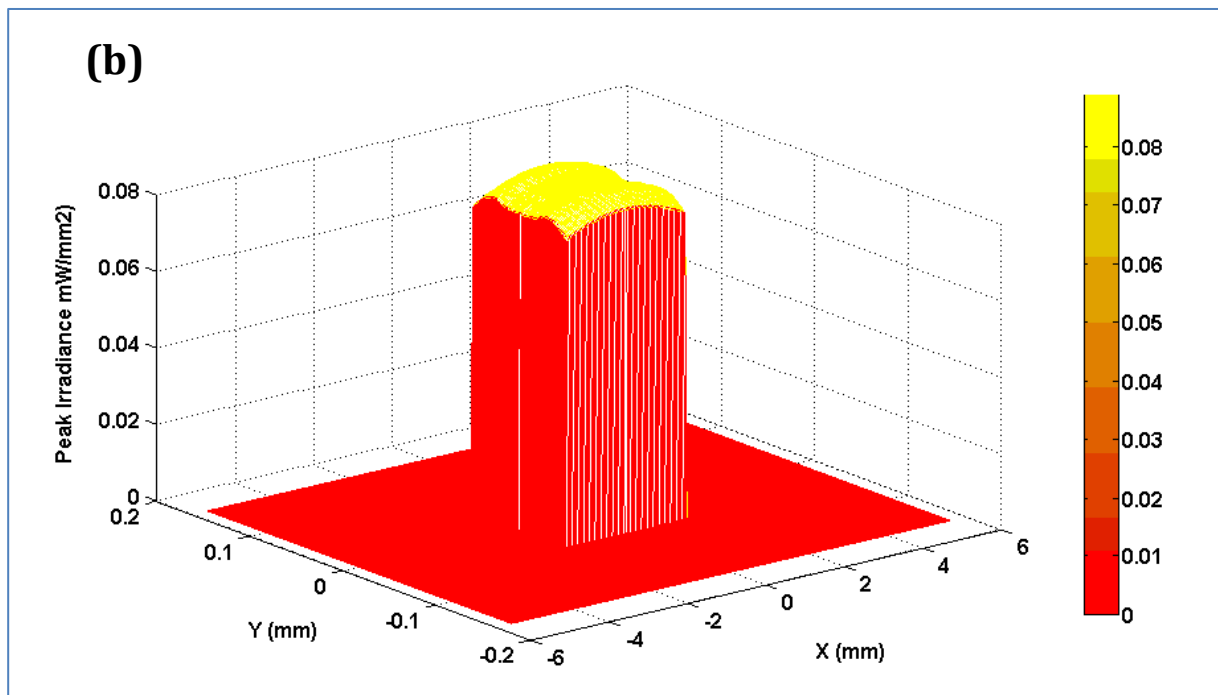
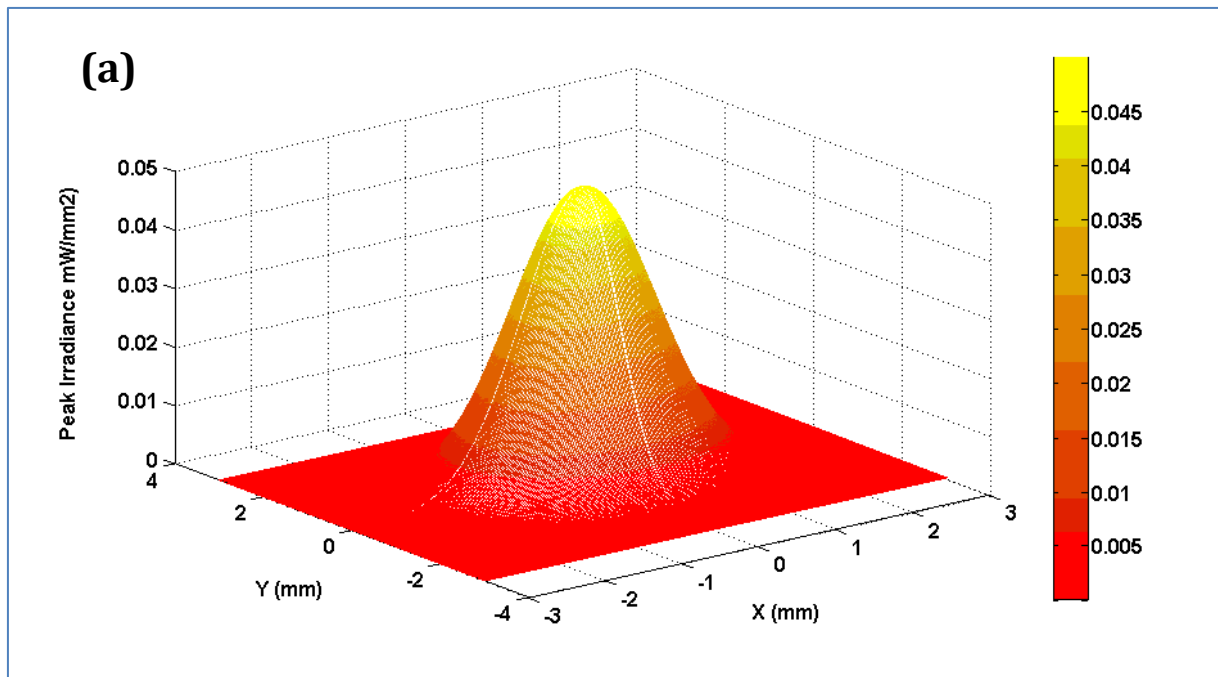
The shaping system is used to convert the Gaussian beam profile of the Nd: YAG laser into homogeneous line with dimension of  $(0.1 \times 3)$  mm<sup>2</sup>. This is done by using a plano-concave cylindrical lens to expand the laser beam in a direction of signal output plane and a plano-convex cylindrical lens to focus the resulting beam in perpendicular direction. An adjustable slit is used to cut the edges of the beam to have a line with a flat top profile and size of  $(0.1 \times 3)$  mm<sup>2</sup> and a shutter, which is attached to a motor is used to change the length of the stripe from 0 to 3 mm. Simulation results for the laser beam profile before and after the shaping system is shown in fig. 12. The homogenous stripe is important to prevent the hot spots during the pumping process.

- **Sample Holder:**

Holder is attached to a translation stage to move the sample in x-y-z directions.

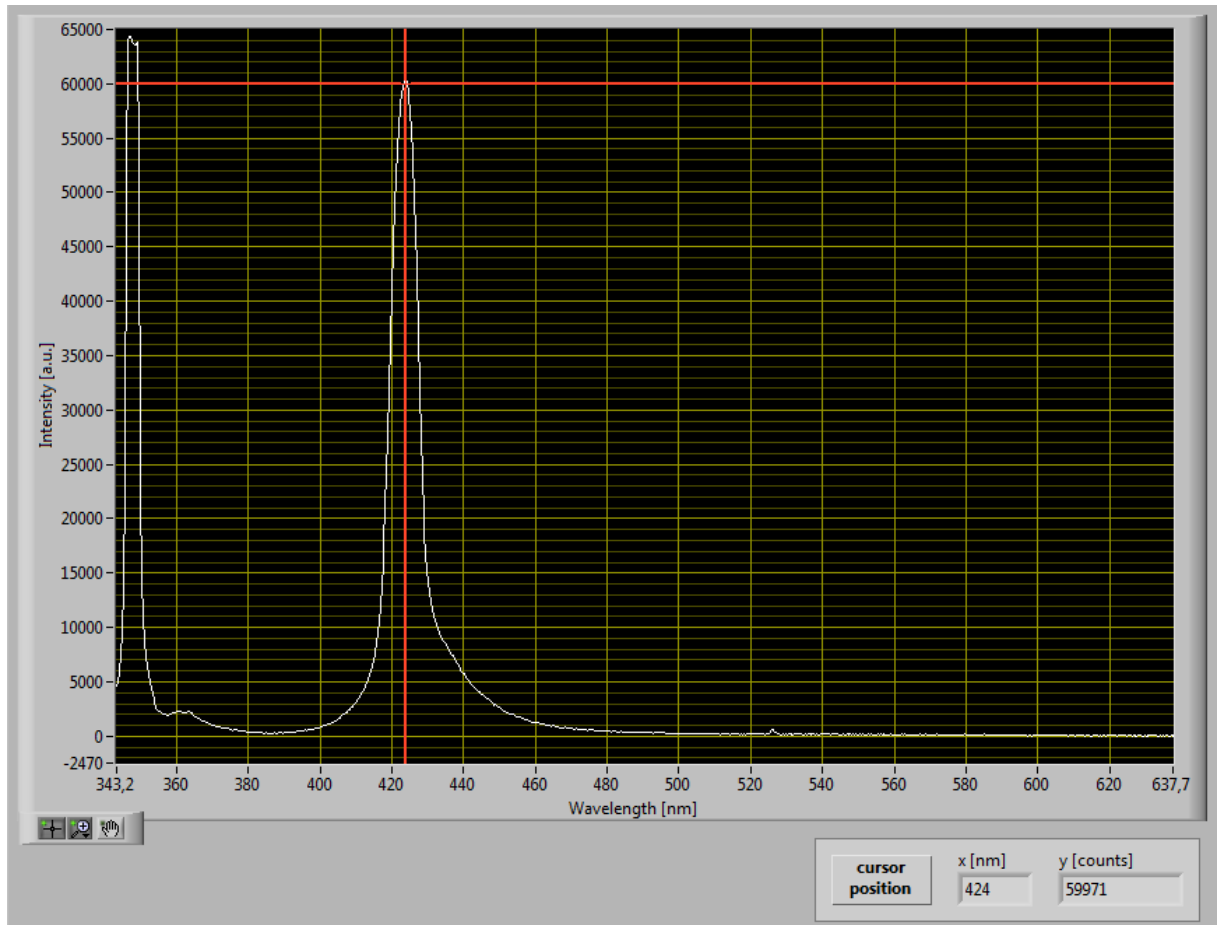
- **Signal Collecting System:**

A spherical lens is used to collect the ASE intensity and focus it into a lens collimator which is connected to a spectrometer via fiber optics.



**Fig. 12:** Simulated laser beam profile a) before and b) after the beam shaping system

## 4. Measurement Procedures



**Fig. 13:** Measurement software

All necessary components of the setup are controlled remotely via LabView. The measured spectrum can be analyzed within the control software (fig. 13). The red cross is your cursor that can be moved around the graph. The actual position (x, y) is shown in the bottom right corner.

Measure the ASE intensity at different stripe lengths between 0 mm and 1.2 mm as shown in fig. 8. Measure the ASE spectrum at each individual stripe length and note the intensity in your measurement log. Repeat for 3 different energy fluencies:

- Set the energy fluency and open the stripe to the maximum value (1.2 mm).
- Measure the spectrum and choose an integration time for which your ASE spectrum counts less than 60,000.
- Close the laser shutter. Store the dark spectrum of your chosen integration time and use the (-) button in order to subtract the dark spectrum from your measurements.

- Measure the ASE spectrum for 1.2 mm stripe length, find the ASE peak and note intensity, wavelength and energy fluency in your measurement log.
- Decrease the stripe length in increments of 0.1 mm and note the intensity at the same wavelength like before.
- At lower stripe length it can be useful to increase the number of averages. Don't change the integration time though!
- Continue until you reach 0 mm stripe length.

Keep the energy fluency constant. Save two ASE spectra in a data sheet with the stripe lengths  $L = 0.4$  mm and  $2L = 0.8$  mm. If necessary increase the integration time beforehand and measure the dark spectrum again.

**Repeat the measurements for overall 3 different energy fluencies.**

## 5. Report

**Your report should include the following:**

- A brief introduction to the variable stripe length measurement.
- Measurement procedure: Explain shortly for each task which steps have been carried out by you and if some specific occurrences have been observed.
- Plot the ASE intensity against the stripe length and fit the results to eq. (4). The optical gain is calculated as shown in fig. 8.
- Calculate and plot the gain vs. wavelength using your saved data and the following equation:

$$g = \frac{1}{L} \ln \left( \frac{I_{2L}}{I_L} - 1 \right) \quad (9)$$

- Discussion of the results

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