MEMS-BASED WIDELY TUNABLE EXTERNAL CAVITY DIODE LASER

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Para Blanca, Daniel y Ramón

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Published and Presented Contents

A series of publications have been made associated to this Ph.D. thesis:

[1] **Álvaro Jiménez**, Tobias Milde, Niklas Staacke, Christian Aßmann, James O’Gorman and Joachim R. Sacher, “Narrow-line diode laser packaging and integration in the NIR and MIR spectral range”. In: *Photonics West* (January 2017). DOI: 10.1117/12.2255635

The main advantages of micro integrating laser devices are presented in this Invited Paper in Photonics West 2017 [1]. I introduced the concept of a micro-assembled tunable laser by means of a chirped grating (described in Subsection 2.4.1) or a setup composed by a transmission grating and a tilting MEMS mirror (described in Subsection 2.4.2).

[2] **Álvaro Jiménez**, Tobias Milde, Niklas Staacke, Christian Aßmann, Guillermo Carpintero and Joachim Sacher, “Narrow-line external cavity diode laser micropackaging in the NIR and MIR spectral range”. In: *Applied Physics B* 123.7 (July 2017), p. 207. ISSN: 1432-0649. DOI: 10.1007/s00340-017-6777-9. URL: <https://doi.org/10.1007/s00340-017-6777-9>

The article in Applied Physics B [2] gives a more theoretical approach to the development of an external cavity laser and the necessary considerations that were taken into account for the MEMS-Based laser of this thesis. All the simulations were performed by myself as well as the linewidth measurement appearing at the end of the article.

[3] **Álvaro Jiménez**, Tobias Milde, Herve Tatenguem, Martin Honsberg, Guillermo Carpintero, James O’Gorman, Joachim Sacher “MEMS based widely tunable external cavity diode laser”. In: *Photonics West* (February 2018). DOI: 10.1117/12.2287849

Measurements and results were shown in this presentation at Photonics West 2018 [3] in San Francisco. We constructed devices at different wavelengths ($\lambda_a = 780nm$, $\lambda_b = 920nm$, $\lambda_c = 960nm$) to demonstrate the concept of our development. Results of the device at 960 nm are included in Subsections 3.2.1 and 3.2.2.

[4] **Álvaro Jiménez**, Morten Hoppe, Sebastian Schmidtman, Tobias Milde, Guillermo Carpintero and Joachim Sacher, “Fast tuning MEMS based laser”. In: *FLAIR* (September 2018).

New results showing the tuning speed and stability of the previously presented devices were introduced in the FLAIR conference [4]. These results are introduced in this thesis in Subsections 3.2.3, 3.2.4 and 3.2.5.

[5] Morten Hoppe, **Álvaro Jiménez**, Hanna Rohling, Sebastian Schmidtman, Jan Grahmann, Hervé Tatenguem, Tobias Milde, Thomas Schanze and Joachim Sacher, “Construction and Characterization of External Cavity Diode Lasers Based on a Microelectromechanical System Device”. In: *IEEE Journal of Selected Topics in Quantum Electronics* 25 (April 2019), pp. 1–9. DOI: 10.1109/JSTQE.2019.2912059

This article [5], which is a compilation of all the collected data throughout my Ph.D. thesis, has been published with the measurements of devices at different wavelengths as it was done in [3]. It shows the benefits of MEMS-based external cavity lasers and stating the achievements accomplished with these devices.

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List of Acronyms and Symbols

AP	Applied Physics
AR	Anti Reflective
BNC	Bayonet Neill Concelman
CAD	Computer Assisted Design
CMOS	Complementary Metal Oxide Semiconductor
COTS	Components Off The Shelf
CW	Continuous Wave
DBR	Distributed Bragg Grating
DFB	Distributed FeedBack
DIL	Dual In-Line
DLP	Digital Light Processing
ECDL	External Cavity Diode Laser
ECL	External Cavity Laser
EIM	Effective Index Method
EM	Electro-magnetic
EO	Electro Optic
ES	Electrostatic
FA	Fast Axis
FD	Finite Difference
FIR	Far Infra-Red
FMM	Film Mode Matching
FP	Fabry Perot
FWHM	Full Width Half Maximum
GUI	Graphic User Interface
HR	High Reflectivity
IEEE	Institute of Electrical and Electronics Engineers
IPMS	Institut für Photonische Mikrosysteme
LASER	Light Amplification by Stimulated Emission of Radiation
LD	Laser Diode
LI	Light Intensity
LNA	Low Noise Amplifier

MEMS	Micro Electro Mechanical System
MIR	Mid Infra-Red
NTC	Negative Temperature Coefficient
OSA	Optical Society of America
OSA	Optical Spectrum Analyzer
PCB	Printed Circuit Board
PE	Piezoelectric
PIC	Photonic Integrated Circuit
PTR	Photo Thermo Refractive
QEPAS	Quartz Enhanced Photo Acoustic Spectroscopy
QS	Quasi-Static
QTF	Quartz Tuning Fork
QW	Quantum Well
RIN	Relative Intensity Noise
RF	Radio Frequency
RFSA	Radio Frequency Spectrum Analyzer
RWE	Ridge Waveguide Emitting
SA	Slow Axis
SEM	Scanning Electron Microscopy
SMSR	Side Mode Suppression Ratio
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
SPIE	Society of Photographic Instrumentation Engineers
TE	Transverse Electric (referred to optical modes propagated through a waveguide)
TEC	Thermo-Electric Cooler
TM	Transverse Magnetic (referred to optical modes propagated through a waveguide)
TQW	Triple Quantum Well
UC3M	Universidad Carlos III de Madrid
USB	Universal Serial Bus
UV	Ultra-Violet
VCSEL	Vertical Cavity Surface Emitting Laser
VHBG	Volume Holographic Bragg Grating
VHG	Volume Holographic Grating

INTRODUCTION TO TUNABLE LASERS

*“Learn to enjoy every minute of your life. Be happy now.
Don’t wait for something outside of yourself to make you
happy in the future. Think how really precious is the time
you have to spend, whether it’s at work or with your family.
Every minute should be enjoyed and savored.”*

- Earl Nightingale

1.1 Introduction

Laser is the acronym for "Light Amplification by Stimulated Emission of Radiation". Such a device was first experimentally demonstrated by Theodore H. Maiman based on the theoretical work developed by many people before its invention in 1960.

Lasers are spatially coherent light sources, and they can also have temporal (or spectral) coherence. Spatial coherence defines the property of lasers that allows laser light to be focused onto a very small spot, as well as to be collimated over long distances. Multiple industrial applications, including free space optical communications, are enabled by the spatial coherence property. The spectral coherence is the property of laser light characterizing its emission on a very narrow spectrum, which can be defined in simple terms as the ability of a laser of being a light source of an extremely pure color. Temporal coherence defines that the light source is a polarized signal of a single wavelength (or a combination of different single wavelengths) whose phase is correlated over a long distance. This property can also be employed to generate very short pulses of light, with numerous applications.

Lasers are usually classified by their emission wavelength in vacuum. The first laser produced by Maiman was a solid-state pink ruby laser which emitted red coherent light of approximately 694 nm. Previously, a lot of work was concentrated on the development of microwave frequency oscillators and amplifiers, the so called masers. Nowadays, lasers are used to generate light ranging from 100 nm (Ultraviolet range) up to tenths

of μm (Mid-Infrared Range) which can be used in many applications. Figure 1.1 shows the electromagnetic spectrum, starting with the very high energy X-rays up to the Far-Infrared. Current commercial lasers are depicted in this figure with their materials and corresponding wavelengths. The great majority of the available lasers are found in the visible and Near-infrared ranges.

Figure 1.1: Laser types with distinct laser lines are shown above the wavelength bar, while below are shown lasers that can emit in a wavelength range.

Figure 1.1 captions also in its lower part materials which can generate light in a range of wavelengths which is not limited to a single frequency. Particularly important are semiconductor lasers, in which their gain section are different III-V materials, which will be addressed in this thesis. Semiconductors, shown as dark green in the figure, span in different ranges of the visible and infra-red areas. This does not imply that every semiconductor laser will lase over the whole possible range, but only indicates the possibility of fabricating a laser with these semiconductor materials for these wavelengths.

1.2 Actual tunable lasers

Semiconductor diode lasers are the ones in which a semiconductor material is used as gain material within the optical resonator. Generally, the semiconductor material is presented as a stack of layers of semiconductor compounds with different alloys deposited on a wafer and then cut into single chips of small dimensions. These devices were developed in 1962 [6]–[8] and are present in many of our daily surroundings. Lasers fabricated on a given semiconductor material can either emit on a fixed wavelength or have the option of tuning their emission frequency, which is determined by the structure of the laser. Since many years, there is great interest in developing semiconductor lasers that can change their emission wavelength over a defined wavelength range. These lasers are defined as **tunable lasers**.

Tunable diode lasers are an important tool for spectroscopy over the last two decades. Starting from laboratory applications, diode lasers become more and more important for

medical, pharmaceutical and industrial measurement applications. Methods employing laser systems have established themselves as one of the most effective ways of offering solutions to a wide range of applications in numerous fields. Different kinds of tunable diode lasers are available nowadays in the market including Distributed Feedback (DFB) Lasers, External Cavity Lasers (ECL), Vertical Cavity Surface Emitting Lasers (VCSEL) and more. The main focus of this thesis will be to develop the design of a novel approach to the External Cavity Laser systems by means of new elements in their structure. The key enabling component of these lasers is the inclusion of Micro Electro Mechanical Systems (MEMS), which ensure unique characteristics such as tuning speed and repeatability. Special emphasis has been made in the commercial side of the development, as the thesis has been developed at Sacher Lasertechnik GmbH, one of the most pioneer companies in the development of this kind of systems [9].

Laboratory environments were the only place for earlier generations of diode laser systems due to their sophistication and complexity related to their large cavity assemblies. More recent developments have led to overcome the drawbacks of laser systems with robust and environmentally insensitive technologies. Cost has also been reduced for these systems, making them affordable and accessible for a broader range of applications. This thesis reports technology breakthroughs, resulting into solutions with high standards of quality that ensure a solution to be commercially exploited with, hopefully, great success.

There are many justifications for wanting tunable laser systems, including reduced manufacturing and operational costs because several wavelengths are addressed with a single system [10]. However, many other applications such as laser spectroscopy will be more important in the near future [11]–[13], specially if small and compact devices are developed, enabling portable systems. Many communication systems rely on tunable lasers for their operation instead of using a whole array of fixed-wavelength elements.

The first chapter will cover the state of the art of the current technology regarding monolithic semiconductor tunable laser systems. In chapter 2, the design of the MEMS External Cavity Diode Lasers (ECDLs) will be presented, ranging from the optimization of the semiconductor laser chips by optical simulation to the characterization of the gratings to be used in the system. The physical design of the lasers system's setup will be also presented in this chapter. Chapter 3 will show the results of the developed system in terms of power and optical spectrum for different wavelength regimes and a complete Relative Intensity Noise characteristic of the system. Chapter 4 will present the conclusions obtained during the thesis. A list of publications related to the thesis development will be appended to the document.

This thesis has demonstrated that narrow linewidth tunable lasers will be available for advanced applications in daily life.

Tunable lasers are defined as those whose frequency of emission can be changed in a controlled way. By definition, every laser gain medium is able of providing gain over a broad spectral region, where the lasing mode can be selected. These tunable lasers can be classified into different categories. If we concentrate on the kind of material they

are made with, the most popular are semiconductor diode lasers (i.e. Indium phosphide, InP, or Gallium arsenide, GaAs), gas lasers (i.e. CO₂ or He-Ne), solid state lasers (dye or transition metal) or fiber lasers. According to their type of tunability, lasers can be classified into the following groups:

- **Single line tuning.** All laser gain materials can emit light over a range of frequencies. For most of the cases, this range is narrow, and can cover spans as low as a hundred of gigahertz (i.e. for the 1064 nm wavelength transition of a Nd:YAG laser, the span is around 120 GHz or 453 pm). If the cavity is big enough to feature more than one longitudinal mode wavelength emission, one of them may be isolated with the use of wavelength selective elements. This will be the case to be thoroughly treated in this thesis.
 - **Multi line tuning.** Some laser gain materials have several transitions on which lasing conditions can be fulfilled, instead of featuring a single broad gain area. As it happens in the single line tuning, by using wavelength selective elements, different frequencies can be selected. For example, argon-ion lasers can tune through different colors from the ultraviolet and blue to green wavelengths.
 - **Narrowband tuning.** We will define narrowband tuning as that which can span over a few nanometers, usually not covering the whole possible band of the materials' operation wavelengths. Usually, narrowband tuning is achieved by means of thermal effects. As an example, Vertical Cavity Surface Emitting Lasers (VCSELs) and Distributed FeedBack (DFB) semiconductor lasers make use of periodic structures which filter a single longitudinal lasing mode. The wavelength selection of the Bragg gratings employed in these kinds of lasers is defined by the physical dimensions of a periodically distributed set of perturbations in the refractive index of the cavity. When these dimensions are altered due to a difference in the chips' temperature, the wavelength suffers a shift or tuning. In order to get an idea of the scope of this effect, the lasers' temperature may be usually altered up to 50 Kelvin degrees. As a reference, lasers used for communications in the 1550 nm IR range tune approximately 0.08 nm/K (10 GHz). The total tuning which would be achieved in this example is of 4 nm, which is a reasonable estimate for DFB lasers in the infrared range.
 - **Wideband tuning.** Many lasers do not make use of the whole available bandwidth in which the materials can provide laser gain. Different techniques have been developed to improve this aspect, extending the tuning range of lasers:
 - *External Cavity Lasers.* An optical grating is used as a wavelength dispersive element. Hence, the beam coming from the laser gain material is spatially distributed. A reflector is used at a specific position to select the wavelength, creating the laser cavity. For external cavity tunable lasers, the elements need to be physically rearranged to select a new lasing frequency. Therefore, it is usual to make use of mechanical pieces for this purpose. Tunable external cavity lasers will be analyzed more in depth in the next section, as they are the basis of the developments presented in this document.
-

- *Sampled Grating DBR Lasers.* Although the previously presented DFB and VCSEL lasers have a narrow tuning band, by engineering the Bragg reflectors we can achieve a much broader tuning range. The Vernier effect, using two or more different selection reflectors, is applied to extend the wavelength range.

Coldren et al. [10] refer to the schematic in Figure 1.2 to explain in a generic way the operation of a tunable laser. The most basic setup for a laser would be to count on both mirrors and the gain material, forming a Fabry-Perot cavity which would show all the possible modes without any kind of filtering. However, we are not interested in a multiple wavelength laser in this development, so a Mode-selection filter (Δm) is placed within the cavity to select only one of the possible wavelength lines. Different mode-selection filters can be engineered for a single frequency laser system: for DFB lasers, a periodic grating is scribed on top of the waveguide in the active material; DBR lasers present the same grating structure, although it is placed outside the active area and located in a passive waveguide region; ECLs make use of an external grating. In this thesis, as it is a development of an external cavity laser, external gratings are the choice for the mode-selection filter.

Figure 1.2: Schematic of a generic tunable laser with relationship of the spectra of each element [10].

The mirrors present in our case are defined by one of the facets of the gain chip, which is High-Reflection (HR) coated to avoid the loss of optical power, and an external mirror placed on a tilting structure. The tuning of the laser, in our case, is made with a tilt (or angular variation). The grating that acts as the mode-selection filter diffracts each wavelength into a given angle and by tilting the reflector at the end of the cavity we can select the appropriate mode to stabilize in the cavity. In addition, as one of the last steps of the developments made in this thesis, a linear displacement (ΔL) of the reflector at the end of the cavity to enable the continuous tuning of the laser. Without this variation of the cavity length, the device would only be able of tuning between the discrete possible modes of Figure 1.2. As a last effect, the Cavity phase (Δn) may be changed for a fine adjustment of the signal, having a similar effect to the one provided by the length increase of the cavity. When modifying the refractive index, n , the optical

path of the light within the cavity is also changed. For the external cavity diode lasers, this index change is achieved by either changing the temperature of the gain chip or its injection current. All these effects can also be derived from Equation 1.1, which provides a solution for the optical modes which can be generated in a Fabry-Perot cavity:

$$\frac{m\lambda}{2} = \bar{n}L \quad (1.1)$$

where m is the optical mode order, λ is the emission wavelength, $\bar{n}$ stands for the refractive index within the optical cavity and L is the length between both mirrors. Please note that we have named $\bar{n}$ the refractive index as it is composed of different areas in the optical path, comprehending the gain material and the free space cavity. Multiple solutions are possible for this equation, but they must all have their solution inside the optical gain spectrum area of the semiconductor material. For a single wavelength laser emission, only one of the optical modes' solutions must be chosen with the mode-selection filter. If we isolate the λ variable (Equation 1.2), we can calculate its derivative (Equation 1.3) to sort out the tuning factors affecting the wavelength:

$$\lambda = \frac{\bar{n}L}{m} \quad (1.2)$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\bar{n}}{\bar{n}} + \frac{\Delta L}{L} - \frac{\Delta m}{m} \quad (1.3)$$

As we can see from both equations, the three tuning mechanisms describes in previous paragraphs may be isolated: $\Delta\bar{n}/\bar{n}$, $\Delta L/L$ and $\Delta m/m$ have an influence over the wavelength of the laser.

Once tunable lasers have been presented, 1.1 is presented as a comparison between the two main kinds of laser technologies available in the market nowadays. While DFBs are a really attractive option in terms of size and ease of use, External Cavity Diode Lasers present higher power, narrower linewidth and there is an enormous difference in the tuning range that can be achieved with this laser choice.

We will concentrate on the external cavity diode lasers to introduce the basic technology behind the present thesis. Furthermore, the devices here developed, overcome also some of the main drawbacks of the currently available ECDLs, such as the wavelength tuning speed.

Table 1.1: Comparison of the two main tunable laser technologies.

Laser technology	Wavelength	Output power	Typical tuning range	Typical mode-hop-free tunability	Typical linewidth
DFB /DBR	633 nm to 3.5 μm	Up to 150 mW	2 to 6 nm	1000 GHz	1 to 5 MHz
ECDL	370 nm to 2.4 μm	Up to 300 mW	Up to 120 nm	50 GHz	10 kHz

1.3 Tunable External Cavity Diode Lasers

Semiconductor diode lasers were developed in 1962 [6]–[8] and are present in many of our daily surroundings. The facets or the chips are usually partially reflective, and this reflectivity is used to form the cavity of the optical resonator, letting a portion of the light out of the chip so that it can be used. However, these laser diodes are not ideal for every application and in order to extend their applicability and improve parameters such as their tuning range. Alternatives based on Bragg gratings have already been mentioned as DFB or DBR lasers, but we will focus on the alternative configuration which consists on the use of an external reflector to form the cavity instead of using the facets of the chip. For this purpose, an Anti Reflection (AR) coating is placed [14] so that the light is only fed back to the cavity from the external reflector.

Figure 1.3: ECDL in Littrow configuration without (left), with (middle) beam-correction mirror, and in Littman-Metcalf configuration (right) [14].

The first appearances of external cavity arrangements date from 1964 [15], and since this first proposal some configurations have been introduced. There are two main configurations for external cavity structures: Littrow and Littmann-Metcalf. Figure 1.3 shows the two different options, including an option with a correction mirror to direct the output beam.

The first configuration to discuss is known as Littrow, shown in Figure 1.3(a), in which a grating mirror is used. Ricci *et al.* [16] described a model in which the radiation emitted from an AR-coated laser diode is collimated and hits a diffraction grating under the Littrow angle. Hence, a portion of the light diffracted in the first order is reflected back into the laser diode, stabilizing the lasing frequency. The remaining light in the zero order can be used for the desired application. As the tuning is achieved by mechanically tilting the grating, the output beam with the new selected wavelength will have a different output

direction. A solution was to introduce a correction mirror, shown in Figure 1.3(b) which has to be shifted at the same angle than the grating. The angular tilt is eliminated but a small side-walk of the beam will still be present.

A more interesting option was presented by Littman *et al.* in 1978 [17]. The right part of Figure 1.3 shows how a mirror (or prism) is introduced to feed back the light diffracted from the first order instead of reflecting it directly back from the grating. The cavity of the optical resonator is set up between the back facet of the chip and the external reflector. In this case, wavelength tuning is given by the tilt of the reflector but the output beam in the order zero of the grating will have a stable position. Although this last option has a slightly more complex setup due to the alignment of the reflector and the mechanical stability compromise of adding another element to the cavity, it is usually a more interesting option in comparison to the Littrow setup.

In this thesis, the main development is made based on the **Littman-Metcalf** cavity setup. However, changes are introduced with respect to the original idea. The reflection diffraction grating is substituted by a transmission grating. The zero order of the grating is therefore taken in transmission instead of reflection, allowing a more compact device. In second place, and most importantly, the reflector used is mounted on a Micro Electro Mechanical System (MEMS) allowing many important upgrades with respect to the classical Littman setup. These advantages will be analysed further in this thesis.

LASER SYSTEM DESIGN

*“We are here to laugh at the odds and live our lives so well,
that death will tremble to take us.”*

- Charles Bukowski

2.1 Building Blocks

As we discussed in the previous chapter, there are different ways of implementing a tunable laser. The configuration developed within this thesis is based on an external cavity with Littman-Metcalf configuration. The building blocks that are required to build such a laser are the following:

- *Semiconductor laser chip* to provide the necessary gain to the optical resonator,
- *wavelength selective element* such an optical grating to select the mode which is to be stabilized,
- *reflectors* to close the resonator’s cavity.

Figure 2.1 shows a schematic drawing of the arrangement of the different building blocks that we have designed. In this chapter we present all the design effort that has been carried out for its development within each of these blocks.

First of all, regarding the semiconductor diode chip, a ridge waveguide containing active material is used to provide the optical gain. In this chapter we present the result of the simulations, specifically for the GaAs substrate material, for lasers with an emission wavelength centered at 785 nm. These results illustrate that the developments presented in this thesis can be extended to any other wavelength of interest. Section 2.2 discusses the simulations performed to optimize the ridge waveguide structure in the active gain semiconductor chip, work which counted with the contribution of M^2K

Regarding the wavelength selective element, a transmission grating has been employed, which allows to use a fraction of the light, between 20% to 40%, to stabilize the cavity. Here the simulations on the necessary amount of power needed to stabilize the external cavity diode laser are included. The remaining optical power goes entirely to the output of the system, providing a high output power. The cavity filter is analyzed in Section 2.4.

In this chapter, we also include the overall mechanical design of the optical cavity. As it was mentioned in the previous chapter, the Littman Metcalf configuration needs a reflecting element to feed back a portion of the light (Figure 1.3) so that it can close the cavity and resonate optically (Figure 2.1). Many ECDLs have already been developed and they usually rely on a mirror or prism that is mounted on a movable arm. This arm can then be mechanically actuated by a screw or even a motor-enabled system which will displace the reflector's arm. In our MEMS-based widely tunable laser system, a MEMS element is introduced to actuate the reflector and therefore select the frequency to be stabilized. Our Micro Electro Mechanical System has a silver coating and it is used directly as the reflector element, which can be tilted to select the frequency of the tunable laser. A description and selection of the MEMS element is made in Section 2.3.

Figure 2.1: Building blocks for a MEMS-based widely tunable laser system.

2.2 Chip-level Simulations

The specification of the gain chips for a laser development is a critical task, of which depends greatly the success of the fabrication. It is also an expensive and time consuming process, which leads to the production of a full wafer of gain chips. In such scenario, simulations are an extremely helpful tool to save time and financial resources, and there-

fore, securing the success of the project. For this thesis, simulations were carried out to optimize the design of the waveguide for the GaAs chips which were to be employed.

The aim of this simulation was to obtain optimized dimensions for the gain chips. These are basically a ridge waveguide of active semiconductor material, which propagates a single transverse mode (with a desired polarization, which in our case is Transverse Electric -TE-).

Two tools were used in for the simulation of the gain chip. On one hand, Phoenix Software (subsection 2.2.1) was used to analyze the optimization of the geometrical parameters of the ridge waveguide structure. On the other, Photon Design (subsection 2.2.2) was used to back-up the results obtained in first place. We will demonstrate good propagation results of the optical mode within the calculated structure.

2.2.1 Waveguide Structure Design

Phoenix Software offers a set of advanced mode solvers, the basic ingredient of optics design steps, being a starting point needed in propagation analysis and waveguide optimization. Phoenix Software uses solvers to calculate the optical modes that can propagate through a defined structure. Among these solvers, we can find different approximation solvers, using one, two and three dimensional options for optical waveguides, overlap, confinement and other post-processing of fields. A comparison between the main mode solvers - Film Mode Matching (FMM), Finite Difference (FD) and Effective Index Method (EIM) - used for this purpose is shown in Table 2.1:

Table 2.1: Comparison of mode solving techniques [18].

FMM	FD	EIM
Fast	Slow	Slow
Very accurate	Sensitive to grid	Sensitive to grid
Gives guided modes only	Gives all modes, including non-guided ones	Calculates modes' interference
	Can calculate optical loss	Propagation simulation

The choice of mode solver for the waveguide optimization is FMM, which is fully vectorial and the perfect tool to process waveguide structures with a rectangular geometry. FMM is a semi-analytic method that does not need any discretization of the structure, provided that the waveguide can be defined by a finite set of rectangles and the solver is ideal for structures that have been epitaxially grown in thin layers such as the ones we need to process. It is of particular importance that the software includes bent waveguide modeling, as this will be one of the specific future targets of the design within the project scope.

Two main concerns were addressed with this software:

- Epilayer structure

- Waveguide geometrical optimization

Regarding the epilayer structure of the semiconductor gain material, rather than specifying it, we have been able to include in our model the epilayer of the wafer on which our gain chips were fabricated. The structure was fully translated and implemented within the software package described before, as it is graphically shown in Figure 2.2.

Figure 2.2: Epilayer structure of the simulated devices.

The active quantum well (QW) structure is made of gallium arsenide phosphide, GaAsP. Both the cladding and waveguide consist of aluminum gallium arsenide, AlGaAs, doped with beryllium (Be) and silicon (Si) for the correspondent N and P structures. The cap is made of gallium arsenide doped with beryllium.

One of the most important key parameters to be simulated are related to the geometrical design of the waveguide. As we have already mentioned, the company in charge of fabricating the gain chips, M²K (<http://www.m2k-laser.de>) defines the epilayer throughout their expertise in semiconductor lasers fabrication. However, we still need to define two parameters of the structure, which are the width of the waveguide and the etching depth.

Our first simulation mapped the optical modes of the waveguide with different parameter definitions. Figure 2.3 and Figure 2.4 show the generated color map with the simulations in OptoDesigner for the number of guided TE and TM modes through the waveguide.

Only one TE mode should be propagated through the waveguide, reducing to zero the number of TM modes. There is a well-defined range of parameters in which these requirements are met, and after a discussion with M²K, a couple of values were extracted. As a final conclusion from the simulations, the waveguide width will be 2.9 μm and the etching depth 0.95 μm .

For the defined values of waveguide width and etching depth, the propagation of the single transverse electric mode was simulated and a slice of the propagated mode within

Figure 2.3: Number of TE modes in the simulated optical waveguide. The figure depicts in color the number of transverse electric modes which propagate through the structure, corresponding to different combinations of waveguide width (measurement in μm , X axis) against etching depth (measurement in μm , Y axis)

Figure 2.4: Number of TM modes in the simulated optical waveguide. The figure depicts in color the number of transverse magnetic modes which propagate through the structure, corresponding to different combinations of waveguide width (measurement in μm , X axis) against etching depth (measurement in μm , Y axis)

Figure 2.5: Simulated TE optical mode propagation for chosen parameters. The etching depth is shallow, so the mode is expanded to a bigger dimension compared to the waveguide width.

the waveguide is shown in 2.5. The optimal geometrical dimensions of the optical waveguide have been obtained from the simulations done with this software and the validation of these results was done in collaboration with M²K, who had reached these values through years of trial and error. At this point, it is really important to underline the importance of including simulations in the development cycle, as they can be really powerful tools that enable saving costs and time. The results calculated here have been cross-checked by a second simulation software in next section (Section 2.2.2).

2.2.2 Propagation Simulation

In order to confirm the results obtained in the previous software, the next stage was to export the obtained results into a more specific software for optical waveguide light propagation. As it happens with the previously analyzed option, Photon Design offers different mode solvers. The same choice was made here, picking the FMM solver in accordance with the work of last section.

The main concern when making this simulation is to solve the propagation of the optical modes within the designed waveguide. The epilayer structure was imported to Photon Design FIMMWAVE, as it is shown in 2.6.

Figure 2.6: Epilayer structure built in Photon Design FIMMWAVE. Parameters are identical to the ones used in Phoenix Software.

The software, using the Film Mode Matching solver, shows the optical mode confined within the designed waveguide, being this a confirmation of the previously obtained data. Figure 2.7 shows the fields conducted through the optical waveguide. This model is in complete accordance to the one presented in 2.5 for Phoenix Software and as it can be seen in both figures, the field is not strictly confined to the ridge waveguide structure. A shallow waveguide enables the possibility of decreasing the propagation losses intrinsic to this kind of structure.

To conclude with the optical simulations, the dimensions of the guiding structures for light within the optical gain chip have been optimized in a single step instead of relying on a trial and error iteration. Simulations have proven to be a solid resource for the correct development of a device like the MEMS-based tunable laser. In the next sections, the MEMS selection will be discussed, as well as the choice of the cavity filter.

Figure 2.7: Optical mode propagation in FIMMWAVE software.

2.3 Tilting mirror

In Chapter 1 I discussed on how a tunable laser needs to actuate the grating reflector (Littrow devices) or the reflector from the cavity (Littman-Metcalf devices) to mechanically tune the wavelength of the external cavity tunable lasers. Nowadays, the tuning mechanisms of the available lasers rely on bulky pieces which are usually tuned with screws, either manually or with the help of a motor. However, these kinds of setups are big and complex, and have a series of drawbacks:

- Complex and usually big structures that reduce portability.
- Mechanical pieces suffer from resonance effects.
- The screws are the cause for mechanical hysteresis, due to the nature of the thread of the screws.

The biggest chances for improvement for External Cavity Tunable Diode lasers are introducing new technologies that enable overcoming the present drawbacks. In this thesis, we propose the inclusion of Micro Electro Mechanical Systems (MEMS) as the tuning mechanism, since they are compact elements for the tuning, which introduce the challenge of the limited amount of force. Therefore they will only be able of moving a very small-sized element. If we were to apply the movement of the MEMS to a Littrow laser, we would need to displace the grating element. This option would only be possible if the grating would be grown directly on the MEMS, but it would imply a specific development to be added to the project. However, MEMS are already available with a reflective coating, so they can be directly used as the reflector of a Littman-Metcalf type of cavity.

Different kinds of MEMS have been developed, and Table 2.2 summarizes the three main categories and their advantages compared to each other.

Table 2.2: Comparison of properties of actuation principles [19].

Category	Electrostatic (ES)	Electromagnetic (EM)	Piezoelectric (PE)
Preferred type	Comb drive	Moving coil	PZT film
Simple fabrication	✓✓✓	✓✓✓	✓✓
Large displacement	✓✓	✓✓✓	✓
High force	✓	✓✓	✓✓✓
Low power	✓✓	✓	✓✓✓
Low voltage	✓	✓✓✓	✓✓
Compactness	✓✓✓	✓	✓✓✓
Linearity	✓	✓✓✓	✓✓

Electrostatic (ES) actuators were the first approach used for MEMS scanners and includes the major part of the published literature in this topic. This fact is caused by two main reasons, which are the fabrication advantages without needing any special or unusual materials, together with the integration possibilities of this kind of devices [19].

If we compare electrostatic actuators to piezoelectric (PE) film actuators, the last ones need the deposition of the piezoelectric material. The electromagnetic (EM) moving coil actuators make use of magnets, making the handling more difficult. When analyzing the properties presented in Table 2.2, we can see that we are mainly looking for a device which can be easily fabricated and integrated within a small and compact package. Therefore, and having discarded the EM actuators due to their complexity and bulky packaging options, we decided to work with the most mature technology, the electrostatic actuators

Electrostatic actuators rely on the attraction or repulsion of two charged plates with opposite charges. The electrostatic force between two charged plates is mathematically defined as:

$$F_{es} = \frac{A\epsilon V^2}{2g^2} \quad (2.1)$$

being A the area of overlap between the two plates, ϵ the dielectric constant of the medium, V the potential difference of the two plates and g the gap between both elements. Two different approaches have been studied for electrostatic elements: parallel plates and comb actuators.

Parallel plate MEMS, which were presented by Petersen in the year 1980 [20] are based on the parallel plates concept, and since then, have been used in many applications with bi-stable mirrors, such as DLP (Digital Light Processing) [21], [22]. Their scan range is very limited, as the voltage requirements grow exponentially with the separation between the plates.

The alternative approach is comb type MEMS (Figure 2.8). This is the preferred choice for high frequency electrostatic operation, in the range of kHz. Although it may seem like a low frequency value, it must be considered as high speed for mechanical systems. In this configuration, two interdigitated rows with a comb shape [23] (one static and another one movable) and they allow larger motion and a more even distribution of the applied force over the whole range. The first MEMS devices with a comb-like structure for actuation were presented by Tang *et al.* in 1990 [24], [25].

Electrostatic actuation devices have a series of advantages, such as their long-term stability. This will enable the stability of the final laser developed in this thesis, a property which is key for applications such as spectroscopy, where a very precise wavelength needs to be addressed continuously. Furthermore, they are really compact devices and the fabrication of ES MEMS can be easily integrated with other CMOS-compatible processes and creating totally integrated tunable lasers within a single chip becomes a real possibility which we aim for. However, not every aspect of ES MEMS is positive and they require high voltages to operate. As an example, the devices which we integrated, need an operation voltage up to 120 V to reach their full mechanical displacement. Moreover, the travel range is limited due to the interaction between the non-linear electrostatic force and the linear elastic restoring force [27]–[29].

Figure 2.8: Two dimensional MEMS from Fraunhofer IPMS [26].

Finally, one of the main concerns when designing the MEMS-based tunable laser is the modulation frequency which can be achieved when tuning the wavelength with the external cavity. For some applications, it is critical to switch between different wavelengths with enough speed to process the data in real time. Bio-medical measurements or energy generation applications, for example, depend on low processing times below 1 millisecond. Currently available tunable laser systems are not able of switching so quickly and therefore our aim is to achieve a kHz range tuning for the whole range of each laser system. Electrostatic MEMS fulfill this specification as discussed in [30] and [31].

2.4 Mode Selection Filter

As a final section of this chapter, we present the design of the mode selection filter, or cavity filtering element. This is one of the key elements defining the performance of the tunable laser, defining key performance characteristics such as the tuning range, the Full Width Half Maximum (FWHM) of the laser's optical mode and even the output power. Hence, it must be closely evaluated to obtain the best possible performance.

For many applications, high power is desirable. For example, in spectroscopy related applications, for the detection or analysis of substances, the sensitivity is proportional to the optical power of the laser source [32]. With our MEMS based tunable laser, we want to improve the results offered by the actual systems. In this section, the role of the Mode Selection Filter is analyzed and a decision is made to build the best possible system. The expertise acquired with external cavity lasers during the first year of my PhD studies has enabled this part of the development. A brief comparison is made between a DFB and an external cavity laser to justify the selection of the latter one in terms of specifications.

It is usual to find DFB lasers mainly due to their tuning characteristics. However, DFB-based systems present a moderate output power due to the losses introduced by the internally engraved grating present in the ridge waveguide. To solve this issue, external cavity is the common choice due to reduced losses. For such schemes, external gratings such as Volume Holographic Gratings (VHGs) or transmission/reflection gratings are used, generating an advantage in terms of the output power generated by the system. In order to compare the magnitude of this difference, the output power of a DFB and an ECDL was measured. Figure 2.9 shows the Power vs. Current performance of a VHG laser compared to a DFB in the 1390 nm range at a temperature of 20 °C. In Figure 2.9 we actually find two different effects.

The first effect that can be observed are the kinks appearing in the ECDL curve (red line). These are due to a change in the lasing mode in the external cavity stabilized by the Volume Holographic Grating. The dominant mode in the external cavity is pushed to higher wavelengths with increasing current due to the rising temperature in the chip. Hence, the lasing mode gets attenuated at the higher end of the band pass filter and the next mode comes into play from the other side of the filter's mask, becoming dominant and beginning to lase. This is a common effect in external cavities, although it does not usually have an impact in the applications we are aiming for.

The second effect is that the threshold current and the output power of external cavity diode lasers are higher for ECDL in comparison to DFB lasers. This responds mainly to the level of optical feedback provided in each case, which is necessary for a proper single mode operation. The mode selection filter that is located in the cavity must be designed to provide enough reflectivity to allow one mode to oscillate in the optical resonator. In the case of DFBs, the gratings are directly engraved on the waveguide, which causes a strong overlap of the lasing mode with the grating and, therefore, high losses within the cavity. As the spectral selectivity is increased to reach the necessary level, so do the losses in the cavity, reducing the output power of the device. For external cavity lasers, we have

Figure 2.9: The output power of a VHG and a DFB laser are compared. The VHG *red* generates an output power of 51.2 mW while the DFB *black* is limited to 16.6 mW [2].

the option of increasing the selectivity of the grating without an impact on the losses derived from this element. This fact allows us to increase the length of the gain section to increase the optical power, at the expense of increasing the current which needs to be injected into these devices. The key factor for achieving a higher output power of the laser is that we can optimize the feedback of the mode selection filter to a lower value. By combining these two changes with respect to a DFB laser, we will obtain an increase in the final output power [14], [33]. Equation 2.2 models the losses in the mirror:

$$k_r = \frac{1}{L} \ln\left(\frac{1}{\sqrt{R_1 R_2}}\right) \quad (2.2)$$

here, k_r stands for the mirror induced losses including the effect of the chip length (L), and the reflectivities at the extremes of the cavity. The losses of k_r vary the threshold current density J_{th} , as the gain needs to overcome them by means of optoelectronic gain provided by the semiconductor material (Equation 2.3):

$$J_{th} = J_0 + \beta^{-1} k_r \quad (2.3)$$

being J_0 the linear extrapolation term [34] and β the gain constant. The output power which is available for the system is affected by the previous parameters as defined by Equation 2.4, which explains the appearance of a maximum on the curve depicting $P_{out}(R_2)$, which relates the reflectivity of the output facet with the output power:

$$P_{out} = \frac{h\nu_{las}}{q} \eta_{int} (I - I_{th}) \frac{k_r}{k_r + \rho} \quad (2.4)$$

Figure 2.10: Output power and threshold current simulation of a laser diode vs the front facet reflectivity. The optical power, *red*, shows its maximum value for a reflectivity of 8.3% while the threshold current, *black*, follows an exponential increase as the front facet reflectivity is decreased.

Figure 2.11: Optical spectrum of a VHG *red* and a DFB laser *black*. The SMSR of the VHG results in a value of 55.91 dB, compared to the SMSR of 41.92 dB of the DFB laser.

The laser's output power depends on Planck's constant, h , the laser's frequency, ν_{las} , the electron's charge, q , the internal efficiency of the laser, η_{int} , and the optical losses of the device, ρ . Both the optical power and the threshold current depend on the amount of feedback provided by the facets of the cavity. The exponential behavior described in Equation 2.3 models the shape of the black curve of Figure 2.10, which is the value of the threshold current vs. the reflectivity of the front facet. The rear facet is assumed to remain at a fix value of 95%. Specially important in this same figure is the Optical power, depicted in red. This power can be optimized by tuning the reflectivity R .

Additionally, external cavity lasers usually show a higher Signal to Noise Ratio (SNR) than DFB lasers. A measurement of two of these devices was made to show this comparison in a real situation and it is shown in Figure 2.11. As expected, the SNR for the ECDL laser had a value of 55.91 dB and the DFB was more than 10 dB lower, with a value of 41.92 dB.

2.4.1 Volume Holographic Grating demonstrator

When the tunable laser was proposed, different tuning setups were proposed. In order to achieve a continuously tunable, compact, single-mode diode laser, an approach via a transmitting chirped Volume Holographic Bragg Grating (VHBG) was investigated. Continuous wave semiconductor lasers have already been developed for very narrow band operation. These lasers show some advantages with respect to conventional ECDLs in Littrow or Littman-Metcalf configurations [35], which are more sensible to acoustic and temperature variations. These problems are overcome by a compact integration of the grating within an external cavity setup, and here the Volume Holographic gratings show their major potential because they can be assembled in a very compact way and achieving very stable laser emission and high output power [36].

However, Volume Holographic Bragg gratings are usually designed for narrow-band operation, in the picometer range, and therefore a variation was proposed to achieve a higher tuning span. A continuous chirp was applied to the grating transversely, varying its period and hence its filter frequency. Lateral translation, which was done laterally as shown in Figure 2.12, was the mechanical way of tuning this laser demonstrator.

The first step is to develop a system with discrete components, including an integrated VHBG, to test the concept of a tunable external cavity with such element acting as a mode selection filter. The elements needed this demonstrator are a ridge waveguide emitting (RWE) gain chip that provides the gain, two cylindrical lenses to collimate the divergent fast and slow axis of the gain chip, and the volume holographic Bragg grating (VHBG) itself.

The gain chip for this setup is a 1200 μm triple quantum well InGaAs RWE chip, soldered on an AlN submount, located on top of a temperature controlled copper micro-bench where the chip itself and the collimation lenses are assembled. The temperature of this block is stabilized at 22 °C through a Negative Temperature Coefficient (NTC) thermistor and a Thermo Electric Cooler (TEC) controller.

The transmitting VHBG is created on photo-thermo-refractive (PTR) glass. It is highly efficient, presenting low losses and achieving a high quality of the laser beam [36], [37]. This VHBG has two important characteristics for the appropriate function of the tunable system: firstly, it is AR-coated and, secondly, it is transversely chirped to achieve wavelength tuning by mechanically displacing the grating. The anti-reflection coating reduces the losses and most importantly the back-reflections of the glass-air interface into the gain chip. The setup for this system is shown in Figure 2.12.

With this scheme, the emission wavelength is tuned by position displacement of the VHBG grating. This grating has a fan-shaped grating structure [1], an approach that was already considered by different authors for distributed feedback dye [38] and semiconductor [39] lasers. The grating was designed to provide a spectral selectivity of 0.59 nm and a tuning range of more than 10 nm, centered at 1060 nm.

Various measurements were done on this demonstrator, being the most important one

Figure 2.12: Schematic of the setup of a chirped Volume Holographic Grating tunable laser system. Tuning is achieved by diagonal translation of the VH. [1]

the optical spectrum, is shown in Figure 2.13. Due to the high feedback level provided by the VHBG, which was measured to be of 54%, the threshold current of the VHBG laser at its center wavelength is only 55 mA (compared to the 100 mA of the ECDL shown in the previous section, means a reduction of 50%). The maximum measured output optical power was obtained at the highest possible injection current in the gain chip: 29.5 mW at 120 mA. For the demonstration, the grating was mounted on a three-axis linear translation stage and swept perpendicularly over its whole 5 mm range. The total tuning span of the VHBG laser reached 4.11 nm with a factor of 0.822 nm/mm .

When tuning the VHBG laser, one of the aims is to expand as much as possible the continuous tuning range (tuning without mode hops). As discussed before in Section 2.4, the Bragg grating acts as the mode selection filter and picks one of the available modes present in the equivalent Fabry-Perot cavity. If the grating is displaced only in vertical direction, the VHBG laser's spectrum will jump from one mode to the next available one, as happened with the ECDL. To extend the mode-hop free tuning range, the length of the cavity must be modified according to the wavelength, requiring a lateral movement of the grating. This means that the grating needs to be kept straight, with a diagonal displacement path (Figure 2.12). The VHBG translation is arranged at an angle of 30 degrees with respect to its perpendicular displacement, achieving a total 0.3 nm (80 GHz) of mode-hop free tuning range. Although this range is by no means comparable to the magnitude of the total tuning range, it is within the range of many commercially available laser systems. However, this laser concept is not considered to be a good approach for this thesis so the option of transmissions gratings was investigated and it is discussed next.

Figure 2.13: High tunability span of the VHBG of 4.11 nm at the opposite positions of the translation stage [1].

Figure 2.14: Mode-hop free tuning range of 0.3 nm while diagonally tuning the VHBG [1].

2.4.2 Transmission Grating demonstrator

As we have presented, different options were considered, mainly using volume holographic gratings and transmission gratings. In the previous section, we have already presented the results obtained with a demonstrator including a VHBG and mechanically movable parts. This approach meets the requirements of the laser source in terms of power, but the tuning range was limited in terms of wavelength and due to the moving parts the setup was compromised in terms of stability, introducing critical resonance points which are undesired for our purpose. In comparison, the transmission gratings solution offers a much wider wavelength tuning range as well as reducing significantly the resonance effects over moving parts, as the tuning is made through Micro Electro Mechanical Systems (MEMS) actuators.

Figure 2.15: Transmission grating diagram.

Transmission gratings operate as a spatial filter for different wavelengths. A single wavelength incoming beam will be diffracted in a unique angle for each wavelength, described in Equation 2.5, which depends on the incoming angle. Figure 2.15 shows a schematic of the parameters in Equation 2.5.

$$a [\sin(\theta_m) - \sin(\theta_i)] = m \lambda \quad (2.5)$$

$$\theta_m = \arcsin \left[\frac{m \lambda}{a} + \sin(\theta_i) \right] \quad (2.6)$$

In the above equations, a is the spacing between the transmission grating's lines. This parameter is selected for each span of wavelengths so that the diffracted angles

may be compensated with a small reflector and they are not too widely spaced between each other. However, going to a narrow value of diffraction angles could lead to a lack of wavelength resolution when reflecting back the desired frequency. θ_i responds for the incident angle of the beam and θ_m is the output angle for the order m and a given wavelength λ . A semiconductor gain chip as the ones we are using for the design of the MEMS based widely tunable lasers provides gain over a continuous span of frequencies, which are diffracted in the shape of a fan due to their wavelength dependency, as it is derived in Equation 2.6. The incident angle is fixed at a small angle (near to 0°) to avoid the reflections from the glass-air interface to go back to the semiconductor diode.

By means of a reflector we can feed back a unique frequency to stabilize it in the laser system. When tilting the reflector with the MEMS electrostatic actuator, the frequency can be selected in a continuous range. Overmore, if the spatial angle span of the diffracted beam is fitted to the MEMS reflector dimensions, the wavelength tuning of the laser system can be matched to the whole gain spectrum of the gain material.

For the purpose of stabilizing the cavity with a transmission grating, a market research was developed to evaluate the available commercial options of this product. Different major providers were considered and a selection was made in order to test the performance of the gratings with our laser diode sources. A transmission grating is an optical element through which a beam is shined, allowing part of the light to pass through and diffracting a portion of the incoming beam in an angle which is proportional to the wavelength of the beam. These transmission gratings are mainly defined by the number of parallel lines per millimeter, which will define the portion of light which is diffracted and its output angle. Elements with 300, 600, 830 and 1200 lines/mm can be easily found commercially, but two drawbacks appear:

- The efficiency of the gratings at the wavelength of interest ($\lambda = 960$ nm) is not enough. In order to support this conclusion, we have published an article in the journal Applied Physics B (DOI 10.1007/s00340-017-6777-9).
- The size of these commercial gratings is too big to fit in our final package.

Due to these limitations, a design was made to fit our requirements, leading to a miniaturized kind of grating with the appropriate diffraction efficiency. Figure 2.16 shows a setup sketch of the transmission grating based laser source. The laser collimated beam is shined through the grating: one portion of the beam is used as output (T0) while another portion (T-1) is back reflected into the laser chip through the MEMS actuator to stabilize the cavity. The MEMS can be tilted and in this way select the appropriate angle to tune the laser source to the desired wavelength. The angular span of the diffracted wavelengths is selected so that they fit as best as possible the chosen MEMS reflector.

The size of the MEMS is limited because of two different factors. The force applied by ES MEMS is not high, so they are not able of displacing heavy elements. Furthermore, the resonance frequency of the MEMS is determined also by the size of the reflectors: the

Figure 2.16: Transmission grating setup sketch.

bigger they are, the lower the resonance frequency becomes. For this purpose, reflectors of 2 mm were chosen and an analysis of their resonance frequency, measured through the Relative Intensity Noise (RIN) of the tunable lasers, will be presented in the next chapter.

Figure 2.17 shows the designed transmission and reflection efficiency of the transmission grating. The transmission in the order -1 (T-1 as named in Figure 2.16) must be tuned to a value close to 50% to stabilize correctly the cavity, as it is discussed in the aforementioned article from Applied Physics B. The reflection efficiency is minimized to reduce undesired effects in the laser source.

A first setup was mounted to measure the suitability of the proposed solution. Figure 2.18 shows a photograph of the implemented experiment at Sacher Lasertechnik. In this case, a manual tuning mirror is employed to test the cavity with the transmission grating instead of the commonly used reflection grating.

This setup shows an excellent tuning performance. Figure 2.19 shows the recorded optical spectrum through the whole gain bandwidth offered by the gain chip, as there was no limitation induced by the mirror tilting or the grating. The optical spectrum was recorded after a 55 dB free space isolator with a constant current of 200 mA, reaching a maximum output power of 67.3 mW. The wavelength can be tuned from 750 nm up to 793 nm, which extends the tuning span of the current commercially available tunable lasers in an extremely compact and stable packaging.

Figure 2.17: Measured transmission and reflection diffraction efficiencies for the designed transmission grating.

Figure 2.18: Transmission grating experimental setup.

Figure 2.19: Tuning range of the transmission grating stabilized diode laser.

LASER SYSTEM DEVELOPMENT AND RESULTS

*“Even if I knew that tomorrow
the world would go to pieces,
I would still plant my apple tree.”*

- Martin Luther

3.1 Introduction

From the previous chapter, in which we have developed different demonstrators, we have concluded that we can discard DFB lasers due to their limited wavelength tuning range. The alternative is an external cavity diode laser system in a Littman configuration.

These systems rely on a screw that moves an arm containing a prism reflector and it can be actuated manually or by means of a motor. Considering that the motor will always be more precise and quicker than a manual action, a comparison was established between the motor actuated device and the MEMS based laser.

The motors employed within the ECDLs nowadays need to accelerate, move the screw at maximum speed and then decelerate the movement to avoid stressing the system. That even being the best possible case, because short wavelength tuning movements of the screw will require proportionally more time because the whole process will be occupied by accelerating and decelerating. These systems can tune over their whole bandwidth in the second, or even the tens of seconds, range. Narrower spans can be quickly tuned due to the addition of a piezoelectric actuator but they only contemplate ranges of GHz, for example, for spectroscopic purposes.

The MEMS based laser system inherits three very important properties from the MEMS element for the wavelength tuning: speed, repeatability and stability [40]. These are the key features that make the MEMS based laser system outstanding in compari-

son to other technologies. If we take a look at comparable systems, they either lack on available tuning bandwidth or they are slow mechanically based devices.

Using the demonstrators shown in the previous section, we selected the MEMS based laser system, for which in this chapter, the fabricated devices are presented and explained. The laser systems have been completely assembled and characterized at Sacher Lasertechnik. Referring to the building blocks in section 2.1, the gain chip generates the necessary optical gain when electrically pumped. The transmission grating filters the light spatially and deviates a calculated amount of light to the MEMS chip. By tilting the mirror in the silicon wafer, the wavelength is selected thanks to the angular distribution generated by the grating. The output beam consists of a portion of the light in the cavity, which is analyzed in this chapter in terms of power, wavelength and noise.

As the most important characteristics of the laser system are inherited from the MEMS, special analysis have also been carried out to take care of the switching speed between different wavelength set points, the repeatability and the wavelength stability of the system.

Three different systems at wavelengths of $\lambda_c = 780 \text{ nm}$, $\lambda_c = 920 \text{ nm}$ and $\lambda_c = 960 \text{ nm}$ were constructed at Sacher Lasertechnik. These three wavelength regimes were selected due to a Stimulated Raman Spectroscopy related project to analyze different gas species concentrations in a development where more partners were involved. The data presented in this chapter is the result of the measurements made at our company.

3.2 Optical characterization

3.2.1 Power Output

The first test that we have performed with the assembled laser system demonstrators is to measure the amount of output power they can deliver. As it was discussed in Chapter 2, if the amount of feedback is properly matched, higher output power levels can be reached. However, there is always a trade-off between power and tuning bandwidth. At the wavelength where the semiconductor material's gain is higher, less feedback is needed to compensate the losses of the resonator and lase in a stable way. Not the same conditions apply at the edges of the tuning range, where the available gain is lower and hence a higher feedback level is needed. Therefore, a compromise was set to make the laser stable in a broad range of wavelengths while not getting the optimal power levels.

The usual way to measure the power in a laser system is to sweep the biasing current of the laser power while recording the power output levels at each step in the Light Intensity (LI) curve. For the first device which was fabricated at $\lambda_c = 960 \text{ nm}$, the LI curves are depicted in Figure 3.1

The eight curves show the higher output power for the maximum gain region, which

Figure 3.1: Optical power vs. current curves for different set points of the fabricated 960 nm MEMS based tunable laser system.

is around the wavelength of $\lambda_c = 960 \text{ nm}$. When moving to the lower wavelength region, the available power decreases and therefore the output power of the system is lower. To illustrate this behavior, Figure 3.2 shows the emission spectrum measured without external feedback of a typical gain chip employed when building tunable lasers in the 960 nm wavelength region.

Figure 3.2: Emission spectrum of a $\lambda_c = 960 \text{ nm}$ gain chip measured without external feedback [41].

Various parameters can be extracted from these graphs. The maximum power achieved by the laser system is of 85 mW at 250 mA. Although the system could be pushed to higher bias currents, we did not want to stress the laser system due to the 1.5 mm length of the gain chip. Higher output powers can be obtained if a longer chip is used, being 2 mm a typical value of a chip length in this wavelength regime. The threshold current at approximately $I_{th} = 30 \text{ mA}$ is an indication of the good collimation of the laser beam and of the alignment of the system. Finally, the efficiency of the laser system can be also extracted from the data presented in Figure 3.1. A simplified equation of the laser output power is:

$$P = \eta(I - I_{th}) \quad (3.1)$$

where η is the efficiency of the laser system. Making a linear approximation of the $\lambda_c = 960 \text{ nm}$ curve, the efficiency is calculated to be $\eta \simeq 0.3863 \text{ mW}/_{\text{mA}}$. Typical values for optimized commercial devices are equivalent, so having such a performance is encouraging for our development.

3.2.2 Optical Spectrum

The second parameter that was measured for the MEMS based laser system demonstrator was its spectral characteristics in an HP 86142A Optical Spectrum Analyzer (OSA). This device has a maximum resolution of 0.06 nm and can sweep over the whole area of interest for our laser demonstrator, allowing us to measure the optical spectrum.

Measurements were made at different wavelength set points of the system, shown in Figure 3.3, where we can see a set of 5 optical spectrums from 935 nm to 978 nm. This means that the system can be tuned over a total span of more than 43 nm. Commercial systems currently available in the market can be found with tuning ranges of 50 nm at the same center wavelength (960 nm), a comparable range to the one achieved by us.

Figure 3.3: Optical spectrum of the $\lambda_c = 960 \text{ nm}$ MEMS-based widely tunable laser system at different wavelengths over its whole tuning range [4].

We want to highlight the extremely high Signal to Noise Ratio (SNR) of this optical spectrums, which is in every case over 80 dB.

3.2.3 Switching Speed

By using a MEMS actuator, the laser system inherits the ability of increasing its tuning speed dramatically. The movement, in this case, is only limited by the physics involving the MEMS actuator, determined by the resonance frequency of the actuator. A small element has been chosen, which is a silver coated round actuator with a diameter of 1.5 mm. Within MEMS actuators, it is usual to find two-dimensional MEMS, with a quasi-static axis and a resonant axis. A detailed analysis of the actuators is made through the noise characteristics of the laser system in Section 3.2.6. Figure 3.4 shows the measured speed of a MEMS based laser system for a span of $\Delta\lambda > 10\text{ nm}$

Figure 3.4: Ultra fast set point change.

The wavelength tuning was achieved by changing the driving voltage of the MEMS actuator from 50 V to 80 V, which meant a tuning of $\Delta\lambda \approx 12\text{ nm}$. A linear relationship cannot be established between the voltage and wavelength change due to the inherent MEMS nonlinearity exposed in equation 2.1, which states that the force on the actuator is proportional to the squared value of the voltage. The switching speed was measured to be of *11 milliseconds* for this transition. For this purpose, a wavelength meter WS6-200 VIS from High Finesse was used.

3.2.4 Repeatability

In addition to the speed, the repeatability is one of the inherited characteristics that the system receives from using a MEMS actuator as part of its construction. To test this feature, the laser system at $\lambda_c = 960\text{ nm}$ was driven consecutively at three different

wavelengths: 957 nm, 961 nm and 978 nm.

Figure 3.5: Tuning of three different wavelengths, showing the repeatability of the system for different set points.

Figure 3.5 shows the system being cyclically tuned over the three predefined set points. The maximum deviation noticed within the set of values is 0.41 pm. To calculate the frequency deviation according to this wavelength increase, we derive the following formula:

$$f = \frac{c}{\lambda} \quad (3.2)$$

$$\Delta f = \frac{-c\Delta\lambda}{\lambda^2} \quad (3.3)$$

or, equivalently for the frequency increase:

$$\Delta\lambda = \frac{-c\Delta f}{f^2} \quad (3.4)$$

According to equation 3.3, the maximum deviation measured is of $\lambda = 0.41 \text{ pm}$, which corresponds to a frequency $f = 133.46 \text{ MHz}$.

3.2.5 Wavelength Stability

As it was discussed in Section 3.2.3, MEMS are known for their stability. Therefore, and speaking about a laser system, it is really important to measure the ability of the system of staying in the same wavelength without major drifts. Data was collected over a 30 minute span with the laser running with temperature stabilization. The results of these measurements are shown in Figure 3.6, in which a drift of 0.9 pm is observed from the beginning of the measurement until the end, being this drift constant and directed to shorter wavelengths. According to the calculations made in Equation 3.3 of Section 3.2.4, the frequency drift is of 287.06 MHz .

Figure 3.6: Wavelength measured in a MEMS based laser system over a 30 minute span. The maximum deviation measured is of 0.9 pm .

This trend is to be considered as part of a thermal process because of its slow speed. Although the laser chip is temperature controlled, the rest of the cavity is slightly dependent on the room temperature.

3.2.6 Relative Intensity Noise

Different options were to be evaluated regarding the MEMS in order to select the best possible option for the MEMS-based laser system. The work in this case is to characterize two different options in terms of the amount of noise which is generated from the MEMS actuator and directly translated into noise in the laser system. After a first evaluation run, where devices from different companies were evaluated, the Fraunhofer Institute from Dresden (Institut für Photonische Mikrosysteme, IPMS) was selected as the MEMS provider. An Scanning Electron Microscopy (SEM) image from their devices was already presented in Figure 2.8. One dimensional and two dimensional devices were evaluated to select the best fit for the system.

Figure 3.7: Scanning Electron Microscopy (SEM) image of an electrostatic comb with interdigitated fingers [42].

In order to characterize the MEMS actuator and the noise which these introduce, we measured the relative intensity noise. An external cavity laser was constructed at a center wavelength of 780 nm.

For this measurement, a complete MEMS-based laser is built to make the Relative Intensity Noise evaluation, as the noise effects are directly translated into the laser cavity. The gain chip employed is one of the simulated and fabricated devices of 750 μm , mounted on a copper chassis. This chassis holds also the MEMS PCB and the transmission grating and is temperature stabilized at 22°C, near room temperature. The operation conditions are kept constant for the 2D and 1D MEMS that have been measured with this

setup, meaning a constant injection current of 100 mA in the laser chip with the Sacher Pilot PZ500 laser diode controller.

The laser is beamed into a silicon photodiode from Thorlabs (DET02AFC). The voltage at the output of the photodiode is recorded with an Agilent L4532A during 10 seconds at a sample rate of 1 MSa/sec.

3.2.6.1 Two-dimensional MEMS

The setup was mounted with the Fraunhofer IPMS 2D MEMS actuators. These are composed of a quasi-static and a resonant axis, which means that one of them will be able to statically stay in a fixed place while the other is designed to oscillate at a resonant frequency. One of the key features offered by the 2D MEMS from Fraunhofer IPMS is their ability to measure their position with a closed loop control, although this operation mode adds noise to the mounted laser because of the control loop.

In our case, only the quasi static axis was used and the resonant one was left unemployed, as the use we intend for the laser and the actual measurement does not contemplate a continuous scanning movement. The quasi-static axis was used to tune the laser over its wavelength tuning range. Applications of the MEMS based tunable laser system may contemplate the use of a resonant axis to scan the laser, although this scan can be also made with the quasi static axis.

A list of measurements is presented on the $\lambda_c = 780\text{ nm}$ laser system with different modes of operation (closed loop or open loop), different driving electronics and even different biasing sources. Two figures are shown for each measurement: one with a 10 kHz span and the second one up to 1 kHz, where the noise and resonance effects can be studied better.

IPMS evaluation kit for quasi-static MEMS scanners

The QSDrive Scan kit enables the evaluation of driving the MEMS scanners fabricated at the Fraunhofer IPMS in an initial step without having to develop the driving electronics. The kit is composed of a MEMS scanner chip mounted on a ceramic dual in-line DIL-20 package that is connected to a printed circuit board. The PCB is named as scanning head and it has a compact design based on two stacked boards as seen in Figure 3.8.

Figure 3.8: Scan head corresponding to the Fraunhofer IPMS evaluation kit for QS MEMS scanners [43].

The MEMS are driven by the control electronics board received from Fraunhofer IPMS. This driver board provides controlled operation of both axis as well as a series

of extra functions like open and closed loop control and trajectories for the scanner. The power supply for the control board used was the one also provided by IPMS, a commercial off the shelf power supply. The MEMS control board was connected to the QS Scan Head and to a computer by USB interface, from which the Queechy software graphic user interface (also provided by IPMS) was used to set the angle of the MEMS mirror actuator. The angle of the MEMS was set to 2.9 degrees, selecting a cavity mode at $\lambda = 770 \text{ nm}$, near the maximum gain provided by the semiconductor chip.

Figure 3.9: RIN measured with the IPMS evaluation kit for 2D QS MEMS scanners.

Narrow peaks appear at multiples of 100 Hz due to the power supply, from 100 Hz up to 3 kHz. The broader peaks are generated by the MEMS resonance. The estimated resonance frequency of the devices is 190 Hz and this can be corroborated by the peak at 190.5 Hz. More peaks appear at 90.9, 290.5, 390.5, 590.5 and 725.6 Hz.

Power supply change

In order to solve the most obvious problem of the 100 Hz noise peaks, the power supply was substituted for a battery and the measurement was repeated with the rest of the conditions unaltered.

The peaks from the power supply have completely disappeared due to the cleanliness of the battery supply, being the rest of the peaks also attenuated. The resonance point is not altered at all. Still two more broad peaks are present at 390.5 and 590.5 Hz. A small set of peaks can be still identified at multiples of 100 Hz up to 3 kHz and between 6 and 7 kHz.

Two more tests were done by setting different operation modes within the Queechy GUI:

- Constant voltage trajectory
- Constant angle trajectory

Figure 3.10: RIN measured with the IPMS evaluation kit for 2D QS MEMS scanners and a battery as power supply.

Results are comparable by all means to the ones from the second test. This concludes that the trajectory and angle set by Queechy software are comparable in terms of RIN.

Closed loop mode

An important change is introduced in this step, setting the constant angle trajectory in close loop mode. The software provided by IPMS makes a regulation to keep the position of the mirror regulated by using a resistive sensor included in the two-dimensional MEMS actuator. Figures 3.11(a) and 3.11(b) show these measurements:

Figure 3.11: RIN measured with the closed loop regulation for the 2D MEMS actuator.

It is clear from the evaluation of the spectral measurements that the noise level has increased in 5 dB. Furthermore, the peaks have been broadened and two new have appeared at 6.5 kHz and 8 kHz, which we assume come from the control loop of the MEMS actuator. For the moment, the closed loop control only adds noise to the system, so it is

not affordable for a laser system control.

Low noise driver

The control electronics from IPMS are substituted by a direct biasing of the MEMS quasi-static axis. A breadboard is used in this test to directly connect the QS Scan Head with an external biasing voltage, meaning that the breadboard is a passive element that allows to plug a BNC connector to each of the channels of the MEMS mirror actuator: Resonant axis channel and Channel 1 and Channel 2 for the quasi-static axis. The voltage is supplied by the low noise electronics from Sacher Lasertechnik, the MEMS Voltage Amplifier, ranging from -20 V to 120 V. This amplifier was specially redesigned for this project in order to reduce the noise in the laser system.

The Voltage Amplifier was specially designed for biasing the MEMS actuator, as it needs a voltage between -100V and 100V for each channel in order to move the actuator in its whole range. The Voltage Amplifier is fed with the voltage signal generated by the Sacher Lasertechnik Pilot PZ500, which can only generate from -12V to 12V and therefore needs an amplification to cover the whole voltage span needed. The polarity of the voltage potential applied to the MEMS does not matter, as the electrostatic force in the comb from the MEMS is proportional to the squared voltage as seen in Equation 2.1.

Figure 3.12: RIN measured with the 2D MEMS actuator biased by the low noise voltage amplifier developed for the project.

Although some minor peaks appear in the measurements of Figures 3.12(a) and 3.12(b), specially at lower frequencies, the resonant peak is reduced due to the low noise of the Sacher amplifier. This is corroborated throughout the next tests, which were made by impedance matching of the terminations corresponding to the non-used channels. No difference was appreciated by this match or even when short circuiting the terminals.

The most important noise reduction is seen in the resonant frequency, decreasing from -80 dBc/Hz to -95 dBc/Hz and meaning a 15 dB difference. It is also important to note that one of the peaks does no longer appear, the one located at 390.5 Hz. This change

was induced when removing the control electronics from Fraunhofer IPMS and biasing the MEMS actuator directly with the low noise voltage supply from Sacher Lasertechnik.

Conclusions for 2D MEMS measurements

The measurements done with 2D MEMS have helped us to understand the behavior of the MEMS actuator with a new characterization method. Thanks to the external cavity of the laser, the mechanical resonances of the MEMS can be studied through the relative intensity noise.

The first attempt showed a poor performance of the power supply, which was easily identified by substituting the provided power supply with a battery supply. Different peaks were deleted with the new spectrally clean battery. The closed loop mode operation of the MEMS actuator generates a big amount of noise, which is spread over the whole spectrum that was measured.

Different noise peaks can be clearly identified throughout all the measurements at 190.5 Hz and 590.5 Hz. When the control board from IPMS is used, another peak at 390.5 Hz also appears in the spectral measurements. By substituting the Fraunhofer driving electronics for the Sacher voltage source, this last peak is deleted and the noise of the MEMS actuator is greatly improved. The noise peaks are decreased up to 15 dB.

3.2.6.2 One-dimensional MEMS

The setup was also mounted with the Fraunhofer IPMS 1D MEMS actuators. These are composed of a quasi-static axis that was used to tune the laser.

This laser allowed us to compare the resonant frequency of the new MEMS actuator against the 2D MEMS. Being the mass 1D MEMS lower, a higher resonant frequency was expected. Different measurements were made, all with the Sacher driving electronics to conclude that the 2D MEMS noise was also lower compared with the Fraunhofer electronics.

Two figures are shown for each measurement: one with a 10 kHz span and the second one up to 2 kHz, where the noise and resonance effects can be studied better. The smaller span has been increased for these measurements as the resonant frequency was exceeding 1 kHz.

Low noise driver

The 1D MEMS were biased with the Sacher voltage amplifier. No terminations were added to the board in this case.

Figure 3.13: RIN measured with the 1D MEMS actuator biased by the low noise voltage amplifier developed for the project.

A resonant frequency of 1.283 kHz can be identified, which corresponds to the expected value for these MEMS. The height of this peak is -90 dBc/Hz, and the total spectral noise goes down to -110 dBc/Hz at 10 kHz, matching the measurements made with the 2D MEMS. Only one peak is present with no harmonics in the measured spectrum.

Impedance matching

A 50 ohm termination was added to channel 2 to match the BNC (Bayonet Neill–Concelman) connector's impedance.

Figure 3.14: RIN measured with the 1D MEMS actuator's unoccupied channels being impedance matched.

The result shown in Figures 3.14(a) and 3.14(b) has not varied with respect to the previous, showing the same behavior as the 2D MEMS. It can be concluded that the 50 ohm termination does not improve the noise spectral behavior of the MEMS laser.

Acoustic disturbances

In order to evaluate the impact of external noise on the laser cavity, the test was run with disturbances in the room during 10 seconds.

Figure 3.15: RIN measured with the 1D MEMS based laser system being acoustically disturbed continuously for 10 seconds.

Small noise figures can be identified around 550 Hz and 800 Hz of Figures 3.15(a) and 3.15(b), corresponding to frequencies in the range of the human voice. The resonant peak

remains unaltered at an approximate value of -90 dBc/Hz .

Conclusions for 1D MEMS measurements

The measurements made for the 2D MEMS were replicated for the 1D MEMS actuator. As well as in the first system, the battery is used to improve the noise in the system and the low noise voltage amplifier makes a big difference when biasing the MEMS actuator.

The external laser cavity shows low noise as it was also measured with the 2D MEMS. As it was expected due to the lower mass of the 1D MEMS in comparison with the 2D version, the resonance frequency is shifted to a higher frequency that was identified to be at 1.283 kHz.

3.3 MEMS-based external cavity evolution

One of the most important aspects in the development of this thesis has been the development of an appropriate cavity for the MEMS based widely tunable laser system. Laboratory setups are usually an effective way of making a proof of concept and even of taking further steps in the development of a new solution. However, it is at one point necessary to think about the development in the way of packaging the device in such a way that it will enable key aspects as portability or stability.

STEP 1

A first approach was mounted on one of the optical tables in the laboratory and was shown in the previous chapter, Figure 2.18. A next step was then made towards the integration of the device into a standalone product. Figure 3.16 depicts the CAD model of this first test. A standard aluminum plate was used to screw discretely the components of the laser system, although a different approach had to be figured out to integrate the MEMS laser system in a more stable way.

Figure 3.16: CAD model of the first approach to build the MEMS laser system based on discrete components.

STEP 2

When referring to laser systems, the best way of achieving mechanical stability is to include all the necessary components on a monolithic assembly. Therefore, the first model developed with a monolithic cavity appears in Figure 3.17.

Figure 3.17: First CAD model of the monolithic cavity, used to provide stability to the laser system.

The model in the previous figure was specifically designed to implement the evaluation kit of the Fraunhofer IPMS MEMS actuator. As it was explained in Section 3.2.6.1, the evaluation kit is composed of two interconnected PCBs containing a holder for the DIL20 package in which the MEMS themselves are located. The lower board, which acts as the controller, holds the upper PCB by means of two posts made of brass. Additionally, the controller PCB presents four holes for it to be attached by screwing it. The monolithic cavity block on Figure 3.17 was specifically designed to make a one-piece laser system.

The laser chip is mounted on an aluminum nitride ceramic submount. A copper microbench serves as a support for this submount and four more electrical contact pads that are glued with epoxy to the copper and serve as a bridge between the wire bondings from the AlN submount and the external cables for the laser. The thermalization of the laser system was made thanks to a peltier cell located below the whole cavity block and a small hole was drilled on the side of the copper to introduce an NTC sensor and regulate the whole cavity's temperature.

Several tests were made with the second version of the monolithic cavity model for the MEMS based laser system. However, we had to address some issues with the laser, mainly concerning the stability of the system. A huge step was made when advancing to a monolithic kind of cavity, but the board in which the MEMS were placed had mechanical tolerances due to various factors like the in-line mount for the DIL20 package or the connection between the PCBs from the evaluation kit. When making an analysis of the elements strictly needed to correctly drive the MEMS actuator, it was determined that the DIL package was enough to operate the system. The boards served as a physical support and added functions through the software provided by IPMS, but these were not

necessary to implement the MEMS based laser system.

STEP 3

The whole evaluation kit was removed and the MEMS actuator was the only element kept for the construction of the cavity.

Figure 3.18: Second CAD version of the monolithic cavity designed for the MEMS based laser system, including the Fraunhofer IPMS evaluation kit for the MEMS.

At this point, the size of the cavity was reduced. Without the need of holding the evaluation PCBs, we were able to reduce the height of the copper cavity's main block. A small sized copper-tungsten frame, screwed to the main block, serves as a support for the glued DIL package containing the MEMS actuator. The electrical connection to the actuator is directly made through the pins of the packaged element. Figure 3.19 shows the design including the aforementioned changes. The thermalization was still applied to the complete cavity and the reduction of the mass to be controlled improved the stabilization and regulation times of the laser system.

Transmission gratings were specifically designed for the project at a wavelength of $\lambda_c = 960 \text{ nm}$. The results with these gratings are optimal at this wavelength range. Other spectral areas need different gratings, as the spatial response directly depends on the wavelength. In addition, not every semiconductor chip will behave in the same way in terms of the feedback they need to stabilize single mode operation. Reflection gratings are more commonly found in ECDL systems in the visible (VIS) and near infrared (NIR) areas due to their polarization dependency.

The reflectivity of reflection gratings highly depends on the polarization of the incident light. Its maximum efficiency is always given for a linear polarization orthogonal to

the lines that define the grating. The light that is generated by the semiconductor chips is linear, and its polarization may be turned by using a retarding waveplate. In this way, the diffraction efficiency can be tuned to its optimal value. For this purpose, a model was developed replacing the transmission grating for a reflection grating and adding a $\lambda/2$ waveplate. The model in Figure 3.19 allows the extension in a practical manner to any wavelength by using components-off-the-shelf (COTS) diffraction gratings and avoiding the need of redesigning them for every new semiconductor chip employed.

Figure 3.19: Reflection grating CAD model of the MEMS based laser system including a $\lambda/2$ retarding waveplate to fine tune the diffraction efficiency.

STEP 4

The next development step is made with the transmission gratings. As shown in Figure 3.20, a smaller transmission grating was cut for the system. Although this step does not provide a significant improvement regarding the actual development phase, the final objective is to miniaturize the system and therefore every element needs to be reduced in size.

The cavity also suffered a major change. All of the monolithic cavities developed up to the moment in this document have the peltier cooler below the cavity's main block to thermalize a bigger mass and make the device more robust against external temperature variations. The main drawback of placing the peltier below the cavity is the big distance between this element and the temperature sensor. A slow regulation and a long startup

time are needed to operate the laser system as it is, so a major change was introduced in the next steps: the peltier cell was located directly under the copper microbench to reduce the distance to the NTC sensor and to reduce the mass that needs to be stabilized. This change had a positive impact in the performance of the laser as it was expected. In order to make the change effective, the NTC sensor was placed directly by the semiconductor chip, glued on the AlN submount and connected through wire bonds to external pads in the same way as with the laser chip was made. By lifting the position of the peltier, the main cavity block only needs to dissipate the heat generated at the chip. In comparison with the previous cavity models, the main block of this evolution can be made out of aluminum instead of copper, reducing significantly the cost and work needed for the production of this part.

One of the main topics to be improved is the continuity in tuning while turning the MEMS actuator. The laser presents slight hops while tuning the wavelength due to a mismatch between the frequency and the cavity length of the laser system. To address this issue, the MEMS actuator is glued to a stacked ring piezoelectric actuator to make a fine tuning of the length of the cavity. The piezoelectric element allows a movement of $5.5 \mu\text{m}$ with which the cavity can be tuned up to 8.2 MHz to compensate the mismatch of the cavity length.

Figure 3.20: First CAD model of the monolithic cavity, used to provide stability to the laser system.

STEP 5

The last step implemented during the development of the thesis was the simplifica-

tion of the cavity design to make fabrication easier. Figure 3.21 shows a cavity block with only straight angles. A bigger tilt angle allows the adjustment of the MEMS DIL package in a straight angle with respect to the laser chip. In this way, the cavity block's production is optimized without an impact in the laser's performance.

Figure 3.21: First CAD model of the monolithic cavity, used to provide stability to the laser system.

Further developments of the cavity are planned to continue its integration into a miniature package such as a butterfly package. A CAD model was also developed for this objective, as it will be the main goal in the project's future and it was included into an article published in Applied Physics B while developing the thesis. MEMS actuators can be acquired as shown in Figure 3.22 to manage the micro integration that is set as an objective.

Figure 3.22: CAD model of the developed micro MEMS based laser system in a butterfly package.

CONCLUSIONS AND FUTURE LINES

*“If you make listening and observation your occupation,
you will gain much more than you can by talk.”*

- Baden Powell

The project of the thesis was successfully developed throughout its stages. Although the concept presented is broad, the tunable laser here presented serves as the introduction of a key feature enabling technology which has numerous benefits. The MEMS based broadly tunable laser system was analyzed, designed and fabricated with good results and even its early introduction into the laser market.

Its compact design allows the portability of the system. Furthermore, plans have already been established for its miniaturization into a butterfly-like package that out-stands through its competitors. Although the size is small, power is not compromised due to the optimal design of every component and avoiding structures with high losses. In this case, it is logical to compare the designed system with DFB lasers, which are surpassed by our design in terms of wavelength tunability range and speed.

The MEMS based broadly tunable laser system has been presented as a concept and one of the most important reasons is that it can be applied to any wavelength of interest. Indeed, I have validated my design for different wavelength regimes and devices were fabricated at 780 nm, 920 nm and 960 nm.

The amount of feedback can be carefully controlled by adapting the elements of the laser system, meaning that conditions for broadband tuning can be met. Taking the presented results as an example, a tuning range of over 40 nm has been achieved at $\lambda_c = 960\text{nm}$. This range was only limited by the available gain bandwidth of the semiconductor chip and it can be extrapolated to any other wavelength regime.

Low relative intensity noise has been measured for the MEMS laser. The results presented in this thesis show values of $\text{RIN} < -110 \text{ dBc/Hz}$ and a low impact of the MEMS resonance frequency. A specially small actuator was selected to reduce its size and therefore increase the resonance frequency, improving the tuning speed of the devices. This tuning speed was measured to be of 11 msec while tuning a span higher than 10 nm, and

hence much quicker than the actual commercially available mechanical based tunable systems.

- Compact design
 - Allows portability
 - Future work – miniaturization into butterfly package
 - High output power
 - Proven to increase signal to noise ratio compared to other laser systems of extended use such as DFB lasers
 - Wavelength selection
 - Application in any wavelength of interest
 - Tests made at 780nm, 920nm and 960nm
 - Broad tuning range
 - Over 40 nm tuning @ $\lambda_c = 960nm$
 - Low noise
 - RIN < -110 dBc/Hz
 - Low impact of MEMS resonance frequency
 - Ultra high tuning speed
-

PROJECT MANAGEMENT AND BUDGET

*“Begin at the beginning
and go on until you come to the end; then stop.”*

- Lewis Carroll

The first stage of this project in the study of the state of the art of tunable lasers and the understanding of each of the necessary elements to build them. After analyzing these elements, we studied the different options we could contribute to the technology and we proposed a working plan. Having developed this thesis in a company makes planning a very important step, as the time and costs invested in the development become critical due to their effect in the competitiveness of the product in the market.

Simulations were run thanks to the collaboration with Universidad Carlos III de Madrid, where a thorough optimization was made for the semiconductor structure to be later used. Results were discussed with the foundry and implemented for the fabrication of the gain material chips used in part of the laser systems. A work methodology was implemented for the simulation and it can be applied for further optimization of semiconductor gain chips.

We also needed to model the laser rate equations to identify the needs in terms of feedback of the system to stabilize the laser cavity while tuning. At this point, all the parameters were defined and the gratings were fabricated to fit the designed specifications.

The next stage of the project was to design the external cavity of the laser. Demonstrators were made to address and compare different tuning schemes, selecting the transmission grating and tilting MEMS as the preferred option following the characterization of each system.

Our aim was to design a product to introduce into the market, and one of the key-stones of this development was to establish an appropriate assembly and packaging for this purpose. Modeling was made with CAD (Computer Assisted Design) software and fabricated to assemble the tunable lasers. Several iterations were done to improve the devices in an analysis, design and characterization cycle. The MEMS-based tunable laser system was introduced in the market successfully after a business plan was established.

All these stages are shown in the temporal line of the Gantt diagram developed in the next page. The project can be subdivided in five main tasks:

- **Concept development.** The basic idea was proposed. A fast and broadly tunable laser is needed for real time analysis of substances. MEMS are brought as a way of increasing the current available lasers in the market.
 - **State of the art study.** Although this kind of lasers has been been investigated, even commercially, it was always based on a very specific substrate (i.e. InP for third window communications) and were not successfully implemented into a commercially available product.
 - **Analysis.** To properly address the need of this kind of systems, a market study was carried out. DFB systems are easy to use and widely spread, but their tunability is limited and their linewidth is not optimal, being one or even two orders of magnitude spectrally broader than ECDLs. Currently available ECDLs comply with almost all of the required characteristics but they lack a tremendous amount of speed. Two ways of approaching the topic were proposed: an ECDL based on a VHG as a filtering and reflecting element, and a MEMS based ECDL with a diffraction grating used as a filter and a MEMS actuator as a reflector and tuning element. After comparing both options, it was clear the MEMS based laser was the path to follow.
- **Simulations** Thanks to the collaboration with Universidad Carlos III de Leganés and their expertise with chip level simulation software, we optimized the geometrical structure of the optical waveguide within the gain chip of the ECDL, boosting the performance of the fabricated devices.
 - **GaAs chips simulation.** The main objective of the project was to obtain the best performance from the gallium arsenide chips which were to be fabricated for the project. The results were successfully achieved and different parameters as optical mode confinement and propagation losses were investigated.
 - * *Waveguide Structure Design*
 - * *Propagation Simulation*
 - **Laser equations.** In order to design the ECDL, a key point is to design the optical feedback level to stabilize the cavity into a single longitudinal lasing mode. By means of a mathematical approach to the laser rate equations, the optimal feedback level was found in order to fabricate the best matching diffraction gratings.
- **System design.** Once all the system elements were defined, the system was to be designed. The most important aspect of the laser system was to create a monolithic cavity. This isolates the laser system from different external perturbations while enabling a compact sized device.
 - **CAD modeling.** The most efficient way of designing the cavity block is to model it with the aid of CAD software. The program *SolidWorks* was used for this purpose. Consecutive iterations of the CAD modeling, some of which

are developed in Section 3.3, were alternated after fabricating the pieces and testing them in a continuous improvement process.

- **Cavity fabrication.** As it is stated in the *CAD modeling* point, the cavity fabrication goes hand by hand with the modeling process. The whole process was eased by the fact of having the mechanic workshop within the *Sacher Lasertechnik* facilities. The materials employed were thoroughly discussed to give the adequate stiffness and heat dissipation to the system.
 - Breadboarding. Before creating a closed package which will be commercially distributed as a product, a lab setup or *breadboard* has to be developed. Assembling, aligning and testing the iterations of the designed cavity is contemplated within this point.
 - **Assembly.** Laboratory work was made at this point, assembling the different elements within a controlled lab environment. At this point, the main part of the work is to align and find the weak spots of the design in order to improve the system.
 - **Characterization.** After each iteration, it is necessary to characterize the assembled devices to evaluate the performance of the freshly introduced changes. By means of this improvement process, at one point the jump to a product can be made. This phase is actually the most important in terms of scientific progress, as many details need to be adjusted from a theoretical to a real life environment.
 - Prototyping. Once the breadboarding phase has reached a stable operation in the device, it is time to take a step further and implement a prototype. The monolithic cavity in its last version was
 - **Prototype design.** In this case, the project was designed to integrate the whole product into a standard 3 unit tall 19 inch rack mount. A final design was achieved with the diode laser controller, laser cavity block and high voltage MEMS controller. The whole laser system could be manually controlled through a panel in the front of the rack mount or remotely from a computer.
 - **Assembly.** At this stage, the assembly process is critical, as every element must fit in a standard housing for easier introduction of the development as a product. A special care and planning allowed to succeed in the 19 inch rack integration.
 - **Final measurements.** Thorough tests were run with the laser system: optical power, wavelength tuning, switching speed, stability and noise intensity.
 - **Business plan.** The development made for this thesis was carried out within a European project that aimed for a Raman scattering analysis instrument. Due to the success in the results presented, already two devices were acquired for these instruments and a business plan was developed for the implementation of more units in different scenarios.
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UNIVERSIDAD CARLOS III DE MADRID
Escuela Politécnica Superior

PRESUPUESTO DE PROYECTO

1.- Author:

Álvaro Jiménez Galindo

2.- Department

Sacher Lasertechnik GmbH in collaboration with Electronics Technology department in UC3M

3.- Project Description:

- Title MEMS BASED WIDELY TUNABLE LASER SYSTEM
- Duration (months) 36
- Indirect costs surcharge: 20%

4.- Project Budget (values in Euro):

237.950,68 Euros

5.- Budget Details (direct costs)

PERSONNEL

Surname(s), Name	ID	Category	Dedication (person · month) ^{a)}	Monthly cost	Cost (Euro)	Compliance signature
Carpintero del Barrio, Guillermo		Senior Engineer	3	4.289,54	12.868,62	
Sacher, Joachim		Senior Engineer	6	4.289,54	25.737,24	
Jiménez Galindo, Álvaro		Engineer	36	2.694,39	96.998,04	
					0,00	
Person · month 45				Total	135.603,90	

^{a)} 1 Person month = 131,25 hours. Maximum annual dedication of 12 person month (1575 hours)
Annual maximum for PDI from Universidad Carlos III de Madrid of 8,8 person month (1.155 hours)

EQUIPMENT

Description	Cost (Euro)	% Project related dedication	Dedication (months)	Depreciation period (months)	Imputed cost ^{d)}
Optical Power Meter	2.000,00	10	24	60	80,00
Sacher Current Source	5.000,00	100	24	60	2.000,00
Optical Spectrum Analyzer	24.000,00	20	12	60	960,00
EXFO Wavelength Meter	18.000,00	25	12	60	900,00
Thorlabs Fast Photodiode	800,00	50	6	60	40,00
Agilent Digitizer	15.000,00	50	3	60	375,00
Simulation software	28.000,00	100	1	12	2.333,33
				Total	6.688,33

^{d)} Amortization calculation:

$$\frac{A}{B} \times C \times D$$

A = Amount of months from the acquisition of the equipment in which it is used
B = Depreciation period (60 months)
C = Equipment cost (w/o VAT)
D = % of project related usage

TASK OUTSOURCING

Description	Company	Imputed cost
Wafer processing	M2K	30.000,00
Grating fabrication	Gitterwerk	10.000,00
Mechanical work	Gerber Feinmechanik	10.000,00
	Total	50.000,00

OTHER DIRECT PROJECT COSTS ^{e)}

Description	Company	Imputed cost
Optical components		5.000,00
Lab equipment		1.000,00
	Total	6.000,00

^{d)} This expense chapter includes all the expenses which cannot be applied to the previous concepts, i.e. consumables, travel and subsistence allowances

6.- Costs summary

Total Cost Budget	Total Cost Budget
Personnel	135.604
Amortization	6.688
Task outsourcing	50.000
Operation costs	6.000
Indirect costs	39.658
Total	237.951

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