Phase and mode control of structured semiconductor lasers

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Abstract

Nowadays, the number of applications based on semiconductor lasers is increasing. This trend started in the field of long range telecommunications, where optical fibers are replacing coaxial cables, to increase the operation bandwidth and reduce the attenuation. At a smaller scale, on-chip and inter-chip data transfer suffer from bottlenecks and would benefit from the same advantages, if the conventional microstrip lines would be replaced by laser-coupled optical interconnects. The transition to all-optical interconnects would especially augment the performance of silicon complementary metal-oxide-semiconductor technology enabling potential switching speeds on the order of 100s of GHz. This transition requires a compact light source compatible with silicon technology. Silicon itself features an indirect electronic bandgap, there is
no record of a silicon based laser operating on an interband nor on an intersubband transition. Germanium possesses a local conduction band minimum at the $\Gamma$ point. It can be epitaxially grown on silicon and is thus a good candidate for integration, but also features an indirect bandgap. Recently, uniaxially strained germanium exhibited a strong luminescence, in agreement with a $k\cdot p$ model which predicts a transition to direct bandgap around 5% strain. In this work we study the design of optical cavities capable of sustaining the strain imposed by direct bandgap germanium. We propose a method to estimate the stress, the gain and the losses of the candidate cavities which combining the results of optical and mechanical simulations with the results of a $k\cdot p$ model. A Fabry-Perot cavity with corner-cube reflectors and a wide distributed feedback cavity stand out as potential candidates. A recent implementation of a corner-cube cavity exhibited an enhanced luminescence. The results of this measurement are presented.

In the field of absorption spectroscopy, mid-infrared single mode quantum cascade lasers are able to resolve the fundamental roto-vibrational resonances of many gas molecules. They enable a detection at the ppb concentration level. Distributed feedback quantum cascade lasers, with their kHz intrinsic linewidths and 300 GHz tuning ranges, are able to resolve gas linewidth of hundreds of MHz, but unfortunately their facet phase dependant mode selectivity causes an indeterministic lasing frequency at fabrication. External cavity QCLs have linewidths around 30 MHz and up to 12 THz of tuning range. They are good candidates for multigas spectroscopy, but suffer from mechanical hysteresis that limit their accuracy to 200 MHz and require careful handling. This limits the feasibility of on-field or hand held applications. In this work we studied a distributed Bragg reflector cavity design with surface emission, featuring a deterministic frequency selection. An array of 10 devices around 9 $\mu$m wavelength was developed to cover a bandwidth of 3 THz. These devices offer the potential for continuous tuning over the whole gain bandwidth in continuous wave operation with a sequential firing of the lasers.
1. Abstract

In the field of astronomy, spectroscopic images of high-energy gas clouds contain important information on their chemical composition. The coincident measurement of a carbon (CII) and an oxygen (OI) cooling line at 1.9 and 4.7 THz respectively are the signature of the ionization of a CO or a CO$_2$ molecule by a high energy ray. Heterodyne detection techniques are employed to measure the spectrum of a source. The collected terahertz light is mixed with a local oscillator on a hot electron bolometer. The heterodyne detection scheme requires a local oscillator with a gaussian output beam within a 5 GHz range of the emission lines. As an example, the instrument GREAT recently took an image of the sky using a heterodyne detection scheme. THz quantum cascade lasers are good local oscillator candidates because of their high power and ability to operate in continuous wave. Quantum cascade lasers with double metal waveguides show the best temperature performance but have the drawback of being multimode and having a structured far-field. In this work we developed antenna coupled THz quantum cascade lasers in order to produce multi-mode far-fields with 95% gaussicity at 1.9 THz. Additionally using an impedance-matched antenna we achieved to reduce the facet reflectivity to 3%, a result that paves the way to external cavity THz quantum cascade lasers using a double metal cavities at 4.7 THz. At 3 THz we investigated a photonic crystal cavity structure producing narrow far-fields, single mode emission in continuous wave operation, that could be a good candidate for a upscaling at 4.7 THz.

In the field of THz spectroscopy, frequency combs are the emerging technology for high-resolution dual-comb spectroscopy. It was recently shown that THz quantum cascade lasers can operate as frequency combs, with a bandwidth of 25%, and operation over the bandwidth of an octave has been recently shown by our group. Unfortunately, the dispersion introduced by the gain hinders the octave spanning comb operation. The integration of a double chirp mirror at the end of the laser ridge is of high interest to compensate the dispersion of the gain and extend the comb operation bandwidth to the full octave, enabling 1f-2f
stabilization techniques. In this work, we measured the non-trivial dispersion of an ultra-broadband THz quantum cascade laser and designed compensating dispersive mirrors. The non-trivial dispersion can’t be compensated by existing designs of dispersive mirrors, thus we employed a genetic optimization algorithm to find a design able to compensate the desired dispersion. Preliminary results are presented and exhibit an over-compensated dispersion, but show the potential of the mirror design and the genetic optimization algorithm.
De nos jours, le nombre d’applications basées sur des lasers à semi-conducteurs est en constante progression. Cette tendance a commencé dans le domaine des télécommunications à longues distances, où les fibres optiques commencent à remplacer les câbles coaxiaux, parce qu’elles bénéficient d’une plus grande bande passante et d’une plus faible atténuation. À plus petite échelle, le transfert de données dans et entre les puces électroniques pourraient exploiter les mêmes avantages si les lignes microruban conventionnelles étaient remplacées par des guides d’ondes optiques. La transition vers les transferts de données tout-optiques pourraient notamment améliorer les performances des technologies CMOS sur silicium, ouvrant le potentiel à des vitesses de communications de l’ordre de la centaine de gigahertz. Cette transition
impose l’existence d’une source lumineuse compatible avec la technologie silicium. Le silicium possède un intervalle de bande indirect pour ses électrons et ne possède pas de minimum local au point Γ, ce qui défie l’existence d’une source de lumière en ce matériau. De plus, la littérature ne fait mention d’aucun laser en silicium exploitant une transition interbande ou intersousbande. Le germanium possède un minimum local en son point Γ, et peut être crû épitaxialement sur silicium. Il serait donc un candidat parfait pour une source laser compatible avec la technologie au silicium, mais il possède aussi un intervalle de bande indirecte. La récente publication de germanium uniaxialement contraint exhibant une forte luminescence, en accord avec les modèles k-p qui prédissent une transition vers un intervalle direct autour d’une contrainte de 5 %, est source d’espoirs. Notre travail se base sur ces modèles k-p et consiste en l’étude de cavités optiques, capables de résister à la contrainte imposée par le germanium à intervalle de bande direct. Nous proposons une méthode d’évaluation de la contrainte mécanique, le gain et les pertes optiques de quatre cavités candidates. Cette méthode combine les résultats du modèle k-p avec la simulation des propriétés optiques et mécaniques des cavités. Une cavité Fabry-Pérot à réflecteurs coins de cubes et un laser à rétroaction partielle sortent du lot en tant que candidats sérieux. La récente implémentation d’une cavité Fabry-Pérot à réflecteurs coins de cubes a démontré une luminescence structurée par les modes de cavité. Les résultats de cette mesure sont présentés ici.

Dans le domaine de la spectroscopie d’absorption, les lasers à cascade quantique dans l’infrarouge moyen sont capables de résoudre les résonances roto-vibrationnelles fondamentales de nombreuses molécules de gaz. Ils permettent la détection de concentrations à l’ordre de la part par milliards. Les lasers à rétroactions partielles avec leur largeurs de lignes de l’ordre du kilohertz et leur gamme d’accord de 300 GHz, sont capables de résoudre l’absorption de gaz avec des largeurs de ligne typiques de l’ordre de la centaine de mégahertz. Malheureusement, leur sélectivité modale est déterminée par la phase de la réfection de
2. Résumé

leur facettes, qui est aléatoire et produit par conséquent, une fréquence laser indéterminée à la fabrication. Les lasers à cascade quantique en cavité externe ont une largeur de ligne autour de 30 MHz et une gamme d’accord s’étalant sur tout le spectre de gain optique du laser de l’ordre de 12 THz. Ils sont d’excellent candidats à la spectroscopie des mélanges de gaz impliquant des lignes d’absorptions séparées en spectre, mais souffrent d’hystérèse mécanique qui limite leurs précision à 200 MHz. Ils requièrent d’être manipulés avec précautions, ce qui limite leur application sur le terrain ou en main. Dans notre travail, nous développons, simulons et mesurons des lasers à cascade quantique enterrés à une longueur d’onde de 9 µm. La cavité laser est un modèle à miroirs de Bragg à émission par la surface, fournissant une sélection modale déterministe. Notre puce est un réseau de dix lasers offrant une couverture spectrale de 3 THz. Ce dispositif offre le potentiel d’un accord de fréquence sur tout le spectre du gain optique en courant continu en employant un allumage séquentiel des lasers.

Dans le domaine de la spectroscopie astronomique, des images résolues en fréquence des nuages gazeux à hautes énergies situés au centre de notre galaxie peuvent révéler des informations importantes sur leur composition chimique. La mesure coïncidente de carbone atomique et d’oxygène atomique par l’émission de leur ligne de refroidissement à 1.9 et 4.7 THz respectivement, est la signature de l’ionisation d’une molécule de monoxyde et dioxyde de carbone par un rayon cosmique de haute énergie. Les méthodes de détection hétérodynes sont employées pour mesurer le spectre de radiation d’une source lumineuse dans la région spectrale de l’infrarouge lointain. Les émission cosmiques sont capturées et mélangées avec l’émission d’un oscillateur local dans un bolomètre à électrons chauds. Par exemple, l’instrument GREAT a récemment pris des images du ciel grâce à un système de détection hétérodyne. La détection hétérodyne requière un oscillateur local en mode d’opération continue avec une fréquence d’oscillation dans un voisinage de 5 GHz de la raie d’émission à détecter. Un laser à cascade quantique en cavité double métal est un bon candidat à la fonction
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d’oscillateur local, puisqu’ils peuvent opérer à ces gammes de fréquence en mode d’opération continue. Malheureusement ces lasers sont multimodes et souffrent d’un champ lointain est fortement structuré. Dans notre travail, nous avons développé des lasers à cascade quantique térahertz couplés à des antennes produisant des champs lointains avec un lobe gaussien à 95 % à 1.9 THz. En outre, en utilisant une antenne accordée en impédance, nous avons pu réduire la réflectivité de la facette du laser au-dessous de 3 %, un résultat qui pose une brique sur le chemin vers des cavités externes exploitant des guides d’onde à double métal dans le térahertz. À 3 THz nous avons investigué des lasers à cascade quantiques à cavités cristal photonique produisant des champs lointains étroits, une émission monomode continue qui serait un bon candidat à un échelonnage à 1.9 ou 4.7 THz.

Dans le domaine de la spectroscopie térahertz, les peignes de fréquence optiques sont la technologie émergente pour la spectroscopie haute résolution à double peignes optiques. Récemment notre groupe de recherche à publié un laser à cascade quantique térahertz émettant un peigne de fréquence optique avec une largeur de bande de 25 %, ainsi qu’une opération sans peigne de fréquence optique sur une largeur de bande excédant une octave. L’interruption de l’opération en peigne est dû à la dispersion créée par le gain optique qui augmente lorsque la largeur de bande s’étend. L’introduction d’un miroir de Bragg à double modulation à l’extrémité du guide d’onde à moulure pourrait compenser la dispersion introduite par le gain et restaurer l’opération en peigne sur une bande d’une octave. Ceci permettrait d’appliquer au laser des techniques de stabilisations 1f-2f pour réduire leur largeur de ligne et augmenter significativement la résolution des mesures. Dans ce travail nous mesurons la dispersion d’un laser à cascade quantique térahertz. La dispersion non-triviale ne peut pas être compensée par un modèle analytique de miroir à double modulation. Par conséquent, nous avons créé et utilisé un script basé sur un algorithme d’optimisation génétique pour générer des modèles de miroirs à double modulation qui pourraient compenser la dispersion du laser. Des résultats prélimi-
2. Résumé

naires sont présentés et montrent une surcompensation de la dispersion, mais découvrent le potentiel du modèle de miroir ainsi que l'algorithme d'optimisation génétique.
2. Résumé
This thesis addresses the techniques that are necessary to design, fabricate and measure semiconductor laser optical cavities at near-, mid- and far-infrared wavelengths. A considerable part of the work lies in the modeling of the cavities. Commercial and home made computer solutions will be presented and various designs tailored for specific applications will be proposed and tested.

3.1 Information technology

Owing to progress in lithographic technology, the transistor density in a computer microprocessor and the computer calculation speed are
3. Motivations

Figure 3.1: Data from http://preshing.com

continuously increasing. The first progresses were mainly towards an increased clock frequency, that rose to 3.8 GHz in the early years 2000s, and only marginally evolved since then. In 2004, the introduction of multiple cores in the processor chip represents an additional boost, but remains limited because it imposes parallelizable tasks. Since then, the yearly speed increase didn’t improve significantly as shown in figure 3.1 where the average rate of instructions per clock cycle is plotted.

Along with the decreasing growth of computation speed, the power consumption is in an increasing trend, leading to problems of heat dissipation. As a solution, Microsoft is exploring the possibility of submerging data centers in the ocean [1], reducing the cooling requirements. Internet accounts for 5% of the world’s energy consumption [2], a big portion of that power is in the electrical core switches that consume up to 10 kW. Coaxial cables that relay the information have losses around 10 dB/km or more. A big portion of the consumption is also attributed to the computations themselves, a processor consumes between 1 and
3. Motivations

50 W.

In the domain of long distance communication, the solution to bandwidth and power consumption was found in the conversion to optical systems. NIR optical fiber is becoming increasingly common in households, and requires sources that can operate around 1310 or 1550 nm, which are usually accompanied by modulators [3, 4] and amplifiers. Optical switches consume about 10 W which is 3 orders of magnitude less power than electrical switches for the same data transfer, additionally the losses in an optical fiber are on the range of 0.2 dB/km, 50 times less that in a coaxial cable. Along with this improvement, all-optical information processing is envisionned, where the logic could be realized with light signals where electronic transistors could be replaced by optical ones [5].

The forthcoming major improvement in computer hardware technology is the transition to all-optical interconnects, where data transfer usually realized by electric signals could be replaced by optical elements. Silicon is nowadays the most used, understood, manufacturable and cheap semiconductor of the sector [6]. The success of silicon originates in the large scale development of complementary metal-oxide-semiconductor (CMOS) for computer logic. Silicon attracts lots of interest in the domain of passive photonics because of the perspectives it opens for all-optical systems. Its performance level come from its high purity and low crystalline defect density [3, 7]. It is therefore natural that the platform for all-optical interconnects will be silicon based. At least one light source is needed to generate the optical signal; the best candidate would be a semiconductor laser integrated to the optical circuit.

Unfortunately standard laser sources are made of III-V semiconductors and can’t be integrated epitaxially to silicon CMOS technology. Silicon itself suffers from a major drawback in this quest for all-optical interconnects; it’s an indirect bandgap semiconductor which is unable of generating gain on the \( \Gamma \)-valley inter-band transition because it misses a minimum in the \( \Gamma \) point. However, silicon Raman lasers were
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already demonstrated with record-low thresholds [8], but an external light source is needed. So far, SiGe-based quantum cascade laser have been investigated, and showed an inter-subband luminescence, but no laser operation.

The semiconductor laser industry shows a growth of 7% in recent market research [9]. It is due to the expansion of applications requiring coherent or powerful light sources from the UV to the far-infrared frequency spectrum. The advantage of semiconductor based source lies in the high level of gain achievable in a small volume at small cost. We find two major categories of semiconductor lasers, the first one includes diode lasers [10, 11] and inter-band cascade lasers [12] (ICLs), where the gain is generated by an inter-band transition, and quantum cascade lasers [13] (QCLs) where the gain is generated by and inter-subband transition. The two categories can address the high and the low energy part of the spectrum respectively. They share common features, both their emission frequencies can be tailored by varying the dimensions of their quantum wells. This method enables the QCLs a possible operation range on about 7 octaves from 1 to 100 THz, while diode laser need many different material systems to range from 100 to 1000 THz.

Apart from a gain active medium, a laser needs an optical cavity. The proper design of the optical cavity determines the way a laser can exploit its gain medium in terms of power, dissipation, number of modes, tuning range, far-field, linewidth or whether it operates as a frequency combs, in this way the laser can be tailored to its application by design.

Germanium is a group IV semiconductor compatible with the Silicon CMOS technology because it can be grown epitaxially on silicon, unfortunately it features an indirect bandgap like silicon. Luckily, it was shown by M. Suess et al. that under a tensile strain germanium’s conduction band decreases in energy and the \( \Gamma \)-valley faster than the \( L \)-valley [14]. At a tensile strain approaching 5% the bandgap is predicted to become direct by an 8-band \( k \cdot p \) model developed by our collaborators from the Paul Scherrer Institute (PSI). In direct bandgap
3. Motivations

Germanium, the conduction band can get populated in its $\Gamma$ point unlocking the possible population inversion, used for the laser operation. The strain can be generated by alloying. The lasing of a germanium-tin alloy was recently demonstrated [15], but the tin in the germanium has the tendency to cluster in islands and lets the germanium relax. The strain can also be generated by mechanical pulling. The geometry used by M. Sueß et al. features large pads that can pull on a narrow free standing germanium bridge, exploiting the prestrain appearing at growth conditions.

In this thesis, my work was in the design of laser optical cavities able to sustain the strain needed to have a direct bandgap germanium. The designs are based on the work of M. Sueß et al. and were evaluated using COMSOL Multiphysics for the mechanical and optical properties. Four different designs are presented, one of which was processed and measured by our collaborators from PSI, namely R. Geiger, T. Zabel, E. Marin and H. Sigg. The preliminary results of this measurement are shown and discussed.

3.2 Health and environment

Human activity is causing an increase of pollution which has ultimately a negative impact on human health. The air quality is severely reduced in big cities, the situation is better in the western countries than after the industrial revolution but is still alarming. The center for disease control and prevention [16] identified the six major air pollutants as, carbon monoxide (CO), lead, nitrogen oxides, ozone, sulfur dioxides and particulate matter. As an example carbon monoxide inhalation leads to cardiovascular diseases, developmental issues of organs, neurological problems and respiratory difficulties, similarly the other pollutants have negative effects on the human health.

There is a strong incentive to measure the concentration of pollutants in cities, the project Opensense [17] was undertaken in collaboration between ETH Zurich, EMPA, the Zurich public transportations
(VBZ) and the university hospital of Lausanne (CHUV). A set of detectors was installed on the top of trams moving in the city of Zurich and monitor the air quality. Real-time maps like the one in figure 3.2 can be found on their website and smart phone application.

For carbon monoxide, the conventional detection method consists of heating a tin-dioxide wire on a ceramic base at 400°C, and whose resistance decrease under the presence of oxygen and increase in the case of carbon monoxide. Other techniques employ acid reactions. Traditional techniques are rather impractical and give a measurement in the order of part per million or are cheap and give only a qualitative measurement, and they are based on chemical reactions.

The fundamental roto-vibrational modes of many molecules like CO and lie in the mid-infrared (MIR) spectra region. These absorption lines are unique fingerprints of each molecule, and even of each isotope of a particular molecule. These lines exhibit stronger absorption than at higher frequency.

Distributed feedback (DFB) quantum cascade lasers are single mode devices with a fundamental linewidth below the kHz regime [18] can tune rapidly over 10 cm$^{-1}$ or 300 GHz of bandwidth [19], unfortunately they suffer from an indeterministic mode selection depending on the facet cleave, ultimately giving an uncertainty of about 5-10 cm$^{-1}$
or 150-300 GHz on their lasing frequency. External cavity quantum cascade lasers have a linewidth around 30 MHz but offer a slow tuning over the whole QCL gain bandwidth of 400 cm\(^{-1}\) or 12 THz [20], unfortunately they suffer from a mechanical hysteresis that leads to a wavelength inaccuracy of the lasing frequency of about 200 MHz. Thus DFB are the best candidates for gas absorption linewidths in the hundreds of MHz whereas external cavity QCLs are useful to resolve broad features. Many articles report the high detectivity of such spectroscopy systems [21, 22, 23, 24], additionally detectivity can be obtained using quartz enhanced photo-acoustic spectroscopy [25, 26, 27] (QEPAS). A measurement of carbon monoxide concentration using an external cavity QCL in a QEPAS configuration could reach a sensitivity of 2 parts per billion, 3 orders of magnitude better than conventional techniques [28]. Ideally, a quantum cascade laser for these application should have a linewidth comparable to DFB lasers and the tuning range of an external cavity setup.

In this work I designed the optical cavities of the lasers, and worked on the characterization. The performance of an array of surface emitting single mode quantum cascade lasers with a deterministic mode selection is shown, enabling the sequential firing of the lasers, giving access to narrow linewidths over a large bandwidth.

3.3 Astronomy

The terahertz spectral domain, similarly to the mid-infrared spectral domain, contains the fingerprints of many molecules and can be exploited in the field of astronomical spectroscopy. The cosmos can reveal different informations at each frequency. The sky was already extensively explored using visible, near-infrared X ray and microwave light, but was so far only marginally explored in the THz regime, because of the lack of efficient detectors.

Figure 3.3 shows images of the M16 Eagle Nebula taken at various wavelengths [29, 30], certain features appear only at specific frequencies.
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At the wavelengths of 63 µm and 158 µm we can find major cooling lines of atomic oxygen [OI] and atomic Carbon [CII]. The ionization of CO and CO$_2$ by high energy radiation will separate the two components, the atoms will radiate light into space by cooling. If this light can be recuperated on earth, it can give the information on the atomic species located at these places. A correlation measurement will be able to give signs of carbon-based activity.

The terahertz spectral domain suffers from a lack of efficient sources and detectors. On the detection side the most common detectors are bolometers, pyroelectric detectors and photoacoustic detectors with response times below 1 ms. Quantum well infrared photodetectors [32] and quantum cascade detectors [33, 34, 35] are based on intersubband transitions. They are still a subject of study but offer the advantage of a fast response time due to the low lifetimes of intersubband transitions. Unfortunately, the intersubband selection rule forbids the absorption of light with an electric field parallel to the quantum well. The detectivity is orders of magnitude below the near-infrared or visible detectors. In addition to these detectors, non-linear crystals are often used in synchronous measurements [36], but the resolution is poor. In this work we aim at a heterodyne detection technique using a local oscillator and a hot electron bolometer mixer [37]. The signal is down converted to the
Figure 3.4: Comparative representation between emitters in different spectral ranges, for pulsed laser operation the peak output power value is plotted [45].

radio frequency regime by the mixer in a bandwidth of about 20 GHz. This is an ideal low-noise technique to resolve the spectrum and the intensity of a line close to the local oscillator frequency. The instrument GREAT [38] to which we participate attempts to measure atomic carbon and oxygen using such heterodyne setup with a hot electron bolometer attached to a parabolic antenna mounted on the airplane SOFIA.

Among THz emitters, we find various types of sources, including chain multipliers [39], photoconductive switches [40], plasmas [41], photo-Dember effect [42], resonant tunneling diodes [43], Gunn diodes [44] with average powers below 100 µW between 1 and 5 THz, and difference frequency generation lasers and p-doped germanium lasers, that are large systems [45] which can be unpractical for some applications. A summary of the principle THz emitters is in figure 3.4.

In an effort to fill the terahertz gap, quantum cascade lasers were first demonstrated in 2002 [46].
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After 13 years of optimization of the gain active region and waveguide [47], THz quantum cascade lasers reach peak output powers up to the Watt level [48, 49]. They can operate from 1 to 5.3 THz and find their optimal working point around 3 THz as seen in figure 3.5. At frequencies around 1 THz the inter-subband transition is on the order of the broadening of the levels thus the subbands merge in a continuum and population inversion can’t be achieved. At energies above 5 THz the intersubband transition approaches the tail of the longitudinal optical phonon band of GaAs at 9 THz and suffers from its absorption.

Terahertz quantum cascade lasers suffer from the drawback of operation temperature, which hasn’t evolved since it reached 199.5 K for pulsed operation in 2012 [51] and about 130 K in continuous wave more recently [52]. In figure 3.6 their maximum temperature of operation [50] under pulsed operation is shown. The maximum operation temperature is located around the optimal working point of 3 THz. The degradation is partially due to the thermal backfilling, where the lower lasers states get repopulated by the electron injector states of the next period, harming the population inversion. It is also due to thermally activated
3. Motivations

Figure 3.6: Compilation of the maximum published operation temperature as a function of the frequency [50].

phonon scattering, a process where the LO-phonons depopulate the upper laser state in a non-radiative transition.

Quantum cascade lasers can be used as local oscillators in a heterodyne detection setup to detect the cosmic cooling of atomic carbon and oxygen. To successfully fulfill this function, the local oscillator needs to be, a single mode device with a frequency accuracy of 1 per mill at 1.9 THz or 4.745 THz, operate in continuous wave, with at least 2 mW of output power in a gaussian output beam at 45 K with less than 2 W of dissipation. Such requirements can only be fulfilled by a double metal waveguide QCL, which unfortunately are inherently multi-mode and have a very structured far-field.

In this thesis we study two designs that would potentially fulfill the necessary conditions of local oscillator. One approach consists in using a photonic crystal cavity to ensure the single mode behavior and a narrow far-field. This work was done in collaboration with Z. Diao and R. Houdré from école polytechnique fédérale de Lausanne, and my contribution is in the partial design of the optical cavity and the characterization of the devices. The second approach exploits the coupling between a quantum cascade laser ridge and a printed antenna in order
to decrease the facet reflectivity to enable a continuous wave terahertz external cavity, or the fabrication of a device without reflector that can be added after process using a piezo-positionner that will determine the laser frequency. In this work I did part of the design, the process and the characterization of the devices.
4.1 Introduction

In 1840, Jean-Daniel Colladon shows that light can be guided by the bent jets of water fountains, using the effect of total internal reflection. In the late 19th century, Lord Rayleigh studies the nature of electromagnetic waves following the work of Maxwell, Fresnel, Lorentz, Helmholtz and Thompson. "... By supposing the conductivity to be so great that practically complete absorption takes place within a distance comparable with the wave-length, we may obtain a theory of metallic reflection which is not without interest... " Simultaneously he writes an analytical formulation of the guided sound wave modes. Contemporary
to Debye and Sommerfeld, his work on optical waveguiding began the following century.

The waveguide is an essential component of semiconductor lasers, with the exception of VECSELs. In a dielectric waveguide the light is confined in a high refractive index medium by total internal reflection, in a metallic waveguide it is confined in a low refractive index region by metallic reflection. The following discussion is restrained to dielectric waveguides and the extension to metallic waveguides can be found in the chapter "Antenna coupled laser".

### 4.1.1 Waveguides

In a dielectric waveguide, the electric and magnetic fields of the light can be expanded into a sum of solutions of the Helmholtz equation. Generally in a square waveguide, two categories of modes can be found, the transverse electric modes with the electric field parallel to the confinement direction and the transverse magnetic mode whose electric field is perpendicular to the confinement direction. The modes are characterized by their propagation vector $\beta$ which is often expressed by the effective refractive index $n_{eff} = \frac{k_0}{\beta}$. The condition of total internal reflection imposes to the value of the effective mode index to be bigger than the refractive index of both cladding layers.

$$\nabla^2 \vec{E}(\vec{r}) + (k_0^2 n^2(\vec{r}) - \beta^2) \vec{E}(\vec{r}) = 0$$

(4.1)

where $n(\vec{r})$ is the refractive index field. Each mode is characterised by its $\beta$ and electric field distribution satisfying the Helmholtz equation. The electric field is concentrated around the high index material. In the case of laser waveguides the $\Gamma$ factor is the overlap of intensity of these mode with the gain region, usually at the core of the waveguide.

$$\Gamma = \frac{\int_{V_{gain}} \epsilon(\vec{r}) |\vec{E}(\vec{r})|^2 d^3\vec{r}}{\int_{V_{total}} \epsilon(\vec{r}) |\vec{E}(\vec{r})|^2 d^3\vec{r}}$$

(4.2)

This expression is used in the case of a laser with two distinct
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regions, the gain region and the surroundings without gain.

4.2 COMSOL Solvers

COMSOL [53] is a software offering an interface to solve optics problems in the frequency domain. One of these problems is the search of eigenmodes of an optical system. COMSOL can take as an input a geometry defined as a computer aided design (aka. .CAD) in two or three dimensions. COMSOL then assigns a mesh of choice tetrahedral, triangular or rectangular to the system and puts meshing points in a semi-automatic way. For good results the density of meshing points should be around $(10n/\lambda)^N$ where $N$ is the dimension of the system and $\lambda$ the wavelength. In the case of metals, the field doesn’t penetrate the material and decays fast, it is desirable to resolve the skin depth. In the case of a dielectric/metal interface, the field variation in the out-of-plane direction is fast and the density of point follows the $(10n_{\text{real,metal}}/\lambda)$ rule but the variation of the field in the in-plane direction has the surface plasmon polariton spacial frequency and thus the density should be $(10n_{\text{diel}}/\lambda)^{N-1}$. After assigning a relative permittivity and permeability as well as conductivity to the various areas of the system, it fixes the desired boundary conditions. As an output, COMSOL gives a set of eigenmodes, including the field distributions and complex frequencies. Additional computations can be carried on, like the far-field or field-overlaps.

The eigenvalue solver of COMSOL attempts to find the solution of the system by solving the Helmholtz differential equation 4.1 using a finite element method. It uses standard solver packages for sparse linear problems like MUMPS [54], SPOOLES [55] and PARADISO [56]. In this work the MUMPS package was mostly used.

MUMPS is the acronym for "MUltifront Massively Parallel sparse direct Solver". It contains set of algorithms that solves systems of linear equations of the type $Ax = b$. Comsol maps the Helmholtz equation to such system of equation, where the vector $x$ is the field at eachpoint of
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the mesh. The solutions are the eigenvalues $\beta$ and eigenvectors are the fields $E$.

MUMPS first preconditions the matrix $A$. Since the value of the electric field in one point depends only on the value of the field at the neighbouring points the matrix $A$ can be rearranged to be diagonal in blocks by swaping lines and columns.

$$A_{\text{pre}} = PD_rAQ_cD_cP^T$$  \hspace{1cm} (4.3)

where $P$ is a symmetrically applied permutation matrix, $D_r$ and $D_c$ are diagonal matrices used for the scaling of the system and $Q_c$ is a column permutation matrix. The system scaling is a very important step, because divergence in scales are able to hit the limit of machine precision. After preconditioning the solver attempts to find the eigenvalues of the system, using LU or Cholesky factorisations. LU factorization attempts to find two matrices $L$ and $U$ that are lower and upper diagonal matrices and satisfy:

$$A = LU$$  \hspace{1cm} (4.4)

The Cholesky factorization can take two forms.

$$A = LL^T \quad \text{or} \quad A = LDL^T$$  \hspace{1cm} (4.5)

The three methods allow us to solve two more simple problems of the form:

$$Ax = A_1 \cdot A_2 x = A_1 y = b, \quad A_2 x = y$$  \hspace{1cm} (4.6)

where $A_1$ and $A_2$ can be the L, D or U matrices depending on the method of choice. The computation cost of such methods is roughly of $(2/3)n^3$ flops, where $n$ is the order of $A$. This is an important aspect of the computation, because it gives an estimate of the computation time.

A post treatment is performed to evaluate the error on the computation. As long as the error $r$ is not small enough with respect to $b$,
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Figure 4.1: Memory requirements per simulations. 1) a 3D heat transfer model, 2) a mechanical model, 3) an electromagnetic model, 4) a mechanical model, 5) a 3D heat transfer model, Figure from the website of COMSOL.

the correction is computed.

\[ A\Delta x = r, \quad x = x + \Delta x, \quad r = b - Ax \] (4.7)

Convergence issues often originate in a too coarse meshing.

Computer requirements

The solver offers a high computation speed for large sparse systems although an enormous amount of memory is needed. The memory need scales faster than the number of mesh points in the system. The MUMPS solver and the operating system circumvents the memory issue by using the RAM to perform front computations an using the hard disk drive. In the long run this feature is undesirable because it slows down the computation significantly. For this reason, the memory required for the computation should be kept below the maximum available RAM of the computer. The amount of RAM needed scales almost linearly with the number of degrees of freedom of the system 4.1.

In the case of the computation of electromagnetic wave solutions there are 6 degrees of freedom per mesh point three directions of electric
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and magnetic fields, where the solver requires a memory of 16 kB/degree of freedom. A typical laser optical cavity size at this frequency would be $1.5 \text{ mm} \times 150 \mu\text{m} \times 10\mu\text{m} = 0.00225 \text{ mm}^3$. An additional requirement for a successful computation is that the near-field of the cavity should not interact with the boundaries. A space of 2 wavelengths at least should surround the laser in order to let the field decay. The new dimensions of the system are then $1.9 \text{ mm} \times 550 \mu\text{m} \times 410\mu\text{m} = 0.43 \text{ mm}^3$. The refractive index of the laser is around 3.6, the density of meshing points should then be 47 times denser for the laser part. The resulting number of meshing points required is above 500,000, that would require a little less than 50 GB of RAM for a wavelength of 100 $\mu\text{m}$, which is just too high for actual personal computers. Such solvers are unable to simulate a whole laser cavity if it is not a microcavity. Some simplification methods will be treated later.

COMSOL offers two other types of solutions that were used in this work, mode analysis and an S-matrix solver named "Frequency domain". The mode analysis is almost identical to the eigenfrequency problem. By modeling the cross section of a waveguide in 2D, COMSOL achieves to find the various waveguide modes, their field distribution and their complex effective refractive index. The Frequency domain solver is a 2D or 3D solver that requires at least one input port as system boundaries in order to excite the system with additional ports depending on the study. The solver computes the stationary solution for each individual frequency which can be cumbersome for large systems with sharp resonances. The result is a stationary field distribution for each frequency together with the complex S-parameters for each port.

4.3 CST microwave studio

Unlike COMSOL, CST microwave studio [57] offers a time domain solver and can solve very efficiently S-matrix problems. It is the numerical equivalent of a time domain spectroscopy setup. The solver feeds a broadband ultra-short pulse into the system by a port and lets
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the electromagnetic waves oscillate with time in the system. The ports are constantly listened and record the time-trace of the output field of the system. From this time-trace the S-matrix is obtained by Fourier transform. Additionally CST offers the possibility to compute far-field patterns and near-field distributions throughout the system. It is the solver of choice for broad-band studies and broad features. For narrow features, CST also provides a frequency-domain solver.

4.4 Large systems

Above a certain size, systems are too big to be simulated entirely. Even the most advanced computation methods fail to simplify the redundancy of such problems and find themselves needing enormous amounts of computational power. Four simple methods can be employed to circumvent the issue of memory.

4.4.1 System disassembling

System disassembling is a trivial concept where the system, is decomposed in its primary elements and rebuilt post-computationally. An exemple of it will be presented in the case of integrated antenna quantum cascade laser, where the mirror reflectivities are the results of CST simulations, the losses are estimated using the Fabry-Perot analytical formula, with frequency dependent mirror reflectivities.

4.4.2 Symmetry reduction

Systems typically exhibit symmetries that are often harnessed in numerical computations. While mirror symmetries allow to reduce the problem in halves, discrete rotational symmetries allow to reduce the system by any integer amount. Additionally, continuous rotation symmetries allow to reduce the dimensionality of the system to 2 or even 1 dimensions. Finally, translation symmetries allow the computation
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Figure 4.2: Axis nomenclature, showing an x,z cross-section and propagation in the y direction.

of infinitely long systems, which is powerful in the case of distributed feedback (DFB) and photonic crystal lasers.

4.4.3 Mode selection

In some cases, the solution of the problem has a defined s- or p-polarization. Such information can be given to the solver and the number of degrees of freedom per mesh point of the system should be reduced from 6 to 3.

4.4.4 Effective index approximation

In order to compute the modes of a ridge laser cavity, the effective index approximation can be used because of the small complexity of the field in the transverse direction (x,z) compared to the propagation direction y, as shown in figure 4.2. The Helmholtz equation is computed in the (x,z) plane and the eigenvalues $\beta_i$ and the associated electric field distributions $f_i(x, z)$ are the solutions. The effective refractive index $n_{\text{eff}}$ is computed for a freespace wavevector $k_0 = \omega/c$.

$$n_{\text{eff}} = \frac{\beta}{k_0}$$  \hspace{1cm} (4.8)

The effective index approximation allows to treat the remaining dimension in a one dimensional case or as a plane wave with a wavevector $n_{\text{eff}} k_0$. 

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\[ E_i(x, y, z) = f_i(x, z)E_{i, \text{plane}}(y) \]  

Finally one-dimensional electric field can be computed using a wave-transfer matrix method.

**Distributed feedback cavity**

DFBs are excellent candidates for this method. Mid-infrared QCL waveguides take the form of a dielectric waveguide with a grating on the surface. In this case, to compute the eigenmodes of the system, we solve the Helmholtz equation for a cross-section taken at the groove and at the highs separately, to get the two associated effective refractive indices \( n_{\text{eff, groove}} \), \( n_{\text{eff, high}} \) and their associated field distributions. These effective indices can be further used to model the three-dimensional mode profile based on a wave transfer matrix method.

### 4.5 Wave transfer matrix method

Many layered systems offer a versatile platform for the development of semiconductor lasers. These systems feature reflections in the direction of light propagation. The reflection typically originates at an interface between two materials with different refractive index, but can more generally be described by an impedance mismatch or a modal mismatch. The two cases will be discussed further. The definitions are found here [58].

The wave transfer matrix is the method of choice to compute the reflectivity or transmission of dielectric anti-reflective coatings or high reflection coatings, but also works to solve the plane wave part of our guided mode.

Mathematically the method is described as follows. Let \( I_f \) and \( O_f \) be the amplitudes of the input and output forward propagating wave and \( I_b \) and \( O_b \) the amplitudes of the input and output backward propagating wave respectively, as pictured in figure 4.3. The system
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![Visual representation of the composition of the wave transfer matrices.](image)

**Figure 4.3:** Visual representation of the composition of the wave transfer matrices.

is described by a succession of interfaces and propagation in media of various refractive indices which are described by the matrices \( M_i \).

\[
O = \begin{pmatrix} O_f \\ O_b \end{pmatrix} = M \cdot \begin{pmatrix} I_f \\ I_b \end{pmatrix} = M_N \cdot ... \cdot M_1 \cdot \begin{pmatrix} I_f \\ I_b \end{pmatrix} = I
\]  \hspace{1cm} (4.10)

The propagation and interface reflection matrices \( P \) and \( R \) take the following form with \( n_1 \) and \( n_2 \) the refractive indices before and after the interface respectively.

\[
P_1 = \begin{pmatrix} e^{-ik_0n_1L} & 0 \\ 0 & e^{ik_0n_1L} \end{pmatrix}, \quad R_{12} = \frac{1}{2n_2} \begin{pmatrix} n_2 + n_1 & n_2 - n_1 \\ n_2 - n_1 & n_2 + n_1 \end{pmatrix}
\]  \hspace{1cm} (4.11)

From the matrix \( M \), the reflection and transmission coefficients can be obtained using the following relations, with \( M_{i,j} \) the matrix element on line \( i \) column \( j \) the the transfer matrix \( M \):

\[
t = \frac{1}{M_{2,2}}, \quad r = \frac{M_{1,2}}{M_{2,2}}
\]  \hspace{1cm} (4.12)

The electric field \( E \) at any point in the system can be obtained by splitting the system into two matrices with \( M = M_a \ast M_b \) where \( M_a \) and \( M_b \) are the matrices after and before the cut point as shown.
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Figure 4.4: Visual representation of the convergence of field reflection at a point in the system.

in Figure 4.4. To compute the electric field profile along the system one should compute the sum of all forward and backward propagating waves. The sum of fields should take into account the reflections $r_a$ and $r_b$ from $M_a$ and $M_b$ respectively.

$$E = (t_a O_b + t_b I_f) + (r_b t_a O_b + r_a t_b I_f) + (r_a r_b t_a O_b + r_b r_a t_b I_f) + ...$$

(4.13)

This term is a geometrical sum that converges for gainless media and thus has an exact solution.

4.5.1 Fabry-Perot resonator

The result of an $O = R \cdot P \cdot R \cdot I$ system with a refractive index $n=3.6$ and a refractive index of 1 for the boundaries is plotted in Figures 4.5 and 4.6.

Figure 4.5 shows the reflection and transmission spectra of this system, a typical Fabry-Perot cavity. The Fabry-Perot modes are at the point of unity transmission. They are characterized by their wavenum-
4. Computing methods

**Figure 4.5:** Typical transmission and reflection spectra of a Fabry-Perot cavity.

**Figure 4.6:** Field profile in a Fabry-Perot cavity under 100 % transmission. With in blue the absolute value of the electric field and in shades of red the time evolution of the transmitted wave.
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ber and spacing:

\[ k_i = \frac{i}{2n_\phi(k)L}, \Delta k = \frac{1}{2n_g(k)L} \tag{4.14} \]

\[ n_g(k) = n_\phi(k) + \omega \frac{dn_\phi}{d\omega} \tag{4.15} \]

where \( n_\phi(k) \) is the frequency dependent phase refractive index, which in the case of a waveguide is the effective refractive index, \( n_g(k) \) is the group refractive index, \( k_i \) is the wavenumber and \( \Delta k_i \) is the free spectral range.

Figure 4.6 shows the normalized electric field profile throughout the system, with reflective boundaries at \( x=2500 \) and \( x=3200 \) \( \mu m \). The phase evolution of the real field is also displayed, and represents the time for fields input from the right of the system.

Transfer matrix models are useful in the case of laser optical cavities. Gain or losses in the layers can be induced in the form of a complex refractive index, the gain added \( g = \frac{4\pi n^\imath}{\lambda_0} \) where \( n^\imath \) is the imaginary part of the refractive index, and \( \lambda_0 \) is the vacuum wavelength of light. Figure 4.7 shows the evolution of the transmission, increasing the gain by fractions of the threshold gain. The linewidth of the Fabry-Perot resonance decreases linearly as a function of the pump parameter, here defined as \( \frac{g}{\alpha_{th}} \). The dynamics of the resonance linewidth around the threshold is described more extensively here [59]. The linewidth follows a linear behavior with the net gain \( \Delta G = g - \alpha_{th} \), under the assumption of a Lorentzian lineshape.

\[ \Delta \nu = \frac{-\Delta G}{2\pi} \tag{4.16} \]

This linear relationship is useful to create a threshold finding algorithm. Ultimately the linewidth becomes smaller than the meshing step and it limits our precision. The threshold point can be extrapolated. The threshold gain obtained by computation is the same as the one from the analytical formula which shows the power of the transfer matrix method. This method is conceptually different from usual solvers.
because it computes the amount of gain needed to overcome the losses and obtain lasing, where usual solvers only compute the losses. For example, Finite Difference Time Domain solvers usually compute the decay time of the field inside the cavity by fitting which is equivalent to a loss computation. An extensive discussion on the subject can be found here [60]. The author proposes a semi-classical method based on constant flux states to model multi-mode lasers below and above threshold.

\[ \alpha_{th} = \frac{1}{2L} \ln \left( \frac{1}{R^2} \right) = \frac{1}{2L} \ln \left( \frac{n_2 + n_1}{n_2 - n_1} \right)^4 \]  

(4.17)

To conclude this chapter, the tool set of optical computation methods was presented. It includes a home-made wave transfer matrix calculator and the standard solvers of COMSOL and CST Microwave Studio.
Photonic crystal cavities were first envisioned by Lord Rayleigh in the 19th century. They are first described as a periodic arrangements of dielectric materials in one, two or three dimensions [61, 62], creating bands of possible states of light. In the mid-infrared wavelength range, the first demonstration of a 2D photonic crystal quantum cascade laser was reported in 2003 by R. Colombelli [63]. It features an air-hole arrangement in a triangular lattice. The lattice is altered in its middle to create a light state between the bands. Two years later, the first THz QCL incorporating a two-dimensional photonic crystal was
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published [64]. It consists of a ridge terminated on both ends by a two-
dimensional arrangement of pillars providing a frequency-dependent re-
fectivity. Two years later, a structure of pillars embedded in a dielectric
polymer arranged in a triangular lattice are reported [65]. It employs
a slow-light mode at the edge of the Brillouin zone. The authors pub-
lished a year later a two-dimensional photonic crystal terahertz quan-
tum cascade laser employing a patterning of the top contact [66]. The
authors presented in the latter work makes use of the reflection origin-
ating at the interruption of the top metal contact. This technique was
further investigated by Y. Chassagneux et al. demonstrating the im-
portance of the photonic crystal boundary conditions [67, 68] and more
recently an engineering of the photonic band-gap to force the operation
on a radiative photonic crystal band [69].

Nowadays, photonic crystal lasers reach Watt levels of output power
in the Near-infrared spectrum [70], hundreds of mW in the MIR re-

gion [71] and tens of mW in the THz range [69]. Photonic crystals
(PhC) lasers can feature single mode emission with a large near-field
area, which gives the potential for high output powers and simultane-
ously a narrow far-field. The fabrication of large devices is challenging,
because small fluctuations of dimensions can cause an inhomogeneous
distribution of the field and ultimately the loss of coherence throughout
the cavity and eventually of the single mode behavior.

5.2 Design of the lasers

In this project we chose a triangular array of cylindrical pillars among
the various possible lattices. The pillars are surrounded by benzocy-
clobutene. Figure 5.1 shows a representation of the photonic crys-
tal cavity. The refractive indices considered for the two materials are
$n_{AR}=3.6$, $n_{BCB}=1.55$. The band structure is displayed in Figure 5.2.
The group velocity of light in the band follows the relation:

$$v_g = \frac{d\omega}{dk} \quad (5.1)$$
5. Photonic crystal laser

The slope of the band is the group velocity of the light. In K and M the group velocity is zero, they are points of slow light where the lasing can take place. They are at the edge of the first Brillouin zone and thus are high symmetry points, in addition to $\Gamma$. The band structure features a full photonic bandgap, which is not a necessary condition for a single mode lasing but the absence of existing modes at higher energy than the K point strengthens the single mode aspect, because it avoids that light couples to a different band. This technique gave rise to a set of documented improvements [64, 66, 72, 73] before reaching the present status, which was published in an article [74] on which the present chapter is largely based.

Compared to other photonic crystal quantum cascade lasers, where the photonic structure is defined by patterning the top metal layer, this work brings two main conceptual differences. The high refractive index mismatch provides a strong coupling constant to the structure and allows the use of small photonic crystal dimension implying a low power dissipation. Secondly, the mode at the first band edge K point is a dielectric band edge mode, the electric field is confined inside the high dielectric constant medium as shown in Figure 5.10. A lower area of QC active material is pumped which results in a dilution of the electrical power dissipation and thus a lower active region average temperature.

Figure 5.1: a) Representation and b) SEM image of the Photonic crystal
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5.2.1 Photonic crystal core

The active region used in this work has a GaAs/Al$_{0.15}$Ga$_{0.85}$As heterostructure forming a hybrid of resonant phonon and bound to continuum scheme [75] described in the appendix 9.2. This 11 $\mu$m thick active layer operates at 3.1 THz with a gain bandwidth of 0.6 THz.

A 2D triangular photonic crystal pattern is defined in the active layer, which fixes the high symmetry points of the reciprocal space to $\Gamma$, K and M figure 5.2. The first photonic band edge K point mode frequency is chosen by appropriately selecting the lattice constant $a$ and filling factor $f_f$, defined as the ratio of surface of pillars to the total surface. The process was optimized for an ultra smooth surface and a nearly perfect vertical sidewall (vertical angle 89.9°) of the active region pillars can be observed in the inset scanning electron microscope picture. The verticality and smoothness are critical in reducing the scattering and absorption losses due to the structural imperfections inside the device.

The vertical field confinement of the QC laser is achieved by a 1 $\mu$m
5. Photonic crystal laser

thick bottom Au layer obtained by thermo-compressive gold-gold wafer bonding and a 1 \( \mu \)m thick top contact Au layer deposited with electron beam evaporation and lift-off. The hexagonal top contact corresponds to the hexagonal symmetry of the triangular lattice: its six edges are perpendicular to the \( \Gamma K \) direction. The simulated electric field of the lasing mode has a centro-symmetric distribution at the edge of the central pumping pad with respect to the central pillar.

5.2.2 The extractor

Typically, photonic crystal lasers rely on an absorbing boundary condition to ensure the single mode operation. The higher order mesa modes are filtered out because of their high overlap with the lossy boundary providing them a larger threshold gain. In the previous demonstrations, where no extractors are implemented, only little energy is radiated at the boundaries, and a larger part is reflected in the laser, additionally the lasing mode \( K \) point is outside of the cone of light which implies that no emission can come from the pillar structure, but only from the edge of the core.

In order to extract the light from the photonic crystal some extractors were places around the central pad. A second order Bragg Au grating is implemented in the \( \Gamma K \) direction to select the radiation in this direction. The parameters of this Bragg grating are defined by the Bragg condition: \( m\lambda_B = 2\Lambda n_{eff} \), where \( \lambda_B \) is the Bragg wavelength, \( n_{eff} \) is the effective refractive index of the QC active layer, \( \Lambda \) is the period of the grating, \( m \) is the order of Bragg reflection, \( m = 2 \). The design of the 2\textsuperscript{nd} order Bragg extractor was optimized with COMSOL. The duty-cycle of the extraction grating was optimized to increase the extension of the mode in the grating region, the width of the first gap tunes the coupling between the grating and the laser core.

Figure 5.3 shows the microscope picture of the extractor, close to one of the feeding wires. We can also clearly distinguish the photonic crystal pillars.
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Figure 5.3: Optical microscope picture of the grating extractor.

Figure 5.4: Comparision between the typical far-field pattern of a photonic crystal without extractor on the left and with extractor on the right.
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**Figure 5.5:** $S_{21}$ element of the scattering matrix, computed using COMSOL. We see the resonance of absorption peaking around -10 dB around 3 THz.

In our design the extractors extend the mode outside the pumped region of the photonic crystal [74] and increase its radiative losses. It increases the radiative losses of the excited modes more than the ones of the fundamental, thus increases the mode selectivity favorably. A typical far-field pattern with and without grating is shown in figure 5.4.

5.2.3 The absorbers

The device is electrically pumped via six bonding pads (70 x 70 µm$^2$) which are 300 µm away from the central pumping pad. A series of metallic absorbers (maximum absorbing frequency at 3.1 THz) are inserted in between the central pumping pad and the bonding pads to prevent feedback and uncontrolled THz emission from the six bonding pads.

Figure 5.5 shows the S-parameter simulation of the absorbers. We can see the coupling to a non-radiative resonance. During the pro-
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Figure 5.6: Microscope picture of a typical feeding line. It features 2 arrays of three frequency filters and a contact pad. One can notice the electrical isolation of the contact pad with the deposition of a SiN layer.

cessing the final position of the absorbers with respect to the pillars is unknown. In the simulation the absorbers are laying on a substrate of index \( n_{\text{avg}} = ff \times n_{\text{active}} + (1 - ff) \times n_{BCB} \). In reality the medium underneath can’t be considered as an effective medium because the size of the features are resonant to the wavelength, but it is the best available approximation.
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Figure 5.7: Measured output power of 1 mm diameter structures with 30 % filling factor as a function of the lattice parameter. The purely single mode devices are displayed with a dot and the partially multi mode devices are displayed with a star. The high-symmetry point lasing is deduced by matching the band diagram with the various spectra.

5.3 Results and discussions

In this work we varied three parameters of the lasers: the core pad with sizes of 600, 800 and 1000 \( \mu m \) diameter, the filling factor with values of 20, 30 and 40% and finally the lattice parameter \( a \) with values of 19 to 23 \( \mu m \), here \( a \) is the distance between the center of two neighboring pillars. The power measurements presented here are done using 16.7 ms pulses with a repetition rate of 30Hz, to enable a lock-in measurement using a Thomas-Keating acousto-optic detector. This time is long enough to let the electronic temperature, the mode competition and the active region temperature become stationary. The spectra were measured in continuous wave operation.

5.3.1 The lattice parameter

The lattice parameter is the main factor that influences the lasing frequency of the laser. We can see in figure 5.7 that the resulting power is higher for lasing frequencies close to the peak gain. When the peak gain is high enough the devices lose their single mode feature and mesa
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Figure 5.8: TM photonic band diagram together with the gain range as a function of the lattice parameter. The gain is represented as a green vertical band.

modes start lasing, which happens for large devices with strong confinement. We see that for a lattice parameter of \( a=19 \, \mu m \) the high symmetry point M is lasing, the K point is outside of the gain bandwidth.

Figure 5.8 displays the reduced energy of the gain with respect to the K and M point for various lattice parameters. We see that for a lattice parameter of 19 \( \mu m \) the gain peaks at the energy of the M point, but for larger lattice parameters it peaks at the K point and it explains the results displayed in figure 5.7.

For other sets of parameter the device with a lattice parameter \( a=19 \, \mu m \) was lasing on the K-point. We could retrieve experimentally the results of the FEM simulation as shown in Figure 5.9. The maximum output power is obtained for a lattice parameter of \( a=21\mu m \).

5.3.2 The filling factor

The filling factor of the photonic crystal lasers influences the overlap of the mode with the active region. The lower band-edge modes features
5. Photonic crystal laser

![Graph showing lasing frequency as a function of lattice constant.]

Figure 5.9: Resulting K-point lasing frequency of all measured devices as a function of the lattice parameter, each bar except $a=23 \, \mu m$ is a collection of measurements. The point in $a=20 \, \mu m$ is 4 different devices.

![Diagram showing electric field distribution in a unit cell of the photonic crystal.]

Figure 5.10: Electric field distribution in a unit cell of the photonic crystal at the K-point. The unit cell is in light blue dotted line and the pillar in red dotted line.

an electric field located in the high refractive index pillars, and has an overlap of 48%, 59% and 67% for the filling factors of 20%, 30% and 40% relatively. The electric field distribution is represented in figure 5.10 for the three used filling factors.

The value of the threshold current density can be expressed as a simplified form:

$$J_{TH} \propto \frac{\alpha_{tot}}{\Gamma} \quad (5.2)$$

In this expression, $\alpha_{tot}$ are the mirror losses and $\Gamma$ is the modal overlap. This expression is often paired with the slope efficiency.

$$\frac{dP}{dI} \propto \frac{\alpha_m}{\alpha_{tot}} \quad (5.3)$$

Here $\alpha_m$ are the mirror losses, but represent in general the extrac-
5. Photonic crystal laser

Figure 5.11: LI characteristics of small devices with $a=21\mu m$ as a function of their filling factors. On the right vertical axis are displayed the overlap factors of the various filling factors with the corresponding colour.

Figure 5.11 shows the LI characteristics of the photonic crystal QCLs for devices with lattice parameter $a=21\mu m$ and of small diameter. The resulting characteristics show an increase of the output power with filling factors. Maximum values of 4, 4.6 and 5.8 mW are obtained from the filling factors of 20, 30 and 40% respectively. These values are proportional to the overlap factors of the field with the active region shown in the second y axis, which scale matches the ff=40 % device with its overlap. This is consistent with the fact that modes of equal volume and losses have their power scaling with the modal overlap, additionally it is the sign that the extraction mechanism used in this case is independent of the filling factor. Additionally we see that the slope efficiency of the lasers is the same regardless of the filling factor. It is consistent with the expression showed earlier.

A second aspect to take into account is the power to be dissipated, which is proportional to the filling factor. The average temperature of the active region will scale in an nontrivial but monotonic manner with the dilution of the active region. In this regard the smaller the filling factor the better. The two aforementioned aspects will settle for an optimum which is around 30 % filling factor as shown in figure 5.16.
5. Photonic crystal laser

Figure 5.12: LI characteristics of devices with the same filling factor and lattice parameter $a=21 \ \mu m$ for various core diameters. The plot is in current density.

5.3.3 The cavity size

Generally, for photonic crystal modes that are below the light cone, the losses decrease exponentially with its surface. In our case the K-point is below the cone of light and the light extraction is achieved by the boundary conditions, which is analogous to a non-radiative case. The size of the crystal will impact the mode volume and the extraction losses, and by extension the total losses. In this case the crystal size is defined as the diameter of the photonic crystal core.

In figure 5.12 we can see that the threshold current density decreases with increasing crystal size, the smaller device has a threshold current density 17% higher than the big one, which is attributed to the change of mirror losses and by extension to the total losses $\alpha_{tot} = \alpha_m + \alpha_{WG}$. Additionally, between the small and the large area laser, the peak output power increases by a factor 1.7 when the pumping area increases by a factor 2.7, we can deduce that 40% of the additional pump power is radiated and the remaining injected power is absorbed.

Figure 5.13 shows the same curves plotted as a function of the current. We observe a decrease of the slope efficiency by a factor 1.7 between the small and the big crystal. It is a measure of the extraction
5. Photonic crystal laser

\[
\frac{\alpha_m}{\alpha_{tot}}. \text{ Assuming } \alpha_{WG}=10 \text{ cm}^{-1} \ [76, 77, 78], \text{ we can deduce the mirror losses for the small device } \alpha_m=4.13 \text{ cm}^{-1}, \text{ and for the large device } \alpha_m=2.08 \text{ cm}^{-1}.
\]

Figure 5.13 shows the important characteristics of the laser. The computed radiative losses for each three sizes and the values deduced from the LI.

**Maximum operation temperature**

The maximum temperature of operation is obtained by the smaller devices with a lattice parameter of a=21 \( \mu \)m. The device with a filling factor of 30% reached 100K. Since it was found that the smaller devices have the largest extraction, we can deduce that the gain degradation due to the heat extraction of large devices is higher than 2 cm\(^{-1}\).

Figure 5.15 shows the LIV characteristics of the laser with the highest temperature of operation. The fact that the device with 30 % filling factor was performing at higher temperature compared to the 20 % and 40 % shows the trade-off between power dissipation and modal gain.
5. Photonic crystal laser

Figure 5.14: Summary of the important characteristics of the three sizes of lasers.

Figure 5.15: LIV characteristics of the device showing the highest temperature of operation.
5.4 Conclusion

In conclusion we studied a large parameter space of the photonic crystal quantum cascade lasers. They performed at a maximum temperature of operation of $100 \text{ K}$ and maximum output power above $10 \text{ mW}$ at $3 \text{ THz}$. These performance are here compared with the literature around $3 \text{ THz}$. A device with a patterned top metal contact 2D photonic crystal was able to lase on a radiative mode, emitting $17 \text{ mW}$ of peak output power and a slope efficiency of $74 \text{ mW/A}$ in a $10^\circ \times 7^\circ$ single-lobed far-field, up to $105\text{K}$ [69] with $1 \%$ duty cycle, unfortunately no continuous wave performance are reported which challenges a direct comparison. A state-of-the-art third order distributed feedback lasers offer up to $15 \text{ mW}$ of peak output power with $130 \text{ mW/A}$ of slope efficiency [79], and a second order distributed feedback laser up to $25 \text{ mW}$ of peak power with continuous wave power in the tens of mW range [80]. A photonic crystal laser made of active region pillars in air that performed in single mode regime around $3 \text{ THz}$ with a similar triangular lattice [81], but no absolute performance are reported.

This work has been carried in the framework of a collaboration with
5. Photonic crystal laser

Laboratory of Advanced Semiconductors for Photonics and Electronics (LASPE), EPFL, Switzerland.
5. Photonic crystal laser
This chapter is largely based on the publication [82], and is further completed by additional measurements.

6.1 Introduction

The mid-infrared (IR) region of the electromagnetic spectrum is of particular interest, as it allows the access to the fundamental roto-vibrational transitions of most gas molecules. It is therefore the wavelength range of choice for trace gas sensing applications.

The gain profile of quantum cascade laser active media allows the heterogeneous stacking of spectrally separated active regions [83, 84]
6. Surface emitting buried ridge laser

to cover large bandwidths. This compact and monolithic coherent light source has been demonstrated in numerous cavity geometries in the mid-infrared spectral range, namely external cavity [20, 85], linear arrays of distributed feedback (DFB) lasers [86, 87], tapered oscillator [88], angled cavity broad area [89] or short wavelength [90] DFBs, ring QCLs with surface emission [91, 92], photonic crystal lasers [93, 74, 94], broadly tunable multi-segment structures [95, 96, 97] or QCL frequency combs [98]. Some realizations found application in spectroscopy [22, 99] where gas and liquid absorptions can be resolved.

The array of DFBs [86, 87] in particular has the advantage of covering a broad spectral range with a high resolution. This geometry features an electrical tunability together with the possibility of sequential firing, enabling a fast acquisition rate. In case of small dispersion, the multiple beams can be combined with a grating technique. This approach still lacks reproducibility because it suffers from an imperfect deterministic mode selection mechanism between the two band edges, one of which is ultimately favored by the phase of the facet reflection. Alternatively, ring cavity QCLs [91, 92] and photonic crystals operate on a band edge mode, they emit vertically at a deterministic wavelength. Both types of cavity have competing radiative and non-radiative modes in surface emission. The radiative modes have more losses than the non-radiative ones and tend to lose the mode competition unless the total losses are engineered accordingly. Additionally, both the ring cavities and the photonic crystals have a footprint above 400x400 $\mu m^2$ per laser, in comparison with DFBs with a footprint above 1000x100 $\mu m^2$ per laser.

As shown schematically in figure 6.1(a), our approach consists of a buried ridge, terminated by a pair of 360 periods long distributed Bragg reflectors (DBR) separated by a spacer of length $(60 + \frac{3}{4})\lambda/n_{eff}$, where $\lambda$ is the target free space wavelength and $n_{eff}$ the effective guided mode index. A unique mode is confined in the middle of the frequency gap. The extraction is realized by an additional second order Bragg grating in the middle of the spacer. The radiation escapes the structure through
6. Surface emitting buried ridge laser

Figure 6.1: (a) Schematic representation of the laser, (b) Scanning electron microscope image of a whole array and a close-up view from the window. [82]
6. Surface emitting buried ridge laser

A rectangular aperture in the top metallic ohmic contact. The aperture is about 9 µm longer and wider than the extractor figure 6.1(b). This design is immune to the phase relation between the grating and the reflection from the cleaved facets. The mode selection and extraction are achieved with two different gratings, unlike the recent proposal of reference [100] where both mechanisms are provided by the same grating.

The waveguide mode is computed for a trapezoidal buried ridge cross section featuring a 30° sidewall inclination and a 8 µm average ridge width, close to the realistic geometry of fabricated devices. The gratings are formed by a 400 nm deep material etching of the InGaAs top cladding with a duty cycle of 50 %, ultimately the groves are refilled with InP. It results in an effective refractive index difference of 0.031 for the two parts of the grating according to COMSOL simulations, taking into account the Drude free carrier correction. The coupling constant of the first order grating is 69 cm\(^{-1}\), the associated decay length is 142 µm. The total expected DBR reflectivity is 94 %. The modal overlap is 61 % for the fundamental mode and 52 % for the higher order lateral one, preventing the undesired lasing action of the latter.

The extraction grating is placed in the middle of the spacer. It features a periodicity \( \Lambda_{\text{extr}} = \frac{N-0.5}{N} \lambda/n_{\text{eff}} \) where \( N \) is the number of grating periods, to suppress the side-lobes of the usual cardinal sine far-field, the near-field amplitude is apodized as shown in figure 6.2(b). The extraction is maximized in the middle of the grating (x=0) where the groove flanks fall at the maxima of the standing wave, and minimized at the edges of the grating where the groove flanks are on a node (figure 6.2(a)). Assuming perfectly reflective DBRs the standing wave can be described by \( E(x) = E_0 \cos(2\pi x/\lambda) \). We select the subset of the grating positions \( x_j = j \ast \Lambda_{\text{extr}} \) where \( j \in [-\frac{N}{2}, \frac{N}{2}] \), consequently the near-field follows this amplitude \( E(x_j) = E_0 \cos(\pi j/N) \). In other terms, the near-field is the baseband from the spacial frequency demodulated by the grating. Thus, the near-field amplitude is shaped like the first half period of a sine function.
6. Surface emitting buried ridge laser

Figure 6.2: Simulation result of the extractor region. (a) the intensity of the $E_z$ field in the ridge. (b) The intensity of the near-field computed at the top edge of the simulation box. (c) Intensity of the $E_x$ field showing the radiating field. [82]
6. Surface emitting buried ridge laser

The efficiency of the second order grating and its optical mode profile is computed using the 2D eigenfrequency solver of COMSOL, which solutions are shown in figure 6.2. The guided standing-wave at the position of the second-order grating couples out vertically and has an electric field component along the x direction as in figure 6.2(c). The amplitude of the near-field at the top border of the simulation box has a bell shape consistently with the distance to the grating and the boundary conditions. The radiative efficiency of the grating expressed in terms of optical losses is $0.045 \text{ cm}^{-1}$ per grating period at the maximum. It results in a total computed losses of $0.22 \text{ cm}^{-1}$ and $0.64 \text{ cm}^{-1}$ for the 7- and 20-period gratings respectively.

Figure 6.3: (a) Envelope of the defect mode in blue and the band-edge mode in red. (b) Close up view of the defect mode together with the effective refractive indices. [82]
6. Surface emitting buried ridge laser

The resulting losses are then introduced as effective values in a one-dimensional transfer-matrix simulation to compute the optical mode profile along the ridge. As shown in Figure 6.3, the optical field intensity of the mode presents a plateau in the second order grating and the spacer region while it exponentially decays in the first order DBR. The extraction grating induces a minor perturbation of the electric field in the middle of the plateau region. Its characteristic coupling strength $\kappa_{\text{extr}} L_{\text{extr}} \simeq 0.1 \ll 1$ is too weak to create an additional mode.

The outer halves of the DBRs are unpumped for the following two reasons. It provides an additional mode selection mechanism between the target mode and the two band-edge modes, because the latter have a 18 % overlap with the unpumped region, while the former has 1 %. Additionally, 40 % less power is dissipated in the ridge accounting for a better temperature management.

6.2 Fabrication

The arrays are constituted of 10 electrically separated lasers and have a footprint of $1.2 \times 1.5 \text{ mm}^2$ per device. The periodicities of the gratings are tuned to cover the complete gain range by steps of $20 \text{ cm}^{-1}$. The radiation couples out through an opening in the electro-plated top contact of $70 \mu m \times 27 \mu m$ and the facets are covered in absorbing insulating varnish.

The 50 periods, two-colors active region used is based on InGaAs/AlInAs material system, lattice-matched to InP and grown using molecular beam epitaxy. The two active region designs were computed by a genetic optimization algorithm, similar to the one in [101] and is shown in the appendix A. The active region is capped with a 450 nm thick InGaAs top confinement layer, which is thicker than usual buried heterostructure distributed feedback QCLs [102]. The grating is determined by a 400 nm deep inductively coupled plasma etching of the top confinement layer. The ridges were defined by wet etching and buried using two steps of metal-organic vapor phase epitaxy. First, an insu-
lating iron-doped InP is deposited between the ridges. Secondly, the devices are planarized by a Si-doped InP top cladding growth. Lastly, a separation etch is performed to isolate the ridges electrically. The fabrication details are done according to the following reference [103].

A high resolution electro-luminescence spectrum of an extractor-less device, measured from the facet, is presented in Figure 6.4. The laser was driven below threshold by 30 ns long pulses at a duty cycle of 30%, to minimize the intra-pulse heating. The spectral peaks are the result of amplified spontaneous emission and are the signature of the optical cavity modes. From the measured value of 7.3 cm\(^{-1}\) stop-band, an index contrast of \(\delta n = \frac{\pi}{2} \frac{\delta \omega}{\omega_{n_{\text{eff}}}} = 3.2 \times 10^{-2}\) is deduced, in agreement with the design value of \(\delta n = 3.1 \times 10^{-2}\). The high peak located at the center of the stop band is the defect mode that appears at the lasing frequency. The two neighboring modes are the band-edge modes. The asymmetry of the band-edge mode intensity originates in the phase of the reflection induced by the cleaved facet, which is the uncertainty from which regular DFBs suffer. Figure 6.4 also displays the result of a transfer-matrix simulation of the same cavity where each mode and their respective losses are plotted over the luminescence spectrum. The observed frequency of the modes of the electro-luminescence is in good agreement with the computation, the latter also predicts a mode discrimination of 10 cm\(^{-1}\) between the defect and the band-edge modes. Such a discrimination is consistent with the observed device behavior which lases consistently at the defect mode.

6.3 Results

Figure 6.5 shows a spectrum of an array of 10 lasers measured at room-temperature in pulsed mode with a high resolution (0.075 cm\(^{-1}\)) FTIR system. All the spectra are single mode and emit from 1030 to 1205 cm\(^{-1}\), spanning a region of 175 cm\(^{-1}\). The side-mode suppression was found to be better than 20 dB. Nine out of ten lasers were operating on the desired defect mode, while the lasing on a band-edge mode is
6. Surface emitting buried ridge laser

![Graph showing luminescent measurement and waveguide losses.](image)

**Figure 6.4:** Measurement of the luminescent of a device without extraction grating, taken from the facet together with the computation of the losses of the modes.

attributed to a fabrication imperfection. Also reported in figure 6.5 is a spontaneous emission spectrum on the same active region. It features a flat broadband region from $1000 \text{ cm}^{-1}$ to $1200 \text{ cm}^{-1}$ in which all of the measured lasers are operating.

The threshold and current at rollover are constant across the array. It is a sign of constant optical gain and losses and of their independence from the phase of the facet reflection. Concomitantly, the low device-to-device fluctuations of the roll-over current reflect the reproducibility in the device ridge width. We attributed the remaining device-to-device power fluctuations to fabrication uncertainties and an uneven regrowth planarization of the device on top of the second order grating. The average threshold current density for the array is 5.2 kA/cm$^2$. The area used for the computation is the length of the top contact multiplied by the width of the ridge, and therefore neglects an eventual current spreading into the unpumped region. The threshold current density is higher than the expected value below 3 kA/cm$^2$ and is attributed to current leakage paths in the iron-doped InP. The maximum device power was measured at 2 mW. This relatively low power is attributed to
the leakage currents, to the relatively low radiative losses (0.2-0.5 cm⁻¹) and to the significant portion of the radiation which is emitted in the substrate.

The far-field patterns of the devices are measured with a goniometer assembly; the result is displayed in figure 6.6. The beam of the twenty periods extractor device is narrower in the longitudinal direction than transverse one where fringes are visible figure 6.6(b). They are attributed to diffraction patterns resulting from the geometry of the electrical top contact; the narrow ridge width excludes the possibility of a lasing action on a higher order lateral mode. The transverse main lobe is expected to be contained in a 69° angle. The longitudinal cross section of the far-field patterns of both the twenty and seven periods devices are shown in figure 6.6(c) from which a constant background attributed to electrical pick-up was removed. They feature a beam full-width half-maximum of 8.3° and 18.3° respectively, in agreement with the model predicting 5.3° and 15.3°. We computed the far-fields using
Figure 6.6: Measurement of the far-field of the device. (a) Angular nomenclature. (b) Far-field measurement of a 20-periods device in 2D. (c) Far-field measurement in one dimension in continuous line plotted with the computed far-field in dotted line.
an array of phased emitters whose positions coincide with the grating flanks and amplitude corresponds to the one of the underlying standing wave.

In conclusion, we presented a design of QCL cavity that combines the advantages of buried heterostructure, a potential for low optical losses and efficient heat dissipation, together with the low threshold current from the high mirror reflectivity. The approach is reliably generating equidistantly spaced emission lines for single mode operation and enables beam combining techniques with gratings, in stand-off applications. The intrinsic limit of performances for these devices is set by the resonant losses and the free carrier absorption, thus a lower threshold current density. The limited performance in the presented case originates in fabrication imperfections and an increase by a factor ten on slope efficiency, with milliwatt level in continuous-wave operation at room-temperature is expected for future realizations. We made compact arrays of surface emitting single mode devices with a high single mode yield at a deterministic wavelength, a single lobed far-field in the longitudinal direction and a bandwidth of 175 cm$^{-1}$.

6.4 Further results

A new design and process of these lasers was done by the company Alpes Laser [104] at a wavelength around 7 µm, and measured by us. Figure 6.7 shows the light-current-voltage performance of this new process. The temperature performance was significantly improved, reaching 1.2 mW of continuous wave output power at room temperature, which is similar to the peak output power of the first generation in pulsed operation. The devices show a continuous wave output power of 10 mW at -20 °C. The devices are mounted like the previous generation, epi-side up and soldered using indium. The devices have a threshold current of 200 mA at room temperature.

Figure 6.8 shows the spectrum of one laser of the array. At a constant temperature of -20 °C the tuning capability is 3.5 cm$^{-1}$ corre-
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**Figure 6.7:** Light-current-voltage characteristics of the surface emitting buried ridge at 7 µm, room temperature and continuous wave, measured with a pyrometer placed above the ridge to collect the surface emission.

**Figure 6.8:** Spectral measurement of a device operating in continuous wave at -20 °C for various currents.
Figure 6.9: Spectral measurement of a device operating in continuous wave measured at a fix voltage for different temperatures.

sponding to 10.5 GHz with the help of the gain. The tuning is unidirectional towards lower frequencies and originates in the temperature increase of the active region.

Figure 6.9 shows the tuning range achievable with heat sink temperature. A total of 10 cm$^{-1}$ which is equivalent to 300 GHz is possible by spanning the Peltier temperature from -25 $^\circ$C to 58 $^\circ$C. The devices show a good resilience to temperature and enable a large tuning.

The device was processed in the form of an array and the single device tuning exceeds the inter-laser spacing. The resulting array is potentially continuously tunable over its whole gain bandwidth of more than 100 cm$^{-1}$.

Figure 6.10 shows the lasing frequencies of an array of devices with their threshold currents at -20 $^\circ$. The threshold current are varying between 110 and 170 mA. This difference is attributed to processing errors and to the non-flat gain causes a non-constant threshold.

Figure 6.11 reports the far-field profile of the laser. The emission
6. Surface emitting buried ridge laser

**Figure 6.10:** Emission spectrum from the devices of the array plotted with their threshold current densities.

**Figure 6.11:** Transverse far-field profile. The black curve is the bare laser, the red curve is the same laser where the facets are covered with absorbing material, the green curve is the same devices covered with more absorbing material.
of these devices is not vertical, peaking at $80^\circ$. It could come from an emission from the facet. Since the device was not designed for facet emission, the quality of the facets is poor and the farfield is structured. To filter the facet components of the far-field, the facets of the devices were covered with absorbing material. The resulting intensity of emission was strongly decreased and an emission in the vertical direction is not achieved. It indicates that the emission comes only from the facet. The absence of surface emission can be caused by a wrong placement of the extraction grating with respect to the DBR, or an offset the window. The light-current-voltage performance measured at the top of the lasers has a poor collection efficiency from the facet emission, thus the LIV doesn’t represent the real output power of the devices.

6.5 Outlook and Conclusion

M. Suess et al. proposed to combine the output beams of the device. A collector ridge was bonded to the back side of the emitter chip as seen in figure 6.12. The collector ridge is placed perpendicularly to the direction of the ridges in the array. The collector ridge has an InGaAs core and an InP cladding. It features a second order grating that combines the beams of all the devices of the array. The results of this work were accepted in Photonics Technology Letters and will be published soon.

In conclusion we designed and fabricated arrays of single mode lasers with a high single mode yield and a deterministic frequency selection. The first generation of devices showed a narrow far-field pattern that follows the design. The second generation showed the resilience of the device to temperature and the expected tuning range of about $10 \text{ cm}^{-1}$. The two processes together open the path towards a continuous frequency tuning over most of the gain bandwidth in a continuous wave operation with a narrow far-field and a small footprint slightly bigger than $1 \text{ mm}^2$. The work from M. Suess et al. offers to operate the devices without collection optics offering a stable and compact
6. Surface emitting buried ridge laser

Figure 6.12: Schematic representation of the outlook device. A figure from Martin Suess

solution. This work was financially supported by Swiss National Foundation under the special measures project HIPROMIS and the quantum cascade laser frequency combs project.
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7

Antenna coupled laser

7.1 Introduction

In 1931 Andre C. Clavier demonstrated the first microwave relay, where data was transmitted between Calais and Dover over 64 km at 1.7 GHz. In the late forties, the domain of microwave communication experienced a tremendous development at Bell Laboratories where a relay between New-York and Boston was set, motivated by the cost effectiveness of cable-less communication. Eighty years later, the microwave electronics field is still being researched and new applications emerge with it.

The terahertz quantum cascade laser is an ideal platform to combine the fields of optics and microwave electronics. B. S. Williams
et al. were the first to demonstrate a microstrip line as a terahertz laser waveguide [76]. Ten years later, Maria I. Amanti [79, 105, 106] demonstrated the use of a phased array of emitters [107, 108, 109] to enhance the directionality of a single mode emitter, and Christoph Walther [110, 111, 112] showed the use of a single LC resonator as a laser cavity.

In this work we propose to use antennas to engineer the laser facet properties of a terahertz quantum cascade laser. A first design at 4.7 THz integrated a slot and a patch array antenna attached to a terahertz QCL and has been reported [113], this chapter presents an analysis of the published results and presents further results at 1.9 THz.

7.2 Double-Metal waveguides and impedance matching

7.2.1 Waveguides

Typical near- and mid-infrared laser waveguides are dielectric waveguides, using refractive index steps for confinement. They are used until the 15-20 µm wavelength range, where the free carrier absorption becomes significant. Additionally, long wavelength infrared lasers requires a regrowth thickness large enough to separate the top electrode from the optical mode, it is ultimately too large and costly at terahertz frequencies. To overcome these limitations, metallic waveguides are used, where surface plasmon polariton modes ensure the mode confinement, from the mid-infrared to the far-infrared spectral range. These modes experience a high confinement at the interface of media with $\varepsilon_{r,1} > 0$ and $\varepsilon_{r,2} < 0$, namely dielectric or semiconductor and metal or highly doped semiconductor.
7. Antenna coupled laser

**Figure 7.1:** Representation of a double metal waveguide seen from the top along with the electric field intensity of its fundamental mode.

**Figure 7.2:** Representation of the reflection induced by an impedance mismatch between two double-metal waveguides

### 7.2.2 Reflection

Plasmonic modes are bound to the semiconductor-metal interface and they are usually difficult to couple to without second order Bragg grating. In the case of double metal waveguides, two metal-dielectric interfaces confine the electric field with almost 100% overlap and a very strong confinement. The laser cavity can be best described by an impedance model, and the facet reflectivity can only be estimated using an impedance mismatch model, 

\[
R = \left( \frac{Z_0 - Z_{WG}}{Z_0 + Z_{WG}} \right)^2.
\]

The impedance of usual microstrip lines is approximated using the Wheeler’s equation:

\[
Z_0 = \frac{\eta_0}{2\pi\sqrt{2}\sqrt{\varepsilon_r + 1}} \cdot \ln \left( 1 - 4 \cdot \left( \frac{h}{W_{eff}} \right) \cdot (X_1 + X_2) \right) \tag{7.1}
\]
7. Antenna coupled laser

Where \( t \) is the metal thickness, \( W \) the width of the line, \( h \) the height of the substrate and \( \epsilon_r \) the substrate dielectric function:

\[
W_{eff} = W + \left( \frac{t}{\pi} \right) \cdot \ln \left\{ \frac{4e}{\sqrt{(\frac{t}{h})^2 + \left( \frac{t}{\omega \pi + 1} \right)^2}} \right\} \cdot \frac{\epsilon_r + 1}{2\epsilon_r} \quad (7.2)
\]

\[
X_1 = 4 \left( \frac{14\epsilon_r + 8}{11\epsilon_r} \right) \left( \frac{h}{W_{eff}} \right) \quad (7.3)
\]

\[
X_2 = \sqrt{16 \cdot \left( \frac{h}{W_{eff}} \right)^2 \cdot \left( \frac{14\epsilon_r + 8}{11\epsilon_r} \right)^2 + \frac{\epsilon_r + 1}{2\epsilon_r} \cdot \pi^2} \quad (7.4)
\]

The microstrip line model only works under the assumption that the wavelength: \( \lambda \gg 2h \cdot \sqrt{\epsilon_r} \). In our case \( \lambda \simeq 2h \cdot \sqrt{\epsilon_r} \), for this reason we have to perform finite element method computations to estimate the impedance.

### 7.2.3 Antenna

In the microwave range, to extract the electro-magnetic waves of a microstrip line, the line is terminated by an antenna. There are many ways to couple a microstrip line to an antenna, in our case we used a direct connexion to the microstrip line. The ground and the signal can’t be short-circuited because the guiding metal layers also plays the role of electrical contacts. We prefered not to pattern the ground electrode.

Patch antennas are ideal candidates in our case. They are mostly characterized by three parameters, the length \( L \) of the patch giving the resonant frequency and the width \( W \) and the thickness \( h \) giving the impedance of the patch. These parameters are displayed in figure 7.3.

The patch antenna is the shortest Fabry-Perot resonator with only half a wavelength of length. The impedance of the patch antenna is typically higher than the one of the microstrip line. It is the microwave equivalent of an anti-reflection coating of the optical regime where the refractive index of the coating is between the indices of both media of the interface. To avoid reflections at the entrance of the patch antenna,
microwave patch antennas are fed with an inset to match the local impedance, as in figure 7.4. However, in our case the dimensions of an inset would be too small for the photolithography.

At both long edges of the antenna, the field is locally rotated to an in-plane polarization. The fringing field is radiated and forms the far-field. The far-field, is thus non-zero and the antenna emits vertically. The polarization of the radiated field is along the L direction, which was the propagation direction of the field in the line. Together with second order gratings and photonic crystals they are the only solutions to achieve a vertical emission from a QCL, because of the inter-subband selection rule [114].

Patch antennas like all antennas can be put in arrays in order to narrow the far-field. In order to radiated vertically, a planar array of emitters has to be phased, the emitters should be separated by an integer number of wavelengths, usually one.
Figure 7.4: Representation of the mechanisms involved in a patch antenna, in green the electric field profile under resonance, in red the current profile under resonance and in dark gray the farfield direction.
7. Antenna coupled laser

7.3 Design

Patch antennas require a reflection at the far edge of the patch close to 100\%, to avoid field leaks in the in-plane direction. This imposes a maximum on the thickness of the antenna substrate. Planar antennas have an upper limit of the substrate thickness \( T_s < \frac{\lambda}{2n_{sub}} \) which fixes an upper bound of 8.45 \( \mu \)m in case of an antenna on GaAs, at 63 \( \mu \)m wavelength and a refractive index of 3.72. In our case a thickness of 12.5 \( \mu \)m of the active region is needed to provide enough radiated power, and would be too thick for the antenna. We designed an antenna on benzocyclobutene, a polymer with a refractive index of 1.55, setting the upper bound of the thickness to 20 \( \mu \)m.

As sketched in figure 7.5(a) our approach is a 20 \( \mu \)m wide dry-etched waveguide embedded in benzocyclobutene, terminated at one end by a high reflection distributed Bragg reflector and at the other end by the antenna. Between the amplifying section and the antenna the active region is tapered to avoid any undesired reflections at the refractive index step. The tapering offers an adiabatic change of the impedance, and thus a low reflection transition.

The fabrication was done according to the description in annexe "Active region designs" and is similar to the photonic crystals (Chapter "Photonic crystal laser"). The only difference lies in the BCB spinning step. The photonic crystal is an array of pillars, the etched and un-etched regions are homogeneously distributed on the sample surface, in the case of antenna devices the presence of ridges separated by hundreds of microns perturbs the BCB planarization.

The cavity elements are designed separately using the time domain solver of CST Microwavestudio following the aforementioned method of system decomposition. The system is too large to be simulated entirely. The system is recomposed as a Fabry-Perot cavity where the facet reflectivity is frequency dependent, both on the antenna and the DBR side, and a small lossy section is added to represent the losses in the impedance matching section. Figure 7.6 summarizes the results of
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Figure 7.5: a) Representation of the 4.7 THz slot array antenna device, b,c,d) SEM pictures of the impedance matching section, the DBR section and the ridge section respectively, taken prior to the BCB deposition, e,f,g) microscope images of the DBR section, the patch array antenna and the slot array antenna respectively.
7. Antenna coupled laser

the computations for the various elements. The impedance matching element transmits 70% of the input electromagnetic wave intensity and reflects only 0.016%. The low reflectivity is the key result, since it hinders undesired feedback to the laser. The distributed Bragg reflector features 76% reflectivity and importantly a low mode conversion, with 97% of the reflected power in the fundamental mode. The patch and slot array antenna show computed reflectivity 4.8% and 2.25% respectively. These values are to be compared with the usual facet reflectivity values for terahertz quantum cascade lasers. For single plasmon waveguides the facet reflectivity is close the the one provided by the index step to free space: 

\[ R = \left( \frac{n_{WG} - 1}{n_{WG} + 1} \right)^2 = 0.31 \text{ to } 0.33, \]

for double metal waveguides it is set by the impedance step between the waveguide and free-space, where \( Z_{WG} \) is typically below 50 Ω which gives reflectivities ranging from 0.87 at 1 THz to 0.65 at 5 THz for a ridge of 10 µm height and 150 µm width.

7.4 Results

To characterize the effect of the antenna one needs to compare it to an antennaless reference device. In our case it is referenced to a device of same processed chip with same length and width, with the same back facet without antenna and without an impedance matching section. Tables 7.1 and 7.2 pinpoint the essential values for comparison and figure 7.7 shows the results in a qualitative way. Antenna devices feature an increase of the threshold current and a reduction of the maximum operating current, an increase of the slope efficiency as well as the maximum output power. Those four are the signature of a more radiative cavity. The antenna radically reduces the facet reflectivity which translates in an increase of the cavity losses and thus of the threshold. Additionally the intra-cavity field of antenna devices are low and so is the photo generated current and the current at maximum power. The slope efficiency is proportional to \( \frac{\alpha_{rad}}{\alpha_{tot}} \) is thus big in antenna devices, and so is the maximum output power. Another sign of the effectiveness
Figure 7.6: a) Results of the computations using CST Microwave Studio, the relevant intensity transmission and reflection are plotted, b) in-plane cut of the vertical electric field component for the slot array antenna, the patch array antenna, the DBR and the impedance matching section.
7. Antenna coupled laser

<table>
<thead>
<tr>
<th>Antenna</th>
<th>$J_{\text{threshold}}$ (A/cm$^2$)</th>
<th>Slope efficiency (mW/A)</th>
<th>Max peak power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>without</td>
<td>240</td>
<td>4.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Patch array</td>
<td>281</td>
<td>18.4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.1: Comparison between the patch array antenna and an antennaless device.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>$J_{\text{threshold}}$ (A/cm$^2$)</th>
<th>Slope efficiency (mW/A)</th>
<th>Max peak power ($\mu$W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>without</td>
<td>257</td>
<td>3.5</td>
<td>400</td>
</tr>
<tr>
<td>Slot array</td>
<td>304</td>
<td>9.5</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 7.2: Comparison between the slot array antenna and an antennaless device.

of the antenna is the far-field pattern, which is similar to the simulated antenna far-field. It means that the contributions to the far-field mostly come from the antenna.

7.5 1.9 THz broadband extractor

The 1.9 THz region is of interest for spectroscopic applications because it has a carbon absorption line [CII]. A stable single mode source could be used as a local oscillator for a heterodyne measurement of emission, or could be used to do absorption measurements. The absorption losses of BCB are three times lower at 1.9 THz than at 4.7 THz as can be seen on figure 7.8.

7.6 Design

The design of the antennas at 1.9 THz was performed by Dr. Matthias Justen in Cologne university. The process and characterizations were done in ETH. It consists of a 2 by 2 and a 3 by 3 array of elliptical
Figure 7.7:  a) Light-current-voltage characteristics of the patch array antenna device in red, of an antennaless device in black, b) continuous wave spectrum of the slot array antenna with a cold finger temperature of 70K, c) angle representation of the far-field measurements, d) far-field computation ant measurement of the patch array antenna device, e) spectra of the slot array antenna device at 10 K operated at 13V in blue, 14V in blue, and the simulated slot array antenna device losses.
7. Antenna coupled laser

Figure 7.8: Absorption of benzocyclobutene at 20 °C

Figure 7.9: Visual representation of the antenna laser at 1.9 THz.

Patch antennas as showed in figure 7.9. Between the amplifier section and the antenna is a reflector with around 60 % reflectivity, that fixes the cavity length and losses. The function of the antenna is to narrow the far-field emission and deflect it in the vertical direction.

7.7 Results

The antenna devices operate up to 75 K in continuous wave (Figure 7.10), and shows a lasing action around 1.8-2 THz. At 10K the device shows a single mode behavior when operated close to threshold.
and a multimode regime when operated close to the maximum output power. Interestingly, with selected current and temperature parameters, one could force the individual lasing of each Fabry-Perot modes, which can be a useful feature for spectroscopic applications.

The far-field pattern of the 3-by-3 antenna shows a single lobe with a divergence of 35 degrees in the transverse direction and 41 degrees in the longitudinal direction 7.12. This measurement was performed in a multimode regime, and is the first reported vertical emitting single lobe multimode quantum cascade laser. The simulated multimode far-field shows a divergence of 30 degrees in both directions. The discrepancy of the simulated and measured far-field is attributed to the fabrication imperfections, especially the thickness of the BCB which is thinner than the simulated one.

The far-field of the 2-by-2 array of antennas 7.13 is also single-lobed and shows a divergence of 43 and 53 degrees in the transverse and longitudinal directions. Additionally it shows and excellent gaussicity
7. Antenna coupled laser

**Figure 7.11:** Continuous wave spectrum measurement of the 1.9 THz laser at 10 K for various currents.

**Figure 7.12:** Simulated and measured far-field pattern from the 3-by-3 antenna array.
7. Antenna coupled laser

Figure 7.13: Measurement of the far-field pattern of the 2-by-2 antenna array.

of 96 %.

7.7.1 Self-mixing

To demonstrate the ability of the antenna coupled laser to collect the terahertz electric field, a self mixing experiment was carried on 7.14. The output beam of the laser is collected on a NA=1, 2 inches parabolic mirror at 90 degrees and sent on a flat mirror 20 cm away through an optical chopper a 200 Hz. The flat mirror is mounted on a travel stage with 5 cm of travel distance, and reflects the light back to the laser output changing the intra-cavity field. The resulting intra-cavity field is the interference of the wave reflected at the laser reflector and the wave reflected at the movable external mirror similarly to the situation in an interferometer. The self-mixing signal is the measurement of this intra-cavity field, the higher the field the lower the voltage for a constant current. In this experiment, the laser is pumped at constant current with a DC power supply through a bias T. The oscillating intra-cavity field generates a variation of voltage in the laser that is recorded by a lock-in amplifier through the AC end of the bias T. The signal recorded by the lock-in is the voltage difference between the free running laser and the chopped external feedback.
7. Antenna coupled laser

Figure 7.14: Representation of the self-mixing setup.

Figure 7.15: Measurement of the self-mixing IV curve
Figure 7.16: Interferogram of the self-mixing at constant current.

Figure 7.15 shows mixing signal together with the IV curve of the laser. In this configuration the position of the flat mirror is fixed. As the laser passes the threshold, the mixing signal appears. It has an oscillatory behavior attributed to the small tuning of the laser frequency in and out of resonance of the external cavity. Compared to similar cases in literature, the self-mixing signal is one order of magnitude lower [115, 116], it is attributed to the high reflectivity of the reflector that isolates the structure optically from the environment, to the multimode nature of the device and to the low operation voltage of our device.

The movable mirror allows us to change the phase of the reflected radiations and thus to measure the interferogram of the laser, in this setup the laser measure its own spectrum. The recorded interferogram is displayed in figure 7.16. We see that the interferogram contains numerous oscillations at a higher frequency than the laser frequency. These are attributed to the reaction of the laser to the oppression of certain optical modes, and the mode competition redistributes the gain to modes with high intra-cavity field, ultimately changing the spectrum of the laser.

Figure 7.17 shows the comparison of the spectrum measured with
7. Antenna coupled laser

**Figure 7.17:** Comparison between the spectrum of the self-mixing and the FTIR.

A commercial high resolution FTIR and with our setup. The spectrum obtained by our setup has a signal-over-noise of 50, and displays sidebands that are attributed to the fluctuations of the chopper speed as well as a weak periodic misalignment of the flat mirror due to the moving stage.

### 7.8 Conclusion

To conclude this chapter, in the process of fabricating a local oscillator for astronomic heterodyne measurements, we successfully integrated various planar antennas to terahertz quantum cascade lasers, using BCB as an insulating low refractive index dielectric antenna substrate. The antennas featured quasi-gaussian far-field patterns and low reflectivity. They could extract the electric field of the laser and couple it back in the laser allowing to perform self-mixing experiments. This opens the path to efficient external mode control and feedback experiments with quantum cascade lasers. This work was performed in the framework of a collaboration with I. Physikalisches Institut, Universität zu Köln, Germany.
7. Antenna coupled laser
8.1 Introduction

The conduction band of germanium tends to decrease in energy when undergoing a tensile strain. The $\Gamma$-point decreases faster than the L valley. At a strain predicted around 5% by an 8-band $k \cdot p$ model realized in PSI, the $\Gamma$ point of the conduction band is lower than the L point, thus germanium transitions to a direct bandgap semiconductor, compatible with a silicon platform. The work by M. Suess et al. mentioned in the motivation chapter achieved to measure a tensile strain above 3.2% using a suspended microbridge as shown in figure 8.1.

The mechanism used here exploits the different thermal expansion
8. Strained Germanium laser

Figure 8.1: Scanning electron microscope image of the pad and bridge geometry used by M. Suess et al. to achieve a 3.2% strain.

Coefficient between germanium and silicon. This creates a prestrain of 0.1-0.2 % in the germanium at room temperature. The prestrain can be rearranged and concentrated in a small portion of the geometry. The latter consists of two free-standing pads of $50 \times 50 \mu m^2$ dimension, that can relax and transfer their strain in a $6 \mu m$ long, $2 \mu m$ wide and $1 \mu m$ thick microbridge. The tensile strain in the microbridge can be tailored, releasing a chosen portion of the pads. Since this geometry displayed so far the highest strain, it became the starting geometry of our work. The fracture occurs at a strain above 3.2 % which is roughly a stress of 3.2 GPa, this value varies strongly with the material and process quality. We think that the maximum strain in a sample is governed by the amount of crystallographic defects and their location in the microbridge. Defects tend to harden materials, thus a higher stress is required to strain a material.
8. Strained Germanium laser

8.1.1 Von Mises stress

In this structure the bandstructure change originates in the tensile strain, but the failure of the microbridge has to be modeled using the von Mises yield criterion [117]. It is a fairly common method of mechanical engineering to predict the fracture of objects of any size under a strain or a load. It accounts for the combined shear and uniaxial stresses in various directions on a non-uniform object. It is an equivalent stress scalar field $\sigma_v$ that can be expressed as a function of $\sigma_{ij}$ the elements of the Cauchy stress tensor. The von Mises stress satisfies the property that two stress states with equal local distortion energy have equal von Mises stress.

$$\sigma_v = 2^{-0.5} \sqrt{(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)} \quad (8.1)$$

We can refer the computation to the rupture point measured on a dogbone sample, to which the microbridge of M. Suess et al. is analogous, thus for a material of same quality any bridge geometry will rupture around a von Mises stress around 3.2 GPa.

8.1.2 Gain in strained germanium

The gain in strained germanium strongly depends on the level of strain and the carrier density in the conduction band. The effect of strain is mainly twofold, it lowers the conduction band, faster at the $\Gamma$ point than $L$ and it splits the light and heavy hole bands. The software Nextnano was used to model the conduction and valence bands. Figure 8.2 shows the effect of strain on the electronic transitions. The figure contains additionally the peak luminescence published by M. Suess et al. [14] that corresponds to the $\Gamma \rightarrow$ Valence Band (VB) transition.

For low levels of strain the structure exhibits absorption, the carriers generated in the $\Gamma$ point of the conduction band escape to the $L$-valley. The recombination is mediated by a phonon scattering pro-
Figure 8.2: Computed interband transition energies for strained germanium. The stars are the peak luminescence measurements measured by M. Suess et al. [14]
8. Strained Germanium laser

cess that lowers the recombination rate. With a strain of 4 % the bandgap remains indirect but it is possible to populate the conduction band in \( \Gamma \). The gain generated in \( \Gamma \) can overcome the losses due free carrier absorptions and net gain can take place. At a strain above 5 % the bandgap is direct and gain is strong.

The gain issuing from this bands can be computed numerically using Nextnano. The figure 8.3 shows the gain computations as a function of wavelength, of the strain and for three different carrier densities. These gains are the result of computations by Richard Geiger in Paul-Scherrer Institute (PSI).

The computations show a strong influence of carrier densities on the net gain, with maximum values of 550, 982 and 1156 cm\(^{-1}\) for the carrier densities of 0.5, 1, 1.5 \( \cdot \) \( 10^{19} \) cm\(^{-3}\). In the three cases, a net gain in germanium can be achieved for strains above 4% and for wavelengths above 2 \( \mu m \).

At a strain of 4 % the interband and inter-valence band transitions are resonant as seen in the figure 8.2. There is a risk of reabsorption of the photons generated by the inter-valence band transition, but It was neglected in the model used, because an experiment showed they are negligible.

8.1.3 Strain measurement

The method developed by M. Suess et al. to measure the strain is a Raman shift mapping measurement. In this method the phonon energy is measured via Raman spectroscopy and since the phonon energy value depends of the lattice parameter it is possible to obtain value of the strain. This method is very accurate as shown in figure 8.5 where a Raman shift measurement is compared the a strain computation.
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Figure 8.3: Gain in uniaxially strained germanium as a function of the strain level for carriers densities of 0.5, 1 and $1.5 \cdot 10^{19}$ cm$^{-3}$ computed by Richard Geiger using Nextnano.
Figure 8.4: Comparison of the strain profile measured by Raman shift and simulated by COMSOL Multiphysics.
8. Strained Germanium laser

8.2 Design

Our goal is to achieve the lasing of a germanium bridge, by designing an optical cavity capable of reaching the lasing threshold before the fracture of the structure. To judge the cavity as a potential candidate for the lasing of strained germanium we search for the threshold and we therefore need to overlap the strain and gain fields. Considering a charge carrier density of $10^{19}$ cm$^{-3}$ we can extract a gain field from the strain. Additionally we can target the point in the structure with the highest von Mises stress and extract the modal gain for this value. It is our figure of merit for the cavities.

$$g_{sup}(n, \lambda, \epsilon_{xx}) = \frac{\int_V n_{refr}^2 E^2(\vec{r}) \ast G(\epsilon_{xx}(\vec{r}), n, \lambda) d\vec{r}}{\int_V n_{refr}^2 E^2(\vec{r}) d\vec{r}} - \alpha_m$$ (8.2)

In the equation 8.2, $V$ is the volume around the cavity, $E$ is the electric field from the optical simulation, $G$ is the gain function as shown in figure 8.3, $\epsilon_{xx}$ is the uniaxial strain, $n$ the carrier density, $n_{refr}$ the effective refractive index, $\lambda$ the wavelength and $\alpha_m$ are the radiative losses. We assume a linear relation between the strain level and von Mises stress in the structure according to Young’s deformations. We want the threshold condition to be as a function of the maximum von Mises stress in the structure, because it will be the location of the rupture.

$$g_{sup}(n, \lambda, \sigma_{max}) = \frac{\int_V n_{refr}^2 E^2(\vec{r}) \ast G\left(\frac{\sigma_{max}}{\frac{\epsilon_{xx}(\vec{r})}{E_y(\vec{r})}}, n, \lambda\right) d\vec{r}}{\int_V n_{refr}^2 E^2(\vec{r}) d\vec{r}} - \alpha_m$$ (8.3)

In equation 8.3 $E_y$ is a conversion field $\epsilon_{xx}(\vec{r}) = \frac{\sigma_{max}}{E_y(\vec{r})}$, here defined as the relation between uniaxial strain ans the maximum von Mises stress. This value is computed with COMSOL.
Figure 8.5: Representation of the four cavity geometries studied in this work.
8.2.1 Air-hole distributed Bragg reflector

One of the highest $Q$ factors ever achieved was obtained using an air hole L3 photonic crystal structure or grating defect resonators [118]. In this approach the vertical confinement is done using a slab waveguide and the horizontal confinement using a 2D photonic crystal. The defect mode is a resonance in the bandgap of the photonic crystal. A precise positioning and dimensioning of the holes neighboring the L3 defect ensures a wave impedance matching and reduce the outcoupling of the mode. The geometry is not compatible with our bridge. Nevertheless it is similar to another high $Q$ approach that consists in using a photonic wire cavity with a 1D photonic crystal [119]. This approach was applied here, the geometry used is in figure 8.6.

The geometry is parametrized as a function of the free space wavelength $\lambda_0$ the bridge is $\frac{\lambda_0}{5}$ wide which is significantly narrower than the bridge published by M. Suess et al., but is necessary to keep a single mode waveguiding. The holes have a radius of $\frac{3\lambda_0}{16}$ and the period is $\frac{\lambda_0}{7}$. The $Q$-factor computed here is the two-dimensional radiative $Q$ for an empty cavity. This geometry could be highly optimized to reach $Q$ factors at least an order of magnitude higher.

The $Q$-factor achieved without any advanced matching techniques is around 30'000 which correspond to a value of losses around $4 \text{ cm}^{-1}$. This value is small compared to level of gain expected for this structure above $500 \text{ cm}^{-1}$. It is the sign that this level of complexity in the optical design suffices for our purpose, and a higher $Q$ isn’t needed.

In addition to an optical field simulation, a strain simulation of the same structure was undertaken. The result is shown in figure 8.7. In this figure we see that the strain concentrates in the bridge section but a closer look reveals that the strain concentrates between the holes and the edge of the wire, and doesn’t penetrate the inter-hole region where the optical field is. It is a clear sign of poor overlap. The figure of merit is nevertheless computed and the result is shown in figure 8.8.
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Figure 8.6: Visual representation of the optical mode a in the air-hole DFB cavity.
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**Figure 8.7:** Stress profile in the air-hole DFB cavity.
8. Strained Germanium laser

Figure 8.8: Performance of the air-hole DFB cavity as a strained laser.

From the figure 8.8 we can conclude that the structure has no chance of lasing. The overlap of the optical and the strain field is too poor and the von Mises stress generated at the borders of the holes is too high to create any strain.

8.2.2 Integrated bow-tie cavity

Another attempt is the bow-tie cavity. Its name originate from the optical path of its ray optics pattern as shown in figure 8.9.

It takes advantage of the high refractive index of germanium and exploits total internal reflections to redirect the light on the narrow ridge. The light escaping the narrow region is collected by an off-axis parabolic mirror then sent to the opposite parabolic mirror and focused back in the narrow region. The four parabolic mirrors are arranged so that the two top ones have their focal point on the bottom edge and vice versa. The Q factors obtained are above 500.

The von Mises stress profile in figure 8.10 reveals a concentration of the von Mises stresses in the concave bends. The strain profile shows a fairly high level of strain in the constriction and a partial strain in the mirror sections.
**Figure 8.9:** Optical field and cavity profile of the bow-tie cavity.
Figure 8.10: Strain and von Mises stress profile of the bow-tie cavity.
The structure was fabricated as in figure 8.11. The structure was strained and measured, unfortunately, no lasing was measured and no cavity modes were found before fracture. The fracture occurred exactly at the location of highest von Mises stress which confirms our modeling. The SEM image reveals that the quality of the sidewalls and the geometry processed is very close to the design.

The failure of the cavity can be explained with the figure of merit used in the two precedent cases shown in figure 8.12. The cavity fails to reach a threshold. In this case the parabolic mirror region is partially strained, it is worse than in the case of the cornercube because it is not possible to induce transparency in the pads due to the partial strain. Inevitably the losses in the pad will hinder the lasing.

Figure 8.11: SEM image of the realization of the bow-tie cavity.
8. Strained Germanium laser

8.2.3 Parabolic cornercube

Patterning the bridge with holes or reflecting structures was proven a too aggressive approach. The following cavity uses the dog-bone geometry for the microbridge. The light emitted from the constriction to the pad region is reflected back in the microbridge. Figure 8.13 shows the shape of the cavity.

The geometry takes advantage of the high refractive index of germanium where the critical angle of total internal reflection with an interface to air is small $14.5^\circ$. Here the light hits a semiconductor air interface above the critical angle and is in principle reflected at 100% regardless of the frequency. The light emitted from the output of the bridge is divergent. One parabolic mirror collects the light in a collimated beam, which is further focused back in the bridge output by a second parabolic mirror. The two parabolic mirror share the same focal point, which is roughly at the output of the bridge. The distance separating the mirror pair from the bridge is around 8.5 $\mu$m. It is a trade-off to be made, between minimizing the light path in the unstrained region and minimizing the impact of the mirror pair on the strain pattern.

There are two major sources of radiative losses in this cavity. The
coupling efficiency of the reflector back in the bridge is one of them. The focal point of the pair of parabolas coincides with the entrance of the constriction, but the mode matching is imperfect. Secondly, the intersection of the two parabolas forms a tip tip that radiates the incoming field. In that point the total internal reflection condition can’t be fulfilled. The resulting Q factor of the empty cavity is around 5000 which results in a mirror loss of 25 cm\(^{-1}\). The radiative losses are higher than the air-hole DBR case. An advantage is that the cavity is multimode and will allow for eventual imprecisions occurring in the gain computations.

Figure 8.14 shows the von Mises stresses and the uniaxial strain in the structure. The maximum occurs at the curvatures at the entrance of the bridge which is typical for dog-bone structures. High stress centers are not necessarily located at the constriction but can appear at concave bends. The uniaxial strain field shows a tensile strain in the constriction and at both end a sudden drop of the strain to zero or even a negative tensile strain, or compressive strain at both ends of the cornercube. The perturbation of the strain pattern in the microbridge
Figure 8.14: COMSOL strain and stress simulation results showing the uniaxial strain in the horizontal direction and the von Mises stress field of the structure.
induced by the parabolic cornercube is negligible.

Figure 8.16 shows the figure of merit of that cavity. The threshold conditions are never reached, and it is due to the free carrier absorption in the unstrained region. We can see that at von Mises stresses around 6 GPa there is a sudden increase in gain. This shows the correct operation of pumping the strained region. Our gain model is limited to values of strain below 6 %, corresponding in this case to 7.2 GPa, $E_y$ is thus 120 GPa for the cornercube cavity. One solution to it is to focus the pumping beam on the strained region and not generate carriers in the unstrained region to avoid losses. So far this approach gave the best experimental results, the luminescence spectrum shows the a series of peak associated with the cavity modes.

The processing and the measurement were performed by E. Marin and T. Zabel in PSI. We see that the luminescence peaks at 2.6 $\mu$m which according to our model is the signature of a strain around 4%, but their measurement of the strain reveals a value around 3.4%. According to our model it means that the bridge was able to survive a von Mises stress of 5 GPa.
8. Strained Germanium laser

Figure 8.16: Photoluminescence spectrum measured in reflection, pumped with a green continuous wave source at 10 mW at room temperature.

8.2.4 Laterally corrugated bridge

In order to exploit the gain, the electric field needs to be confined in the microbridge, therefore the bridge needs to be patterned. The air-hole DBR cavity clearly showed that removing material from the ridge section creates stress centers that inhomogenize the strain and thus the gain, in this case material was added to the sidewalls of the bridge. In this cavity the bridge perturbation is following a periodic pattern as shown in figure 8.17.

Infinite structure

Figure 8.18 shows the photonic bandstructure of the laterally corrugated bridge. In the left half of the figure we see the bands of the forward propagating waves with a positive slope. The bottom band is the fundamental mode. The exited mode bands have a cut-off and start at a finite energy. The backward propagating band are the ones with negative slope.
Figure 8.17: SEM image of the realization of a laterally corrugated ridge.

\[ v_g = \frac{d\omega}{dk} \] (8.4)

At the edge of the first Brillouin zone the forward and backward propagating waves anticross and open a gap, which is highlighted in the right part of the figure 8.18, with yellow splitting for the odd numbered modes and blue for the even numbered. At the edge of the Brillouin zone the bands have a zero group velocity since the slope of the bands drops to zero, they are points of slow light where lasing can potentially take place. Note that the splitting can be larger than the inter-mode frequency spacing, this case is highlighted in brown in the figure where the lower band edge mode of 6\textsuperscript{th} order is lower in energy than the upper band edge mode of 5\textsuperscript{th} order. Since the waveguide is wide multiple modes can propagate. For an unperturbed waveguide these modes are orthogonal and don’t couple to each other.

For perturbed waveguides, the coupling between forward and backward propagating waves is stronger for modes of higher order, the grating on the sides is coupling the modes and a higher modal overlap with the side grating teeth increases the coupling strength, as shown in figure 8.19. Additionally the modes couple to counter-propagating wave
of the same order parity. For example the backward propagating band of the second order mode anticrosses the forward propagating band of the fourth order mode. Consequently there are points of slow light in the first Brillouin zone. As long as these modes stay below the cone of light they don’t out-couple and have a high Q factor.

Figure 8.19 shows a trend valid for relatively small perturbations. It shows the linear behavior of the overlap of the square electric field of the optical mode with the tooth region, highlighted in orange, as a function of the tooth height. Additionally the relative splitting defined as \(2\frac{\nu_2 - \nu_1}{\nu_2 + \nu_1}\) is displayed as function of the tooth height, which also gives a linear relationship for small perturbations.

**Grating optimization**

A small set of parameters govern the behavior of the laterally corrugated bridges. In order to model the band diagram as desired, the grating period, depth, duty cycle and the bridge width have to be adjusted properly.

As shown in figure 8.20, the propagation direction of upper band
8. Strained Germanium laser

Figure 8.19: Comparison between the overlap of the square electric field with the teeth region and the computation of the coupling strength of the grating.

Figure 8.20: Visual representation of the propagation of light in the laterally corrugated ridge.
edge mode of 5th order has an angle \( \theta \). For small angles the light will propagate a longer path in the DFB than with a large incident angle, but the reflectivity has to be optimized. The interaction of the wave with the gratted sidewalls can be studied by computing the reflectivity of such grating. Four key parameter are identified, the grating depth, the period, the incidence angle and the duty cycle of the grating.

Figure 8.21 shows the dependence of the reflectivity with the angle of incidence for a wavelength of 2 \( \mu \)m, a period of 400 nm, a grating depth of 230 nm and a duty cycle of 55\%. The reflectivity is the one depicted in figure 8.20. We see that the peak of reflectivity in this simulation is located around 40 degrees of incidence, that is higher than the critical angle of total internal reflection. The angle of incidence can be chosen tailoring the width of the waveguide. We notice that the reflection at an angle is larger than the normal reflection, it is because the angle is under the angle of total internal reflection and that part of the light is transmitted. The peak angle corresponds to an in-plane wave vector that is half the grating’s wavevector. The width of the reflection peak is due to the finite angle of acceptance in the simulation.

Figure 8.22 shows the dependence of the reflectivity as a function of the duty cycle. Obviously the reflectivity drops to 0 at both extrema of 0 and 1. The duty cycle governs the amount of reflection from the first and the second interface, at the bottom of the top of the grating teeth.
8. Strained Germanium laser

**Figure 8.22:** Simulation of the reflectivity of the grating as a function of the duty cycle of the grating.

**Figure 8.23:** Reflectivity of the grating as a function of the depth of the grating. The blue dot represents the optimal operation point for the lower band-edge modes and the red dot the optimal operation point for the higher band-edge mode.
8. Strained Germanium laser

Figure 8.23 shows the reflectivity as a function of the grating depth, at 40° of incidence angle a period or 400 nm and 55% duty cycle. We see a periodic behavior. The grating is seen as an effective medium with an effective reflective index tailored by the grating duty cycle and the effective thickness is the depth of the grating. At depths of 0, 0.75 and 1.5 $\frac{\lambda}{n_{Ge}}$ there is a zero reflectivity of the grating, the phases reflections on the top and the bottom of the grating tooth are equal and no diffraction occurs. At depths of 0.44 and 1.16 $\frac{\lambda}{n_{Ge}}$ there is a condition of maximum reflectivity, which is the optimum working point for lower band edge modes as marked with a red dot. The optimal point of operation of the higher band edge mode is the middle of the downwards slope as marked with a blue spot. The optimal condition, in both cases, is when the phase of the incident and reflected waves interact constructively. The phase of the reflected wave is controlled by the depth and the effective index of the grated region as in a Gires-Tournois interferometer.

Finite structure

Figure 8.24 shows the resulting Q factors for a 20-period structure. The structure is tailored to operate on the upper band edge mode of 5th order, which is the mode of highest Q factor. In the bandwidth of simulation the solver found the desired mode and as well the lower band edge modes of 6th and 7th order. Additionally some mesa modes are found, interestingly the mesa modes have a lower energy than the fundamental, it is an atypical behavior and can be explained by the bandstructure. The slope of the upper band of 5th order is positive close to the edge of the Brillouin zone, the small variation in wave-vector induced by the finite size brings these excitations to a lower energy.

Figure 8.25 shows the evolution of the Q factor as a function of the number of grating periods. We see a decrease of the growth of Q factor around 20 periods and a stabilization around 25 periods.

We can write the contributions of the directions of loss as follows.
Figure 8.24: 2D result of a COMSOL eigenfrequency simulation of a finite
length bridge, showing the out-of-plane electric field component. The dots in
blue represent the lower band edge modes and the blue dots the upper band
edge modes.

Figure 8.25: 2D result of a COMSOL eigenfrequency simulation of a finite
length bridge, showing the out-of-plane electric field component. The dots in
blue represent the lower band edge modes and the blue dots the upper band
edge modes.
\[ \frac{1}{Q} = \frac{1}{Q_\parallel} + \frac{1}{Q_\perp} \]  

(8.5)

Where \( Q \) is the Q factor of the empty cavity, \( Q_\parallel \) is the component that is parallel to the waveguide direction. This contribution evolves exponentially with the number of periods. For large period numbers \( \frac{1}{Q} \) tends to \( \frac{1}{Q_\perp} \) which is the contribution radiated from the surface.

Our approach 8.17 consist of patterning the sidewalls of the bridge in a square grating in a way that supports a high Q 5th order lateral mode. The shape of the original bridge is conserved and the strain remains homogeneous along the bridge, where the field is also located.

**DFB performance**

The threshold condition is computed for the DFB cavity and shown in figure 8.26. It is the only one of the four cavity designs that fullfilled the threshold condition. It is reached for wavelengths above 2.5 \( \mu \)m and a maximum von Mises stress above 6 GPa. The success is attributed to the high overlap between the field and a constantly high level of strain, and the absence of strong stress centers. The work of M. Suess et al. shows a maximum von Mises stress of slightly more than 3 GPa and the work of E. Marin et al. reached a von Mises stress of 5 GPa. Consequently the germanium layer needs to sustain a slightly higher stress than the previously achieved results.

The model is also out of the gain model span above 9 GPa, which gives \( E_y = 150 \) GPa. So far no evidence of enhanced luminescence was found on the lateral grating cavities. It is due to the slightly smaller tolerance of this cavity. Indeed the strain generation is more expensive in stress, the cavity ruptures before reaching the required strain.

**Limitations**

We can study the effect of disorder on the structures by randomly changing dimensions in a design. The degradation of the optical mode can be quantified and related to the amplitude of disorder.
8. Strained Germanium Laser

Figure 8.26: Threshold prediction of the laterally corrugated ridge.

Figure 8.27: Visualization of the generation of a new design introducing disorder to the standard design.
Figure 8.27 shows the processes of generation of disorder in the structures. A routine, using Matlab to generate a script used by Auto-cad to generate a .cad file used by COMSOL to compute the Q-factor was employed. The contours of the DFB grating are shifted by an random amount. A flat distribution was used allowing the contours to move by an amplitude of 10 nm around the initial value. Ten random structures were tested.

Figure 8.28 shows the result of the introduction of disorder. The average Q factor achieved is around 5200, a shift of the resonant frequency of 1% is noticed, and the fundamental mode and the excited mode start to form a continuum. The reduction in Q factor is attributed to a coupling of the desired mode with propagating modes around the edge of the Brillouin zone.

The simulations of the device were so far always done in two dimensions. We could nevertheless do a 3-dimensional simulation of a single period of the structure, using periodic boundary conditions. When per-
Figure 8.29: Electric field of the TM40 and the TE21 modes with a slab thickness of 800nm
forming a 2-dimensional simulation we always assume that the TE and TM modes are independent. The 3-dimensional study shows that there is a coupling of about $100 \text{ cm}^{-1}$ between certain TE and TM modes. Figure 8.29 shows the target fifth order lateral mode or TM40 mode with 3 different colormaps to identify the directions of the electric field as well as the norm. We see that the electric field norm matches the $z$-component of the electric field. It means that the mode is almost purely TM. The $y$-component doesn’t appear, and a similar conclusion can be made with the side views. On the contrary the TE21 mode is mostly along the $y$-direction as can be seen on the side view plots.

Figure 8.30 shows the evolution of the frequency of the two modes as a function of the slab thickness. A maximum coupling is simulated at the anticrossing around 400 nm, for the nominal thickness of 1 $\mu$m the TM40 mode is expected to have a negligible electric field in the propagation direction $y$. The coupling depicted here could potentially
be the source of losses as part of the electromagnetic energy of the TM40 mode escapes the waveguide by the TE21 mode.

8.3 Conclusion

In conclusion, four cavity geometries were investigated, the cornercube cavity obtained the best experimental results, by local optical pumping of the bridge. Cavity modes of a cornercube cavity were measured, which is the sign of the proximity of the threshold. The laterally corrugated ridge gave the best results in terms of threshold von Mises stress. So far the laterally corrugated bridge showed any cavity mode in their luminescence because the structures fractured before reaching the required amount of strain of 6 GPa. The coupling between TM and TE modes and the decrease in Q factor because of disorder are potential threats to the performance of the cavity. This project is further carried on by the research group of PSI. This work is performed in the framework of a collaboration between various entities, Laboratory for Micro- and Nanotechnology (LMN), Paul Scherrer Institute, Villigen, Switzerland, CEA / Léti, Grenoble, France, Laboratory for Nanometallurgy (LNM), ETH Zurich, Electron Microscopy (EMEZ), ETH Zurich and L-NESS, Dip. di Fisica del Politecnico di Milano, Polo di Como, Italy.
9

Dispersion Compensation in quantum cascade lasers

9.1 Octave spanning semiconductor laser frequency comb

In the field of spectroscopy, frequency combs enable dual-comb techniques. In dual comb spectroscopy, two frequency combs with slightly different repetition rates are used. The light of one comb is used to perform a transmission measurement, using a fast photodetector. The light of the second comb is directly shone on the detector. The beating of the two combs on the detector generates a radio frequency (RF)
comb. The amplitude of the RF comb lines are proportional to the product of amplitude of both light combs. The light absorption spectrum of the first comb is thus appearing in the radio frequency domain and can be recorded by a spectrum analyser. The absorption spectrum is mapped to the optical domain a posteriori.

The resolution of the dual comb technique is given by the linewidth of the two optical frequency combs and is much higher than the measurement performed by a fourier transform interferometer, whose resolution is governed by the length of its delay arm. For mid-IR quantum cascade lasers the resolution of the technique corresponds to an interferometer with a 1 km long delay line. The linewidth of the optical frequency combs is usually governed by the laser driving instruments. However, the fundamental limit of the linewidth, given by Shawlow and Townes, originates in the spontaneous emission rate. To reach this limit, the linewidth of the optical frequency combs needs to be narrowed by stabilization technique, for exemple, locking the optical comb to a stable source. The laser can also be self-referenced, using a 1f-2f technique, if the laser bandwidth exceeds one octave. In this technique, one of the low frequency line is selected and frequency doubled. It is then compared to the closest line of the upper frequencies. The beating of the frequency-doubled line and the high frequency line gives the carrier envelope offset frequency that can be locked to a narrow RF source.

Terahertz quantum cascade lasers were recently shown to operate as frequency combs [120]. They were also recently shown to operate over an octave of bandwidth [121] but not in a comb regime. The dispersion of the gain breaks the comb regime for high gain values. In this work, we try to extend the comb regime of a THz quantum cascade laser to more than an octave in order to enable 1f-2f stabilization techniques.
9. Dispersion Compensation in quantum cascade lasers

Figure 9.1: Visual representation of a pulse compressing dispersive mirror.

9.1.1 Dispersive mirrors

Dispersive mirrors are an important element of the optics tool set. Their usual functionality is to compensate the dispersion of light that arises from the propagation in a medium. For example an optical pulse that was chirped by the propagation in a waveguide can be compacted again by the reflection in a dispersive mirror as sketched in figure 9.1.

Dispersive mirrors are characterized by their group delay dispersion (GDD). The GDD can be computed from the mirror’s complex reflection coefficient $r(\omega)$. The phase of the reflected wave compared to the input wave can be retrieved with $\phi = -\tan^{-1}\left(\frac{\text{Im}(r)}{\text{Re}(r)}\right)$ [122]. The sign of the phase depends on the convention taken for time. The group delay is then obtained with $GD = \frac{d\phi}{d\omega}$ and its dispersion is then

$$GDD = \frac{d^2\phi}{d\omega^2}$$

(9.1)

With a typical unit of $\text{fs}^2$.

Dispersive media are usually described by their group velocity dis-
9. Dispersion Compensation in quantum cascade lasers

Dispersion (GVD). The frequency dependent refractive index is \( n(\omega) \). The group index is defined with \( n_g(\omega) = n(\omega) + \omega \frac{dn}{d\omega} \), the group velocity is simply \( v_g = \frac{c}{n_g} \) and the group velocity dispersion is \( GVD = \frac{d}{d\omega} \left( \frac{1}{v_g} \right) = c^{-1} \frac{dn_g}{d\omega} \) and has a typical unit of \( fs^2/mm \).

If a dispersive mirror attempts to compensate the dispersion induced by a medium of thickness \( d \), the following relation should hold: \( GVD_{medium} \cdot d = -GDD_{mirror} \).

9.1.2 Group velocity dispersion in quantum cascade laser waveguides

Waveguides are strongly dispersive, as shown in figure 9.2, showing the effective refractive index of a typical mid-IR quantum cascade laser waveguide, together with the computed GVD. This simulation is two-dimensional and contains no material, electronic or gain dispersion.

The dispersion of a dielectric waveguide is usually strong and positive for longer wavelength and may become negative at shorter wavelength. This dispersion is problematic when trying to realize a quantum cascade laser frequency comb. Frequency combs are defined in this context as a laser with equidistant frequency lines. In Fabry-Perot cavities the frequency lines are spaced by the free spectral range \( \Delta k = \frac{1}{2n_g(k)L} \), where \( n_g \) is the group refractive index and \( L \) the cavity length. If the group index is constant for any \( k \), the GVD will be zero and the laser operates as a comb. We can compute the constrain of a constant GVD on the refractive index of the medium, or the effective refractive index of a waveguide.

\[
GVD = cst \Rightarrow n_g = c \cdot GVD \cdot \omega + n_0 \Rightarrow n = \frac{a}{\omega} + \frac{c \cdot GVD}{2} \omega + n_0 \quad (9.2)
\]

We can see here that a GVD=cst, the refractive index takes three terms, in \( \omega^{-1} \), a constant and \( \omega^1 \), and if the GVD=0, it takes the form \( \omega^{-1} \) plus a constant. The aforementioned function gives one degree of
Figure 9.2: Electric field of the fundamental mode. Group velocity dispersion and effective refractive indices of the fundamental mode in a conventional buried heterostructure mid-infrared quantum cascade laser. The effective index is computed using COMSOL with tabled refractive indices at 7.5 μm.
freedom on the value of the parameter \( a \). It is generally difficult to engineer a waveguide to have zero GVD on a large bandwidth but the addition of a dispersive mirror can compensate for a known dispersion. The wave transfer matrix method becomes a necessary tool to engineer such a mirror.

### 9.1.3 Dispersion compensation in quantum cascade lasers

The dispersion in quantum cascade lasers is the sum of various dispersions. The (Aluminum) Gallium Arsenide has a material dispersion, especially above 4 THz when approaching the phonon band [123], the signature of this dispersion can be found in the group refractive index deductible from the inter-mode spacing of a Fabry-Perot cavity, it approaches 4.2 for a laser at 4.7 THz where the effective refractive index is around 3.7. The waveguide induces a dispersion, due to the dimension of the mode that scales with the wavelength. In that respect metallic waveguides have a lower dispersion than dielectric waveguides. In some cases the two dispersions can compensate each other, like optical fibers around 1310 nm. The gain is another source of dispersion [124].

Quantum cascade lasers have been shown to operate as frequency combs at small and flat gain regimes for example [120, 125, 98, 126]. It is due to the existence of \( X^{(3)} \) non-linearities, especially the four-wave-mixing (FWM) term [127]. The four-wave mixing imposes a strict energy conservation on the mode’s frequency separation and can compensate for small dispersions. An accurate modeling of the FWM effect on QCLs was done by Villares et al. [128]. As the gain increases the dispersion of the active region increases and becomes too big for the four wave mixing to hold the comb regime. The injection of RF at the round trip frequency of the laser can restore the comb regime or tune the inter-mode beating using \( X^{(2)} \) nonlinearities [129].

In order to measure the dispersion of THz QCLs, the emission of two broadband lasers from the same active region was recorded with
an FTIR. The resolution of the FTIR is $0.075 \text{ cm}^{-1}$. It was virtually increased by zero-padding methods. A peak recognition algorithm was run to obtain the list of operation frequencies as precise as possible. For a Fabry-Perot cavity:

$$\nu_i = \frac{c \cdot i}{2n_{\text{eff}} L} \quad (9.3)$$

In this expression, $\nu_i$ is a list of frequencies, $i$ is the index of the mode, $n_{\text{eff}}$ is the effective refractive index and $L$ the cavity length. We then select the cavity length $L$ that minimizes the difference between the measured and the computed frequencies. In this way we can associate an index to each of our measured Fabry-Perot modes. The phase gained by each of these modes in a roundtrip is then simply $\Phi_i = 2\pi i$, thus:

$$\Phi_i = \frac{4\pi n_{\text{eff}} L \nu_i}{c} \quad (9.4)$$

For small dispersions the phase $\Phi(\omega)_i$ is mainly linear. The phase was fitted using a polynomial decomposition. The zeroth and first order polynomial term contain no informations about the dispersion of the laser. They were removed without impacting the measurement of the GDD. The left-over are the phase residuals.
Figure 9.3 shows the residuals of the phase for the two lasers. Each dot represents a mode of the laser. We can see that this method to retrieve the phase lacks of the necessary resolution to allow the use of a derivative, but is sufficient to recognize a structure. The phase is flat between 1.7 and 2.6 THz and describes a peak at 3 THz, which can be the reason for the interruption of the comb operation for higher gains. For this reason we use a polynomial or Chebyshev polynomial fitting of the phase in order to perform the two derivatives to compute the GDD.

An alternative technique to retrieve the phase from the interferometer measurement is to use the interferogram of the laser. The echoes of the interferogram central burst contain the phase shift information required to compute the GDD. First of all the degree of first order coherence is the measured interferogram value [130].

\[
G^{(1)}(\tau) = \langle E(t)E^*(t + \tau) \rangle_t \tag{9.5}
\]

We can use a field written as a train of pulses.

\[
E(t) = \sum_{n=-\infty}^{+\infty} A(t - n\tau_{cav})e^{i\omega_0(t-n\tau_{cav})}e^{in\phi(\omega)} \tag{9.6}
\]

\(A\) is an enveloppe function centered in 0, \(\omega_0\) is the carrier frequency, \(n\) is the index of the pulse, \(\tau_{cav}\) is the cavity round-trip time and \(\phi(\omega)\) is the frequency dependant phase shift encountered by the wave traveling once in the cavity. If the laser operates as a comb, \(\phi(\omega) = constant\). We can now rewrite the autocorrelation function.

\[
G^{(1)} = \langle \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} A(t-n\tau_{cav})A^*(t+\tau-m\tau_{cav})e^{i\omega_0((m-n)\tau_{cav}+\tau)}e^{i(n-m)\phi(\omega)} \rangle_t \tag{9.7}
\]

The product of enveloppes can be expressed like this.

\[
I_{corr}(\tau) = \int_{-\infty}^{+\infty} A(t)A(t + \tau)dt \tag{9.8}
\]
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For an envelope with a smaller extension than $\tau_{\text{cav}}$. We would like to know the behavior of the interferogram around the first and second echoes of the central burst, when $\tau$ is around $\tau_{\text{cav}}$ and around $2\tau_{\text{cav}}$. The first case implies that $m=n+1$, and thus:

$$G_{n=m+1}^{(1)} = \sum_{n=-\infty}^{+\infty} <A(t-n\tau_{\text{cav}})A^*(t+\tau-m\tau_{\text{cav}})>_t e^{i\omega_0(\tau_{\text{cav}}-\tau)}e^{-i\phi(\omega)}$$  \hspace{1cm} (9.9)

and in the case of the second echo where $n=m+2$ we have:

$$G_{n=m+2}^{(1)} = \sum_{n=-\infty}^{+\infty} <A(t-n\tau_{\text{cav}})A^*(t+\tau-m\tau_{\text{cav}})>_t e^{i\omega_0(2\tau_{\text{cav}}-\tau)}e^{-i2\phi(\omega)}$$  \hspace{1cm} (9.10)

We would like to extract the spectral information so we take the Fourier transform of both preceding expressions.

$$I_{n=m+1} = \mathcal{FT}(I_{\text{corr}}) \ast \delta(\omega - \omega_0)e^{i\omega_0(\tau_{\text{cav}}-\tau)}$$  \hspace{1cm} (9.11)

$$I_{n=m+2} = \mathcal{FT}(I_{\text{corr}}) \ast \delta(\omega - \omega_0)e^{i\omega_0(2\tau_{\text{cav}}-\tau)}$$  \hspace{1cm} (9.12)

To retrieve the phase we combine these two expressions.

$$\Phi = -\tan^{-1}\left(\frac{Im(I_{n=m+2})}{Re(I_{n=m+2})}\right)+\tan^{-1}\left(\frac{Im(I_{n=m+1})}{Re(I_{n=m+1})}\right) = \phi(\omega) - \omega_0\tau_{\text{cav}}$$  \hspace{1cm} (9.13)

The $\omega_0\tau_{\text{cav}}$ term is linear and can be removed by a first order polynomial fitting. The result is the frequency dependent phase.

Figure 9.4 shows the comparison between the two techniques. The results are qualitatively similar. In the first case we first measured the spectrum and retrieve the phase from the reciprocal space of the FTIR and in the second case we retrieved the phase from the direct space. There is a frequency shift between the two measurements which is hardly explainable. A potential explanation is in the uncertainties of
the techniques. The phase is plotted, subtracted from the fitted first order polynomial. Secondly, in the interferogram method the echoes are not clearly distinguishable and they extend over a larger time than the cavity round-trip. An apodization has to be used to isolate the individual echoes, a situation not encountered while measuring a MIR QCL, due to the faster $\frac{1}{\nu}$ period compared to the cavity round-trip time.

### 9.1.4 Gires-Tournois interferometer

There are two main types of mirrors to compensate the dispersion of a semiconductor laser, either a Gires-Tournois interferometer (GTI) [131] or one can use a more elaborate version of the GTI, the double chirp mirror [132, 133, 134]. Figure 9.5 shows a schematic for both mirrors. The GTI is represented on top and features 3 elements, the input waveguide on the left, a dielectric coating in the middle that provides an interface reflectivity $R$ and an optical path $d$ and a gold coating on the back to ensure a broadband reflectivity. The double chirp mirror features the same elements, the input waveguide on the left, the core of the DCM in the middle providing a complex reflectivity function dependent on the position and the wavelength it is then terminated by a
9. Dispersion Compensation in quantum cascade lasers

Figure 9.5: Visual representation of the dispersive effect of Gires-Tournois interferometers and double chirp mirrors.

Bragg mirror to ensure a good reflectivity.

The group delay dispersion from a Gires-Tournois interferometer can be computed analytically summing over all possible reflection combinations. The resulting GDD is the following:

\[
GDD = 2R(1 - R)^2 \tau^2 \sin(\omega \tau)/(1 + R^2 - 2R \cos(\omega \tau))^2
\]  

(9.14)

where \( \tau \) is the roundtrip time. It can also be computed using a transfer matrix method as shown in Figure 9.6.

The down side of GTI as dispersive mirrors is that the degree of freedom is small. There are only two parameters that can possibly change, and if the refractive index of the coating is fixed then only \( \tau \) can be changed. Increasing the round trip time will increase the dispersion induced by the mirror and reduce the bandwidth. On the other hand, double chirp mirrors have been reported to be able to generate a negative GDD over more than an octave of bandwidth [134].

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Figure 9.6: Group delay dispersion of the Gires-Tournois interferometer using our simulation method and the analytical form.

9.1.5 Dispersion of a Bragg Mirror

The building blocks of double chirp mirrors are the same as for Bragg mirrors namely an alternation of various thicknesses of two materials of different refractive indices. The dispersion in the group delay induced by a Bragg mirror is almost flat, is zero at the Bragg frequency and has the characteristic shape described in Figure 9.7. We notice that the flat region is only existing in the high reflectivity zone, outside the stop band the GDD takes strongly varying values. It is a prerequisite for the double chirp mirror that the reflectivity is high, because it attempts to control the phase of the reflected wave. Generally, if the two materials have a strong index mismatch, it is possible to compensate for an amount of dispersion over a large bandwidth, and if the index mismatch is small the mirror can compensate for large dispersions over small bandwidths.

The GDD in double chirp mirrors is often described as being due to a frequency-dependent field penetration depth in the mirror, the high frequencies reflected first and the low frequencies deeper. A frequency-
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Figure 9.7: Group delay dispersion (gray), Reflectivity (red) and phase (black) of the wave reflected by a distributed Bragg reflector.

dependent path difference is induced and, in the case of Fabry-Perot lasers, it would translate into different effective cavity lengths. The penetration depth around the stop band of a DBR mirror are displayed in Figure 9.8.

In this mirror we see that the stop band is present where the field penetration length is small. The band edge modes are also present on the right and left of the stop band.

9.1.6 Duty cycle chirped mirror

We can impose a chirp of the duty cycle of the Bragg mirror while keeping the Bragg frequency at the same value, here \(100\, \text{cm}^{-1}\). The chirp rule is shown in figure 9.9. The ten first periods of the mirror feature a chirp that is linear in stop-band width versus period number starting with 97% duty cycle and ending with 50%. Another 5 periods at 50% duty cycle were added to the mirror to ensure a good reflectivity over the whole range.

The resulting field penetration shows a V-shaped bandgap at the first order Bragg condition. The bandgap appeared at the second order Bragg condition. We desire that the short wavelengths are reflected
Figure 9.8: Field penetration of a Distributed Bragg reflector with a Bragg frequency at 100 cm$^{-1}$

Figure 9.9: Field penetration in a duty-cycle chirped Bragg mirror
by the first part of the mirror and the long wavelengths deeper in the mirror, therefore the Bragg wavelength needs to change with the duty cycle.

### 9.1.7 Bragg wavelength chirped mirror

When imposing a chirp on the Bragg wavelength, where short wavelengths are reflected at the front of the mirror and long wavelengths at the back, a negative group delay dispersion is created, which is the case we would like to pursue. A positive dispersion would cause the additional problem because the short wavelengths light would need to travel to the bottom of the chirped mirror would have to pass the long frequency mirror first, that would diffract the light perpendicularly.

Figure 9.10 shows the field penetration depth in the case of a 10-period frequency chirp of 2.5\% per period and an additional 5 periods at the Bragg frequency. The result is a slightly larger gap. Around 80 wavenumbers we notice some low Q band edge modes that do not penetrate entirely in the mirror. It is due to the impedance mismatch.
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Figure 9.11: Field penetration in a double-chirped mirror

between the mirror and the input region.

9.1.8 Double chirped mirror

Changing simultaneously the Bragg wavelength and the duty cycle allows to generate a negative group delay dispersion, while matching the impedance between the waveguide region and the mirror. The chirp rules used in this example is the combination of the two aforementioned duty cycle chirp and wavelength chirp rules.

Figure 9.11 shows the field penetration depth in case of the double chirp mirror. We notice an absence of strong modes and the curvature on the low wavenumber side.

Figure 9.12 summarizes the GDD observed in three cases, when the duty cycle (DC) is chirped, when the Bragg frequency is chirped and when both are chirped simultaneously. The GDD is slowly varying in the high-reflectivity region in the three cases. The GDD of the mirror where the duty cycle is chirped is comparable to the one of the unchirped mirror, the GDD at the Bragg frequency is zero. At the low frequency side the GDD is negative, corresponding to a negative penetration depth, and on the high frequency side the group delay
Figure 9.12: Comparative graph of the reflectivities (full line) and of the group delay dispersion (dotted line) of a duty-cycle, wavelength, or double chirped mirror.
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dispersion is positive. The wavelength (WL) chirped mirror shows a negative GDD in the zone of interest around the nominal Bragg wavelength, but strong oscillations of the GDD appear in the high bandwidth zone. They are Gires-Tournois types of oscillations originating from the impedance mismatch between the input and the mirror.

In the case of double chirp mirror the induced dispersion of the group delay is much stronger than the two other cases. The Gires-Tournois oscillations have been reduced and the GDD is negative over most of the range of the high reflectivity zone. Many models exist to predict the shape of the induced GDD [133, 132], but it is generally difficult for an analytical model to give a design of a mirror able to compensate an arbitrary GDD. Numerical methods are thus used.

9.1.9 Genetic optimization

In this work, our approach is to engineer the rear part of the quantum cascade laser. The back facet reflection is done by a Bragg mirror composed of active region layers and a polymer with a refractive index of 1.55 as shown in figure 9.13. Here the mode matching between the mirror and the ridge is assumed to be good, we thus neglected any modal mismatch losses or mode conversions.

A genetic optimization script generated the mirror designs, starting from random alterations of a linear double chirp design. The complex amplitude reflectance was computed for each mirror design. The GDD was obtained from the reflectance. The genetic optimization algorithm computes how close the generated mirror is from the desired design using a merit function. The merit function is the root-mean-square of the absolute sum of the GDD of each mirror design and the measured GDD.

\[
merit = \sqrt{|GDD_{mirror} + GDD_{measured laser}|}
\]  

(9.15)

The best candidates are kept and used as parents for the next generation of the algorithm. The algorithm iterates the generations until
the random process fails to improve the mirrors. Five designs were selected and processed in a laser. Unfortunately the process was not as successful as hoped but among the five design one stood up.

The design obtained is shown in figure 9.14, the thicknesses of the layers in micron after the input are, 34.3, $\mathbf{10.0}$, 20.8, $\mathbf{8.91}$, 26.2, $\mathbf{9.86}$, 20.9, $\mathbf{10.2}$, 22.1, $\mathbf{9.34}$, 22.6, $\mathbf{8.24}$, 17.2, $\mathbf{56.8}$ where bold figures are in active region and normal ones are in BCB.

This device attempts to correct for a third order polynomial fit of the reflectance, thus the resulting GDD is linear. The device shows a rather positive GDD and therefore the correction from the mirror should be negative. This design provides a correction of the GDD shown in figure 9.15 on a bandwidth between 1.65 and 2.6 THz. The
9. Dispersion Compensation in quantum cascade lasers

The measurement of the device after processing revealed an under-etching of the structure by roughly 400 nm, which reduces the dimensions of the active region layers by 800 nm and increased the dimension of the BCB layers by the same amount, consequently a blue shift of the GDD is expected.

The frequency spectrum of the device is shown in figure 9.16. It is a similar device than in these publications [84, 121]. The device operated on a bandwidth from 2.05 to 2.95 THz with fairly equidistant
9. Dispersion Compensation in quantum cascade lasers

Figure 9.17: Comparison plot between the phase of the ridge laser, and the phases of the laser with a mirror.

Figure 9.18: Comparison between the measured phase of the mirror and the computed phase.

modes, except one mode around 2.6 THz that doesn’t originate in the Fabry-Perot cavity.

The phase of the Fabry-Perot modes are plotted in figure 9.17 together with the ones of a mirrorless cavity for comparison. The results are fitted with a 2\textsuperscript{nd} order polynomial, that reveals a change of trend of the GDD that changed from positive to negative. From this plot we can conclude that in our case the GVD was overcompensated. To retrieve the contribution of the mirror only we have to subtract the phase of the mirrored device to the one of the bare resonator.

Figure 9.18 shows the mirror phase contribution, that was obtained by interpolating the phase of the mirrorless device with the frequencies
of the simulated device with mirror, then subtract the two curves. This measurement is compared with the phase issued from the mirror. We see a qualitative matching of the simulation and the measurement. One difference lies in the resonance that appears in the simulation around 2.6 THz. This resonance is the signature of a mode living in the mirror itself. We believe that it is the explanation for the extra non-Fabry-Perot mode that is found in the laser spectrum.

9.2 Conclusion

To conclude this chapter, we build a code that allows to generate the design of Bragg mirrors capable of compensating for an arbitrary group velocity dispersion in a terahertz quantum cascade laser waveguide. We successfully integrated a dispersive mirror at the back end of a terahertz quantum cascade laser using a polymer as a low index material for the mirror. The effect of the mirror are seen in the frequency spectrum of the laser. The dispersion introduced by the mirror was able to flip the sign of the measured dispersion. In order to perfect the method some effort have to be put in the processing methods of the device in order to achieve a more precise matching of the design and realization, the layer thicknesses in the design of a double chirp mirror are critical.
A.1 InGaAsP active regions at 1.5 $\mu$m

A.1.1 MOVPE Growth

The active region used is a single InGaAs quantum well with two 140 nm thick InGaAsP barriers of 1.14 $\mu$m bandgap, and capped with a 30 nm thick InGaAsP of of 1.29 $\mu$m bandgap to hinder surface recombinations. The first growth features a 10 nm quantum well, its photoluminescence shows a peak at awavelength of 1588 nm and a shoulder at 1469 nm which is the sign of existence of an excited state in the quantum well.

In order to shift the luminescence towards 1550 nm, a second sam-ple was grown with a 7.5 nm quantum well resulting in a shoulderless
A. Active region designs

Figure A.1: Layer P3137 design and characterization
A. Active region designs

photoluminescence from 1540 nm to 1580 nm.

A.1.2 Microdisk processing

Electron beam lithography is necessary to the pattern the microbridges, because it features objects of 200nm which can’t be achieved by standard ultra-violet photolithography, thus a microdisk geometry was used to test and generate the process flow.

Figure A.3 shows the lasing of the microdisks. They are processed using wet-etching and potassium dichromat and HBr solution as described in the chapter about processing. They show that the epi-layer used in this project provide some gain at the location of the PL.

A.2 Heterogeneous stack of bound-to-continuum at 8-10µm

The active region used for the Mid-Infrared surface emitting devices is a heterogeneous stack of active regions [83, 121, 84]. They are both genetic optimizations of the active region [101, 103] performed by Johanna Wolf using Sewlab [136]. The final structure is composed of 15 periods of an active region peaking at 10.4 µm wavelength followed by 20 periods of a 8.5 µm wavelength active design and again 15 periods of the 10.4 µm. The resulting gain has a flat profile, as showed in Fig. A.6.

A.3 4-Well design at 100 and 63 µm

The four quantum wells design of Maria I. Amanti published in 2009 [79], was proven one on the most versatile active region design for terahertz quantum cascade lasers. Figure A.7 shows its bandstructure.

The four quantum well offers the advantage of a relatively high output power and good temperature performance, above 160 K of maximum temperature of operation. This active region design has proven
Figure A.2: Layer P3137 design and characterization
A. Active region designs

**Figure A.3:** Photoluminescence spectrum of the microdisks

**Figure A.4:** Active region bandstructure peaking at 10.4 $\mu$m used in the heterogeneous stacking. [135]
A. Active region designs

**Figure A.5**: Active region bandstructure peaking at 8.5 µm used in the heterogeneous stacking. [135]

**Figure A.6**: Measured spontaneous emission rate compared with the result of the Sewlab simulations.
A. Active region designs

Figure A.7: Band structure of the four quantum wells bound-to-continuum design
A. Active region designs

Figure A.8: LIV and spectrum of a four quantum well design operating up to 5.4 THz.

It’s scalability with operation frequencies from 1.6 to 5.3 THz [84, 121] as seen from figure A.8.

It was then the natural choice of basing the active region needed at 4.7 THz on this design. The new design was done by Dr. Keita Ohtani. The radiative transition energy was increased from 12 meV to 19.3 meV, from the original design. The rest of the wells and barriers had to be adjusted to match the design.

Figure A.9 shows the bandstructure of the 4.7 THz active region. The states are located higher in the wells, the period length was reduced and the required alignment bias is higher than the original design.

The resulting design has a current density which is double compared to the original design. It also has a larger dynamical range. Figure A.11 shows the luminescence spectra of the layer when approaching and
A. Active region designs

**Figure A.9:** Band structure of the 4 quantum well bound-to-continuum design operating a 4.7 THz.

reaching threshold. We can see clearly the predicted narrowing of the luminescence linewidth.
Figure A.10: LIV characteristics of the 4 quantum wells design operating at 4.7 THz and the device operating at 3 THz.
Figure A.11: Luminescence spectrum of the 4.7 THz design.
A. Active region designs
B.1 Etching

B.1.1 ICP dry-etching

The ICP-RIE system in our case is Oxford Plasmalab 100. In ICP etching each chemical has a proper role to play in the etching process. Chlorine is responsible for the chemical etching, it reacts with the surface components, it is thus sensitive to the surface elements and is not suited for a heterostructure. Argon is the physical etchant, it will etch all chemicals in a similar rate but the selectivity to the mask is poor. For this reason a mixture of both is suitable. Additionally the nitrogen plays two roles, a side wall passivations to avoid an underetching and
will help remove the arsene reactants during the etching. Helium is used a a dilution gas.

(Al)GaAs etching

Recipe for an ICP etching of GaAs/AlGaAs heterostructure. The original recipe here called Dana GaAs was slightly modified to the Chris GaAs with the helpful inputs of Dr. Emre Togan. An important aspect of dry-etching structures that have a gold bottom is that gold will be etched by the plasma if exposed, and can be redeposited in the side-walls of the laser ridge.

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Chris GaAs deep etch</th>
<th>Dana GaAs etch</th>
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</thead>
<tbody>
<tr>
<td>Ar (sccm)</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Cl₂ (sccm)</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>N₂ (sccm)</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>pressure (mTorr)</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>ICP power (W)</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>RF power (W)</td>
<td>80</td>
<td>140</td>
</tr>
<tr>
<td>etch rate (µm/min)</td>
<td>0.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Au etch rate (µm/min)</td>
<td>0.1</td>
<td>&quot;</td>
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InGaAs(P) etching

Recipe for an ICP etching of InP/InGaAsP heterostructure with a SiN hardmask. The recipe is inspired from [?].
B. Processing

<table>
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<th>Recipe</th>
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<tr>
<td>He (sccm)</td>
<td>15</td>
</tr>
<tr>
<td>Ar (sccm)</td>
<td>5</td>
</tr>
<tr>
<td>Cl₂ (sccm)</td>
<td>15</td>
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<tr>
<td>N₂ (sccm)</td>
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<tr>
<td>Temperature (°C)</td>
<td>200</td>
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<tr>
<td>pressure (mTorr)</td>
<td>2.2</td>
</tr>
<tr>
<td>ICP power (W)</td>
<td>600</td>
</tr>
<tr>
<td>RF power (W)</td>
<td>160</td>
</tr>
<tr>
<td>etch rate (µm/min)</td>
<td>5.2</td>
</tr>
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</table>

Figure B.1: SEM image of a micropillar of P3137 etched the recipe Chris InP deep etch. It has a 1 µm SiN hardmask.

The recipe used in figure B.1 is particularly vertical and etches with the same rate InGaAs, InGaAsP or InP. The side-wall shows a rugosity on the scale of 50-100 nm, which is not ideal for our purpose, but the hard mask.

B.1.2 RIE dry-etching

The RIE system in our case is Oxford Plasmalab 80 plus. Recipe for an RIE etching of BCB selectively to (Al)GaAs heterostructure.
B. Processing

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Geiser BCB</th>
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<tr>
<td>CF$_4$ (sccm)</td>
<td>40</td>
</tr>
<tr>
<td>O$_2$ (sccm)</td>
<td>60</td>
</tr>
<tr>
<td>Temperature ($^\circ$ C)</td>
<td>18</td>
</tr>
<tr>
<td>Pressure (mTorr)</td>
<td>100</td>
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<tr>
<td>Forward power (W)</td>
<td>200</td>
</tr>
<tr>
<td>etch rate ($\mu$m/ min)</td>
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Recipe for an RIE etching of SiN$_x$ selectively to resist.

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Dana SiN mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHF$_3$ (sccm)</td>
<td>40</td>
</tr>
<tr>
<td>O$_2$ (sccm)</td>
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</tr>
<tr>
<td>Temperature ($^\circ$ C)</td>
<td>18</td>
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<tr>
<td>Pressure (mTorr)</td>
<td>25</td>
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<td>Forward power (W)</td>
<td>55</td>
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<td>etch rate ($\mu$m/hour)</td>
<td>4.5</td>
</tr>
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</table>

B.1.3 Wet-etching

Aged etchant

DI(water):HBr:HNO$_3$ with ratios 10:1:1. HBr concentration is "47-49. The solution is sensitive to light and was mixed under the yellow light of the photolithography room in a brown bottle. The bottle is then left for aging for a few weeks. As long as it is not in contact with any metal the solution can be reused. The etching rate is about 2um per minute, but slows down with time. In this etchant the Nitric acid is the oxidant and HBr is the etchant.
B. Processing

Figure B.2: SEM image of a microdisk of P3137 etched with 5 minutes of aged etchant and then 30 s of HCl

Figure B.2 is the result of an aged etchant. We see that the top disk is not circular and this is because the aged etchant is not perfectly isotropic. In this project it was important that the etchant stays isotropic so another etchant was used. We see underneath the disk the effect of the underetching of InP. HCl is extremely selective and directional.

Isotropic etchant

Another etchant that is absolutely isotropic, and etches InP and In-GaAsP compound at a similar speed is the following mixture $K_2Cr_2O_7$ (0.5M):$H_3PO_4$:HBr in 1:1:1 as described in here [?]. The potassium dichromate is a strong oxidant and cancels the selectivity of HBr, the phosphoric acid’s role is to improve the surface quality.
Figure B.3: SEM image of a microdisk of P3137 etched with 1 minute of Potassium dichromat etchant

Figure B.3 Shows the result of an etching of sample P3137 using the potassium dichromat etchant. The top image shows the isotropicity of the etchant. The microdisks have a perfectly circular shape compared to the aged etchant case. The bottom image shows the circular profile of the sidewalls. The etching rate of InP and InGaAsP or InGaAs is the same.

Anisotropic/selective etching

HCl or HBr gives the same result when wet-etching of InP, an anisotropic etching which is selective versus arsenide III-V compounds like In-GaAs(P). Such etchant can be buffered with water or phosphoric acid.
Figure B.4 shows the result of an underetching of InP selectively to InGaAsP/InGaAs. The selectivity is perfect. We see that the etchant is strongly anisotropic. Here the structure is seen under two different angles. The top image is seen from the small flat direction and the bottom one from the big flat direction.
B.2 Deposition

B.2.1 Plasma deposition

Recipe for a PECVD deposition of SiN$_x$ for hard mask used for ICP etching.

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Chris SiN</th>
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<tr>
<td>SiH$_4$(N$_2$) 2.5 % (sccm)</td>
<td>400</td>
</tr>
<tr>
<td>NH$_3$ (sccm)</td>
<td>30</td>
</tr>
<tr>
<td>Temperature (° C)</td>
<td>300</td>
</tr>
<tr>
<td>Pressure (mTorr)</td>
<td>1000</td>
</tr>
<tr>
<td>LF power (W)</td>
<td>30</td>
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<tr>
<td>Pulse time (s)</td>
<td>10</td>
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<tr>
<td>RF power (W)</td>
<td>30</td>
</tr>
<tr>
<td>Pulse time (s)</td>
<td>17</td>
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<tr>
<td>deposition rate ($\mu$m/hour)</td>
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Recipe for a PECVD deposition of low temperature SiN$_x$ for hard mask used for ICP etching.

<table>
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<th>Recipe</th>
<th>Dana SiN</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiH$_4$(N$_2$) 2.5 % (sccm)</td>
<td>800</td>
</tr>
<tr>
<td>NH$_3$ (sccm)</td>
<td>30</td>
</tr>
<tr>
<td>Temperature (° C)</td>
<td>0</td>
</tr>
<tr>
<td>Pressure (mTorr)</td>
<td>900</td>
</tr>
<tr>
<td>LF power (W)</td>
<td>0</td>
</tr>
<tr>
<td>Pulse time (s)</td>
<td>0</td>
</tr>
<tr>
<td>RF power (W)</td>
<td>20</td>
</tr>
<tr>
<td>Pulse time (s)</td>
<td>0</td>
</tr>
<tr>
<td>deposition rate ($\mu$m/hour)</td>
<td>0.86</td>
</tr>
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</table>

B.2.2 Spin-coating

BCB was spin coated at 5000 rpm with a ramping time of 5 s and during 50 s. Prior to the deposition of BCB two preconditioning steps have
B. Processing

to be carried, because naturally BCB doesn’t adhere to III-V semiconductors or perfect metals like gold and the BCB would accumulate in droplets on the surface. Firstly an oxygen plasma ashing of 2 min at 200 W and secondly the spin coating of an adhesion promoter AP3000 at 3000 rpm for 30 s with a ramping time of 3 s. After coating the BCB has to be cured at various temperature and times in a total of roughly 6 hours. Each deposition step is depositing roughly 5.2 µm of BCB. The curing of the last deposited BCB layer is done at a slightly higher temperature in order to fuse the layers with each other. The total desired thickness is about twice the height of the underlying structures.

Photoresist AZ5214E was spin-coated at 4000 rpm for 40 s with a ramping time of 4 s, it was then illuminated with 405 nm UV light for about 4 s and then reversed using a flood exposure of about 20 s, and developed. This reversible photoresist was shown giving more reliable results than conventional negative photoresists. Lift-off procedures were done using Dimethylsulfoxide heated at around 85 °C.

Photoresist AZ1815 was spun at 4000 rpm for 40 s with a 4 s ramping and illuminated for about 10 s, and developed. This positive photoresist was proven the best for the patterning of SiN grown by PECVD, it was resistant to the 50-70 min of RIE etching of SiN and was still removable using acetone a posteriori. To ensure a good adhesion to SiN prior to the resist deposition a pre-spin-coting of hexamethyldiisilazane was done at 3000 rpm for 30 s with a 3 s ramp time.
B. Processing


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## Curriculum vitae

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<tr>
<td><strong>Name</strong></td>
<td>Christopher Benjamin Paul Bonzon</td>
</tr>
<tr>
<td><strong>Email</strong></td>
<td><a href="mailto:cbpbonzon@gmail.com">cbpbonzon@gmail.com</a></td>
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<tr>
<td><strong>Nationality</strong></td>
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<tr>
<td><strong>Date of birth</strong></td>
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<tr>
<td><strong>Date</strong></td>
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Curriculum vitae

Institution | Department of Physics, ETH Zurich, Switzerland
Supervisor | Prof. Dr. Jerome Faist; email: jfaist@ethz.ch
Date | 2009 - 2011
Title awarded | Master in Physics
Title awarded | Minor in Management of Technology and Entrepreneurship
Thesis | Terahertz applications for nitride heterostructures
Institution | EPFL, Switzerland
Supervisor | Prof. Dr. Nicolas Grandjean
Date | 2004 - 2009
Title awarded | Bachelor in Physics
Institution | EPFL, Switzerland

Employment

Date | 10/2009 - 06/2015
Institution | ETH Zurich, Quantum Optoelectronics group, Prof. Dr. J. Faist
Activity | Development of terahertz quantum cascade lasers. Research focus on spectral and spatial agility of the lasers.

Date | 03/2011 - today
Position | Junior researcher, Ph. D. student, Post-Doc
Employer | ETH Zurich, Prof. Dr. J. Faist
Activity | Development of semiconductor lasers from the far- to the near-infrared spectral region.

Date | 07/2010 - 08/2010
Position | Operating theater, surgical instrument sterilizing assistant
Employer | Lausanne university hospital, CHUV
## Curriculum vitae

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## Publication list

**Peer-reviewed articles**

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V. 106, p. 071104, 2015,
"Surface emitting multi-wavelength array of single frequency QCL",

Appl. Phys. Letters,
V. 104, p. 161102, 2014,
"Integrated patch and slot array antenna for THz QCLs at 4.7 THz",
C. Bonzon, I. C. Benea Chelmus, K. Ohtani, M.
Geiser, M. Beck, J. Faist

Laser and Photonics Reviews,
V. 7, I. 5, p. 45–50, 2013,
"Continuous-wave vertically emitting photonic crystal THz laser",
Z. Diao, C. Bonzon, G. Scalari, M. Beck, J. Faist, R.
Houdré

**Oral presentations**

Photonics West 2012
"Portable real-time THz imaging setup based on QC lasers"
San Francisco, CA, USA
C. Bonzon, G. Scalari, M. I. Amanti, F. Castellano,
D. Turcinkova, M. Beck, J. Faist

IQCLSW 2012
"THz Photonic Crystal QCL Coupled to a 2nd order Bragg extractor"
Baden, AU
C. Bonzon, Z. Diao, G. Scalari, M. Beck, J. Faist, R.
Houdré

CLEO Europe 2013
"THz Photonic Crystal QCL Coupled to a 2nd order Bragg extractor"
Munich, DE
C. Bonzon, Z. Diao, G. Scalari, M. Beck, J. Faist, R.
Houdré
Curriculum vitae

ÖPG/SPS An. Meet. 2013
"THz Photonic Crystal QCL Coupled to a 2nd order Bragg extractor"
Linz, AU
C. Bonzon, Z. Diao, G. Scalari, M. Beck, J. Faist, R. Houdré

ITQW 2013
"Printed integrated antenna for THz QCL"
Lake George, NY, USA
C. Bonzon, I. C. Benea Chelmus, K. Ohtani, M. Geiser, M. Beck, J. Faist

EOS TMT Sc.&Te 2014
"Integrated planar antennas for QCLs operating at 4.7 THz"
Camogli, IT
C. Bonzon, I. C. Benea Chelmus, K. Ohtani, M. Geiser, M. Beck, J. Faist

IQCLSW 2014
"Integrated antenna arrays on benzocyclobutene for QCL"
Policoro, IT
C. Bonzon, I. C. Benea Chelmus, K. Ohtani, M. Geiser, M. Beck, J. Faist

IQCLSW 2014
"1st and 2nd order DFB gratings-based Surface Emission QCL"
Policoro, IT

Curriculum vitae

"Broadband monolithic extractor" (Best presentation Award)
Innsbruck, AU
C. Bonzon, I. C. Benea Chelmus, K. Ohtani, M. Geiser, M. Beck, J. Faist

CLEO 2015
"Surface Emission QCLs Combining 1st and 2nd order Bragg gratings"
San Jose, CA, USA

NATO Tera-Mir 2016 (invited)
"Broadband monolithic extractor"
Izmir, TUR

Photonics West 2016
"Terahertz Quantum Cascade Lasers with broad band extractors"
San Francisco, CA, USA

Language

<table>
<thead>
<tr>
<th>Language</th>
<th>Ability</th>
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<tbody>
<tr>
<td>French</td>
<td>Native speaker</td>
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<tr>
<td>German</td>
<td>Spoken, read and written with fluency (B1-B2, grade: 5))</td>
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<tr>
<td>Swiss-german</td>
<td>Good understanding (Schweizerdeutsch verstehen, B2-C1)</td>
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<tr>
<td>English</td>
<td>Spoken, read and written with fluency</td>
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Curriculum vitae