

# WORKPACKAGE REPORT

## WP 1 – Integrated Laser System

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Period covered:            from 1. July 2011 to 30. June 2012

## **WP 1- Integrated Laser System**

Work package leader: UHH

### **Introduction**

In work package 1 we aim for the realization of a highly miniaturized but nevertheless flexible laser system for cooling neutral atoms. The laser system can be described by three main components. That is the laser itself, the splitting module and the connection to the rest of the world, i.e. the coupling of the light into optical fibres which will work as connection between laser system and vacuum system.

To achieve the realization of all this, the work package has been divided into five tasks, which are listed in the table below.

Task-Nr.	Task	Task Leader
1.1	Integrated optics modules optimised for 780nm	UNOTT
1.2	Micro-integrated diode lasers for cold atom applications	FBH
1.3	Integration of the entire optical system for the iSense sensor	UHH
1.4	Alternative free-space optical delivery system	Bham
1.5	Review of the technologies to realize visible wavelength diode laser based laser systems, including micro-integrated frequency doubled laser systems	FBH

Task 1.5 is not starting prior to month 24.

### **Summary of progress towards objectives**

- A final layout for the laser system has been developed which can be adapted to a waveguide-based as well as a fibre-based beam distribution scheme.
- DFB lasers were already presented in the last annual report.
- In the production of the DFB-MOPAs there are some delays due to technical difficulties described in detail in the corresponding chapter. This leads to a delay of about 4 months.
- ECDLs for the interferometry have been built and characterized.
- The design for a rubidium spectroscopy module which allows for the stabilization of a laser via modulation transfer spectroscopy or frequency modulation spectroscopy has been developed.
- First GaAlAs waveguide structures have been produced and “qualitatively” tested. The problem of different mode-field diameters between fibre and waveguide has been approached by implementing a tapered region in the waveguide design.
- Tests of the necessary components for a fibre-based beam distribution and switching (fibre splitters, fibre-coupled AOMs, fibre coupled shutters) have been started.
- Packaging design for the laser modules based on a linear beam path inside aluminium boxes has been completed. For the packaging of the reference laser a design based on Zerodur technology has been developed.
- Due to the design of the ECDL boards a direct fibre coupling using Zerodur fibre couplers on the AlN-board is possible and has been demonstrated.

In collaboration with the other partners, the layout for the laser system of iSense was set up, and we are starting with the design and tests of the components. For the creation of the

magneto-optical trap we need cooling as well as repumping light, which will be derived from one DFB-MOPA module and one DFB module from the FBH. These laser modules will be mounted inside an aluminium box each. To achieve maximal thermal stability we will employ a strictly linear design without any mirrors (further described in the section about the packaging). After the initial fibre coupling the splitting and combining for the frequency stabilization is done by either fibre integrated splitters or waveguide structures. The splitting and overlapping for the actual MOT-beams is done in the same manner. For the switching of the light fibre coupled AOMs and fibre integrated shutters will be used or in the waveguide-case MZI-MMI-structures. For the detection of the beat notes we will use G4176-03 photodiodes by Hamamatsu, which will be directly connected to a fibre collimator.

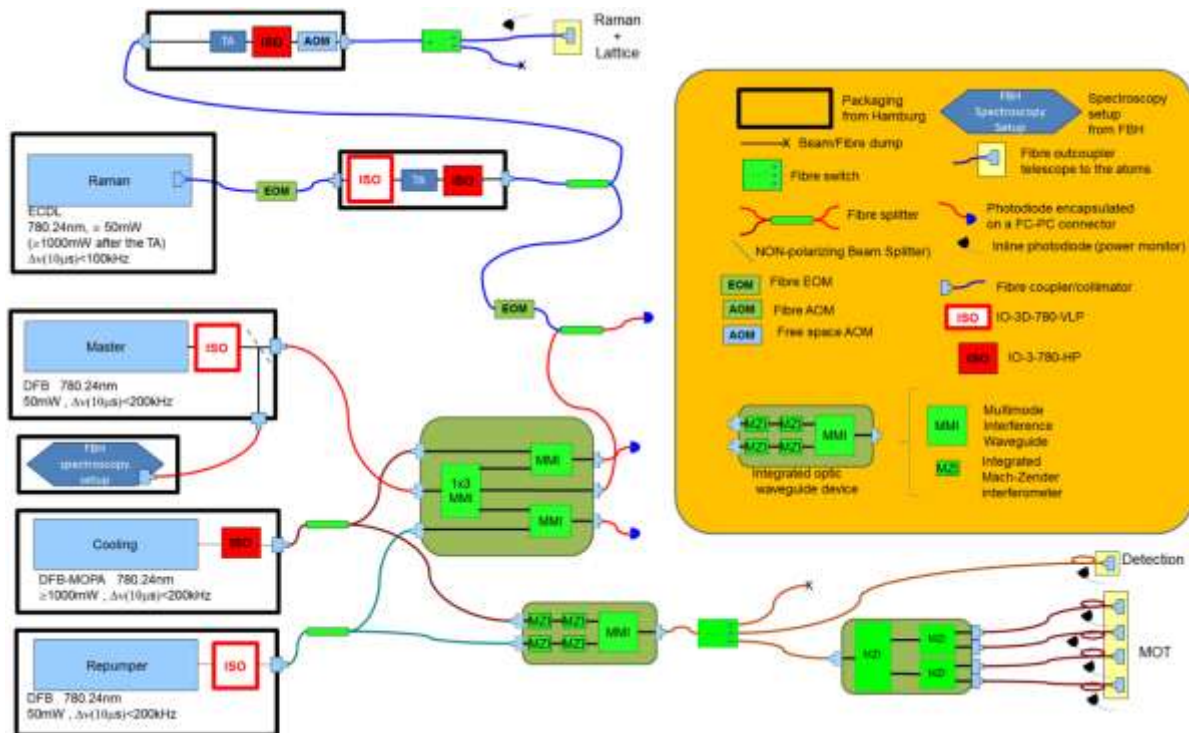


Figure 1: Layout of the iSense laser system

Another DFB-Laser will be used as an absolute frequency reference. This laser will be mounted onto a Zerodur base plate on which the beam will be split in two by using a polarizing beam splitter and then fibre coupled by using the above described Zerodur fibre in-couplers. One fibre will then be connected to the spectroscopy board, where the laser is stabilized with respect to an atomic transition.

The other fibre is connected to an array of fibre splitters in order to superimpose the reference laser light with all the other lasers to offset lock these lasers with respect to the Master laser. For the Raman/Lattice-Laser an extended cavity diode laser (ECCL) is used as a light source. This laser can directly be fibre coupled on its AlN-baseplate by using a Zerodur in-coupler. A fibre-coupled EOM operating at 6.8GHz will be used to generate the necessary sidebands for driving the stimulated Raman transitions. This light is then amplified in a tapered amplifier and again coupled into an optical fibre. A few mW of this light is used for offset locking. For this purpose another fibre-EOM operated at 7 GHz is utilized to generate higher order sidebands. By stabilizing one of these sidebands to the master laser's frequency we should be able to generate the required frequency offset of the RAMAN and lattice laser light of about 50GHz.

The remaining light will pass through a secondary TA in case we are not able to saturate the first TA with the light from the ECDL. This is to make sure a full 1W of output power can be obtained at the output of the amplifier. The light from the TA will then pass through an optical isolator and an AOM for fast switching. After the AOM the light is finally fibre coupled and guided to the vacuum chamber. To allow for a larger extinction ratio between light on and light off a fibre integrated switch will be incorporated into this fibre.

## Details for each task

### *Task 1.1*

- *Transfer telecom technology integrated optics to 780nm operation (months 7-16).*

This task aims to deliver integrated optics replacements for bulky fibre-based components, achieving active (such as phase modulation) and passive (such as signal splitting) optical signal processing on semiconductor chips of approximately 25 mm x 10 mm x 0.5 mm in size. Such components have been made at telecommunications wavelengths but not yet at the short wavelength of 780nm required for the iSense application

The tasks of work package 1.1 were assumed by the School of Physics and Astronomy at the University of Nottingham (UNOTT) in September, 2011 and 3 of the team members attended the iSense annual review meeting in Brussels at that time. Following the recruitment of a new team member with specialist semiconductor device fabrication experience in October 2011, and the supply of test epitaxial wafers, also grown in-house by Molecular Beam Epitaxy (MBE), the process development of III-V semiconductor waveguide devices began in mid January 2012. This is the first time that III-V semiconductor photonic waveguide devices have been grown and fabricated at the University of Nottingham.

In the last year, we have completed the design and modelling of the semiconductor waveguide structures for use in the integrated optics. This design work was undertaken using a commercial design package, Optiwave, and cross-checked with codes written by Prof Benson's team in the Department of Electrical and Electronic Engineering at the University of Nottingham.

First arrays of different waveguides for testing purposes were fabricated and it could be verified that the first produced test waveguide structures guide light at 780nm as well as at 1550nm (see Figure 2).



Figure 2: Observation of wave guiding. The camera was tilted so that the light entering the waveguide can be seen in the upper circle whereas the transmitted light can be observed in the lower circle.

The test waveguides have been supplied to the collaborators at the Universities of Birmingham and Hamburg, for optical loss measurements. Optical evaluation is now

underway at the University of Hamburg. All epitaxial wafers have been characterised by X-ray diffraction and the MBE-grown layers have shown high structural quality and compositional accuracy. Some photoluminescence measurements of suitable test structures have also been made which are indicative of some optical loss mechanisms in the material. Whether these relate directly to the absorption losses of the full waveguide structure will be confirmed by the waveguide loss measurements of simple straight waveguides. A new regime of epitaxial growth will be explored for new epilayers grown, together with test structures for photoluminescence, to confirm the dependence of optical loss mechanisms on the growth temperature and V-III ratio

A meeting was held for members of the Laser Workgroup at the University of Birmingham on Tuesday, 8<sup>th</sup> May 2012 to discuss in detail the optics scheme for the iSense experiment. It was attended by collaborators from Birmingham, Hamburg and Nottingham. Optical subsystems were identified as suitable for replacement with on-chip integrated optics designs consistent with the iSense aim of a lightweight, compact, robust, cold atom gravimeter. The simple waveguide structures fabricated at the University of Nottingham were passed over to collaborators in Birmingham and Hamburg at this meeting, with information about the waveguide patterns (see Fig. 3). A follow-on meeting was held at the University of Nottingham on 17<sup>th</sup> May 2012, with collaborators from Nottingham and Birmingham, to agree on the numbers of inputs and outputs of these integrated chips and the approximate optical input power to each chip.



Figure 3: Optical microscopy image of an array of waveguides etched to a depth of 4.8 mm, of widths between 1.5 mm (top of image) and 10 mm (lower part of image), fabricated by plasma etching using chlorine-based etch chemistry

- ***Realisation of an integrated 1:3 splitter for 780nm light (months 15-25)***

Given the decision on the scheme and atom chip, it was decided that the 1:3 splitter from the original proposal shall be replaced by a 1:4 splitter device.

With the design of the above waveguides first designs of splitters based on MultiMode Interference (MMI) and switches based on a Mach-Zehnder Interferometer (MZI) were designed. The modelling show that an extinction ratio of 30dB can be achieved with a switching voltage of <10V, but it has to be noted that losses were not included in the modelling which may reduce the extinction ratio.

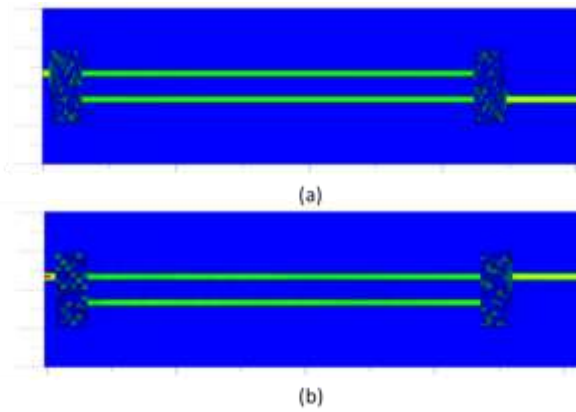


Figure 4: MZI switch when arm voltage = (a) 0 V, (b) 9.6 V

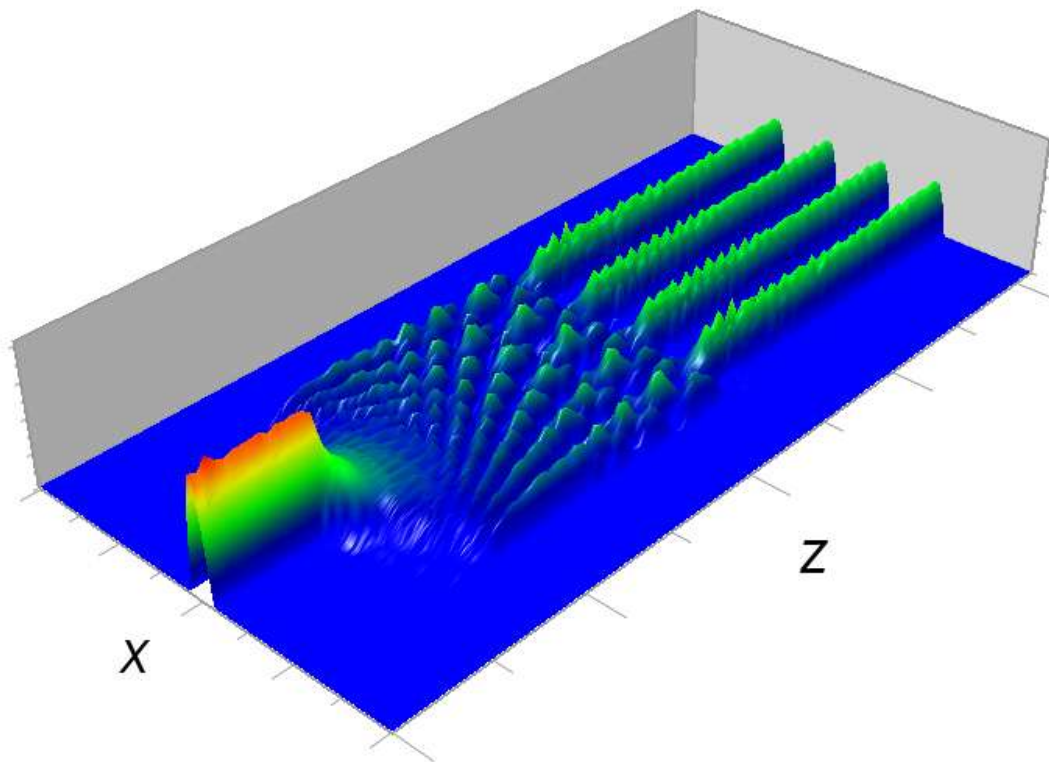


Figure 5: Optiwave simulation of the 1-to-4-way splitter, showing spatial variation of the beam intensity

- ***Development of an integrated optics system for atom cooling (months 25-30)***

A new mask set has been designed to incorporate the integrated optic device functionality required using the discrete, polarisation-maintaining MMI and MMI-MZI devices previously designed. The mask set also incorporates discrete devices and test structures required for monitoring the process flow and alignment structures designed to achieve the extremely demanding alignment tolerances. The following three integrated optic circuits have been identified as part of the scheme; the master laser distribution (MLDC) circuit, the repumper distribution circuit (RDC) and the MOT cooling circuit (MOTCC) (see Fig. 6).



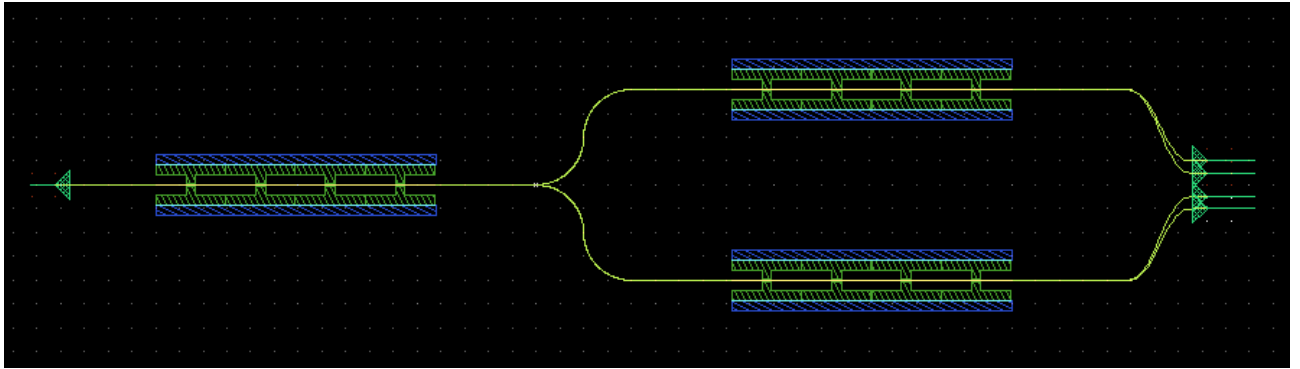


Figure 6: Schematic of the mask design for the integrated optic circuit for the Magneto-optical Trap Cooling Circuit. Approximate chip dimensions are 25 mm x 10 mm. This chip design has the functionality required to replace several macroscopic fibre-based components with a single compact photonic integrated circuit.

### Task 1.2

#### - *Micro-integrated extended cavity diode lasers for Rb spectroscopy (months 1-20).*

For the highly precise acceleration measurements via atom interferometry the linewidth of a DFB-laser is not sufficiently small so that for the realization of the Raman interferometer lasers with an extended cavity have to be utilized. These lasers use an external volume holographic Bragg grating (VHBG) which allows for longer resonator lengths and so a reduction in frequency noise by 1-2 orders of magnitude.

First tests showed that the additional requirements concerning mechanical stability could not be fulfilled with the design which is used for the DFB lasers. Therefore a next step concerning the integration of laser modules had to be made.

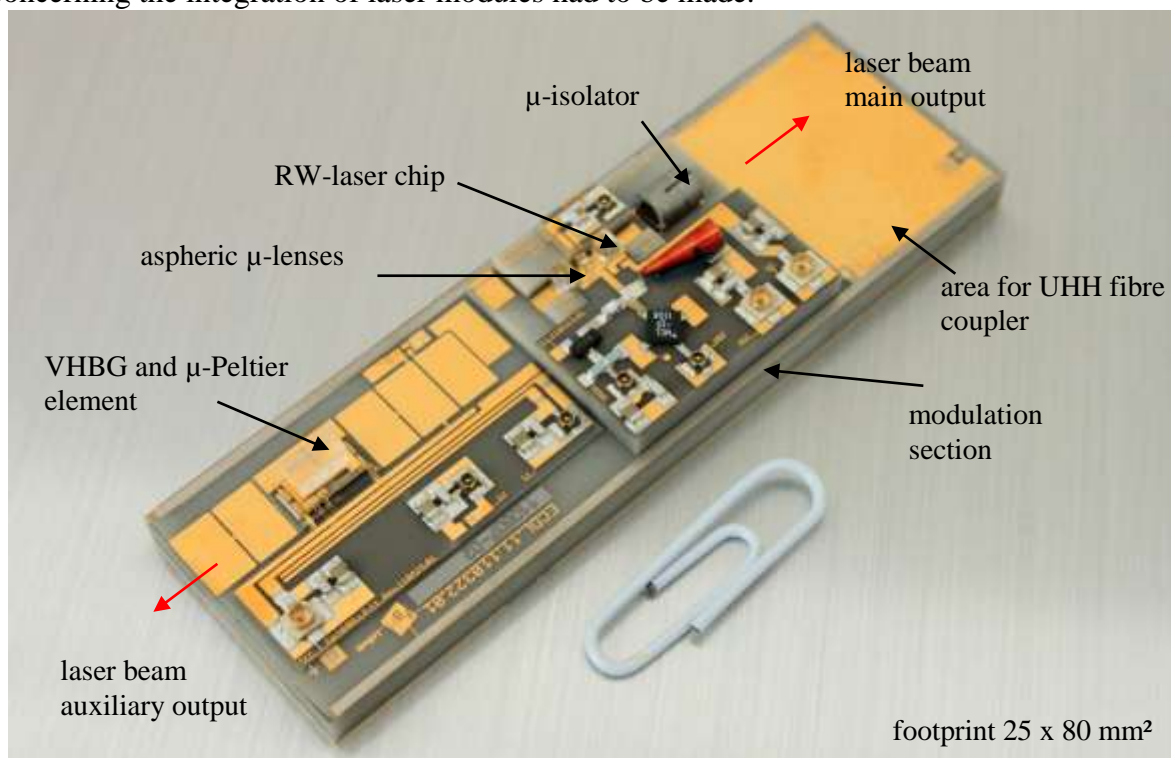


Figure 7: Picture of an ECDL module with electronics interface

These modules feature an AlN base plate which is about 5 times thicker than the standard plate the MOPAs and DFB lasers are mounted on and therefore provide an improved mechanical stability.

Additionally an electrical interface was included in the laser module design which not only allows for supplying the laser with its injection current but also features an LF modulation (DC...10 MHz) and a  $\mu$ -wave modulation input via a bias-tee.

Also temperature monitoring of the laser chip, the grating and the AlN body are included. These ECDLs can provide output power around 20mW at injection currents of 140mA at a temperature of 23°C at the laser chip, and 23.5°C at the grating (included are the losses due to the isolator).

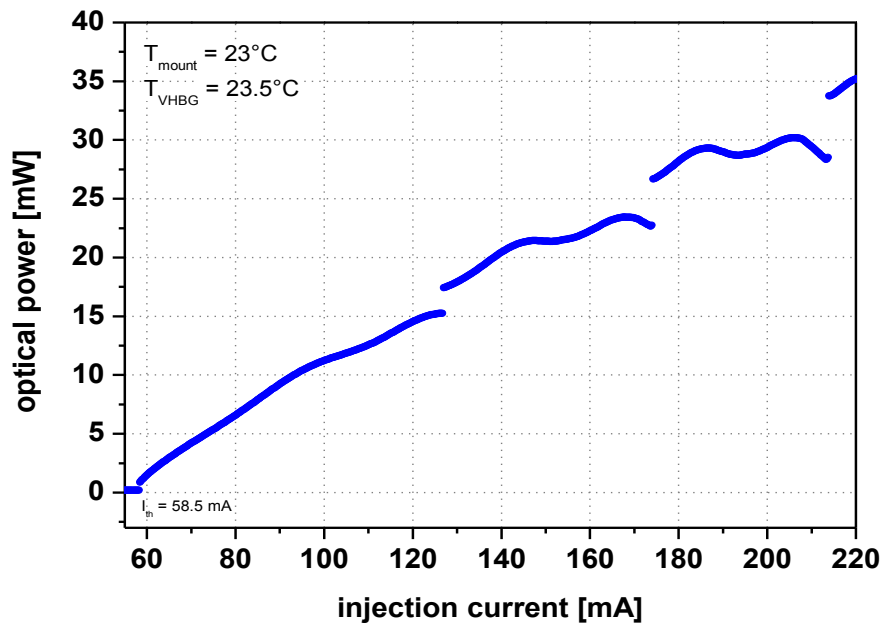


Figure 8: Optical power output as a function of the injection current



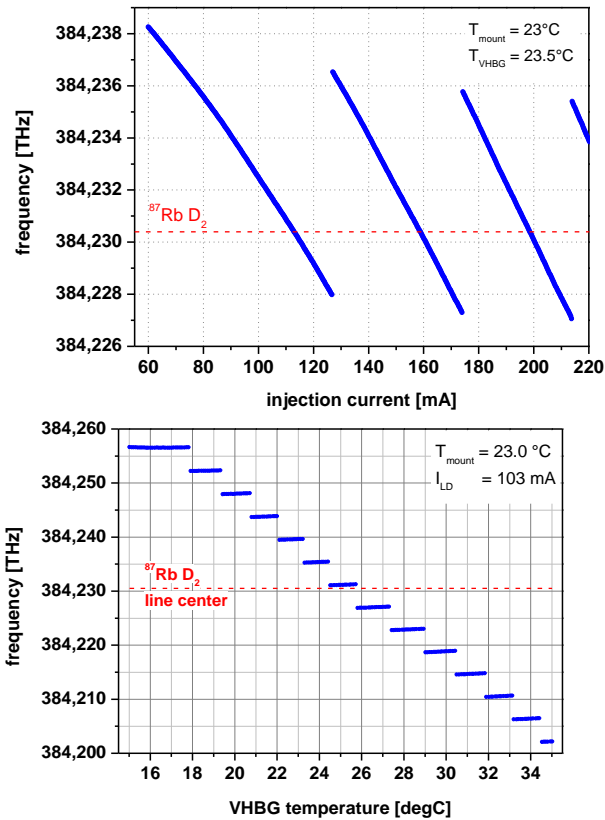


Figure 9: Laser frequency as a function of the injection current (left) and of the grating temperature (right)

The frequency tuning of these laser is done by either tuning the injection current or by changing the temperature of the grating (see fig 9). The temperature of the grating allows for a coarse tuning of the frequency by choosing the frequency at which the light is fed back into the diode. Tuning with the injection current allow for a fine tuning of the frequency by sweeping over one free spectral range of the extended cavity. That way a mode-hop-free tuning over the range of one free spectral range ( $\sim 4\text{GHz}$ ) is achieved. If a broader range of mode-hop-free tuning is required grating temperature and injection current can be varied synchronously. In this way the mode-hop-free tuning range could be extended to up to  $30\text{GHz}$  (see fig 10).

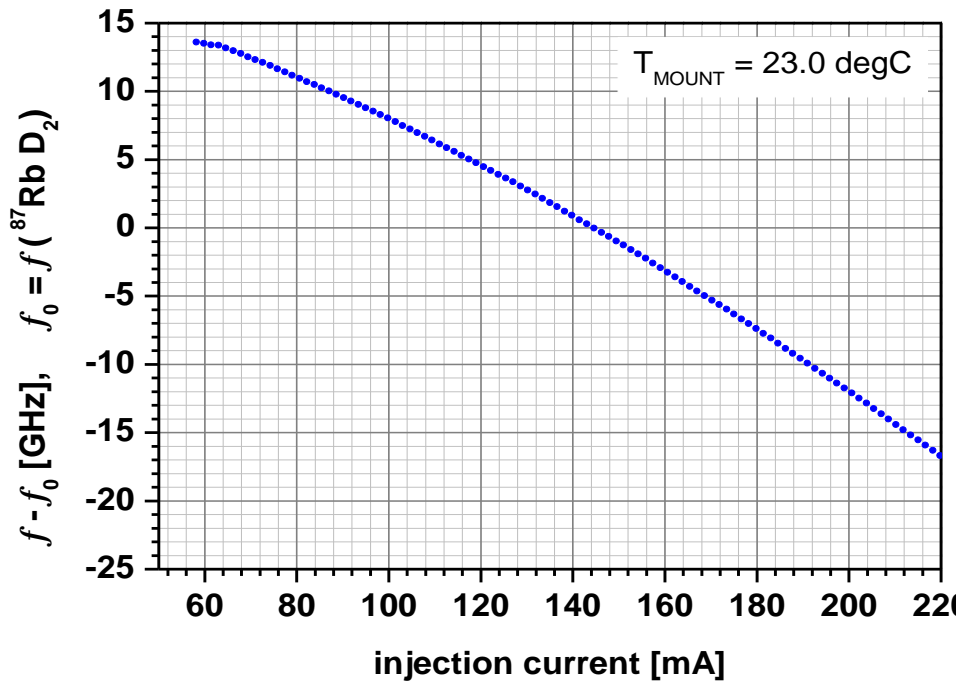


Figure 10: Extension of the modehop-free tuning range to more than 30 GHz

The linewidth of this laser module was also measured, by a self heterodyne linewidth measurement. At this measurement the laser light is split into two parts and one beam was delayed by a 2km optical fibre whereas the other one was frequency shifted with an AOM to observe a non-zero centre-frequency. The beams were then overlapped and the beat-frequency was measured with a fast photodiode. The linewidth was measured using three different injection currents and are summarized in the table 1.

Injection current	FWHM linewidth (10 $\mu$ s)	Intrinsic linewidth
70mA	-	-
120mA	100kHz	650Hz
234mA	240kHz	300Hz

Table 1: Overview of the measured line widths for varying injection currents

At an injection current of 70mA no reliable linewidth could be extracted as there were indications that the two overlapped beams were still partially coherent. The detailed noise characteristics can be obtained from the frequency noise power spectral density in the figure 11 whereas it should be noted that the fibre delay acts as a high pass for frequencies below 100 kHz.

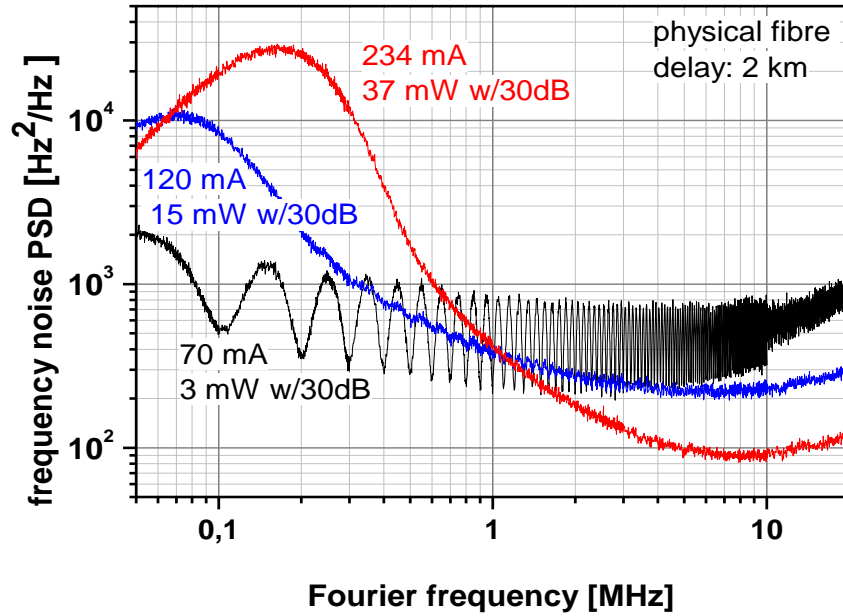


Figure 11: Frequency noise power spectral density of the ECDL

- *Realization of power amplifiers (months 1-24).*

For the purpose of the amplification of the Raman lasers (ECDLs) tapered power amplifiers chips were realized. The amplifiers provide an optical output power of  $\sim 1$  W. The tapered power amplifier will be integrated on an micro-optical bench with a footprint of  $10 \times 50$  mm<sup>2</sup>. The concept is similar to the concept of the MOPAs and of the reference and repumper laser modules described in the next section. The figure 12 shows a CAD-drawing of the amplifier module. Micro-optics are used in order to couple the seed beam into the tapered amplifier chip and to collimate the output beam. The module requires an input power of 10 ... 50 mW to ensure saturation of the amplifier.

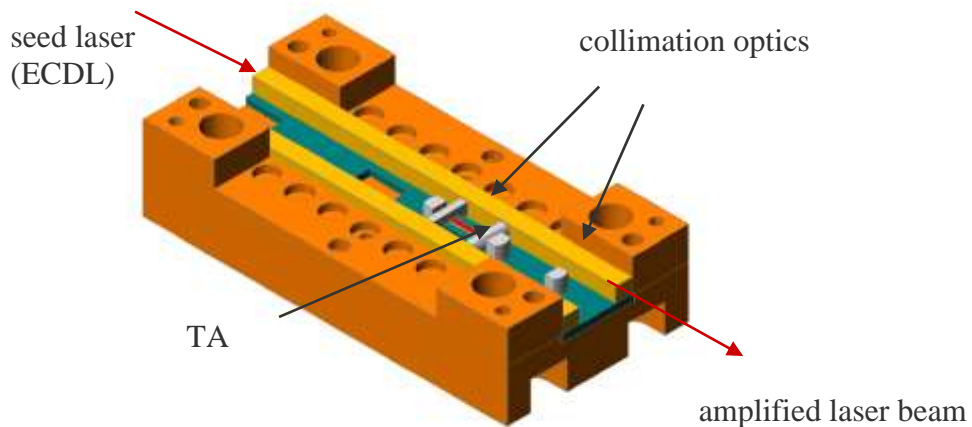


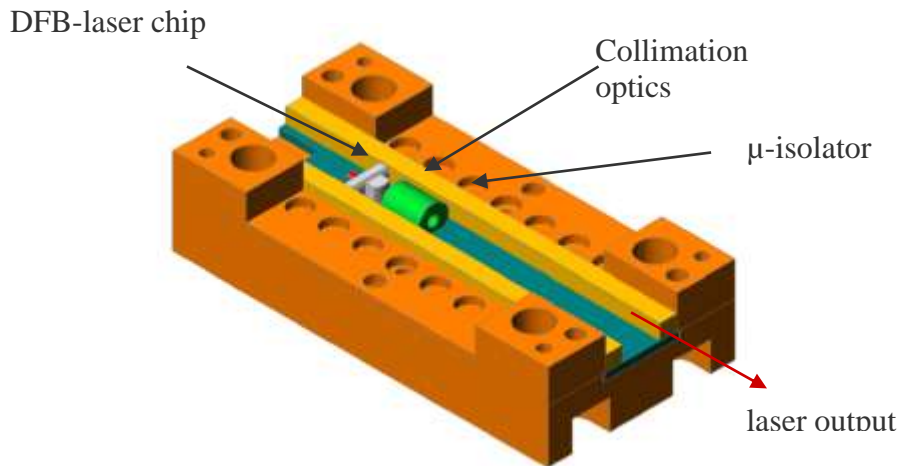
Figure 12: Power Amplifier module with a footprint of  $25 \times 50$  mm<sup>2</sup>

Similar power amplifier chips will be used for the DFB-MOPAs. For the electro-optical characterization of the amplifier chips hence refer to the next section.

- *Realization of DFBs and DFB-MOPAs near 780 nm (months 12-26).*

### **DFBs**

Laser modules consisting out of only a DFB (distributed feedback) laser diode will be used for providing the absolute frequency reference as well as light for repumping. The laser module contains the laser chip, a 30dB  $\mu$ -isolator and collimation optics. The module has a footprint of 25 x 50mm<sup>2</sup> and the characteristics of these modules were already presented in the last report.

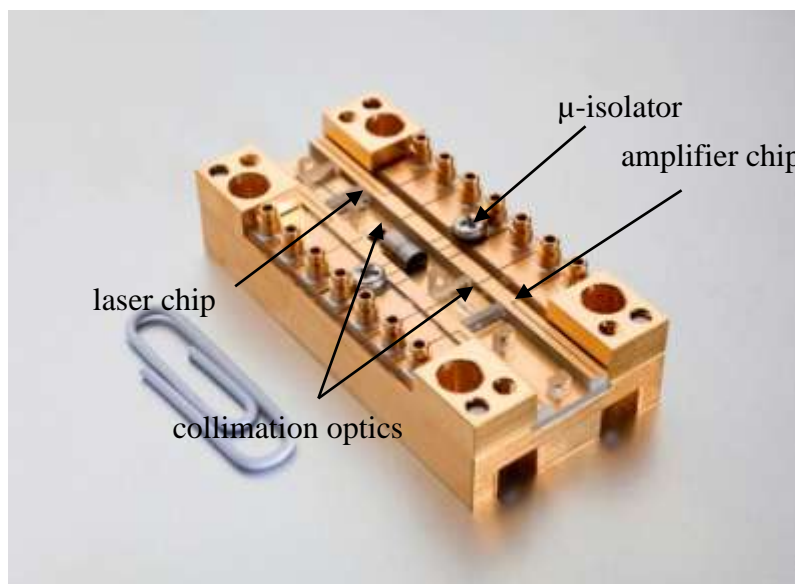


**Figure 13: Concept of a micro-integrated DFB-laser**

### **DFB-MOPAs**

DFB lasers combined with a tapered amplifier will be used as a light source for the cooling laser. This concept combines the advantages of the narrow linewidth of a DFB laser with the high output power of a power amplifier. These two laser chips will be integrated on the same AlN-microbench, thus having the same footprint than a single DFB-laser.

The specs of these modules were also already presented in last year's report, however since then problems with burn-in effects / aging effects for the DFB diodes and problems with the  $\mu$ -isolators occurred. This leads to a delay in the production of the MOPAs of about four months.



**Figure 14: Picture of a MOPA laser module**

Additional to the DFB-MOPAs at 780.24 nm for the cooling light there are also DFB-lasers as master oscillator available which run at a wavelength of 781 nm. The DFB-MOPAs at 781 nm can be used as an alternative for the creation of the light for the optical lattice.

The electro-optical characterization of a DFB laser shows that it can produce the required wavelength of 781.0nm at an injection current of 200mA at a temperature of 25°C.

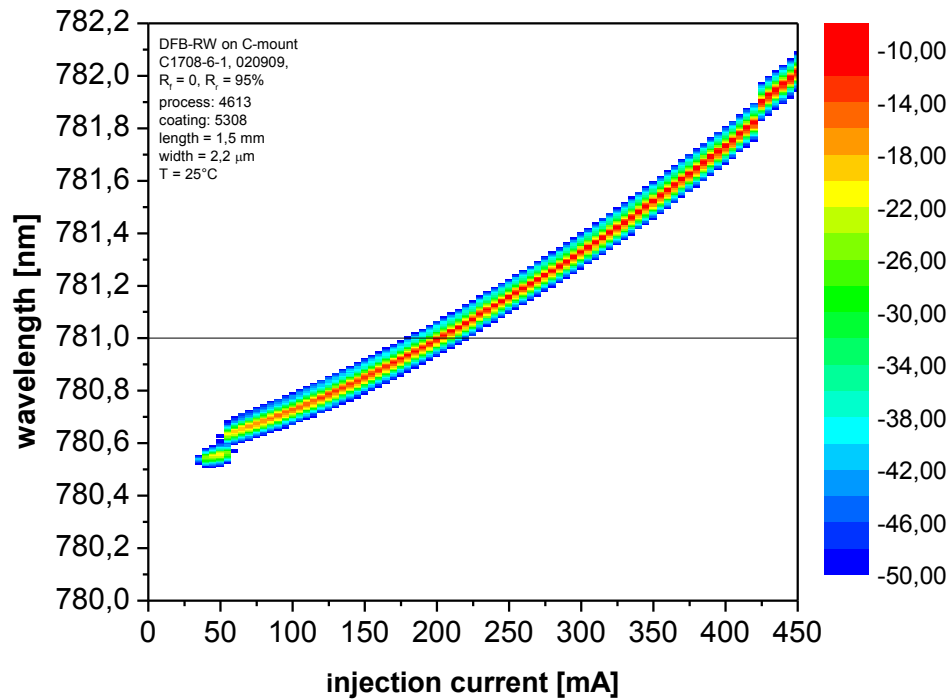


Figure 15: Optical spectrum as a function of the injection current

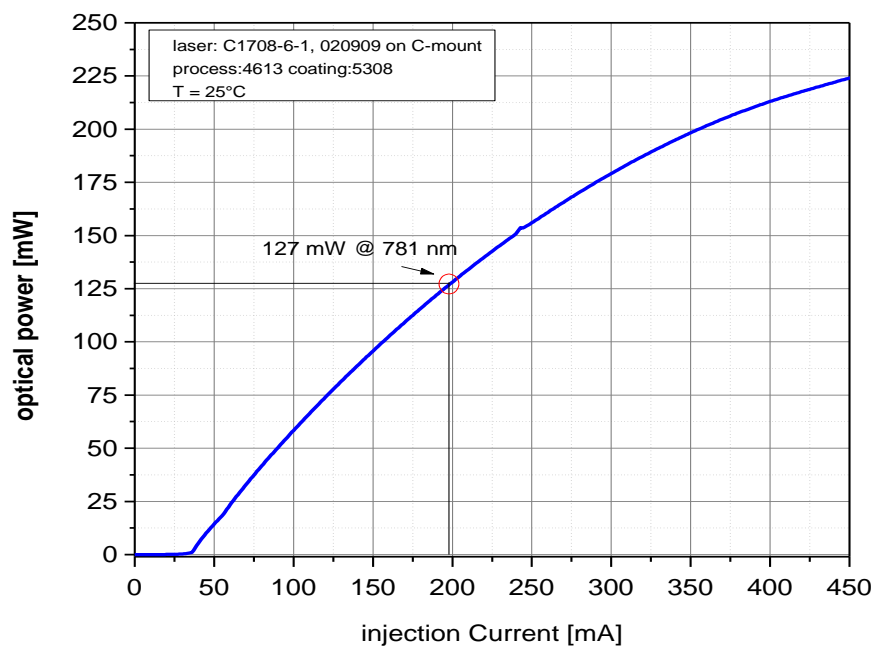
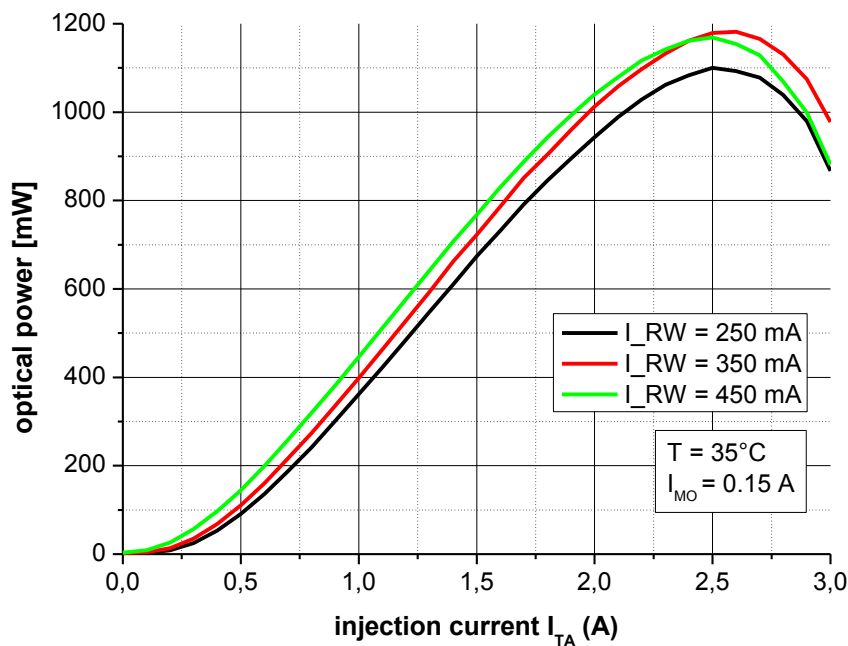


Figure 16: Optical output power as a function of the injection current

At these specs the laser will deliver about 125mW of output power (~60mW including the losses due to a 30db-isolator).

The amplifier chips itself consist of two parts, which are the tapered region and a ridge waveguide-section in front of it. The facets are AR coated to have a residual reflectivity of 0.01% or less.

To characterize the amplifier chips they were seeded with a DFB diode with an output power of 60mW. From the figure below we can deduct that the desired output power of 1W can be obtained at a TA-injection current of 2.0A and a RW-injection current of about 350mA.

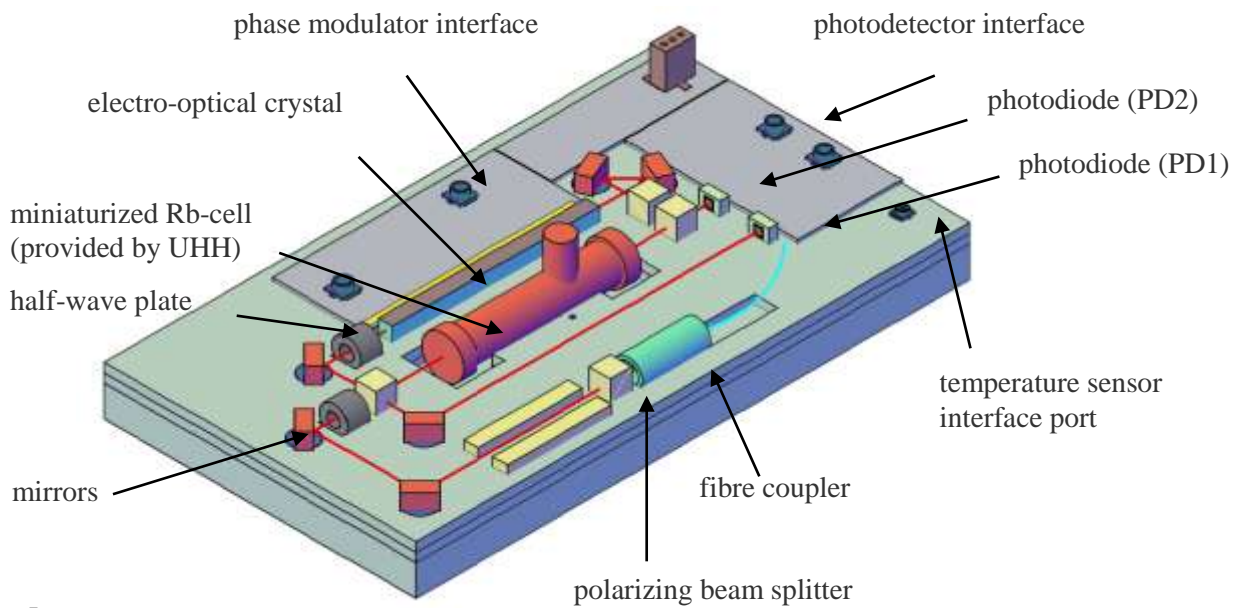


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Figure 17: Optical power as a function of the TA-injection current for different RW-injection currents

- *Micro-optical integration of the spectroscopy setup (cell and optics) with the ECDL and an optical isolator on a common microbench (month 20-27).*



**Figure 18: Design of the modulation transfer spectroscopy module**

For the generation of the reference light, this light has to be stabilized onto an atomic reference which will be done with the help of the module depicted above (figure 18). This module will allow for modulation transfer spectroscopy and is integrated onto an AlN board with a footprint of 45x80mm<sup>2</sup>. The design also allows for the realization of frequency modulation spectroscopy as an alternative. However in both cases the frequency modulation is provided by a free-space EOM which will be integrated onto the AlN-board. To allow for a maximal flexibility the module is connected to the laser itself with an optical fibre.

The electrical interface (for reading out the photodiodes, for driving the EOM and for power supply) is also directly on the module itself.

### **Task 1.3**

#### **- Evaluation of waveguide to fibre coupling methods (months 1-16).**

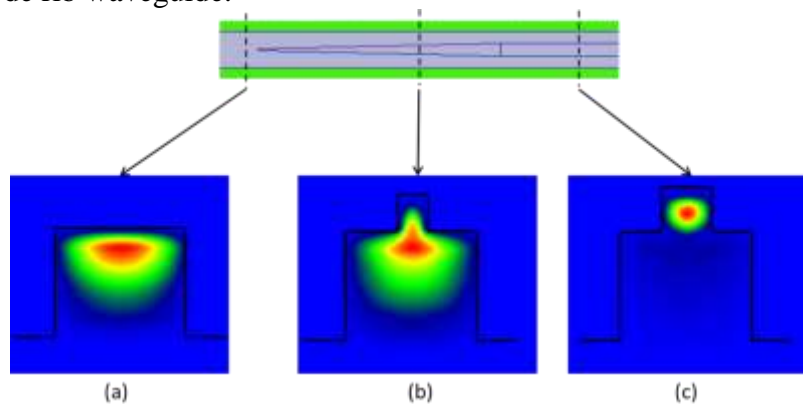
In addition to the waveguide to fibre coupling investigations with ppKTP waveguides presented last year, a quite detailed design and modelling of the semiconductor was done. Having undertaken detailed modelling to determine the structure of the straight waveguide, consideration was given to the issue of coupling the fibre mode of 5-6 micron diameter to the fundamental waveguide mode of 2.5 micron diameter. Various coupling methods were reviewed in the literature and discussions took place at the April 2012 meeting of the laser workgroup to identify the best approach to matching the modes of fibre and waveguide to sub-micron precision in 3 dimensions along 3 axes. Clearly, significant losses of laser power both into and out of the integrated optic chip may occur if coupling losses are high. Moreover, such coupling has to be compatible with the heat-sinking and wire-bonding of the integrated optics chip to its package. These aspects will be finalised for the delivered integrated optic circuits at the University of Birmingham.

We have developed new single-mode polarisation-maintaining and non-polarisation-maintaining waveguide structures. The waveguide structures have an integrated mode filter



so that the fundamental modes propagate with much lower loss than higher order modes, effectively making the guide single mode. Discussions within the work group determined that we should focus on waveguides which actively maintain the polarisation of the light in the structure. This is achieved by having a layered core to introduce a high differential leakage rate between the TE and TM modes; allowing the TE mode to propagate with low loss and the TM mode to quickly leak away into the substrate.

In order to overcome the problem of coupling light into and out of the integrated optics, the guides incorporate a tapered input and output region, which transfers the fibre mode (with a diameter of approximately  $5\mu\text{m}$ ) into the hard-walled (“rib”) waveguide (with a width of  $2.5\mu\text{m}$ ) or vice versa for the output. The fibre mode is initially launched into a lower (mesa) waveguide [Fig. 19(a)]. The second waveguide on top of the mesa waveguide has a higher refractive index, and the slow increase of the taper allows the adiabatic transfer of the light into the rib [Fig. 19(b)]. The light then propagates along the top waveguide [Fig. 19(c)] as for a single mode rib waveguide.



*Figure 19: Mode transfer between the fibre mode to RIB waveguide. Upper figure shows the plan view on the tapered region. The solid black line shows the waveguide cross section, (a) shows the mesa waveguide with fibre mode, (b) shows the intermediate stage of mode transfer, and (c) shows the light transferred into the rib waveguide*

The mode converter adds negligible extra length ( $< 1\text{ mm}$ ) to the fabricated device but greatly eases the tolerances required on fibre-interfacing to the integrated optic chip. In practical terms the complex chip is more easily useable by partners in the iSense consortium responsible for interfacing the whole experiment.

However, this extra functionality adds complexity to the epitaxial structure required, making it 4 times as thick and thus requiring long 24-hr growth runs. It also requires the ability to fabricate precisely-aligned, sub-micron features and, therefore, a process flow which requires e-beam lithography as well as photolithography and the ability to align these with an accuracy of  $10^3$ 's of nanometres. Thus the overall complexity of both the epitaxy and the device fabrication is increased.

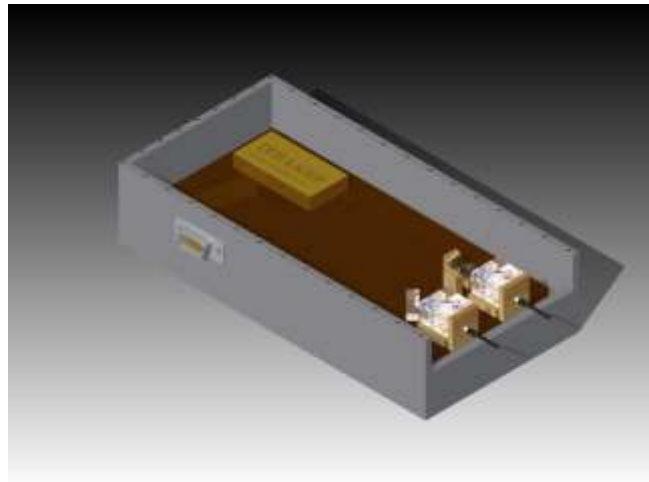
The respectively optimized waveguides are still under production, such that coupling results cannot be presented, yet. All of our ideas from last year's report are however still valid and we expect them to work out well as soon as waveguides of the final dimensions and material properties will be available for testing.

- ***Integration of the optical system*** (months 27-36)

To allow for the integration of the laser system into the complete experiment the modules have to be packaged and fibre coupled. This will be done using different techniques. For the

second generation lasers (DFB lasers and DFB-MOPAs) we intend to place them into an aluminium box. To reach the desired coupling stability we will use a highly linear setup which gets along without any steering mirrors and the laser beam being a straight line from laser to fibre coupler. Using such a design thermal expansions should compensate and lead to the desired fibre coupling stability.

For the master laser this design is not applicable as the beam has to be split prior to the first fibre coupling. Therefore the use of at least one mirror can't be avoided and a strictly linear design is not possible. To still reach a high stability of the fibre coupling efficiency this module will be mounted on a Zerodur base plate. Zerodur is a ceramic which has the advantage of a non-existent coefficient of thermal expansion over a wide temperature range (0°C-120°C) and is therefore a premium choice when ultimate temperature stability is required.



**Figure 20: Design of the packaging and fibre coupling of the master laser**

The ECDLs feature the possibility of integrating a modified Zerodur fibre coupler directly onto the AlN-board which allows for the highest fibre coupling stability. A coupler following this design was already fabricated and the coupling was tested with a DFB diode which was integrated on a similar AlN-board than the ECDLs. With that we could obtain a coupling efficiency of over 60%. Thermal tests are still to be done, however as the AlN-board has to be temperature stabilized for the laser to work no problems with fibre coupling efficiency are expected.



**Figure 21: Zerodur fibre in-coupler mounted onto an AlN-board with a DFB-diode**

### Task 1.4

#### - Alternative free-space optical delivery system (months 12-24)

We have developed a design based on commercial fibre optical components as depicted in fig. 22. For the distribution it is mainly based on commercially available 2x2 fibre splitters. These devices can be produced with arbitrary splitting ratios and by splicing several of these splitters together one can obtain arbitrary power ratios for any desired number of output beams. Splice-free networks with arbitrary power ratios can also be found commercially.

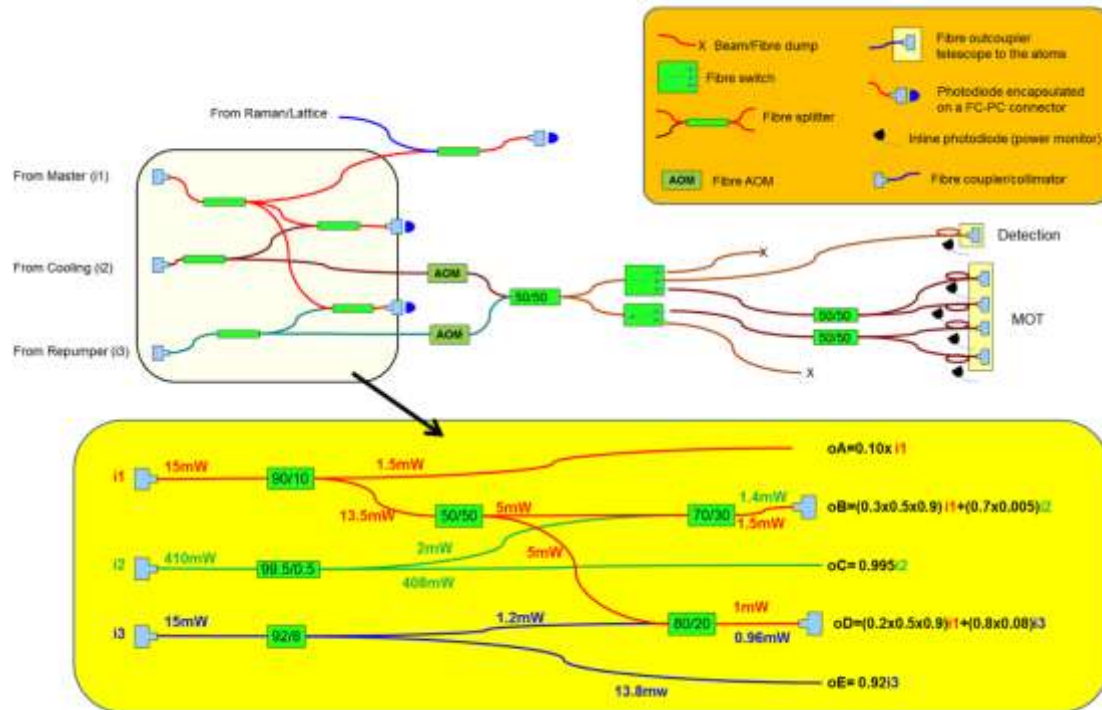


Figure 22: Fibre-based alternative delivery system. In the yellow box the detailed design of the splitting/combining unit for obtaining a beat note of the cooling and repumper laser with the master laser

For the switching of the light two approaches are followed. For a fast switching with switching times in the range of  $\mu\text{s}$ , fibre-coupled AOMs will be used. These were already tested with respect to their transmission and timing and it turned out that these devices absorb about 33-50% of the incoming optical power while they are able to switch in microseconds. However they only reach extinction ratios of about 30dB, which may not be sufficient for precision measurements of atoms in an optical lattice. Therefore mechanical shutters which are also fibre coupled will be used. These shutters are based on a mechanical movement of the ingoing fibre with respect to the multiple outgoing fibres so that the light is no longer coupled from one fibre to the other.

This allows either for simple on/off-switching of the intensity or for switching light from one outgoing fibre to another one which may be important if high intensities have to be dumped in a controlled manner. However these shutters need longer switching times in the range of ms, which makes them unsuitable for the timing of e.g. the interferometry pulses as a stand-alone solution. But they allow for a much higher extinction ratio. A fibre switch by LEONI was also already ordered for testing purposes but broke during a vibration test. This was diagnosed to be due to a fabrication problem and the switch has now been repaired and been retested. This test showed the suitability of this technology.

**Clearly significant results**

- The realisation of waveguides at 780nm opens integrated telecom technologies for applications using cold atoms for the first time.
- The production of micro-integrated laser systems with narrow linewidth and high output power is a significant step towards small and robust laser systems for cold atom applications.
- The fully integrated laser system design paves the way towards turnkey cold atom modules.

**Deviations from Annex I and their impact on other tasks, available resources and planning**

NA

**Reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources**

Due to the necessity to develop efficient light-transfer structures on the integrated waveguides there is a delay of a few months anticipated for the testing and delivery of the full integrated waveguide system. Due to the implementation of an alternative fiber based system for initial investigations until the availability of the GaAlAs device we do not expect any significant impact on other tasks or the project as a whole.

Due to the occurrence of some risks, some of the micro-integrated laser systems are delayed by up to 4 months. This is in part compensated by advances in the module design. We also have the possibility to make a standard laser system available to the project, such that the remainder of the project can proceed as planned and the laser modules can be dropped in as they arrive. We do not anticipate any impact on the overall goals of the project.

**Statement on the use of resources, highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1**

The use of resources is in general agreement with Annex-I.