Final report

Title of the project:

Timing the future: micro-integrated lasers for next generation portable optical atomic clocks

Leibniz-Institute: Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik

Reference number: SAW-2013-FBH-3

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1 Executive summary

Optical atomic clocks are at the forefront of the second quantum revolution and are bound to replace microwave clocks in applications where highest stability and accuracy are required. However, portable optical atomic clocks that can be operated in the field still fill a truck and require constant readjustment in order to function properly. One of the main current technological limitations is the availability of compact and robust laser technology that would enable the miniaturisation of the clocks and enhance their resilience to harsh environments.

The present project aims at the development of a micro-integrated laser system for spectroscopy on the clock transition of a portable aluminium ion quantum logic optical atomic clock. The laser system comprises a micro-integrated laser module emitting at 1069.6 nm, a commercially available single-pass second harmonic generation (SHG) module for frequency doubling to 534.8 nm and a resonant SHG cavity for frequency conversion to clock transition at 267.4 nm. The architecture for the laser emitting at 1069.6 nm is a master-oscillator-power-amplifier (MOPA), with an extended cavity diode laser (ECDL) as master oscillator and a ridge-waveguide semiconductor optical amplifier. The resonant SHG module is based on a monolithic cavity in a BBO-crystal.

Moreover, a slightly modified laser system operating at 532 nm, with a micro-integrated laser module emitting at 1064 nm and a commercially available single-pass SHG module, is built in order to test the suitability of such a laser system into a frequency reference based on molecular iodine.

The ECDL-MOPA modules operating at 1064 nm and 1069.6 nm achieve up to 615 mW output power ex-fibre and exhibit a free-running linewidth of better than 30 kHz in a measurement time of 1 ms. Moreover, the lasers exhibit a side mode suppression ratio better than 50 dB at the working point, together with a long-term power stability below 1%. From these results, it can be concluded that the ECDL-MOPA built in this work fulfils the requirements for the local oscillator of the Al^+ quantum logic clock.

Moreover, the ECDL-MOPA operating at 1064 nm was stabilized on a transition in molecular iodine, proving its suitability as local oscillator for an iodine-based frequency reference. Indeed, taking advantage of the development work carried out in the present project, the FBH delivered two ECDL-MOPA operating at 1064 nm in the frame of the JOKARUS experiment on board a sounding rocket in May 2018, thus demonstrating the first iodine-based frequency reference in space.

A model for the operation of a resonant cavity for second harmonic generation based on walk-off compensation in a monolithic BBO crystal was developed. The optimal parameters for efficient frequency conversion into the deep UV were calculated and a workflow for the processing of the BBO crystals was developed accordingly. A monolithic cavity offers the advantage of an easy micro-integration, but comes at the cost of very tight angular tolerances while aligning the normal vectors of the resonator facets to the optical axis of the crystal. After a first trial failed, a new approach that ensures that the required angular tolerances during the processing of the BBO crystals are achieved has been developed and tested.

2 Initial questions and goals

Optical atomic clocks have surpassed primary microwave atomic clocks in terms of stability and accuracy. It is expected that the official unit of time, the second, will eventually be redefined based on an optical clock. Many applications, such as relativistic geodesy and frequency comparisons between distant systems, require portable clocks. However, optical atomic clocks are still handcrafted prototypes that require a well-controlled laboratory environment for operation and are by no means transportable. One of the current main technological limitations is the availability of a laser technology concept that allows for an operation of a portable optical clock “in the field” or in space: the lasers have to be compact, mechanically robust, radiation hard and energy efficient.

This project aims at the development of a micro-integrated laser system operating at a wavelength of 267.4 nm for spectroscopy on the clock transition of a portable aluminium ion quantum logic optical atomic clock. Micro-integration of the diode laser chips with optics provides very robust, energy efficient and extremely compact laser modules: in comparison to available devices, which cannot be space qualified, micro-integrated diode lasers take up a volume that can be a factor of 500 smaller.

The project combines the unique expertise of the Ferdinand-Braun Institut (FBH), of the Quantum Metrology Group of the Institute of Physics at the Humboldt-Universität zu Berlin (HUB), and of the Physikalisch-Techische Bundesanstalt in Braunschweig (PTB) to initiate a long-term partnership with the ultimate goal of bringing optical clocks from laboratory into space. This partnership is an essential and indispensable prerequisite for future activities in a field that is just emerging and is expected to have a large impact in technology and society.

3 Overview and progress

3.1 Project plan and deliverables

The original project plan foresaw the development of three laser systems at the wavelength 267.5 nm, each consisting of an extended cavity diode laser (ECDL) module with a preamplifier at the wavelength 1069.6 nm, a single-pass second harmonic generation (SHG) module to 534.8 nm with an integrated semiconductor optical amplifier for laser light at 1069.6 nm and a SHG module for frequency conversion to 267.4 nm based on a resonant cavity. Five work packets (WP) were defined, that would cover all the technical tasks required for the fulfilment of the project goals:

- WP1: Master Oscillator Module: 1069.6 nm ECDL
- WP2: Single Pass SHG Module: 1069.6 nm → 534.8 nm
- WP3: Frequency stabilization to Hz-Stability and Molecular Reference
- WP4: Resonant SHG Module: 534.8 nm → 267.4 nm
- WP5: Integration into Al-ion Clock and Technology Validation

Within the project, two changes to the deliverables were operated:

1. the recent commercial availability of fibre-coupled SHG modules for frequency conversion from 1069.6 nm to 534.8 nm prompted the project partners to modify the different modules. The ECDL master oscillator at 1069.6 nm and the amplifier would come into 1 module in a master-oscillator-power-amplifier (MOPA) architecture, frequency conversion to 534.8 nm would take place in a commercial SHG module, and

frequency conversion to 267.4 nm would still be carried out into a resonant cavity developed by the project partners.

2. the interest from the scientific community for optical frequency references opened the opportunity to investigate the suitability of the ECDL-MOPA laser module for the application. Hence, 2 ECDL-MOPA operating at 1064 nm were included in the list of deliverables, in order to realize a frequency reference based on molecular iodine with stabilization of the laser on a spectroscopic line at 532 nm (the same family of commercial SHG modules as for the 1069.6 nm lasers can be used). As a trade-off, one laser system (comprising 1069.6 nm ECDL-MOPA, commercial SHG and resonant SHG) was cancelled.

As a result, WP1 and WP2 were fused into a single new WP1: ECDL-MOPA module.

3.2 Project timeline

The original project duration applied for was 3 years, between 01.04.2013 and 31.03.2016. However, a delay of 12 months was accumulated in the fabrication of the module bodies and housings in WP1 due to design changes in order to include a heat spreader for the on-board fibre couplers that also required a new layout of the thin film patterning of the ceramic substrates. Moreover, in WP4, the process flow designed for the alignment of the lateral surfaces of the BBO crystals to the optical axis of the crystals could not yield the required accuracy in practice. The delay of 12 months accumulated due to unforeseen technical difficulties in WP1 and WP4 impacted on WP3 and WP5, which heavily rely on the hardware produced in WP1 and WP4. This situation prompted the project partners to apply for an extension of the project for a further 12 months, until 31.03.2017.

During the project extension of 1 year, the main project scientist at FBH went on parental leave for 9 months. At the same time, the project leader and the project scientist at HUB went for 5 months and 2 months parental leave, respectively. During that period, the micro-integration of the laser modules could progress, with internal assignment of new personnel to the project at FBH. However, no personnel with the required expertise on BBO crystals and monolithic resonators could be found in order to pursue the work in WP4. In order to complete the project work, the partners decided to apply for a further extension of the project for a period of 9 months until 31.12.2017.

3.3 Project methodology and progress

3.3.1 <u>WP1: ECDL-MOPA module</u>

<u>Diode laser chips</u>

The epitaxial laser design of the diode laser chips processed for implementation as ECDL master oscillator or ridge-waveguide amplifier (RWA) in the ECDL-MOPA modules was optimized for operation at 1070 nm. The chips feature an InGaAs double quantum well active region with GaAsP barrier and spacers embedded into AlGaAs waveguide and cladding layers. The 4.8 µm wide asymmetric large optical cavity results in a a far field angle of 15° FWHM, which facilitates beam forming. The ridge-waveguide structures all have a width of 5 µm.

The optical resonator of the ECDLs is formed between the front facet of a 2 mm long laser diode chip and the effective mirror plane of a volume holographic Bragg grating (VHBG), as depicted in *Figure 1*. In order to reduce parasitic compound cavity effects, all optical interfaces within the ECDL resonator are AR-coated. The geometric length of the laser cavity is approximately 20 mm and exhibits a free spectral range of around 4.8 GHz. The effective wavelength of the ECDL is set by the VHBG that has a bandwidth of 20 GHz. The ECDL-MOPAs at 1064 nm or 1069.6 nm are quasi-identically implemented, with the only difference of the VHBG that sets the emission wavelength. The RWA are processed to a 6 mm long chip with a tilted RW having an angle of 3°

to both AR-coated facets of the chip. In the ECDL-MOPA concept, the output emission of the ECDL is fed into the RWA for amplification of the laser radiation.

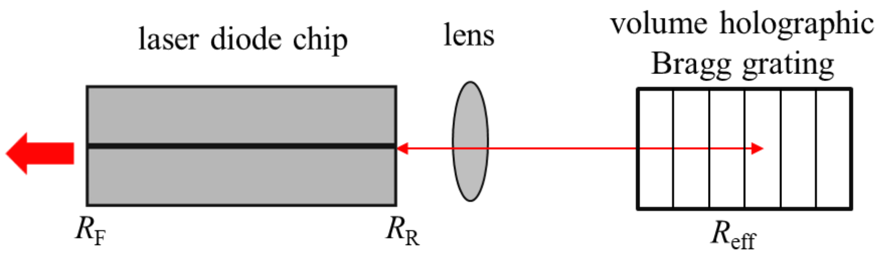

Figure 1 Schematic of the ECDL concept. R_F: Front facet reflectivity, typ. 30%; R_R: Rear facet reflectivity, AR-coated, typ. 10^{-4}; R_{eff}: effective reflectivity of VHBG, typ. 70%.

Setup for burn-in and characterization of diode laser chips

A new measurement bench for the burn-in and for the characterization of the diode laser chips was designed and implemented. The chips, mounted on an AlN heat spreader are clamped inside a massive holder made of Bronze (CuSn6), where thermal contact between chip and holder is ensured. Electrical contacting of the chips is achieved by wire bonding to circuits boards on both flanks of the holder. Aspheric lenses placed on an xyz-stage with nominal travel resolution of 1 nm in each axis ensure the in- and out-coupling of light into/from the chips. With optical access to both facets, the measurement setup can be used to characterize both ECDL and RWA chips.

For the characterization of ECDL chips, the VHBG is mounted on a mirror mount that offers a resolution of 1 µrad in each of the lateral tilt axes. The mirror mount sits on a linear stage that sets the axial distance and thus the resonator geometrical length, also with a nominal resolution of 1 nm. The aspheric lens facing the VHBG is used as intra-cavity lens, whereas the lens at the front facet collimates the laser output en route to measuring instruments.

In the case of an RWA, the lens at the input facet focuses light from a seed laser source into the waveguide of the amplifier, whereas the lens at the output facet collimates the emission before it is fed into the measurement instrumentation.

Moreover the thermal, electrical and optical interfacing of the chips on the burn-in setup reproduce the conditions inside the laser module to a high fidelity, which is very important while selecting chips that would be integrated into a laser module. Figure 2 shows a picture of the measurement setup.

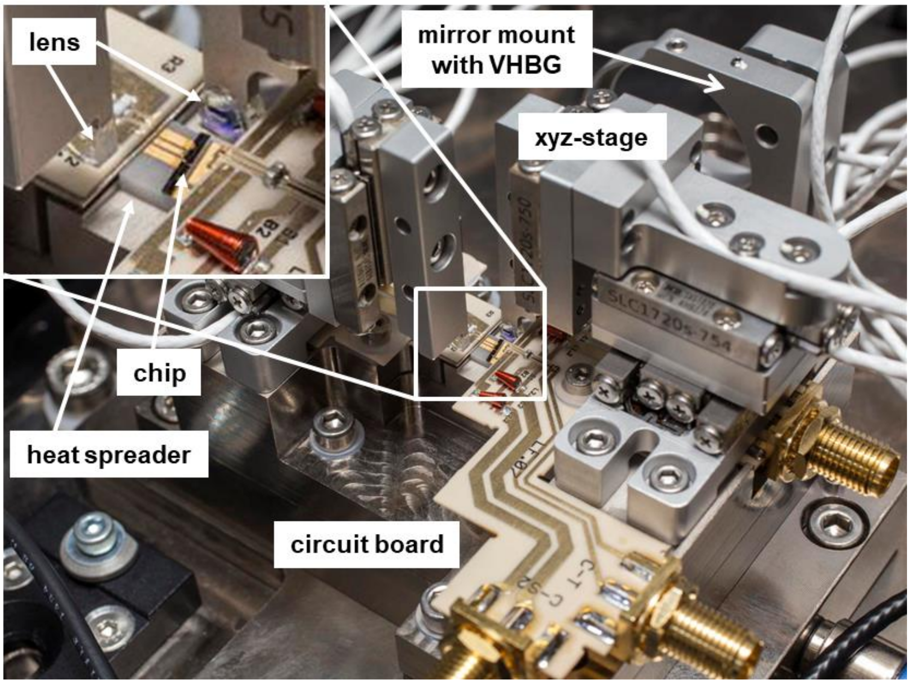

Figure 2 Picture of measurement setup for diode laser chips. The VHBG and the linear stage for the axial displacement of the mirror mount are not shown in the picture.

ECDL-MOPA laser module

The laser module body and the housing for the ECDL-MOPA used in this project are based on the MiLas technology developed at FBH[1]. The conceptual approach to these laser modules rests on versatility and multi-functionality, embodied by a design incorporating two arbitrary semiconductor-based active or passive chips and two optical ports that can be used as input or output ports according to the requirements, see *Figure 3*. The ECDL-MOPA incorporates an ECDL (chip 1), a RWA (chip 2), and two optical output ports, one behind the rear facet of the laser chip and the other in front of the output facet of the RWA. The laser diode chips, each of which are either soldered or adhesively bonded on an AlN sub-mount, are integrated inside the space between the rails by adhesive bonding. The intermediate AlN plate and the three rails, together with mechanical structures cut-out inside the AlN, also serve as anchor points for the attachment of the optical components. Electrical connections between chips and the AlN ceramic module body are implemented by conventional Au-wire bonding.

The source of laser light on the ECDL-MOPA is the ECDL with two exit beams, a main local oscillator beam at the front facet of the chip and an auxiliary beam at the rear facet of the VHBG. The main local oscillator beam is collimated and travels through a µ-isolator before being focused into the waveguide of the RWA chip. At its output, the amplified light is collimated before being deflected twice with the help of µ-mirrors positioned at 45° to the beam axis. The beam is subsequently injected into a fibre coupler ferrule, consisting of a coupling lens and a single-mode, polarization-maintaining fibre whose facet lies in the focal plane of the lens. Throughout the optical path, beam shaping is carried out by either cylindrical or aspheric micro-lenses and a polarizing beam splitter in front of the fibre coupler filters out the fraction of the optical field oscillating in the undesired polarization. Since µ-isolators in this form factor (Ø 4mm, 5 mm long) cannot handle the optical intensity exiting the RWA (typ. 175 Wcm^{-2}), the isolator is omitted between RWA and fibre coupler.

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[1] A. Wicht et al., "Narrow linewidth diode laser modules for quantum optical sensor applications in the field and in space", Proc. of SPIE Vol. 10085

The beam exiting the ECDL through the VHBG is, per resonator design, quite collimated. This auxiliary beam path is very similar to that of the main beam emitted by the RWA, except that here a µ-isolator is placed between the two µ-mirrors in order to avoid feedback into the local oscillator through the auxiliary port.

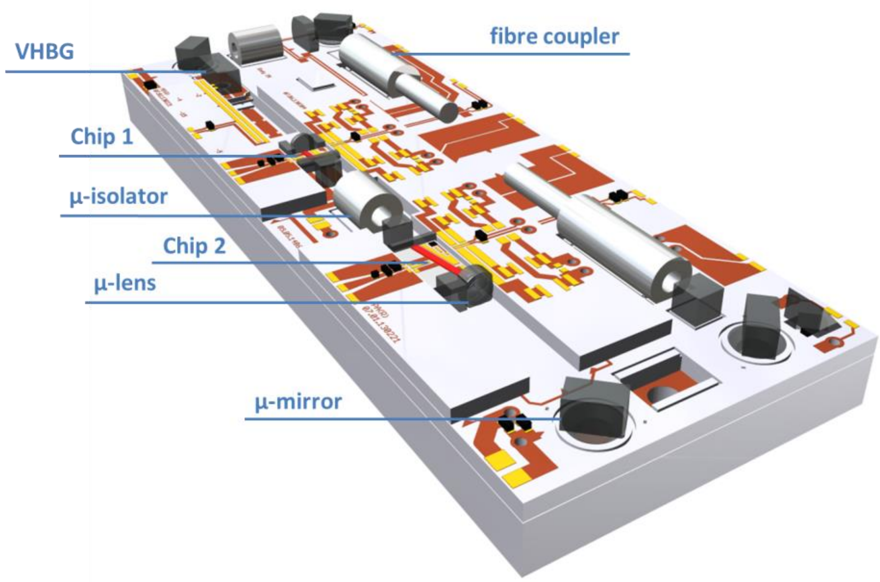


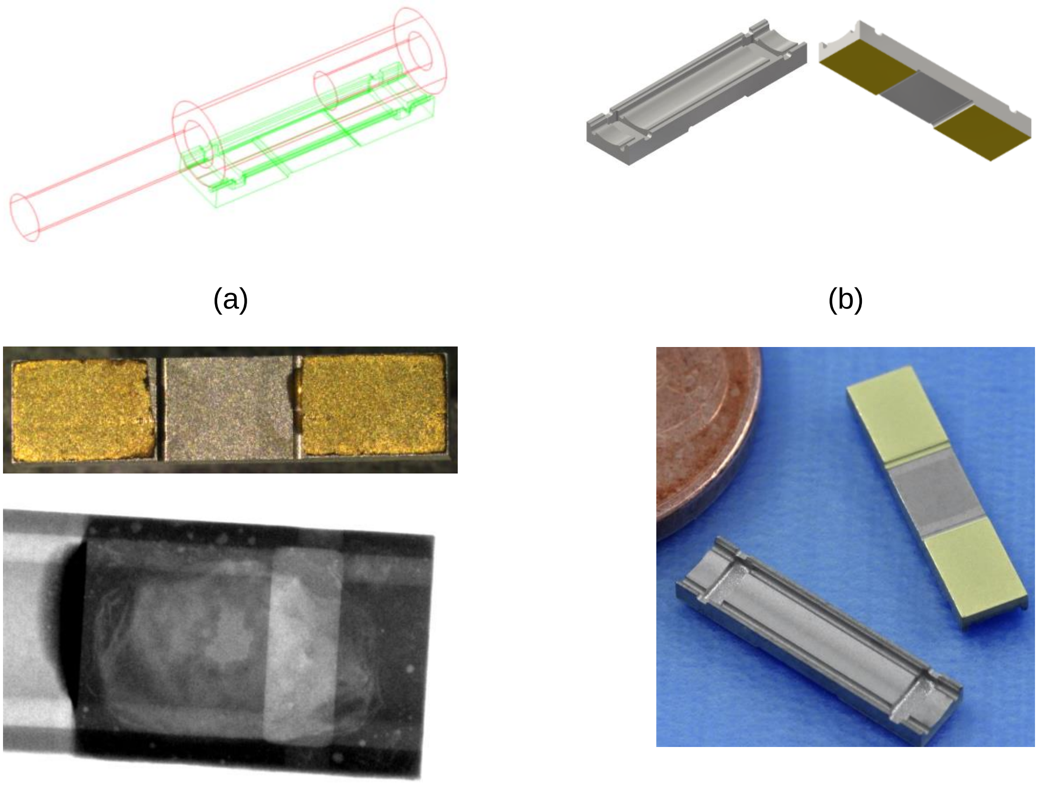
Figure 3 CAD Model of an ECDL-MOPA module with dimensions 30 x 80 x 10 mm³. VHBG: volume holographic Bragg grating; µ-isolator: micro-optical isolator; µ-mirror: micro-mirror; µ-lens: micro-lens. The optical fibres exiting the fibre coupler are not shown in the figure.

<u>Re-design of the interface between fibre coupler and ceramic substrate</u>

The fibre coupling concept designed in MiLas was intended for a maximum optical power of around 100 mW entering the fibre coupler. In its implementation, the concept worked up to powers of approximately 80 mW. In this project, the expected power on the fibre couplers can go up to 1W. Hence, the fibre coupler concept had to be modified in order to accommodate such high optical powers.

A careful analysis of the system (fibre coupler + interface on AlN substrate + adhesives in between) showed that the injection power was limited by thermal effects in the fiber coupler and that the bottleneck lay at the interface coupler-substrate. Hence, a heat spreader that would facilitate the heat transport between the fiber coupler tubing made of Kovar and the AlN substrate was designed. Figure 4 depicts the heat spreader: (a) conceptual form, (b) CAD rendering, (c) first fabrication (generation 1) and X-ray picture of wetting of AuSn-solder under the heat spreader, (d) generation 2 of heat spreader.

The body of the heat spreader is formed via wire eroding, then Ni-plated. Subsequently, the two bond pads on the bottom of the heat spreader gold plated. The heat spreader is soldered onto the AlN substrate of the module body with AuSn solder. In a first generation of heat spreaders, the bond pads were plated with 1 µm Au and the masking was done with an adhesive pad. The surface quality of the gold was very poor and bonding tests revealed a very poor wetting of the AuSn solder to the bond pads (< 20%). In a second generation, the bond pads were sputtered with 200 nm fine gold and the masking was done with Aluminium masks. Wetting tests showed nearly 100% wetting. The generation 2 heat spreaders are now implemented in MiLas modules as standard part. As a result, a stable thermal behaviour of the fiber couplers has been demonstrated for optical powers of up to 900 mW, with a coupling efficiency approaching 70% (600 mW at the fiber output).



(a) (b) (c) (d)

Figure 4 Design and fabrication of heat spreaders. (a) conceptual design with fibre coupler in red and heat spreader in green; (b) CAD rendering. The surface of the parts made in Kovar is Ni-plated, while the 2 bond pads at the bottom (golden) are Au-plated; (c) first generation of heat spreaders, where the gold-plating of the bond pads did not yield the expected results. On the X-ray picture, depicting a bond pad after soldering onto an AlN substrate with AuSn, it can be seen that the solder wetting (dark areas) is of very poor quality (< 20% wetting); (d) generation 2 of head spreaders with sputtering of 200 nm Au on the bond pads. All soldering tests were passed and generation 2 heat spreaders are implemented in all MiLas modules.

<u>Packaging concept</u>

The housing is made of Kovar, a very well established material for integration with AlN the field of electronic hybrids. Further, also as heritage from electronic hybrid technology, a glass-soldering technology exists that allows for integration of electrical feedthroughs into the housing. Optical feedthrough of the fibres is done via a flange made of Kovar , with an Indium O-ring as interface between the flange and the housing wall. The flange is fixed with 3 screws to the housing wall and the seat load applied on the indium induces a cold weld that seals the interface. The housing shown in Figure 5 features a form factor of 175 x 75 x 22.5 mm^3 and a mass of approximately 750 g.

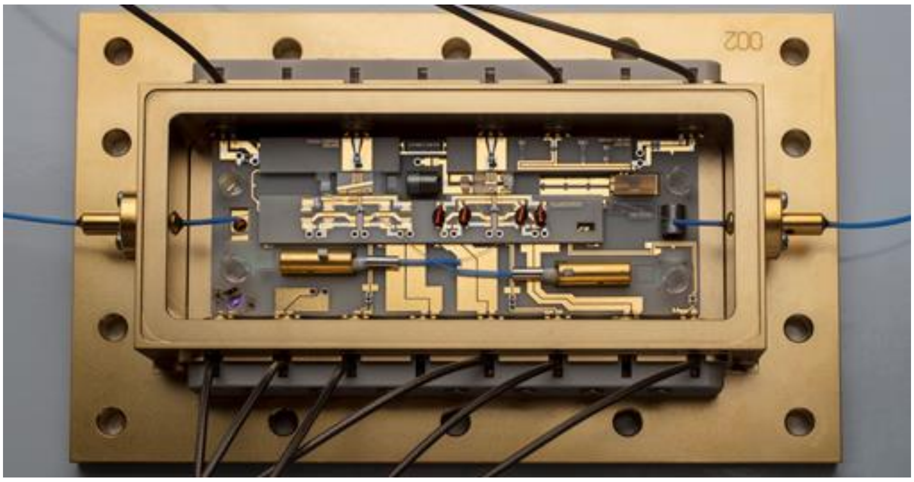


Figure 5 fully integrated ECDL-MOPA module

<u>Electro-optical performance</u>

Two ECDL-MOPA modules were implemented, one emitting at a wavelength of 1064 nm, the second one emitting at a wavelength of 1069.8 nm. Both laser modules exhibit very similar electro-optical (EO) characteristics and, in the following, only the results of the 1069.6 nm ECDL-MOPA shall be presented.

The EO characteristics of the ECDL-MOPA module emitting at 1069.6 nm were thoroughly investigated, especially with respect to its application as local oscillator for an Al^+ quantum logic optical atomic clock. The expected and the achieved performance are summarized in table Table1.

Parameter	Unit	expected performance	performance achieved	Notes
Frequency (vacuum)	THz	280.25385	280.25385	
Linewidth	kHz	< 100 (10 µs)	17 (1 ms)	
side mode suppression ratio (SMSR)	dB	-	> 50	
Output power	mW	700	615	
Detuning	GHz	> 1	4	within 1 mode hop
relative intensity noise (RIN)	1/√Hz	shot noise limited for > 100 kHz	9×10^{-8}	with 135 µW on photodetector (eq. shot noise 5×10^{-8})
long term power stability	%	< 10	0.8	
Polarization extinction ratio	dB	> 13	19	

Table1 EO characteristics of the ECDL-MOPA at the emission wavelength of 1069.6 nm

The results listed in table Table1 show that most of the requirements on the free running ECDL-MOPA for operation as local oscillator in an Al^+ quantum logic optical atomic clock are fulfilled, most often even surpassed. Only for the output power of the system, where 700 mW were targeted, only 615 mW were achieved. However, as described in section 3.3.3, the design of the resonant cavity for SHG into the UV-range is such, that higher output powers than expected can be achieved, thus allowing the expected UV-power to be achieved with less NIR-power from the local oscillator. The relative intensity noise (RIN) is measured to be higher than the shot noise limit above Fourier Frequencies of 100 kHz. However, the measurement was carried out with only 135 µW impinging on the detector and the RIN would be much lower if measured at the maximal output power of 600 mW.

The characteristic curves for the measurement of the different EO parameters are shown in Figure 6: (a) optical output power as a function of DC current sweep of the power amplifier; (b) optical frequency and (c) SMSR as a function of DC current sweep of the ECDL; (d) long term power stability; (e) RIN; (f) beat note spectrum (linewidth inferred using the method of the β-separation-line[2]).

From these results, it can be concluded that the ECDL-MOPA built in this work fulfils the requirements for the local oscillator of the Al^+ quantum logic clock.

3.3.2 WP 3: Frequency Stabilization and Molecular Reference

Frequency stabilization scheme for the ECDL-MOPA

For operation as local oscillator of an optical atomic clock, the frequency of the laser output of ECDL-MOPA laser module needs to be stabilized to sub-Hz stability (8 mHz in the case of the Al^+ quantum logic optical atomic clock). This is usually achieved via stabilization on a highly stable optical resonator. In addition to the highly stable optical resonator, laser stabilization to an optical cavity requires a feedback loop using a locking module. Figure 7 shows a sketch of the proposed servo-electronics and the connecting ports of the ECDL-MOPA module used for stabilizing the 1070 nm master oscillator to an optical reference cavity.

The module is operated using precision Laser Diode Controllers (LDC) from Newport Corporation. This type of controllers combine a precision laser diode current source with thermoelectric temperature controller that typically achieve temperature stability within ±0.004°C. Modulation input ports are available for both current and temperature controllers.

As shown in Figure 7, the current driver in LDC-3724C (0 – 500 mA) is used as a current source to the master oscillator (MO) via the connecting pin MO.S, while the current driver in LDC-3744C (0 – 4000 mA) is used as current source to the power amplifier (PA) via the connecting pin PA.S. The temperature controller in the LDC-3724C is connected to a thermo-electric cooler (TEC.Housing) situated under the module housing and is used to control the temperature of the ceramic body of the laser module. The LDC-3744C is connected to a thermo-electric cooler (TEC.VHBG) situated directly under the VHBG and that controls its temperature. In addition, a TEC controller type Meerstetter - TEC-1091, is used, via the TEC.Heatsink pin, to stabilize the temperature of the heatsink on which the module, TEC-Housing inclusive, is placed.

For the PDH laser stabilization setup, the error signal generated at the optical cavity is fed to a locking module that is, as depicted in figure Figure 7, proposed to be a FALC 100 (from Toptica).

The FALC integrates the error signal and delivers slow and fast modulation signals to ensure the frequency stabilization of the module. The fast feedback signal is connected to the modulation input port of the MO via MO.MOD pin. The slow feedback signal is connected to the modulation input port of the LDC temperature controller that is connected to the Peltier element at pin TEC.Housing.

[2] G. D. Domenico et al., "simple approach to the relation between laser frequency noise and laser line shape"; Applied Optics 49, issue 25 4801-4807, 2010

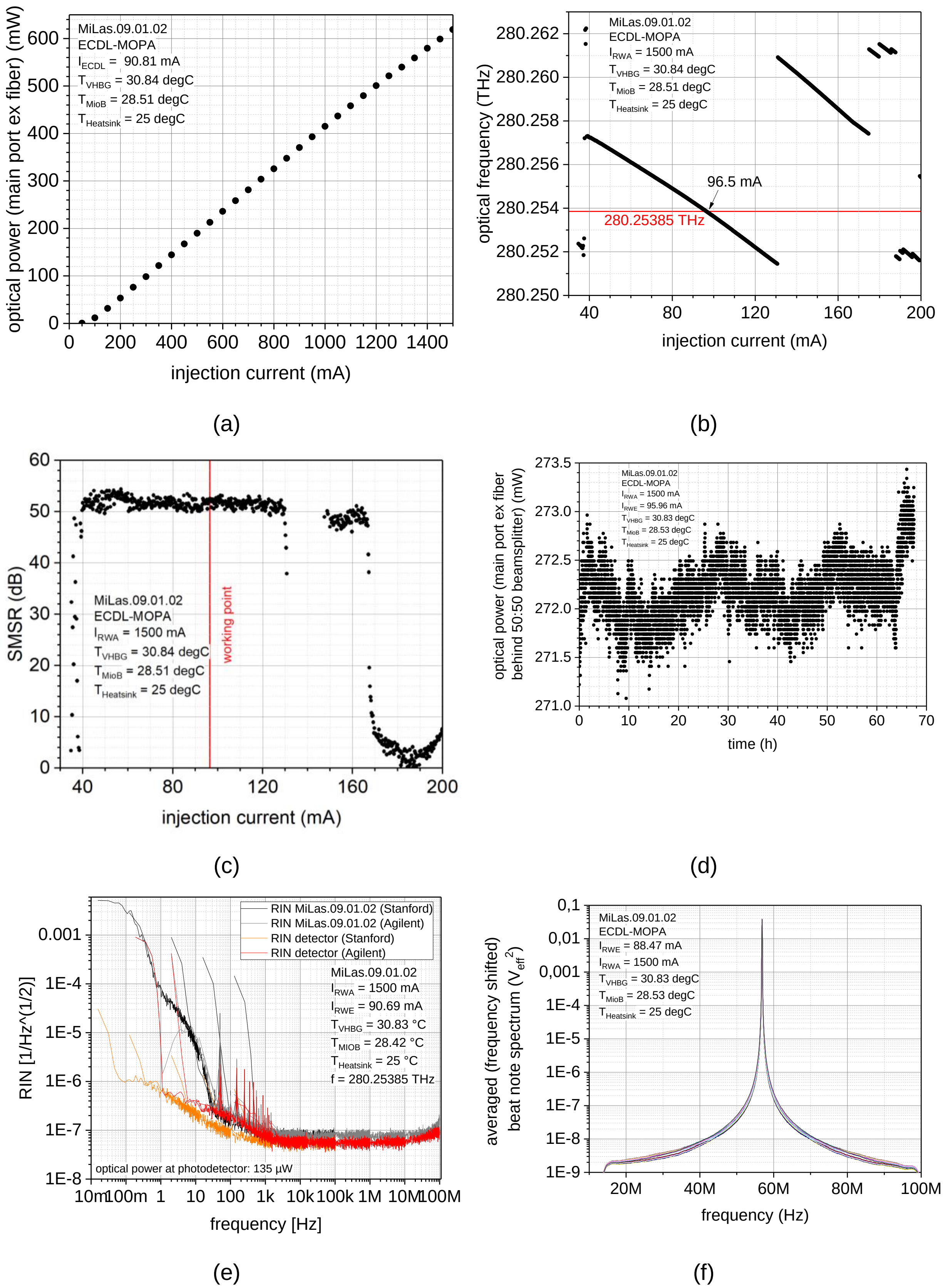


Figure 6 Characteristic curves for EO parameters of the ECDL-MOPA

Important remark: the main output voltage ranges of the FALC (± 2V for the fast branch and ± 5 V for the slow branch) exceed the limited input voltage values of the modules (0…1V for the MO.MOD and 0…4.7V for the TEC.Housing). Thus modifications must be done on the output signal of the FALC, or a different PID could be used.

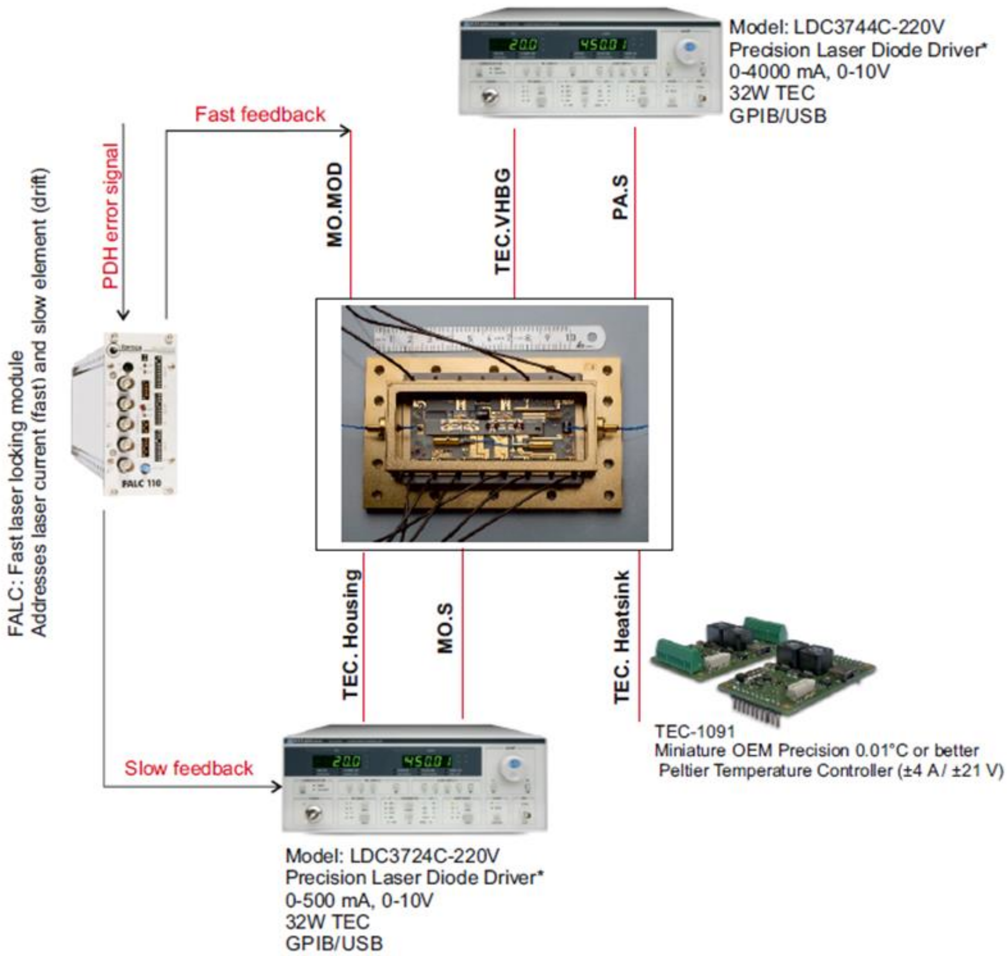


Figure 7 Servo-electronics setup for the Pound-Drever-Hall (PDH) stabilization of the ECDL-MOPA to an optical reference cavity.

Laser stabilization to an iodine reference

The output signal of the ECDL-MOPA operating at 1064 nm was frequency-doubled to 532 nm using a commercially available SHG module (WH-0532-000-F-B-C from NTT electronics) and the frequency-doubled signal was stabilized to a ro-vibronic transition in molecular iodine. The laser was stabilized using the modulation transfer spectroscopy signal of the transition R(56)32-0:a_1 and the frequency stability of the laser was determined from a beat-note measurement with a Nd:YAG NPRO laser that was simultaneously stabilized to an optical high finesse cavity. The frequency noise of the free-running and the frequency stabilized ECDL-MOPA is shown in Figure 8.

An improvement in the frequency noise amplitude spectral density (ASD) of the ECDL-MOPA locked on iodine of 5 orders of magnitude can be observed at low frequencies (10^{-4} Hz). At higher frequencies, the improvement in the frequency noise of the locked laser w.r.t to the free running laser decreases, until a cross-over is observed at around 8 kHz, where the frequency noise ASD of the free-running laser is lower than that of the locked laser. However, the measurement of the laser in-lock and free-running where made using two different laser current drivers, that have different noise performances, which explain the additional noise seen on the laser in-lock at high frequencies (the current driver used for the free-running laser noise is actually less noisy than the one used while measuring the locked laser performance). Taking this fact into account, it can be concluded that the ECDL-MOPA was successfully locked onto a transition in molecular iodine.

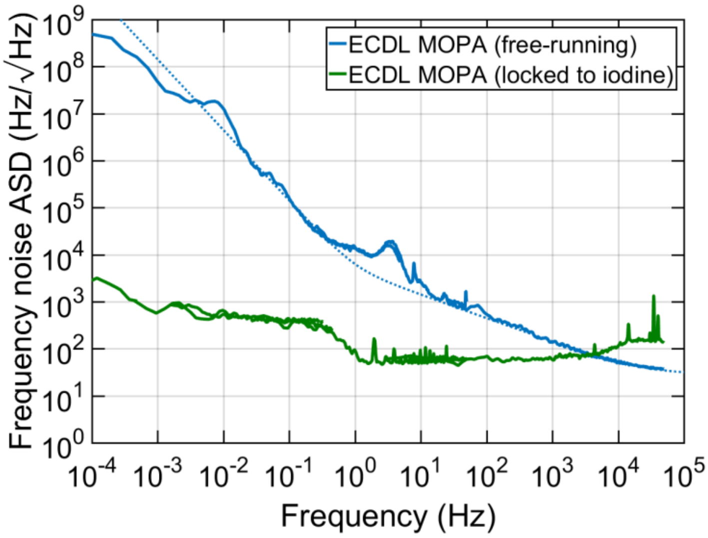


Figure 8 Linear spectral density of laser frequency noise. This figure shows the comparison of laser frequency noise of an ECDL-MOPA at 1064 nm in free-running mode and when locked to a ro-vibronic transition in molecular iodine.

3.3.3 WP 4: Resonant SHG Module: 535 nm → 267 nm

Concept for a monolithic resonant SHG cavity

In the last stage of the clock laser for the Al^+ quantum logic clock, where laser light at the wavelength of 267.4 nm is required, the concept of a resonant SHG cavity in BBO with walk-off compensation[3] is chosen to convert the laser light at 534.8 nm into the UV. However, in this work, a monolithic cavity, instead of a semi-monolithic cavity is considered. The principle behind the monolithic BBO resonant cavity is depicted in Figure 9.

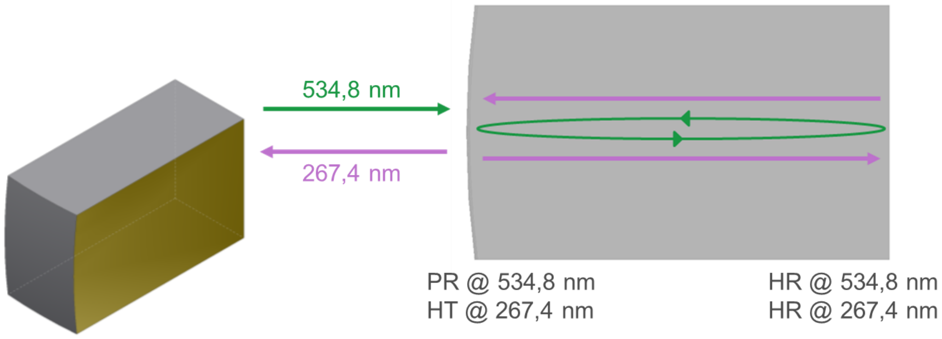
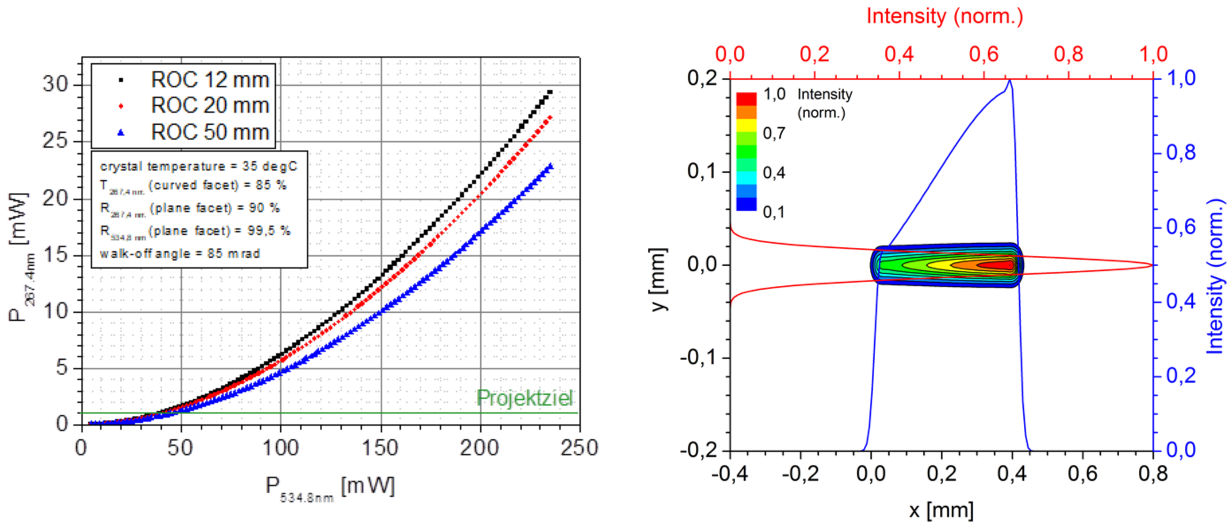


Figure 9. CAD rendering of the monolithicBBO cavity(left) and sketch of the principle behind the cavity (right). The plane-concave cavity is resonant (and stable) for the fundamental light at 534.8 nm and the concave entry facet is PR-coated for 534.8 nm and AR-coated for 267.4 nm. The plane facet is HR-coated for both wavelengths.

[3] B. G. Klappauf et al., "Detailed study of an efficient blue laser source by second-harmonic generation in a semimonolithic cavity for the cooling of strontium atoms", APPLIED OPTICS Vol. 43, No. 12 (2004)

The resonant frequency of the cavity is controlled by varying the optical length using a slow actuator, the temperature of the crystal, and a fast actuator, the refractive index of the crystal. the latter is achieved by the electro-optical effect via a voltage applied on electrodes placed on the side facets of the crystal (gold surface in Figure 9). The control signal is for the fast actuator is obtained via a Hänsch-Couillaud[4] detection scheme operated in reflection.

The electro-optical characteristics of the SHG light are modelled by calculating the propagation of the electric field amplitudes inside the cavity in multi-pass configuration. An optimization algorithm is then successively applied to the different cavity and laser parameters in order to iteratively find the optimal conditions for efficient second harmonic generation. The scheme used in this work exhibits the advantages of having an enhancement of the output UV-light by a factor of 2 as compared to a conventional resonant cavity. Moreover, walk-off compensation results in a slowly divergent beam across the beam plane perpendicular to the k-vector inside the crystal. The calculated output power in the UV and the distribution of the beam intensity are depicted in Figure 10.



(a) (b)

Figure 10. (a) Output power at 267.4 nm as a function of input power at 534.8 nm and different radii of curvature (ROC) of the BBO-crystal. (b) Beam profile of the UV-light at the output facet of the resonator. The expected 1 mW of laser light at 267.4 nm can already be achieved with approximately 50 mW of green light at 534.8 nm according to this scheme.

Mechanical processing of the BBO crystals

The monolithic resonant SHG crystal offers the critical advantage, that it can be easily micro-integrated. However, its processing includes one critical step, namely that of aligning the normal to the crystal facets on each other and on the optical axis of the crystal to a rest-angle deviation of better than 0.5 mrad. Owing to this tight angular tolerance, the correction angle for each crystal can only be determined experimentally. Moreover, the null point reference during the experimental determination of the correction angle in the lab and during the processing of the crystal in a precision optics fab need to coincide to better than 0.5 mrad.

In a first run, the tolerance on the null point reference could not be met. Therefore, a new process flow has been developed, that allows for the null point reference to be transferred from the lab measurement to the mechanical processing in the precision optics fab. One batch of

[4] T. W. Hänsch and B. Couillaud, "Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity", Optics Communications, Volume 35, number 3 (1980).

BBO crystals has been processed according to the new method. Unfortunately, due to time constraints, the further processing of the BBO crystals could not be pursued.

Layout for the micro-integrated resonant SHG module

The optical layout for a micro-integrated resonant SHG module based on the monolithic BBO crystal is presented in figure Figure 11. The ceramic substrate is made of AlN and has a footprint of 80 x 30 mm², identical to that of the ECDL-MOPA. The same housing and feedthrough concept as for the ECDL-MOPA can also be foreseen for this module here.

Light at the fundamental wavelength 534.8 nm is fed into the module via a fibre coupler. The collimated light first goes through a polarization beam splitter (PBS) in order to filter out TM-polarized light and thus achieve a purely TE-polarized mode propagating through the optical system. Behind the PBS, a dichroic mirror filters out rest NIR light that is transmitted together with the green light out of the single-pass SHG module. The visible light is then steered through a pair of mirrors onto an adjustable telescope that ensures the mode matching to the BBO resonator. Behind the telescope, the light is once again steered with a mirror pair and sent via a Fresnel window for pick-up of the green light reflected by the BBO crystal onto a Hänsch-Couillaud detection scheme in reflection (not shown in the figure). The light transmitted by the Fresnel window is passed through a dichroic mirror that out-couples the UV output at 267.4 nm and fed into the BBO crystal for resonant SHG. As already mentioned, the UV light deflected by the dichroic mirror is the output of the module.

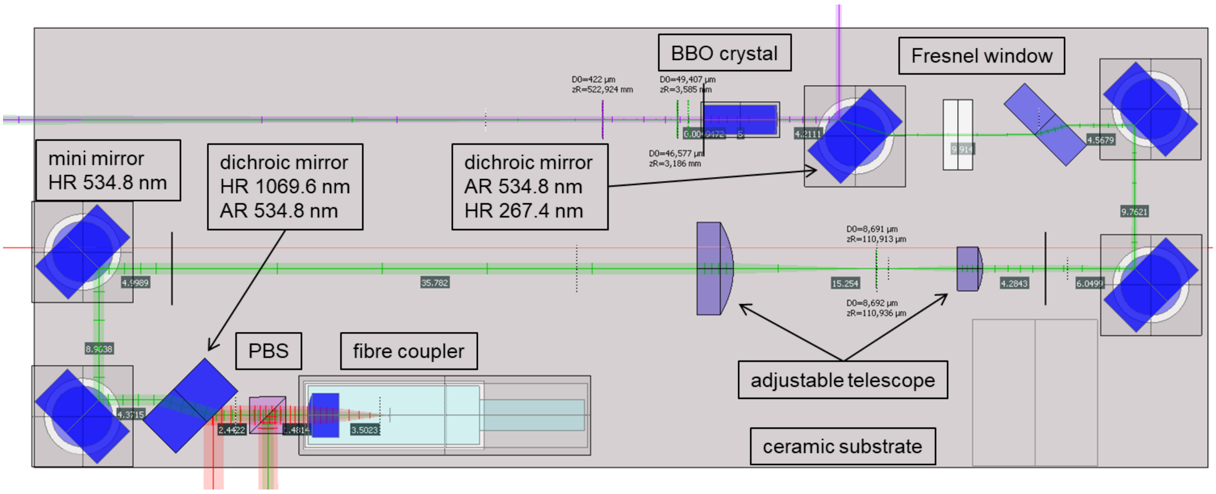


Figure 11 Optical layout for a micro-integrated resonant SHG module based on the monolithic BBO-cavity.

4 Results and discussion

4.1.1 WP1: Master Oscillator Module: 1069.6 nm ECDL

The goals set in this work package, that is, to provide a local oscillator module for the clock laser in an Al^+ quantum logic clock were fully met with respect to the electro-optical characteristics expected of such a laser. Moreover, the compact and robust laser module ensure that the performance is still achieved upon deployment in harsh environments.

The results achieved with the local oscillator operating at 1069.6 nm have paved the way for the development of an identical ECDL-MOPA operating at 871 nm as clock laser for a Yb^+ optical clock together with PTB and HUB, among other partners.

Moreover, a laser operating at 1064 nm was integrated and used to achieve the goals of work package 3.

4.1.2 WP2: Single Pass SHG Module: 1069.6 nm → 534.8 nm

This work package was cancelled and commercially available SHG modules were used instead.

4.1.3 WP3: Frequency stabilization to Hz-Stability and Molecular Reference

In this work package, the concepts for the stabilization of the local oscillators have been developed. In a first step, the concept for the stabilization of the local oscillator emitting at 1069.6 nm on an ultra-stable cavity based on a Pound-Drever-Hall scheme has been developed. This concept shall then be implemented in work package 5, upon integration of the local oscillator into the Al^+ clock setup.

With the ECDL-MOPA operating at 1064 nm, the basic component of an optical atomic clock working on a slightly different principle and on a different stability class was thus made available. In work package 3, the concept of such a frequency reference was demonstrated via the stabilization of the laser output at 1064 nm on a transition in molecular iodine.

The experience gathered in work package 3 has paved the way to the success of the JOKARUS experiment[5], the first iodine-based frequency reference to be operated in space, which was launched on a sounding rocket in May 2018.

4.1.4 WP4: Resonant SHG Module: 534.8 nm → 267.4 nm

A very ambitious concept for a monolithic resonant SHG cavity based on a BBO crystal was put forward. Such a concept would enable the micro-integration of the crystal into a resonant SHG module.

The physics of the SHG in the monolithic resonant cavity was modelled via the propagation and non-linear interaction of the electric field amplitudes into the crystal. In such a way, the crytsal parameters were optimized in order to achieve efficient SHG into the UV.

A concept for the mechanical processing of the BBO crystals was developed according to the optimized SHG and a corresponding optical layout for the resonant SHG module was conceived. However, the angular tolerances required to align the normal to the cavity facets to the optical axis of the crystal proved to be very challenging. After a first failed trial, a new concept for the processing of the crystals has been developed and tested.

4.1.5 WP5: Integration into Al-ion Clock and Technology Validation

Due to the problems encountered in work package 4, work package 5 could not be fulfilled as expected. FBH and PTB are implementing the ECDL-MOPA local oscillator into the Al^+ clock setup at the PTB.

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[5] https://www.fbh-berlin.com/press/press-releases/detail/frequency-stable-laser-systems-for-space

5 Economic merit

The present project has contributed to the further development of the ECDL-MOPA laser module that was initiated and preliminarily developed in the project MiLas[6]. The micro-integrated ECDL-MOPA laser module harbours a great potential to become a successful commercial product, especially in the fields of quantum optical applications or coherent optical communications in the field or in space. Several projects either use identical ECDL-MOPA's as in this project or use specific developments achieved in the present project:

- JOKARUS[7]: first optical frequency reference based on molecular iodine in space. The ECDL-MOPA at 1064 nm, the commercial SHG modules and the stabilization on molecular iodine in the present project were directly beneficial to JOKARUS. The iodine-based frequency reference is currently being considered as a potential candidate for generation 2 Galileo clocks.
- OptiClock[8]: Pilot project for a portable Yb^+ optical atomic clock. The clock laser concept at 871 nm is directly inspired from the ECDL-MOPA operating at 1069.6 nm
- MAIUS-II/BECCAL (DLR): projects involving experiments on cold atom gases in micro-gravity (sounding rockets or International Space Station) with a total amount of more than 50 ECDL-MOPA to be delivered. These projects partly use the laser chip and some packaging concepts developed in the present project.

The FBH is actually developing a business plan for the commercialisation of the ECDL-MOPA laser module.

Moreover, the micro-integrated monolithic SHG resonator would fill a gap in the accessibility of compact and robust sources of deep-UV light and thus have high potential for commercialisation. In this case, the very long and labour-intensive process for the processing of the BBO-crystals needs to be optimized w.r.t. costs and yield.

6 Contribution of cooperation partners

Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Dr. Andreas Wicht)

- project coordination
- development of the ECDL-MOPA module
- development of the resonant SHG cavity

FBH acknowledges the contribution of Dr. Vasile Tronciu of TU Moldova and of Dr. Mindaugas Radziunas of Weierstrass-Institut to the time-resolved modelling of the ECDL laser cavities used in the project.

Humboldt-Universität zu Berlin (Prof. Achim Peters, PhD)

- development of frequency stabilization servo loop for the ECDL-MOPA laser

[6] MiLas: "Mikrointegrierte Diodenlasersysteme" funded through the DLR with funds provided by the Federal Ministry for Economic Affairs and Energy under grant No. 50WM1141

[7] https://www.fbh-berlin.com/press/press-releases/detail/frequency-stable-laser-systems-for-space

[8] https://www.opticlock.de/info/

- provide support in laser design and characterization
- test of the 1064 nm ECDL-MOPA in a frequency reference setup based on molecular iodine.

Physikalisch-Technische Bundesanstalt (Prof. Dr. Piet O. Schmidt)

- provide support in laser design, especially with respect to resonant SHG
- integration of the laser system in the Al single ion quantum logic optical clock

7 Dissemination of results

7.1 Academic qualifications

Fischer, T. (2015), "Optimierung der Resonatorlänge in Hinblick auf die spektralen Eigenschaften von Extended-Cavity Diode Lasern für hochpräzise Spektroskopieanwendungen", Bachelor of engineering, Beuth Hochschule für Technik, Berlin

Vowe, S. (2016), "Characterization of Single-Mode-Coupling-Efficiency of Ridge-Waveguide Amplifiers with different Ridge-Geometries**"**, Bachelor of science, Humboldt-Universität zu Berlin

7.2 Peer-reviewed publications

S. Hannig, J. Mielke, J. Fenske, M. Misera, N. Beef, C. Ospelkaus, P.O. Schmidt, "A highly stable monolithic enhancement cavity for second harmonic generation in the ultraviolet", Review of scientific Instruments 89, 013106 (2018)

Mandy Krüger, Vasile Z. Tronciu, Ahmad Bawamia, Christian Kürbis, Mindaugas Radziunas, Hans Wenzel, Andreas Wicht, Achim Peters, Günther Tränkle, "Improving the spectral performance of extended cavity diode lasers using angled-facet diode laser chips", submitted for publication

CH. Kürbis, A. Bawamia, M. Krüger, R. Smol, A. Wicht, A. Peters, G. Tränkle, "Extended cavity diode laser master-oscillator-power-amplifier for precision iodine spectroscopy in space", to be published

7.3 Conference contributions

A. Bawamia, M. Krüger, Ch. Kürbis, E. Luvsandamdin, M. Heyne, A. Wicht, A. Peters, G. Erbert, " Compact Semiconductor Laser Modules for Precision Quantum Optical Experiments in Space", European Time and Frequency Forum 2014

W. Lewoczko-Adamczyk, A. Bawamia, M. Krüger, B. Arar, Ch. Kürbis, M. Heyne, A. Wicht, G. Erbert, A. Peters, G. Tränkle, "Compact semiconductor laser modules for precision quantum optical experiments in space", International Conference on Atomic Physics 2014

Ch. Kürbis, A. Bawamia, B. Arar, M. Krüger, A. Wicht, G. Erbert, A. Peters, G. Tränkle, "Technology platform for packaged micro-integrated semiconductor laser modules for quantum optical sensor applications in space", International Conference on Space Optics 2014

Mandy Krüger, Ahmad Bawamia, Christian Kürbis, Wojciech Lewoczko-Adamczyk, Christoph Pyrlik, Götz Erbert, Achim Peters, Günther Tränkle, " Micro-integrated semiconductor laser modules for precision quantum optical experiments in space", International Frequency Control Symposium- European Time and Frequency Forum 2015

A. Bawamia, M. Krüger, Ch. Kürbis, W. Lewoczko-Adamczyk, A. Wicht, G. Erbert, G. Tränkle, S. Hannig, P.O. Schmidt, S. Amairi Pyka, A. Peters, "Micro-integrated semiconductor laser system

operating in the UV for deployment in a portable optical atomic clock", 8th Symposium on Frequency Standards and Metrology 2015

M. Kastner, A. Bawamia, M. Krüger, Ch. Kürbis, W. Lewoczko-Adamczyk, C. Pyrlik, A. Wicht, G. Erbert, A. Peters, G. Tränkle, "Micro-integrated semiconductor laser modules for precision quantum optical experiments in space", International Conference on Space Optical Systems and Applications 2015

M. Krüger, B. Arar, A. Bawamia, M. Kastner, A. Kohfeldt, Ch. Kürbis, W. Lewoczko-Adamczyk, C. Pyrlik, R. Smol, A. Wicht, G. Erbert, A. Peters, G. Tränkle, " Micro-integrated semiconductor laser modules for precision quantum optical experiments in space", Space Tech Expo Europe 2015

A. Bawamia, M. Krüger, Ch. Kürbis, A. Wicht, G. Erbert, G. Tränkle, S. Hannig, P.O. Schmidt, S. Amairi Pyka, A. Peters, "Narrow-Linewidth, micro-integrated UV laser system for precision spectroscopy applications", European Time and Frequency Forum 2016

W. Lewoczko-Adamczyk, A. Bawamia, B. Arar, A. Kohfeldt, M. Krüger, Ch. Kürbis, C. Pyrlik, A. Wicht, G. Erbert, A. Peters, G. Tränkle, "Micro-integrated semiconductor laser modules for precision quantum optical experiments in space", SPIE Photonics Europe 2016

W. Lewoczko-Adamczyk, A. Bawamia, B. Arar, A. Kohfeldt, M. Krüger, Ch. Kürbis, C. Pyrlik, A. Wicht, G. Erbert, A. Peters, G. Tränkle, "Micro-integrated semiconductor laser modules for precision quantum optical experiments in space", ILA Berlin Air Show 2016

M. Schiemangk, B. Arar, A. Bawamia, H. Christopher, A. Kohfeldt, M. Krüger, Ch. Kürbis, W. Lewoczko-Adamczyk, E. Luvsandamdin, C. Pyrlik, A. Peters, A. Wicht, G. Tränkle, "Micro-integrated semiconductor laser module platform for precision quantum optical experiments on Earth and in space", International Conference on Atomic Physics 2016

M. Schiemangk, B. Arar, A. Bawamia, M. Krüger, Ch. Kürbis, W. Lewoczko-Adamczyk, A. Wicht, A. Peters, G. Tränkle, "Micro-integrated semiocnductor laser modules for optical satellite communication", SPIE Security and Defence 2016

A. Bawamia, B. Arar, M. Krüger, Ch. Kürbis, W. Lewoczko-Adamczyk, M. Schiemangk, A. Wicht, A. Peters, G. Tränkle, "Technology Platform for Micro-Integrated, Semiconductor Laser Modules for Space Applications", International Conference on Space Optics 2016

A. Wicht, A. Bawamia, M. Krüger, Ch. Kürbis, M. Schiemangk, R. Smol, A. Peters, G. Tränkle, " Narrow linewidth laser modules for quantum optical sensor applications in the field and in space", Proc. of SPIE Vol. 10085, doi: 10.1117/12.2253655

M. Krüger, A. Bawamia, Ch. Kürbis, R. Smol, A. Wicht, G. Erbert, G. Tränkle, S. Hannig, P.O. Schmidt, S. Amairi Pyka, A. Peters, "Semiconductor-based, narrow-linewidth, micro-integrated UV laser system for precision quantum optical experiments in the field", European Time and Frequency Forum 2017

7.4 Research data management

The collection and protection of research in the frame of the project has been carried out throughout following the standards set at the FBH. These include a differential backup of all files on a daily basis and a weekly full-backup of all data. The full backup is stored on two physically separate servers for increased data security. The transfer of research data to partners has been carried out via dedicated FTP servers provided either by the FBH or by the Humboldt-Universität zu Berlin.

Berlin, 26.06.2018,

Dr. Andreas Wicht (project leader)