Series Production of Next-Generation Guide-Star Lasers at TOPTICA and MPBC

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ABSTRACT

Large telescopes equipped with adaptive optics require high power 589-nm continuous-wave sources with emission linewidths of ~5 MHz. These guide-star lasers should be highly reliable and simple to operate and maintain for many years at the top of a mountain facility. After delivery of the first 20-W systems to our lead customer ESO, TOPTICA and MPBC have begun series production of next-generation sodium guide-star lasers.
The chosen approach is based on ESO's patented narrow-band Raman fiber amplifier (RFA) technology [1]. A master oscillator signal from a TOPTICA 50-mW, 1178-nm diode laser, with stabilized emission frequency and linewidth of ~ 1 MHz, is amplified in an MPBC polarization-maintaining (PM) RFA pumped by a high-power 1120-nm PM fiber laser. With efficient stimulated Brillouin scattering suppression, an unprecedented 40 W of narrow-band RFA output has been obtained. This is spatially mode-matched into a patented resonant-cavity frequency doubler providing also the repumper light [2]. With a diffraction-limited output beam and doubling efficiencies > 80%, all ESO design goals have been easily fulfilled. Together with a wall-plug efficiency of > 3%, including all system controls, and a cooling liquid flow of only 5 l/min, the modular, turn-key, maintenance-free and compact system design allows a direct integration with a launch telescope.
With these fiber-based guide star lasers, TOPTICA for the first time offers a fully engineered, off-the-shelf guide star laser system for ground-based optical telescopes.
Here we present a comparison of test results of the first batch of laser systems, demonstrating the reproducibility of excellent optical characteristics.

Keywords: laser guide stars, diode laser, fiber lasers, next generation telescope, adaptive optics, sodium return flux

1. INTRODUCTION

In the frame of a contract with the European Southern Observatory (ESO) and W. M. Keck Observatory (WMKO), TOPTICA Photonics and its partner MPB Communications have developed a novel guide star laser system. The goal has been a continuous wave (CW) sodium guide star laser that overcomes the limitations of state-of-the-art dye, solid-state and pulsed laser formats. These are limitations with respect to wall-plug efficiencies and tough cooling requirements for dye and solid-state lasers, or the spectroscopy performance of pulsed lasers.

The newly developed laser architecture [3] provides a narrow-linewidth high-power 20-W-class CW output signal, precisely stabilized to the sodium resonance and having a diffraction-limited beam quality. Each laser unit (LU) is designed in a modular way based on the concept of line replaceable units (LRU). In case of a failure, any LRU can be replaced within four hours. It is designed and tailored to provide turn-key operation in a remote and harsh location such as the Paranal Observatory in the Chilean Atacama desert or the 4200-m summit of Mauna Kea in Hawaii.

Each laser unit is divided into two spatially separated and environmentally shielded parts, shown in Fig. 1:

- The electronics cabinet, accommodating the seed laser, the wavelength stabilization, the fiber pump laser and its driver, the coolant distribution system and the largest part of the control electronics. The individual LRUs are listed in Tab. 1.

- The laser head, comprising the Raman fiber amplifier (RFA) and the second harmonic generation module (SHG) module. It is a LRU on its own.

The earthquake-proof electronics cabinet, weighing ~600 kg, has dimensions of 925 mm (L) x 900 mm (W) x 1730 mm (H) and includes a 10-cm thick layer of thermal insulation to ensure that the surface temperature of the laser unit does not deviate by more than 1.5 °C from the surrounding ambient air. Most of the heat dissipated by the laser system is generated within the electronics cabinet and is entirely removed by liquid cooling. The dimensions of the laser head are 700 mm (L) x 500 mm (W) x 285 mm (H) excluding thermal insulation (925 mm x 720 mm x 400 mm with insulation cover). Its weight amounts to approximately 61 kg (77 kg).

Fig. 1: Photograph of the laser system consisting of a laser head and an electronics cabinet. On the left: Laser head with Raman fiber amplifier (RFA) and second-harmonic generation (SHG) modules installed on a water-cooled cold plate on top of a stainless steel frame. The interface (fiber-optical, electrical and coolant connections) is on the rear side. The thermal and protection shields have been removed. On the right: The cabinet with external and coolant interfaces on the bottom and laser head interface on the top.

FLPS	the fiber laser power supply is power supply for FLPM
FLPM	the fiber laser pump module contains the pump laser for the RFA, providing 100 W at 1120 nm
Splice Box	sliding tray for pump laser splice point
WMM	the wavelength measurement module provides the wavelength measurement of the seed laser
PLCM	the programmable logic controller module contains all the safety circuitry of the laser unit
PEM	the power entry module is the main power supply of the laser unit
MSM	the main controller / seed module contains main controller and seed laser (50 mW @ 1178 nm)
HYD	the ‘hydraulics’ module provides coolant distribution

Tab. 1: Line replaceable units of the electronics cabinet from top to bottom. The laser head is another LRU.

In contrast to previously used dye or solid state laser systems which required a stationary laser clean room and exhibited a thermal footprint of several kilowatts, the presented next generation laser system is designed to be directly attached to the centerpiece of the telescope, in direct proximity to the main mirror (ESO case). As an alternative, there is a remote pumping version which allows the electronics cabinet and the laser head to be separated by up to 27 m. In this case, the electronics cabinet can, for example, be mounted on the Nasmyth platform (special lateral platform of Nasmyth-type telescopes), with only the laser head directly attached to the pivoted part of the telescope (Keck case). The opto-mechanics of both electronics cabinet and laser head have been specially designed to guarantee stable laser operation under varying gravity vectors and vibrations of the type induced by wind, dome sounds and telescope structure.

In the ESO case, four laser units surround the primary mirror of the telescope with a single heat exchanger supplying the four laser units with temperature-stabilized coolant. Each laser head is mounted right on top of the beam control and diagnostics system (BCDS) of its corresponding launch telescope.

The power consumption of one laser unit at operational power level amounts to less than 700 W. The largest part of the heat is generated within the electronics cabinet by the diode-pumped fiber pump laser, only about 100 W are dissipated within the laser head and therefore a moderate coolant flow rate of about 1 l/min suffices to remove the heat from the laser head, introducing negligible amounts of vibration.

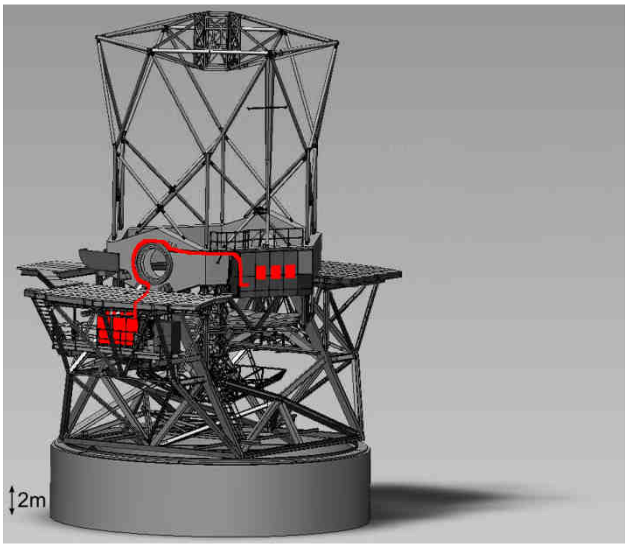

Fig. 2: CAD model of the W. M. Keck telescope structure. Sketched in red are three guide star laser electronics cabinets located on the Nasmyth platform (left) and the corresponding laser heads which are directly fixed to the centerpiece of the telescope (right). The indicated PM fiber link in between has a length of 27 m (model by courtesy of W. M. Keck Observatory).

After successful completion and testing of a Pre-Production Unit (PPU) in 2012, the project was transferred from TOPTICA's R&D to its production department in 2013 by establishing a reliable production process and supply chain with more than 1000 different component parts. Together with defined responsibilities for incoming goods inspection and comprehensive work instructions for production and testing, this has facilitated efficient and reproducible manufacturing of ESO's LU1 to LU4 up to March 2014, followed by an additional service backup ESO LU5 and the first remote-pumping system for Keck.

2. OPTICAL SYSTEM DESIGN

The breakthrough concept has been realized based on a master oscillator power amplifier (MOPA) approach with subsequent resonant second harmonic generation. A narrow-band tunable diode laser emitting in the near infrared spectral region is employed to seed a highly-efficient polarization-maintaining Raman fiber amplifier based on ESO's EFRA technology [1]. Subsequently, the high-power infrared signal is frequency-doubled into the yellow spectral range.

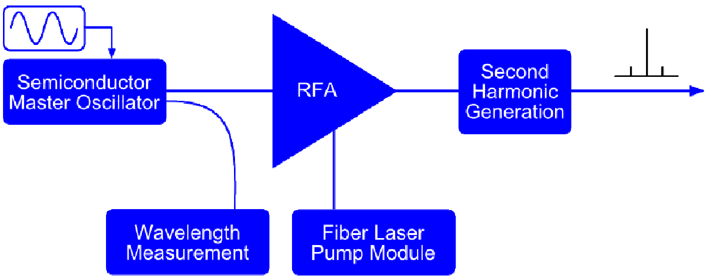

Fig. 3: Schematic of the optical laser design comprising a semiconductor master oscillator (1178 nm) as the seed source for a polarization-maintaining Raman fiber amplifier which is pumped by a polarized fiber laser itself. The emission wavelength of the seed laser is measured and actively stabilized via a highly accurate wavelength meter. Subsequent to amplification, the high-power laser radiation is converted to the yellow spectral region (589 nm) in the second harmonic generation module. Frequency sidebands at 589 nm for repumping are generated via current modulation of the 1178-nm seed laser.

The master oscillator of the laser system is a tunable diode laser, utilizing a quantum dot distributed feedback (DFB) laser diode emitting 50 mW in the near infrared spectral region at 1178 nm with a linewidth of ~ 1 MHz. This serves as the narrow-linewidth seed signal for Raman amplification. Direct modulation of the diode driving current allows for the generation of Pound-Drever-Hall and/or repumper sidebands without additional, potentially wavefront-disturbing, optical elements.

The emission wavelength of the seed laser at 1178.316 nm is measured and stabilized with an internal high-resolution solid-state wavelength meter (TOPTICA HF WSU/10) which has a relative accuracy of 10 MHz. The absolute accuracy is guaranteed by periodic calibration against an stabilized helium-neon reference laser integrated into the system design. The wavelength meter does not contain any moving parts and uses a charge-coupled device (CCD) for fringe detection. Therefore, it allows vibration-free and fast data acquisition. Together with a fast diode current control, this allows for an effective >10-Hz wavelength control bandwidth. Coarse wavelength control is performed by the slower thermo-electric controller of the laser diode. The current laser setup is optimized for a detuning of 5 GHz without noticeable (< 1%) changes in yellow output power. The design, however, allows an easy adaptation for larger detuning ranges of > 25 GHz.

The optical signal of the master oscillator is amplified to a high power level of the order of 35 W at 1178 nm in a polarization-maintaining (PM) Raman fiber amplifier (RFA). The RFA is pumped by the 1120-nm polarized output of the MPBC 100-W-class fiber laser pump module (FLPM). The RFA preserves the spectral and polarization characteristics of the seed laser signal including the introduced sideband modulation. No spectral linewidth broadening has been observed with this high-power amplifier architecture.

The high-power infrared signal is delivered to the SHG module via a short fiber-optic link. The signal is collimated, optically isolated and spatially mode-matched to a resonant frequency-doubling resonator. The heart of this resonator is the non-linear optical crystal lithium triborate (LBO) which converts the light from the infrared spectral region into the yellow via non-critical phase matching with a conversion efficiency >80%. Apart from the high efficiency, this way of generating 589-nm light has major advantages for the resulting beam quality. First, in type I phase matching, two ordinarily polarized photons of the fundamental wave are converted into an extraordinary photon at the second harmonic. Thus, the SHG process itself acts as a polarizer emitting perfectly linearly polarized light. Additionally, the polarization of the second-harmonic photon is also parallel to a principle axis of the refractive index ellipsoid, such that there is no spatial walk-off. Together with the optical resonator being a very effective spatial mode filter that suppresses any transverse mode apart from TEM_{00} when properly aligned, a diffraction-limited beam at 589 nm can be coupled out. The length of the resonator is actively stabilized to an integer multiple of the fundamental wavelength via the Pound–Drever–Hall technique. The spectral linewidth of the emitted frequency-doubled output beam amounts to roughly 5 MHz in accordance with the specific requirements of the guide star laser system. The broadening with respect to the 1-MHz seed linewidth is almost entirely due to the SHG process (theoretical factor of 4 for Lorentzian profiles), which confirms the linewidth-conserving nature of the RFA. The control electronics of the SHG module has been integrated into the cover of the module resulting in a stand-alone sub-unit that can be located up to 27 m away from the electronics cabinet.

Radiofrequency modulation at a frequency matching the hyperfine splitting of the sodium ground state is applied directly to the driving current of the seed laser in order to generate spectral sidebands at a separation of 1.713 GHz. One of these sidebands allows the generation of photons resonant with the D_2b line for repumping of the mesospheric sodium atoms´ electronic population after it has decayed to the other hyperfine ground state [5]. The total length of the frequency doubling resonator is chosen such that the free spectral range of the cavity coincides with the D_2a–D_2b splitting. Therefore, the spectral sidebands are simultaneously resonant within the cavity and optical sidebands are generated via sum-frequency generation (SFG). Due to the higher efficiency of SFG compared to SHG, this patented [2] modulation scheme allows for sideband ratios beyond 10% for most seed diodes. The intensity of the sidebands can be automatically determined with an integrated Fabry–Perot interferometer (FPI).

It is also possible to completely detune the laser from the sodium resonance (detuning of 5 GHz within less than 5 s) for example in order to measure and correct for the Rayleigh scattering background generated by the laser when travelling through the atmosphere.

In summary, the presented laser design beneficially combines a narrow-linewidth tunable diode laser with PM fiber technology with its major inherent advantages relating to stable maintenance-free operation, efficiency, beam quality, compactness and flexible installation options. The SHG output stage adds highly-efficient frequency conversion as well as additional polarization and mode filtering for a diffraction-limited beam ideally suited for guide-star applications.

3. USER OPERATIONAL INTERFACE

Due to the high optical power of the laser system, precautions have to be taken in order to prevent the system from harming its operator or damaging itself. Therefore, special care has been taken by TOPTICA in designing and implementing the supervision and communications infrastructure (Fig. 4). The control of the laser system is split into two independent circuits avoiding a single point of failure and generating a completely redundant control mechanism for all safety related laser system functions. The supervision functionality is implemented using a programmable logic controller (PLC), which communicates with other LRUs using digital I/O lines. As a real-time system, the PLC represents the over-riding safety authority that can bring the laser system into a safe state even on a complete failure of the rest of the communications infrastructure. Furthermore, it provides several digital interlock and status lines to interface with the telescope control center.

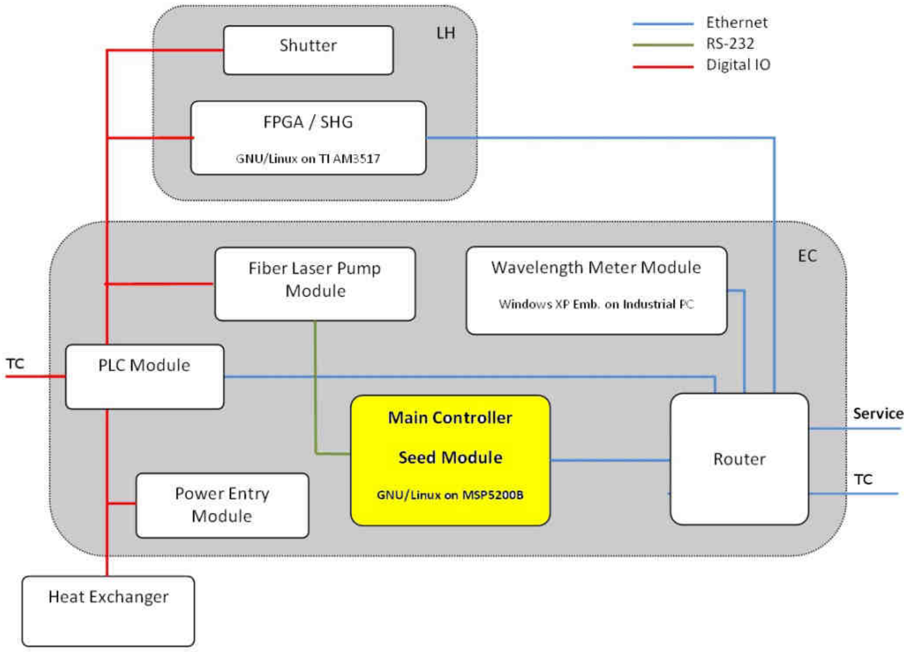

Fig. 4: Laser unit communication architecture. Shown are inter-module connections as well as the links to the telescope control (TC) system and a local service computer. Ethernet communication is implemented in a master/slave configuration with the MSM as the master.

More complex communication between different LRUs uses a standard TCP/IP Ethernet. The used text based protocol allows for comfortable debugging and easy interfacing using a standard telnet terminal connection. A master/slave hierarchy is used between the modules in which the MSM acts as the master incorporating both the seed laser diode controller with wavelength stabilization and the main laser system controller.

Analogous to the internal infrastructure, the external control interface is separated in two parts as well. Interlock and status conditions are available as digital I/O lines. The TCP/IP *command line* allows for setting and querying of parameters and execution of commands whereas *monitoring lines* serve as an event based status feedback allowing a user defined subset of parameters with individually adjustable sampling rates to be subscribed. A configurable laser log file saves alarm messages and parameter readings with exact time stamps for in-depth fault analysis and detection of long-term parameter drifts.

The laser unit has three *operation modes* which allow access to different subsets of commands and parameters. For everyday telescope control, *normal operation mode* mainly allows changing the *operation states* of the laser, which are *standby*, *ready*, *on* and *observation*. The transition from *standby* to *ready* makes sure that the wavelength meter is calibrated. When the laser is turned off by going to *ready* only, a constant start-up time of < 2 minutes from *ready* to *on state* provides the telescope controller with a maximum of flexibility. This includes about 30 s for starting and stabilizing the seed laser as well as stabilization of the wavelength control loop and another minute for starting FLPM, RFA and locking the SHG. During transition to *observation* only the shutter is opened. Thus, it is more or less instantaneous but can be delayed via a user configurable delay time. A software system of parameter supervisions issues *warnings* and *failures* and, in the latter case, gently brings the system down into *standby* state.

Apart from *normal operation mode*, there are two modes with extended user authorization: *maintenance mode* and *service mode*. Maintenance mode features dedicated health check and optimization routines. In contrast to normal operation mode, where only dependencies between parameters are supervised, these automated maintenance routines are able to optimize parameters and allow for deeper root-cause analysis of possible inconsistencies (see next chapter). Except for a few exceptions during health checks, the safety layers described above are fully intact. In service mode, the software safety layer is deactivated, or at least deprived of its capacity to act. This allows for full manual control of the laser system, recalibration of certain sensors and even better fault isolation.

Service mode is not intended to be activated via the telescope control software, but only from a dedicated service laptop running TOPTICA's service software GUI. The main window of the former is shown in Fig. 5. This GUI offers intuitive control of the laser system, with fast overview of all relevant parameters, as well as possible issues via green, yellow or red light indicators. The software includes graphical tools for long-term and short-term parameter traces as well as oscilloscope and spectrum analyzer views of the Pound–Drever–Hall locking parameters and the FPI signal. Since *service mode* allows the modification of all laser control parameters and the actions performed in this mode can potentially bring the LU into a non-safe state, it requires specially trained factory-authorized service personnel.

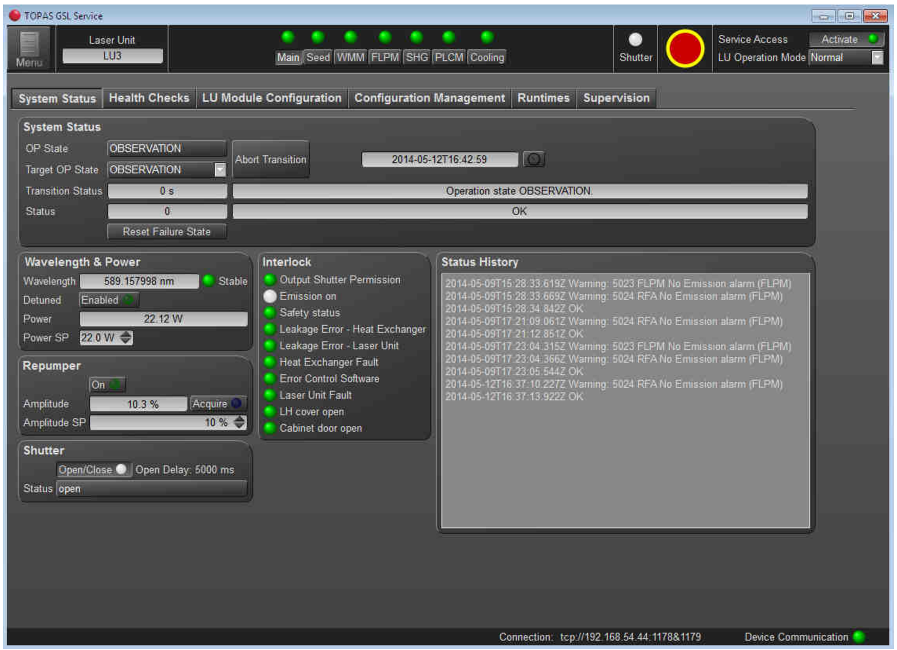

Fig. 5: Main window of TOPTICA’s guide star laser service software featuring tabs for each LRU for intuitive laser control and a clear overview over parameter readings, interlocks and status messages.

4. LASER MODULARITY AND MAINTENANCE STRATEGY

During the design phase, great attention was given to the laser system’s reliability, maintainability and serviceability. Based on an initial thorough reliability analysis, the mean time between failure (MTBF) of the overall system comprising four laser units plus the heat exchanger has been determined to exceed one year. The overall system lifetime is designed to exceed 10 years.

For effective failure analysis, there are > 150 alarm codes and > 80 configurable parameter supervision channels. As an integral part of the LRU concept, alarm messages are issued by the sub-devices and, thus, allow the source of the malfunction to be tracked down to well below LRU level. This is enabled by a distributed soft- and hardware architecture, where all LRUs except for the power supplies and the HYD have their own microcontrollers.

In order to reduce maintenance services that require physical access to the LU to an absolute minimum, the system has been equipped with several automated self-repair and maintenance routines. One is the absolute wavelength recalibration of the wavelength meter with the integrated helium-neon reference laser, which takes place regularly during transition from *standby* to *ready operation state*. Others routines are part of the *health checks* which can be executed on demand:

- motorized mirror mounts and dedicated software algorithms for 4D position optimization of all free-space optical beams.
- recalibration of output power and sideband amplitude setpoints.
- adjustment of wavelength controller for maximum stroke of the fast diode current control and optimal frequency toggling performance.
- compensation for ageing of the seed laser diode by automated adjustment of seed diode current and temperature, optimizing the constraints regarding output power and wavelength.
- compensation for ageing processes of the FLPM pump diodes.

The service concept itself takes advantage of the modular design of the laser units as well. Each of these LRUs can be exchanged within 4 hours to bring the laser back to operation in case of a failure. No critical alignments of free-space optical components by service technicians are necessary. In order to replace the FLPM, the high-power pump fiber has to be fusion-spliced. The sensitive bare fiber is located and protected in a splice box on a sliding tray.

Under a dedicated support and service contract it is planned to periodically inspect the lasers, regularly review logged data for preventive maintenance actions, provide on-call support to the observatory's maintenance staff, hold available a suitable set of spares at the factory, and repair LRUs when the need arises.

5. SYSTEM CHARACTERIZATION

Results of PPU acceptance tests have been published in Ref. [7]. LUs 1 to 4 have undergone and passed the same test procedures. All test results are summarized together with ESO's specifications Tab. 2.

The table underlines the reproducibility of the laser design as well as the production processes. All parameters are within ESO specification and even meet the more stringent ESO goals. The most important characteristic for guide star applications certainly is the optical quality of the output beam. The measured wavefront errors of $(0.03 \pm 0.01) * \lambda$ are well beyond the Maréchal criterion and, thus, demonstrate the diffraction-limited character of the beam. Further prerequisites for maximum guide star return flux are the narrow linewidth of close to 5 MHz, the well defined linear polarization with PER > 22 dB and the effective wavelength stabilization with peak-to-peak variations < 50 MHz, which is well below the 1-GHz FWHM of the Doppler-broadened sodium D_{2a} line at T = 200 K in the earth's mesosphere.

The stability of the essential characteristics, i.e. beam pointing, laser output power and wavelength, has been verified in 14-hour measurements with > 1 Hz measurement bandwidth. The output power variation has also been shown to be well below 1% in a 50-s measurement with 10-kHz bandwidth. An additionally test simulates a typical observation night at the telescope with hourly frequency toggling by 5 GHz. Output power and wavelength during this sequence are shown in Fig. 6. Further stability tests have been performed for beam pointing over a period of one month as well as for a varying gravity vector, simulating the conditions during telescope tilting. The result of the first is shown in Fig. 7. There is a slight change in pointing directly after the first adjustment on March 25th. Thereafter, the pointing is constant within a few µrad and, in particular, no long-term drift has been observed. The result of the LU1 gravity measurement is shown in Fig. 8. The laser head is mounted on an ESO BCDS dummy containing a test setup for beam tilt, lateral shift and power measurement. The stack of BCDS and laser head is then mounted on a tilt stand which allows for ± 90° tilting. Both pointing and lateral shift vary by a maximum of 20 µrad or 20 µm, respectively, during a 90° tilt. This is well within ESO specifications as well as goals.

Additionally, environmental tests both under operational conditions (0 to 15°C, ambient pressure down to 580 mbar corresponding to the height of Mauna Kea, Hawaii) and functional conditions (-10 to +30 °C), as well as transport climate and shock and vibration tests have been successfully conducted and passed.

Tab. 2: Test summary and critical data comparison for the first five LUs produced, i.e. PPU, LU1 – LU4

Test	Unit	ESO spec. (ESO goal)	PPU	LU1	LU2	LU3	LU4
Output power							
power in carrier	[W]	18	18	18.2	18.9	18.6	18.8
blue sideband	[W]	2	2.1	2.2	2	1.9	1.9
red sideband	[W]		2.1	1.7	1.4	1.6	1.4
carrier power within ±1 FWHM	[%]	> 70	75	75	75	79	84
Long-term stability (14h)							
mean power	[W]	22	22.73	20.49	21.94	21.86	22.19
standard deviation	[mW]		39	91	80	72	54
standard deviation	[%]		0.17	0.44	0.36	0.33	0.24
peak-to-peak variation	[%]	< 15 (< 10)	2	2.1	2	2	2
Short-term stability (50s)							
mean power	[W]	22	22.2	22	22	22	22
standard deviation	[mW]		6.5	12	45	68	40
standard deviation	[%]	< 6 (< 3)	0.03	0.05	0.20	0.31	0.18
Beam pointing (14h, incl. start-up)							
pointing (rms)	[µrad]	< 160 (< 80)			< 1		< 1
pointing (peak-to-peak)	[µrad]		< 30	< 10	< 9	< 20	< 8
lateral shift (rms)	[µm]	< 100 (< 50)	< 20				
Emission wavelength (14h)							
standard deviation	[MHz]		2.7	2.8	2.3	1.5	1.6
peak-to-peak variation	[MHz]	< 80	41.9	51.8	20.7	12.1	15.5
Frequency toggling							
detuning frequency	[GHZ]	5	5	5	5	5	5
detuning time	[s]	< 10 (< 5)	3	< 5	< 5	< 5	< 5
power variation	[%]	< 5	0.5	0.5	1	0.5	0.5
Laser linewidth (measured with 1GHz FPI)							
FWHM	[MHz]	< 250 (5 ± 1)	< 4.5	< 4	< 6	< 5	< 8
Optical quality							
wavefront error (rms)	[nm]	< 70 (< 25)	23	16	18	14	23
wavefront error (rms)	[λ]		0.039	0.027	0.031	0.024	0.039
Beam waist and asymmetry							
beam waist diameter x	[mm]	3.0 ± 0.1	3.09	3.03	3.02	3.06	3.07
beam waist diameter y	[mm]	3.0 ± 0.1	2.91	2.97	3.03	2.97	2.97
beam waist location x	[m]	0 ± 2m	-0.75	1.14	0.84	-0.59	-0.33
beam waist location y	[m]	0 ± 2m	1.07	-1.23	-1.4	-0.17	0.08
beam asymmetry		0,93 - 1,07	0.942	0.980	1.003	0.971	0.967
Polarization							
polarization extinction ratio (PER)	[dB]	> 20 (> 23)	> 24	> 24	> 23	> 22	> 24
polarization direction (deviation)	[deg]	< 2	2	1	1	< 1	< 1
Power Consumption (@ BOL)							
max. power	[W]		614	560	583	612	620
max. power	[VA]		662	609	633	657	664
electrical power factor		> 0,85	0.93	0.92	0.92	0.93	0.93
Accumulated runtime	[days]		70	35	20	25	90

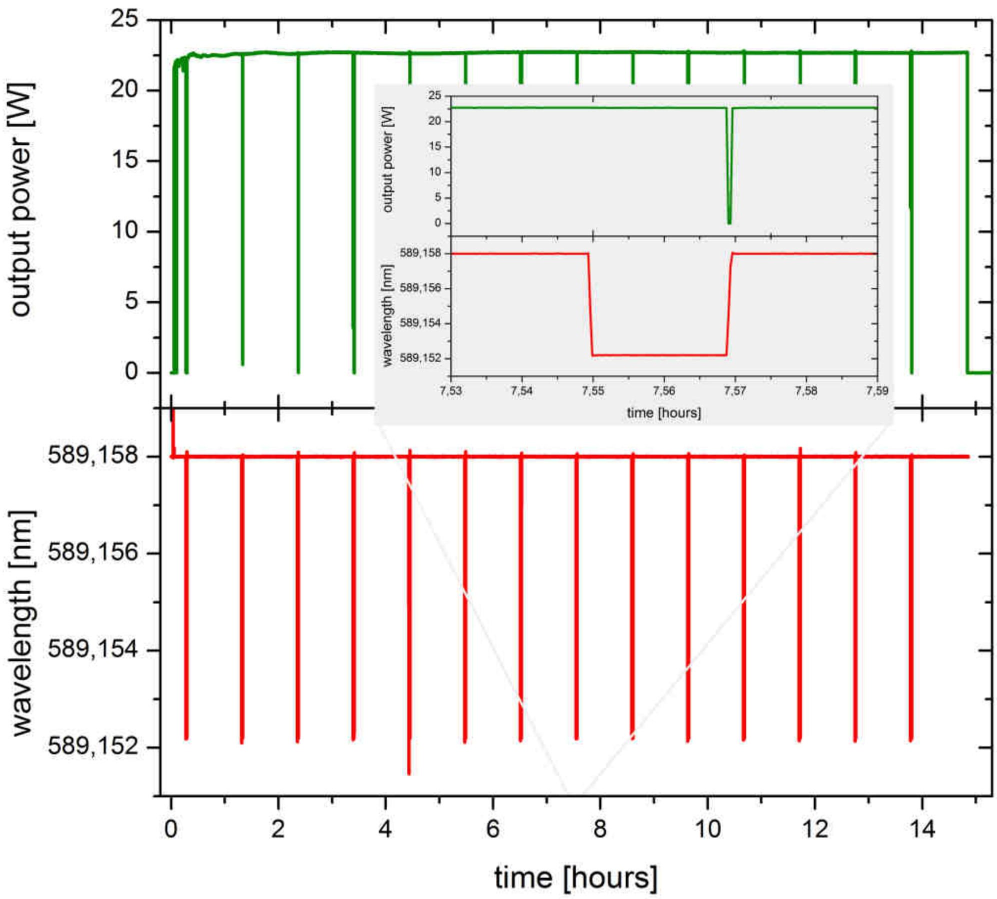

Fig. 6: 14-hour system test including the sequence of a typical ESO observation night with hourly frequency toggling by 5 GHz. This is done at the telescope to subtract the Rayleigh background from the observed guide star return light. Power drops during retuning are due to relocking the SHG cavity in order to keep the cavity piezo in mid-range also during long-term measurements with potentially varying temperatures of the cooling liquid.

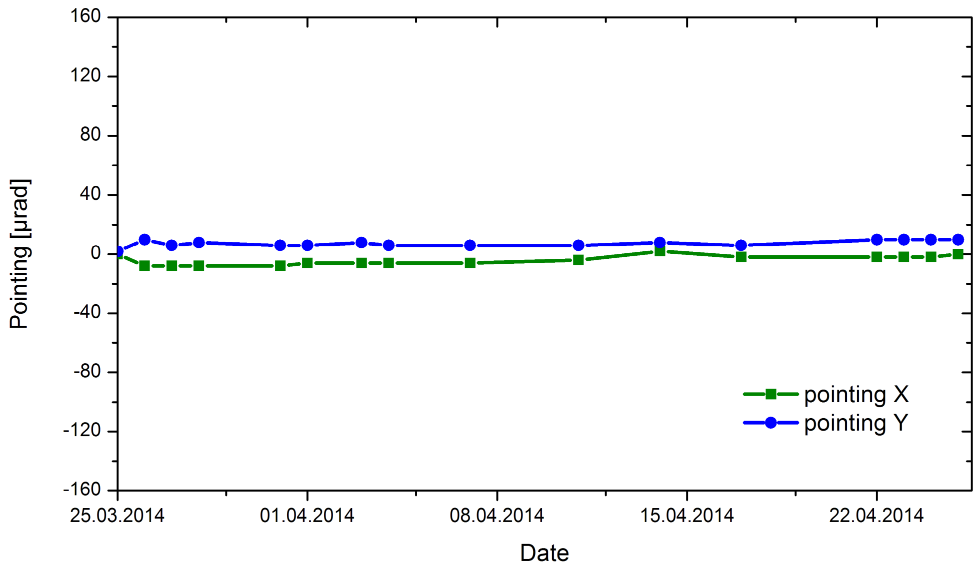

Fig. 7: One month pointing measurement of LU3 showing no long-term drifts.

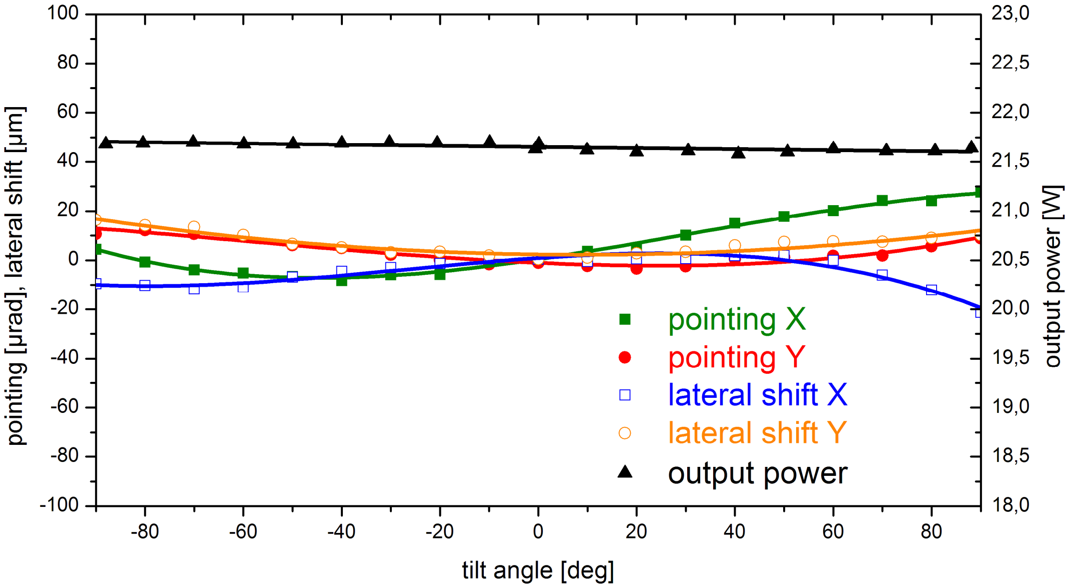

Fig. 8: Testing of LU1 under varying gravity conditions using a tilt test stand and the ESO BCDS unit.

6. DISCUSSION AND SUMMARY

The laser concept originally developed and tested at ESO [3],[4],[6], comprising a diode laser seed, a Raman fiber amplifier and a highly-efficient frequency doubling stage, combines the respective inherent advantages of these different technologies. Our fully engineered LUs embody these advantages in a robust and compact system design. The seed laser technology based on a distributed feedback diode guarantees intrinsic and robust single mode operation and allows precise wavelength stabilization and fast toggling for determining the Rayleigh scattering background. The high-power fiber amplification has its known strong points: no need for optical alignment due to an all-fiber design, surface-to-volume ratio of fiber allows favorable power scalability, excellent polarization properties due to an all-PM fiber approach, and the absence of linewidth broadening during amplification. The frequency doubling technique is highly efficient, based on state-of-the-art optomechanics. Employing a newly-developed doubly-resonant SHG architecture avoids the insertion of any additional wavefront-critical optical modulation devices such as an EOM or AOM when the repumping technique is employed. The reproducibility of excellent optical characteristics of the first five ESO lasers and, thus, the reliability of the production processes have been convincingly demonstrated.

The engineering of a deployable laser system designed around the original concept was based on a set of stringent specifications which have led to a ruggedized, compact and modular solution, keeping ease of operation and serviceability in mind. The inclusion of the control electronics in the SHG module, in combination with the flexibility of the RFA/fiber pump laser architecture, makes possible an installation plan incorporating remote pumping as has been requested by WMKO. This new technique allows a large spatial separation between the compact laser head and the electronics cabinet and, therefore, enables more flexible telescope integration. The compact laser head can be located in close proximity to the laser launch telescope, while the relatively bulky electronics cabinet containing pump diodes, drive electronics and power supplies (heat sources), can be installed in a more convenient location far away from the launch telescope. The separation is currently limited by a maximum pump fiber length of 27 m.

The inherent advantages of the applied technologies result in a laser system suited for deployment in remote and harsh locations such as observatory sites. The laser system combines excellent optical wavefront quality, high-precision wavelength stabilization, and straight-forward implementation of repumping schemes with the convenience of a turn-key system. It eliminates the need for labor-intensive daily alignment tune-ups and lengthy system warm-up times. The maintenance is reduced to a minimum and a viable support scheme is planned for the LRUs to minimize downtime and manpower requirements at the observatories. For future needs, the design offers the possibility of scaling the output power to even higher levels while preserving the excellent beam quality.

The work reported has been conducted in the frame of the ESO contract for the laser system of the Adaptive Optics Facility and an additional delta-specifications contract with W. M. Keck Observatory and the Thirty Meter Telescope.

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