Robust Remote-Pumping Sodium Laser for advanced LIDAR and Guide Star Applications

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ABSTRACT

The performance of large ground-based optical telescopes is limited due to wavefront distortions induced by atmospheric turbulence. Adaptive optics systems using natural guide stars with sufficient brightness provide a practical way for correcting the wavefront errors by means of deformable mirrors. Unfortunately, the sky coverage of bright stars is poor and therefore the concept of laser guide stars was invented, creating an artificial star by exciting resonance fluorescence from the mesospheric sodium layer about 90 km above the earth's surface. Until now, mainly dye lasers or sum-frequency mixing of solid state lasers were used to generate laser guide stars. However, these kinds of lasers require a stationary laser clean room for operation and are extremely demanding in maintenance. Under a development contract with the European Southern Observatory (ESO) and W. M. Keck Observatory (WMKO), TOPTICA Photonics AG and its partner MPB Communications have finalized the development of a next-generation sodium guide star laser system which is available now as a commercial off-the-shelf product. The laser is based on a narrow-band diode laser, Raman fiber amplifier (RFA) technology and resonant second-harmonic generation (SHG), thus highly reliable and simple to operate and maintain. It emits > 22 W of narrow-linewidth (≈ 5 MHz) continuous-wave radiation at sodium resonance and includes a re-pumping scheme for boosting sodium return flux. Due to the SHG resonator acting as spatial mode filter and polarizer, the output is diffraction-limited with RMS wavefront error < $\lambda/25$. Apart from this unique optical design, a major effort has been dedicated to integrating all optical components into a ruggedized system, providing a maximum of convenience and reliability for telescope operators. The new remote-pumping architecture allows for a large spatial separation between the main part of the laser and the compact laser head. Together with a cooling-water flow of less than 5 l/min and an overall power consumption of < 700 W, the system offers a maximum of flexibility with minimal infrastructure demands on site. Each system is built in a modular way, based on the concept of line-replaceable units (LRU). A comprehensive system software, as well as an intuitive service GUI, allow for remote control and error tracking down to at least the LRU level. In case of a failure, any LRU can be easily replaced. 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 providing convenient, turn-key operation in remote and harsh locations. Reliability and flexibility will be beneficial in particular for advanced satellite and space debris tracking as well as LIDAR applications.

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

1. INTRODUCTION

The newly developed laser architecture, based on the narrow-band Raman Fiber Amplifier development at ESO [1], 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 (600 kg, 925 mm x 905 mm x 1730 mm), 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 includes a 10-cm thick layer of thermal insulation to ensure that the external surface temperature of the cabinet 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 the 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.

This modular design of the laser units based on LRUs was selected to establish an easy and comfortable service concept. 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. More information can be found in [2] where the maintenance concept and the intuitive user interface is presented in more detail.

The opto-mechanics of both the electronics cabinet and laser head has 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. Thus, the complete laser system can be directly attached to the centerpiece of the telescope. In this scheme the spatial separation between the laser head and the electronics cabinet would be only ~2 m (ESO case).

For additional flexibility in telescope integration, a remote-pumping version of the laser system has been developed (Fig. 2). It 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 pivoting part of the telescope (Keck case). Two additional splice boxes close to the laser head allow for easy dismounting without the necessity of removing the 27 m of fiber routing. This configuration minimizes the effort for integration with existing telescope infrastructure and does not lead to any additional power losses.

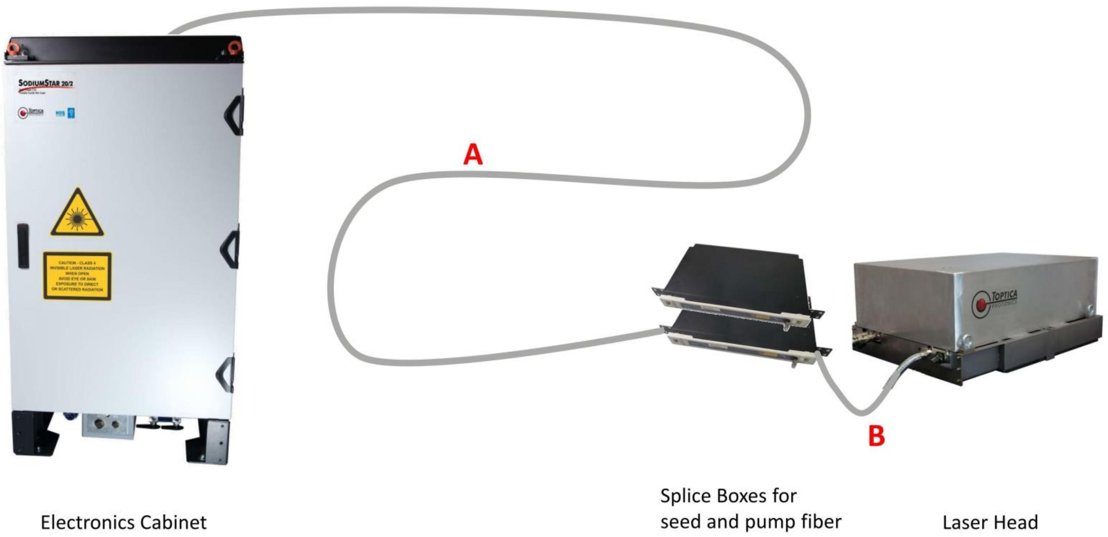

Fig. 2: Remote pumping configuration as used for the W. M. Keck telescope. The distance between LH and EC is 27 m (fiber length A + B). Two splice boxes for the seed and pump fibers are located close to the LH.

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.

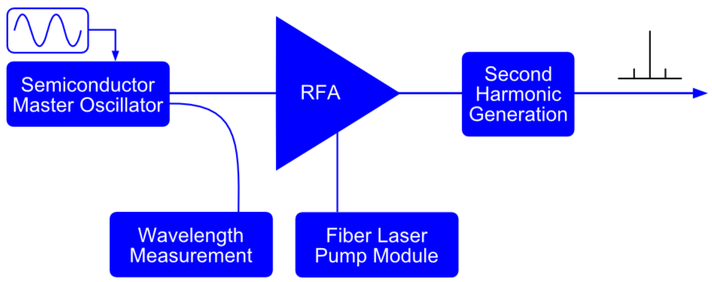

Fig. 3: Schematic of the optical laser design comprising a semiconductor master oscillator (1178 nm) as the seed source for a polarization-maintaining Raman fiber amplifier which is pumped by a polarized fiber laser. The emission wavelength of the seed laser is measured and actively stabilized via a 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 re-pumping 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 and offers superior stability with a mode-hop-free tuning range of hundreds of gigahertz. Direct modulation of the diode driving current allows for the generation of Pound-Drever-Hall sidebands at 80 MHz as well as re-pumper sidebands at 1.7 GHz 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 a stabilized helium-neon reference laser integrated into the system. 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 ordinary 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. The optical resonator is also a very effective spatial mode filter that suppresses any transverse mode apart from TEM_{00} when properly aligned, and thus the 589-nm output of the SHG module is inherently a diffraction-limited beam. 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 re-pumping of the mesospheric sodium atoms' electronic population after it has decayed to the other hyperfine ground state [3]. The total length of the SHG 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 [4] 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 travelling through the atmosphere.

In summary, the 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. SYSTEM CHARACTERIZATION

Before starting with the serial production of the guide star laser, following the ESO Statement of Work, a so-called Pre-Production Unit (PPU) was assembled and tested. Environmental tests both under operational conditions (0 to 15°C and ambient pressures down to 580 mbar corresponding to the height of Mauna Kea, Hawaii) and functional conditions (-10 to +30 °C), as well as shock and vibration and transport climatic tests were successfully conducted and passed. Results of these PPU acceptance tests have been published in Ref. [5].

After successful completion and testing of the Pre-Production Unit (PPU) in 2012, the project was transferred from TOPTICA's R&D to its production department in 2013. Here a reliable and efficient production process and supply chain with more than 1000 different component parts was established and during 2014 the first batch of four Laser Units was assembled. These LUs have undergone and successfully passed the same test procedures [2] as the PPU and, after an additional testing period of several months at ESO's premises, all delivered laser units have been accepted by ESO.

Here we present the system verification results of the first remote-pumping systems, where the small laser head consisting of RFA and SHG stage is separated by 27 m from the larger electronics cabinet. In the meantime, three such laser units have been delivered to customers and the first system has already passed the acceptance tests at Keck headquarters in Hawaii. In addition to the standard configuration, all essential optical parameters of the laser, such as wavelength, output power and polarization extinction ratio, have been tested while bending the remote delivery fibers down to radii as small as 10 cm.

3.1 Optical power and emission wavelength

Fig. 4 shows a long-term measurement where the stability of the laser power and emission wavelength was verified in a 10-day measurement. The mean value of the laser power amounts to 21.92 W with a standard deviation of 71 mW and a peak-to-peak variation of 0.45 W or 2.1% of the mean value. Of the total output power, 18 W are within the carrier (D_2a line), 2 W in the re-pumper signal (D_2b line) while another 2 W are wasted due to the symmetry of the sideband modulation scheme. The peak-to-peak variation of the emission wavelength is 41 MHz, thus easily fulfilling the specified criteria to be within ±40 MHz from the line center of the D_2a line. Bending of the optical fibers has no influence on the power or wavelength readings.

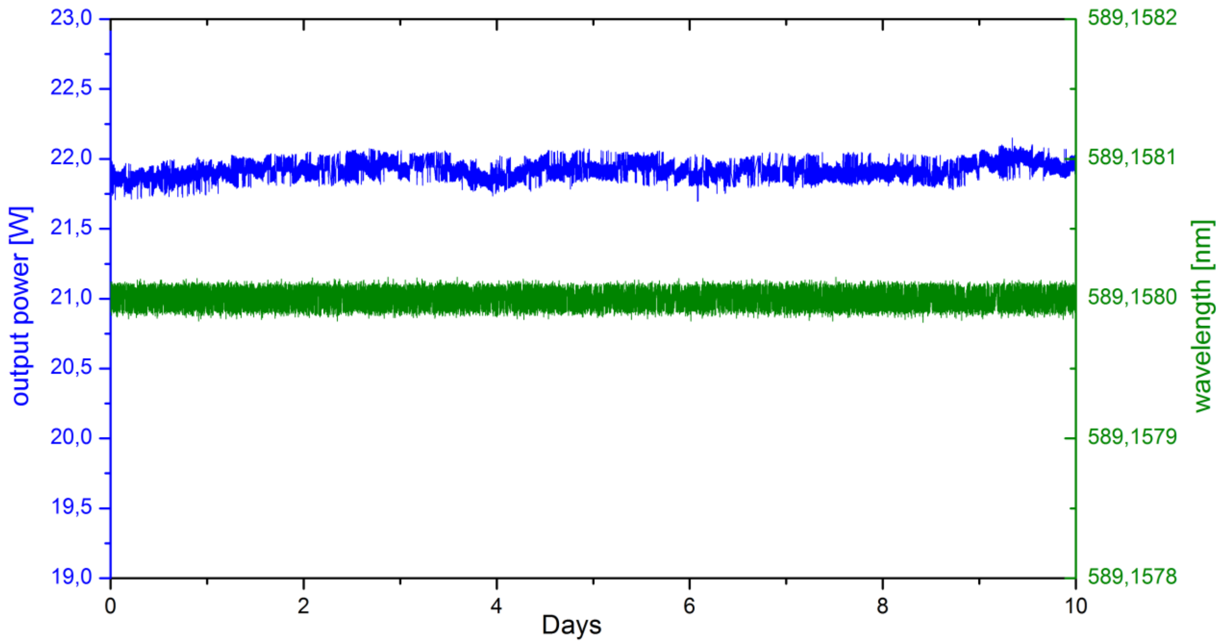

Fig. 4: Output power and wavelength measurement of laser unit SN #6 over a period of 10 days showing excellent stability without any long-term drifts.

3.2 Beam Quality

One of the most important characteristics for guide star applications certainly is the optical quality of the output beam. Fig. 5 shows the wavefront measurements of the three remote pumping laser units using a Shack-Hartmann sensor. These measurements have been corrected for piston and tip/tilt and the resulting RMS wavefront errors amount to 0.036 / 0.027 / 0.027 waves, respectively, 21 / 16 / 16 nm. The measured wavefront errors of are well beyond the Maréchal criterion and thus demonstrate the diffraction-limited character of the beam.

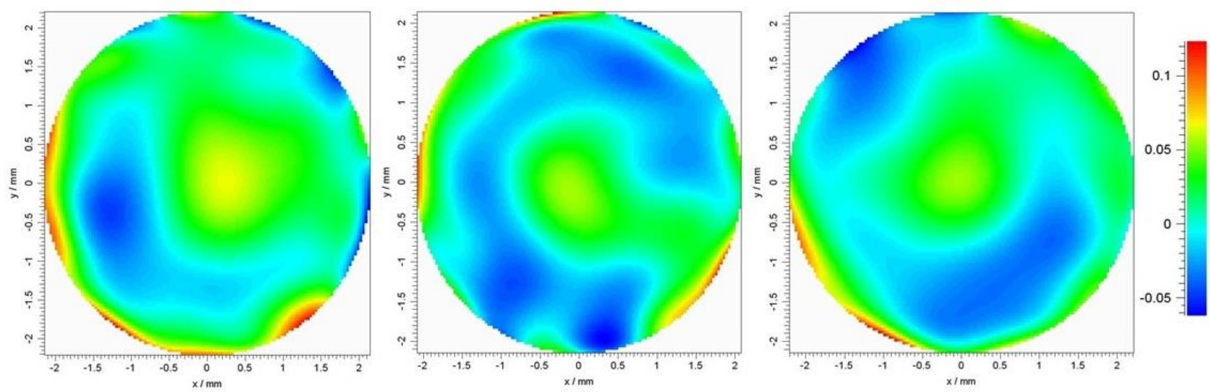

Fig. 5: The above plot shows the wavefront quality measured with a Shack-Hartmann wavefront sensor over √2 times the beam diameter (3 mm). The scale on the right shows the color code of the wavefront error in waves

3.3 Tilt test

For simulating the varying gravity conditions during telescope tilting, the laser head has been operated under different inclination angles. For this measurement, the laser head is mounted on an ESO beam diagnostic system (BCDS) 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.

The tilt angle was incremented in steps of 15 degrees and the results of this gravity measurement are shown in Fig. 6 and Fig. 7. Emission wavelength and output power remained extremely stable during movement of the tilt stand. Both pointing and lateral shift varied by a maximum of 40 µrad or 20 µm, respectively, during a tilt from -90° to +90°. This is well within the ESO/Keck specifications of 160 µrad and 100 µm.

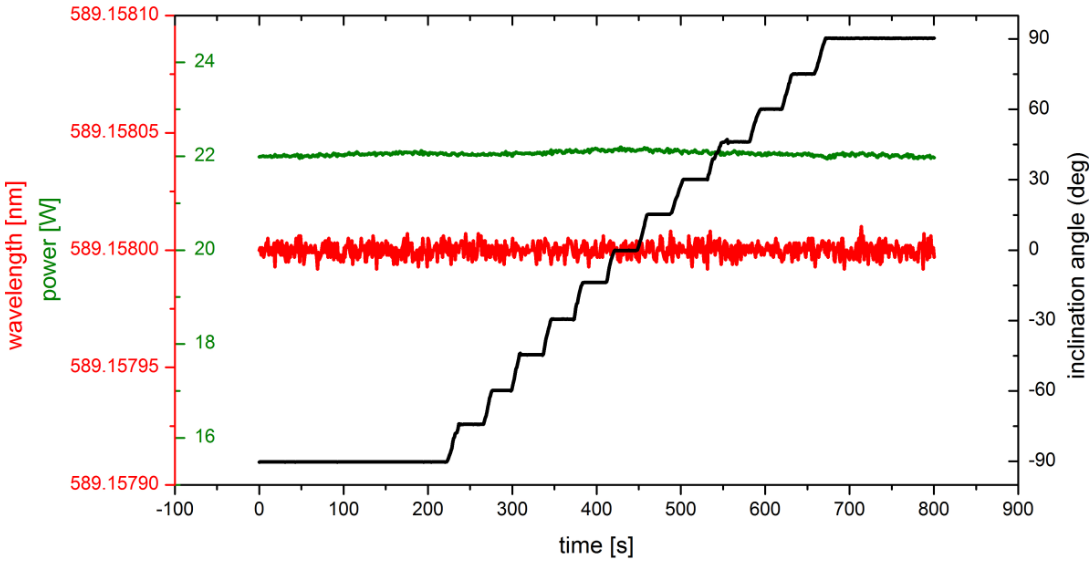

Fig. 6: Output power and emission wavelength of the laser with varying inclination angles of the laser head.

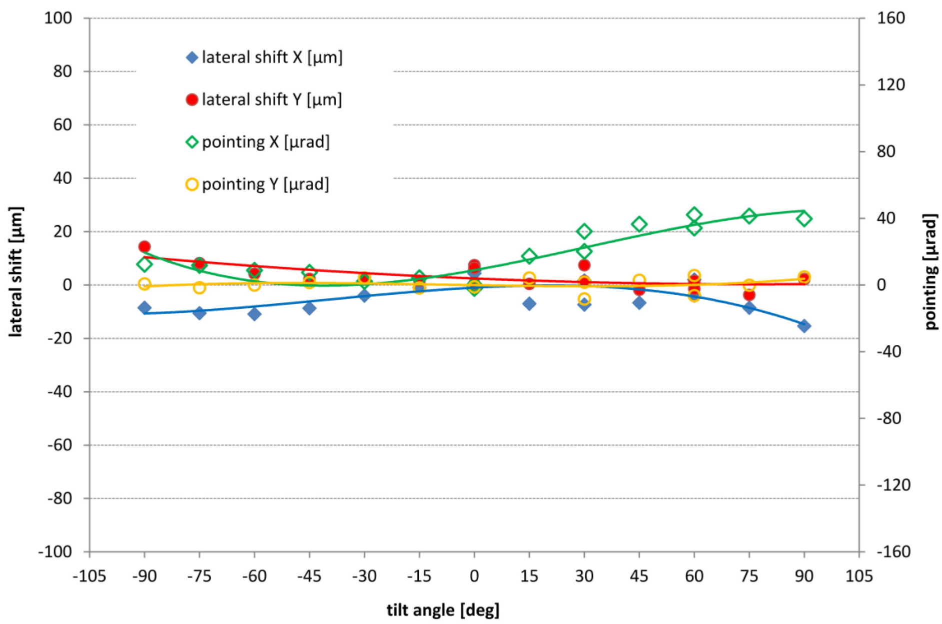

Fig. 7: Lateral shift and pointing of the laser beam under varying gravity conditions using a tilt test stand and the ESO BCDS unit.

3.4 Wall plug efficiency

The power consumption of the laser units has been tested with 208VAC/60Hz for the four operation states using an electrical testing instrument (SECUTEST SIII).

Operation State	Real Power	Apparent Power	Power Factor
Standby	216W	311VA	0.71
Ready	225W	317VA	0.71
On	555W	600VA	0.92
Observation	562W	608VA	0.92

Tab. 2: Electrical power consumption of the remote pumping laser unit with serial number SN #10.

The power consumption at beginning of life (BOL) of one laser unit at operational power level amounts to about 600 W. The largest part of the heat is generated within the electronics cabinet by the diode-pumped fiber pump laser, less than 100 W are dissipated within the laser head. Therefore, a moderate coolant flow rate of about 3-4 l/min and 1 l/min suffices to remove the heat from the electronics cabinet and the laser head, respectively, introducing negligible amounts of vibration.

4. DISCUSSION AND SUMMARY

A summary of the system test results together with the ESO/Keck specifications is shown in Tab. 3.

Test	Unit	ESO / Keck spec. (goal)	Serial #6	Serial #9	Serial #10
Output power					
power in carrier	W	18	19	18.5	18.4
blue sideband	W	2	1.9	2.3	2.1
red sideband	W	-	1.1	1.5	1.4
carrier power within ±1 FWHM	%	> 70	> 80	85	>85
Long-term stability (14h)					
mean power	W	22	21.93	22.33	22.18
standard deviation	mW		36	34	36
standard deviation	%		0.16	0.15	0.16
peak-to-peak variation	%	< 15 (< 10)	< 2	2	<2
Short-term stability (50s)					
mean power	W	22	22	22	22
standard deviation	mW		42	26	30
standard deviation	%	< 6 (< 3)	0.19	0.12	0.13
Beam pointing (14h, incl. start-up)					
pointing (rms)	µrad	< 160 (< 80)	2.1	3.4	1.6
pointing (peak-to-peak)	µrad		15	16	13
lateral shift (rms)	µm	< 100 (< 50)	1.6	1.7	2.1
Emission wavelength (14h)					
standard deviation	MHz		3	3.2	2.3
peak-to-peak variation	MHz	< 80	25	29	22
Frequency toggling					
detuning frequency	GHZ	5	5	5	5
detuning time	s	< 10 (< 5)	< 5	< 5	< 5
power variation	%	< 5	0.5	0.5	0.5
Laser linewidth (measured with 1GHz FPI)					

FWHM	MHz	< 250 (5 ± 1)	8.5	6	8
Optical quality					
wavefront error (rms)	nm	< 70 (< 25)	21.4	16	16
wavefront error (rms)	λ		0.036	0.027	0.027
Beam waist and asymmetry					
beam waist diameter x	mm	3.0 ± 0.1	3.05	3.08	3
beam waist diameter y	mm	3.0 ± 0.1	3.05	3.06	2.95
beam waist location x	m	0 ± 2m	0.91	0.4	-0.89
beam waist location y	m	0 ± 2m	0.22	-0.06	-0.06
beam asymmetry		0,93 - 1,07	0.99	0.99	98
Polarization					
polarization extinction ratio (PER)	dB	> 20 (> 23)	> 23	> 24	> 24
polarization direction (deviation)	deg	< 2	<1	<1	<1
Power consumption (@ BOL)					
max. real power	W		550	562	562
max. apparent power	VA		610	607	608
electrical power factor		> 0,85	0.9	0.92	0.92

Tab. 3: Test summary and critical data comparison for the first three remote pumping laser units.

All parameters are within specifications provided by ESO / WMKO and even meet the more stringent goals. A comparison with the corresponding measurement data of the first five laser units (Ref [2]) shows excellent agreement, thus underlining the reproducibility of the laser design as well as the production processes. We therefore were able to demonstrate that the performance of the remote pumping configuration is identical to the standard laser configuration. All essential optical parameters of the laser, such as wavelength, output power and polarization extinction ratio, are unaffected by bending the remote fibers down to bend radii as small as 10 cm. Thus, the motion of the fibers in the cable wrap during operation of the telescope will not influence the performance of the guide star laser.

The engineering of a deployable laser system design based on the concept originally developed and tested at ESO [6],[7],[8], have led to a ruggedized, compact and modular solution, keeping ease of operation and serviceability in mind. 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 an innovative straight-forward re-pumper generation scheme 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 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. This allows for a flexibility similar to, but much less lossy than, remote fiber delivery of the yellow light and will be beneficial in particular for small and agile telescopes such as those used for satellite and space debris tracking [9] as well as LIDAR [10] applications.

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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