Results of Lab & On-Sky tests, at XingLong Observatory, of a SFG Pulsed Laser for Laser Guide Star Application

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Introduction

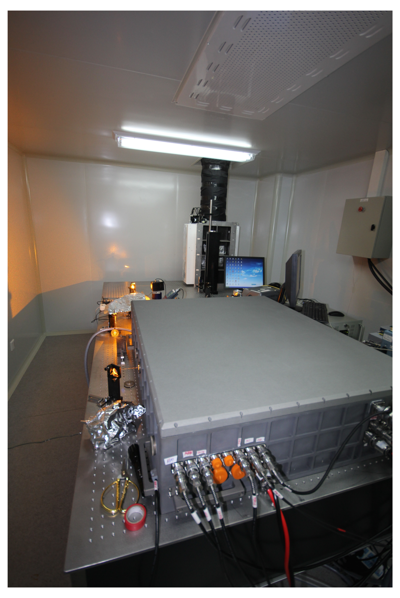
Hereby, we present results from on-sky and laboratory testing of a quasi-continuous-wave (QCW) pulsed laser, based on a Sum-Frequency-Generation (SFG) approach, designed and built by the Technical Institute of Physics and Chemistry (TIPC) and intended for application in a Laser Guide Star (LGS) system. China is a partner of the TMT International Observatory and has shown strong interest in providing the laser units required to support the TMT's adaptive optics system. The results shown in here are from a prototype laser built in 2014, tested in Dec-04/Feb-05, and intended to demonstrate the ability to meet the TMT performance requirements in terms of: power output, wavelength stability, laser beam quality, laser beam jitter, as well as laser coupling efficiency to the sodium atoms in the mesosphere relating to the LGS photon flux.

Goals of this Study

- Verification of the TIPC laser performance parameters, against TMT requirements: specifically, power output and power stability, wavelength stability, laser beam quality and laser beam jitter.
- On-sky testing of the laser to check the LGS photon flux under various laser light formats: circular and linear polarizations, each with and without re-pumping of the D_{2b} Na line.
- Determination of the laser coupling efficiency (S_{ce}) to the mesospheric Na atoms for the conditions met during on-sky testing, and estimation of the Sce for an sub-arcsecond angular size LGS (this last point required use of an available physical model of the laser).

Location and Setup

- All tests were conducted at the XingLong Observatory of he National Astronomical Observatories (Chinese Academy of Sciences) nearby Beijing, China. The coordinates of the testing sites are: 40°23'47.58" N, 117° 34'52.50" E, 960 m altitude.
- At this location, and as of 31JAN2015, the strength of the geomagnetic field, inclination and declination of the geomagnetic field lines, at the altitude of the mesospheric Na layer are: |B| = 0.519 Gauss, Incl=+59.11° (down from south to north, measured with reference to the horizontal plane), Az = -6.90° (west), respectively (Ref #1).
- The setup included: a) The TIPC pulsed laser (Fig. 1), a Lidar system for monitoring of the Na atoms column density, and a receiving optical telescope for the imaging of the LGS and reference natural stars (Fig. 2).



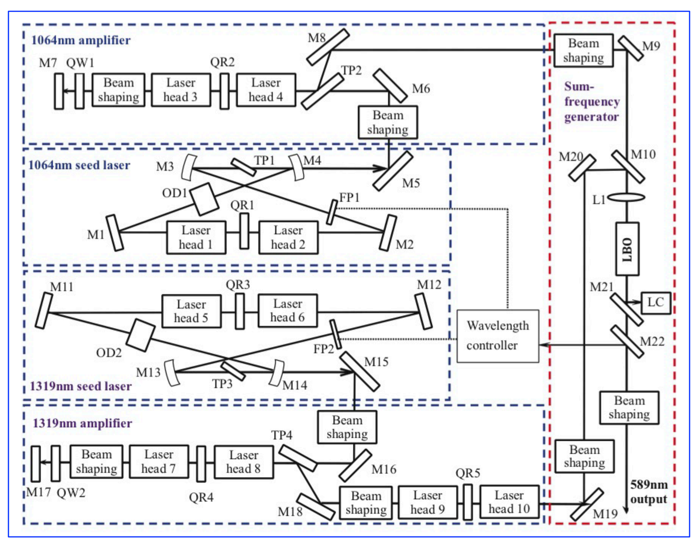


Fig. 1: View of the TIPC laser head and laser launch telescope tube (left), Laser Optics diagram (right). Table with main laser parameters specification (below)

Laser Parameter	Specification
Output Power @ 589nm	~25W (stable mean), 32W (max) @ 800 Hz
Beam quality of 589nm light beam	$M^2 \sim 1.4$
Linewdith	400 MHz
Pulse Repetition Rate	500 Hz – 800 Hz (adjustable)
Pulse Length	120 µs – 75 µs (6% duty cycle)
1064 nm Power	90 W
1319 nm Power	70 W
Optical Power Conversion Efficiency	~ 16%

Parameter	Description
Telescope	14" PlaneWave
Camera	PI VersArray 512B
Imaging Sensor	E2V CCD77-00
	512x512 pixels
	24 µm x 24 µm pixel size
	3 e- rms readout noise

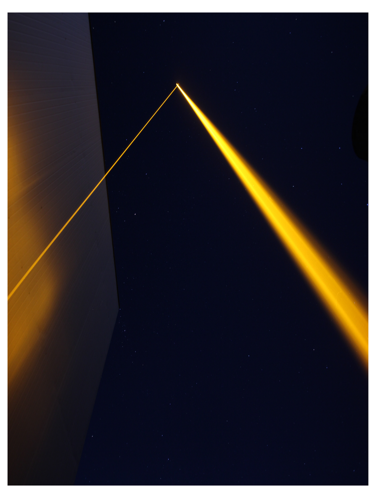


Fig. 2: View of the 14" aperture PlaneWave Imaging Telescope (left) Table with main parameters of the imaging system (center) and view of the Lidar and TIPC laser beams project onto the sky (right)

Bibliography

[1] http://www.ngdc.noaa.gov/geomag-web/#declination

[2] Rochester et al., 2012, J. Opt. Soc. Am. B, 29 (8), pp. 2176-2187.

Laboratory Tests Results

Power Output & Power Stability: The TIPC laser includes a diagnostics & monitoring stage to help continuously monitor, among other parameters, the laser power its wavelength and beam shape. The power monitor instrument is a ThorLabs model PM100D equipped with a sensor model S120C. The S120C sensor has a wavelength range coverage of 400 nm to 1100 nm and accepts a power inputs in the range of 50nW to 130mW (a 3.4 $^0/_{00}$) of the 589nm laser beam power is diverted into the power monitor sensor.

Several long-term tests, 4 hours up to 12 hours, were run to check the magnitude of the 589nm laser beam power and its stability. Fig. 3 shows, a ½ window time series at 3 ms time resolution and statistical histogram, of one of such tests. In the results shown below the power statistics, operating the laser at 800 Hz PRR, are: P_{mean} = 25.56W, σ_P = 0.47W, $3\sigma_P/P_{mean}$ = 5.5%, range = 2.21W, range (99%-1%)/mean = 8.6%. These statistics are similar than those of longer tests. ***The TMT requirement for the lasers power output is P > 21.6 W (using D2b re-pumping), short-term (or pulse-to-pulse) power fluctuations <= 6% (with a goal of 3%) and long-term power fluctuations (in 12-hours) better than 15% (with a goal of 6%).***

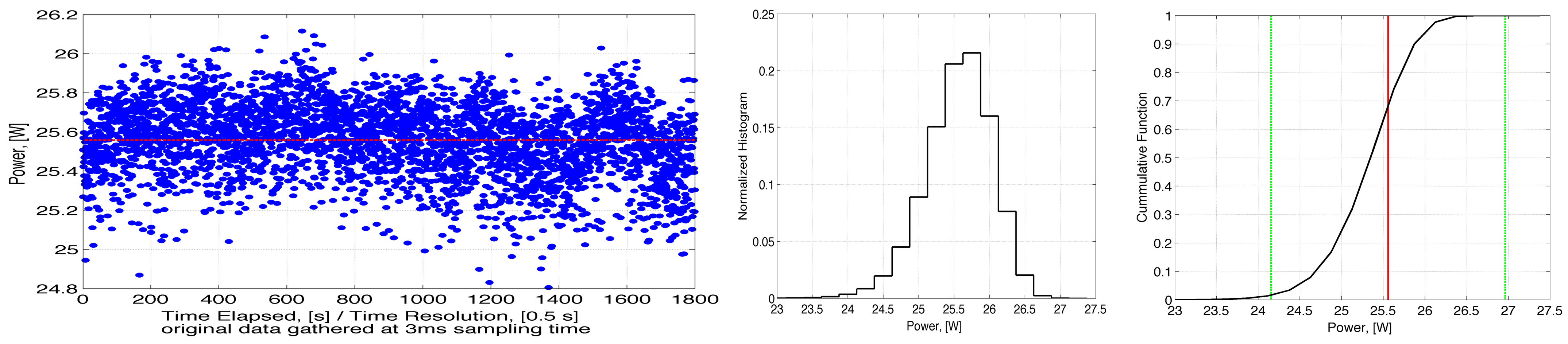


Fig. 3: Time series and statistics of the TIPC laser 589nm power output. The solid red lines shows the mean value, the segmented red and green, lines shows +/- 1-sigma and +/- 3-sigma range, respectively.

Wavelength Stability: The TIPC laser wavelength is continuously monitored using a HighFinesse GmbH's WS-7L wavelength meter. This instruments works in the range 350-1120 nm, with a relative accuracy of 1 part in 10^7. At the wavelength of the laser (589 nm), this translates into a frequency accuracy of ~ 51 MHz (dν = 589nm*1E-7 / 589nm^2 /c, with c the speed of light). Fig. 4 shows the time series of the laser stability (in terms of frequency) with respect to the D2a Na line. ***The TMT specification ask for a frequency stability of +/- 200 MHz (this translates into about 0.231 pm wavelength stability around the D2a Na line). The goal is +/- 100 MHz (0.116 pm).***

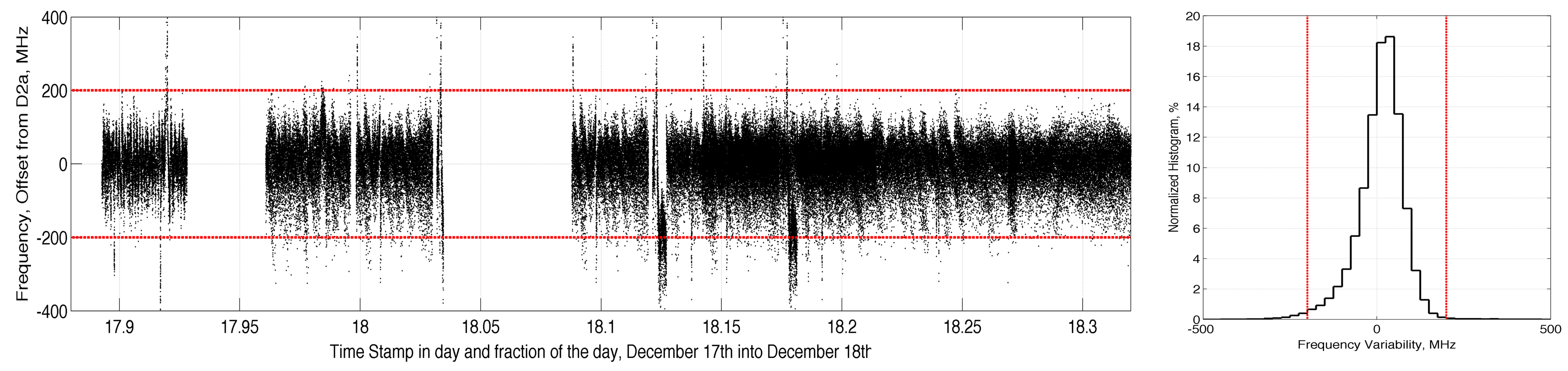


Fig. 4: Time series and histogram of the TIPC laser (prototype #3) frequency stability, the red lines shows the TMT specification of +/- 200 MHz frequency stability (i.e. 0.231 pm wavelength stability around the D2a Na line).

On-Sky Tests Results

Statistics of the absolute photon flux return (in millions of photons/m²/s) for the **Test #2** the night of Jan 31st to Feb 1st, 2015. The TIPC pulsed laser was operated at 800 Hz PRR, with **circularly polarized laser light** and switching between D2b re-pumping OFF and ON. The test was run for various levels of laser Power from 5W up to 20W of generated power.

The Na atoms column density was monitored during the test time using a collocated Lidar, the beam transfer optics throughput (Tbto) is 0.75 and the atmospheric transmission (Ta) is 0.70, and LGS spot size in the mesosphere is 4 arcsecs FWHM. These information was used to compute the laser coupling efficiency.

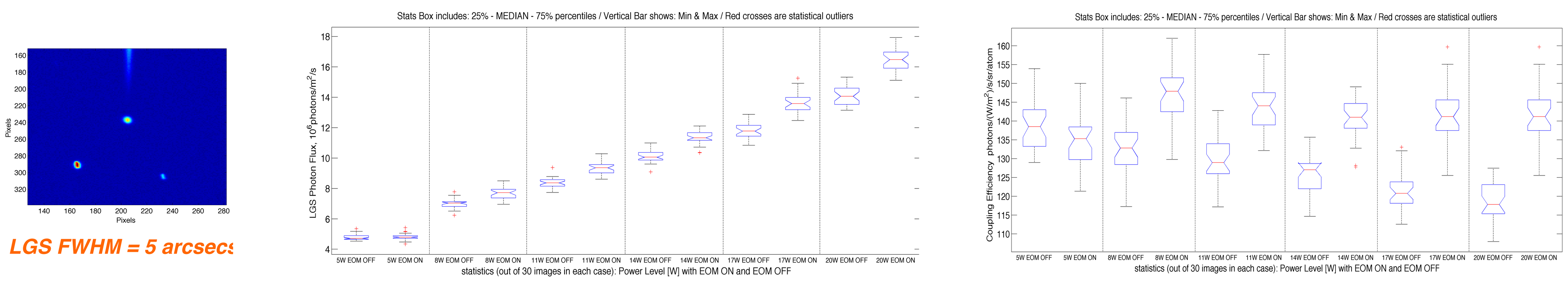


Fig. 5: LGS photon flux return (in millions of photons/m²/s) as a function of generated laser power (left), and Laser Coupling Efficiency (Sce), in photons/s/sr/(W/m²), obtained from the observations and other known parameters (right).

Comparison of Laser Coupling Efficiency between A Physical Model of the laser and observations

A physical model of the laser (*Rochester et al., 2012,*) using a true pulse shape of the TIPC laser, setup with the known magnitudes for the Na atoms column density, beam transfer optics throughput, atmospheric transmission, laser generated power and LGS spot size, was run as to estimate the photon flux return of the LGS spot. ***The results (MODEL) agreed within 10% with the median results obtained during the on-sky test observations (OBS).***

Laser Power [W]	Φ_{OBS} ph/m²/s	Φ_{MODEL} ph/m²/s	Sce ph/(W/m²)/s/sr/atom
5	3.2×10^6	3.0×10^6	142
8	4.4×10^6	5.0×10^6	148
11	7.0×10^6	7.1×10^6	151
14	8.6×10^6	9.2×10^6	156
17	10.7×10^6	11.4×10^6	159
20	12.4×10^6	13.6×10^6	161

S_{ce} at small angular Size LGS

Power [W]	LGS Spot FWHM [arcsecs]	Φ_{MODEL} [ph/m²/s]	Sce, [ph/(W/m²)/s/sr/atom]
22	1.0	13.2×10^6	142.4
22	0.6	10.7×10^6	115.4