The laser guide star system for adaptive optics system at Subaru Telescope

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ABSTRACT

We report on the current status of developing the new laser guide star (LGS) system for the Subaru adaptive optics (AO) system. We have three major subsystems: the laser unit, the relay optical fiber and the laser launching telescope.

A 4W-class all-solid-state 589nm laser has been developed as a light source for sodium laser guide star. We use two mode-locked Nd:YAG lasers operated at the wavelength of 1064nm and 1319nm to generate sum-frequency conversion into 589nm. The side-LD pumped configuration is used for the mode-locked Nd:YAG lasers. We have carefully considered the thermal lens effect in the cavity to achieve a high beam quality with TEM_{00}, $M^2 = 1.06$. The mode-locked frequency is selected at 143 MHz. We obtained the output powers of 16.5 W and 5.0 W at 1064nm and 1319 nm. Sum frequency generated by mixing two synchronized Nd:YAG mode-locked pulsed beams is precisely tuned to the sodium D2 line by thermal control of the etalon in the 1064nm Nd:YAG laser by observing the maximum fluorescence intensity of heated sodium vapor cell. The maximum output power at 589.159 nm reaches to 4.6 W using a PPMgOSLT crystal as a nonlinear optical crystal. And the output power can be maintained within a stability of 1.2% for more than 3 days without optical damage.

We developed a single-mode photonic crystal fiber (PCF) to relay the laser beam from laser clean room, in which the laser unit is located on the Nasmyth platform, to the laser launching telescope mounted behind the secondary mirror of Subaru Telescope. The photonic crystal fiber has solid pure silica core with the mode field diameter of 14.3 micron, which is relatively larger than that of the conventional step-index type single mode fiber. The length of the PCF is 35m and transmission loss due to the pure silica is 10dB/km at 589nm, which means PCF transmits 92% of the laser beam. We have preliminary achieved 75% throughput in total. Small mode-locked pulse width in time allows us to transmit the high-power laser beam with no suffer from the non-linear scatter effect, i.e. stimulated Brillouin scatter, in the PCF.

The laser launching telescope (LLT) has an output clear aperture as 50 cm. It is classical Cassegrain type optical configuration with tertiary mirror to insert the laser beam from the side. The wavefront error is designed to be 60 to 70nm. The LLT is a copy product what European Southern Observatory has been designed for the laser guide star system at Very Large Telescope.

We succeeded to launch the laser beam to the sky on October 12, 2006. After several tests on the sky, we succeeded to get an image of the laser guide star with the size of more than 10 arc second. The larger size of the laser guide star is caused by the large optical aberration on the primary mirror of LLT due to the heat stress generated at the trigonal support points.

1. INTRODUCTION

We are developing the laser guide star adaptive optics system for Subaru Telescope since 2002 [1]. This adaptive optics system is based on a curvature wavefront sensing technique and bimorph type deformable mirror. The number of sub-apertures in the wavefront sensor and the number of electrode at the deformable mirror are 188.

The laser guide star system creates the artificial guide star at the altitude of 90 km in the Sodium layer. We have three main sub systems in the laser guide star system. First sub system is a sum frequency generating laser system at the wavelength of 589nm as a light source and the laser diagnostic system. The second sub system is a solid-core photonic crystal optical fiber as a laser beam transfer optics including the coupling optics into the optical fiber. The third sub system is a laser launching telescope to project the laser beam to the sky. System overview of laser guide star system at Subaru Telescope is shown in Fig. 1. The laser light source and the laser diagnostics system are installed in the laser clean room, which is built on the Nasmyth platform. Laser beam is projected from the laser launching telescope mounted behind the secondary mirror of Subaru Telescope. The photonic crystal optical fiber cable transfers the laser beam from Nasmyth platform to the laser launching telescope. The length of the photonic crystal optical fiber cable is 35 m.

This paper explains the current status of each sub system of the laser guide star system at Subaru Telescope.

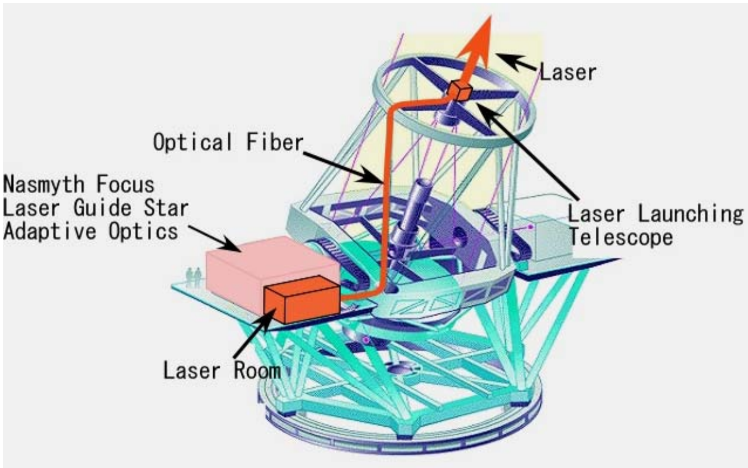

Fig. 1 Layout of the laser guide star system on Subaru Telescope.

2. LASER LIGHT SOURCE

Several characteristics are required in coherent sodium D_2 resonance light sources to produce the artificial guide star required by the laser guide star adaptive optics system at Subaru Telescope. The output beam quality should be a single transverse mode of TEM_{00}, $M^2<1.1$. The spectral bandwidth should be narrow compared with the Doppler broadened sodium absorption spectrum, (about 2.77 GHz) in the mesosphere. Continuous-wave (CW), quasi-CW, or macropulse–micropulse operation is preferred to avoid saturation. With these characteristics, an all-solid-state laser system with an average output power of at least 4 W is suitable to yield a stable and efficient photon return from the laser guide star.

We designed and manufactured a simple and efficient system of sodium D_2 resonance light source [2] as shown in Fig. 2. Single-pass sum frequency generation is carried out by mixing synchronized 1064 nm and 1319 nm pulse trains in time domain generated from actively mode-locked Nd:YAG lasers pumped by laser-diodes (LD). Periodically poled MgO-doped stoichiometric lithium tantalite (PPMgO:SLT) crystals are used in sum frequency generation. The 1064 nm and 1319 nm oscillators were each composed of two pumping chambers. A quartz 90°

polarization rotator at each wavelength was placed between the pumping chambers to compensate for polarization dependent birefringence. The pumping chambers consisted of three LD arrays, which were symmetrically set around a Nd:YAG rod. The cavity length of each 1064 nm and 1319 nm oscillator was adjusted to about 1 m. Output power of 1064 nm oscillator is about 16.5 W and that of 1319 nm oscillator is about 5.0 W. The quality of each output beam was measured to be TEM_{00}, $M^2<1.1$, by using a ModeMaster (Coherent Inc.). The frequency of acousto-optic mode lockers (AOMLs) was selected to be 143 MHz to maintain the beam quality at this cavity length. The synchronization of the mode-locked pulse trains at 1064 nm and 1319 nm was accomplished by controlling the phase difference between radio frequencies fed to the AOMLs. The output beams were collimated by telescopes and were focused to the PPMgO:SLT crystal (Oxide Co. and SWING Ltd.) for single-pass sum frequency generation. The crystal was packaged in a temperature-controlled oven. We controlled the oven at around 52°C. We achieved about 4.6 W at the wavelength of 589nm. The stability of output power is less than 1.2 % for at least 3 days (see Fig. 3). The output beam after sum frequency generation was injected into the sodium vapor cell using a sufficiently attenuated leak beam transmitted through from a high reflective relay mirror. The sodium vapor cell was heated at 90°C. A photomultiplier tube (PMT) is mounted on the side of the cell with chopper detected the intensity of sodium fluorescence by monitoring a modulated amplitude by chopper using a lock-in amplifier. The change in modulated amplitude tells us the degree of wavelength tuning into sodium D_2 resonance line. Precise tuning was accomplished by temperature control of etalons in the 1064nm Nd:YAG oscillator. The tuning range at output wavelength from 589.1564 to 589.1628 nm in about 0.3 pm steps has achieved. The spectral bandwidth was measured to be approximately 1.6 GHz

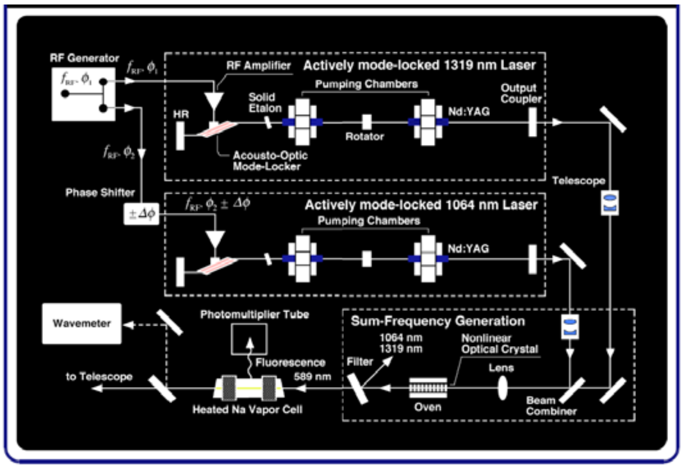

Fig. 2 Components inside the sum frequency generating laser.

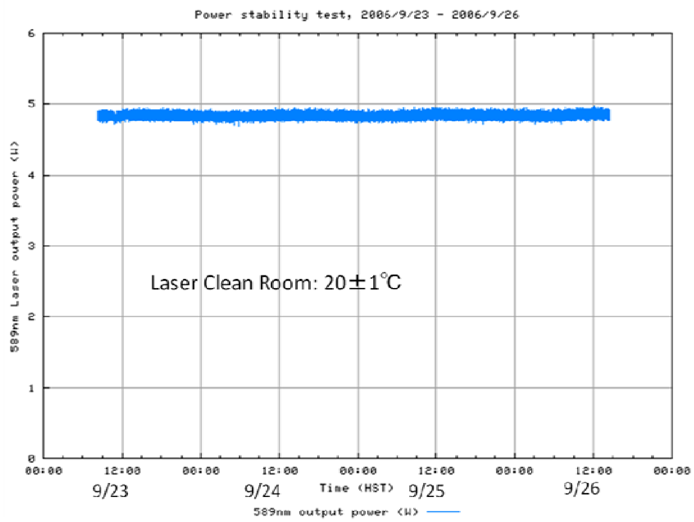

Fig. 3 Output power stability of sum frequency laser at 589nm for 3 days.

3. RELAY OPTICAL FIBER

Laser beam should be relayed from laser clean room to the laser launching telescope with minimum loss and minimum degradation of beam mode. Two methods have been proposed. One is mirror relay and the other is optical fiber relay. There are some reasons that optical fiber relay is better than relaying by mirror. (1) The fiber relay makes it easier to maintain a good beam quality because a single mode fiber preserves a transverse mode of laser beam as TEM_{00} through the optical fiber relay. (2) The optical fiber can guide the laser beam flexibly from the laser location to the laser launching telescope. We installed the laser system in the laser clean room on Nasmyth floor, while the laser launching telescope is attached behind of secondary mirror of Subaru Telescope. The distance between the two locations is about 35 m. However, the fiber relay has some drawbacks comparing to the mirror relay. (1)It needs high-precision adjustment of optimum input to the single mode optical fiber. We have to adjust the position of the optical fiber and coupling lens as 0.1 μm accuracy if we transmit the beam as effective as possible. (2) Pure Silica as the material of the fiber makes attenuation of light. The loss by fiber's material is 10 to 15 dB/km, it corresponds to 89% to 92 % transmission for 35m. (3) The most important difference between the optical fiber and the mirrors is that the optical fiber suffers from nonlinear effects for high power laser realy. High energy density at the core generates the nonlinear effects, especially Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS).

We selected a solid-core photonic crystal fiber to relay the laser beam. Solid-core photonic crystal fiber is an optical fiber which obtains its waveguide properties not from a radial profile of refractive index distribution controlled by dopants in the fiber material, but from a hexagonal pattern of very tiny air holes which go through the whole length of optical fiber. An advantage of the photonic crystal fiber is that it can be made with large cores (10-17 μm) than those of the conventional single mode optical fiber (around 3 to 5 μm). The larger size core allows to reduce the energy density at the optical fiber core and to make it easy to couple the laser beam to the photonic crystal fiber core, and to raise the threshold level of stimulated nonlinear scattering effect in the optical fiber. Our requirement for solid-core photonic crystal fiber is summarized in Table. 1.

Table 1. Requirement for optical relay fiber.

Items	Values
Cutoff wavelength	< 589.159 nm (Sodium D2 line)
Input laser power	> 4 W
Transfer beam mode	M^2 < 1.1
Fiber end AR coating	< 0.2%
Mode field diameter	> 14μm
Fiber length	35 m
Transmission loss	< 15 dB/km

Mitsubishi Cable Industry succeeded to fabricate the photonic crystal fiber cable within our specification. (See Figure 2) The cable contains 6 photonic crystal fibers. They achieved the transmission loss of 10 db/km, finally.

We estimated the lower limit of threshold level of a non-linear stimulated scattering in the photonic crystal fiber to be more than 30 W, when we use our mode-locked quasi-continuous wave sum-frequency laser [3].

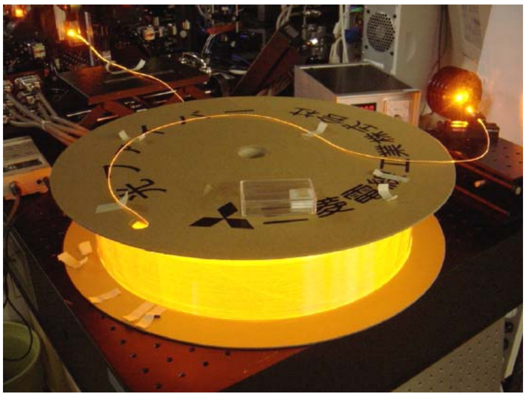

Fig 4. Photonic crystal fiber testing with injecting sum frequency generating 589nm laser.

We achieved about 75 % transmission in maximum including coupling efficiency and transmission of a photonic crystal fiber itself defined by its material.

4. LASER LAUNCHING TELESCOPE

Laser launching telescope is mounted behind the secondary mirror. The design of laser launching telescope is a design copy from that of ESO [5], [6]. The laser launching telescope has already manufactured and tested by the Space Business Unit of Galileo Avionica (Italy). The summary of optical design is shown in the Table 2.

Table 2. Specification of laser launching telescope.

Items	Values
Telescope design	Cassegrain with tertiary mirror.
Exit pupil diameter	500 mm
Angular magnification	12.5
Entrance pupil diameter	40 mm
Field of view	2 arcmin
Wavefront error	< 70 nm rms
Weight	70 kg

We observed unexpected wavefront error due to the operating low temperature environment at the summit. Off focus stellar image and on focus stellar image are shown in Fig. 5. This wavefront error is induced by the lateral stress force on the primary mirror support. Galileo Avionica at Italy has changed the design of supporting the primary mirror as well as the supporting structure of tertiary mirror to compensate this wavefront error.

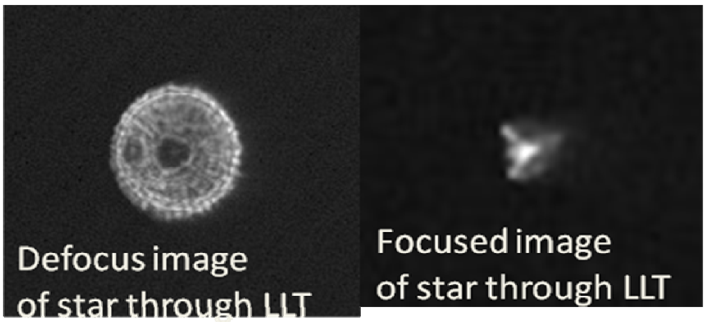

Fig. 5 Wavefront measurement on the laser launching telescope using star.

5. LASER CLEAN ROOM

We locate the laser clean room on the Nasmyth floor. The overall size of the laser room is 3 m x 5 m x 2.5 m. Laser clean room has two chambers. First you can enter the anterior chamber, where the control electronics for laser system and diagnostics system and chillers for exhausting the heat at the laser head are installed. The size of this chamber is 1.7 m x 2.9 m x 2.5 m. The coolant line provided from the telescope ethylene glycol resource is circulated in the heat exchangers to exhaust the generated heat at the anterior chamber. When we operate the laser, the temperature at the anterior chamber is about 20°C.

The clean chamber, next to the anterior chamber, is actually a clean room where the laser system is placed. The air temperature in this chamber is controlled at 22.0°C and stabilized within 0.1°C. This size is 3.15 m x 2.9 m x 2.5 m. Cleanliness of the chamber is less than 10000 even when an laser operator or a maintenance person enters in this chamber. If we let the chamber desolate, the cleanliness becomes less than 1000. Humidity is not actively controlled, because humidity at Nasmyth platform, where the air is cooled down around 0°C to 5°C in daytime, does not exceed 90%. Typical humidity is around 2% to 10%.

Fig. 6 shows the construction phase of laser clean room. Blue covered material is the laser unit.

Fig. 6 Laser clean room at construction phase. A view from clean chamber side.

6. FIRST LASER LAUNCHING TEST

We succeeded to launch the laser beam to the sky on October 12, 2006 (Fig. 7). Projected laser power is expected to be about 3 W at the exit window of laser launching telescope, while the laser output power is 4.6 W at the exit window of laser unit. After several tests on the sky, we succeeded to get an image of the laser guide star with the size of more than 10 arc second (Fig. 8). The larger size of the laser guide star is caused by the large optical aberration on the primary mirror of laser launching telescope due to the stress generated at the trigonal support points at low temperature environment at the summit.

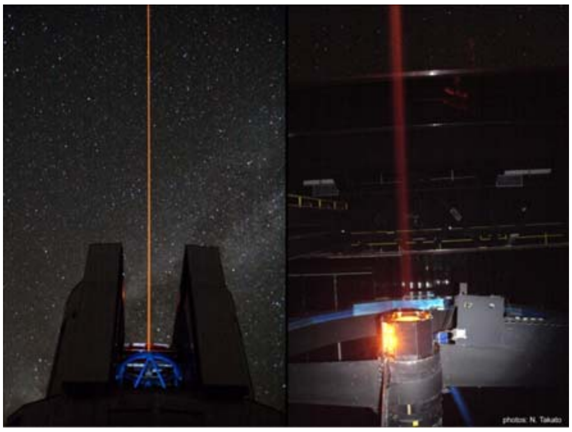

Fig. 7 First laser launch on October 12, 2006 from Subaru Telescope.

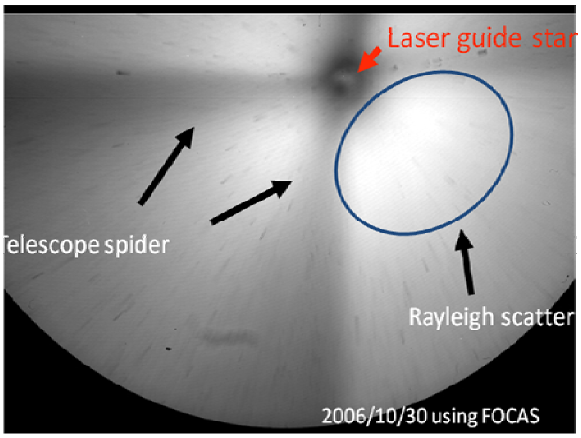

Fig. 8 First light image of laser guide star.

7. MILESTONES TOWARDS OPEN USE OF LGSAO 188

After the first light of laser guide star, we started to make a schedule of the repair of laser launching telescope wavefornt error. We disassembled the laser launching telescope on June, 2007 and all optical and mechanical support parts were shipped back to Galielo Avionica premises. After re-machined or newly manufactured the mechanical support parts, all components have been arrived on September 2007. Now we are ready to re-assemble the laser launching telescope.

We had serious trouble on laser diodes in the sum frequency laser on April 2007. This is due to the lifetime of laser diodes itself. Actually, we have used laser diodes more than 4000 hours. Overhaul of sum frequency laser system is planned this fall, 2007.

The testing and checking the optical quality of laser launching telescope will start around October, 2007. After the sum frequency laser is finished the overhaul, we resume to project the laser beam to the sky around December, 2007. The adaptive optics system with 188 elements for Subaru Telescope will be brought up again to the summit around spring of 2008 and we will start final commissioning around early summer of 2008.

8. REFERENCES

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