

# 589 nm sum-frequency generation laser for the LGS/AO of Subaru Telescope

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## ABSTRACT

We developed a high power and high beam quality 589 nm coherent light source by sum-frequency generation in order to utilize it as a laser guide star at the Subaru telescope. The sum-frequency generation is a nonlinear frequency conversion in which two mode-locked Nd:YAG lasers oscillating at 1064 and 1319 nm mix in a nonlinear crystal to generate a wave at the sum frequency. We achieved the qualities required for the laser guide star. The power of laser is reached to 4.5 W mixing 15.65 W at 1064 nm and 4.99 W at 1319 nm when the wavelength is adjusted to 589.159 nm. The wavelength is controllable in accuracy of 0.1 pm from 589.060 and 589.170 nm. The stability of the power holds within 1.3% during seven hours operation. The transverse mode of the beam is the TEM<sub>00</sub> and M<sup>2</sup> of the beam is smaller than 1.2. We achieved these qualities by the following technical sources; (1) simple construction of the oscillator for high beam quality, (2) synchronization of mode-locked pulses at 1064 and 1319 nm by the control of phase difference between two radio frequencies fed to acousto-optic mode lockers, (3) precise tunability of wavelength and spectral band width, and (4) proper selection of nonlinear optical crystal. We report in this paper how we built up each technical source and how we combined those.

**Keywords:** Adaptive Optics, Laser Guide Star, Sodium Laser

## 1. INTRODUCTION

Adaptive optics (AO) has been recognized as a key technology for astronomy. However, there is a limitation that the AO works only if the natural guide star is bright enough for the wave front sensing. In order to overcome this problem, development of a laser guide star (LGS)<sup>1-4</sup> is desired. A LGS greatly expands the fraction of the sky which is available for AO. At the Subaru telescope, the LGS/AO project have started in 2002.<sup>5</sup>

In order to achieve high Strehl ratio as obtained with a natural guide star, it is essential to supply the laser that has a sufficient output power, optimized wavelength, and spectral band width. The sodium laser guide star is produced by the resonant backscatter originated from spontaneous decay of excited sodium in the atmospheric sodium layer at the ~ 90 km altitude. The wavelength of the laser must be 589 nm for the excitation of sodium.

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**Table 1.** Specification of 589 nm SFG Laser

Wavelength	589.159nm (Tunable from 589.060 to 589.170 nm)
Output laser power	4.5W
Bandwidth	2.06 GHz
Beam quality	TEM <sub>00</sub> , $M^2 < 1.1$
Polarization	linear
Power stability	$\pm 1.3\%$
Oscillation	Mode-locked Pulse (Repetition Rate: 143 MHz)

When we started the development of the laser for LGS/AO, there were two realistic methods to derive the high power 589 nm coherent light source. One is the dye laser and the other is the sum-frequency generation (SFG) laser. The 589 nm dye laser is obtained from an oscillation of fluorescent light of Rhodamine 6G (Rh6G) pumped by 532 nm Nd:YAG laser. SFG laser is generated by mixing two oscillation lines of 1064 and 1319 nm of neodymium-doped yttrium aluminum garnet(Nd:YAG). We chose to develop the SFG laser considering high possibility to reach the required performance and ease of maintenance of the solid laser. The group of Subaru LGS/AO has initiated to develop the 589 nm SFG laser in association with Solid-State Optical Science Research Unit of RIKEN and Megaopto Co., Ltd. We introduce the details of the specification and the technical sources of our 589 nm SFG laser in this paper.

## 2. SPECIFICATION

The specification of our 589 nm SFG laser is shown in table.1. The requirements for the use as a laser guide star are not only sufficient power but also optimum wavelength and bandwidth, high beam quality, and controllable polarization. If there is any lack of the performance in the specification, we cannot obtain sufficient brightness as a laser guide star. In the process of developing our laser, actually, the power of laser was improved step-by-step keeping the other performances.

The brightness of the laser guide star sensitively varies with the wavelength of laser. The wavelength of our laser must be adjusted to completely optimum wavelength. We obtained the optimum wavelength, as we can control our laser by the fine tuning in steps of 0.1 pm from 589.060 to 589.170 nm.

We estimated the brightness of the laser guide star by convolving the absorption cross-section of sodium and the laser power. Both of them are the functions of wavelength. Although the optimum bandwidth of laser should be slightly narrower than 2.06 GHz, it does not affect the brightness of a laser guide star significantly.

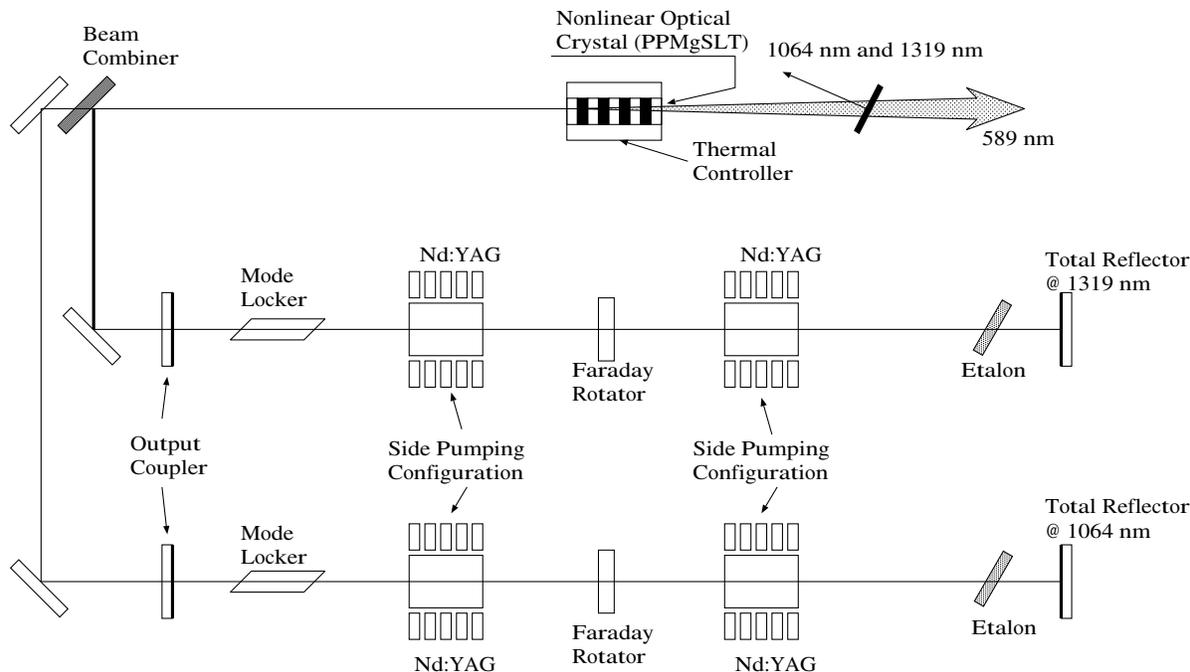
At the time of astronomical observations, our laser is transferred to the laser launching telescope mounted on the back of the secondary mirror through the optical fiber. Our laser must be input to the optical fiber without any energy loss. For this purpose, the transverse mode of our laser must be a single Gaussian beam (TEM<sub>00</sub>) and  $M^2$  must be as small as 1.0.

The polarization state must be controllable, although the relation between the brightness of a laser guide star and polarization state of the laser is still not clear. We adopt the linearly-polarized laser which is easily converted to other polarization states.

The power of our laser is remarkably stable. This performance is superior to our requirement ( $\pm 5\%$ ). The all other performances are stable in long time operation.

## 3. TECHNICAL SOURCES

We discuss our technical sources in the following subsections. We developed our laser by integrating these technical sources. Some key technical elements of our laser were published elsewhere.<sup>6-9</sup>



**Figure 1.** Configuration of our 589 nm SFG laser.

### 3.1. Construction of oscillator

We developed the oscillator of 1064 and 1319 nm Nd:YAG laser keeping the both of high power and high beam quality. Our laser is constructed as shown in Fig.1. 1064 and 1319 nm Nd:YAG lasers are set up in laser diode (LD) side-pumping configuration and have two side-pumping systems. The maximum incident power of a side-pumping system is 240 W ( $80 \text{ W} \times 3$ ). Two Nd:YAG laser are superimposed on the same axis and were input in a nonlinear optical crystal in which the wavelength of two Nd:YAG lasers are transformed to 589 nm. The acousto-optic mode lockers are set in the cavities at the Brewster angle at each wavelength.

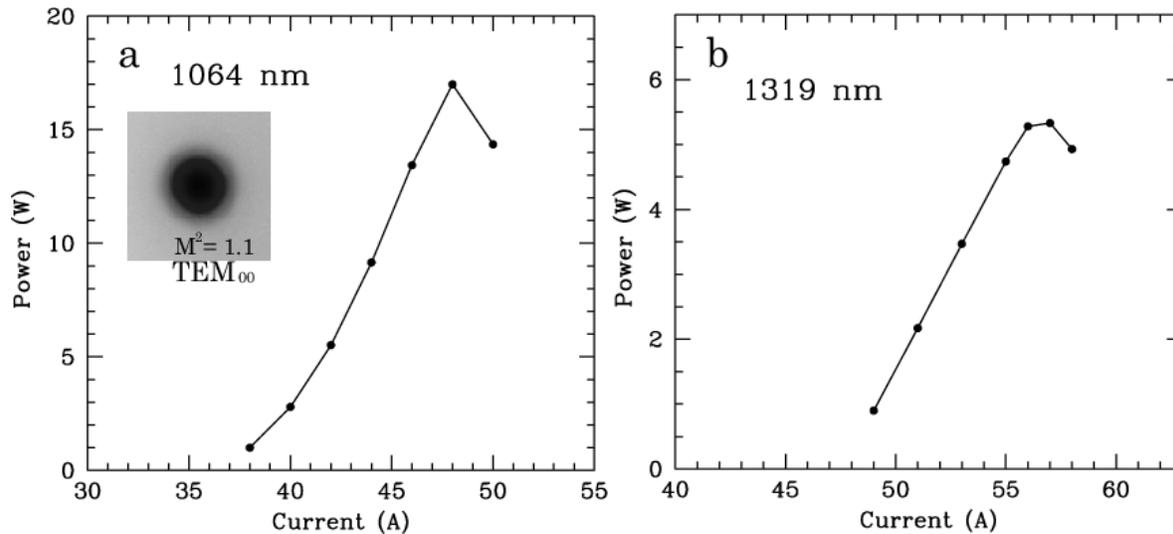
For generating high power at 589 nm, we need to put high power into LD of 1064 and 1319 nm Nd:YAG lasers. If the LD power of Nd:YAG laser increases, thermal lensing effect should appear in the oscillator and the effective excitation volume of the rod of LD should be changed. The thermal lens affects the beam quality (transverse mode). We constructed two oscillators to be able to keep  $\text{TEM}_{00}$  mode in any input power of LD. The relation of the input LD current and the output power of 1064 and 1319 nm laser is shown in Fig.2. The output power of 1064 and 1319 nm Nd:YAG laser are 15.65 W and 4.99 W, respectively to derive the output power of 589 nm stably. The  $\text{TEM}_{00}$  of our 589 nm laser is kept in any power of two Nd:YAG lasers as shown in Fig.2a.

The other advantage of these oscillators is adjustability of the cavity length of two Nd:YAG lasers. The cavity length of one Nd:YAG laser must be completely the same as that of the other for the phase adjustment of these two mode-locked lasers. Because the thermal lensing effect is different between 1064 and 1319 nm Nd:YAG lasers generally, the cavity length is also different between them. However we can adjust the cavity length of two lasers by optimization of the diameter of the LD rod.

The method of the phase adjustment of mode-locked lasers is discussed in next subsection.

### 3.2. Synchronization of mode-locked pulses

We successfully optimized the 589 nm output power by synchronization of two pluses of mode-locked Nd:YAG lasers. Especially, high conversion efficiency in SFG of our laser was obtained by this synchronization. The mode



**Figure 2.** Relation between the current of LD and the output power of 1064 and 1319 nm Nd:YAG lasers. In Fig.(a), the beam profile of 589 nm is displayed.

locker is operated using the radio frequency (RF) generator and the phase shifter as shown in Fig.3. RF is set at approximately 75 MHz. The generated RF is split into two paths. One is input to the mode locker of one laser through the RF amplifier after phase adjustment using the phase shifter. The other is input to the mode locker of the other laser without phase adjustment. The phase difference  $\Delta\phi$  between the split RFs can be controlled from  $0^\circ$  to  $360^\circ$  in steps of  $1^\circ$ .

The change of pulse timing is shown in Fig.4a, which is measured in an experiment using the same mode-locked system with our laser. The peaks of both pulses completely overlapped at a phase difference  $\Delta\phi \sim 30^\circ$  on an oscilloscope. The relation between  $\Delta\phi$  and the output power of 589 nm is shown in Fig.4b. The step of  $\Delta\phi$  is  $2^\circ$ . We can clearly find the peak of intensity of 589 nm in Fig.4b.

This controllability of  $\Delta\phi$  in our mode-lock system makes us adjust the output power of 589 nm.

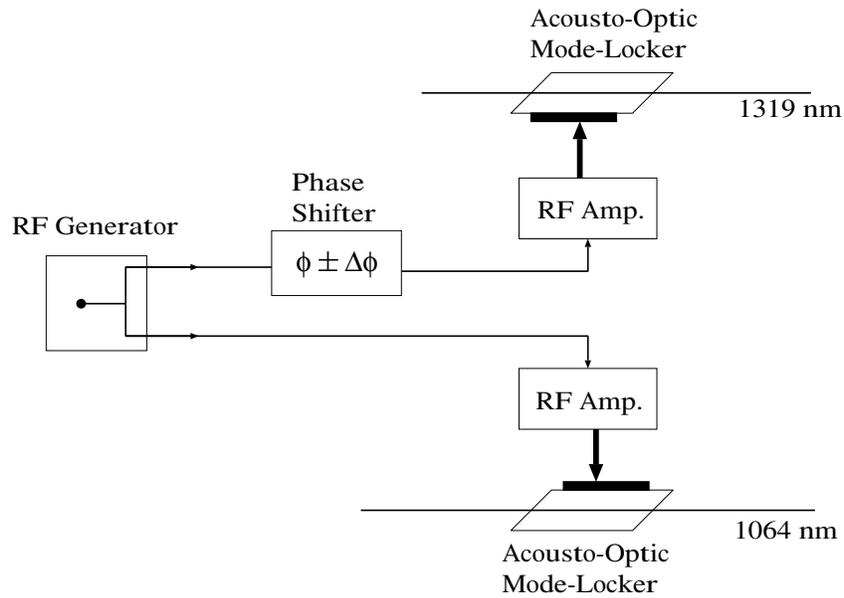
### 3.3. Tunability of wavelength and spectral band width

The wavelength and the spectral band width of laser is adjusted by the etalon. The wavelength of our laser is controllable in accuracy of 0.1 pm both by the temperature control of etalon and by the control of etalon angle. While the etalon angle control has good responsivity, its reproducibility is not accurate. We adopted the etalon temperature control for remote operation of our laser, because the temperature control has accurate reproducibility. The responsivity of the etalon temperature control is valid for the wavelength control with frequency of  $< 1\text{Hz}$ . Our laser does not need high frequency control of the wavelength because of its stability. In our laser, the temperature control of etalon in 1064 nm oscillator is used to adjust 589 nm wavelength in accuracy of 0.0008 nm/ $^\circ\text{C}$ .

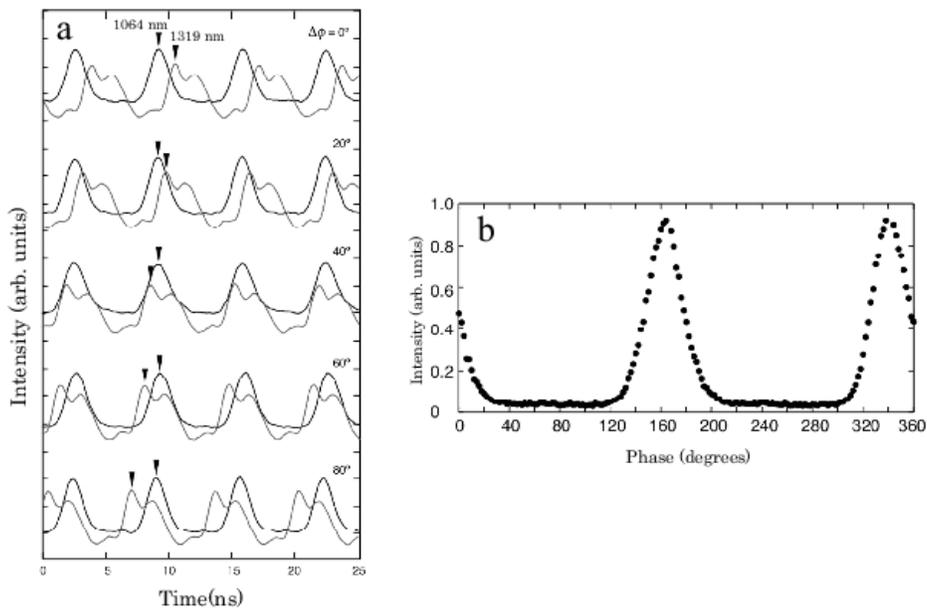
The wavelength of laser is sensitive to the temperature of environment. For example, if the temperature changes by  $1^\circ\text{C}$ , the wavelength of laser sometimes shifts up to 1 pm. We install our laser in the temperature-controlled room manufactured by MYEKAWA MFG. CO.,LTD. Since the temperature is controlled within  $\pm 1^\circ\text{C}$  in this room, we can minimize the effect of wavelength shifts.

### 3.4. Selection of nonlinear optical crystal

We adopted the periodically poled MgO-doped near-stoichiometric lithium tantalate (PPMgSLT) as a nonlinear optical crystal. The nonlinear optical crystal is required to have high conversion efficiency to 589 nm and high damage thresholds. PPMgSLT crystal satisfies these requirement.



**Figure 3.** The conceptual diagram of operation of mode-lockers.



**Figure 4.** a) The pulse trains of 1064 and 1319 nm mode-locked lasers. The timing of two pulse trains changes continuously by the shift of phase of 1319 nm. b) Relation between the phase of 1319 nm and the intensity of 589 nm laser.

The lithium triborate (LBO:LiB<sub>3</sub>O<sub>5</sub>) crystal and the periodically poled KTiOPO<sub>4</sub> (PPKTP) were other candidates as the crystal of our SFG. LBO crystal has high damage threshold. However its conversion efficiency is not so high that can satisfy our requirements for the laser.

The periodically poled crystal has phase matching condition using high nonlinear coefficient  $d_{33}$ , while it is not available for the bulk crystal like as LBO. The conversion efficiency of SFG ( $\eta_{SFG}$ ) is calculated according to  $\eta_{SFG} = d_{eff}^2 L^2 P_2 / \pi w_0$ , where  $d_{eff}$ ,  $L$ ,  $P_2$ , and  $w_0$  are the effective nonlinear coefficient, the interaction length, the input pump power at longer wavelength, and the beam radius, respectively. The value of  $d_{eff}$  depends on the crystal. Since LBO and PPKTP have  $d_{eff} = 0.85\text{pm/V}$  and  $d_{eff} = 16.9\text{pm/V}$ , respectively, PPKTP crystal can be expected to have sufficiently high conversion efficiency to 589 nm. However, PPKTP cannot avoid photorefractive damage. For example, surface damage thresholds of PPKTP and LBO are  $4.6\text{GW/cm}^2$  and  $18.9\text{GW/cm}^2$  respectively. Additionally, the optical damage of PPKTP occurs at several hundreds  $\text{MW/cm}^2$  in actually. PPMgSLT is also a periodically poled crystal and its effective nonlinear coefficient is the same as PPKTP. While the surface damage thresholds of PPMgSLT is reported to be  $> 100\text{MW/cm}^2$ , we found that it should be higher than PPKTP in our experiments.

The aperture and length of PPMgSLT are  $0.5 \times 2\text{mm}$  and  $20\text{mm}$ , respectively. The temperature of crystal is set to the optimum one for the quasi-phase matching.

#### 4. LASER DIAGNOSTIC SYSTEM

As mentioned in section 2, our laser is transferred to the laser launching telescope through the optical fiber. An optics for coupling the beam of our laser with the optical fiber is constructed on the optical table on which our laser is installed. The 589 nm laser has two paths after its ejection from laser window in the fiber coupling optics. One is the main path through which the 589 nm laser is coupled with the optical fiber. Two tip-tilt mirrors are arranged on the main path, and they are automatically controlled for reducing the effect of jitter of the beam. The jitter of the beam is detected by two PSDs (position sensitive detectors).

The other path is utilized for measuring the beam quality by ModeMaster(Coherent Inc.) and for excitation of sodium in sodium cell. The spontaneous decay of excited sodium emits the scatter light. The measured intensity of this scattered light is used for adjustment of the wavelength of laser. We call the system consisting of these two paths as laser diagnostic system. The laser power ratio of the two paths is controlled by a  $\lambda/2$  plate and a polarized beam splitter. For avoiding the damage of the fiber, the laser power in the main path is reduced by this power control at the beam alignment for coupling the beam with the optical fiber.

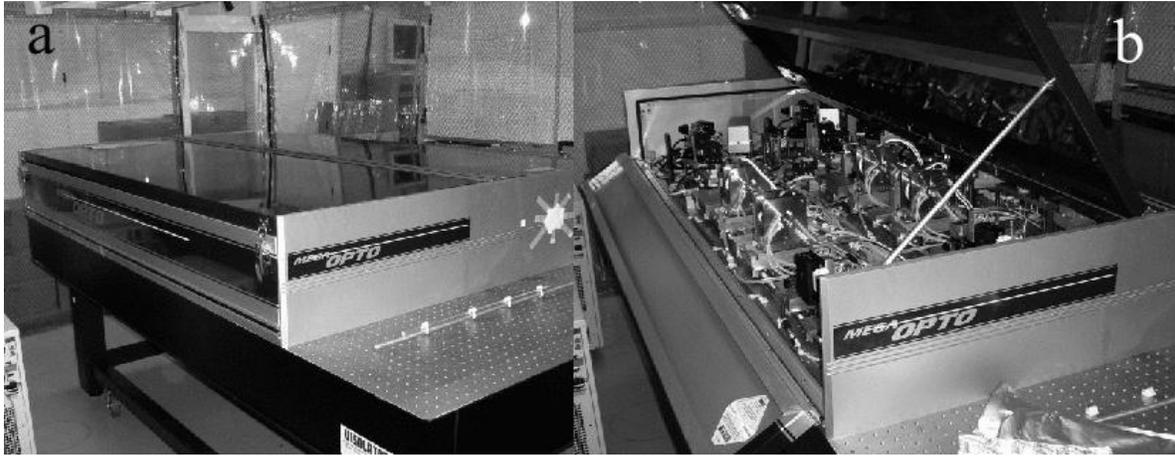
The key role of the laser diagnostic system is the support of our laser system for bringing out its best performances.

#### 5. REMOTE CONTROL SYSTEM

Our laser system is installed on Nasmyth floor of the Subaru telescope. We operate the laser system at the observation room in the control building. We constructed the remote control system for the fine tuning of our laser.

Start-up, initialize, and shutdown of our laser are fundamental functions of the remote control system. Each of these functions have a sequential procedure that is carried out by a few simple commands. The shutdown also interlocks with alarm signals. There is three alarm levels in our laser system. While the alarm message is displayed at the alarm level 1, all shutters of our laser system are closed at alarm level 2. At alarm level 3, all chillers and temperature controllers are also stopped. This shutdown interlock system ensures the safety operation and protects our laser itself.

The remote control system has some components that are controlled at real-time. The output power, wavelength, and direction of the beam are monitored in operation of our laser. If these parameters are out of optimum value, adjustment sequences run at real-time. For example, the temperature of the etalon in the 1064 nm oscillator is controlled based on the monitored intensity of sodium scatter for the real-time fine tuning of the wavelength. The remote control is required for all components of the laser diagnostic system. The acquired parameters in the laser diagnostic system provided to the remote control system of our laser. The remote control system allows us the efficient operation of our laser.



**Figure 5.** The completed our 589 nm SFG laser: a) The package of the laser, b) The inside of the package.

## 6. SUMMARY

Fig.5 shows our 589 nm laser system manufactured by Megaopto Co., Ltd. The dimensions of our laser are  $1970 \times 1200 \times 270$  mm. We have developed our laser improving technical sources and discussing about required specification. We constructed the simple and high-performance oscillator of Nd:YAG lasers, established the method of phase matching of two mode locked laser, realized the fine tuning system of the wavelength, and selected the optimum nonlinear optical crystal. We successfully completed the laser development integrating these technical sources. The specification of our laser is satisfied for our requirement of our laser.

We have already planned to develop  $> 10$ W class laser for application of our development of 4W laser. We plan to introduce MOPA (master oscillator power amplifier) system for achieving 10W power. We must clear the problem of thermal lens that should affect beam quality and mode matching.

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