Development and Demonstration of Australian First Working Sodium Guide Star Laser

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Abstract

The Australian first working sodium guide star laser system has been designed and developed for various astronomical and space-related applications. A completely diode-pumped pulsed system was developed initially followed by a largely fiber-based continuous wave (CW) system operating at 589 nm achieved through a unique wavelength conversion scheme by combining 1342 and 1050 nm through a sum frequency generation process. For the CW system, single-mode laser beams at both 1342 and 1050 nm are achieved from fiber-based seed oscillators and fiber amplifiers. The output power of ~25 W at 1342 nm is achieved from a single frequency fiber Raman amplifier. Output power up to 70 W at 1050 nm is achieved from a Yb-doped fiber pre-amplifier followed by a Yb-doped fiber power amplifier. For the sum frequency generation process, optimum focusing parameters are evaluated and determined. The CW system has generated more than 20 W output power at 589 nm, a circularly polarised beam with a good beam quality, spectral linewidth $\leq$ 2 MHz, and the laser output locked on the sodium D_2 line at 589.159 nm. The system has been successfully demonstrated at EOS Space Research Centre, Mt Stromlo, Canberra, and become the Australian first working sodium guide star laser system.

Keywords

Fiber Laser, Continuous Wave Laser, Pulsed Laser, Diode Pump, Solid State, Sum Frequency Generation, Adaptive Optics, Sodium Laser Guide Star

1. Introduction

More than 60 years after astronomer Horace Babcock proposed the concept of Adaptive Optics (AO) as a method for improving the resolution of astronomical telescopes by compensating optical distortions introduced by the atmosphere,

AO systems have become practical due to significant progress made in laser, optics and sensor technologies. EOS acquired our own 177-channel and 107.6 mm diameter deformable mirror with an integrated tip-tilt stage in 2009. Now most advanced and ground-based large astronomical telescopes such as Gemini North, Gemini South, and Keck are equipped with AO systems in combination with a laser guide star which is the essential part of AO systems. The most efficient laser guide star mechanism has been the resonant scattering from sodium ions in the mesosphere at an altitude of around 90 km with an average thickness of 10 km. An efficient laser operating at the sodium D_2 resonance line close to 589 nm resonantly pumps the sodium ions generating resonance fluorescence and providing a bright artificial beacon.

Laser excitation of the mesospheric sodium layer is a complex matter and has been the subject of extensive studies for guide star applications [1] for many years. The sodium column density in the mesospheric layer is rather low (~5 × 10^{13} atoms/m²) and varies with seasons and locations, the spectral linewidth of the sodium D_2 line is quite narrow, only ~3 GHz [2], and these mean that careful attention needs to be paid to the format and characters of the laser technologies chosen to ensure the efficient photon returns. The amount of resonant photon returns from the sodium layer depends on many factors, including if the laser is pulsed or continuous wave (CW), the spectral linewidth, the beam quality, and the polarization properties, rather than the output power of the laser alone.

The main challenge associated with sodium guide star laser technology is to produce the laser output that is spectrally narrow and stable so it can always stay inside the D_2 line and powerful enough so sufficient photon returns can be generated with a good signal to noise ratio for the wave-front sensors.

A guide star laser program has been initiated within EOS with the primary objective of developing a field-deployable laser system capable of generating efficient laser output at the sodium D_2 line for astronomical and space-related applications. The latest sodium guide star laser developed is a CW system and has achieved more than 20 W output power at 589 nm with the laser output locked on the sodium D_2 line while maintaining a good beam quality inside the temporary enclosure mounted on the telescope. The 589 nm wavelength output is achieved through a unique wavelength conversion scheme by combining 1342 and 1050 nm laser beams through Sum Frequency Generation (SFG) process. In early 2021 the Australian first sodium laser guide star system has been demonstrated successfully at EOS Space Research Centre, Mt Stromlo, Canberra.

In the following sections, the descriptions of the laser, different laser technologies developed, system characterizations, test results and a summary of future plans will be provided.

2. System Design and Performance

2.1. Determination of System Configuration and Gain Media

Trade-off studies between different laser technologies, including diode-pumped

solid-state lasers with pulsed and CW formats, fiber laser, and Optically Pumped Semiconductor Laser (OPSL) have been conducted theoretically and experimentally [3]. The different wavelength or frequency conversion schemes, including an optical parametric oscillator, optical parametric generator, optical parametric amplifier, and SFG have also been investigated either independently or in collaboration with Australian National University [4]. Through these investigations, the efficiency for generating laser output at 589 nm, the effectiveness for generating the maximum photon returns, and the reliability of different laser technologies, including pulsed and CW lasers have been evaluated. The advantages and disadvantages of different types of lasers, wavelength conversions schemes, and approaches have been thoroughly assessed.

The amount of photon returns obtained from the mesospheric sodium layer depends strongly on the polarization property of the laser, *i.e.* if it is circularly or linearly polarized. The sodium ground state is composed of two hyperfine energy levels separated by 1.77 GHz. The excited state is composed of four hyperfine energy levels distributed over a ~100 MHz frequency range. The quantum selection rules indicate optical pumping by circularly polarized light is preferred providing a substantial increase in signal return per watt of transmitted laser power compared with linearly polarized light [5]. Experiments have also demonstrated that circularly polarized light can improve photon returns by a factor of ~2 compared with linearly polarized light [6].

For pulsed laser format factors considered include the appropriate pulse width and repetition rate, the maximum average power that the gain media can handle, the maximum dimensions of the specific types of gain media available on the market, etc. One of the major challenges for developing a pulsed solid-state laser is to allow the system to operate at a high repetition rate and still maintain good beam quality through the correction of thermal-mechanical distortions, including thermal lensing, and depolarization of the solid-state laser gain media, caused by the waste heat deposited into the laser gain media by optical pumping. As a result, Neodymium (Nd) doped Yttrium Aluminium Garnet (Nd:YAG) was chosen as the gain media in the forms of the most advanced solid-state laser configurations: thin disks and composite rods. The thin disks use gain media in the shape of a disk with thickness typically between 100 to 300 μm and composite rods are formed with low Nd-doping concentration central YAG rod with un-doped YAG end caps.

For CW laser format factors considered include key technologies, assemblies, and components that are most advanced but non-proprietary and can be sourced on the market and delivered within a reasonable timeframe. Finally, Nd-doped Yttrium Ortho-Vanadate (Nd:YVO$_4$) and Yb-doped silicate fiber have become the preferred gain media.

The wavelength or frequency conversion scheme adopted for both pulsed and CW laser formats is SFG.

SFG process can be expressed as

$$\omega_1 + \omega_2 = \omega_{out} \tag{1}$$

where ω_1 is the input frequency-1, ω_2 is the input frequency-2, and ω_{out} is the output frequency.

There are several approaches to getting 589 nm output through the SFG process, including single-pass SFG using Periodically Poled MgO-doped Stoichiometric Lithium Tantalate (PP-MgO:SLT) crystals and ring cavity resonant SFG using bulk Lithium Triborate (LBO) crystals. Different approaches have their own advantages. The ring cavity resonant SFG offers higher conversion efficiency (>60%) but requires complex cavity control and single frequency locking electronics. Single-pass SFG offers lower conversion efficiency (30% - 40%) but does not require complex control electronics. We investigated both approaches and adopted single pass SFG using PP-MgO:SLT crystals for both pulsed and CW laser formats.

Generating a sufficient sodium laser guide star depends on the suitable laser format and many other operating parameters of the laser. The laser power needs to be delivered in diffraction-limited beams. In addition to a suitable laser format, many other optical, electronic, and optomechanical technologies and assemblies are required for developing a practical and reliable sodium guide star laser system.

2.2. System Development

So far 2 generations, a completely diode-pumped pulsed system, and a largely fiber-based CW system have been designed, developed, and tested. The pulsed system can provide a broader spectral linewidth and the CW system offers higher output power with narrower spectral linewidth.

2.2.1. A Completely Diode-Pumped Pulsed System

~15 years ago in the AO and guide star laser communities there was a strong belief that CW lasers tend to saturate the sodium ions easily and are not good for generating efficient photon returns if the spectral linewidth is less than 20 MHz. While one of the natures of pulsed lasers is that they normally provide broader spectral linewidth so it was believed that they should be resistant to saturation and should be able to return more signal photons per watt of transmitted laser power than that obtained using CW lasers [7] [8]. Under those influences, EOS started with developing a completely diode-pumped pulsed laser system based on direct sum frequency mixing of the two spectral lines of Nd:YAG at 1064 and 1319 nm to generate the light at 589 nm. This approach uses a fluke of nature in that two gain lines in Nd:YAG, the 1064 and 1319 nm lines, are almost perfect for sum frequency mixing to produce laser emission at 589 nm. It formed the basis of an all solid-state system amenable to diode laser pumping using one of the most mature solid-state laser materials—Nd:YAG. It was therefore quite attractive for this application. Following technologies and assemblies were designed, developed, tested, and comprehensively evaluated by EOS:

- 2 actively mode-locked laser oscillators with 100 MHz frequency generating output at 1064 and 1319 nm respectively,
- Spectral line width selection,
- Wavelength tuning and stabilization,
- Single frequency monitoring, stabilization, and locking on the sodium spectral absorption line using the linear magneto-optics technique,
- Timing stabilization assembly for improving the temporal overlapping of two laser pulse trains at two laser wavelengths,
- Beam pointing stability control assembly for improving the spatial overlapping of two laser beams at two laser wavelengths.

It is well known that the 1319 nm spectral line of Nd:YAG is of low gain. It has an emission cross-section of $\sim 0.95 \times 10^{-19}$ cm^2 [9] so a lot of pump radiation is transferred into heat in the process of generating 1319 nm output which leads to issues such as thermal lensing, thermally induced birefringence, and depolarization in the gain media for the 1319 nm oscillator and amplifiers. The thermal lensing, birefringence, and depolarization lead to beam wander. The beam wanders consequently makes the SFG process difficult. In order to address these issues, several rounds of investigations and experiments, including developing oscillators and amplifiers for 1319 nm spectral lines using the most advanced solid-state laser technologies, thin disks, and composite rods have been conducted. Experiments to evaluate and compare the performance of thin disk and composite rod based oscillators and amplifiers to see which one is the best for effectively compensating and minimizing the birefringence and depolarisation, efficient power generation, and producing the best beam quality for 1319 nm spectral line with minimal beam wander have also been conducted.

A series of 10 mm diameter single crystal and ceramic Nd:YAG thin disks with Nd-doping concentration between 1.3% to 4%, and disk thickness between 100 to 150 μm have been designed, manufactured, and tested.

Several types of composite Nd:YAG rods—2 mm and 3 mm diameters with different barrel finishes, such as micro-scratches barrels have been investigated and it has been found that the amount of thermal lensing, birefringence, depolarisation, and consequently the amount of beam wander increased with the increase of the diameter of the composite rods. For achieving higher output power a larger diameter of the gain media is required because of the surface damage threshold which is measured in terms of power density, W/cm^2. On the other hand, a larger diameter would make the thermal lensing, birefringence, depolarisation, and consequently the beam wander worse.

Both the 2 mm and 3 mm diameter Nd:YAG rods were actively cooled using deionized water flowing longitudinally. For the composite rods, it is important to have the sealing O-rings holding the un-doped YAG end caps.

It has been concluded that the composite rods are the best for effectively compensating and minimizing the birefringence and depolarisation, efficient power generation, and producing the best beam quality for the 1319 nm spectral

line. A mode-locked laser oscillator based on 3 mm diameter composite ceramic rods that were longitudinally pumped was designed, assembled, and tested. Stable power output with good beam quality has been obtained at 1319 nm.

For the 1064 nm spectral line which has a much higher gain than the 1319 nm line, a mode-locked oscillator based on 2 mm diameter conventional rods that were side pumped was designed, assembled, and tested.

The output beams at 1319 and 1064 nm were aligned and mixed at the PP-MgO:SLT SFG crystal in a single pass configuration.

Following beam quality results in terms of M^2-value for 1319, 1064 and 589 nm beams have been obtained:

1319 nm:	M_X^2 : 1.10	
	M_Y^2 : 1.00	
1064 nm:	M_X^2 : 1.00	
	M_Y^2 : 1.06	
589 nm:	M_X^2 : 1.27	
	M_Y^2 : 1.14	

More than 4 W output power at 589 nm with ~25% conversion efficiency from the IR inputs (1319 and 1064 nm) to 589 nm output has been achieved. The laser output had the micro-pulse format—trains of 600 picosecond duration pulses separated by 10 ns. The spectral linewidth of the laser was ~600 MHz. Precise wavelength measurement and wavelength tuning using etalon were performed. A correct sodium absorption line profile was observed. Resonant fluorescence was observed at 589.158 nm in the vacuum. The key system specifications achieved are shown in **Table 1**.

Table 1. Key system specifications achieved for pulsed guide star laser.

Parameters	Result Achieved
Output Power (W)	≥4
Spectral Linewidth (MHz)	600
Micro Pulse Width (ps)	600
Micro Pulse Separation (ns)	10
Resonant Fluorescence Observed in Vacuum (nm)	589.158
Beam Quality @ 589 nm	M_X^2 : 1.27 M_Y^2 : 1.14
System Conversion Efficiency	25%

2.2.2. A Largely Fiber-Based CW System

Following the investigations and experiments on the pulsed laser system, it has been concluded that the output power from the 3 mm diameter gain media is adequate for generating ~10 W pulsed output at 589 nm when the beam wander can be adequately controlled using the beam pointing stability control assembly. Average output power higher than 10 W at 589 nm has been achieved by a few

groups with similar configurations but generally with poor stability and most importantly the output power degraded rapidly with time. When stable and reliable system performance with output power much higher than 10 W at 589 nm is required a more efficient gain medium that should have a higher gain around 1300 nm should be considered so less heat is generated which leads to less thermal lensing, less birefringence, less depolarization, and minimum beam wander.

Nd:YVO$_4$ has been identified as the new gain medium. It has an emission cross-section of ~6×10^{-19} cm^2 at 1342 nm [10] [11], much higher than that of Nd:YAG (~0.95×10^{-19} cm^2) at 1319 nm. SFG process ($\omega_1 + \omega_2 = \omega_{out}$) requires the input wavelength-2 to be 1050 nm when the input wavelength-1 is 1342 nm in order to achieve an output wavelength of 589 nm. Fortunately, 1050 nm is within the gain profile of Yb-doped silicate fiber which has been widely used as the gain fiber for high power fiber lasers and amplifiers. Adopting Yb-doped silicate fiber as the gain material for 1050 nm also laid a solid foundation for developing a high efficiency fiber laser and amplifier chain. Based on the above considerations a unique wavelength conversion scheme by combining 1342 and 1050 nm laser beams through the SFG process to achieve 589 nm output, as shown in Figure 1 has been proposed.
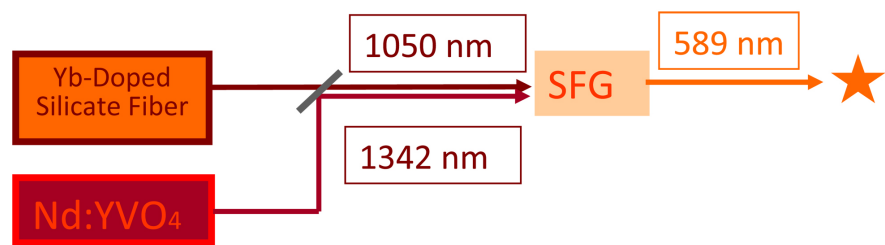

Figure 1. Unique wavelength conversion scheme.

In the last 10 years or so there have been a lot of investigations done on photon returns from the mesospheric sodium layer excited by different laser formats, including pulsed and CW lasers with different output power and spectral linewidths. Predicting photon returns from a sodium guide star laser depends on a lot of complex atomic physics which involves multiple and hyperfine energy levels and transitions, thermalization of sodium atoms by collision, saturation, etc. Theoretical studies and experimental investigations have proven that the high beam quality single-mode CW lasers are more efficient than most of the multi-mode and pulsed lasers [12] [13]. There has been a certain level of saturation observed when the sodium layer is excited by single-mode CW lasers but the level of saturation is not as significant as theoretically predicted previously [14].

Based on the theoretical studies and experimental investigations, it has been decided to develop a high beam quality single-mode CW laser system with narrow spectral linewidth based on the new wavelength conversion scheme of converting 1342 and 1050 nm wavelength beams to 589 nm laser output. The system schematic is shown in Figure 2.
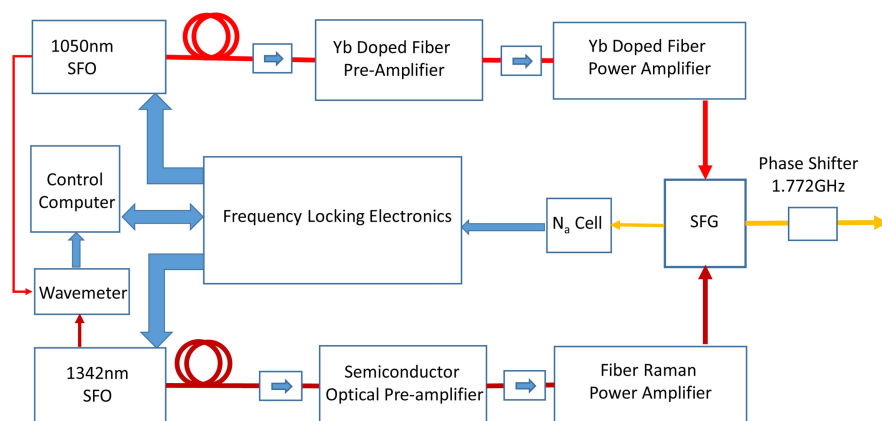
Figure 2. Laser system schematic.

For the 1342 nm wavelength branch, the single frequency seed oscillator using Nd:YVO$_4$ as the gain medium with a spectral linewidth ≤ 2 MHz was accommodated in a temperature-controlled environment. Its output was coupled into a semiconductor pre-amplifier through a 50 m long optical fiber. The output from the pre-amplifier was then coupled into a single frequency fiber Raman amplifier through a fiber link. This branch was capable of generating up to 25 W output power at 1342 nm in a single-mode beam.

For the 1050 nm wavelength branch the single-frequency seed oscillator with a spectral linewidth < 100 kHz was also accommodated in a temperature-controlled environment with the output coupled into a Yb-doped fiber pre-amplifier followed by a Yb-doped fiber power amplifier through a 50 m long fiber. This wavelength branch can generate up to 70 W output power at 1050 nm in a single-mode beam.

Priority has been given to improving the conversion efficiency from the fundamental wavelength beams at 1342 and 1050 nm to SFG output at 589 nm. For these kinds of nonlinear conversion processes, the main challenge is to achieve good temperature uniformity along the nonlinear crystals as otherwise, we would not be able to properly phase match the nonlinear interactions. Good thermal contacts between the nonlinear crystals and their mounts are also very important for ensuring that the phase-matching conditions can be maintained across the whole length of the crystals. Different mounting mechanisms with copper, Indium foil, and thermally conductive adhesives were designed, developed, and tested. Optimal mounting mechanism using copper as the base material and spring plate which can regulate the pressure applied on the thin PP-MgO:SLT crystals with different dimensions was finally determined and used. In the whole process, there has been no thin nonlinear crystal broken.

Theoretically, the optimum length of the nonlinear crystal is determined by several factors including the amount of absorption and loss. However in practice the design and development of PP-MgO:SLT crystals have reached the limit of existing technologies and can only be supplied by very few suppliers in the world. PP-MgO:SLT crystals that could be developed with good yield are normally quite

thin, 0.5 - 1 mm and the longest length is 30 mm. We used a dual-stage SFG approach in order to get the best phase-matching conditions along the PP-MgO:SLT crystals and the best possible conversion efficiency. For the 1st stage SFG the length of the PP-MgO:SLT crystal is 30 mm and for the 2nd stage SFG the length of the PP-MgO:SLT crystal is 24 mm. Both crystals have a Quasi-Phase-Matching (QPM) period of 10.75 μm and a theoretical phase-matching temperature of ~95˚C. Different beam diameters for λ_1 = 1342 nm and λ_2 = 1050 nm beams and the required beam collimation and mode matching optics were designed and evaluated. Focusing the beams into different positions inside the crystals was theoretically modeled and tested in order to find the optimum power density inside the PP-MgO:SLT crystals while avoiding overheating the nonlinear crystals and consequently destroying the phase-matching conditions.

Theoretically, for sum frequency generation process using focused Gaussian beams, the optimal focusing condition is defined as the focusing parameter [15], and given by:

$$\xi = \frac{L}{b_1} = \frac{L}{b_2} \tag{2}$$

where L is the length of the nonlinear crystal, b_1 and b_2 are the confocal parameters of the input beams inside the nonlinear crystals which are measures of the length of the focal region and are given by:

$$b_1 = \frac{2\pi n_1 W_{10}^2}{\lambda_1} \tag{3}$$

$$b_2 = \frac{2\pi n_2 W_{20}^2}{\lambda_2} \tag{4}$$

where n_1 and n_2 are the refractive indexes, W_{10}, and W_{20} are the beam waist radius at λ_1 = 1342 nm, and λ_2 = 1050 nm. An optimum focusing parameter, ξ_m = 2.84 has been determined by G. D. Boyd and D. A. Kleinman [15]. With a crystal length L = 30 mm, a series of beam waist diameters were calculated against different focusing parameters, from 1 to 4, as shown in **Figure 3** below.

Optimal beam waist diameters, $2W_{10}$ = 65.2 μm at 1342 nm and $2W_{20}$ = 57.5 μm at 1050 nm were achieved with optimum focusing parameter ξ_m = 2.84 indicated by the arrow in **Figure 3**. For the 1st stage SFG, the beam waist diameters, $2W_{1342}$ = 68 μm, $2W_{1050}$ = 56 μm measured using a camera resulted in the best power output. Considering the experimental accuracy and measurement errors the measured results agree very well with the theoretically predicted values. For the 2nd stage SFG beam diameters at 1342 and 1050 nm are basically the same as the 1st stage. Different phase matching temperatures for 2 stages of SFGs were also tested with the optimal phase-matching temperatures of 96.2˚C for the 1st stage and 88.6˚C for the 2nd stage identified.

Totally 20 W at 589 nm has been achieved including the contributions from 2 stages of SFG: 1st stage: 15 W, 2nd stage: 5 W. The overall system conversion efficiency from the fundamental wavelength laser beams at 1342 and 1050 nm to
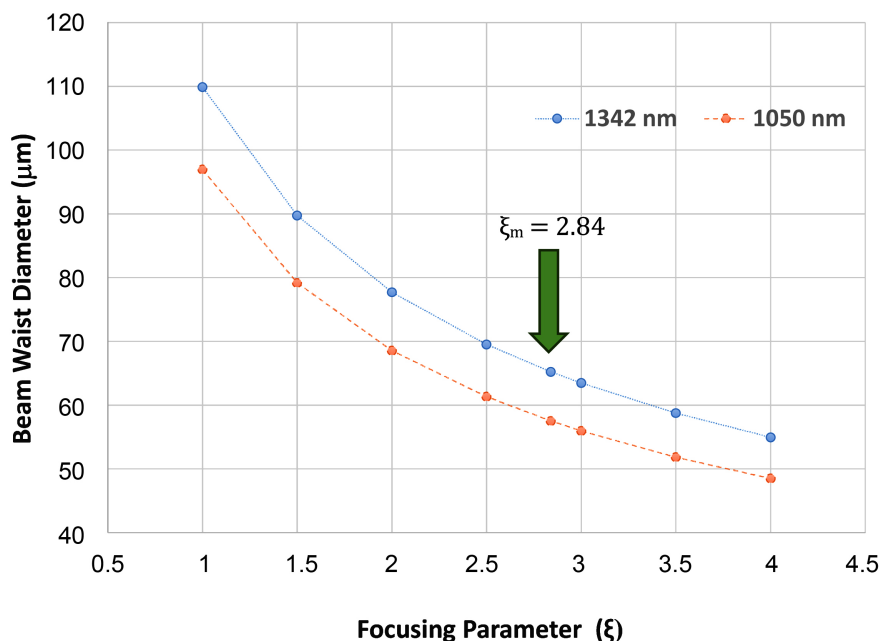
Figure 3. Beam waist diameter.

SFG output wavelength 589 nm is 36.2%.

Our CW sodium guide star laser has achieved all the key specifications as shown in **Table 2**.

Table 2. Key system specifications achieved for CW guide star laser.

Parameters	Result Achieved
Output Power (W)	≥20
Spectral Linewidth (MHz)	≤2 MHz
Resonant Fluorescence Observed in Vacuum (nm)	589.159
Beam Size (Diameter at $1/e^2$ Intensity Point, mm)	2.8
Polarization	Circular
System Conversion Efficiency	36.2%

The CW system using $Nd:YVO_4$ as the gain medium for the single frequency seed oscillator was designed and developed for system evaluation and testing during the early stage of the project. Later when a more advanced technology—External Cavity Diode Laser (ECDL) with a built-in grating has become available on the market we replaced the $Nd:YVO_4$ based seed oscillator with an ECDL generating output at 1342 nm with a spectral linewidth ≤ 2 MHz so both 1342 and 1050 nm branches have become fully fiber-based.

3. System Performance and Demonstration

In addition to achieving more than 20 W output power at 589 nm, resonant fluorescence has been observed at 589.159 nm in the vacuum. The laser output has

also been locked on the sodium D_2 line. As shown in Figure 4, strong resonant fluorescence has been observed from the reference sodium cell.
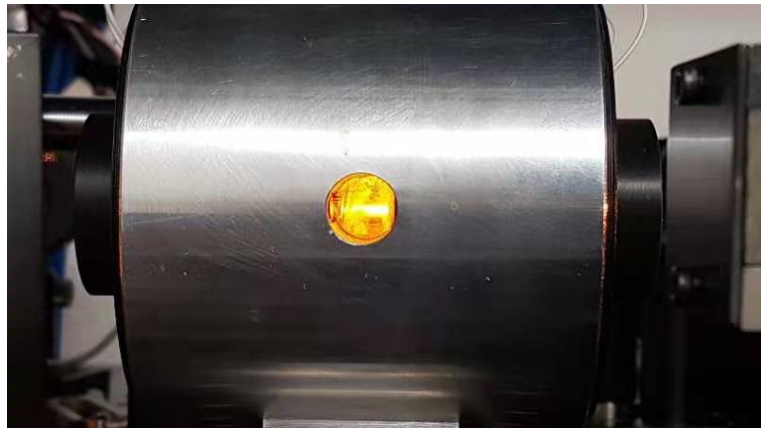

Figure 4. Resonant fluorescence observed from the reference sodium cell.

After achieving the key specifications in the laboratory the laser system has been moved to a temporary enclosure mounted on the telescope. In March and April 2021 the Australian first sodium laser guide star system has been successfully demonstrated at EOS Space Research Centre, Mt Stromlo, Canberra, as shown in Figure 5.

Figure 5. Australian first sodium laser guide star at Mt Stromlo.

4. Conclusion

A primarily fiber-based CW sodium guide star laser system operating at 589 nm has been successfully designed and developed following more than 10 years of theoretical and experimental investigations on different laser technologies with pulsed and CW formats with the primary objective of developing a field-deployable sodium

guide star laser system for astronomical and space-related applications. As a sodium guide star laser it has generated more than 20 W output power at 589 nm, a circularly polarised beam, spectral linewidth ≤ 2 MHz with the laser output locked on the sodium D_2 line at 589.159 nm, and achieved all the design specifications and performance objectives. The system has been successfully demonstrated at Mt Stromlo, Canberra, and become the Australian first and only working sodium guide star laser system.

5. Future Plan

At the moment the limiting factor for generating more power at 589 nm is the output power of the 1342 nm wavelength branch which is 25 W. The output power of the single-frequency Raman amplifier is going to be upgraded to 30 W. The output power from the 1050 nm wavelength branch can reach more than 70 W. Theoretical simulations show that with 30 W power at 1342 nm and more than 70 W at 1050 nm, we will be able to achieve 25 W output power at 589 nm through single pass SFG using PP-MgO:SLT crystals. With 30 W at 1342 nm and more than 70 W at 1050 nm, we will be able to achieve at least 40 W output power at 589 nm through ring cavity resonant SFG using bulk LBO crystals.

Studies on the optimization of sodium laser guide star efficiency suggest that the sodium photon returns can be boosted by simultaneous excitation (re-pumping) of D_{2a} and D_{2b} lines [16]. A sideband with a frequency separation of ~1.77 GHz and ~10% of the total laser output power will be generated using a phase modulator for re-pumping the D_{2b} line.

Priority will be given to propagating the 589 nm laser beam through the beam transfer optics and characterizing the laser guide star in the sky as a part of the AO system. The laser beam quality in the laser enclosure, after transmitted through the beam transfer optics, the spot size of the sodium laser guide star, and the consequent photon returns will be comprehensively investigated.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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