From Dye Laser Factory to Portable Semiconductor Laser: Four Generations of Sodium Guide Star Lasers for Adaptive Optics in Astronomy and Space Situational Awareness

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ABSTRACT

This paper recalls the history of sodium guide star laser systems used in astronomy and space situational awareness adaptive optics, analyzing the impact that sodium laser technology evolution has had on routine telescope operations. While it would not be practical to describe every single sodium guide star laser system developed to date, it is possible to characterize their evolution in broad technology terms. The first generation of sodium lasers used dye laser technology to create the first sodium laser guide stars in Hawaii, California, and Spain in the late 1980s and 1990s. These experimental systems were turned into the first laser guide star facilities to equip medium-to-large diameter adaptive optics telescopes, opening a new era of Laser Guide Star Adaptive Optics (LGS AO)-enabled diffraction-limited imaging from the ground. Although they produced exciting scientific results, these laser guide star facilities were large, power-hungry and messy. In the USA, a second-generation of sodium lasers was developed in the 2000s that used cleaner, yet still large and complex, solid-state laser technology. These are the systems in routine operation at the 8 to 10m-class astronomical telescopes and 4m-class satellite imaging facilities today. Meanwhile in Europe, a third generation of sodium lasers was being developed using inherently compact and efficient fiber laser technology, and resulting in the only commercially available sodium guide star laser system to date. Fiber-based sodium lasers will be deployed at three astronomical telescopes and one space debris tracking station in the next couple of years. Although highly promising, these systems remain significantly expensive and they have yet to demonstrate high performance in the field. We are proposing to develop a fourth generation of sodium lasers: based on semiconductor technology, these lasers could provide a definitive solution to the problem of sodium LGS AO laser sources for all astronomy and space situational awareness applications.

1. SODIUM LASER GUIDE STAR ADAPTIVE OPTICS

Sodium Laser Guide Star Adaptive Optics (LGS AO) is a technique that compensates for wavefront aberrations created by atmospheric turbulence in real time. It has been used in astronomy to restore the diffraction limit of large ground-based telescopes, and in Space Situational Awareness (SSA) applications to improve imaging of satellites and laser tracking of space debris. This paper discusses the use and availability of sodium laser sources in the field of sodium LGS AO for astronomy and SSA applications.

The principles of Adaptive Optics (AO) were first described in 1953 by Horace Babcock [1]. AO use an adaptive optical component (typically, a deformable mirror) that changes shape in real-time to compensate for optical distortions measured by a wavefront sensor. Accurate, fast measurements require bright sources to yield high enough signal-to-noise ratios for the AO system to perform optimally. In astronomy, Natural Guide Star (NGS) AO systems use a star or star-like astronomical source located at or near the science object as the bright reference source. The idea to create an artificial star to probe the atmosphere when no NGS is available in the vicinity of the science object was first published in 1985 by Foy and Labeyrie [2]. This idea consists of using a laser pointed in the direction of the science object to create a Laser Guide Star (LGS).

There are two types of LGS: "Rayleigh" guide stars, and "sodium" guide stars. Lasers of many wavelengths can be propagated and focused at relatively low altitudes (10-20 kms) where the atmosphere is dense enough to create so-called "Rayleigh" guide stars. Rayleigh guide star AO systems use the light backscattered by the atmosphere in the direction of the observing telescope as their LGS. Popular wavelengths to create Rayleigh guide stars are green (typically 532 nm), which many affordable laser systems can produce, and ultra-violet (typically 355 nm), which offer the added advantage of eye-safe outdoor laser propagation. Alternatively, a yellow laser specifically tuned to the sodium D2 line at 589 nm can be used to excite mesospheric sodium atoms located at 85-100 kms above sea level to create a "sodium" LGS. Because sodium LGS provide higher altitude reference sources to probe the atmosphere, this technique is favored by large aperture astronomical telescopes (8 meter diameters and above) working in the near infra-red, and SSA applications using smaller diameter telescopes (1.5-2.0 meter) but also working at shorter wavelengths. In both cases high altitude sodium LGSs are required to minimize focus anisoplanatism (also called the "cone effect") and enable medium-to-high AO-corrected Strehl ratios.

In 1987 Thompson and Gardner created the first sodium LGS above the summit of Mauna Kea in Hawaii [3]. To demonstrate the feasibility and suitability of sodium LGS in astronomy, they used a sodium Light Detection and Ranging (LIDAR) laser system owned by the University of Illinois Urbana-Champaign that was normally used for atmospheric physics experiments, and the University of Hawaii 0.6 meter and 2.2 meter telescopes to respectively launch the laser beam and image the resulting sodium guide star. Their work was published in Nature in 1987, at a time when the US Air Force was getting ready to conduct the first, classified LGS AO experiments at the Starfire Optical Range at Kirtland Air Force Base in Albuquerque, New Mexico [4]. Given the similarities between civilian and military pursuits to achieve LGS AO corrected images of astronomical and space objects, the results of military AO experiments were declassified in the early 1990s, opening up a new era of laser-guided AO systems for astronomy and SSA applications.

In [4], Thompson recalls: "*The Thompson and Gardner experimental work -- plus engineering design calculations by Thompson, Gardner, and Gardner's students showing the feasibility of building laser guided systems -- provided the basis for several proposals to the National Science Foundation for funding to move ahead with the construction of such a system. The first Thompson & Gardner NSF proposal was submitted in Fall 1987. Reviewers turned it down. The second Thompson & Gardner NSF proposal was submitted in Fall 1988. Again, reviewers turned it down. Both years there were many excuses cited for doing so. The only comment of substance was the fact that* ***the ideal sodium laser was not available*****.**"

In the nearly 30 years since the first sodium LGS was demonstrated, a large number of astronomical and SSA observatories have developed experimental as well as facility LGS AO capabilities. Although a variety of sodium guidestar laser technologies have been investigated and developed to date, the same concern about sodium guidestar laser sources still remains today. Over the years, different sodium laser technology choices have been made based on the maturity versus perceived potential of old and new technologies, the availability of critical laser components, development costs, perceptions of laser system ease of operation and maintenance costs, historical affinities of LGS AO scientists with certain technologies, geo-political constraints, and our evolving understanding of the sodium/light interaction physics. For a detailed understanding of the sodium/light interaction physics and their historical impact on sodium laser technology choices, please refer to [8-21].

Sections 2, 3, and 4 below provide an overview of the first three generations of sodium guidestar laser technologies (liquid dye, solid-state with bulk optics, and fiber laser technologies) that have been used at civilian and military observatories around the world in the period 1987-2015, and those that have already been selected for field installation in the coming years. For comparison purposes, Table 1 provides a snapshot of the technical and operational characteristics of these systems. Minimal details about the laser system architectures are reported in the table and text, but references provided throughout sections 2, 3, and 4 include detailed information about the laser design architectures and developments, associated LGS facilities, and LGS AO system performance and science results.

So far past efforts made toward commercialization of sodium guidestar laser sources based on the first three generations of laser technologies have had very mixed success, with the notable exception of the Raman fiber laser approach described in greater details in section 4.2. Section 5 presents the rationale for developing a fourth generation of sodium guidestar lasers based on semiconductor technology. The section details the current state of the art for semiconductor lasers operating at the sodium wavelength (589 nm), and the reasons why this technology promises to be vastly superior to other technologies in terms of cost, size, and ease of operation. On-going work and plans to develop and test a guidestar semiconductor laser prototype as a first step towards commercialization are also presented.

Table 1. Technical and operational characteristics of sodium guidestar laser systems.

Laser System	**Technology**	**Output Power**	**CW or Pulse Length (Repetition Rate)**	**Spectral Bandwidth**	**Location**	**On-Sky/Lab Experiment (Year) or Facility (Years of Operation)**	**References**
U. of Illinois LIDAR	Pulsed dye		Pulsed		Mauna Kea, Hawaii, USA	On-Sky Experiment (1987)	3
AVLIS LLNL laser	Pulsed dye	1100 W	Pulsed		Livermore, California, USA	On-Sky Experiment (1994)	22, 23
Lick dye laser	Pulsed dye	9-12 W	150 ns (11 kHz)	2 GHz (EO modulated)	3m Shane Telescope, Lick Observatory, Mount Hamilton, California, USA	Facility (1996-Present)	21, 24, 25, 26
Keck II dye laser	Pulsed dye	12-15 W	100 ns (26 kHz)	2 GHz (EO modulated)	Keck II Telescope, W. M. Keck Observatory, Mauna Kea, Hawaii, USA	Facility (2001-2015)	27, 28
U. of Chicago dye laser	CW dye	1.2 W	CW		Yerkes Observatory, Wisconsin, USA (1992), and 6.5m Multi-Mirror Telescope, Mount Hopkins, Arizona, USA (1993)	On-Sky Experiment (1992 and 1993)	29, 30, 31
ALFA laser	CW dye		CW		3.5m Telescope, Calar Alto Observatory, Spain	Facility (1996-2001)	32
PARSEC	CW dye		CW		ESO 8m Unit Telescope 4, Paranal Observatory, Chile	Facility (2006-2013)	34, 35, 36
MIT-LL laser	Flash Lamp-Pumped Solid State	2.5 W	Micro-macro pulsed (10 Hz)		N/A	Lab Experiment (1991)	37
U. of Chicago sum-frequency laser	Diode Pumped Solid State	8 W	Macro pulses: 150 μs (400 Hz) Micro pulses: 1 ns (100 MHz)	1 GHz	3.5m ARC Telescope, Apache Point Observatory (1995), and Vacuum Tower Telescope, Sacramento Peak (1997), New Mexico, USA 5.1m Hale Telescope, Palomar Observatory, California, USA (2005-2010)	On-Sky Experiment (1995 and 1997); Facility (2005-2010)	29, 38, 39, 40, 41
TMT lasers	Diode Pumped Solid State	16 W	Micro-macro pulses: 120 μs (500 Hz)	0.4 GHz	1.8m Telescope, Yunnan, China (2011) TMT, Hawaii, USA	On-Sky Experiment (2011) Facility (2020+)	42, 43, 44

SOR lasers	Diode Pumped Solid State	20 W and 50 W	CW	10 kHz	3.5m Telescope, Starfire Optical Range, Kirtland Air Force Base, New Mexico, USA	Facility (2003-Present)	46, 47, 48
Gemini North laser	Diode Pumped Solid State	12 W	CW mode-locked: 0.7 ns (76 MHz)	550 MHz	Gemini North 8m Telescope, Hawaii, USA	Facility (2005-Present)	51, 52
Keck I laser	Diode Pumped Solid State	20 W	CW mode-locked: 0.4 ns (77 MHz)		Keck I Telescope, Hawaii, USA	Facility (2011-Present)	53
Gemini South laser	Diode Pumped Solid State	50 W	CW mode-locked: 0.4 ns (77 MHz)	2.1 GHz	Gemini South Telescope, Chile	Facility (2011-Present)	54
Subaru laser	Diode Pumped Solid State	5 W	CW mode-locked: 1.0 ns (143 MHz)	1.7 GHz	Subaru 8m Telescope, Hawaii, USA	Facility (2006-Present)	55
LLNL fiber laser	Fiber sum-frequency laser	3-4 W in 2006 [57] (10 W later reported in [21])	CW or pulsed with 3 μs pulses (17 kHz) [57] or 200 ns pulses (500 kHz) [21]	1.8 GHz reported in [21] for 10 W pulsed laser with 200 ns pulses at 10% duty cycle	3m Shane Telescope, Lick Observatory, Mount Hamilton, California, USA	Lab Experiment (2006-Present); Facility (2016+)	21, 26, 57
EOS fiber laser	Fiber sum-frequency laser		CW		EOS laser tracking station, Mount Stromlo Observatory, Australia	Lab Experiment (2011-Present); Facility (2016+)	59
ESO PARLA fiber laser	Raman fiber laser	20 W	CW	550 MHz (EO modulated)	ESO 8m Unit Telescope 4, Paranal Observatory, Chile	Facility (2013-Present)	61, 62
ESO 4LGSF fiber lasers (Toptica)	Raman fiber laser	20 W	CW	5 MHz	ESO 8m Unit Telescope 4, Paranal Observatory, Chile	Facility (2015+)	63, 64, 65
E-ELT fiber lasers (Toptica)	Raman fiber lasers	20 W	CW	5 MHz	39m European Extremely Large Telescope, Chile	Facility (2020+)	61
Keck II fiber laser (Toptica)	Raman fiber laser	20 W	CW	5 MHz	10m Keck II Telescope, Hawaii, USA	Facility (2015+)	
GMT lasers (Toptica)	Raman fiber lasers	20 W	CW	5 MHz	25m Giant Magellan Telescope, Chile	Facility (2020+)	66

2. LIQUID DYE LASERS

2.1 Pulsed Dye Lasers

Studied and developed since the beginning of lasers some 50 years ago, liquid dye lasers were by far the most mature technology option for sodium light generation when in 1987 Thompson and Gardner sought to demonstrate the first sodium LGS in the history of LGS AO. The laser they used was a pulsed dye laser originally built by the University of Illinois Urbana-Champaign for use in mesospheric sodium LIDAR measurements [3]. A picture of the sodium LGS that was produced is shown in [4]. Over the years subsequent incarnations of the University of Illinois LIDAR laser system have been deployed at various other sites (e.g. at the Starfire Optical Range in New Mexico in 1994 and in 1997-2000 [5], on Mount Haleakala in Maui, Hawaii, in 2000-2005, and near Cerró Pachon in Chile from 2008 to Present [6-7]) to perform sodium layer monitoring campaigns, which have provided sodium abundance information and helped to refine the sodium laser requirements for LGS AO systems at these sites.

Throughout the 1970s, 1980s and 1990s, several billion dollars were invested to develop pulsed dye laser technology for the Atomic Vapor Laser Isotope Separation (AVLIS) program in the USA [22]. In 1994, Lawrence Livermore National Laboratory (LLNL) scientists diverted the 1.1 kW LLNL AVLIS dye laser beam to the sky to create the brightest sodium LGS ever over the city of Livermore in California [23]. This spectacular proof of concept paved the way for the design, fabrication, installation, and commissioning by the LLNL guidestar laser team of the first sodium guidestar facility laser at Lick Observatory in California [24]. The Lick dye laser has been operating since it had first light in 1996 [25], and will remain operational until next year when it is to be replaced by the LLNL fiber laser described in section 4.1 [26]. Building on their success, the LLNL team went on to build a second generation pulsed dye laser to be installed on the Keck II telescope in Hawaii [27]. Although large, cumbersome to operate, and messy, akin to a “dye laser factory”, this laser has served the W. M. Keck Observatory well from its first light in 2001 until today (2015) [28]. Later this year the Keck II dye laser will be decommissioned and replaced with the commercial Raman fiber laser described in section 4.2 below.

2.2 Continuous-Wave (CW) Dye Lasers

In the 1990s and early 2000s, smaller dye laser systems based on commercially available pump lasers and modified, commercial continuous wave (CW) dye laser cavities have also been used at various locations for sodium guidestar proof-of-concept experiments, including at the Yerkes Observatory in 1992 [29], and at the Multi-Mirror Telescope in Arizona in 1993 [30-31].

More advanced CW dye laser systems were subsequently developed to equip facility LGS AO systems at astronomical telescopes. In 1996, the Max Planck Institute for Astronomy and for Extra-Terrestrial Physics initiated the commissioning of the ALFA laser system on the Calar Alto Observatory 3.5-meter telescope in Spain [32]. During its five years of semi-regular operation until it was decommissioned in 2001, ALFA demonstrated to the European astronomy community that sodium LGS AO could work [33]. It also made it clear that a combination of higher laser output powers and more efficient laser spectro-temporal profiles to enhance mesospheric sodium photon return were required in order to enable sustainable, routine LGS AO operations at an astronomical observatory.

Lessons learned with ALFA were applied towards developing PARSEC, a second generation CW dye laser system for the European Southern Observatory (ESO) Unit Telescope 4 (UT4) at Paranal Observatory in Chile [34]. PARSEC used a custom dye laser cavity which pushed the limits of what two free flowing jets pumped by two commercial doubled Nd:YAG lasers each could achieve [35]. In 2006 PARSEC created the first sodium LGS in the Chilean skies [36], enabling sodium LGS AO operations at ESO Paranal until 2013 when PARSEC was replaced by the PARLA Raman fiber laser system described in section 4.1 below.

3. SOLID-STATE LASERS WITH BULK OPTICS

The late 1980s and early 1990s saw the emergence of solid-state laser technology. Solid-state lasers held the promise of replacing messy liquid dye lasers, most of which employed flammable solvents and/or carcinogenic dyes both unwelcome at remote telescope locations, with clean, safer laser systems using non-linear crystals to produce sodium light.

3.1 Macro-Micro-Pulsed Sum-Frequency Lasers

The first sodium solid-state laser source was developed as early as 1991 at the Massachusetts Institute of Technology/Lincoln Lab (MIT/LL) [37]. The MIT/LL laser, which combined two flash lamp-pumped Nd:YAG macro-micro pulsed laser beams at 1064 nm and 1319 nm in a non-linear crystal to produce 589 nm, proved the concept of a sodium guidestar solid-state laser viable in the laboratory. MIT/LL went on to develop a second generation of their "sum-frequency laser" for the University of Chicago, this time using diode lasers instead of flash lamps to pump the Nd:YAG laser crystals. The laser was brought to the 3.5-meter ARC telescope at Apache Point Observatory, New Mexico, where in 1995 it was successfully tested on the sky as part of the Chicago Adaptive Optics System, ChAOS [38], and later at the NOAO Vacuum Telescope Tower at Sacramento Peak [29, 39]. The University of Chicago developed a third generation sum-frequency laser 4, which was installed at the 5-meter Hale Telescope at Palomar Observatory, California, in 2004. The University of Chicago sum-frequency laser became part of the Palomar Adaptive Optics (PALAO) system for a number of years until it was decommissioned due to budgetary constraints [41].

The Thirty-Meter Telescope (TMT) is currently the only Extremely-Large Telescope (ELT) organization that is planning to use macro-micro-pulsed sum-frequency lasers to create six to nine sodium LGS for the TMT AO system [42] at horizon ~2020 in Hawaii. The TMT sodium guidestar lasers are being developed by the Technical Institute of Physics and Chemistry (TIPC) in Beijing, China [43]. A number of on-sky tests have been performed in China to characterize the sodium photon return from the TIPC sum-frequency laser prototype [44]. Encouraging results from these on-sky experiments indicate that the technology has the potential to meet the TMT sodium photon return requirements as predicted by [20].

3.2 Continuous-Wave Sum-Frequency Lasers

In parallel with the astronomy community's early efforts to develop sodium LGS AO [3], Rayleigh LGS AO experiments were being conducted for the US Defense community at the Starfire Optical Range in Kirtland Air Force Base, New Mexico, using Rayleigh lasers [45]. These experiments confirmed the need for higher altitude LGS if LGS AO systems were to deliver greater AO correction performance for on-going satellite imaging and future space debris tracking applications. A sodium guidestar laser development program was initiated in the early 2000s, which selected a CW sum-frequency laser architecture in order to achieve the highest possible laser output powers and sodium photon returns. A 20 W version was built and commissioned on sky at the SOR in 2003 [46]. A more powerful, second generation CW sum-frequency laser was also developed which delivered 50 W of 589 nm single frequency, diffraction-limited laser output, and produced the highest photon return per Watt of laser power measured to date [47]. In 2006 both lasers were used in a landmark on-sky experiment showing that illuminating the sodium layer with a combination of single frequency laser beams respectively locked to the sodium D2a and D2b lines significantly enhanced the sodium photon return as predicted by simulations [48].

3.3 Continuous-Wave Mode-Locked Lasers

Meanwhile in the early 2000s the Gemini Observatory set out to design and build the first (and to date only) facility Multi-Conjugate Adaptive Optics (MCAO) system for the Gemini South 8-meter telescope in Chile [49]. The Gemini MCAO System (GeMS) required five sodium LGS to operate [13], and Gemini identified the SOR CW sum-frequency laser technology as the technology of choice to meet the sodium photon return specifications for MCAO. The SOR 50 W laser was also the only laser system that had demonstrated output powers beyond 20 W both in the laboratory and on-sky. Multiple attempts were made to transfer the SOR CW sum-frequency laser technology for use by the international Gemini astronomy community, but these attempts failed due to insurmountable ITAR restrictions and IP logistics issues. Had this technology transfer succeeded, the landscape of sodium LGS AO systems in astronomy would probably look quite different today.

The only course of action left to the Gemini Observatory in order to procure a 50 W laser system for the MCAO project was to launch an ambitious, civilian laser research and development program. To that effect, the Gemini Observatory partnered with the NSF-funded Center for Adaptive Optics, the W. M. Keck Observatory, and the US Air Force Research Laboratory, and submitted a white paper proposal to the NSF seeking to develop "Facility Class Guide Star Laser Systems for Astronomical Adaptive Optics". The proposal was successful and in 2004 NSF awarded US$3.3M to the project [50]. Complementary funding and significant in-kind resources were provided by the international Gemini partnership, the Center for Adaptive Optics, the W. M. Keck Observatory, and the US Air Force Research Laboratory. The overarching Gemini laser R&D program enabled the design, fabrication, installation and commissioning of three facility sodium guidestar lasers based on CW mode-locked sum-frequency laser technology developed by Lockheed Martin Coherent Technologies (LMCT) in Colorado: a 14 W laser for the Gemini North 8-meter telescope in Hawaii [51, 52]; a 20 W laser for the Keck I telescope in Hawaii [53]; and a 50 W laser for the Gemini South telescope in Chile [54]. The Gemini North laser was propagated to the sky for the first time in 2005, while the Keck I and Gemini South lasers had their first light six years later in 2011.

In 2002 the 8-meter Subaru telescope in Hawaii also adopted sum-frequency CW mode-locked laser technology as their baseline approach for the Subaru sodium LGS AO system, albeit with a more modest output power goal of 5 W. The Subaru laser was developed in Japan, and installed on the Subaru 8 meter telescope in Hawaii in 2006. The laser has been used for LGS AO observations since 2010 [55].

Nowadays four of the largest astronomical telescopes in the world (Subaru, Gemini North, Gemini South, and the Keck I telescope) offer routine sodium LGS AO science observations enabled by sum-frequency CW mode-locked laser technology. Although this technology has provided significant improvements over CW and pulsed dye laser technologies, it remains too expensive for broad adoption by other, less endowed observatories. Over time, sum-frequency CW mode-locked laser systems have also proved rather difficult to operate and maintain. Most importantly, CW mode-locked laser spectro-temporal formats are showing to be less efficient in exciting sodium atoms than CW single frequency lasers of comparable powers by a factor of ~3 or more [56], thus negating their output power advantage over less powerful but more efficient systems. As a result, both the Gemini South telescope and the Subaru telescope are now looking at the possibility to replace each of their sum-frequency lasers with the commercial Raman fiber laser described in the next section.

4. FIBER LASERS

Fiber lasers provide an appealing technology avenue to develop sodium guidestar lasers, due to their excellent beam quality, inherent sturdiness, and user friendliness once the corresponding fiber technology has reached full maturity. A number of technical approaches have been investigated which are described below.

4.1 Sum-Frequency Fiber Lasers

In ~2003, the Lawrence Livermore National Laboratory (LLNL) started to investigate an all-fiber sodium guidestar laser system architecture combining a 1583 nm beam with a 938 nm beam in a periodically poled stoichiometric lithium tantalate (PPSLT) non-linear crystal [57]. Although a number of technical and funding difficulties have slowed down the development of the LLNL fiber laser over the years, the system is now producing 10 W of pulsed output power with 200 ns pulses at 10% duty cycle in the Laboratory for Adaptive Optics at UC Santa Cruz, California. It is expected that the LLNL fiber laser will be installed on the Shane Telescope at Lick Observatory to replace the aging LLNL pulsed dye laser in 2016 [26].

Another type of sum-frequency fiber laser is being developed by EOS Space Systems, Australia, for use in LGS AO-enhanced space debris tracking applications [58]. The EOS fiber laser system combines a 1050 nm beam with a 1342 nm beam in a non-linear crystal to produce 589 nm [59]. The laser will be mounted on the EOS laser tracking station at the Mount Stromlo Observatory near Canberra, to enable LGS AO laser tracking of space debris with the AO Demonstrator bench built by the Australian National University (ANU). Within the framework of the Cooperative Research Centre for Space Environment Management (SERC) [60], SERC participants ANU, EOS Space Systems, and Lockheed Martin Space Systems, are also investigating the possibility to procure a commercial version of the Raman fiber laser described in section 4.2 below. This laser would be installed on the EOS 1.8-meter telescope at Mount Stromlo for use by SERC Research Programs #1 (Tracking, Characterization and Identification of Space Objects) and #4 (Preservation of the Space Environment, i.e. de-orbiting of space debris via photon pressure).

4.2 Raman Fiber Lasers

In 2005, while solid-state laser technologies using bulk optics were being developed in the United States, the European Southern Observatory (ESO) initiated their own research and development program to develop sodium guidestar laser sources based on Raman fiber technology. The approach identified by ESO as the most promising technology to create high power, stable 589 nm output relies on the non-linear Raman effect to convert 1120 nm light into 1178 nm light in a Raman fiber. The 1178nm Raman fiber laser output is then converted to 589 nm via Second Harmonic Generation (SHG) in a non-linear lithium tri-borate (LBO) crystal. Initial experiments were conducted at the ESO headquarters in Garching, Germany, in close collaboration with industry [61]. In 2009, 589 nm output powers in excess of 50 W were demonstrated in the ESO laboratory. ESO went on to develop PARLA, a rugged version of the ESO Raman fiber laser prototype meant to replace PARSEC, the CW dye laser installed on the Very Large Telescope (VLT) Unit Telescope 4 (UT4) at Paranal Observatory. The 20 W PARLA laser was successfully commissioned in 2013 [62].

During that time ESO also entered into a licensing agreement with their industry partners, German laser company Toptica, and Canadian fiber laser company MPB Communications, so that the Raman fiber laser could be fully engineered and produced commercially [63]. ESO procured the first four commercial units of the Toptica "SodiumStar" laser [64] in order to equip the ESO AO Facility on the VLT UT4 with four sodium LGS. The first of the four SodiumStar lasers was propagated over Cerró Paranal earlier this year [65]. Commissioning of the other SodiumStar lasers in the 4LGS Facility is on-going. The SodiumStar laser development effort by Toptica and MPB Communications was led by ESO with collaboration from the W. M. Keck Observatory, the Thirty Meter Telescope (TMT) Organization, the Association of Universities for Research in Astronomy (AURA), and the Giant Magellan Telescope (GMT) Organization, using ESO and National Science Foundation (NSF) funding. Keck Observatory received the fifth Toptica SodiumStar unit in 2014 as part of this collaboration. The Keck SodiumStar laser is expected to replace the Keck II dye laser later this year.

The Toptica SodiumStar laser is currently the only commercially available sodium guidestar laser source. Both the ESO European Extremely Large Telescope (E-ELT), which will have six to eight sodium LGS, and the Giant Magellan Telescope (GMT), which will have six sodium LGS, have adopted Toptica SodiumStars as their baseline sodium guidestar laser option [61, 66]. Commissioning of the E-ELT and GMT LGS facilities are planned sometime during the first half of the next decade (2020s).

5. SODIUM SEMICONDUCTOR LASERS

The 2000s and early 2010s have seen the emergence and rapid development of semiconductor laser technology. Used in combination with non-linear frequency conversion schemes, semiconductor lasers offer new, efficient, scalable laser architectures to create a wide range of IR and visible wavelengths for a large variety of applications (see for instance [67, 68]). Early efforts to produce 589 nm output with semiconductor laser technology have yielded highly promising results [69-71]. This section describes the development status of 589 nm semiconductor lasers, the multiple advantages of these systems over first, second, and third generation sodium guidestar systems, and plans to develop sodium guidestar semiconductor lasers as the fourth generation, and possibly definitive solution for astronomy and SSA LGS AO applications.

5.1 Optically Pumped Semiconductor Laser (OPSL) Technology

Optically Pumped Semiconductor Lasers (OPSLs), also known as Vertical External-Cavity Semiconductor Lasers (VECSELs), have inherent advantages as laser sources for precision spectroscopic applications [70]. Foundry costs to reach new wavelengths are relatively low because OPSLs, grown with Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD), require little post-growth processing. OPSLs require no lateral confinement regions, electrical contacts, or other features across the wafer requiring masks for post-growth processing. Band-gap engineering of the lasing material allows for broad coverage of wavelengths, which can in turn provide wavelengths ranging from infrared to the UV through nonlinea1 frequency conversion [72]. The excellent beam quality and multi-Watt powers at fundamental wavelengths provided by OPSLs make single-step or sequential frequency conversion processes practical. Single spatial and longitudinal mode operation can be achieved with modest optical arrangements [73, 74, 75] and frequency stabilization [76, 77] is achieved using relatively standard techniques.

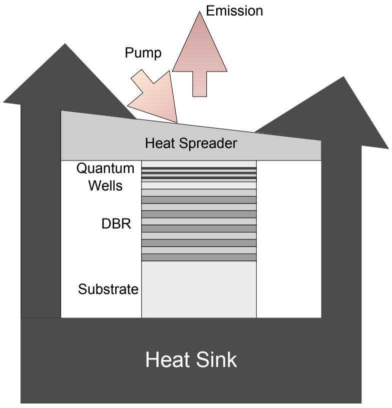

Fig. 1. Schematic of semiconductor gain structure and mounting scheme.

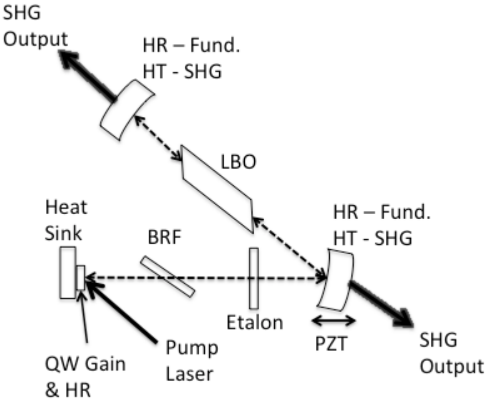

Fig. 2. Three-mirror cavity with frequency selection and second harmonic generation.

A schematic of the semiconductor gain structure (gain chip or gain mirror) is shown in Fig. 1. A high reflectivity Distributed Bragg Reflector (DBR) is grown on a GaAs substrate. A periodic quantum well (QW) gain region is grown on top of the DBR. A diamond heat spreader is bonded to the top of the structure. Pump light enters the structure through the heat spreader.

Thermal management is a key issue for all high power lasers. Heat in a high-power OPSL is generated in a "pancake" with a diameter of approximately 400 microns (the pump beam diameter) and a thickness of a few microns (the thickness of the QW gain region). As in other thin disk lasers this large aspect ratio is conducive to efficient heat removal. Chemical vapor deposition fabricated diamond heat spreaders have excellent thermal and optical properties. Thus most of the heat in the mounted OPSL chip is removed through the diamond at the top of the structure while the optical quality of the cavity is preserved.

The gain mirror is grown by MBE in a fashion to produce gain at 1178 nm [70]. Laser output resonant with the 589 nm wavelength transition in sodium is achieved through intra-cavity frequency doubling using a lithium triborate (LBO) non-linear crystal.

Fig. 2 shows the three-mirror cavity used to produce single-frequency output at the second harmonic of the fundamental laser wavelength. The cavity is similar to the two-mirror fundamental cavity with the addition of an intra-cavity turning mirror, mounted to a piezoelectric transducer (PZT), and a LBO nonlinear crystal, for Second Harmonic Generation (SHG). The cavity is designed to produce a waist at the semiconductor gain chip and also in the LBO. The intra-cavity turning mirror and the output coupler are both high transmission at the SHG wavelength, thus producing SHG output in two directions. A single-beam output can be obtained from this cavity by using a high reflectivity coating for the second harmonic on the output coupler, resulting in a single SHG beam exiting the intra-cavity turning mirror. To maximize the intra-cavity power at the fundamental wavelength the output coupler and intra-cavity turning mirror have high reflectivity at the fundamental wavelength.

Stable single-frequency output is obtained by temperature stabilizing the intra-cavity frequency selective elements (the Birefringent Filter (BRF) and etalon) and by active stabilization of the cavity length. Standard techniques for stabilization and tuning can straightforwardly be applied to the OPSLs. It is worth noting that the short, periodic gain structure in OPSLs eliminates spatial hole burning, which combined with the homogeneous broadening of the QWs means OPSLs can rather easily be made to run single frequency.

5.2 Early Guidestar OPSL Developments

In 2009 Areté Associates received a Small Business Innovation Research (SBIR) grant from the National Science Foundation (NSF) to explore the *feasibility* of OSPLs for LGS applications. That work successfully developed the breadboard, moderate-power (3 W), single-frequency, 589 nm laser described in this section.

The Optoelectronics Research Center (ORC) at Tampere University of Technology in Finland grew the 1178 nm OPSL chips used in the SBIR effort. ORC has been involved in OPSL research for more than 15 years. Other foundries have the necessary equipment and knowledge but lack their depth of experience. Areté has had a successful collaboration with ORC on OPSL development for nine years, producing OPSL chips for a variety of wavelengths, including 1178 nm. Gain materials to be used in future efforts to develop a guidestar OPSL will capitalize on the successful development of materials for the SBIR effort.

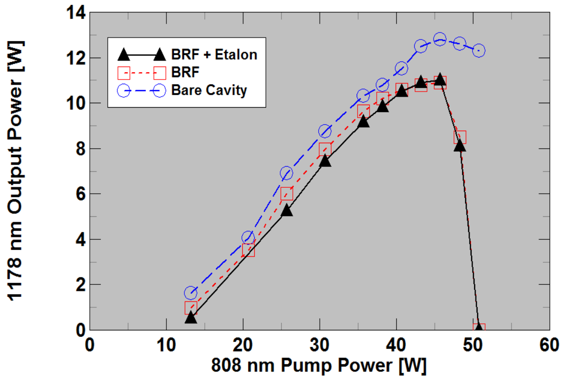

Fig. 3. Output power of the two-mirror fundamental OPSL cavity operating at ~1178 nm. Gain chip cooling water temperature was 15C.

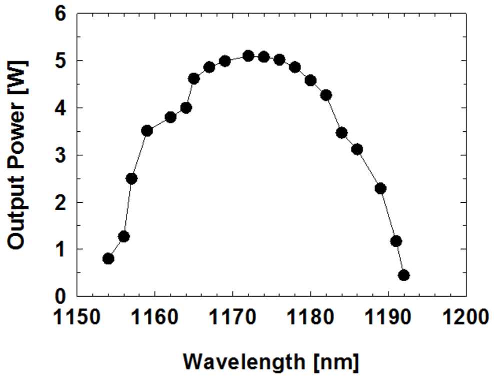

Fig. 4. Output power of the two-mirror cavity tuned in the vicinity of 1178 nm with the birefringent filter.

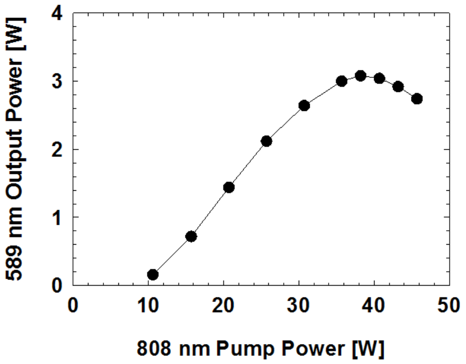

Fig. 5. Output power of the frequency-doubled, three-mirror cavity producing ~589nm.

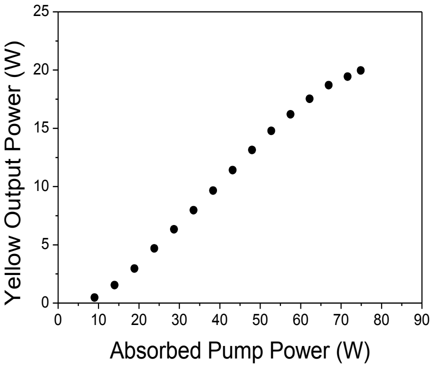

Fig. 6. Recent OPSL results demonstrating 20 W yellow output at 588nm.

The OPSL chip was used in two-mirror and three-mirror laser cavity configurations. The 1178 nm output power of the two-mirror fundamental cavity is shown in Fig. 3 for the bare cavity, cavity with BRF, and cavity with BRF and etalon [70]. The maximum output power, ~12 W, dropped by only ~10% with the addition of intra-cavity elements required for reliable single-frequency operation. The additional optical losses of the BRF and etalon reduce the pump power at which thermal rollover is observed. This is not surprising given the low-gain nature of “vertical” semiconductor lasers - due to the very short gain length of the quantum well structure. Subsequent work using gain chips from the same wafer and lower operating temperatures reported up to 14.2 W of 1178 nm output power with a BRF in the cavity [74].

Fig. 4 shows the broad tuning obtained with the 1178 nm OPSL using a two-mirror cavity with the etalon removed and a pump power of 26 W. The OPSL tuning was obtained by angle tuning the BRF; the observed tuning range of over 30 nm is typical of OPSL technology and illustrates that growth of the desired structures does not have to hit the desired wavelength with high precision. The gain structure produced during the SBIR effort is well suited for high-power 1178 nm operation and demonstrates our ability to produce OPSL chips optimized for the required LGS wavelength.

Fig. 5 shows the frequency-doubled output power of a three-mirror OPSL employing an LBO nonlinear crystal for SHG. We obtained a maximum of 3.1 W at a pump power of 38 W for a diode-to-yellow efficiency of 8%, however the SHG conversion efficiency of the SBIR OPSL was not optimized. We estimate that with optimized optics this OPSL could have output twice as much yellow light, yielding a diode-to-yellow efficiency of 16%.

Spectral analysis of the 1178 nm and the 589 nm light exiting the OPSL was carried out with a scanning Fabry-Perot interferometer. The short-term (seconds) frequency stability of the 1178 nm output was observed to be of order 10 MHz. A portion of the 589nm light was directed into a sodium vapor cell. Strong fluorescence was measured as the laser was tuned across both sodium D2 features.

5.3 Present and Future Guidestar OPSL Developments

The NSF SBIR effort confirmed that OPSLs could provide multi-watt, continuously tunable, good beam quality output narrowed and tuned to the sodium D2 transition.

Power scaling of the 589 nm OPSL requires the cavity to efficiently extract power from the pumped region of the OPSL chip while simultaneously removing heat from the gain material. Beyond the NSF SBIR, Areté Associates and ORC have continued work on power scaling OPSLs and demonstrated up to 20 W of multimode output (Fig. 6) at a wavelength of 588 nm [71]. The 20 W output was accomplished with 28% conversion efficiency from diode laser light to yellow – an impressive and encouraging result. Up to 15 W of single-frequency 588 nm output was obtained at the peak of the OPSL chip tuning range using a far-from-optimized cavity setup. When tuned to 589 nm the output power dropped but was still in excess of 12 W. This improved performance was primarily due to better thermal management and a cavity design matching the beam profile to a high-quality LBO crystal. Thus we have high confidence that a single-chip OPSL will produce 15-20 W output with little additional optical design required.

The Toptica SodiumStar laser provides a benchmark for present and future guidestar semiconductor laser development in terms of spectro-temporal format (CW single frequency), output power at the sodium D_{2a} line (20 W), re-pumping power at the sodium D_{2b} line (2 W), spectral linewidth (5 MHz), and near-diffraction-limited beam quality. Our goal is to develop a guidestar semiconductor laser with comparable or better performance characteristics, in a significantly smaller package and at a significantly lower acquisition and operational cost for the astronomical and Space Situational Awareness LGS AO communities.

As predicted in [18, 19] and demonstrated in [47, 48], putting narrow frequency light on the sky on both sodium D_2 transitions is important to maximize the sodium photon return flux. For optimal results at the 20 W laser output level the ratio of power on the D_{2a} to D_{2b} transition is approximately 10:1. There are two options for using OPSLs to produce a two-wavelength guide star output. First, because of the OPSL simple configuration it is possible to have one high-power laser locked to the D_{2a} transition and a second low-power laser locked to the D_{2b} transition. The two laser outputs could be combined using a polarization beam combining approach. Beam combining has to be done accurately to assure the beams overlap well in the sodium layer. A second means of achieving a two-wavelength output is to incorporate an electro-optic (EO) phase modulator to generate a low-power sideband on the high-power D_{2a} beam that is shifted to the D_{2b} line. Electro-optic modulators that can withstand the high optical power of the D_{2a} laser are currently available but optical damage of the crystal is a concern with extended use.

Producing higher powers with OPSLs is possible through careful thermal management and secondly through the use of multiple gain elements within the laser resonator. Optimizing the power output of any OPSL system requires good thermal management to extract heat from the gain region. The limiting mechanism in optical power generation is almost always thermally induced loss mechanisms in the gain mirror. Researchers at the University of Arizona achieved over 100W of output power near 1030nm through an innovative combination of heat spreaders, thermoelectric and water cooling [79].

Power scaling can also be readily achieved by series coupling of gain media as illustrated in Fig. 7 where multiple gain mirrors are within a single resonator and power output is effectively doubled [80, 81]. Power scaling in this fashion can also be used with intra-cavity frequency doubling to obtain very high powers in the visible region of the spectrum. In [80], nearly 25 W of laser power was generated using a dual gain mirror cavity incorporating a Lithium Triborate crystal to accomplish non-linear frequency conversion to 561 nm. Using a single gain mirror, 11.5 W were obtained with an M^2 of 1.04. Insertion of an intracavity etalon to obtain single frequency operation reduced the RMS noise of the output. The power loss resulting from insertion of the etalon was not reported but in Areté's experience this usually results in a twenty percent decrease in output power at the harmonic wavelength. Researchers from Coherent Inc. used three gain mirrors to achieve up to 55 watts of frequency doubled output at 532nm in a TEM_{00} beam with an M^2 value of 1.2 [81]. The impressive results of this experiment are shown in Fig. 7.

While power scaling in this manner lengthens the resonator and concomitantly reduces the longitudinal mode spacing, Areté has demonstrated single longitudinal mode operation of OPSLs using an intracavity etalon in resonators 60 cm in length. Because of the relatively small size of the gain media in OPSLs, power scaling and single mode operation can be simultaneously achieved in resonators of such length.

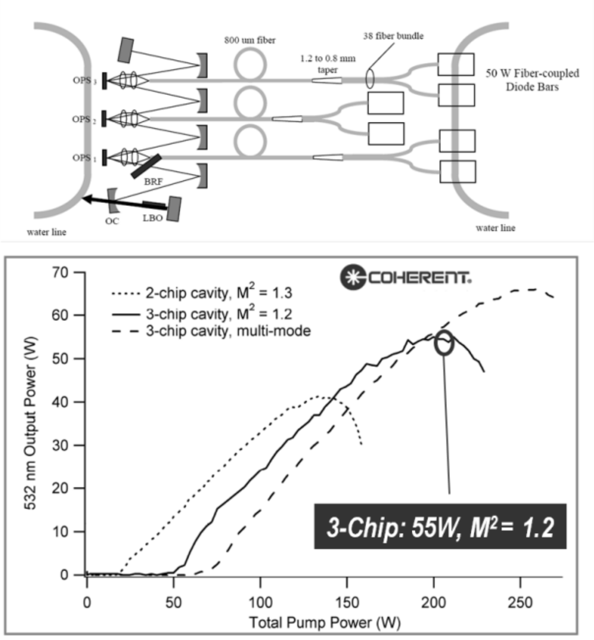

Fig. 7. 55W output power frequency doubled 532 nm demonstration using multiple gain mirrors in a single cavity. (Used with permission of Coherent Inc.)

Finally, it is important to note that temporal modulation of the output of OPSL lasers is relatively easy to achieve through pump laser current modulation and other methods. Consequently, it is straightforward to produce a wide variety of waveforms with pulse durations of 1-100 microseconds and longer.

An Advanced Technology and Instrumentation (ATI) proposal submission to the US National Science Foundation for a three year, US$1.3M program to produce a full scale sodium guidestar OPSL prototype, and conduct on sky tests to demonstrate the system performance and reliability, was recently declined despite very good reviews.

The Australian National University (ANU) has also been investigating ways to progress the development of sodium guidestar semiconductor technology for the Australian and international LGS AO communities. The ANU is involved in a number of sodium LGS AO projects, which would greatly benefit from the availability of a smaller, simpler, and more affordable sodium laser source. ANU LGS AO projects include the Laser Tomography Adaptive Optics (LTAO) for the 25 meter Giant Magellan Telescope (GMT) [66], the sodium LGS AO Demonstrator for the EOS laser tracking station at Mount Stromlo Observatory near Canberra, Australia [58, 59], and a number of on-going and prospective commercial projects for LGS AO-enhanced observations of satellite imaging and space debris ranging and deorbiting. Because ANU is a 5% partner in the international Giant Magellan Telescope project (along with Australian Astronomy Ltd, which contributes another 5% to the GMT project), and a participant in the Australian Government-funded Space Environment Management Cooperative Research Centre [60], the ANU is particularly keen to develop a sodium guidestar semiconductor laser solution that would benefit both the astronomy and Space Situational Awareness (SSA) communities.

To that effect, the ANU has partnered with the Australian Astronomical Observatory (AAO), the University of New South Wales (UNSW), the Giant Magellan Telescope Organization, and SERC participants EOS Space Systems and Lockheed Martin Space Systems, to propose a Linkage Infrastructure Equipment and Facility (LIEF) program to the Australian Research Council (ARC). This AU$1.3M program aims to deliver the first prototype semiconductor sodium laser for astronomy, space debris tracking, and bio-fuel combustion experiments, and to demonstrate the prototype in the laboratory at UNSW in Canberra, and on-sky at the EOS laser tracking station on Mount Stromlo. Areté Associates would contribute significant in-kind to the program and be the principal contractor to develop the semiconductor laser prototype. The ARC is expected to announce the results of the 2016 LIEF program in the October/November 2015 time frame.

5.4 A Smaller, Simpler, and More Affordable Guidestar Laser

Table 2 presents the advantages of OPSL technology where sodium guidestar laser applications are concerned. One of the primary advantages associated with OPSLs is the ability to generate the desired wavelength with straightforward and mechanically robust methods. The low complexity of the OPSL laser head minimizes acquisition and operational costs of the system. In particular, observatory technicians will be able to carry out routine OPSL operation and maintenance without advanced training.

Table 2. Summary of OPSL advantages for sodium guidestar applications.

Characteristic	Description	Guide Star Laser Implications
Low Acquisition Cost	20-40 k$/W	Affordable to large and small observatories Spare laser is a realistic option
Low Complexity	Low parts count Impervious to gravity orientation	Small number of failure points Reduced maintenance time
Small Size	Laser Head ~2 ft^3 Electronics Head ~ 2 ft^3	Flexible mounting on telescope structure is enabled
Serviceability	Routine maintenance by technician Laser head is field replaceable	Minimizes system downtime and repair costs
Supply Chain	Components are commonly available Multiple vendor options Standard semiconductor growth means multiple vendors exist for OPSL chips	High likelihood Areté will be able to continue production well into the future for the limited guide star laser market

OPSLs operating at visible wavelengths have demonstrated lifetimes greater than 10,000 hours which bodes well for operation in observatories. The compact nature and relatively low cost of the OPSL also positively impact service and reliability. The laser head and pump diodes are likely to be separate field replaceable units. The low cost of the laser head makes it possible for the observatory to own a spare and the size allows replacement with minimal telescope downtime. Repair of the problem laser head will occur at the factory, not at the observatory, thus eliminating expensive service calls to remote sites.

Areté Associates estimates that it can produce a laser guide star system, comprised of a single 15-20 W laser head and the ancillary equipment necessary to provide laser operation, diagnostics, environmental control, and a user interface for approximately US$800,000 once initial laser development is complete. This corresponds to a cost of US$40,000/Watt, roughly a factor of 2.5 less than the cost estimated for existing sodium guidestar laser systems in the AO Roadmap document produced by the US AO community in 2008 [78]. Where multiple lasers are deployed within the same observatory additional cost savings will be recognized because the control system cost will be distributed across the number of lasers. Note that these are estimates of first time costs. Once product maturity is established, for systems utilizing multiple lasers, production costs of $20,000-30,000/W are achievable representing a factor of five cost savings in comparison to the AO Roadmap Committee's benchmark cost.

In comparison with other technologies the OPSL technology has a low-risk supply chain because the components are readily available from multiple vendors. The only critical component is the OPSL chip but since the chip is grown by standard semiconductor growth techniques using standard semiconductor materials we expect that multiple vendors can produce chips if quantities are needed beyond the current supply. A 2 inch wafer produces hundreds of gain chips and can be produced for less than $100,000.

6. CONCLUSION

Sodium Laser Guide Star Adaptive Optics for astronomy and Space Situational Awareness applications require powerful, reliable 589 nm laser sources with spectro-temporal formats tailored to maximize the mesospheric sodium photon return. Three generations of sodium guidestar technologies have been developed since the LGS concept was initially proposed in the 1980s: dye lasers in the ~1990s, solid-state sum-frequency lasers in the ~2000s, and fiber lasers in the ~2010s.

The Toptica SodiumStar laser based on Raman fiber laser technology developed at the European Southern Observatory (ESO) is currently the only commercially available option for sodium guidestar applications. Four SodiumStar laser units are about to be deployed in the field by ESO in Chile, and one more unit by the Keck Observatory in Hawaii. A number of other observatories are also considering the possibility to replace their existing sodium laser systems with Toptica lasers, and two of the three Extremely Large Telescopes (the E-ELT and GMT) include six or more Toptica lasers in their baseline LGS facility designs. Although third generation fiber lasers represent a very significant improvement over the first generation (dye) and second generation (solid state) lasers, these systems remain expensive to procure, and there is technical and programmatic risks associated with the current sole source supplier situation.

Past and present semiconductor laser technology developments have proven that semiconductor guidestar lasers are a viable option to produce a fourth generation sodium guidestar laser source. Areté Associates, the Australian National University, and their academic and industry partners, believe that semiconductor laser technology could provide a competitive alternative to Raman fiber lasers, and are actively seeking funding to develop a first, full-scale prototype of a semiconductor laser for astronomy and Space Situational Awareness applications.

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