# AFRL Advanced Electric Lasers Branch: construction and upgrade of a 50-watt facility-class sodium guidestar pump laser

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## Abstract

The development of a reliable and effective laser source for pumping mesospheric sodium to generate an artificial guidestar has been well documented. From the early achievements with 589nm high-power dye lasers at the Keck and Lick observatories to the ground-breaking 50W CW FASOR (Frequency Addition Source of Optical Radiation) Guidestar at the Air Force's Starfire Optical Range (SOR), there has been intense interest in this technology from both the academic and military communities. Beginning in the fall of 2008, the Air Force Research Laboratory's Advanced Electric Lasers Branch began a project to build, test, verify and deliver an upgraded version of the SOR FASOR for use at the AF Maui Optical Station (AMOS) in the summer of 2010. This device, called 'FASOR-X', will be similar in design to the existing SOR device and produce 50W of diffraction limited, linearly polarized narrow linewidth 589nm light by combining the output of two injection-locked Nd:YAG ring lasers (operating at 1064nm and 1319nm) using resonant sum-frequency generation in a lithium triborate crystal (LBO). This upgraded system will include features such as modularized sub-components, embedded control electronics, and a simplified cooling system.

The first portion of this upgrade project is to test and build the two injection laser cavities while validating the improved control mechanisms FASOR-X will employ. In parallel with this effort, the technical plans for the modularization and re-packaging of the FASOR will be finalized and coordinated with the staff at Maui. This paper summarizes the results of these efforts to date and provides updates on the AMOS FASOR-X status. Additionally, AFRL plans for next-generation guidestar pump sources will be discussed.

## 1. Introduction

Advanced adaptive optics (AO) systems are enhanced by artificial, rather than natural, guidestars as the latter provide full sky coverage and overall improved performance. These artificial guidestars are achieved by resonantly pumping the D2a line of mesospheric sodium (see Fig. 1), located in a layer 10km thick and approximately 90km above the earth's surface. The requirements for the 589nm sodium-only laser source, which [broadly] include multiple watts of polarization-maintained, stable operation at a very narrow (approximately kHz) linewidth and $TEM_{00}$ mode quality, are demanding. The development of a reliable and effective laser for artificial guidestar operation has been well documented (see [1] for an example), but undoubtedly a huge step forward in this technology was achieved by the Air Force Research Laboratory (AFRL) team led by Craig Denman and Paul Hillman, who successfully demonstrated the first 50W-class guidestar in 2005 at the Starfire Optical Range [2]. Their achievement was reached with a 'FASOR' device that generated the needed signal by combining the output of two injection-locked Nd:YAG ring lasers (operating at 1064nm and 1319nm) via resonant, non-critical phase matching in a lithium triborate crystal. A number of Pound-Drever-Hall (PDH) loops [3] are also employed in the FASOR design in order to ensure the appropriate cavity length matching in and between the injections lasers and with the SFG to guarantee stable generation of single frequency yellow light.

In the fall of 2008 a new, a new Air Force program of artificial guidestar development was initiated, again teaming AFRL's Directed Energy Directorate Optics and Lasers Divisions. The first stage in this program is currently well underway as a small team in AFRL's Advanced Electric Lasers Branch has begun the test and construction of a new

50W FASOR based on the Denman-Hillman design to be delivered to the AMOS facility in the summer of 2010. This device, called 'FASOR-X' (due to its scheduled completion in 2010), will leverage the same Nd:YAG diode-pumped gain modules to amplify two narrow-linewidth 1064nm and 1319nm NPRO seed laser sources for subsequent SFG combination in an LBO oven. FASOR-X will include a number of improvements over the current SOR FASOR that will make it much easier to operate and maintain. The main improvements include embedded hardware controllers, a simplified cooling system, modularization of key sub-components, improved packaging, an improved software and controller interface, fine tuning of gain module current and temperature, internal diagnostics and all digital locking servos.

## 2. FASOR-X Summary

The Fraunhofer D-lines, or sodium doublet transitions, have been identified as well-suited for use as guidestar beacon sources due to their strong resonant scattering of visible light and the abundance of sodium in the Earth's mesosphere. Specifically, the D2 line is within the range of ubiquitous Nd:YAG solid-state laser sources and has a larger scattering section than the D1 line; thus the focus on guidestar pump sources at D2a or 589.15908nm.

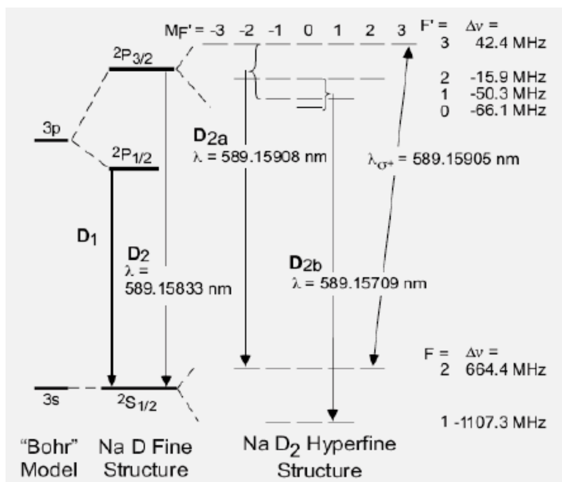


Fig. 1. The energy level diagram of sodium described, by three different models of increasingly complexity (from left to right). The reader is referred to [4] and [5] (and sources therein) for additional discussion of theoretical and experimental investigations of sodium excitation for guidestar purposes. *From [5]*.

The task of generating a laser source with enough energy and narrow enough frequency operation to excite the D2a transition is not an easy one. Frequency addition of 1064nm and 1319nm, which are serendipitously two of the strongest emissions in Nd:YAG, is a clear way to result in 589nm generation, but there are no single frequency laser sources at these wavelengths with enough power to directly generate a strong enough guidestar. The Denman *et al.* team solved this problem by frequency-locking narrow linewidth ring oscillator 1064nm and 1319nm seed sources to Nd:YAG gain elements in a ring cavity configuration. The amplified output of these seed sources was then additionally locked to the SFG cavity and the 589nm output is maintained by another locking loop that ties the system back to the NPRO seeds (see Fig. 2). Throughout this system, analog PDH control loops were employed to maintain the appropriate optical path length matching to keep the seed lasers, injection lasers, and final output all stably tuned to the D2a transition. FASOR-X will include all digital control servos, which will provide a large improvement in the simplicity and precision of these important controls over the previous FASOR system. This novel digital control was validated in an important test in December of 2008 and the reader is referred to [6] in these proceedings for a full discussion on this topic.

The two gain modules (GMs) themselves are Brewster cut Nd:YAG rods pumped via an open interface by three 808nm diodes. These GMs are unique items produced by a former Lightwave Electronics team (now owned by JDS Uniphase) and the FASOR-X includes four of these devices for the 1064nm ring cavity and six at 1319nm. These modules add a lot of 'personality' to the system because each GM and their diodes require tailored temperatures and currents to achieve an output optimal for effectively mode-matching within each cavity and also due to the specifically arranged optical components needed to operate each ring cavity. Thus, some of the major improvements of FASOR-X over the groundbreaking system still in operation at the SOR will be precision tuning and control of the temperature and current at each pair of GMs and new internal diagnostics to verify optical alignment in each GM cavity. This current control is enabled via power MOSfet current shunts in each respective injection laser ring cavity, while the temperature tuning is achieved with individual temperature controllers tied to 150W heaters at each GM pair. These improvements are summarized in Fig. 3 below.

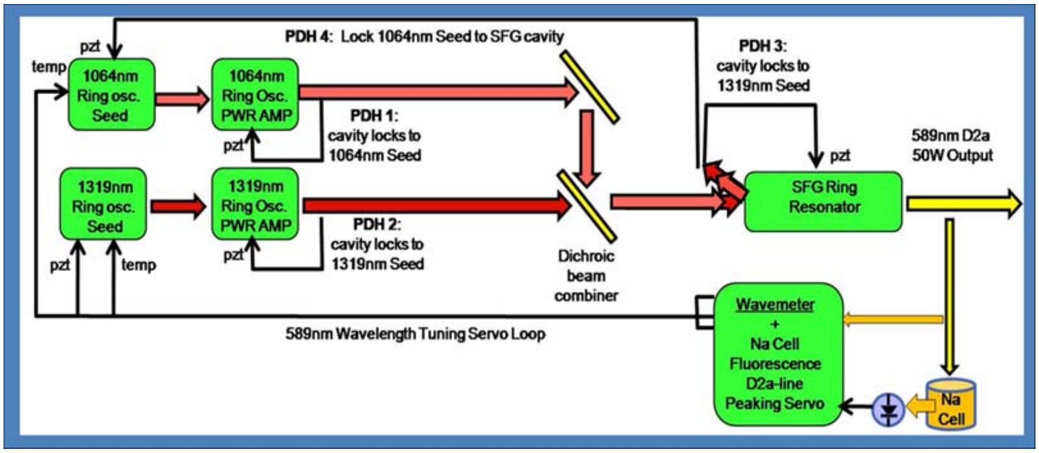


Fig. 2 A schematic showing the main subsystems and control loops for FASOR-X. *Image courtesy of J. Baker.*

## 3. FASOR-X Status

The small team at AFRL's Advanced Electric Lasers Branch was officially awarded this challenging project in the middle of 2008. A unique aspect of the project was that a majority of the essential laser hardware had already been purchased, thus the team had to work well within the existing strengths and weaknesses of the SOR FASOR system and has since dedicated much effort to improving the latter (hence the aforementioned controls upgrades). This has resulted in parallel efforts in both researching and validating the laser sub-systems while working to design, fabricate, and test the final modularized components for FASOR-X. A major accomplishment was reached in December of 2008 with a laboratory demonstration of ring laser locking with the novel all-digital servo [6]. A number of validation and risk-reduction tests have also been accomplished for many of the controls and feedback subsystems as well. The team has also been assisted by a number of important facility upgrades, such as the installation of a 450 $ft^2$ class 1000 clean room which was completed in April of 2009.

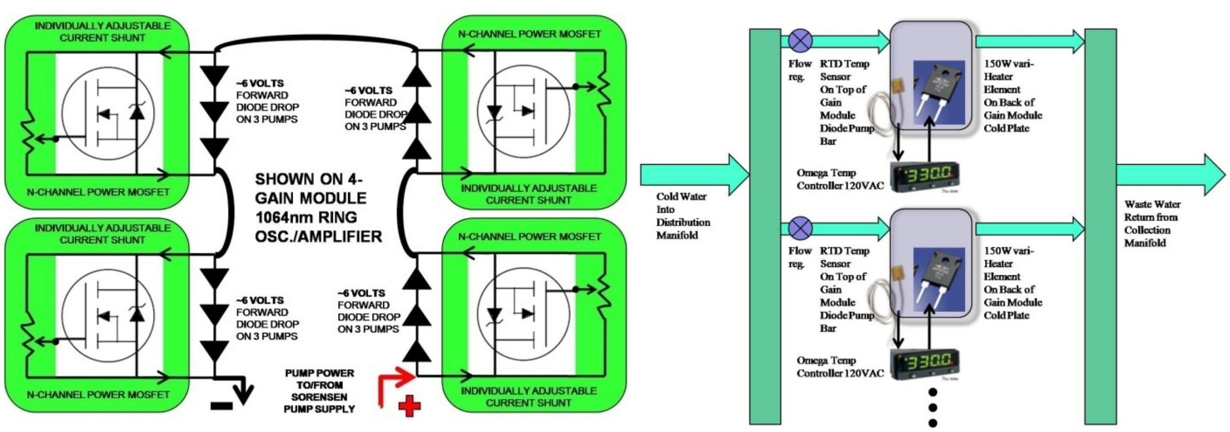


Fig. 3 A diagram of the current and temperature tuning systems for FASOR-X. These control systems are some of the major upgrades in FASOR-X over the SOR FASOR and will result in a more robust system that is easier to use.

Since the completion of this cleanroom, which unfortunately ran nearly four months behind schedule due to some administrative issues, the laboratory efforts have been primarily focused on the necessary research into the provided GM units to iteratively build to working high power ring cavities. To that end, the individual GMs were all thoroughly characterized to validate their performance and identify the most likely GMs to pair in cavity operation (i.e. those that had the closest matching temperatures during individual characterization and optimization). These units were all optimized at 20W with excellent beam quality by July of this year. At the date of these proceedings, the team's most recent accomplishment was the initial operation of a two GM element 1064nm cavity at over 50W. This result is a good indicator that the FASOR-X will meet the Air Force's need for a high power laser guidestar beacon at AMOS and a testament to the thorough and careful application of the Branch's solid-state laser expertise to this challenging project

## 4. Future guidestar work from the Advanced Electric Lasers Branch

The design, research, construction, test, and delivery of FASOR-X are all just the first phase of this multi-year effort. There are two additional phases planned, which are scheduled to deliver a multi-line guidestar device and 'next-generation' guidestar based on an innovative fiber or spinning-disk gain media design. The Advanced Electric Lasers Branch has a proven track record in both the fiber and bulk solid-state media fields, and will leverage its in-house expertise to find solutions to the next two phases of this project.

In the near term, work has begun on a fiber-based 1178nm source. This source be directly frequency doubled for 589nm generation and would maximize the near perfect beam quality and single frequency operation that fiber-based lasers can provide. Of course, single frequency operation at high power in fiber waveguides is inherently difficult due to the deleterious non-linear effects, such as Stimulated Brillouin Scattering, that occur at such high intensities; but Branch's fiber team is uniquely positioned to address these with some patented in-house non-linear mitigation techniques. A fiber guidestar would have much simpler architecture, and thus be more robust and easy to use, than the current rod-based FASOR designs. There are many options available to pursue this goal and the fiber team is currently completing a theoretical investigation on a number of them. One possibility is to directly amplify an 1178nm seed source in a passive Raman fiber, as illustrated in Fig. 4. Much of the required equipment to investigate various fiber designs has been purchased and a laboratory proof of concept of these novel guidestar designs is planned for the spring of 2010.

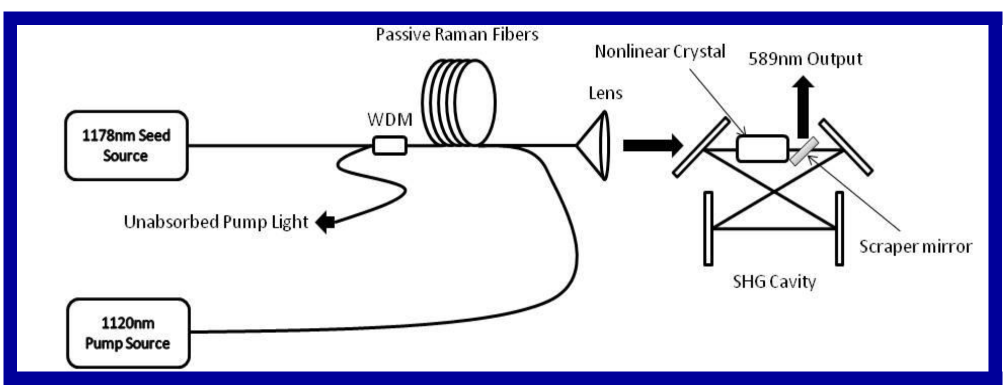


Fig. 4 A block diagram of a Raman amplifier device for a high power sodium guidestar pump laser. This is one research project currently on-going at AFRL and will help prove new technology solutions to the next phases of the Air Force's artificial guidestar program.

## 5. Conclusion

Since its invention of adaptive optics and ground-breaking work in sodium guidestar beacon sources, the Air Force Research Lab has been a leader in technologies to enable ground-based astronomy and near-earth object detection. The ongoing work with FASOR and next-generation solid state laser guidestar technologies highlights that AFRL will continue to be a major player in this field. With the continued importance of ground-based observations for missions such as Space Situational Awareness, the development and delivery of these technologies will be an important role for the Air Force's R&D leaders. Currently, AFRL's Advanced Electric Lasers Branch has a small, dedicated team of civilian, contractor, and military members working in earnest to deliver an upgraded 50W FASOR to AMOS in the summer of 2010. This team has made a solid start on this effort and has accomplished important demonstrations of novel control technologies that will make FASOR-X a robust and reliable AO guidestar beacon.

## 7. References


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