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Design of a Fieldable Laser System for a Sodium Guide Star*

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ABSTRACT

The design and background data for a sodium layer laser guide star system to be installed on the 3 meter telescope at Lick Observatory is presented. A 30 W dye laser at 589 nm and 10 kHz will be mounted on the telescope and will be pumped by fiber coupled, frequency doubled YAG laser located in a separate room.

1. INTRODUCTION

A single sodium-layer, laser guide star can provide an effective means of correcting a moderate size telescope in the mid IR if the (visible) seeing is of the order of an arcsecond. Under these conditions, a 30 W laser at 589 nm can correct a 3 meter telescope to a Strehl of about 0.5 if the adaptive optics system has a sufficient number of actuators and bandwidth. Such an adaptive optics system is being tested on the Lick Observatory 40 inch Nickel telescope and will be moved to the 3 meter Shane telescope in the summer of 1994. The design of the adaptive optics system and recent results using natural guide stars are discussed in separate paper presented at this conference.¹ This paper concentrates on the design of the laser system for the sodium-layer guide star and the beam transport system.

The laser technology chosen for this purpose is a high repetition rate dye laser pumped by a set of frequency doubled YAG lasers. The pump laser light is delivered to the dye laser via fiber optic links and it is this configuration which gives the laser system its main features. With a remotely located pump laser, the waste heat associated with these inefficient devices can be easily handled without destroying the "dome" seeing qualities of the facility. Also, the dye laser portion of the system is small enough to permit mounting it directly on the truss structure of the telescope thereby eliminating complex and lossy optical links through traditional routes such as the coude or Nasmyth foci.

The pump laser technology is an outgrowth of commercially available units popular with the medical community for its robust and reliable performance. The dye laser technology has been developed by the Atomic Vapor Laser Isotope Separation (AVLIS) Program and is similar to that reported previously.² The major difference between this design and the previous effort is the substitution of the solid state laser for the copper vapor laser as the pump source. The CVL's developed at LLNL are not well suited for this low power application and have several logistic problems. For kilowatt applications, CVL's may still be the technology of choice, but for power levels up to the hundred watt range, the solid state laser is better suited.

2. PERFORMANCE PREDICTIONS

In the beginning stages of this program, an auxiliary telescope located just outside the dome was to be used for the laser beam director. This concept provided the least interference with the operations of the 3 meter telescope and allowed the installation and checkout of the laser system to be carried out independently. Initial estimates of the Strehl performance for 10 and 20 watts are shown in Fig. 1a and elsewhere in this conference proceeding.³ Here the laser power refers to the power propagated to the sodium layer and does not include optical or atmospheric losses. These losses are typically 50% corresponding to an optics transmission factor of about 70% and an atmospheric propagation loss of a similar amount.

The distance between the center of the beam director and the 3 meter telescope is about 25 meters and this separation creates an elongated sodium spot. The elongation factor increases the laser power needed to measure the centroids of the Hartmann wavefront sensor spots to a given accuracy. Equivalently, for the same laser power, a coaxial laser beam with no guide star elongation can increase the system Strehl by a large amount as shown in Fig. 1b. The system performance is essentially unchanged if the laser beam is transmitted directly alongside the telescope barrel and this is the design concept chosen for the program. Assuming again, a 50% overall loss due to optics and atmospheric, a 20 W laser can produce a Strehl of

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over 50% at an observation wavelength of 2.2 microns. For these reasons, the off axis approach was abandoned in favor of a near coaxial configuration with the laser mounted directly on the telescope. The separation between the laser beam and the edge of the 3 meter mirror is approximately a meter.

(a)

(b)

Figure 1. System performance for off axis (a) and coaxial (b) lasers.

The pulse format of the laser is adjusted to avoid saturation in the sodium layer in the following manner. The optimum spot diameter is given by the resolution limit of a subaperture, $(\lambda/r_0)R$, where λ is the sodium wavelength, r_0 is the turbulence correlation length and R is the altitude of the sodium layer. At Lick, where r_0 is approximately 10 cm, the spot diameter is about 60 cm. For a 20 W laser, with 10 W incident at the sodium layer, the laser pulse format at 10 kHz and a pulse duration of 150 ns gives a peak power of about 2 W/cm², which is about a factor of two less than the saturation flux.

3. PULSED LASER POWER DESCRIPTION

A block diagram for the 30 W laser system is shown in Fig. 2. The frequency doubled YAG lasers which pump the dye cells are located in a room below the floor of the dome about 50 feet from the base of the telescope. Light from the pump lasers is fed to the dye lasers using multimode fibers with a length of about 70 meters, taking into account all the large radius bends and pathways needed to reach the laser location on the telescope.

Figure 2. Layout of the laser system.

The dye laser is split in two parts. The Dye Master Oscillator (DMO) is located next to the pump lasers for environmental thermal control and stability. The DMO is the only coherent portion of the dye laser containing the laser cavity, single mode control, frequency stability, and frequency modulation electronics. A single mode fiber feeds the DMO signal to the dye amplifiers located on the telescope. The amplifier chain consists of a preamplifier and power amplifier with relay optics. The optical control system includes a closed cycle pointing and centering loop, a closed cycle, high bandwidth tip-tilt correction loop, and Hartmann wavefront sensors. There is also provision for a closed loop deformable mirror system which will not be implemented for the 30 W laser but will probably be required for laser powers in the hundred watt range. The beam transport system which follows the power amplifier centers and points the beam and expands it to a diameter of 20 cm. This beam diameter is about twice r_g which will produce the desired 60 cm spot assuming that the laser wavefront is nearly diffraction limited. The output wavefront is measured by a Hartmann sensor on the telescope.

4. PUMP LASERS

Each YAG laser consists of two packages, a power supply and Q switch control unit, which fit in a standard electronics rack, and the laser head with dimensions of 1' x 1' x 3'. Each laser dissipates about 8 kW and the waste heat is removed by cooling water supplied by the facility. Each laser head has three fiber outputs, one for the DMO located in the same room, and one each for the preamplifier and power amplifier located on the telescope. The 70 meter fibers have 600 micron cores and an insertion loss of less than 1 db at the 532 nm wavelength.

The frequency doubled YAG lasers are built at LLNL using commercially available modules, i.e., the laser rod and (CW) lamp assembly with power supply, Q switch crystal and driver, and KTP doubling crystal. The components are assembled with a cavity design which delivers the frequency doubled light in a pulse format optimized for the guide star application. In general, these lasers have a pulse format which is not quite suited to sodium guide star applications. The pulse repetition frequency, PRF, varies between 5 kHz and 25 kHz with roughly constant output power, but with a pulse duration which is roughly proportional to the PRF. At low PRF, the pulse duration is 250 ns increasing to over 500 ns at the high PRF.

Although these long pulse durations are attractive in the sense that at high PRF and long pulse durations, the sodium layer will not be saturated even for average powers in the several hundred watt range, the dye laser conversion efficiency suffers and acceptable system performance cannot be achieved with present technology. Commercially available⁴ YAG lasers using this standard pulse format are available with excellent reliability and lifetime specifications but shorter pulse durations cannot be easily obtained from these units. There is no doubt that such lasers will be available commercially in the near future, but for this project, the LLNL version optimized for a single operating point, 10 kHz at 150 ns, has been chosen. A photograph of the laser head is shown in Fig. 3. Using a larger YAG rod and lamp assembly and larger KTP crystal, over 70 W at 532 nm have been achieved.

This frequency doubled YAG laser is ideally suited to this application. Solid state lasers traditionally supply efficient, raw power at low cost, however, usually with poor beam quality. Here beam quality is unimportant because of the dye pumping scheme and fiber delivery. The beam quality need only be sufficient to couple to a multimode fiber. The CW flashlamp is very efficient, requires no high power switch, has long lifetime, and is inexpensive. Expensive diode arrays are not required for this system.

Figure 3. Laser head assembly for the pump laser.

5. DYE MASTER OSCILLATOR

The DMO, shown in Fig. 4, will be located adjacent to the pump laser in the equipment room below the telescope with the output fiber fed to the amplifiers located on the telescope. Although this arrangement requires a preamplifier to be located on the telescope to make up for the power limitations of the single mode fiber link, it allows the DMO to be mounted stably to the floor. Since the DMO unit contains only the coherent portions of the system, i.e., dye laser cavity, mode and frequency selection and phase modulation, the increased stability of a fixed mount is well worth the extra preamplifier on the telescope. The DMO is pumped by a pair of fibers from the YAG lasers, with one delayed by about 100 ns with respect to the other. This pumping scheme helps extend the DMO pulse duration to match the temporal gain distribution in the final amplifiers.

Figure 4. Dye Master Oscillator

The frequency control system, shown schematically in Fig. 5, includes a PZT controlled grating as the rear cavity mirror, high and low frequency etalons for single mode control, and a sodium optogalvanic lamp for precise wavelength calibration. A phase modulation scheme⁵ broadens the natural linewidth of the laser, of the order of 50 MHz, to about 2 GHz, with a profile which closely matches the "doubled bumped" absorption spectrum characteristic of mesospheric sodium, as shown in Fig. 6. These DMO units have been produced for the AVLIS program for several years and are "standardized" in their design.

Figure 5. Schematic diagram of the DMO control system.

Figure 6. Phase modulation format.

6. DYE LASER AMPLIFIERS

The phase modulated output of the DMO is fed to the dye preamplifier on the telescope using a single mode optical fiber. The peak power which this fiber can transmit without nonlinear effects is limited to a value of several megawatts per square centimeter which corresponds to a few milliwatts of average power for our pulsed laser format. It is for this reason that a preamplifier is needed to boost the signal for the power amplifier which requires a power level of a few hundred milliwatts for efficient power extraction. The preamplifier uses the same dye cell as the DMO but without any of the frequency control apparatus. With an input power from the DMO of a few milliwatts, output powers from the preamplifier of a few hundred milliwatts have been produced. This is the power level required to drive the power amplifier into saturation for efficient system operation.

The output of the preamplifier is (optically) relayed into the power amplifier with the output power results shown in Fig. 7. The lower curve shows the output power with an injected signal strength of a few hundred milliwatts and the equivalent of one of the YAG pump lasers. The solid line is a model calculation based upon available cross section data. The "multiplier" of 0.62 indicates that this model cannot predict the absolute power level of such dye lasers to better than a factor of two. However, there is extensive data within the AVLIS program that if the curve shape fits the data, extrapolations of the model to higher pump power levels is well described with the model assuming the same multiplier value. With the addition of a second YAG pump laser, an output power level of about 25 W is expected.

Figure 7. Output power of the dye laser system.

At the higher power levels, saturation is an issue. For the 60 cm optimum spot diameter corresponding to a value of r_0 of 10 cm, the saturation value is reached at 20 W assuming the same pulse format. The saturation value depends critically on the assumption of spot diameter so that for a more probable spot diameter of one meter, saturation is not reached until the incident power reaches the 50 W level. In any case, for the power level required for visible observation wavelengths, saturation will be reached for the present pulse format. The remedy is to increase the PRF rather than the pulse duration since peak power is needed for efficient dye laser conversion. For hundred watt class lasers, another dye laser amplifier and more pump lasers are needed. The pump lasers would be grouped in sets of 10 kHz each and the pulses interleaved to achieve system PRF's of multiples of 10 kHz. With the present dye laser technology, about 30 kHz is the limit imposed by structural considerations. At 30 kHz (and the same value of pulse duration of 150 ns), saturation is reached at the 60 W level for 60 cm spots and 150 W for the one meter spots. Of course, at that visible wavelength, multiple guide stars are needed so that the laser power is distributed over more area and saturation should not be a problem for this technology.

The dye laser system is presently in the breadboard phase prior to final installation on optics tables which will then be mounted on the telescope. A photograph of the dye laser amplifier breadboard is shown in Fig. 8.

Figure 8. Dye laser amplifier system.

7. BEAM TRANSPORT AND LASER INSTALLATION

The two major advantages of the pulsed dye laser system are the ability to separate the pump laser and DMO from the dye laser and the ability to mount the dye laser directly on the truss of the telescope. The latter feature frees up valuable space in the coude room or on the Nasmyth platform and leaves the center of the azimuthal and elevation bearings free for other applications. The laser system is mounted on three tables, one for laser, a second for the beam handling and diagnostics, and the third for the output lens of the beam projection telescope. The configuration is illustrated in Fig. 9. However, even with the dye laser on the telescope, beam transport functions such as pointing, centering, wavefront measurement, etc., are still required. The schematic diagram of the beam transport layout for the Lick installation is shown in Fig. 10.

Figure 9. Concept for telescope mounted laser.

Figure 10. Layout of the dye laser and beam transport system on the telescope.

For the Lick installation, the laser table is located at the level of the primary mirror, the diagnostics table is above the tertiary mirror level, and the projection lens is located at the secondary mirror level. All necessary optics controls are motorized and controlled from a central (MAC) computer work station using Labview as the control software.

The single mode fiber from the DMO feeds the input signal to the preamplifier. An optical system consisting of an aperture slit, pointing and centering "dog leg", and telescope relays the output of the preamplifier into the power amplifier ensuring alignment and mode overlap. Before projecting the beam onto the diagnostics table, the beam wavefront is sampled and low order corrections are removed by adjusting the relay telescope. The beam travels to the diagnostics table located about 23 feet away. In this free space propagation mode, the beam grows by diffraction to a diameter of about 20 mm which reduces the magnification of the final telescope to about 10:1. The space between these two tables is an exclusion zone for this telescope because the coude beam from the tertiary mirror passes here.

Once the beam is on the diagnostics table, a dog leg points and centers the beam for the final adjustment. The diagnostics for the pointing and centering functions are two cameras, one at the far field (tilt) and the other at the near field (centering). One of the mirrors in this dog leg is a high bandwidth tip-tilt mirror. The purpose of this tip-tilt mirror is to remove high speed tilts from the beam to ensure that the guide star spot remains inside the (Rayleigh) scattered light rejection filter (pinhole) in the adaptive optics system. High speed tilts may come from a variety of sources, including the dye laser itself, vibrations in the optics or telescope mount and, most of all, from the turbulence in the uplink propagation path. All of these tilts are sensed by the Hartmann wavefront sensor of the adaptive optics system. This tilt information is normally discarded because such information cannot be used to correct the wavefront of the science object but it is used to correct the guide star beam path to maintain pinhole registration.

The output telescope for the guide star consists of the negative lens and the 20 cm projection lens. Pointing of the laser beam is accomplished by translating the negative lens and adjusting the pointing and centering dog leg just upstream to keep the laser beam coaxial with the axis of the telescope. The lenses of the output telescope are held rigidly in a light weight, aluminum tube and they are prealigned to the axis of the tube. The tube is mounted on a two axis gimbal at the large end and free to point at the small end. A rack mechanism allows the negative lens to slide along the tube axis for final focus adjustment. This telescope acts in much the same manner as a finder scope on the main telescope.

Finally, a retro flat samples the output wavefront using the Hartmann sensor on the diagnostics table. The output wavefront is used to adjust the telescope for minimum guide star diameter. Both wavefront sensors have a wavefront reference developed at LLNL consisting of a single mode fiber and collimated lens assembly all mounted on an invar rod for thermal stability. This wavefront reference assembly is also used on LLNL's adaptive optics package and is essential to the system performance.

8. CONTROL AND SAFETY SYSTEM

The entire control system is activated by a single Mac Quadra 800 using Labview software as shown in Fig. 11. The Mac is located in the equipment room adjacent to the YAG pump lasers, DMO and the support equipment for the dye laser system, i.e., pumps, chillers, etc. All necessary mirrors and shutters on the laser and diagnostics tables on the telescope are motorized and controlled by the Mac. The pointing and centering diagnostics on the second table control two mirrors in one of the dog legs in a closed loop system which is monitored on the Mac. Other cameras on the two tables are connected to video monitors next to the Mac to provide visual status to the operator. A computer screen has been developed to monitor the status of the laser and beam transport system and is shown in Fig. 12. Manually controlled mirrors are selected by clicking on the mirror icons in the beam-transport schematic and moved by clicking on the appropriate buttons in the control menu.

Figure 11. Control System Layout

Figure 12. Computer screen for system control.

The internal safety system includes shutters on the YAG laser outputs and a full diameter shutter located at the output of the beam projection telescope. There are also diagnostic shutters which are part of the wavefront sensor system but these are not considered safety shutters. Access into the laser area can also be interlocked or administratively controlled depending upon the specific safety protocol at the facility. Shutter and laser control is handled by a key lock system with the safety officer having control of the enabling keys.

The design of the external safety system is dictated by the FAA since the beam is not eye safe at normal aircraft altitudes and there are three major airports near Lick. A visual observer will be required to warn of approaching aircraft, however, there is no need for a rotating search radar because of the height of the Lick Observatory. An automatic, boresight radar with automatic shutter control will be required. LLNL has adapted an airborne weather radar, similar to the unit used by the Air Force Phillips Labs at SOR, in conjunction with a fast shutter located just after the negative where the beam is still small. The fast shutter blocks the beam before any aircraft can intercept the laser beam once a signal has been received from the radar. A boresight calibration procedure has been developed for this radar which will be located behind the secondary mirror of the main telescope.

9. CONCLUSIONS

A laser system has been designed which incorporates state-of-the-art, solid state pump lasers and well developed dye lasers as the frequency tunable converter. With the advent of efficient, quartz fibers, the pump laser and Dye Master Oscillator can be located far from the telescope allowing simple thermal management and providing a stable environment for the coherent part of the laser system. The remainder of the system consisting of single pass dye amplifiers is mounted directly on the telescope thereby eliminating complex and lossy beam transport configurations.

A key feature of this laser system is the scalability to higher powers which will be required for observation wavelengths in the visible region. Most of the cost and complexity exists in this "front end" of the system. Adding another dye laser amplifier, which can be accommodated on the same laser table, and adding more pump lasers in the equipment area, can raise the output power level to the hundred watt range.

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