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Laser Beam Control and Diagnostic Systems for the Copper-Pumped Dye Laser System at Lawrence Livermore National Laboratory

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**Laser beam control and diagnostic systems for the copper-pumped
dye laser system at Lawrence Livermore National Laboratory**

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ABSTRACT

The laser system described in the previous paper¹ is used for experiments in which success requires tight tolerances on beam position, direction, and wavefront. Indeed, the optimum performance of the laser itself depends on careful delivery of copper laser light to the dye amplifiers, precise propagation of dye laser beams through restricted amplifier apertures, and accurate monitoring of laser power at key locations. This paper describes the alignment systems, wavefront correction systems, and laser diagnostics systems which ensure that the control requirements of both the laser and associated experiments are met. Because laser isotope separation processes utilize more than one wavelength, these systems monitor and control multiple wavelengths simultaneously.

1. INTRODUCTION

Effective operation of the LLNL dye laser system in isotope separation experiments requires full integration of its optical, mechanical, electronic, and control components. The result must be stable propagation from beginning to end, good beam intensity uniformity in the vapor interaction region of the separator, and reliable characterization of the important properties of each beam throughout the system. Table I summarizes the performance we have achieved to date.

Table I. Control and diagnostic performance

parameter	best on-line performance
Alignment: rms centering accuracy rms pointing accuracy bandwidth	0.1 mm 1.5 μ r 200 Hz
Wavefront: correction range rms control accuracy bandwidth	$\pm 5 \lambda$ 0.1 λ 1 Hz
Power: calorimeter limit accuracy	4500 W $\pm 5\%$

Figure 1 gives an indication of the number and locations of beam control and diagnostic (BCD) subsystems. The components themselves incorporate a modular approach to design and a capability for off-line assembly and test. The control and diagnostic subsystems reflect our intention to implement automatic operation of as many functions as possible while providing effective monitoring capability for operators. Two examples of this approach are the utilization of video data as the best shared format for operators and control loops when complex information is involved and the provision of system-wide access for monitoring and control in both local and consolidated control areas.

Fig. 1. BCD locations: a = alignment function, w = wavefront function, p = power sample, c = calorimeter (full beam, insertable).

2. ALIGNMENT CONTROL

2.1. General approach

2.2.1. Basic concepts

Before different wavelengths are combined, as with the two dye master oscillator beams at the input of one chain and the two dye chains on the dye combination wall, alignment of each wavelength must be separately controlled. After all beams are combined, however, accomplishing correct alignment for one of them will assure that the others are also transported accurately. As shown in Figure 1, we use a separate alignment "pilot" beam for this purpose. Because this beam plays no part in the actual separation process, we can operate it at fixed power, design main beam mirror coatings to leak a desired fraction of its light, and choose a smaller beam size so that small alignment changes do not cause clipping.

Beam alignment tolerances vary in different parts of the laser optical system, but alignment measurements are all made in the same general way. Figure 2 illustrates schematically the basic approaches to measurements of beam position (centering) and direction (pointing). Centering optics image the beam and a physical position reference in a near-field plane of interest, and pointing optics view the far-field of the beam to measure direction. All sampling is accomplished using light which leaks through main beam turning mirrors. CCD cameras view all alignment images, and their images are accessible throughout the laser facility on video switching systems.

Fig. 2. Basic approach to (a) centering and (b) pointing measurements.

The concept of a common reference for coalignment of multiple wavelengths is extremely important in our system. The laser isotope separation process requires multiple wavelength beams to be accurately overlapped in the separator to maintain high ionization efficiency. If the separate alignment detectors for each wavelength were used as absolute references for overlap purposes, any drift in their unshared optical or electronic components would cause different wavelengths to be offset from each other in centering or pointing. Therefore, for all beam overlap alignment systems, we treat individual alignment CCD cameras or position sensitive diodes as secondary references and use shared cross hairs (or cameras) as the primary references. Even for single wavelength loops we use permanent or accurately insertable cross hairs as close as possible to key alignment points for the primary references. This reduces the importance of alignment drift in transport optics that bring light to the alignment sensor packages.

2.1.2 Sensor modules

Actual alignment packages are, of course, more complicated than suggested by the Figure 2 schematics.² Each module includes both centering and pointing channels, and it incorporates multiple element optical systems for compactness, bandpass and polarizing filters for discrimination, and neutral density filters as well as closed-loop liquid crystal attenuators for signal level control. The photographs in Figures 3 show two alignment modules. We use the small two foot long version between dye amplifiers in the dye chains and the full size (four or five foot) version at all other alignment locations.

Fig. 3. Alignment modules: (a) two foot long dye relay telescope package (b) five foot basic module.

The modular packages serve as building blocks for the implementation of cost effective multiple wavelength subsystems such as the one required for the precise overlap of our two dye beams and two system pilot beams (The alignment pilot beam is described above, and the wavefront pilot beam is described in section 3.1.) Figure 4 shows how three of the modules, including one with internal polarization discrimination for the two pilot beams, are combined with an external shared telescope and external shared references to meet the beam combination requirements.

Fig. 4. Beam combination alignment sensor subsystem.

2.2. Closed-loop control

2.2.1. Low bandwidth operation

The largest alignment changes in our 1-2 kW laser and optical transport systems result from beam induced thermal effects. The optical and mechanical design minimizes absorption by the optics and heating of the optical mounts, but residual effects remain, as illustrated in Figure 5. Because the time constant for these thermally induced changes is usually measured

Fig. 5. Alignment correction with time as laser power to the transport system is decreased and then increased.

in minutes, the bandwidth constraint imposed by standard CCD cameras is not an issue. Video data from the sensor packages passes through the system-wide video switcher to image processing systems which frame grab, digitize, and measure image parameters at the standard video rate of 30 frames per second². Each of these systems resides on a VME chassis with a microprocessor closed-loop controller. For low bandwidth (approximately 1 Hz) operation, we configure each video system to sequentially process single frames from 24 CCD cameras. The image parameters of interest are the number of multiple pixel spots after thresholding the image at a selected pixel intensity, the size of each spot, and the centroid location of each spot.

For each pair of centering and pointing images, the closed-loop controller applies validity checks and then converts the image parameters to measured alignment errors by comparing image position information with the control positions previously specified by an operator. Figure 6 shows a typical centering image before and after processing. Easy access

(a)

(b)

Fig. 6. A dye beam centering image (a) before image processing and (b) after image processing.

to these images and related control settings gives the operator an effective means of monitoring and adjusting system performance. Although control positions are usually chosen to be centered on a cross hair or other fixed reference, operators have the option to set control points at offset positions if operating conditions or experimental test plans require it. The final step is to convert measured errors to actuator commands for the stepper motors or PZT's in the loop. This is also done by the closed-loop microprocessor.

2.2.2. High bandwidth operation

Smaller, but important, alignment changes result from density gradients in the air surrounding the dye chain and from mechanical vibrations which find their way into the optical system in spite of strong efforts to eliminate and isolate vibration sources. Therefore, we incorporate high bandwidth alignment control in the system at a few key locations. For example, residual vibration from the dye flow system serving our eight dye laser amplifiers is detectable on the beams at the dye beam combination sensors (Fig. 4). Accordingly, we use a commercially available PZT driven tilt stage to hold a $1\frac{1}{2}$ " diameter mirror in the post amp telescope of each dye chain and in the formatting telescope for the pilot beams. For each fast mirror a high-bandwidth lateral-effect photodiode in the pointing leg of the associated combination sensor module provides feedback through a dedicated microprocessor. Figure 7 shows the performance obtained from these systems.

Fig. 7. Vibration reduction with a $1\frac{1}{2}$ in. diameter high-bandwidth pointing mirror. The closed loop integrated angle variation is $1.5 \mu\text{rms}$.

2.3. Integration of control for multiple alignment loops

2.3.1. Loops optically in series

Many of the alignment loops in our system are optically in series as seen in Figure 1. If each loop operates independently of the others, an alignment change near the front of the system will be seen by all subsequent alignment sensors, and multiple closed loops will start correcting for the same error. At the very least this causes unnecessary operation of stepper motors and leads to excessive wear in the gear trains attached to the motors. At worst, it leads to oscillation in down-stream loops and an unstable alignment system. Some form of communication between loops is required.³ Figure 8 illustrates our current approach for the simplest case of two loops in series. The key feature in this form of integration is that

Fig. 8. Integrated control illustrated for the case of two alignment loops optically in series.

even though each loop(n) still calculates full correction for all the errors seen by its sensors, it also passes equivalent but opposite motor commands to the next loop (n+1) and receives the same information from the preceding loop (n-1). Combining each loop's own commands with those sent to it by the preceding loop has the effect of cancelling all redundant motor moves before they are implemented.

2.3.2. High and low bandwidth loops

Coordination of high and low bandwidth loops is also important. In our system, one or more low bandwidth loops may exist within a high bandwidth loop. It is impossible to define and maintain precisely the same operating point for two independent systems. Therefore, if both types of loops are turned on to run independently, the general condition is that they compete with each other. Initially the high bandwidth system prevails because of its much shorter response time. In the long run, however, it is unable to operate because of its limited range compared to the low bandwidth system.

We avoid high and low bandwidth competition by turning off the loop containing the low bandwidth camera most closely corresponding to each high bandwidth diode, and we protect the high bandwidth mirror mount against large excursions by using the now unlocked low bandwidth gimbals to back out DC offsets when they exceed selected values. Figure 9 is a simplified control schematic for the case of a high bandwidth loop encompassing the two low bandwidth loops of Figure 8. Integrated control of the full alignment system is accomplished using generalizations of the simple cases discussed here.

Fig. 9. Controls integration for two low bandwidth loops within a high bandwidth loop

3. WAVEFRONT CORRECTION

3.1. General approach

The efficiency of the laser isotope separation process is highest when uniform beam intensity is attained in the separator volume. This fact, combined with the long propagation distances in our system, leads to a desire for near diffraction limited wavefront quality. Just as the separate dye beams need to be coaligned when they are combined, they must also have the same wavefront at the combination point. After that, all beams experience the same aberrations, and as with alignment we introduce a separate wavefront pilot beam for control.

Fig. 10. Basic approach to wavefront measurement and correction

Figure 10 shows the basic approach to wavefront measurement and correction.^{4,5} A Mach-Zehnder interferometer with remote wavelength selection provides detailed measurements of each beam's wavefront, and separate Hartmann wavefront sensors for each beam provide data for closed-loop operation. A wavefront reference source, which is carefully engineered for long term stability and has no on-line adjustments, produces an accurately flat wavefront with which to periodically calibrate the interferometer, Hartmann sensors, and wavefront control transport optics. The function of this wavefront reference is analogous to the common references for alignment described in subsection 2.1.1. Each beam has a separate deformable mirror.

3.2. Optical components

3.2.1. Deformable mirrors

We designed deformable mirrors specifically to correct the wavefront errors generated by our high power dye laser system.⁶ In comparison with state of the art deformable mirrors for atmospheric compensation, we require fewer actuators and lower bandwidth. In addition, the dielectric coatings already developed for LLNL dye lasers have sufficiently low absorption that no cooling is required. All of our current deformable mirrors have a correction range of plus or minus five waves in the visible, are built with a monolithic dielectric substrate, and use from 12 to 25 low voltage actuators. Figure 11 illustrates the deformable mirror architecture with drawings of a 25 PZT mirror and a photograph of a 12 PZT mirror.

Fig. 11. LLNL deformable mirror architecture: (a) 25 PZT zonal deformable mirror and (b) 12 PZT zonal mirror.

Making the mirrors noticeably larger than the beam size effectively minimizes edge effects. Actuator attachment is accomplished by epoxying the substrate legs into cups which are part of the flexure assembly. The epoxy bond, however, is only on the sides of the legs. Therefore, epoxy shrinkage exerts stress in the plane of the mirror surface only and causes minimal distortion of the mirror. Flexures between the mirror and the PZT housings reduce transmission of shear forces between the mirror and actuators. This is necessary to make the mirror less sensitive to nonpiston components of actuator motion during operation. Finally, the monolithic substrate eliminates any concerns associated with the attachment of a face plate.

The measured low order wavefront shapes in Figure 12 give an indication of the capabilities of the 25 PZT mirror. When used for correcting generalized wavefront errors on a real laser beam, the mirror assumes more complicated shapes.

Fig. 12. Measured low order shapes generated by a 25 PZT zonal deformable mirror.

3.2.2. Hartmann sensors

The closed-loop sensors in our wavefront control systems use Hartmann-Shack pointing sensor arrays.⁷ Each channel of the Hartmann array measures the propagation direction of the light, i.e. the slope of the wavefront, for a particular part of the beam. The complete array of measurements fully characterizes the wavefront with a spatial resolution limited by the spacing of the channels. Compared to interferometric options, we prefer Hartmann sensors as being more tolerant of wavefront excursions, more easily matched to our mirrors, less demanding for data processing, and more intuitive to system designers and operators. For the relatively small number of detector channels required, we achieve both a plus or minus five wave range and better than tenth wave accuracy.

Two separate types of Hartmann sensors operate in our systems. The first design uses a discrete 8 x 4 array of lens and lateral effect photodiode pairs.⁴ The second is a more compact version using a microlens array and a CCD camera.⁸ Figure 13 shows a cut-away drawing of a diode-based instrument and a photograph of the video model.

Fig. 13. (a) Diode array Hartmann wavefront sensor and (b) video Hartmann sensor with microlens array.

Our two diode-based packages and two CCD-based packages all perform reliably, but the video systems have several advantages. A CCD camera needs much less signal than the diodes, and although we are not typically short of light for monitoring dye beams, the signal from a pilot beam may be quite low. Furthermore, the dimensions of a CCD-based sensor are considerably smaller than the diode array, and it is correspondingly easier to equip the sensor with remotely controlled wavelength and signal level filters. Cabling is also easier since a CCD camera needs three cables at the most, while each lateral effect photodiode has five leads. Finally, because of our extensive use of video processing in the alignment systems, we are well prepared to apply video technology to wavefront correction also.

3.2.3. Interferometers and wavefront references

The LLNL self-referencing Mach-Zehnder interferometer measures beam wavefront to an accuracy of one tenth wave peak to valley. By an optimum combination of refractive and reflective optics, low angles of incidence, and an equal path configuration the interferometer maintains its accuracy over a wavelength range from 600-900 nm without readjustment of the optical components.⁹ Figure 14 is a schematic diagram of the instrument.

Fig. 14. Self-referencing Mach-Zehnder interferometer.

A CCD camera views the output from the interferometer, and selected frames from the camera are digitized for analysis on a fast array processor. The interferometer is adjusted with sufficient angle between the reference and the signal beams that the interferogram can be processed using a Fourier transform fringe analysis technique.¹⁰ Elapsed time from operator initiation of a frame grab to 3D display of the wavefront is less than five seconds. The interferogram analysis system is accessible on standard workstations throughout the facility and accommodates three users.

The wavelength flexibility of the interferometer makes it possible to use a wavefront reference source of fixed wavelength.⁹ High power is not required, and HeNe is a convenient choice of laser for reasons of cost, reliability, and size. Heat generated by the laser is a potentially severe problem because it can cause time-dependent density gradients in the path where the wavefront is being measured. We avoid this difficulty by installing the laser in an insensitive location and transporting the light over a single mode fiber to the reference location as illustrated in Figure 15. Proper choice of the fiber diameter and the f/no and clear aperture of the collimating optics produces the desired tradeoff between reference beam size, uniformity, and power.

Fig. 15. Optical schematic of a wavefront reference source.

Successful implementation of a wavefront reference source requires an extremely stable mechanical design. We incorporate the minimum number of adjustable parts and use a super-invar cavity structure with a common mounting plate for the fiber and the collimating lens. Once a suitably stable reference is built, initial adjustment of the wavefront depends on the ability to make an absolute wavefront measurement. Our interferometer laboratory contains a BaTiO₃ phase conjugate interferometer for this purpose.⁹ Three wavefront references are in routine use in our wavefront correction systems.

Figure 16 shows the layout of Hartmann sensors, interferometer, wavefront references, and transport optics for the dye and pilot beam wavefront combination subsystem.

Fig. 16. Dye and pilot beam wavefront combination subsystem.

3.3. Closed-loop control

3.3.1. Low bandwidth operation

As noted in the discussion of alignment control, beam induced thermal effects are the largest source of optical change in our laser and beam transport systems. Although the temperatures of mirrors, windows, and mounts change slowly, they are coupled strongly enough to laser power that fixed wavefront properties can only be achieved by changing actuator settings on the deformable mirrors. Moreover, asymmetries in the optical system design and the nonuniform distribution of low level absorption in the substrates and coatings cause wavefront distortions which are too complicated for simple operator response. Therefore, our wavefront correction systems must have closed-loop capability.

For each wavefront control system, a dedicated microprocessor analyzes Hartmann sensor data in the form of detector voltages from a lateral effect photodiode array or focussed spot locations from the digitized CCD image of a video Hartmann sensor. For each Hartmann spot, the closed-loop controller translates the raw data into x and y slope changes relative to desired control positions. The full set of departures from the control positions are the error inputs from which the controller calculates moves for the deformable mirror actuators. This process occurs 6-8 times per second, giving the control system a bandwidth of about 1 Hz.

The control positions may correspond to a flat wavefront previously confirmed by the interferometer and the wavefront reference source, but this is not a requirement. Sometimes experimental conditions dictate controlling to a simple non-flat wavefront. Figure 17 shows examples of both cases. In one case, a dye beam is controlled to a nearly flat condition with a residual peak to valley error of 0.2 waves and an rms error of 0.04 waves. In the other case, the operator has entered a control offset of -0.75 waves of long axis curvature in the closed-loop controller.

Fig. 17. Examples of controlled wavefronts: (a) flat to 0.04 waves rms (b) 0.75 waves of divergence on the long axis.

We have a deformable mirror at the end of each dye chain to compensate for wavefront changes caused by the lasers and match the beam wavefronts to each other. At the entrance to the separator, which is a significant distance away, we have another deformable mirror to assure optimum wavefront properties for the input light at all wavelengths. Between the two parts of the system, beam size can be changed by adding convergence or divergence with the dye chain output mirrors and recollimating with the separator input mirror. Isotope separation experiments sometimes call for a variation of beam size and aspect ratio, and operators implement such changes by entering control offsets with curvatures of opposite sign at the two deformable mirror locations. The LLNL deformable mirrors have enough range to accomplish wavefront smoothing and beam size adjustments at the same time. Figure 18 illustrates this secondary use of our wavefront control systems.

Fig. 18. Use of a deformable mirror pair to change beam size.

3.3.2. High bandwidth capabilities

Recent measurements on our system in which a high speed camera replaced the usual CCD camera on a video Hartmann sensor show that some higher frequency variations in wavefront also occur. They probably are a result of air motion in the dye chains. The residual amplitude after variations of 1 Hz and slower are compensated is about 0.15 waves rms. For this reason, it is usually necessary to average a number of interferometer measurements to get consistent results. In fact, the wavefront representations in Figure 17 are actually averages of eight and five separate measurements, respectively. The deformable mirrors described above are capable of operation at over 100 Hz, and we are presently considering the importance of increasing our control bandwidth.

4. POWER DIAGNOSTICS

Power measurements complete the characterization of system performance. In fact, beam power measured at a distance and supplemented with information about its spatial distribution is the most direct way to confirm that alignment and wavefront tasks have been successfully accomplished. We design all power measurement systems with a goal of plus or minus 5% absolute accuracy at full scale and with the intent that they should function reliably over the maximum possible range.

4.1. Basic instrumentation

4.1.1. Water-cooled calorimeters

There are many ways to sample laser power for purposes of monitoring power changes while allowing most of the light to propagate further for another purpose. However, calibration of such sampling diagnostics or subsequent verification of their performance always requires a way to measure the full power of the beam for a short period of time. Figure 19 shows the simplest implementation of this generic approach.

Fig. 19. Primary and secondary power measurement.

Water-cooled calorimeters are well suited for full power measurements when they are properly designed and implemented. Accurate power values are calculated from first principles and depend only on the specific heat capacity of water and on measurements of temperature and flow rate. Figure 20 is a schematic diagram of such a calorimeter. We have designs ranging from three inches to eight inches in characteristic dimension, and we use them to measure powers up to 4500 Watts.

Fig. 20. A 3" square calorimeter.

There are a number of important details in the design and application of this approach. The flow meter is on the water input side to prevent temperature changes from influencing the operation of the flow meter. The internal path for the water is very shallow to minimize the water volume, but it directly cools most of the area within the beam dimensions. The illuminated surface is thin, and the total mass of the copper block is minimized within reasonable mechanical constraints to shorten the time constant of the instrument. The thermistors are mounted directly in the water flow but outside the body of the calorimeter to preclude any heating of the flowing water before the input thermistor or after the output one. A diffuser in the output line guarantees uniform temperature in the water flowing past the exit thermistor. Delrin standoffs thermally isolate the entire unit from its mechanical support. A series of light trapping grooves and a diffuse black surface treatment limit loss of light by scattering to four percent, and we correct for this in data processing. Finally, the maximum power rating for the calorimeter is set below the level at which radiation from the heated front surface becomes an important loss mechanism.

In short, making accurate flow and temperature measurements and guaranteeing that heat is lost only to the flowing water assures a correct power value. To maintain confidence in the accuracy of the calorimeters, we compare different calorimeters with each other, make absolute measurements of scatter loss, and periodically compare on-line flow meters with a carefully calibrated test meter. From all of these checks we conclude that the calorimeters measure with an absolute accuracy of better than five percent.

4.1.2. Secondary monitors

Photodiodes are our principal device for secondary power measurements. The details of the associated front end electronics depend on whether the requirement is for time-averaged or time-resolved data. Because both kinds of information are often important in our system, most diodes are mounted in a modular unit containing one of each type of diode.

Figure 21 is a cross-section drawing of a dual diode assembly. Light enters at the left and passes through a set of fixed neutral density filters and an angle-adjustable bandpass filter if appropriate. The longest part of the assembly is an integrating bar, a piece of glass with a square cross-section and a ten to one aspect ratio. The entrance has a diffuse surface, and all of the

Fig. 21. Integrating bar assembly with two photodiodes.

other surfaces are polished. The scatter from the bar's front surface and the multiple reflections from the sides cause the light to be thoroughly mixed and essentially uniform by the time it reaches the back surface. This makes it possible to obtain a fixed fraction sample for the two diodes. Both diodes are mounted in close proximity to the bar's exit surface on a small printed circuit board which contains appropriate circuitry for preprocessing the output data from both the slow and fast diodes.

4.2. Applications

4.2.1. Single wavelength time-averaged power

The laser and optical transport systems have an integrating bar assembly or equivalent photodiode mounting arrangement for each wavelength at the numerous secondary power locations identified in Figure 1. In most cases the diodes are easily calibrated by the remote insertion of a dedicated full beam calorimeter. In some less critical locations, a calibration check requires manual insertion of a portable calorimeter.

4.2.2. Single wavelength time-resolved power

The dye laser chains produce 50 ns pulses at repetition rates ranging from 4.4 kHz to 26 kHz in multiples of 4.4 kHz.¹ The higher than 4.4 kHz rates are achieved by optical multiplexing of light from different copper vapor laser chains to the same dye amplifiers. Since the pump power from each copper laser is slightly different, the interlaced 4.4 kHz pulse trains do not generally have the same power. We gate the fast diodes at the output of each dye laser chain and separately monitor the signal from each interlaced pulse train. The data is used for adjusting the power balance between trains, and as input to separation process simulation calculations.

Synchronization of the arrival times of copper laser pump pulses and the dye laser pulses in the dye amplifiers is critical for maximizing conversion efficiency and minimizing amplified spontaneous emission (ASE). The chain output fast diodes are also used to observe this relative timing.

4.2.3. Monitoring ASE

When a propagating dye pulse and a copper laser pump pulse exactly overlap in both time and space, the maximum fraction of pump power is converted to dye laser light. When (or where) this overlap is imperfect, some of the pump power is converted into spontaneous emission which has much broader spectral content. Some of this light follows the same path as the laser light and exits the dye chain as ASE. We take advantage of the spectral differences to monitor ASE in two ways.

ASE resulting from poor spatial overlap is observed by imaging the optically pumped volume and blocking the narrower bandwidth laser light. The centering image from a dye amplifier alignment module is an image of the amplifier aperture. Addition of a bandpass filter which includes a portion of the ASE spectrum but excludes the laser line produces an image of the ASE originating in the amplifier. Figure 22 is such an image. These images provide an important indication of relative pump and dye light alignment. Optimized overlap produces a symmetric halo of ASE around the blocked laser light.

Fig. 22. An alignment camera image of ASE in a dye amplifier. The laser wavelength is filtered out.

Actual ASE calorimetry requires more detailed spectral discrimination. One way to obtain a very small input source for a holographic grating spectrograph is to focus a representative sample of the beam onto a tapered optical fiber. The output from the fiber is positioned at the spectrograph entrance slit and dispersed onto a linear photodiode detector array. Figure 23 illustrates this arrangement, including a representation of the display seen on an oscilloscope when it reads out the linear array. The area under the full curve is proportional to the total beam power, and the ratio of the area under the narrow dye laser part of curve to the total area is a measure of the fraction of the output power which is ASE.

Fig. 23. A spectrograph for measuring ASE fraction in a dye chain output beam.

4.2.4. Integrated diagnostic packages

At the entrance and exit of the separator a complete characterization of beam power and spatial intensity distribution for each wavelength is important for calculations which predict the performance of the separation process. Integrated laser diagnostic packages (LDPs) are installed for this purpose. The separator input LDP comprises separate optimized modules for distributing the input light, monitoring alignment into the package, acquiring simultaneous near field images for multiple wavelengths, and simultaneously measuring power for multiple wavelengths. This LDP is shown schematically in Figure 24.

Fig. 24. Separator optical system laser diagnostics (a) schematic layout (b) description of functions by module.

5. SUMMARY

The laser beam control and diagnostic systems for the copper-pumped dye laser system at Lawrence Livermore National Laboratory are comprehensive and carefully matched to the needs of the laser isotope separation program at LLNL. System capabilities have grown significantly over the last one and a half years while at the same time supporting a series of increasingly demanding separation experiments and demonstrations.

Development of beam control and diagnostic components and systems will continue with emphasis on higher bandwidth for alignment and wavefront correction and on increased modularity, decreased size, and improved reliability for operation in industrial environments. While the primary goal of this work is to prepare our high power laser system for application in a uranium isotope separation plant, the beam control and diagnostic capabilities described are applicable to many types of lasers and applications.

6. ACKNOWLEDGMENTS

Although each of the authors has guided particular parts of the work described in this paper, key contributions from as many as one hundred program personnel could easily be identified as being individually important to its success. We specifically acknowledge the essential role of the isotope separation program's computer organization in providing innovative and reliable software, operator interfaces, and system-wide networking.

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7. REFERENCES

1. R. H. Hackel and B. E. Warner, "The copper-pumped dye laser system at Lawrence Livermore National Laboratory," *Laser Isotope Separation*, SPIE proceedings series Vol. 1859, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1993.
2. W. J. Rundle, E. S. Bliss, R. E. English, Jr., M. W. Kartz, R. L. Peterson, G. R. Thompson, and D. M. Uhlich, "Design and performance of an automated video-based laser beam alignment system," *Current developments in optical design and optical engineering II*, SPIE proceedings series Vol. 1752, pp. 20-31, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1991.
3. T. W. Long and E. S. Bliss, "Application of decentralized control to a laser alignment system," *Proceedings of the American Control Conference*, Chicago, June 1992.
4. J. T. Salmon, E. S. Bliss, T. W. Long, E. L. Orham, R. W. Presta, C. D. Swift, and R. W. Ward, "Real-time wavefront correction system using a zonal deformable mirror and a Hartmann sensor," *Active and Adaptive Optical Systems*, SPIE proceedings series Vol. 1543, pp. 459-467, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1991.
5. J. T. Salmon, T. W. Long, E. L. Orham, R. W. Presta, C. D. Swift, R. S. Ward, C. L. Weinzapfel, J. W. Bergum, and R. A. Thomas, "On-line closed-loop wavefront correction for a multi-kilowatt dye laser system," *Conference on Lasers and Electro-Optics 1992 Technical Digest Series*, Vol. 12, pp. 402-405, Optical Society of America, Washington, DC, 1992.
6. C. S. Swift, J. W. Bergum, E. S. Bliss, F. A. House, M. A. Libkind, J. T. Salmon, and C. L. Weinzapfel, "Zonal deformable mirror for laser wavefront control," *Active and Adaptive Optical Components*, SPIE proceedings series Vol. 1543, pp. 107-119, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1992.
7. B. Platt and R. V. Shack, "Lenticular Hartmann screen," *Optical Sciences Center Newsletter*, Vol. 5, p. 15, March 1971.
8. J. S. Toppen, E. S. Bliss, T. W. Long, and J. T. Salmon, "Video Hartmann wavefront diagnostic that incorporates a monolithic microlens array," *Miniature and Micro-Optics: Fabrication and System Applications*, SPIE proceedings series Vol. 1544, pp. 218-225, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1991.
9. M. Feldman, D. J. Mockler, R. E. English, Jr., J. L. Byrd, and J. T. Salmon, "Self-referencing Mach-Zehnder interferometer as a laser system diagnostic," *Active and Adaptive Optical Systems*, SPIE proceedings series Vol. 1543, pp. 490-501, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1991.
10. M. Takeda, "Spatial carrier heterodyne techniques for precision interferometry and profilometry: an overview," *Interferometry*, SPIE proceedings series Vol. 1121, pp. 73-88, Society of Photo-Optical Instrumentation Engineers, Bellingham, 1990.

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