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R. Edward English Jr.
Steve A. Johnson

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R. Edward English Jr.
Steve A. Johnson

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550

1. ABSTRACT

We present a system architecture for a high power fiber optic delivery system to deliver laser power from many sources to many destinations. For our application, the sources are copper vapor laser chains and the destinations are dye laser amplifiers. By means of this fiber delivery architecture, the delivery system can be configured conveniently in a fully redundant fashion. In this system the light arriving at every destination includes an equal fraction from every source. We also describe the functions of the opto-mechanical components necessary for implementation of this architecture.

2. OVERVIEW

The atomic vapor laser isotope separation (AVLIS) program at Lawrence Livermore National Laboratory (LLNL) is a DOE funded technology development and demonstration effort. A goal of the program is to demonstrate system capabilities at a scale commensurate with full-scale deployment of an isotope enrichment facility in the late 1990's.

One technology thrust within the overall program is development of a tunable laser source capable of sufficient average power, spectral purity, and beam quality to support laser isotope separation. Other applications include materials processing and laser guide stars.

A block diagram illustrating the overall AVLIS system architecture is shown in Fig. 1. A collection of copper laser chains provide pump light for multiple dye laser chains. The multiple dye laser beams are combined into a single beam that is transported by discrete mirrors to the separator area. Reflecting telescope optics format the beam (e.g., adjust beam size) for optimum propagation through an atomic vapor within an evacuated separator assembly. Within this separator/enrichment area, an electron beam gun vaporizes molten material (e.g., uranium). The tunable laser source selectively photoionizes the desired isotope, and then the ionized material is separated from the vapor flow using electric fields applied to collection plates. An artist rendering of the AVLIS facility at LLNL is shown in Fig. 2.

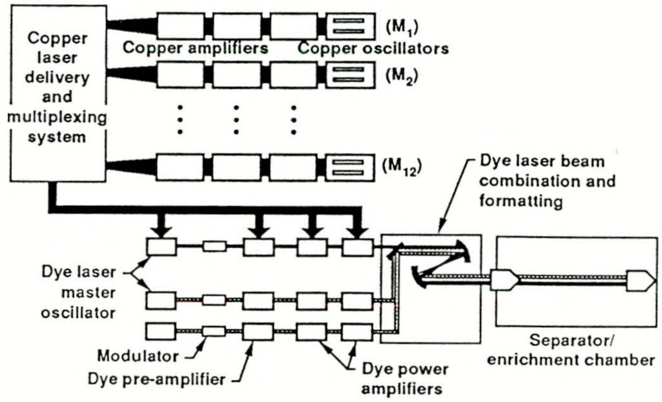

Fig. 1. Block diagram of AVLIS laser system. Copper laser chains pump dye laser chains, both in a master oscillator-power amplifier (MOPA) configuration. Multiple dye beams are combined and transported to the separator area, where the beam size is adjusted for propagation through an atomic vapor. Within the separator, isotopes are selectively photoionized and collected.

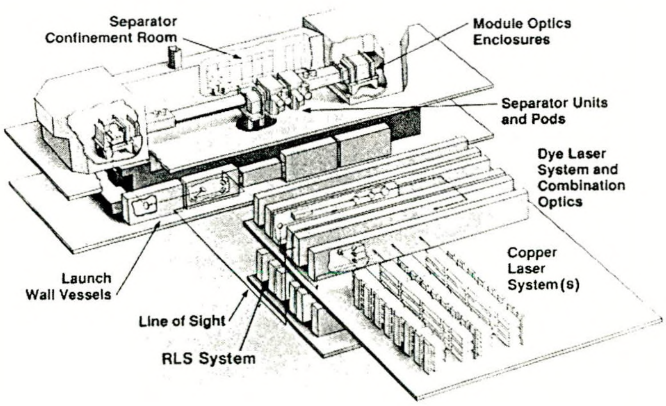

Fig. 2. Artist rendering of the current Atomic Vapor Laser Isotope Separation (AVLIS) system being used at Lawrence Livermore National Laboratory. It shows how the laser subsystems are integrated together with the uranium separator chamber.

The copper laser chains comprise an oscillator and three single-pass amplifier heads (master oscillator-power amplifier, MOPA configuration). Pulsed laser light is generated at the two copper vapor laser lines (511 & 578 nm) in a green:yellow ratio of about 60:40.

The dye laser chains are also operated in a MOPA configuration. The oscillator and amplifiers are optically pumped by either the green or yellow constituent colors of the copper laser chain. The tunable output is in the visible region of the spectrum.

In our current Laser Demonstration Facility (LDF), the delivery of copper laser pump light to the dye laser amplifiers is accomplished by means of discrete optical components. These components are distributed along a total air path that can exceed 70 feet from the end of the copper laser chain to the dye laser amplifier. Components include flat mirrors (to direct the beam and provide alignment control), beamsplitters & dichroics (to produce the desired redundancy and power/color splitting), and spherical & cylindrical optics (to produce the desired pump zone illumination pattern). We have successfully demonstrated the performance of these systems.

There are, however, many drawbacks to this type of distributed, discrete system. Chief among these are alignment drifts, sensitivity to copper laser chain performance (e.g., beam collimation), overall system maintainability, and cost. The desire for a system with greater "turn-key" capabilities provided a key motivation for our development of high-power fiber optic delivery systems.

3. FIBER DELIVERY NETWORK

We have developed fully redundant fiber optic delivery system architectures that distribute light from multiple copper laser chains to multiple dye laser chains. To some extent, these fiber routing diagrams resemble network diagrams. They show copper laser chains (sources), numbers of fibers per chain, and how the fibers are distributed among the multiple dye laser amplifiers (destinations). An example fiber delivery network is shown in Fig. 3.

The light from each copper laser chain is injected into a multiplicity of fibers by a fiber injection device. This device separates the copper laser beam into its two constituent colors and subdivides the beam into sections that contain between 50 and 100 W (average power). This optical power is injected into large core optical fibers (1.0 mm diameter).

The light from these optical fibers is imaged and formatted to match the dye laser amplifier pump zone by an anamorphic optical system called a fiber-to-amp relay. Each amplifier has two (one per side). This optical system forms an illumination stripe wherein amplification of an injected signal occurs.

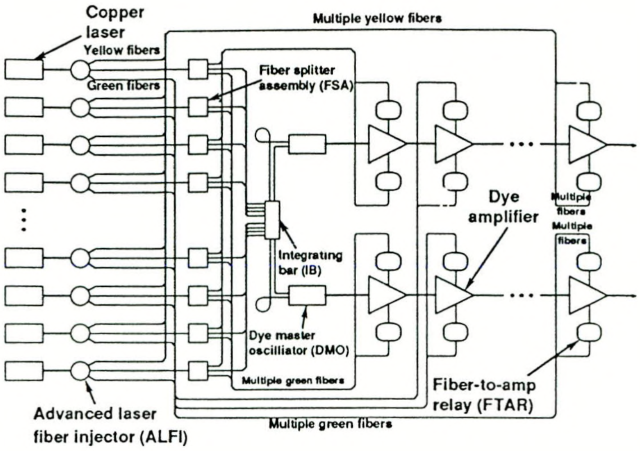

Fig. 3. Fiber optic delivery system schematic diagram (example). Copper laser chains, dye master oscillators, and dye amplifiers comprise the laser system. Advanced laser fiber injectors, fiber, fiber-to-amp relays, fiber splitter assemblies, and integrating bars comprise the delivery system.

It is important to understand the feature of full redundancy because it is a major factor in the design of the delivery system. In a production environment, light availability is an important consideration relating to productivity and profit. Single-point failure modes must be reduced or eliminated. The pump light delivery system achieves this by design. The pump light delivered to any dye laser amplifier comprises an equal contribution from every copper laser chain; this is true for every destination in the delivery system. If a copper laser chain is unavailable (e.g, due to maintenance), then the pump power delivered to every dye laser amplifier is reduced by the same proportionate amount. The system effect is a commensurate reduction in available tunable power, but the system continues to operate in a balanced and acceptable manner.

Redundancy affects delivery system design by constraining the manner in which pump power can be distributed. Since there are some number, say N, of individual sources (copper laser chains) and each side of a dye laser amplifier represents an individual destination, the number of fibers routed to a particular destination must N, 2N, etc. For the various system designs that we have investigated (varying numbers of copper laser chains and varying numbers of dye laser amplifiers), this constraint does not prevent attainment of satisfactory pump power distribution.

Before the fiber routing design is generated, a dye laser chain design is performed. This design determines the optimal distribution of pump power and color required at each of the amplifiers given the properties of the dye amplifiers and the available amount of copper laser pump light. Other factors can influence the design as well (e.g., required power per chain, hardware constraints, and cost). Knowing the optimal distribution, fiber delivery constraints can be applied. Some of these constraints include maximum power per fiber, maximum number of fibers per dye laser amplifier, and minimum set of fibers (redundancy-driven). In every case that we have examined, these fiber constraints do not seriously affect the dye chain performance.

In the fiber delivery network shown (Fig. 3), light from a copper laser chain is injected into a multiplicity of fibers by a fiber injector. These fibers are distributed or routed to all of the dye laser amplifiers so that each copper laser source contributes an equal fraction of the pump light at each dye laser amplifier.

The front-end of the system requires an additional level of complexity because the optical pump power required is significantly lower than the pump power required for the later amplifiers. It is difficult to design the fiber injector so that such a small amount of light is split off for the DMOs and pre-amplifiers. In the two-stage system shown, a single fiber from each fiber injector is routed to a second splitting assembly. This splitting assembly distributes light from the single input fiber into multiple output fibers.

All but one of these output fibers are routed to the pre-amplifiers. This other output fiber is routed to an integrating bar, which mixes light from all the splitting assemblies and distributes it to DMO fibers. Optical pulse length considerations require that the DMO be pumped with copper light of a slightly longer pulse (15-25 ns longer). This is achieved by making one of the DMO fibers leaving the integrating bar longer than the other DMO fiber. In this way, every DMO sees pump light from every copper laser that is stretched by the appropriate amount.

4. FIBER DELIVERY COMPONENTS

4.1. Fiber Injector

The fiber injector is a key interface between the copper laser chain and the fiber delivery network. Its general function is to split the copper laser beam into its constituent colors and subdivide the laser power into a multiplicity of fibers. The number of fibers is determined by the dye laser chain pump power distribution. In addition, the system requirement of full redundancy and the maximum power per fiber limit affect the fiber count.

We have built and tested a copper laser fiber injector. In the prototype device we have built and tested, the incoming copper laser beam is subdivided into 21 'channels.' These individual channels then pass through separate optical systems that inject light into a multimode fiber. We underfill the fiber core to provide some alignment tolerance. We used 1.0 mm diameter silica-on-silica multimode fiber, and the maximum average power density on the input fiber face is ≤ 30 kW/cm^2.

4.2. Fiber

We use commercially available, silica-on-silica, multimode fiber. Most of the fiber delivery network comprises fiber with a core diameter of 1.0 mm. We have experimentally determined that well-prepared fibers of core diameter 1.0 mm can withstand up to 300-400 W average power input without visible damage. (These average power levels were for copper laser light with a repetition rate of 4.3 kHz and a pulse width of 60 ns. About 70% of the fiber face area was illuminated. The average power damage limit under controlled conditions is about 50-70 kW/cm^2; the peak power damage limit is 210-280 MW/cm^2.)

If the fiber faces are prepared by polishing, then one must use techniques that do not leave cerium oxide or other polishing compounds embedded in the surface. In our applications we prepare most of our fiber faces by cleaving as opposed to polishing. The key reason is inherent higher damage resistance, but they are also faster and easier to prepare.

4.3. Fiber-to-Amp Relay

The fiber-to-amp relay optical system is the interface between the fiber delivery network and the dye laser amplifier. The general function is to receive light contained within fibers that originate at all of the fiber injectors (copper laser sources) and form an illumination stripe appropriate for the dimensions of the particular amplifier. Because of the requirement that light from each copper laser source illuminate each dye amplifier destination (redundancy), light from each fiber must illuminate the entire gain volume within the dye laser amplifier.

The fibers must illuminate a rectangular volume through which an organic dye solution (gain medium) flows. The fiber-to-amp relay is an anamorphic optical system that receives light from a collection of fibers and illuminates the gain volume in the dye amplifier. The optical assembly is very compact and is attached to the side of the amplifier. Since the amplifier is pumped from both sides, there are two fiber-to-amp relays (see Fig. 4).

5. RESULTS

We have tested a prototype of the fiber injector near its design-rated power. The system performed well and demonstrated very good "turn-key" operation. Initial alignment of the fiber injector was achieved off-line in an alignment fixture; deployment in the system required no further adjustment.

We have demonstrated successful performance of the fiber-to-amp relay devices for low to moderate-power dye laser amplifiers. These systems showed excellent alignment stability and ease of use. Comparison of dye conversion efficiencies with discrete optical pumping was favorable. We have utilized these devices for over a year with few problems.

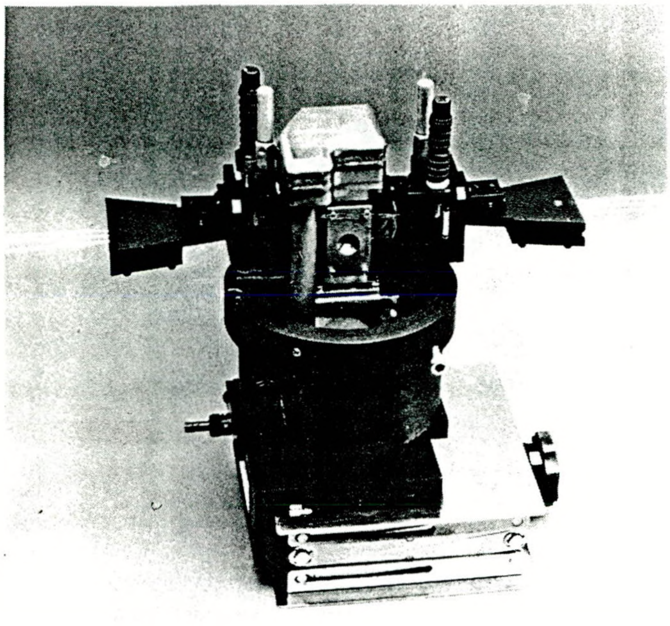

Fig. 4 Photograph of prototype fiber-to-amp relay mounted on a dye amplifier.

Additionally, we have integrated these two pieces of hardware in a partial system configuration. We measured high transmission from the end of copper laser chain to dye laser amplifier. Day-to-day operation is very repeatable and robust.

We are continuing to develop and test the full implementation of the hardware and system.

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R. Edward English Jr. is Group Leader for optical design in the U-AVLIS program. He received a Ph.D. in Optics from the University of Rochester in 1988 for his work in diffraction theory.

Steve A. Johnson is Deputy Associate Program Leader and manager of the optical systems section in the U-AVLIS program He has over 17 years experience of designing, building and operating large high power laser systems.

Both authors can be reached at Lawrence Livermore National Laboratory, P.O. Box 808, L-462, Livermore, CA 94551.