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Laser Science and Technology Update – 1999

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Laser Science and Technology

LS&T laser scientist inside the large-aperture diffractive optics production chamber, where the meter-scale diffraction gratings (used for compressing nanosecond spectrally chirped pulse to femtosecond duration) are produced. The gratings are produced by holographic exposure of a photoresist layer using two interfering 413-nm laser beams. The exposed fine structures are subsequently removed by wet etching and are overcoated with gold.

The Laser Science and Technology (LS&T) Program's mission is to provide advanced solid-state laser and optics technologies for the Laboratory, government, and industry. The primary activities of LS&T in 1998 have been threefold—to complete the laser technology development and laser component testing for the ICF/NIF Program, to develop advanced solid-state laser systems and optical components for the Department of Defense (DoD) and DOE, and to address the needs of other government agencies and U.S. industry.

After a four-year campaign, the LS&T Program achieved timely completion of the laser development effort for the NIF in 1998. This effort includes the special laser and component development, integrated performance testing on Beamlet, and detailed design and cost optimization using computation codes. Upon completing the Title II design review, the focus of the LS&T support effort has been shifted toward NIF laser hardware acquisition and deployment. The LS&T team also continued to develop advanced high-power solid-state laser technology for both the U.S. government and industrial partners. Progress was also made in several new areas: (a) diode-pumped solid-state laser drivers for high-energy-density physics and inertial fusion energy; (b) high-average-power femtosecond and nanosecond lasers for materials processing; and (c) femtosecond lasers for the generation of advanced light sources.

Completion of NIF Laser Component Development

The NIF laser technology development effort was successfully completed in 1998. All key components required for deploying the NIF's 1.8-MJ laser system were developed and tested. These components include the optical pulse generator, main amplifier, power conditioning, plasma electrode Pockels cell (PEPC), beam control, and integrated computer control systems. The overall system performance was tested at full-scale aperture in the Beamlet facility. Data collected from Beamlet were subsequently used by the engineers to validate the design and cost of the NIF laser. Timely completion of this development effort enabled the NIF Project to maintain its schedule to proceed toward the first-bundle operation and target experiment beginning in 2002.

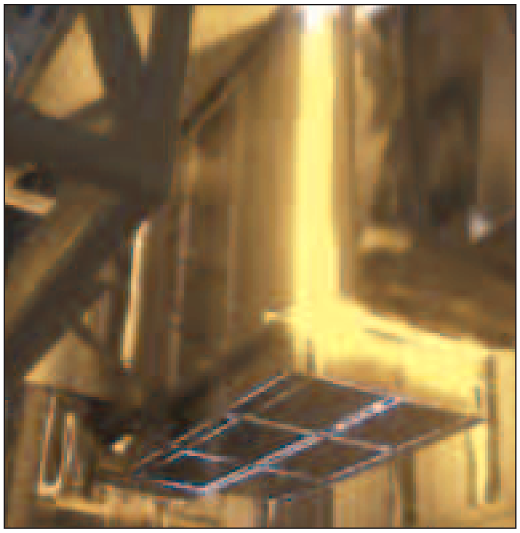
The front end of the NIF laser chains is an optical pulse generation system that consists of an optical fiber-based master oscillator, fiber amplitude and frequency modulators for pulse shaping, and a fiber amplifier network that delivers nanojoule-level inputs to the 48 preamplifier modules. In 1998, LS&T assembled a prototype optical pulse generation system and successfully verified its performance at NIF operating conditions.

Progress was also made in the NIF laser amplifier area. The Amplifier Module Prototype Laboratory (AMPLAB), a facility specifically constructed for testing of full-scale NIF amplifiers, was in operation in 1998. Amplifier gain, gain uniformity, prompt pump-induced wavefront distortion, and thermal recovery time of amplifier structures were systematically measured under various operating conditions. Engineering data on amplifier assembly, maintenance, and cleanliness requirements were also obtained. Current results indicate that the residual optical distortion introduced by the preceding laser pulses can be adequately reduced within a 7-hour time frame. To develop qualified vendors for the NIF, the AMPLAB engineers worked closely with several potential vendors and validated the performance of vendor-produced flashlamps and capacitors.

A NIF-size, 4 × 1 PEPC was constructed and tested. Simultaneous switching of all four apertures was demonstrated with an extinction ratio (which is a measure of the fraction of laser light remaining in the undesired polarization) exceeding that required for NIF operation. A prototype power-conditioning module using a Maxwell/PI sparkgap switch design was also assembled and tested at SNL, Albuquerque. LS&T also completed the development and testing of a 40-cm deformable mirror (controlled with 39 actuators) in Beamlet. The LS&T team was able to build another 40-cm mirror capable of reducing static and pump-induced wavefront distortion to yield an output beam near 2× diffraction-limited. Vendor development to produce large-aperture deformable mirrors for NIF is ongoing.

Development of the NIF computer control system was concentrated on the overall system architecture and supervisory software framework. In the beam control areas, a prototype power balance diagnostic system was developed. This special tool enabled the simultaneous measurement of the power of both 1ω and 3ω beams with high accuracy.

Beamlet completed its main mission as the laser physics and engineering testbed in 1998. During its entire service life, over 1000 full-system laser shots were fired, which supported over 20 experimental campaigns. LS&T demonstrated 1ω output beam quality equivalent to that required for achieving ignition in the NIF. The performance of the final optics assembly was tested under NIF operating conditions (using lasers with fluence near 8 J/cm^2 at 3ω). The final optics assembly consists of large-aperture frequency conversion crystals, a focusing lens, and a diffractive optics package. Beamlet experiments demonstrated that over 73% of the



A full-scale slab amplifier being tested in the AMPLAB facility. The facility is capable of testing 4 × 2 modules (four slabs high by two slabs wide, up to three slabs long) under various operating configurations.

1ω beam power could be efficiently converted to 3ω using rapid-growth KDP crystals. Beamlet experiments utilizing beam smoothing by spectral dispersion (SSD) clearly demonstrated that the current NIF design is adequate to control the uniformity of the focused beam on target.

Upon completing its mission, the Beamlet facility was disassembled. The majority of its components have been shipped to SNL at Albuquerque, where they will be utilized to construct a high-power laser beamlet in the Z-accelerator facility to generate x rays for backlighting experiments. In 1998, LS&T scientists completed a conceptual design for SNL's beamlet. When constructed, Z-Beamlet will have an output of 2 kJ at 2ω with a pulse duration of 2 ns.

Laser Modeling and Optimization

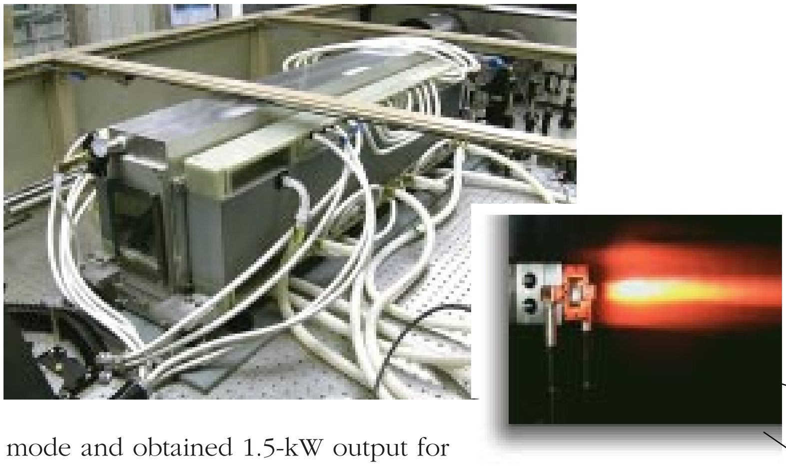
LS&T continues to refine the laser physics models and carry out modeling calculations to optimize the performance of the NIF laser. The majority of the NIF's optical components was examined with an ultimate goal of reducing costs and risks. Wavefront distortion introduced by the mirror fabrication and coating processes was investigated. A comprehensive wavefront correction model that can account for most of the factors influencing NIF beam quality was developed. Current calculation indicates that air turbulence near the main amplifier system can have a large impact on the spot size achievable in the NIF. A 3-dimensional ray trace code has also been developed to model the optical gain and gain profile in the amplifier slabs. Utilizing this code, LS&T scientists have been able to optimize the design of NIF amplifiers with confidence without additional experiments.

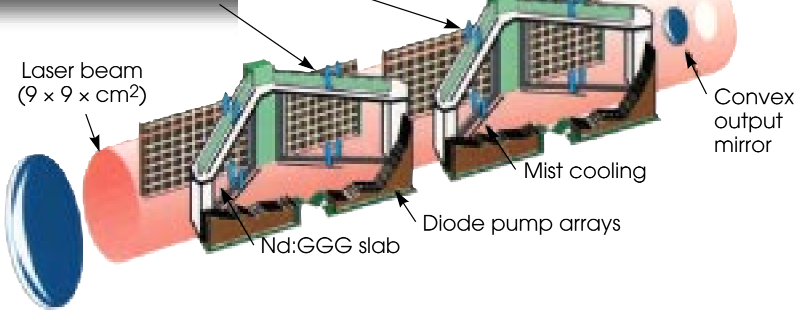
A flashlamp-pumped Nd:glass zig-zag laser (60-J, 600-ns green pulses at 3 Hz with 2× diffraction-limited beam quality) for the Air Force's Advanced Imaging Testbed project at the Starfire Optical Range for use as a satellite illuminator.

High-Average-Power Solid-State Lasers for the Department of Defense

High-power solid-state laser and large-aperture optics capabilities developed by LS&T have many defense applications. In 1998, a flashlamp-pumped Nd:glass zig-zag laser was completed for the Air Force's Advanced Imaging Testbed (AIT) project at the Starfire Optical Range. This laser has four gain modules with four output beams that are phase-locked together in a phase-conjugating cell filled with high-pressure xenon. The AIT laser was delivered to the Air Force Research Laboratory at Albuquerque in January 1998. It can deliver up to 60-J, 600-ns green pulses at 3 Hz with beam quality, coherence length, and pointing stability very close to the Air Force's requirements. The Air Force currently uses the AIT laser as a utility for the satellite illumination experiments. In partnership with a major aerospace company, LS&T is also investigating a high-average-power, high-brightness Yb:YAG rod laser for military target illuminators. When completed, it will have a Q-switched output of >400 W with $M^2 < 3$.

LS&T is working in partnership with Raytheon Corporation to develop a 100-kW-class solid-state laser for the High Energy Laser Strategic Test Facility (HELSTF) in New Mexico. The HELSTF laser is based on LLNL's heat-capacity operation concept. When completed, it will be pumped by high-power laser diode arrays and will be capable of delivering 100 kW-to-MW output power (burst mode for the duration of several seconds) for point defense against tactical missiles. In 1998, using flashlamps as a surrogate pump source, LS&T successfully demonstrated laser operation in the heat-capacity





A heat-capacity laser testbed using flashlamps as a surrogate pump source operated to investigate beam quality limits. The schematic shows the configuration of a 100-kW diode-pumped prototype developed for the Army's HELSTF. A 10-bar prototype monolithic diode array is operational and delivers 300 W at 940 nm.

mode and obtained 1.5-kW output for 10 s from a three-slab testbed. LS&T scientists also investigated several diode cooling and packaging techniques. A monolithic microchannel cooler, capable of removing waste heat from the diode arrays at 1 kW/cm^2, was designed and tested. A 10-bar prototype monolithic diode array was operated. An adaptive resonator cavity was also developed to control the beam quality of heat-capacity lasers. Vendor development to produce low-cost laser diode bars and diode coolers for HELSTF is ongoing. In support of a Laboratory Directed Research and Development (LDRD) project, LS&T is also investigating a high-power Yb:YAG thin-disk laser for possible tactical weapons applications.

Low-Cost and Reliable Solid-State Laser and Optical Material for AVLIS

To further reduce the capital and operating costs of the potential future AVLIS plant, LS&T continued to evaluate low-cost solid-state lasers and optical materials for AVLIS. In 1998, LS&T developed a tunable, line-narrowed all-solid-state fiber laser system for AVLIS as a possible replacement for the dye master oscillator currently planned for a plant. By frequency summing the output from a diode-pumped Yb:silica fiber with that of a Nd:YAG laser in a periodically poled lithium niobate crystal, LS&T successfully generated over 50-mW output in the visible range. The overall system is very compact and reliable and can be manufactured at low cost. LS&T scientists are also exploring new optical materials that can be used for frequency doubling under noncritical phase-matching conditions using innovative inorganic crystals with chemical structure similar to that of Gd-COB.

Diode-Pumped Solid-State Laser for IFE

Flashlamp-pumped Nd:glass lasers are ideal for demonstrating fusion, but MJ-class, repetition-rated lasers with higher electrical efficiency are required for driving an inertial fusion energy (IFE) power plant. In 1998, LS&T completed facility construction for a diode-pumped solid-state laser (Mercury), which will be the first of a new generation of laser drivers for high-energy-density physics and inertial confinement fusion. The Mercury laser is based on gas-cooled, diode-pumped, crystal laser technology. The current design has several unique features over that of the flashlamp-pumped systems: (a) employing near-sonic helium to cool the laser slabs, (b) using high-power and efficient laser diode arrays as a pump source, and (c) utilizing Yb-doped strontium fluoroapatite (Yb:S-FAP) as the lasing media. Yb:S-FAP has greater energy storage capability, has higher thermal conductivity than Nd:glass, and is an ideal material for fusion applications. High-power laser diode arrays with peak output irradiance near 1 kW/cm^2 were fabricated. Gas cooling of the amplifier slab was demonstrated, and several

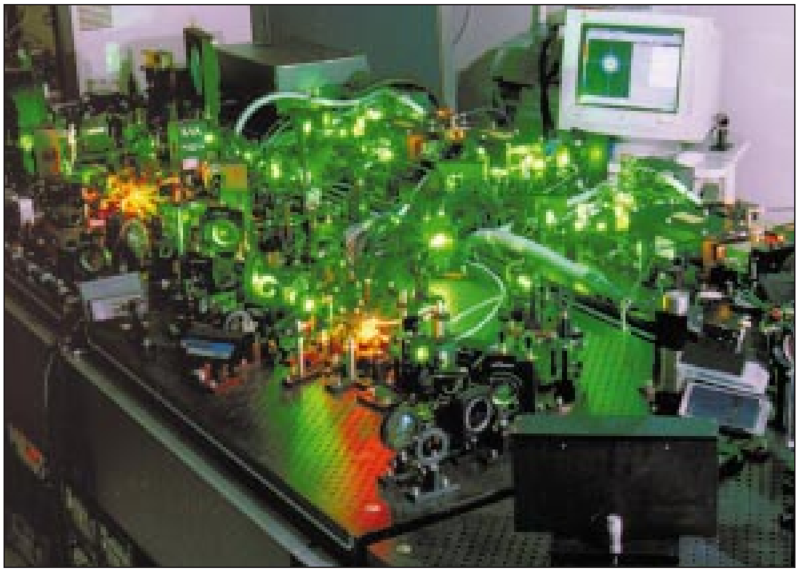
Yb:crystals have been grown for initial optical testing. Full operation of the Mercury facility is planned for 2001. When completed, it should deliver 100 J at 10 Hz with 10% efficiency.

Petawatt Laser and Large-Aperture Diffractive Optics

The Petawatt laser facility was in full operation in 1998. It routinely produced more than 500-J laser pulses at 500-fs and supported a series of experiments to evaluate the fast-ignitor concept, generate MeV fast electrons or x rays for radiography research, and produce ps-100-MeV γ-rays (at 5 × 1020 W/cm^2) for nuclear physics experiments. One of the critical technologies enabling the generation of petawatt laser pulses was the manufacturing of large-aperture and high-damage-threshold diffraction gratings for chirped pulse compression. Using both holographic and direct digital patterning, LS&T engineers successfully manufactured tens of large-aperture diffraction gratings as well as prototypical color separation gratings and kinoform phase plates for the NIF. LS&T is also developing large-aperture Fresnel lenses for space applications, which have a number of inherent advantages over conventional lenses. They can be made very thin and lightweight and have a much greater tolerance to surface-figure aberrations compared to a mirror. In 1998, LS&T developed a replicating process for fabricating Fresnel lenses for space-based applications. The aim is to eventually produce multimeter-size Fresnel lenses using thin membrane. LS&T engineers have also developed an Alvarez lens pair to correct astigmatism in the AVLIS laser systems. (An Alvarez lens pair consists of two phase profiles fabricated on two separate optics that enable the introduction of a variable amount of second-order aberration in the beam.)

Femtosecond Lasers for Advanced Light Source Development

Under the support of LDRD funds, the LS&T Program is building a high-average-power, high-peak-power femtosecond laser facility, FALCON, for advanced light source development. The goal of FALCON is to generate a 100-TW repetitively pulsed laser system that can deliver ultrashort pulses with energy ~4 J, a pulse width of 30 femtoseconds, at a repetition rate of 0.5 Hz. When completed, LS&T will integrate the output from FALCON with the 100-MeV electron beam generated by the linear accelerator (Linac, located in the basement of Building 194) to produce ultrafast x rays for a number of experiments of importance to the Laboratory's Stockpile Stewardship Program. Major experiments include the measurement of the dynamical properties of materials under shock compression conditions. The FALCON laser currently produces 5-TW, femtosecond pulses at 10 Hz. The beam transport system and final target chamber for laser–electron interaction are under construction. The goal in 1999 is to demonstrate laser–electron synchronization and to perform the scattering experiments using the 20-TW, 35-fs laser beam and Linac's 5-MeV electron beam.



A fully automated femtosecond laser cutting machine developed by LS&T, which will be installed and operated on the factory floor at the Y-12 plant. This turnkey laser system has an output of 15 W and can cut materials with very high precision, small kerf, and minimal heat-affected zone.

Materials Processing Using High-Power Solid-State Lasers

Spin-off developments of LS&T's high-power solid-state laser technologies provided several unique machining tools for government and commercial needs. In 1998, LS&T developed a fully automated femtosecond laser system for DOE's Y-12 Plant for use as a precision cutting machine in the Stockpile Life Extension Program. This high-repetition-rate Ti:sapphire laser has an output power of 15 W and can cut materials with very small kerf and with a minimal heat-affected zone. This precision cutting machine, a first of its kind, is currently being used daily on Y-12's factory floor as a utility. Several U.S. auto and aerospace companies are also working with LS&T to develop short-pulse laser systems for precision machining of high-value components. High-quality thin films were also produced using the femtosecond laser as an ablation source. The high-energy plasma generated during the ablation enables the deposition of smooth films without the presence of particulates. LS&T scientists were able to deposit high-quality films, such as diamond-like carbon, on various substrates at a high rate.

Under a Cooperative Research and Development Agreement partnership, LS&T developed a high-energy pulsed laser system for the Metal Improvement Company, Inc., for use as a shock-peening tool for treatment of metal surfaces. In the peening process, the output of a pulsed high-energy laser (AIT-type laser with an output of 100 J/pulse and pulse duration of 20 ns) is condensed to approximately 200 J/cm^2 and is directed onto the surface of the work pieces. With an appropriate absorptive/insulating coating and a thin overlay of transparent material, a high-pressure shock wave of 10,000 atmospheres (150,000 psi) can be generated across the metal surface. This shock treatment process induces deep residual compressive stress, which results in improved resistance to fatigue, galling, and stress corrosion. The shock-peening process can potentially be used by the aerospace industry to build safer, more reliable, and longer-lasting jet engines, helicopter gears, landing gears, and airframe structures. An important DOE application may be in enhancing corrosion fatigue resistance for nuclear waste storage containers. Laser treatment will also result in improved lifetime and reliability for many medical components, such as replacement of hip joints. By eliminating fatigue failure in orthopedic implants, one could improve the healing success of bone fractures. LS&T's high-power and high-energy solid-state laser technologies allow for the first time high-throughput implementation of laser shock processing.

Solid-State Laser for Active Remote Sensing

In partnership with LLNL's Nonproliferation, Arms Control, and International Security (NAI) Directorate, LS&T has developed a high-repetition-rate, frequency-agile, solid-state differential absorption lidar (DIAL) system for airborne chemical remote sensing. Tunable output in the mid-infrared region is generated by an optical parametric oscillator (OPO), using periodically poled lithium niobate crystals as the nonlinear material and a diode-pumped Nd:YAG laser as the pump source. Frequency tuning is achieved by changing the angle of the pumping beam in the OPO using an acousto-optics beam deflector. LS&T successfully demonstrated stable output of 3 W at 10 kHz and wavelength tunability at the 3.2- to 3.6-μm region. A prototype laser system has been built and will be mounted on an Air Force C-135 aircraft for airborne field tests in 1999. This will be the first demonstration of a frequency-agile, solid-state lidar system for simultaneous detection of multiple chemicals.

A compact, high-repetition-rate, frequency-agile, solid-state DIAL system (3 W at 10 kHz, tunable 3–4 mm, optical parameter oscillator) for airborne chemical sensing experiments.

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