



Solid-State High-Energy LASER WEAPONS

Jeff Hecht

For better or for worse, the dramatic advances in semiconductor and solid-state lasers that have made many gas lasers obsolete are finding application in the realm of laser weaponry. High-power diode-pumped solid-state lasers promise the military the same advantages they offer industry: greater efficiency in a package that is far more portable and compact. But with the development of high-energy laser weapons come tough questions about the dangers of eye injury, both to soldiers and noncombatants.



When Ronald Reagan created the Strategic Defense Initiative twenty years ago, one of the biggest problems faced by developers of high-energy lasers was literally getting them off the ground. At the time, one well-placed laser scientist was said to have joked that laser weapons were so massive that their only military use would be to drop them on the enemy. The biggest testbed, a deuterium-fluoride laser called MIRACL (for Mid-InfraRed Advanced Chemical Laser) generated an impressive two

megawatts of power for a few seconds at a time. Yet the massive laser needed a fuel-flow system like a rocket engine because of its thirst for chemical fuels.

Twenty years ago, solid-state lasers weren't even in the race. Continuous diode lasers topped out at tens of milliwatts, and diode-pumped solid-state lasers were feeble. Today, diode laser arrays can generate tens of kilowatts in average power, and lamp-pumped solid-state lasers have exceeded average powers of 10 kW in 10-second bursts. Military developers

Solid-state 13-kW heat capacity laser.
[Courtesy Lawrence Livermore National Laboratory.]



Full-size engineering model of a conceptual 100-kW laser system mounted on an actual hybrid-electric Humvee. This model includes representations of a full operating system including batteries, electrical pulsers, laser head, thermal management, beam transport and a beam director. It was developed in conjunction with General Atomics, Integrated Defense Technologies and B.F. Goodrich. [Courtesy Lawrence Livermore National Laboratory.]

expect diode-pumped solid-state slab lasers to hit the 100-kW level well before the end of the decade.

Of course, today's laser weapons are still a long way from the handheld ray guns of science fiction lore. Not counting the power supply, a 100-kW solid-state laser is likely to top a household refrigerator in size. Yet that's still small enough to fit on a plane, ship or small truck, and that's good enough for the U.S. Air Force, Navy and Army to be already making plans to deploy them on the battlefield.

Challenging gas lasers

When Theodore Maiman made the first laser from a small ruby rod in 1960, he demonstrated that solid-state lasers could generate powerful short pulses. Yet infrared gas lasers have long provided the highest continuous—or average—powers because of their efficiency and because of the ability of flowing gas to dissipate waste heat. Military researchers have an affinity for chemical lasers because weapons must

be mobile, and because chemical fuels pack much more energy per kilogram than batteries. The biggest laser weapon in development today, the Airborne Laser, is a megawatt-class chemical oxygen iodine laser (COIL) being installed in a Boeing 747 for tests against a ballistic missile in 2004. Solid-state lasers have yet to approach the megawatt class, but they are poised to challenge gas lasers in the 100-kW class.

When it was used to shoot down missiles and an artillery shell in tests at the White Sands Missile Range, the U.S.-Israeli Tactical High Energy Laser (THEL), based on a deuterium-fluoride laser, occupied five trailers. In the planned mobile THEL, the laser will be squeezed into one trailer and the fuel into a second. The Air Force employs a COIL in its 70-kW Advanced Tactical Laser, which is intended for use in a C-130 transport or a large helicopter. But chemical fuels are hazardous, raise logistical issues and can run out. Solid-state lasers promise what military developers call “a deep magazine,” one that

can continue firing for longer periods of time. They can also operate in a repetitive-pulse mode that enhances absorption as well as the effects of laser energy on the target.

High-efficiency pumping

Dramatic improvements in diode laser power and efficiency are driving the trend. At high powers, some diode lasers can convert more than half the input electrical energy into light, yielding an impressive 50% efficiency rate. The beam quality of diode lasers is generally too poor to focus high powers onto a distant military target, but their raw power can be efficiently converted into a high-quality beam by pumping a solid-state laser. Matching the diode-laser wavelength to the pump band of the solid-state laser allows pump efficiencies of up to 80% in the laboratory. In contrast, lamp pumping is, at best, only about 1% efficient.

The payoff is in lower heat loading and drive power. It takes 1 MW of electrical input to generate 10 kW of light from a lamp-pumped solid-state laser, with the remaining 99% of the input energy winding up as waste heat which must be removed from the laser. In contrast, 1 MW of power can generate 100 kW from a diode-pumped laser, according to Brent Dane of Lawrence Livermore National Laboratory (LLNL). That means that a lamp-pumped laser, as it emits light, would have to dissipate 99 times as much energy as heat. A diode-pumped laser would have to dissipate only nine times as much heat—and that includes the energy needed to operate the cooling system.

Slab technology vs. phase-locked arrays

Two solid-state laser designs are in the running. LLNL's solid-state heat capacity laser is based on the slab laser technology already used in industry. Dane says the large, unstable resonator with a single aperture is robust enough to withstand use in vehicles. The alternative is an array of fiber lasers phase-locked so their outputs combine coherently into a single beam. The Air Force is looking at that approach for the Joint Strike Fighter being developed by Lockheed Martin. Rudy Martinez, directed energy senior scientist

at the Air Force Research Laboratory in New Mexico, says the advantages of the phase-locked fiber laser array approach include simple optics, high efficiency pumping, single-mode output and easy cooling of the fibers.

High-power solid-state development

Dane's group at LLNL is working toward demonstrating, by 2007, a 100-kW solid-state laser that the Army can mount on a hybrid electric version of its highly mobile multipurpose wheeled vehicle (Humvee). The researchers have already made their first solid-state heat capacity laser, in which banks of flashlamps pump nine disks of neodymium-doped glass. The lamps draw one megawatt of electricity, driving the laser to fire pulses of 500 joules or more 20 times a seconds for several seconds, for an average power of 13 kW. The laser drilled a 1-cm hole through a 2-cm stack of steel plates in just six seconds during December 2001 tests at the White Sands Missile Range.

To raise the average power to 100 kW, the scientists plan to switch to diode pumping, increase the repetition rate to 200 Hz, and replace the glass slabs with Nd-doped gadolinium-gallium garnet (GGG). The crystal is both stronger and more conductive than glass, so it can handle the higher heat load. Nd-GGG also converts pump light to laser output more efficiently. The major obstacle is the need to grow high-quality crystals up to 20 cm in diameter; the biggest so far are 15 cm. Each output pulse will last 300–500 microseconds, with peak power of 1–2 MW.

Cooling the densely packed pump diodes is a challenge because they must operate near room temperature, a factor which rules out forced-air and radiative cooling. To solve that problem, LLNL engineer Barry Freitas mounted the lasers on silicon substrates permeated by 30- μ m channels that carry cooling water. That solution has allowed the arrays to emit 8-kW average powers. Scientists at LLNL are also testing arrays, developed by Armstrong Laser Technology, which are cooled by water flowing through a more conventional copper microchannel flow system.

To prevent heat build-up in the Nd-GGG slabs, each module will include a pair of slabs which can slide back and forth from the pump chamber to a cooling



Saber 203 Laser Illuminator. [Courtesy Air Force Research Laboratory.]

Nonlethal Lasers

In early November 2002, the National Academy of Sciences released a report that generally endorsed the use of "non-lethal" weapons. In the shadow of the disastrous Russian use of a supposedly non-lethal gas to subdue Chechen hostage-takers in Moscow, most attention was focused on chemical agents. Yet the report also touched on several laser technologies which could become controversial. Most have not yet been tested in the field.

The U.S. has tested laser "dazzlers," which use bright, visible beams to flash-blind, scare or disorient. A red diode laser illuminator, the Saber 203, was effective in Somalia because it was attached to a grenade launcher and people thought a deadly weapon might follow the beam. The illuminator was never fielded routinely because it was ineffective in daylight and raised eye-safety concerns. A similar device, called HALT, is mounted on an infantry rifle, and a handheld "Dissuader" works like a flashlight. Both use red diode lasers, although dual red-blue versions are being investigated.

An alternative is the veiling glare laser, which would obscure vision by inducing visible fluorescence in the eye itself with an ultraviolet laser beam at 360–440 nm. The fluorescence would appear diffuse and defocused, obscuring vision. The report warns that the potential for damaging the retina or other parts of the eye remains unknown.

Higher energy lasers are being investigated for two types of nonlethal antipersonnel systems. One is the pulsed-energy projectile, which would use pulses from a distributed feedback (DF) chemical laser to ionize a plasma at the target—presumably the person's clothing—that would generate a painful pressure wave. The pulsed impulsive kill laser, developed by the Army Tank, Automotive and Armament Command, embodies a similar concept that has been demonstrated with a pulsed DF laser, but could be extended to solid-state lasers. Developers say its range could reach 2 km and that it could be used in crowd control or battles.



area. As one slab cools, the laser fires using the other slab, then automatically swaps slabs so the second can cool. Adaptive optics will be used if necessary to correct slight alignment differences, as well as to compensate for distortion.

In March or April of 2003, in an attempt to test and adjust their design, scientists at LLNL plan to fire up a 15-kW diode-pumped laser powered by lithium-ion batteries. The next step will be to build a submodule for the planned 100-kW laser, an approach that has already been used at LLNL in the construction of large solid-state fusion lasers. Plans call for the submodule to deliver about 25 kW, and be finished by the end of fiscal year 2004.

Researchers at LLNL plan a series of additional demonstrations, starting with a 15-kW diode-pumped laser powered by lithium-ion batteries. The target for 2007 is to deliver a 2-m long, less than 1-m wide package, powered by the Humvee's on-board generator and batteries, that is capable of firing 10-second bursts averaging 100 kW. In reality, Dane says, "typical engagements of threats of interest are going to take place for 0.5–2 seconds." After each target is destroyed, the laser will need 1.5–3 seconds to acquire, track, stabilize and engage the next target. The Army Space and Missile Defense Command plans to target rockets and artillery at ranges of 1–10 km.

Laser-armed fighter jets

The Air Force wants to put similar 100-kW solid-state lasers on board one version of the F-35 Joint Strike Fighter that it hopes to begin deploying around 2010. Fighters, which must be sleek, fast and highly maneuverable, can't carry heavy loads but need the latest in weapons. The solid-state laser could take advantage of a 27,000-horsepower drive shaft that will run along the length of an F-35 version originally designed for vertical landings. Replacing the vertical landing fan with a generator could provide a "basically bottomless source of electrical energy" for a laser, says John Kent of Lockheed Martin.

The Air Force plans to start laser tests at about the same time the first F-35s are deployed in 2010, with another five or more

years to adopt a laser-equipped version of the F-35 for battlefield use. Since the F-35 is a stealth fighter, designers must avoid obvious protrusions that could reflect radar. Initially the laser could emit through a hole in the bottom of the plane, allowing pilots to shoot downward, says Kent. Pilots could maneuver the plane to shoot at other targets, and future versions could have beam apertures on top and bottom.

A 100-kW laser wouldn't have to vaporize targets. "The nice thing about lasers is that they're very precise," says Martinez. "When you have a truck, you might want to hit one tire or the fuel tank or the engine compartment." A laser beam aimed at the engine could "cook it and it's dead, but you haven't hurt anybody," says Martinez. With a 1-ft beam from an aircraft-mounted laser "you could take out one terrorist" in an urban environment. A laser also could destroy cell phone towers, communication lines, power grids and fuel depots—without the extensive collateral damage caused by bombs. Laser-equipped fighters could target vulnerable parts of enemy aircraft. Near-infrared beams could go right through a plane's plastic canopy into the crew compartment, knocking out instruments and sensors—and possibly blinding crew members. That possibility, and the dangers of stray laser beams to those on the ground, raise the sensitive issue of blinding lasers.

Eye vulnerability

The position of authorities at the Pentagon is that eyes are not legitimate targets for laser weapons. "It's not a humane thing to go after the air crew members and blind them," says Martinez. A protocol adding blinding lasers to inhumane weapons covered by the Geneva Convention was adopted in 1996 and ratified in 1999 by the United States. Yet just as stray munitions can cause grievous wounds, so stray laser beams can blind.

From the protocol's legal standpoint, the critical question is one of intent. The protocol bans laser weapons "specifically designed" to blind. Yet it explicitly excludes blinding "as an incidental or collateral effect of the legitimate military employment of laser systems." That excludes

existing laser rangefinders and target designators, as well as high-energy laser weapons intended to destroy military targets. It outlaws only laser systems at intermediate power levels that specifically target eyes, which no country is likely to admit making.

From a practical viewpoint, the real issue is the danger of inadvertent exposure to eye-damaging levels of laser light. Even testing under controlled conditions can pose problems, an Air Force study has shown. Rough calculations for a megawatt-class laser show that its unattenuated beam would remain an eye hazard for a distance of 28,000 kilometers! Interaction with the atmosphere doubtless would reduce its intensity, but the beam still could stray from any conceivable test range, potentially endangering civilians on the ground or in aircraft outside the range. In training exercises, it's easy to predict the areas in which the beam would remain dangerous. It's not easy in battle situations, such as when a fighter pilot is given the difficult task of striking military targets in civilian areas. The beam can be pinpointed at critical radio towers, but some of the laser energy is sure to reach the people behind them.

Reflected light poses a larger problem, albeit over a much smaller area. Angles shift continually as a moving laser illuminates a flying target such as a missile. If a laser targets a truck engine, some of the light is sure to be reflected onto the soldiers inside. Targets pinpointed in civilian areas likewise will reflect potentially dangerous levels of light in unpredictable directions. Soldiers from the U.S. and other developed countries are likely to come equipped with laser safety goggles; non-combatants are not.

Like any military development, high-energy laser weapons bring both gains and perils. Pinpoint laser beams should do far less damage to areas surrounding their target than bombs. Yet some people in the vicinity might survive only at the price of seriously impaired vision.

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