NEW ADVANCES IN DEFENSE APPLICATIONS

HIGH-ENERG

An artist's rendering of a fully operational maritime laser demonstrator.

Office of Naval Research/ Northrop Grumman

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GY LASERS

In March 2014, Rear Admiral Matthew Klunder, chief of naval research, tracked targets using the Laser Weapons System on a tour of the U.S. Naval Directed Energy Center.

Courtesy of U.S. Navy/John F. Williams

Directed-energy weapons systems could provide efficient, cost-effective countermeasures in an age of drones and other airborne threats. Recent scientific and engineering breakthroughs are bringing these systems closer to deployment.

Long before George Lucas conceived of the Death Star with its super laser focused on Alderaan, even before H.G. Wells wrote *War of the Worlds* with its hostile aliens and their heat-ray weapon, the Greek inventor Archimedes concocted his own heat ray composed of mirrors to concentrate sunlight and ignite the sails of invading Roman ships. The invention of the first working laser in 1960 further inspired militaries around the world to research and develop high-energy lasers (HELs) for the protection of their troops. While the quest has taken decades, the year 2014 alone has seen numerous milestones come to pass.

In the United States, lasers receive more R&D funding than other directed-energy weapons because they are the most promising for lightweight, effective, low-cost operation. Specifically, energy from HELs can be delivered at the speed of light, unlike the supersonic or subsonic speeds of conventional missiles. Another factor driving the development of HEL weapons is their low shot-to-shot operational cost. Whereas it may cost millions to develop laser weapons, their cost per firing is orders of magnitude lower than that of conventional ballistics and projectiles.

The concept of pointing a powerful laser at a target to vaporize it is a simplistic take on what is actually required to create an operational HEL weapon. The biggest challenge for researchers is creating a laser that can reach high enough powers to partially destroy or defeat a target while tracking numerous objects simultaneously. In turbulent atmospheric conditions, like dust and humidity, the laser must propagate efficiently and stay accurately focused on the target. The system must compensate for the movement of the target, the motion of the platform and the distortion of

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the beam from weather or environmental conditions. The platform must be compact enough to fit on a vehicle or even a soldier's shoulder, while the optics must be ruggedized to withstand shock and high irradiance. In addition to these requirements for size, weight and power (SWaP), they must be safer to use than chemical-based high-energy lasers.

Many engineering breakthroughs have contributed to the current state of HEL technology, which has nearly every branch of the U.S. military and numerous defense contractors approaching solutions to the problem from many different angles. Current projects include the use of commercial-off-the-shelf fiber lasers, diode-pumped solid-state approaches, free-electron lasers and even liquid lasers.

HEL on wheels

In 2008, Boeing Directed Energy Systems (Albuquerque, N.M., U.S.A.) began developing the High Energy Laser Mobile Demonstrator (HEL MD) for the U.S. Army, a solid-state laser system designed to track and destroy rockets, artillery, mortars and drones (RAMD) from ground-based vehicles.

"The UAV [unmanned aerial vehicle] is an increasing threat," says David DeYoung, director of Boeing Directed Energy Systems. "They are small and hard to detect, so intercepting them is difficult, and they are increasingly being used as guided weapons systems."

Although 100 kW is the industry benchmark and goal for the military, several defense contractors are demonstrating the destruction of RAMD with lower-power systems. The prototype HEL MD system incorporates a commercial-off-the-shelf 10 kW solid-state fiber laser at an infrared (IR) wavelength around one micron. Fiber lasers typically require less power to maintain high beam quality and are more compact than other HEL designs. The laser and beam control system are mounted on a truck adapted to carry the laser and its accompanying cooling system. The adaptive-optics system, a subset of the beam control system, uses mirrors, high-speed processors and high-speed optical sensors to reshape and align the beam so it focuses directly on the target in real time. In November 2013, Boeing tested the HEL MD system at the White Sands Missile

A selection of ongoing high-energy laser weapons projects

▸ Area Defense Anti-Munitions (ADAM)

U.S. GOVT. AGENCY	None (commercial venture)
CONTRACTOR	Lockheed Martin
DESCRIPTION	Fiber, commerical off-the-shelf
POWER	10 kW
STATUS	Prototype stage

▸ Gamma

U.S. GOVT. AGENCY	None (commercial venture)
CONTRACTOR	Northrop Grumman
DESCRIPTION	Solid-state "slab" architecture
POWER	13.3 kW building blocks
STATUS	Initial testing completed in 2012

▸ Excalibur

U.S. GOVT. AGENCY	Defense Advanced Research Projects Agency
CONTRACTOR	Optonicus
DESCRIPTION	Fiber with optical phased array
POWER	10s of kW; scaling to100 kW in next 3 years
STATUS	Demo in 2013

▸ High Energy Liquid Laser Area Defense System (HELLADS)

U.S. GOVT. AGENCY	Defense Advanced Research Projects Agency
CONTRACTOR	General Atomics
DESCRIPTION	Liquid, aircraft-mountable
POWER	150 kW (10 15-kW modules)
STATUS	Final development phase

▸ High Energy Laser Mobile Demonstrator (HEL MD)

U.S. GOVT. AGENCY	Army
CONTRACTOR	Boeing
DESCRIPTION	Solid state; ground platform
POWER	10 kW; 50/100 kW lasers in development
STATUS	Successful test

▸ Joint High Power Solid-State Laser

U.S. GOVT. AGENCY	Army/Air Force/Navy
CONTRACTOR	Northrop Grumman
DESCRIPTION	Solid-state slab
POWER	105 kW (7 15-kW building blocks)
STATUS	Successful maritime testing in 2011

▸ Laser Weapon System (LaWS)

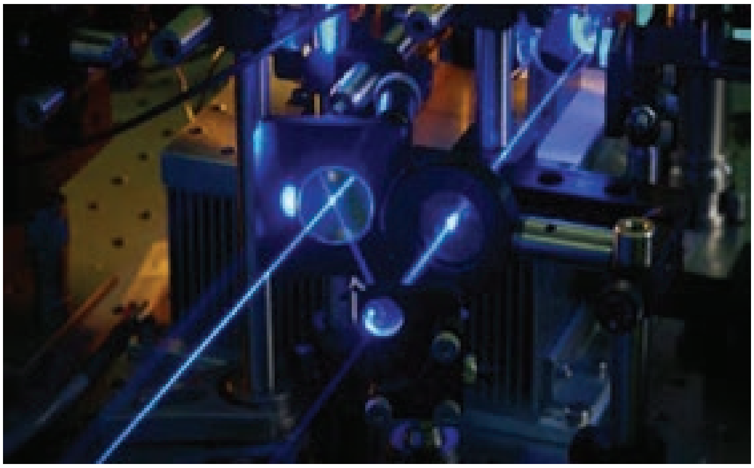
U.S. GOVT. AGENCY	Office of Naval Research
CONTRACTOR	Kratos
DESCRIPTION	Solid state; IR commercial off-the-shelf
POWER	Classified (possibly 15 to 50 kW)
STATUS	Trial deployment; installation on USS Ponce scheduled for summer 2014

▸ Robust Electric Laser Initiative (RELI)

U.S. GOVT. AGENCY	Department of Defense
CONTRACTOR	Lockheed Martin, Northrop Grumman and Boeing
DESCRIPTION	Fiber, truck mounted
POWER	100 kW (goal); 60 kW laser in development
STATUS	Tests of 30 kW in 2013 (Boeing) and early 2014 (Lockheed)

▸ Solid-State Laser - Technology Maturation

U.S. GOVT. AGENCY	Office of Naval Research
CONTRACTOR	Kratos, Raytheon, Northrop Grumman and BAE Sytems
DESCRIPTION	Light tactical-vehicle-mounted
POWER	N/A
STATUS	Design stage



Like this blue beam-combining setup, Lockheed's 30 kW fiber laser combines an array of separate fibers with different wavelengths into a free-space combiner to create one spectrally combined beam. Most high-energy lasers are in the invisible IR region. Lockheed Martin

Range in New Mexico, where it successfully disrupted the trajectory or otherwise destroyed more than 70 incoming mortar rounds and several UAVs.

When it comes to mortars, the advantage of HEL weapons on the battlefield is time. Mortars aren't aloft for very long, and if several mortars are launched simultaneously, a fast radar detection and handoff to tracking mode is critical.

"Within two seconds, the laser is on and we've got a beam on a potential target," said

The LaWS system prototype, designed to be operated by a single sailor for defense against UAVs and small boats, will be the first of its kind to deploy aboard an operational U.S. Naval ship.

Dexter Henson, communications manager for Strategic Defense Systems at Boeing in Huntsville, Alab., U.S.A. "Not only does it work, it works with a 10 kW laser. We surprised some people with the capability of a 10 kW laser."

Another test in early 2014 at Eglin Air Force Base (Valparaiso, Fla., U.S.A.) demonstrated that the HEL MD could acquire, track and target mortars and UAVs in a more demanding maritime environment at up to 5 km away. Whereas the White Sands Missile Range is a hot, dry and dusty environment, the Eglin test exposed the HEL MD system to swampy, high-humidity conditions. The system continued to perform in a heavy rainstorm, even after a lightning strike hit near the system, according to DeYoung.

Performance is still a major challenge for contractors, but the armed services are focused on the savings these HEL systems will provide to taxpayers. A HEL weapon uses US$1 to $5 of diesel fuel to shoot down a UAV, as opposed to a missile costing US$100,000 or more. Lasers are also well suited to defeat UAVs with optical sensors used as intelligence surveillance reconnaissance platforms. A laser directed at an optical camera sensor can disable it without using much power, even at a long range.

"Imagine a hostile threat," says DeYoung. "The warfighter can choose from either missiles or lasers. It gives them more capability. It's like having an infinite magazine. They don't run out of bullets."

While other contractors have agreements with the U.S. Army and other customers to develop more powerful 100 kW lasers to incorporate into the system, Boeing is designing their own 50 kW and 100 kW lasers for later versions of the HEL MD system as well as updates to the accompanying thermal management and power subsystems. These improvements will increase the effective range of the laser and decrease the time it takes to destroy targets.

At-sea testing

In 2014, the U.S. Navy announced that the high-energy Laser Weapon System (LaWS) is ready for installation in late summer 2014 on the USS Ponce for 12 months of at-sea testing in the Persian Gulf. The LaWS system prototype, designed to be operated by a single sailor for defense against UAVs and small boats, will be the first of its kind to deploy aboard an operational U.S. Naval ship. Kratos Defense & Security Solutions (San Diego, Calif., U.S.A.) developed LaWS for the U.S. Office of Naval Research (ONR) to operate via a handheld controller similar to those found on game systems like Xbox and PlayStation.

The LaWS system integrates six solid-state IR beams, tunable to either low output for warning and sensor crippling, or high output for target destruction. The Navy successfully tested the LaWS system in 2011 and 2012 when it took down several small boats and a surveillance drone from the Arleigh Burke-class destroyer USS Dewey—the first ever shootdown of UAVs from a HEL system on a U.S. vessel. In more recent months, a team of 65 Navy engineers and scientists directed by Theresa Gennaro tested the upgraded LaWS system, demonstrating that the tracking system on the pre-existing radar-based Phalanx close-in weapon system (CIWS, or *sea-whiz*) is capable of handling the laser's tracking and targeting functions. The onboard CIWS system targets with an effective range of 1.6 km with an estimated power ranging from 15 to 50 kW.

Data from the USS Ponce test deployment will determine the direction of ONR's Solid-State Laser Technology Maturation (SSL-TM) program, which is tasked with establishing a future acquisition program and providing solid-state HEL weapons capability across the fleet. Under the SSL-TM program, ONR chose contractors Raytheon, Northrop Grumman and BAE Systems as the designated developers of cost-effective, combat-ready HEL prototype systems that can fire 100 kW of power at fast-moving remote targets.

RELI ready

Similarly, the U.S. Army's Robust Electric Laser Initiative (RELI) project awarded several contracts beginning in 2010 to develop an operational 100 kW–class weapons-grade laser system for defensive applications on land, sea and air platforms. For one, Lockheed Martin Laser and Sensor Systems (Bothell, Wash., U.S.A.) received US$14 million under the RELI program in 2010 to design a HEL weapons system that works a bit like an inverse prism, using spectral beam combining of multiple custom fiber lasers with slightly different wavelengths to create a single high-power beam.

Lockheed demonstrated a 30 kW version of its electric fiber laser in January 2014, the "highest power ever documented while retaining beam quality and electrical efficiency," according to the company. The laser system uses 50 percent less electricity than more conventional solid-state designs, which means it requires less cooling and thus takes up less space.

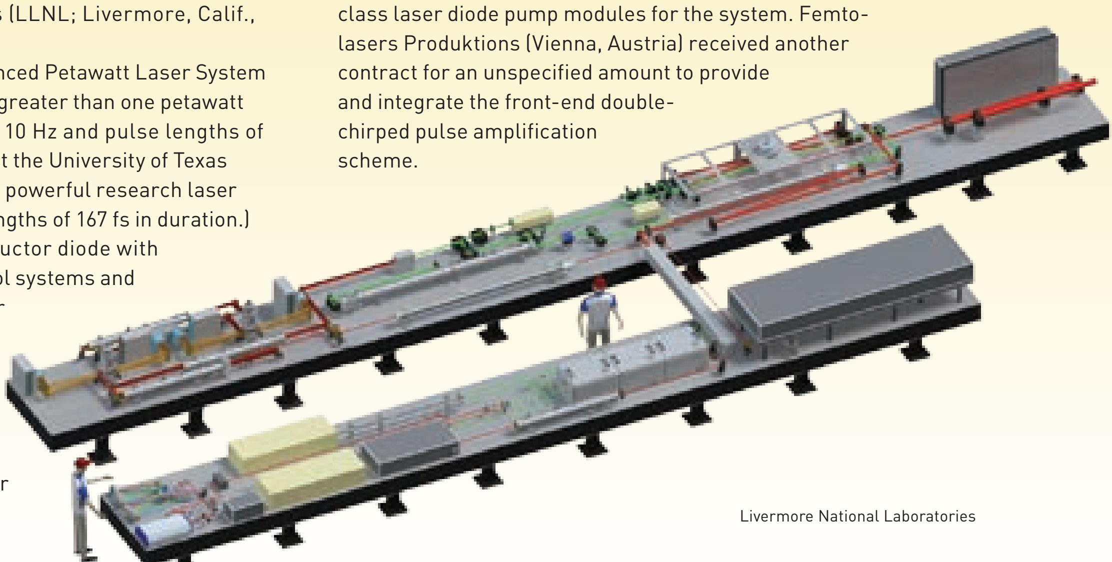
In February 2014, the U.S. Army followed up on this successful testing with a US$25 million contract for Lockheed to take the fiber system to "weapons-grade" at 60 kW. Lockheed claims that a 60 kW system is powerful enough to down fast-moving targets as well as mission systems on military platforms including aircraft, trucks and ships. The next step is to integrate the fiber laser on

THE MOST POWERFUL OF ALL

The value of a high-energy laser weapon lies in its high average power, not high peak power. When it comes to peak power, however, a new laser in development at Lawrence Livermore National Laboratories (LLNL; Livermore, Calif., U.S.A.) wins the prize.

The High Repetition Rate Advanced Petawatt Laser System (HAPLS) will deliver peak powers greater than one petawatt (10^{15} watts) at a repetition rate of 10 Hz and pulse lengths of 30 fs. (The Texas Petawatt Laser at the University of Texas at Austin, in comparison, the most powerful research laser operating today, features pulse lengths of 167 fs in duration.) The HAPLS design is a semiconductor diode with advanced optics, integrated control systems and an ultrashort pulse seed oscillator on the front end. The system is being built for the European Extreme Light Infrastructure Beamlines science facility in the Czech Republic (OPN, 2014 July/Aug, p. 12), and is designed for purely academic research.

As the main developer of the system, LLNL announced in September 2013 a 12-month, US$5 million subcontract award to Lasertel (Tucscon, Ariz., U.S.A.) to develop the megawatt-class laser diode pump modules for the system. Femtolasers Produktions (Vienna, Austria) received another contract for an unspecified amount to provide and integrate the front-end double-chirped pulse amplification scheme.



Livermore National Laboratories

(Left) Lockheed's prototype 10 kW Area Defense Anti-Munitions (ADAM) laser system is a transportable ground-based fiber laser system. (Center) In a test, the ADAM laser system destroyed 11 small-caliber rocket targets at a range of 2 km. (Right) In May 2014, the first maritime tests of the prototype ADAM laser system burned a hole through the rubber hull of a boat moving in the ocean. Lockheed Martin

the Army's HEL MD. The company expects to reach 100 kW within the next year or two.

In May, Lockheed announced the results of testing in another venture, the Area Defense Anti-Munitions (ADAM) system, against rocket and maritime targets. In testing off the coast of California, a prototype 10 kW IR fiber laser system burned through compartments in the rubber hull of two military-grade small boats maneuvering in the ocean at a distance of a mile in less than 30 seconds. The system can track moving airborne rockets and UAVs in flight at a range of 5 km, and can engage targets up to 1.9 km away. This transportable 10 kW fiber laser weapon system shot down eight free-flying Qassam-like rocket targets in tests at a distance of almost a mile in 2013. According to Lockheed, the ADAM architecture is scalable to accommodate higher-power lasers as they become available.

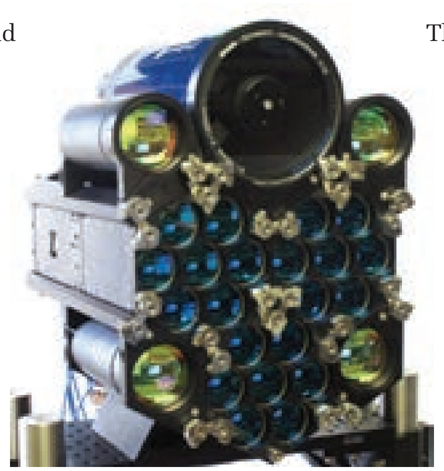
The laser system uses 50 percent less electricity than more conventional solid-state designs, which means it requires less cooling and thus takes up less space.

Doug Graham, vice president of advanced programs, Lockheed Martin Space Systems Company, says, "The next step is to enhance the ADAM system with more powerful lasers. When we designed ADAM four years ago, 10 kW lasers were the most powerful single-mode fiber lasers with good beam quality available. We have shown that 10 kW is adequate to defeat simple threats, but since then, fiber laser technology has continued to mature."

Small, energy efficient and cool

The U.S. Defense Advanced Research Projects Agency (DARPA) is pursuing a conventional optics approach to high-energy lasers with potential application to military weapons or high-bandwidth communications devices. HEL systems are confined by their SWaP limitations, so Optonicus (Dayton, Ohio, U.S.A.) developed a 21-element optical phased array (OPA) for DARPA's Excalibur program, with low power requirements, long-range turbulence correction and scalability. The OPA design consists of three identical clusters of seven tightly packed fiber lasers, each cluster only 10 cm across. The nature of the phased-array design enables control of the individual fiber lasers to correct for atmospheric turbulence at levels comparable to that of conventional optics. The Excalibur array, featuring high power efficiencies of 35 percent and near-perfect beam quality, was used to precisely hit a target more than 6.4 km away.

The Excalibur OPA demonstrated compensation for atmospheric aberration on a sub-millisecond timescale to maximize the laser irradiance at the target. The test was conducted several tens of meters above ground, where atmospheric effects are highly detrimental for aircraft and naval platforms, among other military applications. The array is one step closer to multi-100-kW-class HELs in a package 10 times lighter and more compact than previously tested high-power laser systems.


DARPA and partner Optonicus designed this optical phased array used in the Excalibur demonstration to improve laser weapons performance. Optonicus

When it comes to HEL weapons, one of the biggest challenges is dealing with the immense amount of heat they generate. Although Excalibur is a highly efficient fiber laser system, the cooling requirements are still an obstacle to operation at 100 kW. In a FY2015 budget request to Congress, DARPA's Excalibur program is to be extended under the related Endurance project, which aims to develop pod-mounted lasers to protect aircraft from more advanced surface-to-air missile threats, and would earmark US$13.1 million to miniaturize the components needed for high-precision target tracking, identification and lightweight agile beam control.

"The Excalibur program is in its final few months of effort," said program manager Joseph Mangano. "We accomplished our primary goal of demonstrating the potential for coherently combining the outputs of kilowatt-class lasers into much higher power beams at very high electrical-to-optical efficiency while maintaining the near-perfect beam quality." A follow-on program, Fire Line Advanced Situational Awareness for Handhelds, will address the potential of OPA technology to acquire and track minimally cooperative targets while mitigating the effects of deep atmospheric turbulence.

Another DARPA program, the High Energy Liquid Laser Area Defense System (HELLADS), aims to develop a 150 kW laser weapon system 10 times smaller and lighter than lasers of similar power, for integration onto tactical aircraft, like the Avenger Unmanned Aerial Combat Vehicle from General Atomics (formerly the Predator C). The project goal is to create a HEL system that weighs less than five kg/kW at a size of only three cubic meters. The program is in the final development phase, which will combine two laser modules to generate 150 kW of power. The prototype will then be transported to White Sands Missile Range for testing against rockets, surface-to-air missiles and mortars.

The technology behind HELLADS is a liquid laser in which the fluid lasing medium contains the active chemical species pumped for laser action. While the details of the design are classified, industry veterans have speculated that the liquid is actively cooled to avoid the problems inherent in solid-state HELs.

High-energy laser weapons have matured rapidly in the past several years, reaching many critical milestones. Commercial and scientific ventures have joined together to show that it might not be long before quality, ruggedized systems are deployed in actual military and defense applications. OPN

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