

The new laser weapons

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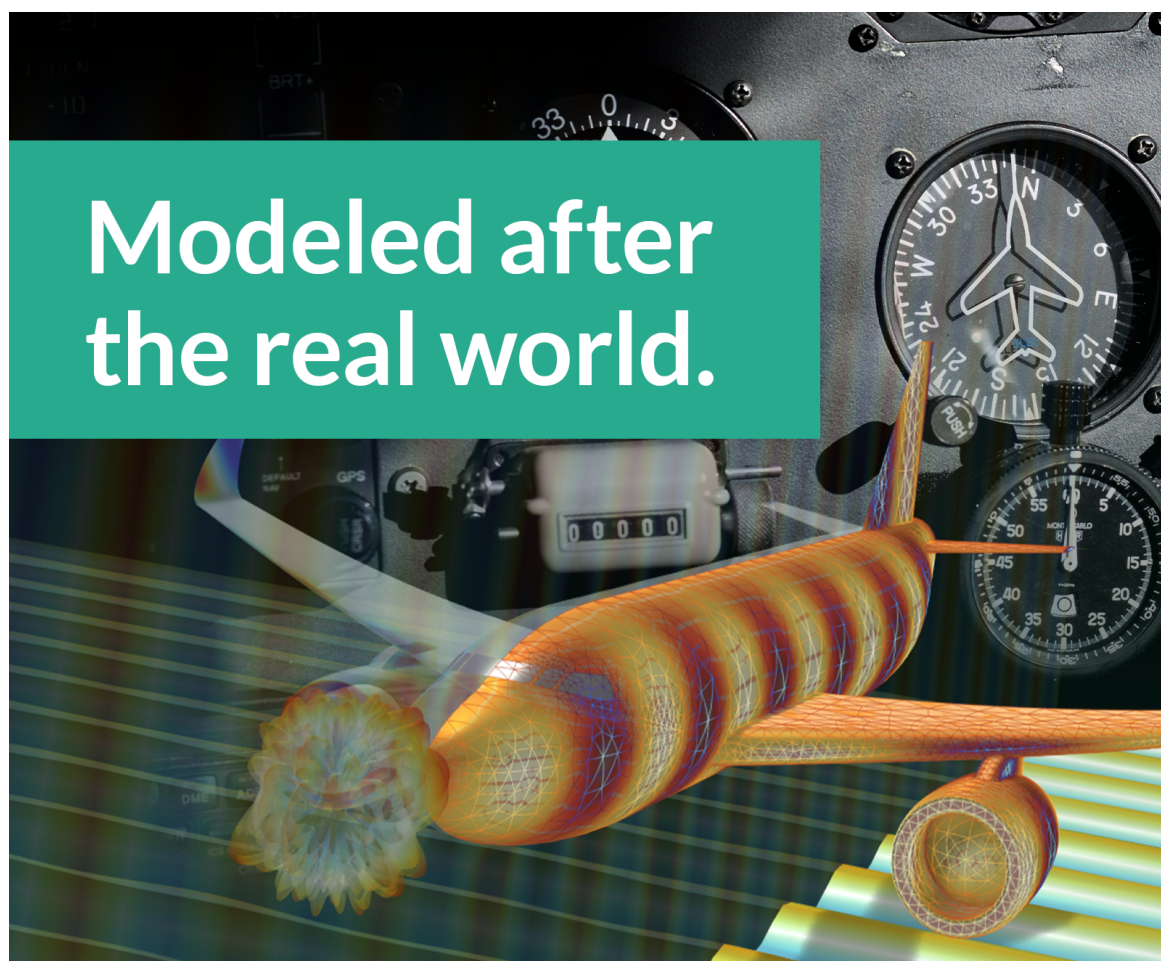


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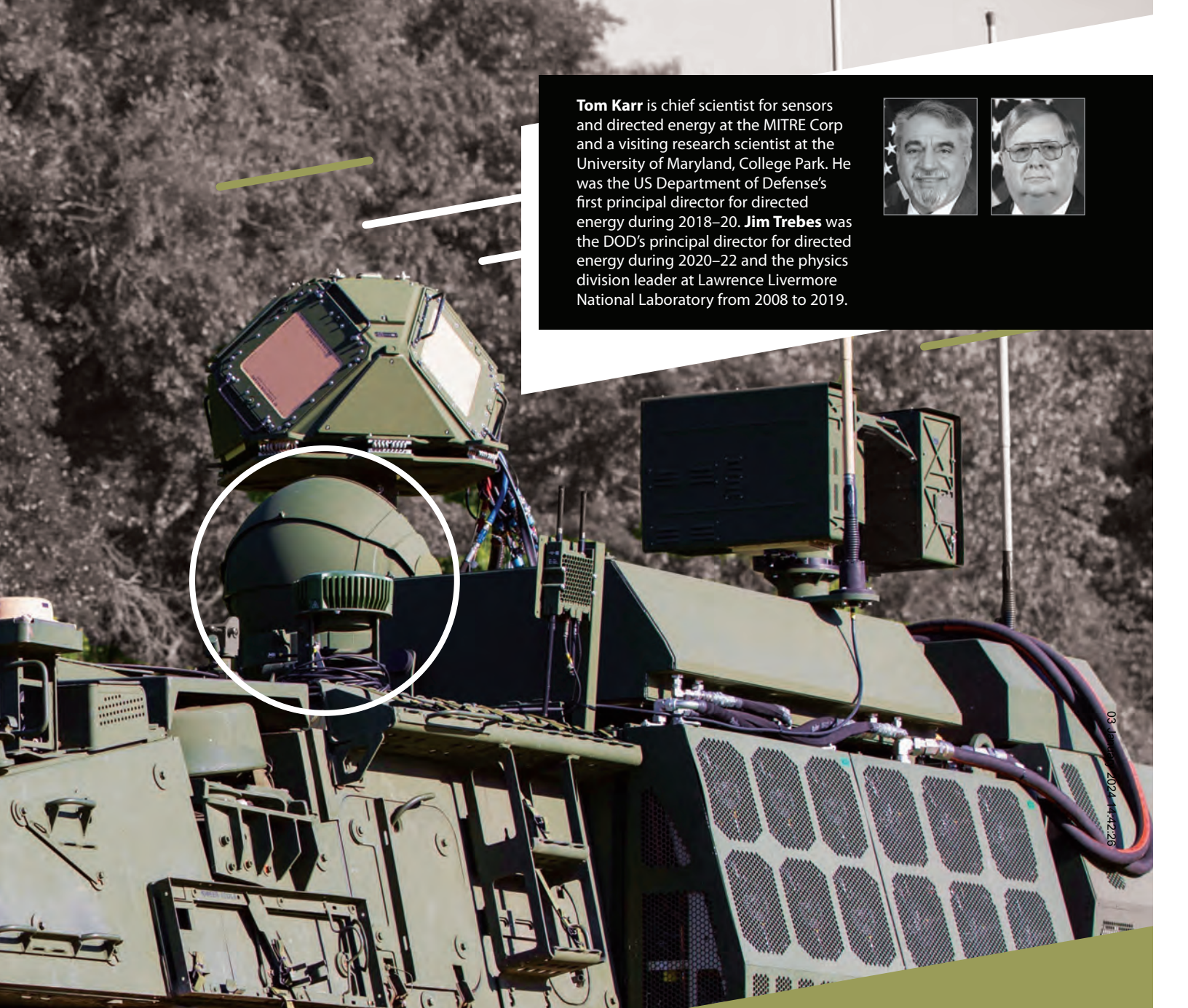
THE NEW LASER WEAPONS

THOMAS KARR AND JAMES TREBES

The US faces a world with a large and growing number of drones and cruise missiles. For tactical defense, military leaders are beginning to adopt a new generation of weapons.



The US Army's Directed Energy Maneuver-Short Range Air Defense 50 kW laser weapon system, mounted on a Stryker armored vehicle. The laser weapon (circled) is the closed clamshell on top of the vehicle; mounted above it is the tracking radar. (Courtesy of the US Army.)



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The US military defines a directed-energy weapon (DEW) as a “device that affects a target by focusing onto it a beam of electromagnetic energy or atomic particles.” The focus of the military’s efforts is on high-energy lasers (HELs) and high-power microwaves (HPMs). HELs include both pulsed and continuous-wave (CW) devices, and their emissions span a broad spectral range—from long-wave IR down to x rays or even gamma rays. HPM devices, by contrast, are pulsed RF beams, whose emission may extend up to the millimeter-wave or higher frequency.

DEWs recently existed only in science fiction, commonly seen in the *Star Wars* movies and in the *Star Trek* television series. Despite the excitement among developers and many billions of dollars in military funding over six decades, lasers and other directed-energy devices were not common operational weapons. Indeed, developers of traditional kinetic-energy weapons (KEWs)—guns, bombs, and missiles, for instance—have jokingly said that DEWs are “the weapons of tomorrow,

and always will be.” But because of recent technical advances and changes in military conditions, they are currently getting a serious reappraisal by military planners, and the US and several other nations are putting them in the field.

The technical advances have led to compact solid-state HELs that are scalable to high power, and the changes in military conditions include an exponential increase in offensive threats that cannot be fully addressed by defensive KEWs alone. Today,

Box 1. High-power microwave technology

Today's high-power microwave (HPM) systems use both vacuum-tube and solid-state microwave-generation technology and operate in single-pulse, multi-pulse, and continuous-wave modes. Vacuum-tube technology traces its roots back to the original vacuum tubes used for radar in World War II. Today the most mature microwave sources—relativistic magnetrons—reach 5 GW power levels. A wide range of tube types and geometries efficiently produce high power over a broad bandwidth—from ultrahigh frequencies (0.3–3 GHz) up to X-band ones (8–12 GHz).⁹

The use of solid-state phased arrays offer increased flexibility, smaller size and weight, and lower cost, compared with vacuum-tube technologies. Improvements in materials processing and manufacturing have led scientists to produce higher-breakdown-voltage semiconductor materials, such as gallium nitride. Research into microwave sources for weapons is currently quite active. Scientists focus on sources that use solid-state and vacuum-based systems capable of flexi-

ble waveforms, wide bandwidth, and high power. They also seek out novel materials that enable high-voltage and high-switching-rate operation.

A target can be attacked with HPMs using two basic methods. The so-called front-door method exploits an antenna on the target to collect the HPM signal and deliver it inside the target, typically to a low-noise amplifier. Enough signal power delivered to the amplifier can damage or destroy it. The back-door method exploits cracks, gaps, and power feeds as pathways that can leak HPM energy into the target, where it can likewise damage or destroy electronic components or subsystems for a mission kill.

An example of a vacuum-tube-based system is the Tactical High-Power Operational Responder (THOR), pictured at top and developed and tested by the US Air Force for counterdrone missions. Its mechanically steered antenna rotates 360°, allowing it to attack any target in its range. Below it is the Stryker Leonidas HPM system, an example of a solid-state system also intended for counterdrone missions



and currently under development by the US Army. The flat panel is a gallium nitride transistor phased-array antenna that produces an electronically steered HPM beam. (THOR photo courtesy of the US Air Force; Leonidas photo courtesy of Epirus Inc.)

the US military fields 21 laser weapons whose average power varies from a few watts to 60 kW, and the Department of Defense's High Energy Laser Scaling Initiative (HELSI) has demonstrated three lasers with an average power of 300 kW in three distinct laser architectures.

This article focuses on laser weapons, which are receiving most of the military's DEW funding. The US and other countries are also developing and testing HPM weapons, but many details are classified, and little information is publicly available. For a summary of the technology, see box 1.

Killing the target

Against a target, a DEW can cause a hard kill—the target's physical destruction—or a soft kill, a mission kill, or a mission defeat, any of which degrades the target enough to render it unable to complete its mission. Imagine a hard kill as a wing being blown off an aircraft, for instance. To be considered a valuable tool, a DEW must also satisfy practical operational constraints, such as cost, operational feasibility, and reliability.

The standard metric of HEL-weapon quality is the fraction of power it can transmit at wavelength λ from an aperture of diameter D onto a target at range R in a "spot bucket" of diameter $3\lambda R/D$ (slightly larger than the central Airy spot of a perfect diffraction-limited beam), referred to as the power in the bucket. Its value has direct bearing on the ability to form a lethal spot on a target at range. The best HELs today produce a near-diffraction-limited beam and put roughly $\frac{2}{3}$ of their power into the bucket.

The more direct question is, How much energy would be needed for an HEL to destroy a conventional drone or missile?

Melting a large enough hole in a cruise missile to destroy whatever mechanism is inside, for instance, would result in a hard kill. Conventional missiles and aircraft are typically made of aluminum, and small drones are usually made of hard plastic, such as polyamide. Ignoring the losses from thermal diffusion, a laser can melt a target's aluminum shell by depositing about 2.8 kJ/cm^3 into the shell, or vaporize it with $\sim 32 \text{ kJ/cm}^3$. The corresponding energy density to melt polyamide is 0.7 kJ/cm^3 , and only slightly more to vaporize it.

But the amount of energy a weapon needs to deliver is also affected by distance. A useful HEL weapon could destroy a threat target in a few seconds at a range well outside the threat's lethal zone—what one might call a tactically interesting range. Consider a hypothetical HEL weapon whose $1 \mu\text{m}$ wavelength emission (a common one for HELs today) through a 0.5 m transmitter aperture is used to attack a threat target at a range of 20 km . The spot bucket on the target would be about 12 cm in diameter and 113 cm^2 in area. The HEL would need to generate about twice the above energy per unit volume to confidently account for losses due to target aspect and reflection, thermal diffusion, and the atmospheric path. Suppose the target's aluminum shell is 1 cm thick. To melt a 12 cm hole, the HEL would have to produce about 550 kJ .

With those weapons and engagement parameters, a 300 kW HEL, today's largest electrical laser, could deposit enough energy to kill the aluminum-shelled target in about 2.5 seconds and the plastic-shelled one in less than a second, preceded by a few seconds of slewing and tracking the target. The US military is very interested in HELs that can destroy targets so quickly. HELs with much lower energies—as little as a few millijoules per pulse—

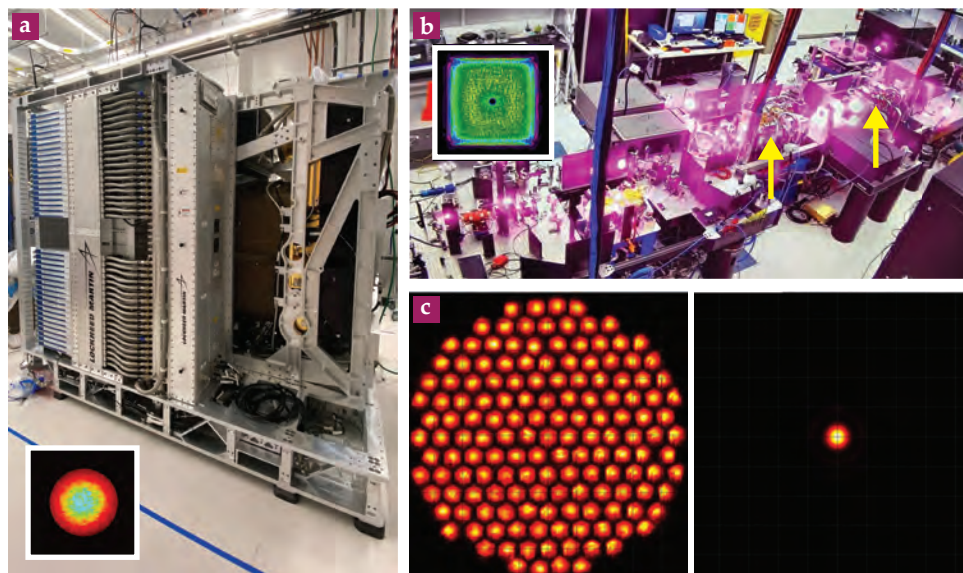


FIGURE 1. HIGH-ENERGY LASERS, produced by the scaling initiative coordinated by the Department of Defense. **(a)** This photograph of Lockheed Martin's 300 kW spectral combined fiber laser shows the edges of module boards (each of which contains a fiber laser), the pump diodes, and the control system. The inset shows the laser's far-field near-Gaussian irradiance pattern. **(b)** General Atomics' 300 kW distributed-gain laser is pictured in operation. Yellow arrows point out the compact laser-gain cells, and the inset shows the output beam's uniform near-field irradiance pattern. **(c)** The near-field (left) and far-field (right) irradiance patterns show the high quality of nLIGHT's 300 kW coherently combined fiber laser. (Photos and images courtesy of and adapted from the Naval Surface Warfare Center Dahlgren Division.)

are able to damage IR sensors, and even lower-power lasers (on the scale of 1 W) can “dazzle” (or blind) those sensors.

In the 1980s and 1990s—the Strategic Defense Initiative, or “Star Wars,” era—developers were striving to make weapons capable of killing intercontinental ballistic missiles in their boost phase over thousands of kilometers. At the time, the primary HELs of interest were gas lasers: hydrogen fluoride lasers, deuterium fluoride lasers, and the chemical oxygen–iodine laser, all of which derived their power from chemical reactions. Weapons developers believed they could scale up chemical lasers in power, at least conceptually—the trick was to just use more gas in the gain cell—but they had difficulty building a gas laser that met practical military constraints, had a high average power, and had a high-quality, near-diffraction-limited beam.

During that era, US HELs were heavy, occupied large facilities, and used hazardous materials—all operational drawbacks. Searching for alternate sources, designers studied excimer and free-electron lasers as well. Although excimers never matured into weapon-level devices, the early investment in xenon fluoride, krypton fluoride, and argon fluoride lasers helped excimer lasers become the principal UV light source for semiconductor chip fabrication. In 1987 a study group on the science and technology of DEWs concluded in a report to the American Physical Society that DEW technology of the era fell short of technical requirements for boost-phase strategic missile defense and that there was no realistic prospect of meeting those requirements in any foreseeable time frame.¹

In the 1990s and 2000s the DOD attempted to develop a megawatt-class chemical oxygen–iodine laser on a Boeing 747 for tactical ballistic-missile defense. The DOD determined its operational role highly questionable, and the program was canceled. Since then, US ballistic-missile defense has focused on kinetic interceptors, and DEW development has focused mainly on tactical military missions requiring shorter range and lower power than strategic missile defense.

The new DEW technologies

In the US, chemically pumped laser weapons are now a thing of the past. The most significant new laser technologies for

DEWs in the 21st century are diode-pumped solid-state and gas lasers. Laser diodes are efficient; the best ones convert more than 50% of electrical input power into hundreds of watts of laser output power in a small package. But because they produce light in a tiny interaction region (on the scale of $10\ \mu\text{m}^2$ on a chip face), their output beams have large divergence and therefore low beam quality.

The laser diodes may interfere with sensors or blind weapons at short range, but they are not hard-kill weapons. Rather, the diode-pumped laser weapons of today are essentially beam-quality cleaners that convert the low-quality pump light into a larger high-power, low-divergence, and near-diffraction-limited laser beam.

In 2004 the Defense Advanced Research Projects Agency invested in scaling up a laser-diode-pumped solid-state crystal laser geometry called the distributed-gain laser.² Its geometry passes the beam through many thin crystal sheets in a gain cell pumped by diode light and cooled by liquid flowing between the sheets, and it lases at a wavelength of roughly $1\ \mu\text{m}$. To increase its power, a designer can add more crystal sheets or chain together several gain cells. In 2015, General Atomics, the contractor for the distributed-gain laser, achieved 100 kW class power—at the time the highest average power ever achieved in an electrically pumped laser.

In the 2000s the commercial laser industry developed high-power CW ytterbium-doped glass-fiber lasers pumped by laser diodes, lasing at a wavelength of about $1\ \mu\text{m}$. Today multimode fiber lasers boast powers that exceed 20 kW, and such multikilowatt varieties have become common devices for material processing. But multimode lasers are poor candidates for a laser weapon because only a small fraction of their power can be focused into the bucket. Fortunately, the commercial market also produces single-mode Yb-doped fiber lasers. And they have a nearly perfect Gaussian output beam—close to the fiber core's diffraction limit—which makes them an excellent weapon candidate. Single-mode, diode-pumped, large-mode-area fiber lasers today combine that near-diffraction-limited-beam quality with a high electrical-to-optical conversion efficiency with CW power that exceeds 1 kW.

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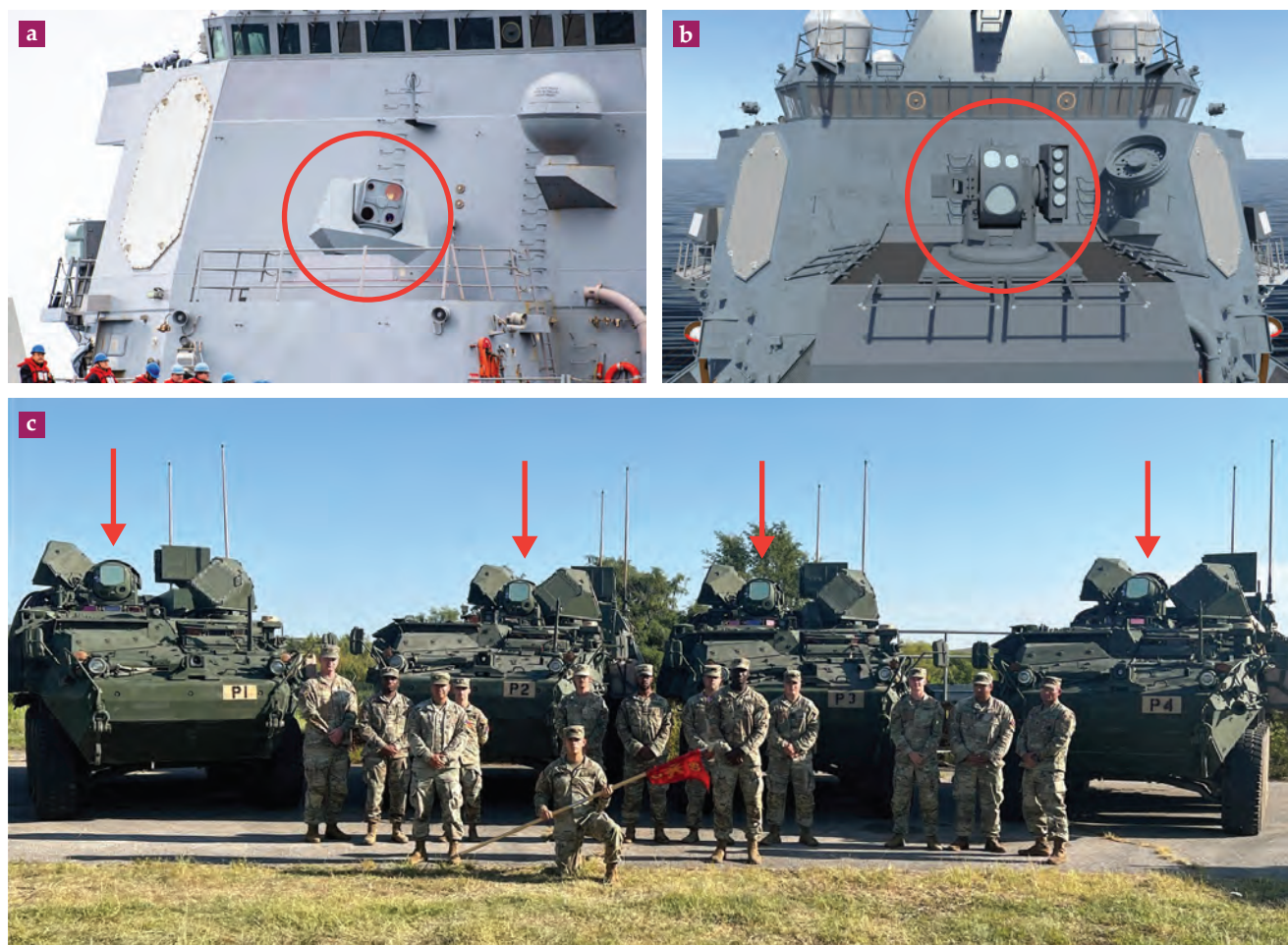


FIGURE 2. MOBILE WEAPONRY. (a) The Optical Dazzler Interdictor, Navy, on the *USS Stockdale*, is designed to blind adversarial IR sensors with a low-power laser beam. Circled are apertures for guiding the beam and tracking targets. (Courtesy of the US Navy/MCSN Elisha Smith.) (b) The 60 kW High Energy Laser with Integrated Optical-Dazzler and Surveillance is mounted on the *USS Preble*. Circled are the beam director (the large aperture at the bottom) and other apertures for tracking sensors and illuminating laser beams. (Courtesy of Lockheed Martin.) (c) The first platoon of four 50 kW US Army laser weapon systems in Fort Sill, Oklahoma. Red arrows point to each vehicle's laser. (Courtesy of the US Army.)

Single-mode fibers can be combined in various ways to produce higher-power CW lasers—for an explanation of various combining schemes, see box 2. Both the spectrally confined fiber and coherently combined fiber architectures are modular systems that can be scaled up with the addition of more fiber-laser units. Most of the laser's pump light is efficiently converted into the high-power signal, and the high peak power needed to drive the diodes is typically delivered by batteries that are recharged at lower power. Waste heat in the diodes and fibers is removed by conduction to water-cooled plates. The spectrally confined fiber, coherently combined fiber, and distributed-gain-laser architectures are solid-state systems, power-scalable, compact, inherently rugged, and suitable for integration into mobile platforms, including surface vehicles, ships, and aircraft.

The higher the average power of a DEW, the greater the number of targets it can engage in a given time and the longer the range over which it can engage them. In 2019 that capability prompted the DOD to begin HELSI, which scales up the power of diode-pumped solid-state lasers, reduces their size and weight, and increases their efficiency.

HELSI's first objective was a 300 kW laser with good beam

quality and the highest efficiency, lowest size, and lowest weight achievable in the short term. Three contractors—Lockheed Martin, nLIGHT, and General Atomics—proposed three different laser architectures to achieve those milestones, and they did so in 2022. Two representatives, shown in figure 1, are the highest-average-power electrically pumped lasers in the world today. This past year the DOD began the next phase of HELSI, with the goal of extending laser power above 1000 kW to enable DEWs to engage targets more quickly and over a longer range and to reduce laser size and weight to make it fits into a greater variety of military platforms. The DOD plans to demonstrate those lasers in 2026.

Another diode-pumped laser may also scale up as a DEW: the diode-pumped alkali laser.³ A three-level laser of alkali atoms in a buffer gas, the device uses diode lasers to pump the alkali atoms from the ground to an excited state, the buffer gas moves them to a slightly lower excited state, and they lase on the transition back to the ground state. Researchers can scale the laser up in power by enlarging the gain volume and increasing diode brightness. Maintaining good beam quality and efficiency with increasing power comes with practical challenges. Even so, since

Box 2. Fiber lasers, creatively combined

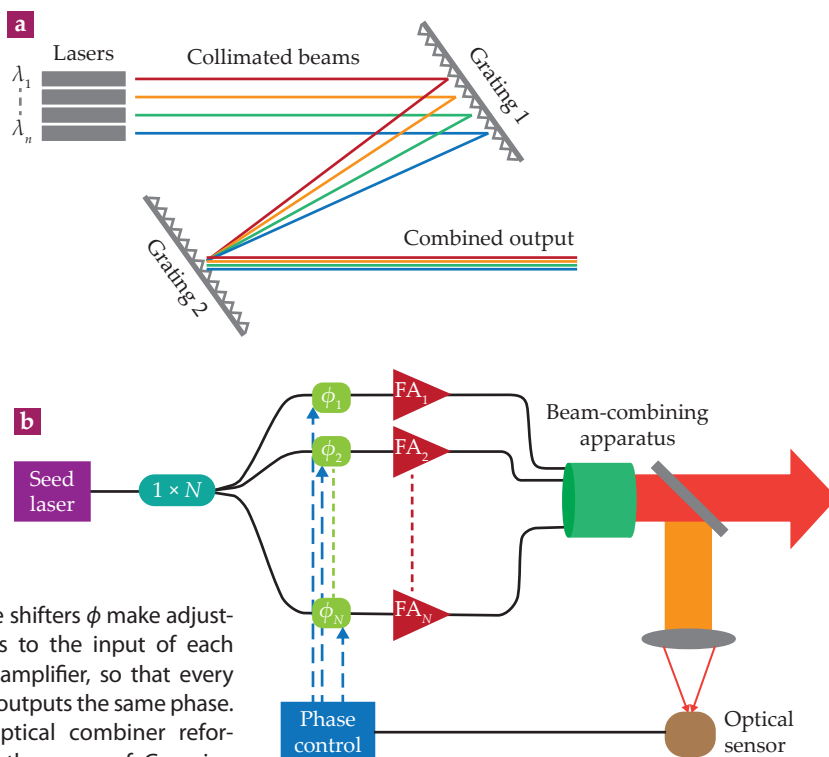
The spectrally combined fiber laser can be thought of as a prism run backward.¹⁰ Imagine a few fiber lasers, as shown in panel a, each emitting a different wavelength λ . The beams are arrayed in space and directed at diffraction grating 1. They all diffract from the grating at different angles, such that they strike grating 2 at the same point and are diffracted at the same departing angle—the different wavelengths combine, forming a single, collimated beam. As long as the wavelength spread of the fiber lasers is small, all wavelengths focus at the same point on the target.

The coherently combined fiber laser,¹¹ by contrast, is a phased array of beams, all with the same wavelength from a seed laser, as shown in panel b. For the beams to focus at the same point on the target, they must all have the same phase. But the phase of each fiber output changes with thermal and mechanical fluctuations. The array's coherence is maintained by electronic closed-loop control of the fiber beams. A small amount of power from the array is diverted to a wavefront sensor, which measures the phase of each beam.

Phase shifters ϕ make adjustments to the input of each fiber amplifier, so that every fiber outputs the same phase. An optical combiner re-formats the array of Gaussian beams into a more uniform irradiance across the output aperture.

The advantage of lasers made by combining fibers is that they can be scaled up in power by increasing the power of each fiber-laser amplifier and by increasing the

number of spectral or spatial fiber channels. (Panel a courtesy of and adapted from the Air Force Research Laboratory; panel b adapted from C. L. Linsal et al., *ISSS J. Micro Smart Syst.* **11**, 277, 2022.)



2001, various universities, the Air Force Research Laboratory, and Lawrence Livermore National Laboratory have been conducting research that strives to do just that.

The military's evolving role

The US military no longer overmatches its potential adversaries in conventional weapons. It now faces a world with large and growing numbers of sophisticated unmanned air systems, known as drones,⁴ and precision-strike cruise and ballistic missiles⁵ supported by networks of intelligence, surveillance, and

reconnaissance sensors and soon to be enhanced with artificial intelligence. An adversary could attack with conventional weapons in swarms so large that a conventional kinetic defense against them would be prohibitively expensive. DEWs offer military planners a potentially affordable layer of tactical defense against the growing threats.

Electric DEWs are particularly appealing. They can operate for as long as they have electrical power and cooling—that is, they have a “deep magazine” that does not run out of shots. Indeed, their cost per shot is low, needing little more than fuel



FIGURE 3. NON-US SYSTEMS. (a) China's Silent Hunter laser weapon is housed in a transportable container. Apertures contain the high-energy laser, tracking sensors, and illuminating lasers. (Courtesy of the Defense Systems Information Analysis Center.) (b) Russia's Peresvet “dazzler” weapon is mounted atop a transportable military container. The white beam director rotates about two axes to track a target in space. (Courtesy of the Russian Ministry of Defense, CC BY 4.0 DEED.) (c) The Dragonfire laser⁸ is the UK's demonstration of a high-energy laser weapon. The larger aperture houses the weapon's beam director, and the smaller aperture houses a tracking sensor. (Courtesy of MBDA.)

to generate electricity, and their effects are scalable, running from reversible interference to catastrophic destruction.

But they have weaknesses as well. A DEW kill is less obvious than one from a KEW, which generally produces flaming wreckage. Also, most DEWs must be guided much more accurately than most KEWs. To produce an effect, the beam from an HEL often must be put within a fraction of a meter of a vulnerable target spot. What's more, the use of DEWs in combat is immature; commanders and troops have little experience with such weapons in the field.

Because the performance of a DEW deteriorates in the presence of bad weather and turbulence, HELs require a relatively clear line of sight to their targets. HPM weapons are less affected by weather because RF beams can propagate (albeit with some loss) through clouds and rain. Nevertheless, their environmental sensitivity does not make DEWs inferior to KEWs. Direct-fire KEWs similarly require a clear line of sight, and most modern indirect-fire KEWs, such as rockets, artillery, missiles, and glide bombs, must be precisely aimed and targeted by sensors. All targeting sensors, including those used to guide KEWs, can be degraded by turbulence, smoke, clouds, and rain, as can the command and control links between sensors and weapons.

US and foreign developments

For decades DEW programs have been limited to demonstration units that operate at sites such as White Sands Missile Range in New Mexico. Today the potential military value of DEWs has motivated several nations to cautiously move them beyond demonstrations and into limited operational deployment. Easy missions that can be done today against soft and slow targets at short range include interfering with intelligence, surveillance, and reconnaissance sensors; destroying drones, artillery and mortar shells, and short-range rockets; and attacking ground vehicles and infrastructure from the air.

The US is currently deploying multiple HEL-weapon systems, some of which are shown in figure 2. The US Navy operates two. The first is the Optical Dazzler Interdictor, Navy—a laser used to dazzle sensors on drones and small boats and interfere with adversaries' intelligence, surveillance, reconnaissance, and targeting systems. Seven such lasers have already been installed on destroyers, and one more is planned. The second is the HEL with Integrated Optical-Dazzler and Surveillance, a 60 kW fiber laser made by Lockheed Martin and mounted on the *USS Preble* in 2023.

Meanwhile, the US Army is moving forward with its Directed Energy Maneuver-Short Range Air Defense systems. With a 50 kW laser mounted on a Stryker armored vehicle, the weapon is intended to defend mobile forces against rockets, artillery, mortars, drones, and helicopters. The army took delivery in 2023 of the first platoon of four systems.⁶

The size and weight of the new 300 kW lasers is appropriate for large platforms, such as ships or trucks and fixed installations. Two development programs use those lasers as part of HELSI: the army's trailer-transportable Indirect Fire Protection Capability-High Energy Laser and the navy's High Energy Laser Counter Anti-Ship Cruise Missile Project.

The US is not alone in its DEW ambitions. Other countries pursuing them include Australia, China, France, Germany,

India, Iran, Israel, Japan, Russia, Turkey, and the UK.⁷ Little information is available on the efforts of those countries, but a few weapons are shown in figure 3.

Challenges

A DEW is much more than just the directed-energy source. It requires pointing, tracking, beam control, and fire control. Beam control is the technology that delivers the HEL's power to a target. Atmospheric turbulence and thermal blooming can broaden the beam and reduce flux on the target. Adaptive optics is critical to ameliorating those effects.

The DOD in 1991 declassified much of its groundbreaking work on atmospheric optical propagation and adaptive optics (see *PHYSICS TODAY*, February 1992, page 17). Leveraging that DOD work, astronomers introduced many innovative adaptive-optics approaches and technologies. The beam directors in future HEL-weapon systems will probably use wavefront sensors and deformable mirrors to guide the laser beam and partially correct for turbulence on its way to a target.

Military services want highly efficient DEWs that can be mounted on mobile platforms with light and small power and cooling units. Chemical bonds are an excellent way to compactly store energy, and chemical lasers efficiently transform that energy into laser light (though with hazardous chemicals and infrastructure too large for military platforms). Although the new electrical lasers have a form well suited for military platforms, they are less efficient, need a separate source of electrical power, and convert at least $\frac{2}{3}$ of that into waste heat. As electrical HELs grow in power, they will need higher efficiency and more compact sources of power and methods of cooling.

If the new DEWs realize their potential—a deep magazine, little cost per shot, and simplified logistics—and if designers can overcome DEWs' current weaknesses, they may help fill the growing gap between kinetic offense and defense. That's a big "if." But military planners need new tools to deal with the new threats, and increasingly they are turning to DEWs.

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