Directed Energy Weapons Are Real . . . And Disruptive

By Henry "Trey" Obering, III

In the 1951 science fiction film, "The Day the Earth Stood Still," powerful ray guns are shown vaporizing rifles and even tanks. In the Star Wars movies, a wide variety of directed energy weapons are depicted, from handheld light sabers to massive, spaceship-mounted laser cannons.

What exactly is a directed energy weapon? Are these weapons still science fiction, lab experiments, or are they real? How can they be used and how disruptive can they be? What are the challenges and next steps? This article will examine answers to these questions.

What are Directed Energy Weapons?

According to DOD's Joint Publication 3–13 Electronic Warfare, directed energy (DE) is described as an;

> *umbrella term covering technologies that produce a beam of concentrated electromagnetic energy or atomic or subatomic particles. A DE weapon is a system using DE primarily as a direct means to disable, damage or destroy adversary equipment, facilities, and personnel. DE warfare is military action involving the use of DE weapons, devices, and countermeasures to either cause direct damage or destruction of adversary equipment, facilities, and personnel, or to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum (EMS) through damage, destruction, and disruption.*[1]

DE weapons include high-energy lasers, high-power radio frequency or microwave devices, and charged or neutral particle beam weapons.[2] Microwaves and lasers are both part of the electromagnetic spectrum, which includes light energy and radio waves. The distinction between them is the wavelength/frequency of the energy. While they are both part of the electromagnetic spectrum, laser and microwave weapons operate very differently and have very different effects.

Think of the difference between a laser pointer and a flashlight. The laser light is coherent in a single color, and the flashlight is broad-spectrum light. Because of its coherence, laser light can stay concentrated for very long distances—even thousands of miles into space. But with laser weapons, instead of thinking in terms

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of a laser pointer, the mental image should be more like a powerful, long-range blowtorch!

Lasers can be categorized as gas, solid state, or a hybrid of the two. The lasers on the current path to weaponization include solid state combined fiber and crystal slab as well as hybrid lasers. Fiber lasers are lasers in which the active medium being used is an optical fiber that has been doped in rare elements, most often Erbium.[3] Slab lasers represent one class of high-power solid-state lasers in which the laser crystal has the form of a slab.[4] Hybrid lasers such as a diode pumped alkali laser use a combination of trace gas with semiconductor diode arrays for even higher power and efficiency.[5]

The destructive power of directed energy weapons (their lethality) derives from the amount of energy transferred to the target over time. This concentrated energy can have effects across the entire spectrum from non-lethal to lethal. For example, lasers can cut through steel, aluminum, and many other materials in a matter of seconds. They can be very effective in causing pressurized vessels to explode such as missile propellant and oxidizer tanks. They can destroy, degrade or blind many other systems that contain sensors and electronics. For high energy lasers, lethality depends on the power output of the laser, the purity and concentration of the light (beam quality), the target range, the ability to keep the laser on the target aimpoint (jitter control and tracking), and the atmospheric environment the laser traverses to the target. In this last factor, the frequency of the laser and the engagement altitude will have a significant impact on how much the atmosphere effects the laser's lethality. Laser energy can be generated as a continuous wave or in pulses, which also influences its lethality. High-energy lasers (HEL) can range from a few kilowatts to megawatts of average power.

High-power microwave (HPM) and high-power millimeter wave weapons emit beams of electromagnetic energy typically from about 10 megahertz to the 100 gigahertz frequency range. Like lasers, HPM weapons can operate in a pulsed or continuous manner and are classified using "peak" or "average" power respectively. Most HPM systems are based on short pulses of radiofrequency (RF) energy, for which peak power is the important metric. The antenna gain of the weapon system is also very important, and when combined with the power of the RF source, yields the Effective Radiated Power (ERP) of the weapon. Depending on the particulars of the weapon, and how it is used, ERP levels can reach into the hundreds of gigawatts or higher. For continuous wave systems, which use high average power to effect targets, levels are typically from 50 to 100s of kilowatts up to several megawatts of power. The power levels are driven by prime power generation limitations, and ERP's depend on the antenna design and aperture (i.e., size).[6]

Almost everyone has probably experienced the "lethality" of a microwave device when they inadvertently put a metal object into a kitchen microwave oven and watched the "sparks fly." This same energy can be applied at higher powers for weapon effects. There are numerous pathways and entry points through which microwave energy can penetrate electronic systems. If the microwave energy travels through the target's own antenna, dome, or other sensor opening, then this pathway is commonly referred to as the "front door."[7] On the other hand, if the microwave emissions travel through cracks, seams, trailing wires, metal conduits, or seals of the target, then this pathway is called the "back door."[8]

In the weapons version, the microwave energy effects or lethality depends on the power and range to target, but the energy beams tend to be larger and not as sensitive to jitter as is the case for the high energy lasers. HPM lethality can be affected by atmospheric conditions as well, but to a much lesser degree than high-energy laser (HEL) weapons. HPM weapons lethality is typically described in terms of their ability to deny, degrade, damage or destroy a target's capabilities.

The term "deny" is defined as the ability to eliminate the enemy's ability to operate without inflicting harm on the system. A microwave weapon can achieve this result by causing malfunctions within certain relay and processing circuits within the enemy target system. For example, the static and distortion that high voltage power lines have on a car radio causes no lasting damage to the radio after the car leaves the area. Thus, the "deny" capability is not permanent because the affected systems can be easily restored to their previous operational condition.

The meaning of "degrade" is to remove the enemy's ability to operate and to potentially inflict minimal injury on electronic hardware systems. Examples of this capability include signal overrides or insertion, power cycling (turning power on and off at irregular intervals) and causing the system to "lock-up." These effects are not permanent because the target system will return to normal operation within a specified time, which obviously varies according to the weapon. In most cases, the target system must be shut off and restarted, and may require minor repairs before it can operate normally again.

The idea of "damage" is to inflict moderate injury on enemy communications facilities, weapons systems, and subsystems hardware, and to do so in order to incapacitate the enemy for a certain time. Examples include damaging individual components, circuit cards, or the "mother boards" in a desktop computer. This damage may create permanent effects depending upon the severity of the attack and the ability of the enemy to diagnose, replace, or repair the affected systems.

Finally, the concept of "destroy" involves the ability to inflict catastrophic and permanent injury on the enemy functions and systems. In this case, the enemy would be required to totally replace entire systems, facilities, and hardware if it was to regain any degree of operational status.[9]

In addition to being able to scale effects on a target, directed energy weapons have inherent attributes that are attractive to the warfighter. These include:

- speed of light engagement which makes responsiveness and tracking much faster than kinetic weapons;
- deep shot magazines which are only limited by the electrical power supplied to and re-generated by the system;
- "stealth-like" performance (quiet and invisible beams) that are hard to detect or intercept;
- precision targeting for both lethal and non-lethal applications; and
- low-cost per shot compared to traditional munitions.

Directed energy weapons have been in development for decades in our nation's research and development organizations, national laboratories and industry. So how close are they to becoming weaponized?

Are Directed Energy Weapons Still Science Fiction, Lab Experiments or Ready for the Warfighters?

In early versions of laser weapons, the light was generated by chemical reactions. Between 2000–05, a prototype chemical laser successfully destroyed 46 rockets, artillery shells and mortar rounds in flight during field tests. However, these lasers were generally large and heavy. In fact, the megawatt-class Airborne Laser developed in the late 1990s and early 2000s required an entire 747 aircraft to hold the equipment. Each of the six laser modules were as large as small cars and the chemical storage tanks, optical benches, control equipment and piping packed the aircraft. In 2010, the Airborne Laser shot down two missiles (both solid and liquid propelled) in their boost phase during flight testing which demonstrated the lethality of the laser against missile targets. We proved that the technology could be effective, but its size, weight, and power (SWaP) requirements made the laser weapons impracticable to field.

Today, solid state electrical (including fiber) and hybrid lasers are being developed that are much lighter and smaller. The combination of technology advancements improving lethality and reducing SWaP in high energy laser technology and the advent of threats such as hypersonic weapons for which kinetic solutions are problematic has resulted in high energy lasers and directed energy weapons more generally being pursued vigorously across the services consistent with the *National Defense Strategy*.[10]

In recent years the U.S. Navy deployed a 30kW class solid state laser weapon system (LaWS) prototype on the Afloat Forward Staging Base, USS *Ponce*. It was capable of damaging or destroying fast attack boats, unmanned aerial vehicles and was used for intelligence, surveillance, and reconnaissance (ISR). When the LaWS was being integrated onto the ship, the designers and developers envisioned that it would be used several hours a day. It turned out that during its three-year deployment, from 2011–14, it was used nearly around the clock in its ISR mode.

Because of the strategic imperative to protect U.S. carrier battlegroups to enable us to project power, the U.S. Navy is following this prototyping effort with a much broader "Navy Laser Family of Systems" or NLFoS program, which will put the Navy on a path to develop and deploy lasers ranging from low power laser "dazzlers" to much higher power lasers capable of destroying anti-ship and high-speed cruise missiles. Examples of NLFoS weapons include: a 60kW laser called HELIOS (High Energy Laser with Integrated Optical-dazzler and Surveillance) expected to be deployed by 2021 that will be capable of burning through small boats and shooting down drones; the SSL–TM (Solid State Laser–Technology Maturation system), which will eventually be a 150kW laser weapon on the LPD–27 amphibious ship; and the ODIN (Optical Dazzling Interdictor, Navy) that will also go on a destroyer.[11]

The U.S. Army has also been moving out aggressively in developing and deploying directed energy weapons as part of its Air and Missile Defense modernization priority. Within that priority area, the Army is focused on the use of high energy lasers to provide Indirect Fire Protection Capability (IFPC) and Maneuver—Short-Range Air Defense (M-SHORAD). The Army's Rapid Capabilities and Critical Technologies Office is now asked to make DE technology available to the warfighters as quickly as possible. Building on the Army's DE efforts during the past 5 to 7 years, the Rapid Capabilities and Critical Technologies Office (RCCTO) is committed to fielding 50kW lasers on four Strykers (eight wheeled armored fighting vehicles), delivering a residual combat capability at the Platoon level as part of the M-SHORAD mission in support of a Brigade Combat Team.

Building a Stryker with a 50kW laser is a follow-on to the 5kW laser the Army tested on the vehicle just a year ago in Germany at the Joint Warfighting Assessment and related efforts. *DefenseNews* in their coverage of the March 2018 Booz Allen Hamilton/CSBA Directed Energy Summit in Washington highlighted the remark by Colonel Dennis Wille, the Army G3 strategic program chief for U.S. Army Europe, that over the weekend the 2nd Stryker Cavalry Regiment (supported by the 7th Army Training Command and the Fires Center of Excellence at Fort Sill, Oklahoma) had conducted a live-fire engagement of the 5kW Mobile Expeditionary High-Energy Laser demonstrator at the Grafenwoehr Training Area, Germany. This is just the beginning of a plan to deploy 50kW lasers on four of its Stryker vehicles over the next few years for operational use.[12]

A fire support noncommissioned officer with 4th Division Artillery, 4th Infantry Division, who participated in the testing of a 2kW version of the laser vehicle at Fort Sill, Oklahoma against unmanned drones was quoted in a February 28, 2018 *Army Times* article as saying, "It was extremely efficient, I was able to bring them down as [fast as] they were able to put them up."[13]

The Army used Navy-, and Air Force- developed HPM weapons during recent conflicts to counter improvised explosive devices (IEDs). These devices have also been demonstrated to stall or damage car, truck, or boat motors. This capability would be very useful at checkpoints or for stopping escaping vehicles.

In 2017, the Air Force Secretary and Chief of Staff signed the DE Flight Plan outlining the path ahead for the Air Force to develop and deploy both high-energy lasers and high-power RF weapons for its aircraft. This plan includes a program which aims to test high energy lasers on aircraft against surface to air and air to air missile threats. Similar to the Army's RCCTO and the Navy's Accelerated Acquisition (AA) Process, the Air Force is leveraging both Air Force Research Laboratory's DE Directorate and Air Force Strategic Development Planning and Experimentation Office to expedite delivery of capabilities to address key capability gaps identified in the DE flight plan: Forward Base Defense, Precision Strike, and Aircraft Self-Protect. In addition, the Air Force has partnered with the Navy in the development of a high-power RF weapon called High-power Joint Electromagnetic Non-Kinetic Strike (HiJENKS) capable of attacking electronics, communications and computer networks.

The Air Force also recently demonstrated the ability of an HPM weapon to bring down multiple drones in testing at White Sands Missile Range in New Mexico, according to a recent Military.com article:

> *"After decades of research and investment, we believe these advanced directed-energy applications will soon be ready for the battlefield to help protect people, assets and infrastructure." Thomas Bussing, Raytheon Advanced Missile Systems vice president, said in a news release accompanying the announcement. The release noted the HPM and HEL systems engaged and defeated "dozens of unmanned aerial system targets" during the exercise.*[14]

But by far, the most ambitious program underway in DOD is being led by the Missile Defense Agency (MDA). It is developing a very high-power laser capable of being eventually deployed on a space-based platform to target missiles during their boost/ascent/midcourse phase. This laser would be megawatt class and have a range of hundreds of miles.

The first step in this endeavor is underway with funding for laser scaling and beam quality improvements for both combined fiber lasers as well as hybrid lasers such as the diode pumped alkali laser or DPALS. These lasers, combined with significant improvements in computational power, represent dramatic advances in technology over those used in the Airborne Laser program. The

The High Energy Laser Mobile Demonstrator, or HEL MD, is the result of U.S. Army Space and Missile Defense Command research. (Army photo) laser diodes, fiber amplifiers, battery and power management, thermal control, and optical systems are also much more advanced.

The United States will soon be reaching the point where it can generate a megawatt of power in a size, weight, and volume capable of being put on a high-altitude aircraft or space-based platform. As DOD works to develop and incorporate these technologies, much of the work should be collaborative, such as improvements in materials, power generation, thermal control, etc. to reduce size, weight, and power required to operate these weapons. However, the wide variety of missions, platforms, and implementation environments necessitates continued service-differentiated development activities. This also includes fundamental differences such as the wavelength of the lasers and the beam quality required for success.

For example, a Navy ship-to-air laser will have different requirements than an Air Force air-to-air system, which will have different requirements than a space-based missile defense system and therefore different technological considerations. Discrete, mission-aligned efforts will maintain our pace of development in the race to get these technologies to the field.

How Can They Be Used and How Disruptive Can They Be?

Some applications of directed energy weapons to solve today's challenges have already been described, such as stopping swarms of small adversary boats which have been harassing U.S. ships in international waters, or stopping vehicles carrying improvised explosive devices at a safe distance from U.S. personnel. As another example, high energy lasers could be used to protect forward-deployed troops and bases from attacks by swarms of unmanned aircraft carrying explosive devices.

But let us broaden these applications somewhat. In addition to the nuclear ballistic missile threat posed by North Korea, which can be defended by U.S. missile defense systems, there is a North Korean threat which cannot be defended against today . . . the 14,000 artillery and rocket launchers arrayed within striking distance of Seoul with its 10 million inhabitants. Imagine how much the geopolitical calculus would change on the peninsula if a layered, integrated system of high energy lasers and high-power microwave weapons was deployed to defend against these threats.

Turning to the air, the United States spent billions of dollars to develop and deploy stealth technology for its fighters and bombers to avoid radar detection and being targeted by surface to air missiles. What if the United States could deploy effective anti-missile lasers on its' aircraft to defeat any missile(s) fired at them? In effect, the United States would have provided "stealth-like" capability to entire fleets of aircraft.

In a much more dramatic application, the recently released *Missile Defense Review* (MDR), the first update to *U.S. Missile Defense Strategy* in nearly a decade, delivers a visionary plan to protect the United States from ever-intensifying threats around the world. For example, the MDR proposes that the Missile Defense Agency study the potential to develop and field space-based lasers to intercept ballistic missiles.[15]

Space-based lasers would have a profound impact on the U.S. ability to defend and if necessary, fight in space. Not only could they be used to defend against ballistic missiles in the boost/ascent and midcourse phase, but they could also be used to defend critical space-based assets against enemy anti-satellite attack.

Directed energy weapons could also play a key role in defending against what has been described as the number one threat to the United States by the Undersecretary of Defense for Research and Engineering Dr. Mike Griffin—hypersonic weapons. He has pressed for the development of hypersonic weapons by the United States as well as a defense against them. In a March 6, 2018 speech, said, "I'm sorry for everybody out there who champions some other high priority, some technical thing; it's not that I disagree with those," he told the room, "But there has to be a first, and hypersonics is my first."[16]

There are two types of hypersonic weapons, boost glide and air-launched high-speed cruise missiles. Boost glide weapons are launched atop ballistic missiles then released to glide to the target. The air-launched uses scramjets or rockets to power it throughout flight. These high-speed missiles fly at Mach 5 (five times the speed of sound) and greater. They can not only achieve these speeds but can maneuver at them as well including varying trajectories, headings and altitudes. Therefore, currently deployed defenses against ballistic missiles will not be effective in defending against these non-ballistic threats. There is no "silver bullet" defense against these weapons and in fact there will have to be an architectural approach in defending against them, but directed energy weapons can potentially play a major role.

Since these weapons maneuver, the United States needs to be able to precisely track the hypersonic missile throughout its entire flight or "birth to death." The only cost-effective way to accomplish this is using space-based satellites. Developing hypersonic interceptors will also be an option in the U.S. defense architecture. But there is a rule of thumb that states that an interceptor needs to be capable of three times the speed of the target it is defending against to be able to maneuver to destroy it. So hypersonic kinetic interceptors would have to be capable of achieving speeds of Mach 15 and higher.

One of the greatest attributes of directed energy weapons is that they operate at the speed of light. So, for a hypersonic weapon that is travelling at 25 times the speed of sound, a high- energy laser can engage it at roughly 35,000 times its speed. This makes targeting and tracking easier as well. Space-based high energy lasers could be brought to bear especially in the boost/ascent phase of boost glide hypersonic missiles where a high-energy laser could destroy the vehicle early in its trajectory. At the speeds that these hypersonic missiles fly, they have vulnerabilities which could be exploited by directed energy weapons. Therefore, HELs and HPMs could also play a role in the midcourse/terminal phase of both types of hypersonic missile flight.

Directed energy weapons are no longer just science fiction. They are real and are maturing rapidly. In the next several years, the U.S. Army, Navy and Air Force all plan to develop and field these weapons at an increasing pace. They will be deployed on land vehicles, aircraft, helicopters, and ships.

Even the most conservative market projections for directed energy weapons indicate nearly $30 billion being spent by the United States during the next ten years. They are not the answer to all the challenges, and will not replace kinetic weapons, but they are an essential adjunct to countering specific threats and providing dominance in land, air, sea, and space. The United States has the technology, the resources, the talent, and the infrastructure to develop and deploy directed energy weapons to meet today's and tomorrow's emerging threats.

The only question is whether the United States and its allies will achieve that dominance before an adversary does.

What Are the Challenges and Next Steps?

The United States has come a very long way in the development of directed energy weapon capabilities and is now at a critical juncture. The technology is maturing rapidly, threats are emerging which directed energy can almost uniquely address, and the warfighters are signaling their support.

However, as with the development of any unprecedented military capability, there are risks, challenges and limitations involving their cost, schedule and performance. In the case of directed energy weapons, there has been significant risk reduction which has been accomplished over several decades. Examples of this cited earlier included the Airborne Laser, the Navy's LaWS program, and others. However, risks, challenges and limitations remain.

For example, atmospheric conditions such as turbulence, haze, clouds, etc. can affect a laser's performance but there are ways to address these phenomena. First, the choice of a laser's wavelength can help to mitigate the affect because different laser wavelengths perform much better in the atmosphere than others. And of course, lasers employed at higher altitudes or in space would have very little to no atmospheric affects.

In addition, a technique known as "adaptive optics" has been developed for many years. In this case, the laser weapon system would sense the atmospheric conditions to the target, then using fast steering mirrors, it would deform the main laser beam as it leaves the weapon to use the atmosphere to the target much like the lens of a pair of glasses to refocus the beam on the target. Increasing laser power and improving the beam quality can also help to mitigate atmospheric effects in many cases.

Challenges remain in terms of the size, weight and power input requirements of today's laser systems, especially in the thermal control and power management subsystems. But again, there are major advances in these areas being made especially with the technology that has been developing in the electric car industry.

When using laser weapons, the warfighters will need new situational awareness and battle management tools because of the potential long-range effects to avoid friendly systems fratricide. But again, advances in computational power coming out of the gaming industry (such as graphics processing units) and artificial intelligence coming from autonomous automobile development can be instrumental in providing these needed capabilities.

While the development costs of directed energy systems can be high, there are several factors in play which can reduce these costs or at least provide better return on the investment over the life cycle. For example, as mentioned earlier, directed energy weapons development can take advantage of progress being made in commercial industry around processors, power generation and management and even lasers subsystems themselves.

In addition, the "cost per shot" of a directed energy weapons could be orders of magnitude less expensive than current kinetic weapons. Consider that today the United States will launch kinetic interceptors at an incoming threat warhead that cost tens of millions of dollars and multiple interceptors are fired for maximum probability of success. Compare that to a high energy laser which could kill multiple threat missiles with a single "magazine" charge for a tiny fraction of the cost. In addition, while you are firing on one power source, you can be charging another for near continuous operation.

More importantly, peer and near-peer nations are developing these weapons at an alarming rate. The United States must realize that it has to resource the development and fielding of these capabilities. The United States cannot allow itself to fall behind in yet another area of warfighting as has happened in hypersonics.

To maximize the United States' ability to field DE weapons, here is a ten-part approach to get us going in the right direction:

1. **Power Scaling and Improved Beam Quality.** DOD should significantly scale up laser power and improve beam quality; as well as develop higher power compact microwave weapons. The pace of maturing these capabilities is not "technology limited;" it is "funding limited," therefore the United States should ensure that funding for directed energy weapon development supports the needed developments. Levels of $3 billion or above per year should be maintained.

2. **SWaP Reduction.** The United States should accelerate efforts to reduce the size, power input, weight, and cost requirements of these weapons. Since the most demanding size, weight and power inputs requirements are in the missile defense arena, MDA laser programs should be fully funded to increase laser power levels for high-altitude and space-based applications.
3. **Warfighter Tactical Decision Aids.** DOD should provide warfighters with tactical decision aids to ensure they know how and when to use these weapons. This will go far toward instilling confidence in the warfighters that these weapons will be effective in combat against multiple threats. These aids would include a guide to their effectiveness, similar to what the Joint Munitions Effectiveness Manual does for kinetic weapons.
4. **Lethality.** The Office of the Secretary of Defense should fund a program to focus broadly on improving understanding of microwave and laser weapon lethality. While a tremendous amount of work has been done, DOD should also conduct further research to enhance understanding of laser and high-power microwave lethality and reliability across an increasing range of weather and atmospheric conditions. This research should also focus on minimizing any collateral damage.
5. **Accelerated Acquisition.** DOD should accelerate acquisition of DE capabilities using non-traditional practices. According to Griffin, at the 9th Annual Defense Programs Conference in March 2018, DOD takes an estimated 16.5 years to bring new technologies from statement of need to deployment. But there are several examples where the timelines have been dramatically shortened such as the Navy's Rapid Prototyping Experimentation and Demonstration (RPED) program for mission-critical capabilities and the use of specialized acquisition authorities by the MDA. DOD should use such accelerated processes for DE development and deployment.
6. **Long-term Commitment.** DOD must signal a long-term commitment to directed energy, so the industrial base will know there will be a market for its products in the coming years. In doing so, DOD should prepare, and encourage, the industrial base to support the rising need for first-, second-, and third-tier suppliers.
7. **Testing Infrastructure.** DOD should provide the needed testing infrastructure for directed energy weapons especially as they can achieve longer and longer ranges. This needs to include rapid airspace deconfliction capabilities.
8. **Increased Collaboration.** All parties involved in directed energy development should continue to talk to each other. Significant progress has been made in communication and collaboration across the technical community through their involvement in the Directed Energy Professional Society (DEPS) and by the HEL Joint Technology Office. DOD needs to better articulate its requirements for deployable lasers. But also, the industrial base must interface better with DOD and its leadership to increase understanding of innovative laser weapon capabilities.
9. **Training.** DOD must also prioritize warfighter training. There is currently no established directed energy training pipeline; that is because laser and microwave weapons have no formal programs of record (PORs). Once the PORs are set up, training must follow. To assist in establishing PORs, DOD should encourage wargames and operational analysis to investigate and better articulate the battlefield benefits of lasers.
10. **Command and Control.** DOD should adapt command-and-control functions to address

rapidly evolving threats, such as hypersonics, to reduce the engagement times of defensive systems. Very short engagement timelines will likely necessitate the incorporation of artificial intelligence capabilities to help the United States leverage the speed-of-light engagement that directed energy weapons offer.

These are steps to take to bring directed energy prototype systems to the warfighters. The brave men and women who confront dangerous threats across all physical domains—land, air, sea, and space—need nothing less than the world's most promising new capabilities to protect U.S. national security. Adversaries are not waiting to develop directed energy weapons. Neither should we. PRISM

Notes

[1] Department of Defense Joint Publication 3-13.1, Electronic Warfare (Washington, DC: Department of Defense, 2012).

[2] According to the Lawrence Livermore Laboratory,

> *The word "laser" is an acronym for light amplification by stimulated emission of radiation. Laser light is created when the electrons in atoms in special glasses, crystals, or gases absorb energy from an electrical current or another laser and become "excited." The excited electrons move from a lower-energy orbit to a higher-energy orbit around the atom's nucleus. When they return to their normal or "ground" state, the electrons emit photons (particles of light). These photons are all at the same wavelength and are "coherent," meaning the crests and troughs of the light waves are all in lockstep. In contrast, ordinary visible light comprises multiple wavelengths and is not coherent.*

Additional information on "How Lasers Work," is available on the Lawrence Livermore National Lab website, <https://lasers.llnl.gov/education/how_lasers_work>.

[3] "How a Fiber Laser Works," SPI Lasers International website, available at <https://www.spilasers.com/industrial-fiber-lasers/how-fiber-lasers-work/>.

[4] "Slab Lasers," RP Photonics Encyclopedia website, available at <https://www.rp-photonics.com/slab_lasers.html>.

[5] Ibid.

[6] David Stoudt, Ph.D., Electrical Engineering, private communication.

[7] David M. Sowders et al., "High Power Microwave (HPM) and Ultrawideband (UWB): A Primer on High Power RF," PL-TR-95-1111, Special Report, Phillips Laboratory, March 1996, 76.

[8] Ibid, 79.

[9] Eileen Walling, "High Power Microwaves, Strategic and Operational Implications for Warfare," Occasional Paper no. 11, Air War College Center for Strategy and Technology, May 2000.

[10] Department of Defense, *The National Defense Strategy 2018* (Washington D.C.: Office of the Secretary of Defense, 2018).

[11] Megan Eckstein, "Navy to Field High-Energy Laser Weapon, Laser Dazzler on Ships This Year as Development Continues," USNI News, May 30, 2019.

[12] Jen Judson, "U.S. Army Successfully Demos Laser Weapon Stryker in Germany," DefenseNews.com, March 21, 2018, available at < https://www.defensenews.com/land/2018/03/21/us-army-successfully-demos-laser-weapon-on-stryker-in-europe/>.

[13] Todd South, "Soldiers in Europe are now Using Lasers to Shoot Down Drones," ArmyTimes.com, February 8, 2018, available at < https://www.armytimes.com/news/your-army/2018/02/28/soldiers-in-europe-are-now-using-lasers-to-shoot-down-drones/>.

[14] Oriana Powlyk, "Raytheon Directed-Energy Weapons Down Drones in Air Force Demonstration," Military.com, May 1, 2019, available at <https://www.military.com/daily-news/2019/05/01/raytheon-directed-energy-weapons-down-drones-air-force-demonstration.html>.

[15] Office of the Secretary of Defense, "Missile Defense Review," January 2019, available at < https://www.defense.gov/Portals/1/Interactive/2018/11-2019-Missile-Defense-Review/The%202019%20MDR_Executive%20Summary.pdf>.

[16] R. Jeffrey Smith, "Hypersonic Missiles Are Unstoppable and They're Starting a New Global Arms Race," *New York Times Magazin*e, June 19, 2019.