ARL-SR-0440 ● MAR 2021

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Review of Recent Capability Improvements in Ultrashort Pulse Laser Sources: Closing the Relevancy Gap for Directed Energy Applications

by Anthony Valenzuela and Daniel Matyas

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ARL-SR-0440 • MAR 2021

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 2021

2. REPORT TYPE
Special Report

3. DATES COVERED (From - To)
June 2020–October 2020

4. TITLE AND SUBTITLE
Review of Recent Capability Improvements in Ultrashort Pulse Laser Sources: Closing the Relevancy Gap for Directed Energy Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Anthony Valenzuela and Daniel Matyas

5d. PROJECT NUMBER
AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army DEVCOM Army Research Laboratory
ATTN: FCDD-RLW-TA
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-SR-0440

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
primary author's email: <anthony.r.valenzuela6.civ@mail.mil>.

14. ABSTRACT

Recent developments indicate the horizon for directed energy applications using ultrashort pulse lasers (USPLs) is quickly approaching. Historically, USPLs were mainly confined to laboratory applications due to strict environmental requirements and complex operations requiring a high degree of operator education. These USPLs were based on solid-state technology involving titanium:sapphire gain material, which is highly intolerant of temperature and humidity changes, vibrations, and atmospheric particulates. The new generation of USPLs have moved to new gain materials and new architectures that have realized not only an improvement in environmental tolerance but also significant reductions in size, weight, and power consumption metrics. This led to new classes of USPLs that have achieved average powers and pulse repetition rates orders of magnitude higher than commercially available systems from as late as 2015.

15. SUBJECT TERMS
Directed energy, ultrashort pulse lasers, nonlinear optics

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UU	35

19a. NAME OF RESPONSIBLE PERSON
Anthony R Valenzuela

19b. TELEPHONE NUMBER (Include area code)
410-278-9876

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

The authors wish to thank the following people in alphabetical order: Trenton Ensley (US Army Combat Capabilities Development Command [DEVCOM] Army Research Laboratory [ARL]), Michael Helle (US Naval Research Laboratory [NRL]), Andrew Mott (DEVCOM ARL), Zachary Quine (ARL), Eric Rosenthal (NRL), Charlene Rusnak (NRL), Andreas Schmitt-Sody (Air Force Research Laboratory), Aaron Schweinsberg (ARL), and Steven Segletes (ARL).

1. Introduction

Recent developments indicate the horizon for directed energy (DE) applications using ultrashort pulse lasers (USPLs) is quickly approaching. Historically, USPLs were mainly confined to laboratory applications due to strict environmental requirements and complex operations requiring a high degree of operator education. These USPLs were based on solid-state technology involving titanium:sapphire (Ti:Sa) gain material, which is highly intolerant of temperature and humidity changes, vibrations, and atmospheric particulates. The new generation of USPLs have moved to new gain materials and new architectures that have realized not only an improvement in environmental tolerance but also significant reductions in size, weight, and power consumption (SWaP) metrics. This has led to new classes of USPLs that have achieved average powers (P_{avg}) and pulse repetition rates (f_p) orders of magnitude higher than commercially available systems from as late as 2015.

USPLs operate over a wide range of wavelengths (λ), primarily in the infrared spectrum. The infrared is roughly broken down into the near (NIR, 0.7–1.4 µm), shortwave (SWIR, 1.4–3.0 µm), midwave (MWIR, 3.0–8.0 µm), longwave (LWIR, 8.0–15.0 µm), and far (FIR, 15.0–30.0 µm) ranges. For DE applications, we are often interested in propagating in air and thus limit our interests to particular wavelength ranges that minimize losses like absorption and scattering. These "atmospheric windows" are roughly in the visible and NIR (0.4–1.4 µm), the SWIR (2.0–2.5 µm), the MWIR (3.0–5.0 µm), and LWIR (8.0–14.0 µm), see Fig. 1. In addition, the human retina is sensitive in the NIR and common silicon-based sensors are sensitive up to about 1.0 µm. An ideal USPL system for DE would emit at a wavelength in one of the atmospheric windows and be outside the sensitivity range of the retina and silicon sensor to minimize collateral effects.

There is a sizeable range of applications of USPLs and the specific requirements of laser systems can vary, limiting certain improvements that currently lack a business case. In Section 4, applications that have a possible relation to defense applications will be highlighted. With the new generation of high average power USPLs being commercially available, new applications and new markets could develop in the next few years. "Table-top" sources of X-rays, electron beams, and proton beams could see widespread use as diagnostic tools for medicine, preventive maintenance, and materials science with improved SWaP metrics and reductions in cost. Yet all of

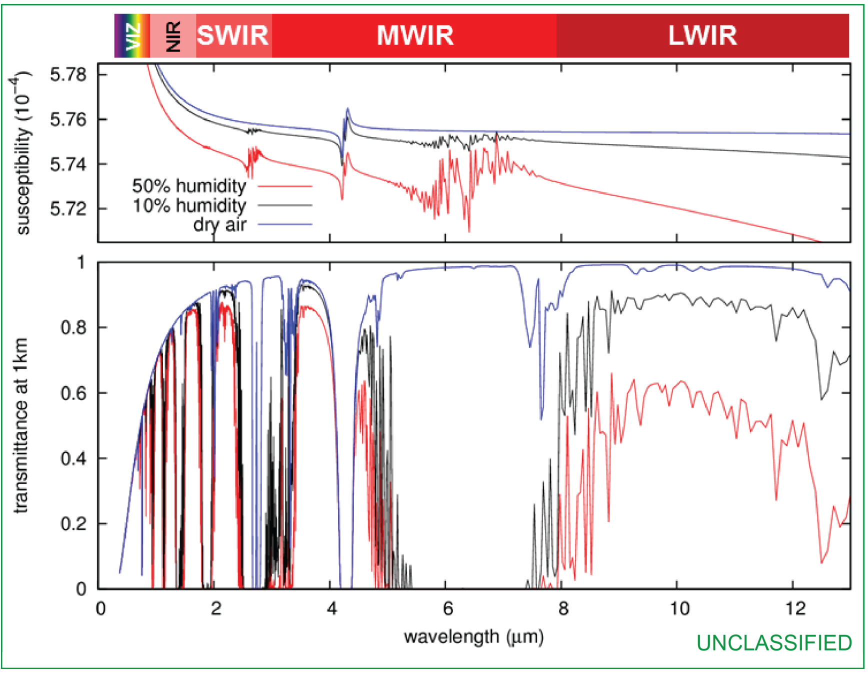

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Fig. 1 HITRAN atmospheric simulation of 1-km laser propagation vs. wavelength across VIS and IR ranges, courtesy of Prof Jerome Moloney

these applications will one way or another make use of the special realm of physics, nonlinear optics, that USPLs are able to access.

2. Harnessing Nonlinear Optics

Ultrashort lasers can be roughly defined as having a pulse duration, τ, of a few picoseconds (1 ps = 10^{-12} s) or shorter. These ultrashort pulse durations are needed to convert modest amounts of energy (typically microjoules to a few joules) into high intensities, I, greater than 10^{12} W/cm^2 when focused. These high intensities are useful for accessing the realm of nonlinear optics that arise from the expansion of the index of refraction, n:

$$n = n_0 + n_2 I + ... \tag{1}$$

where n_0 is the linear index of refraction and n_2 is the second-order nonlinear index of refraction that is typically of the order of 10^{14} cm^2/W or smaller in matter. As well, the short temporal duration of the pulses allows for the sudden interaction with matter before thermal equilibrium can occur, resulting in unique behavior compared to longer laser pulses even at the same intensity. This effect has proven to be extremely useful in realms outside of DE like laser machining and particle acceleration. As such, comparisons between USPLs and longer pulse or continuous wave (CW) lasers often rely on the need to access nonlinear effects. Until recently, USPLs were limited to P_{avg} many orders of magnitude lower than achievable with CW lasers. For bulk laser machining, P_{avg} > 1 kW were needed to effectively cut through metals and ceramics though high intensities are not necessary. On the other hand, if fine ablation is needed to produce very precise markings and cuts of materials, USPLs are far superior to CW lasers.

2.1 Ultrashort Pulse Generation

The current route to generate the short, intense bursts of light uses optical techniques to circumvent damaging optics in a laser system. The primary technique, Chirped Pulse Amplification (CPA),[1] has gone on to revolutionize the worlds of optics and high-field physics and garnered the developers, Profs Donna Strickland and Gerard Mourou, the Nobel Prize in Physics in 2018.[2] The general concept behind CPA (see Fig. 2) is to start with a seed ultrashort laser pulse with a small amount of energy, stretch the pulse in time, amplify the stretched pulse, and finally compress the pulse back to ultrashort. The amplification is accomplished by having pump lasers, usually with much longer pulse duration, transfer some of their energy into the seed pulse via a gain medium. Currently, most gain media are solid state dielectrics, transparent ceramics, or crystalline materials with very special chemical compositions. These compositions often involve doping a host crystalline material with particular metal ions that produce emission at characteristic wavelengths. These emissions have been shown to span across the NIR, SWIR, and MWIR regimes (0.7–5 µm). For LWIR applications, the current exemplar candidate is electrical pumping of CO_2 gas, which produces emission around 10 µm with pulse durations of a few picoseconds. Further discussion of sources will be given in Section 3.

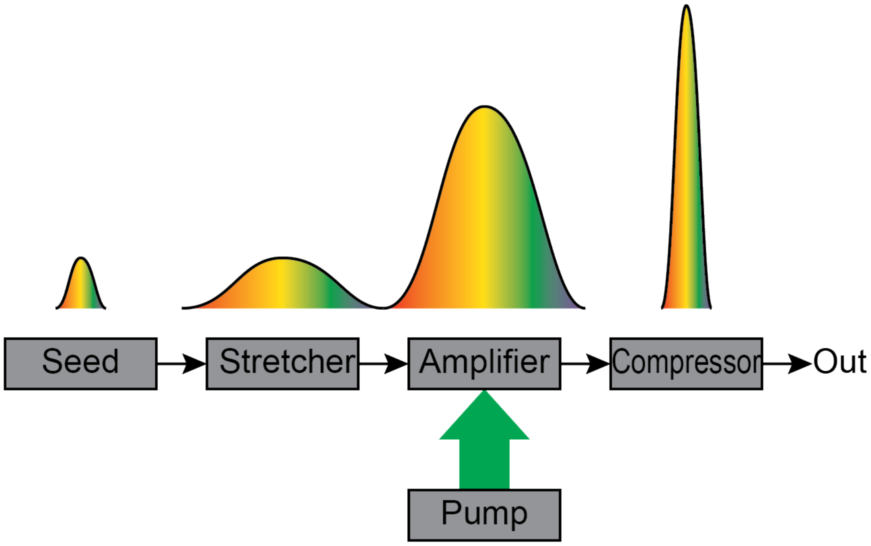

Fig. 2 Illustration of the Chirped Pulse Amplification technique where a seed laser with sufficient bandwidth is stretched in time to better amplify the pulse energy via a pumping mechanism and then compressed to an ultrashort pulse

2.2 Focusing and Nonlinear Propagation

The paraxial approximation for propagation leads to a set of linear equations using a Gaussian function to describe the transverse intensity profile. This results in a set of relatively simple equations that describe how light would propagate, say, through a focusing lens. For example, take a laser pulse with energy per pulse of E_p and initial diameter of d_0 that propagates through a thin lens with a focal length of f. The cylindrically symmetric intensity profile at a distance z from the focal point of the lens is approximated by:

$$I(r,z) = \frac{E_P}{\pi \tau w_0^2}[1 + (z/z_R)^2)] \tag{2}$$

where w_0 is the beam radius waist at the focal point approximated by $2\lambda f/d_0$ and the Rayleigh range $z_R = \pi w_0^2/\lambda$. This approximation relies on a linear index of refraction where Eq. 1 gives us $n = n_0$. USPLs have the ability to achieve extreme peak powers and that leads to changes to propagation and a feedback mechanism resulting in increasing intensity. This process is known as Kerr self-focusing[3] and will cause the beam to collapse before reaching the geometrical focal point at $z = 0$. With the rising intensity of the laser pulse, the energy can be absorbed into the molecules of air. If the intensity is greater than 10^{12} W/cm^2, the energy can be sufficient to liberate outer shell electrons in the molecules, creating a plasma. An interesting and useful regime called filamentation[4] can be achieved by balancing the self-focusing with the nonlinear effect from plasma that tries to defocus the beam (see Fig. 3). Filamentation has been an intense area of research for the last 25 years and Refs. 5–7 provide excellent reviews.

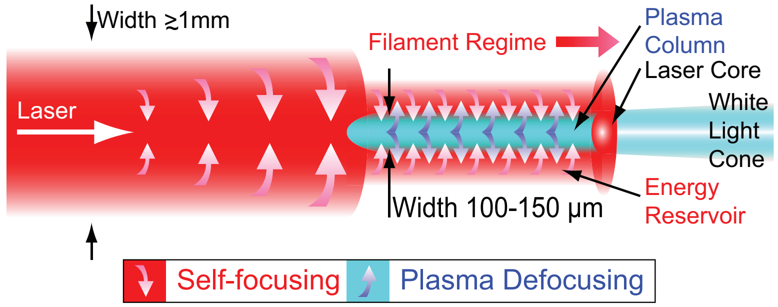

Fig. 3 Illustration of the filamentation process where an intense laser pulse self-focuses to create a defocusing plasma. The balance of the self-focusing energy reservoir and the defocusing of the plasma column creates a filament for up to hundreds of meters in air and produces a narrow cone of white light.

Developing a comprehensive theoretical framework for self-focusing and filamentation has been a vigorous endeavor since the first observations of the phenomenon. Measuring the peak power ($P_p = E_p/\tau_p$) provides a good metric for determining whether self-focusing will occur. This is done using the Marburger formula,[3] which relates a critical power, P_{cr}, to the optical properties of the media the laser pulse is traversing by the formula:

$$P_{cr} = \frac{3.72\lambda^2}{8\pi n_0 n_2} \tag{3}$$

For reference, P_{cr} for a NIR USPL in standard atmospheric conditions would be on the order of a few gigawatts. A fascinating observation is when $P_p \geq 2P_{cr}$ multiple filaments are likely to form, usually in integer relation to the number of P_{cr} in the power of the beam. This means, even in the absence of a focusing optic, the laser beam will decrease in radius to the point where localized hotspots preferentially form an array of filaments. By using precise control of the phase and intensity of a laser pulse, prescribed geometries of filaments can be created.

2.3 Ramifications of Increased Average Power and Repetition Rate

Stemming from recent developments in the capabilities of USPLs (see Section 3), new regimes of increased repetition rate and average power are unlocking a wider range of physical phenomena. For the first two decades of filamentation experimental work, USPLs with necessary $P_p > P_{cr}$ often operated at f_p = 1–100 Hz. These laser pulses lasted for less than a picosecond and the resultant plasma generated by the filament lasted for a few nanoseconds, yet there would remain 10s to 100s of milliseconds between pulses. This dichotomy in time scales meant that each pulse could be effectively treated as a singular event. This visually resulted in an erratic filament with fluctuating white light generation from pulse to pulse. With the advent of USPLs with repetition rates of 1 kHz or greater, a more steady-state filament was observed. Further experimental evidence and a theoretical framework for this phenomenon was given by Jhajj et al.[8] that showed the small amount of energy deposited by the filament caused an acoustic shock and thermal imprint in air that lasts for about 1 millisecond. Hence, a 1 kHz repetition rate laser creates a quasi-steady-state filament where one filament creates a preferential path for the next filament. The extent of this phenomenon is not currently known given the recent increase in repetition rate up to 100 kHz and the ability to irradiate the heated air with increasing average power.

3. USPL Sources

The development of CPA techniques has spurred increasing improvements and a wider variety of USPL source materials. The seminal paper by Strickland and Mourou[1] used Neodymium:Yttrium Aluminum Garnet (Nd:YAG) as the seed laser source, stretched through a glass fiber, to a block of Nd:glass as the amplification medium, and finally to a pair of gratings to compress the pulse. These represent the critical elements with most large-scale developments occurring with the seed laser and amplification medium while the stretching and compressing components have received necessary refinements to handle increased power and wider range of wavelengths. The seed laser requires a wide enough bandwidth to be compressible after amplification. The amplification medium will define the resultant laser wavelength and can be a solid state, ceramic, glass, fiber, or gas medium. In addition, later development of optical parametric amplification (OPA), optical parametric chirped pulse amplification (OPCPA), and difference frequency generation (DFG) can offer tunability to the resultant laser wavelength, in some cases spanning the UV, VIS, and IR spectra.

3.1 USPL Architecture

Advances in USPL architecture have enabled more efficient and powerful sources but often use the same general CPA principles and subcomponents. The key central component is the gain medium, which emits at certain wavelengths depending on the material properties. As seen in Fig. 2, a seed laser source provides a stretched initiation signal into the gain media amplifier, which is pumped by either flash lamps or another laser at a different wavelength. For instance, with Ti:Sa sources, a seed laser operating at a high repetition rate (e.g., 80 MHz) is stretched and focused into the Ti:Sa crystal that is pumped with frequency doubled Nd:YAG laser pulses at 0.532 µm. The resultant emission around 0.8 µm is then compressed through a series of gratings. At this point, frequency conversion techniques can be used to change the laser emission wavelength as described in Section 3.3. With increasing USPL powers, heating of these systems becomes critical and can introduce additional complexities. As well, laser designers must be careful to take into account damage threshold and nonlinear propagation effects. This can result in extraordinarily complex USPLs, particularly for Ti:Sa systems, requiring cryogenic cooling and evacuated chambers for the compressor gratings.

Newer techniques such as using larger or longer gain media as well as being able to efficiently combine multiple laser outputs offer promising avenues to mitigate these concerns. By using larger gain media, thermal energy can be more efficiently managed. Implementation of this concept is usually in the form of thin-disk lasers (TDLs) using doped gain material as described in Section 3.2. To date, TDLs have achieved high repetition rates and high average powers with very good beam quality, yet it remains a challenge to efficiently produce shorter pulse durations less than 100 femtoseconds. A different method for achieving high average powers is coherent beam combination (CBC), that utilizes multiple individual fiber lasers that couple together coherently to produce a single laser pulse. These fiber lasers tend to have much shorter pulse durations than TDLs and as such result in high peak power systems, though the complexity of coherent combination of multiple fibers is a challenge.[9] Yet, this has been successfully done for dozens of fibers and results in a superior beam quality with the advantage of being extremely scalable technology.[10] As advances are made in a wider range of laser gain materials, future implementations of TDL and CBC technologies are expected to cover a wider range of wavelengths.

3.2 Direct Emission Sources

Development of CPA-based USPLs utilized solid-state media that emitted at a particular wavelength. This paradigm can be called “direct emission sources” since we do not perform any conversion of this wavelength upon exiting the laser amplifier. These sources involve doping a host material (crystalline, glass, or ceramic) with metal ions to lase at a characteristic wavelength, see Table 1. In addition, these host materials are pumped either by flash lamps or another laser at particular wavelengths. Currently, the most powerful direct emission USPL sources emit in the NIR with Ti:Sa being the traditional source; however, materials doped with ytterbium (Yb) are making the biggest gains. The most promising form factors for high P_{avg} gain material are glass-based fibers and ceramic thin disks. Both offer unique advantages for implementation within a system or a larger platform with the former minimizing free-space propagation and the latter reducing the demands on gain material cooling. In addition, chalcogenide-based laser for the SWIR and MWIR show promise in delivering efficient generation with ultrashort pulse durations but have yet to be perfected. Beyond these solid gain materials, CO_2 gas lasers are still used to generate LWIR USPL with ps pulse duration around 10 µm.

Table 1 List of USPL gain material dopant and hosts with sufficient bandwidth centered at characteristic wavelength(s), λ

Dopant	Host	λ (µm)
Ti	Sapphire (Al_2O_3)	0.8
Yb	Glass, Crystal	1.03–1.04
Nd	Glass, Crystal	1.06
Er	Glass, Crystal	1.55, 2.9
Tm	Glass, Crystal	1.95
Ho	Glass, Crystal	2.05
Cr	Chalcogenide	1.8–3.4
Fe	Chalcogenide	3–8

3.3 Indirect Emission Sources

Indirect emission sources utilize a method of frequency conversion to augment the emitted laser wavelength. The most common form is to generate harmonics by propagation through special crystals. For instance, many green laser pointers are actually NIR lasers generating 1 µm that propagate through a crystal to produce second harmonic emission around 0.5 µm. Harmonic generation will produce specific wavelengths of light offering many viable choices in the NIR, VIS, and UV regimes. Another form of frequency conversion uses mixing of two or more frequencies to create tunable emission. Optical parametric amplification (OPA) uses a second frequency of light to amplify the original and emit a tunable difference wavelength. Difference Frequency Generation (DFG) takes this further by utilizing a signal frequency (or wavelength) and an idler frequency that are close to each, mixing the two to create a broad range of tunable emission with longer wavelengths. This technique was established using Ti:Sa USPLs and has gone on to be employed using other laser gain materials like Yb and erbium (Er). However, OPA and DFG based systems often see very low conversion efficiencies, particularly as the emission wavelength is pushed further into the IR.

4. USPL Applications

USPLs deliver sub-picosecond light that can probe at the molecular level and propagate at the kilometer level. Fundamental scientific research into ultrasfast phenomenon using ultrashort laser pulses has transitioned into a wide array of applications. These applications have, in turn, influenced further scientific research as well as development of newer, more capable USPLs. The wide scope of influence of USPLs was a driver for the awarding of the Nobel Prize to Strickland and Mourou. We will list a few research and development areas that make use of USPLs though this list is not inclusive of all applications.

4.1 Laser Machining

USPLs have excelled in the realm of laser machining by offering completely unique features with ever increasing capabilities. Femtosecond Laser Machining (FLM) has arguably been the main force in driving improvements in USPLs up until roughly 2017. FLM involves the precise manipulation of USPL ablation of solid surfaces where sub-picosecond pulses result in clean ablation craters with minimal spall compared to longer pulse lasers.[11] In addition, pulsed lasers, in particular USPLs, have demonstrated the ability to create microstructures on solid surfaces just below the ablation threshold. These patterns, laser-induced periodic surface structures, have demonstrated the ability to create superhydrophobic and superhydrophillic structures without the need of chemical etching.[12] Class-leading USPLs for FLM lead the way to more powerful systems that operate at kHz or greater repetition rates and more compact form factors. Until recently, these USPLs were primarily Ti:Sa systems but lately this application area has also taken advantage of newer paradigms like fiber and TDLs to greatly increase their throughput. However, the requirements of FLM do not necessarily include certain aspects that may be of broader interest like beam quality, ruggedizability, and wavelength tunability.

4.2 Frequency Conversion and Microscopy

By focusing intense USPLs into matter, nonlinearities can be generated and manipulated to cover broad spectral regions. Crystalline materials with strong nonlinearities were used early-on to generate second and third order harmonics of laser wavelength as described previously. A key piece of evidence that sufficiently intense USPLs can create filaments was in the observation of a narrow white light cone generated in the forward direction. Indeed, this white light peaked at the driving laser wavelength and covered many octaves above and below the original wavelength. The white light cone is typically narrow, roughly 5 degrees, with distinct spectral ring-like features within the wider cone. Experiments involving propagating intense NIR USPLs through gasses yielded a much broader range of harmonics and became known as High Harmonic Generation (HHG). Subsequently, it was discovered that by using a longer wavelength driving laser, HHG could extend out to the XUV and X-ray regime through noble gasses,[13] liquids,[14] or reflected off solids.[15] As such, HHG research has been a significant driver of longer wavelength MWIR and LWIR laser sources that would offer a much smaller footprint for generating coherent X-rays compared to linear accelerators. In addition, the shorter the wavelength of the harmonics, the shorter the pulse duration leading to the new field of attosecond (10^{-18} s) science.[16] Attosecond X-rays generated from HHG can be used to probe matter with ultrafast temporal precision from a “table-top” source.[17]

4.3 Particle Acceleration and High-Energy Physics

At the high end of USPL systems, there is active global competition to build the next generation of petawatt facilities. These efforts center around increasing E_p to a few joules while also decreasing τ to a few picoseconds to achieve $P_p > 10^{15}$ W. These systems typically operate in the NIR with f_p of 10 Hz or much less, and require complex evacuated experimental chambers. When focused, these PW pulses are able to interact with matter with relativistic intensities and simulate high-energy density physics (e.g., stellar astrophysics). These pulses can interact with a gaseous or solid metal target to produce energetic particle beams of electrons or protons in a much smaller footprint compared to a linear accelerator. While these systems do not readily lend themselves to DE applications, the individual enabling technologies may prove practical for a broader range of applications.

Of note in this area is the collaborative effort in Europe called the Extreme Light Infrastructure (ELI).[18] The goal of ELI is to establish world-leading experimental facilities while pushing the bounds of laser technology. ELI established two laboratory centers in Romania and Czechia while drawing in personnel and support from across the European Union and partner nations. Indeed, many US researchers have been involved in ELI and have gained or will gain access to the facilities to conduct experiments. The two facilities distinguish themselves by laser capabilities, often trading high peak power for high average power while also exploring the realms of longer laser wavelength. The ELI Romania facility will specialize in high energy physics and particle acceleration while the ELI Czechia facility and related center in Hungary will seek to advance technologies using high average power and longer wavelength USPLs. Further discussion of the impact of ELI on advancing USPL technology will be given in Section 5.

4.4 Laser Directed Energy and Propagation

Directed Energy applications for USPLs take advantage of the nonlinear optics achievable with high intensities. Primary among these effects is the ability to propagate over long distances with minimized divergence and distortions from turbulence.[19] Indeed, experiments have demonstrated the ability to project filaments over kilometer distances[20] and through clouds[21] and fog.[22] A significant challenge has been in the size and complexity of USPLs, particularly those using Ti:Sa technology. The European consortium, Teramobile, successfully built a transportable Ti:Sa high power laser system that performed groundbreaking experiments at remote sites on both sides of the Atlantic.[23] Nevertheless, the system was still complex and required highly trained personnel to maintain and operate. Subsequent improvements in Ti:Sa USPL resulted in a more encapsulated and semi-ruggedized system that proved resilient to being transported to experimental range facilities.[19] However, these systems still fall short on key SWaP metrics and indications are that we are near the limit using current concepts for Ti:Sa technology. Future systems will require not only higher average powers but also SWaP that greatly exceed the best Ti:Sa metrics to date. An intriguing example is the European Laser Lightning Rod program[24] currently in development that seeks to use filaments to direct electrical discharge from clouds. Extending this concept to a portable system will require a more robust, ruggedized, low-SWaP, low-maintenance USPL.

4.5 Other Applications

The previous applications are just a few that have been enabled by advanced USPL technology but represent some that may be more salient to defense applications. Notable omissions include ultrafast spectroscopy and the fast evolving world of biomedical applications that take advantage of the precision of USPLs. For the former, USPLs can provide detailed spectroscopic information regarding a wide range of materials undergoing chemical reactions. For the latter, laser-assisted surgery can benefit from using USPLs for many of the same features described previously for laser machining. Filament propagation may have unique benefits where long standoffs are required, like in burning holes through clouds, power beaming, or laser communications. Most of the discussion has centered around propagation through air and solids but propagation through liquids, particularly water, is of keen interest and builds upon much of the same physics. It should be emphasized that while the applications make use of common physics, each may have differing requirements when it comes to fundamental laser properties such as wavelength, pulse duration, or repetition rate.

5. Current and Future Developments of USPLs

Analogously, 10–15 years ago, CW kilowatt-class fiber amplifier lasers found themselves in a similar scenario to USPL sources of today. The telecommunications industry had invested heavily in the development of compact, efficient fiber optic and semiconductor components for transmitters, amplifiers, and multiplexers. In parallel, the laser manufacturing and automotive sectors were pushing investment in efficient, multimode fiber lasers with 10s of kW output. It required a concerted effort between the DOD and industry to marry the low power telecommunication components with the high power components of the laser manufacturing sector while developing common-use parameters and specifications for DOD lasers. This effort scaled single mode fiber amplifiers with sub 40% efficiency and 10s–100s of W to the approximately 50% efficiency, 2+ kW outputs, and while maintaining single mode operation. One final note of importance is that this power scaling alone was not even enough to enable the demonstrators being built across the DOD as this very paper is written. This scaling would have been for naught without the beam combination techniques that were developed to combine individual fiber amplifier lasers operating near their physics limits into one tactical laser source with 10s of kilowatt output, such as the Joint Robust Electrical Laser Initiative (RELI) between the Army, Air Force, and Direct Energy Joint Transition Office (DE-JTO). The USPL community is now on the cusp of its own power scaling and beam combination revolutions, with participants in ELI leading the way.

5.1 Current and Planned USPL systems

The recent spate of USPL development has enabled a broader selection of technologies to complement the traditional Ti:Sa architecture. This has also meant a broader range of wavelengths, repetition rates, and pulse duration are available. As shown in Table 2, cutting-edge laser systems reported in the open literature are demonstrating breakthroughs across the NIR, SWIR, and MWIR bands pushing average powers toward and beyond the kilowatt level. The dominant architectures of TDLs and CBCs for NIR wavelengths may be translated to SWIR and MWIR wavelengths with further materials development in laser gain sources. In fact, these improvements have already transitioned into commercially available USPL systems as shown in Table 3. Germany has excelled in creating a fast transition pipeline for both TDL and CBC technology that has been undoubtedly accelerated by the ELI program. This has already led to an almost order of magnitude advantage for German high P_{avg} USPLs compared to US commercial products as shown in Fig. 4. As such, we can expect to see further gains towards 10 kW USPLs and even surpassing the 100 kW threshold in the coming years. While the US has excelled at perfecting more capable Ti:Sa USPLs, commercialization of TDL and CBC technology is greatly lagging European counterparts. That is not to say various US academic institutions have not been instrumental in developing the necessary technologies but rather there does not seem to be the same economic driving factor for domestic commercialization of these technologies. In fact, a number of US institutions are leaders in developing novel laser gain materials and developed some of the earliest proof-of-concepts in CBC.

Table 2 Representative list of USPLs recently developed at academic institutions

IR Band	λ (µm)	Year	Architecture	τ (ps)	f_p (kHz)	P_{avg} (W)	P_{peak} (GW)	M^2	Ref.
NIR	1.03	2020	Yb TDL	0.92	1	720	689	2.1	25
	1.03	2020	Yb TDL	1.3	25	1900	3.7	1.5	26
	1.03	2020	Yb fiber	0.008	100	10	13.2	N/A	27
	1.03	2020	Yb fiber, CBC	0.26	2000	1000	1.95	1.11	10
	1.05	2016	Yb fiber, CBC	0.26	1000	1000	3.8	1.1	28
	1.05	2018	Yb fiber, CBC	0.43	80000	3500	0.1	1.24	29
	1.05	2020	Yb fiber, CBC	0.25	80000	10400	0.51	1.2	30
SWIR	2.05	2020	Ho:YLF	2.4	1	53	17	1.2	31
	2.1	2020	Yb:YAG, OPCPA	0.03	10	27	90	1.1	32
	2-3	2019	Cr:ZnS	0.019	78000	0.004	3	N/A	33
MWIR	4.4	2019	Fe:ZnSe	0.15	0.01	0.0035	23	1.8	34
	4.4	2020	Fe:ZnSe	0.73	10^5	0.042	5.7×10^{-6}	N/A	35
	5.1	2017	Ho:YLF, OPCPA	0.075	1	0.65	7.7	N/A	36

Table 3 Selected list of commercially available high average power USPLs

Company	Year	Architecture	λ (µm)	f_p (kHz)	P_{avg} (W)	P_{peak} (GW)	Size (liters)	Mass (kg)	ϵ_{wp}	Cooling	Ref.
Coherent	2015	Ti:Sa	0.8	1	7	200	260	280	0.03%	Water	37
KM Labs	2018	Ti:Sa	0.8	10	13	52	400	NA	NA	Cryo	38
MKS	2019	Ti:Sa	0.8	10	16	110	275	NA	NA	NA	39
Trumpf	2019	Yb, TDL	1.046	10	750	95	150	750	3%	NA	40
AFS	2019	Yb fiber, CBC	1.046	20000	2000	60	600	est. 5000	NA	NA	41
MKS	2020	Yb, TDL	1.03	30000	140	1.5	76	70	3.80%	Water	39
AFS	2020	Tm fiber, CBC	1.95	25000	300	20	1500	700	NA	NA	41

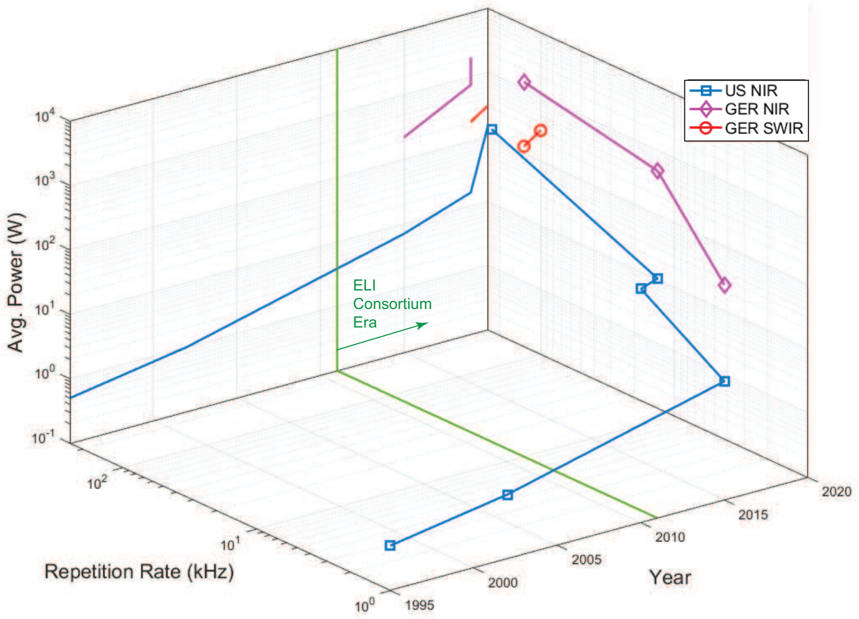

Fig. 4 Evolution of kilohertz-class pulse repetition rate USPL systems toward higher average power by year between the USA and Germany. US systems are almost exclusively in the NIR (blue line) whereas Germany has also started producing powerful SWIR systems (red line) in addition to world-leading NIR systems (purple line). The green line delineates the establishment of Europe's Extreme Light Infrastructure program with subsequent investment resulting in orders-of-magnitude increase in average power since 2017.

5.2 Developing USPL SWaP requirements

Since the mid-90s, the SWaP metrics of USPL sources have drastically reduced. Early USPL sources commonly occupied entire rooms or their own buildings at national laboratories. Today, one can purchase high peak power lasers with specs exceeding those early sources that can sit on a single optics table from multiple vendors with diversity in internal laser architecture options. The advent of the aforementioned CPA techniques coupled with advances in material manufacturing of doped ceramics, disks, and fibers have driven down this SWaP. The recently developed diode-pumped architectures for 1–2 µm sources leveraged the modern engineering of diode pump banks in the NIR and SWIR. These fiber-coupled commercial off-the-shelf products have experienced increases to greater than 50% in efficiency and SWaP reductions to 3.7×10^{-4} kg/W in one newer product.[42]

Two critical SWaP parameters to consider are power-volume density (L/W) and power-mass density (kg/W), which when combined provide a representative SWaP comparison between two laser sources. As seen in Fig. 5, recent lasers utilizing thin disks and coherent beam combination of fibers have significantly reduced both power densities to tenths of L/W and on the order of a kg/W rather than tens of liters and kilograms for similar Ti:Sa systems. These values remain two orders of magnitude larger than CW fiber and diode designs. However, this is indicative of their immature engineering state, not physical limitations, and their SWaP should continue to scale smaller. The electrical-to-optical efficiency also is required to do an accurate assessment of SWaP. For a free-standing CW diode-pumped fiber laser system, the electrical power and thermal management subsystems can attribute greater than 25% and 75% of the power-volume and power-mass densities, respectively. Also seen in Fig. 5, Trumpf's disk laser series[40] has been able to achieve efficiencies on the order of a percent rather than the hundredths of percent commonly seen in Ti:Sa systems. This improvement should not be overlooked or trivialized. As these sources push into the kilowatt average power regime, significant stress will be placed on both the electrical and thermal subsystems.

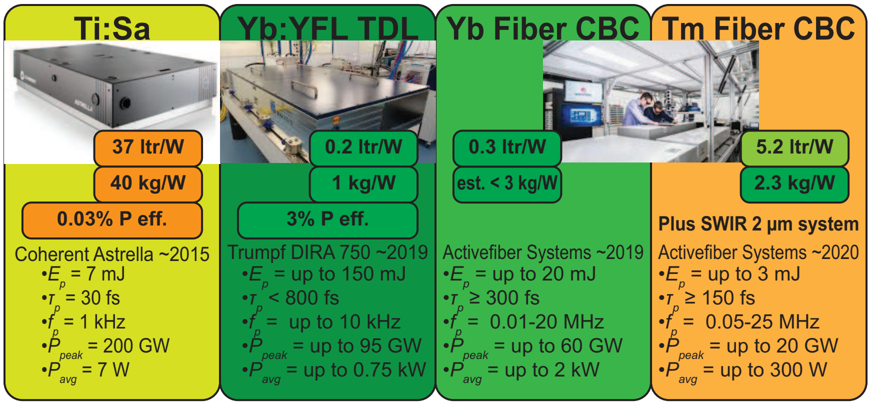

Fig. 5 Comparison of select USPLs demonstrating improvements in SWaP metrics with newer gain materials and architectures

6. Conclusion

Across the globe, newer, more capable USPL systems are being designed and installed in laboratory facilities. While the petawatt-class lasers demonstrate the forefront in providing new tools for high energy density physics and astrophysics, new facilities taking advantage of higher average power, kilowatt-class, USPLs are enabling different sets of physics, biology, and chemistry. For the latter class, Europe has taken a clear lead in both development of these lasers and in establishing coordinated multinational facilities to foster research using these new lasers. As mentioned previously, ELI will establish multiple facilities in Eastern Europe proving both petawatt-class lasers at ELI-NP and a wider range of high repetition rate lasers at ELI-ALPS and the related HiLASE facility. In addition, the Laser Lightning Rod project will seek to establish advancements in atmospheric propagation and electrical discharge work in a real world setting in Switzerland. Industrial capacity in Germany is enabling these projects with advanced laser architectures that have seen logarithmic growth in average power and repetition rates as shown in Fig. 4. France is also pushing the forefront in coherent combination with a planned 61-channel demonstration at the XCAN facility.[10] The XCAN initiative is another example of coordinating academic (Ecole Polytechnique) efforts with an industrial partner (Thales France, SAS).

Meanwhile, the US has only recently and in a limited fashion ventured into the high average power USPL domain and remains well behind the European state-of-the-art. Acknowledging that ELI has drastically changed the landscape of USPL technology, the Brightest Light Initiative (BLI)[43] seeks to organize a broad collaboration of US Academia and Industry to accelerate USPL R&D domestically. BLI is being proposed to the National Science Foundation as a key investment in domestic scientific infrastructure and STEM (Science, Technology, Engineering, and Math) education while also providing the framework and resources to integrate the US's disparate USPL R&D climate. While petawatt-class lasers are a key driver, the BLI proposal also seeks to further work in high average power USPL, particularly with upgrades to laser labs like the Lawrence Berkeley National Lab's BELLA Lab.[44] The proposed upgrade, kBELLA, will provide for kHz repetition rate laser pulses using CBC and will explore the feasibility of moving to 2 μm technology. Such efforts will likely provide a much needed economic boost for domestic USPL R&D as well as establish domestic lab facilities that DOD researchers could use to advance scientific understanding for defense purposes. In addition, more capable laser facilities will ensure that the next generation of scientists and engineers bring the latest concepts to tackle future threats and opportunities facing the US Defense enterprise.

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List of Symbols, Abbreviations, and Acronyms

BLI – Brightest Light Initiative

CBC – coherent beam combination

CPA – Chirped Pulse Amplification

CW – continuous wave

DE – directed energy

DE-JTO – Directed Energy Joint Transition Office

DFG – Difference Frequency Generation

DOD – Department of Defense

ELI – Extreme Light Infrastructure

FIR – far infrared

FLM – Femtosecond Laser Machining

HHG – High Harmonic Generation

IR – infrared

RELI – Joint Robust Electrical Laser Initiative

LWIR – longwave infrared

MWIR – midwave infrared

Nd:YAG – Neodymium:Yttrium Aluminum Garnet

NIR – near infrared

OPA – optical parametric amplification

OPCPA – optical parametric chirped pulse amplification

SWaP – size, weight, and power

SWIR – shortwave infrared

TDL – thin disk laser

Ti:Sa – Titanium:Sapphire

USPL – ultrashort pulse laser

UV – Ultraviolet

VIS – Visible spectrum

d_0 – initial laser beam diameter

E_P – pulse energy

f_p – laser pulse repetition rate

I – intensity of laser pulse

λ – laser wavelength

n – index of refraction

n_2 – second-order nonlinear index of refraction

P_{avg} – average power

P_{cr} – critical power for self-focusing

P_P – peak power of laser pulse

τ – pulse duration

w_0 – beam radius waist at focal point

z_R – Rayleigh range

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