

LIA TODAY

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DENVER, CO | OCTOBER 5-8, 2026

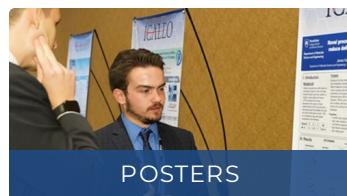
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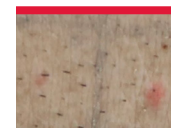
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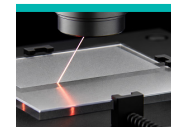
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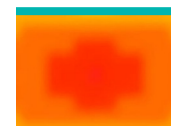
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EXECUTIVE DIRECTOR'S MESSAGE

Shaun Oleson

LIA EXECUTIVE DIRECTOR

Thank you to the subcommittee members who carry the Z136 standards, to the members of our Handheld Laser Device Safety Advisory Group, to the regional photonics clusters we now work alongside, and to every volunteer who gives this organization their time.

The Z136 volunteers work in drafts and comment resolutions, on their own time, over years. That work produces the consensus-led series of user safety standards this community relies on. Their contribution is not acknowledged often enough.

The Handheld Laser Device Safety Advisory Group brings together several of the world's largest manufacturers of handheld laser systems, along with the end users who operate them and safety specialists. Many of the people operating these devices are meeting laser hazards for the first time. The group's current effort is a handheld laser safety card, now in final review, written to reach the operator directly. Competitors are collaborating here alongside the people who use the equipment, and I am grateful to all of them.

We have established partnerships with Arizona's Optics Valley, the Colorado Photonics Industry Association, and the Florida Photonics Cluster. Conversations with other clusters are underway, and I expect this list to grow.

We are in the final stages of developing a national certification for industrial laser operators working in materials processing,

created in collaboration with ARCTOS, a DCS company. It is built on a completed job task analysis and aimed at the people running the equipment, a population that has not had a credential of its own. We will share the certification blueprint at ICALEO, and ARCTOS will walk attendees through the companion mobile assessment cart in a virtual demonstration.

The Member Mentorship Program has proven itself. Its first cohort finished this year, and the feedback from mentors and participants alike was resoundingly positive. I would like the next cohort to be larger, and I hope you will consider taking part on either side of it. Details are at lia.org/membership/mentorship.

Two dates. ICALEO returns to Denver October 5 to 8 for its forty fifth year, and registration is open. ILSC follows March 8 to 11, 2027, at the Royal Sonesta Houston Galleria. Subscribe at ilsc.ngo/subscribe for the call for papers.

The weeks when this community is together in one place are the best part of my year, whichever room it happens to be. If you are looking for a way to contribute, we need peer reviewers, advisory group and task force members, track and session chairs, mentors, and trustees. Speak with any member of our staff, or reach us at lia.org/contact, and we will find you a place.



PRESIDENT'S MESSAGE

Sam Salama, Ph.D.

LIA PRESIDENT

As we prepare to gather at ICALEO, I have been reflecting on both the remarkable history of our industry and the transformation now taking place around us.

For much of its history, LIA has been closely associated with laser materials processing - and for good reason. Lasers have transformed how we cut, weld, drill, mark, modify and increasingly manufacture materials with extraordinary precision. That foundation remains central to who we are. But the world around us is changing, and our community is changing with it.

We are entering an era in which photon energy is becoming as important to computing, communication and system architecture as it has long been to manufacturing and materials processing. The explosive growth of AI and high-performance computing is creating unprecedented demands for computational power, data movement, bandwidth and energy efficiency. Photonics and optical interconnects are increasingly becoming part of the solution.

At the same time, lasers continue to enable advances across semiconductor manufacturing and advanced packaging, aerospace and defense, medicine and healthcare, quantum technologies, sensing, communications and many other fields.

This evolution presents an important opportunity for LIA. We should preserve

the technical foundation that has made this organization successful while broadening the community we bring together. Our future should connect laser materials processing with the rapidly expanding worlds of photonics, advanced computing, communications and emerging applications.

As we expand that horizon, however, we must remain equally committed to the responsibilities that have long distinguished LIA. Laser safety must remain fundamental to our mission. Education and training must grow alongside the technology. And as laser technologies continue to advance in medicine and healthcare, LIA should remain a trusted forum for knowledge, safety and professional development across those applications as well.

Technology alone will not create the next generation of innovation. We need the people, skills, standards, manufacturing capabilities and collaborative ecosystem required to translate scientific advancement into real-world impact. That is where I believe LIA has an increasingly important role to play. Our opportunity is not simply to follow where laser technology is going, but to help bring together the people and disciplines that will shape where it goes next.

I look forward to continuing that conversation with many of you at ICALEO in few weeks.

Member Updates & Upcoming Events

Events

CLASSROOM TRAINING (NON-MEDICAL)		
DATE	EVENT	LOCATION
SEPT 23-24, 2026	Industrial Laser Safety Officer	Novi, MI
OCT 12-17, 2026	Calculating Laser System Hazards	Zoom
NOV 2-6, 2026	Laser Safety Officer with Hazard Analysis	Orlando, FL
NOV 2-4, 2026	Laser Safety Officer	Orlando, FL
NOV 11-12, 2026	Industrial Laser Safety Officer (ILSO) Training	Plymouth, MI
NOV 21-22, 2026	Medical Laser Safety Officer	Zoom
DEC 14-18, 2026	Calculating Laser System Hazards	Zoom
FEB 15-19, 2027	Laser Safety Officer w Hazard Analysis	Orlando, FL
FEB 15-17, 2027	Laser Safety Officer	Orlando, FL
MAR 9-12, 2027	Calculating Laser System Hazards	Zoom
MAY 17-21, 2027	Calculating Laser System Hazards	Zoom

CLASSROOM TRAINING (MEDICAL)		
DATE	EVENT	LOCATION
NOV 21-22, 2026	Medical Laser Safety Officer (MLSO) Training	Zoom (Virtual)

CONFERENCES		
DATE	EVENT	LOCATION
OCT 5-8, 2026	International Congress on Applications of Lasers and Electro-Optics (ICALEO) 2026	Denver, CO (Hilton Denver City Center)
MARCH 8-11, 2027	International Laser Safety Conference (ILSC) 2026	Houston, TX (The Royal Sonesta Houston Galleria)

Member Updates



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FEATURE

Thermadite 800

TIM

Photonics: The Invisible Infrastructure of Artificial Intelligence

IMG 1 –Advanced thermal materials help move and spread heat more effectively through the thermal stack, supporting the growing cooling demands of high-power AI processors.

By Qiongying Hu, Coherent Corp.

ABSTRACT

Artificial intelligence may live in software, but it depends on a rapidly expanding physical infrastructure. Advanced chips must be manufactured, enormous volumes of data must move between processors, heat must be removed, and expanding datacenters need more power. Across these challenges, photonics and advanced materials are playing important roles. From semiconductor manufacturing and optical connectivity to thermal management and emerging energy technologies, they are becoming part of the physical infrastructure behind AI.

Artificial intelligence may feel like a software revolution, but its growth is reshaping physical infrastructure that supports it. Advanced chips are becoming more complex, vast amounts of data must move between processors, power densities are rising, and datacenters are consuming more electricity.

Behind these challenges is a growing need for technologies that can build, connect, cool, and ultimately power AI infrastructure. Photonics is becoming an important layer of that infrastructure.

That story starts with the chip.

Build: Making the chips behind AI

The role of photonics in advanced lithography is well established. Lasers and precision optics help create the extremely small features found on today's most advanced chips. But making those features is only part of the challenge.

As chip features become smaller and more complex, manufacturers need to detect increasingly small defects that can affect performance and yield. The result is not only a steep increase in inspection steps, reaching more than 100 for today's most advanced nodes, but also greater demands on the lasers used for optical inspection.

Improving chip performance is no longer only about making smaller features. As physical limits and rising costs slow down the traditional pace of Moore's Law, advanced packaging is becoming another path to higher performance. By bringing processors, memory, and other functions closer together, it allows more computing power to work as one system.

Advanced packaging also demands exceptional precision and process control. Lasers enable processes ranging from drilling and cutting to inspection, bonding and debonding, with excimer, CO₂, solid state, and diode lasers serving different applications. Advanced materials, such as silicon carbide and diamond are critical to thermocompression bonding and other processes.

IMAGES COURTESY OF COHERENT CORP.

As AI pushes chip performance forward, photonics is becoming important not only in making smaller features, but across a much broader part of how advanced chips are inspected, assembled, and packaged.



IMG 2 – The Coherent Azure NX deep-ultraviolet laser supports advanced semiconductor wafer inspection, enabling detection of increasingly smaller defects as chip features shrink.



IMG 3 – Silicon carbide nozzles support thermocompression bonding processes used in advanced packaging.

Connect: AI Scales on Optics

Making more powerful chips is only part of the equation. Modern AI workloads are too large for a single processor to handle, so those chips must also communicate quickly with many others.

That connectivity challenge grows as AI infrastructure scales along three dimensions. Scale-up tightly connects processors within a rack or several racks. Scale-out connects computing clusters across the datacenter. Scale-across connects geographically distributed datacenters. Each creates different networking demands.

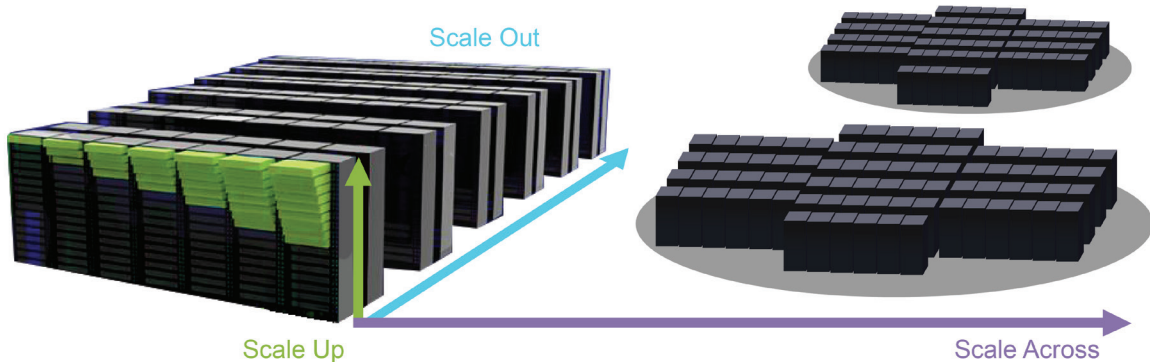
As data rates increase and distances grow, optical connectivity becomes increasingly important. Its combination of bandwidth, reach, and energy efficiency makes it essential to scaling AI infrastructure.

Put simply, AI runs on compute, but it scales on optics.

Cool: Managing the Heat

Scaling comes with another physical challenge: heat. As AI processors become more powerful and more densely packed, keeping them cool is becoming one of the biggest challenges in datacenter design.

The industry is already moving from traditional air cooling toward liquid cooling. But heat still must travel from the chip through several layers and interfaces before it reaches the cooling system. At today’s power densities, those materials can become part of the bottleneck.



IMG 4 – AI infrastructure scales along three dimensions: scale-up within a rack or several racks, scale-out across datacenter clusters, and scale-across geographically distributed datacenters.

IMAGES COURTESY OF COHERENT CORP.

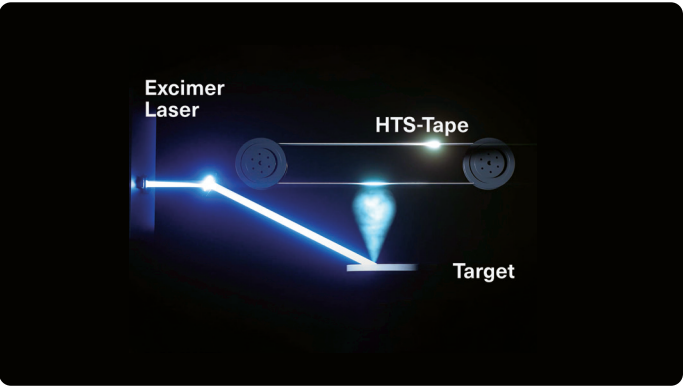
Advanced materials can help move and spread heat more effectively. These include silicon carbide, advanced composites such as Thermadite and increasingly diamond.

Many of the same materials that support demanding semiconductor applications can also help address one of AI’s biggest infrastructure challenges: heat.

Power: Meeting AI’s Growing Energy Needs

Better cooling can make AI infrastructure more efficient. But as that infrastructure continues to grow, efficiency alone will not answer the larger question: Where will the power come from? The scale is striking. AI datacenters can require hundreds of megawatts, while some of the largest planned infrastructure projects are already being planned at gigawatt scale.

Looking further ahead, fusion energy could become an important source of clean, reliable power as electricity demand grows, including demand from AI infrastructure. Photonics is an enabling technology across both major fusion pathways.



IMG 5 –Excimer-laser-based pulsed laser deposition (PLD) is used commercially to manufacture high-temperature superconducting (HTS) tape for applications including magnetic confinement fusion.

In magnetic confinement fusion, excimer-laser-based pulsed laser deposition (PLD) helps manufacture high-temperature superconducting (HTS) tape for powerful magnets. In laser inertial fusion, high-power lasers, nonlinear crystals, optics, and advanced materials are key enabling technologies.

PLD is undergoing a notable transition of its own. Long established as a research technique for creating complex thin-film materials, it is now moving from the laboratory to industrial-scale manufacturing of HTS tape.

HTS is also being explored for high-density power delivery, including the potential to move megawatts of electricity through smaller, lighter cables in future AI datacenters.

The same HTS technology that excimer lasers help manufacture for future fusion energy may also help solve the challenge of delivering enormous amounts of electricity to AI infrastructure.

For Coherent, these trends converge across a broad portfolio spanning lasers, optics, and advanced materials. Together, these technologies extend across the physical infrastructure behind AI, from semiconductor manufacturing and optical connectivity to thermal management and emerging energy technologies.

The Invisible Infrastructure Behind AI

AI will continue to push the limits of computing. But scaling it will require progress far beyond the processor itself.

From the factory floor to the datacenter and the energy systems that power it, photonics is becoming more deeply embedded in the infrastructure behind AI.

As AI advances, photonics will increasingly form the invisible infrastructure that makes its next phase possible.

ABOUT THE AUTHOR



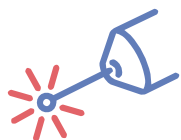
Qiongying Hu

Qiongying Hu is Director of Corporate Strategic Marketing at Coherent Corp., where she focuses on industrial markets and emerging technologies. She has over a decade of experience spanning R&D, product strategy, and market development, with a background in semiconductor and display technologies. She holds a Ph.D. in Chemical Physics from Columbia University.

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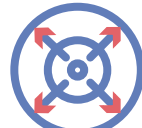
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JOURNAL OF LASER APPLICATIONS

JLA Featured Article

Porcine skin damage thresholds and computational modeling of continuous-wave laser exposure at 1567 nm

By Michael P. DeLisi, Emily M. Corbin, Andrea L. Smith, Amanda M. Peterson, Maria A. T. Hoffman, Alejandro Ramirez, Amanda J. Tijerina, Semih S. Kumru

ABSTRACT

Continued development of high-power laser technology necessitates a robust framework for ensuring safe operation and hazard assessment. Many laser systems pertinent to atmospheric propagation applications operate in the infrared region where the potential for damage to the skin becomes similar in magnitude to that of the eye. This

study investigated minimum visible lesion (MVL) damage thresholds for skin to 1567 nm laser exposure in Yucatan mini pig subjects, for exposure durations between 0.01 and 10 s, at Gaussian beam diameters of 0.63, 1.05, and 1.8 cm (1/e²). MVL thresholds, expressed as ED₅₀ values, were compared to the maximum permissible exposure (MPE) limits as defined by the ANSI Z136.1-2022 laser safety standard. The resulting safety factors of the tested parameters range from 10.3 to 31.0, demonstrating the adequacy of the MPE limits in protecting skin from 1567 nm laser exposure and even making a case for less restrictive definitions. Histological analysis of a limited subset of exposures implies that exposures at or slightly above the MVL threshold involve superficial dermis damage, with deep partial thickness burns occurring at approximately twice the MVL level of exposure. Additionally, computational models of laser skin interactions produced reasonable agreement with experiments, with an average absolute percent difference of 9.6% for peak temperature simulations and 13.3% for threshold power estimates, across all parameters. These results demonstrate a robust computational modeling framework for the simulation of 1567 nm laser exposure to skin.

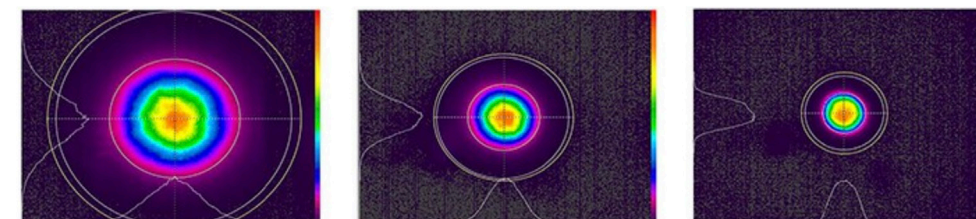


FIG 2 – Approximately Gaussian beam profiles (1/e²), measured to be (left) 1.8, (center) 1.05, and (right) 0.63 cm..



FIG 3 – Example lesions from 1567 nm laser exposure with a beam diameter of 1.05 cm. The left lesion is a MVL due to exposure at the threshold level, while the right lesion is more visible and was formed from an exposure at 1.25× the threshold level.

J. Laser Appl. 38, 042001 (2026)
<https://doi.org/10.2351/7.0002119>
Published: September 2026



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Unlocking More Value from Aluminum Scrap with LIBS Sorting

By Yvette Mattley, Ocean Optics

ABSTRACT

As demand for recycled aluminum grows, recyclers need dependable ways to separate mixed scrap into material fractions with the chemistry needed for reuse in new aluminum products. This article explains how laser-induced breakdown spectroscopy, or LIBS, supports that challenge by identifying elemental differences between aluminum alloys in real time. Using SpeedSorter as an example, it shows how laser sensing, spectroscopy, and sorting automation can work together to direct aluminum scrap into cleaner, higher-value fractions while supporting practical deployment, material validation, and improved recycling performance.

The challenge of turning mixed scrap into cleaner aluminum fractions

Aluminum recycling already has a strong sustainability case. According to the International Aluminium Institute, producing recycled aluminum can require about 95% less energy than producing primary aluminum and can significantly reduce greenhouse gas emissions. For industrial markets that depend on reliable secondary, or recycled, aluminum streams, the next challenge is not simply collecting more scrap. It is sorting that scrap into fractions that better match the required chemistry before remelting, the step that prepares scrap for reuse in new aluminum products.

That is where spectroscopy, lasers, and automated sorting technologies are moving from specialized tools into practical industrial infrastructure. Mixed non-ferrous scrap can contain cast and wrought aluminum, 5xxx and 6xxx families, magnesium-rich pieces, zinc-bearing alloys, coatings, attached materials, and surface contamination. For example, a recycler

may want to separate a magnesium-bearing 5xxx aluminum fraction from a silicon-bearing 6xxx fraction before remelting.

Bulk separation methods can recover aluminum-rich material, but producing cleaner, alloy-specific fractions from mixed non-ferrous scrap often requires a more specific decision: which pieces match the target chemistry, and which should be diverted elsewhere.

For recyclers, this distinction matters because cleaner, alloy-specific aluminum fractions can be more useful and more valuable than mixed scrap.

SpeedSorter: applying laser spectroscopy to industrial sorting

SpeedSorter applies laser-induced breakdown spectroscopy, or LIBS, to industrial metal sorting. In LIBS, a focused laser pulse strikes a small area of the material surface and creates a short-lived plasma. As the plasma cools, atoms and ions emit

Unlocking More Value from Aluminum Scrap with LIBS Sorting

light at wavelengths associated with the presence of specific elements. A spectrometer measures the emitted light, and the sorting software uses the resulting spectral data to support a real-time decision as scrap moves through an automated industrial sorting line.

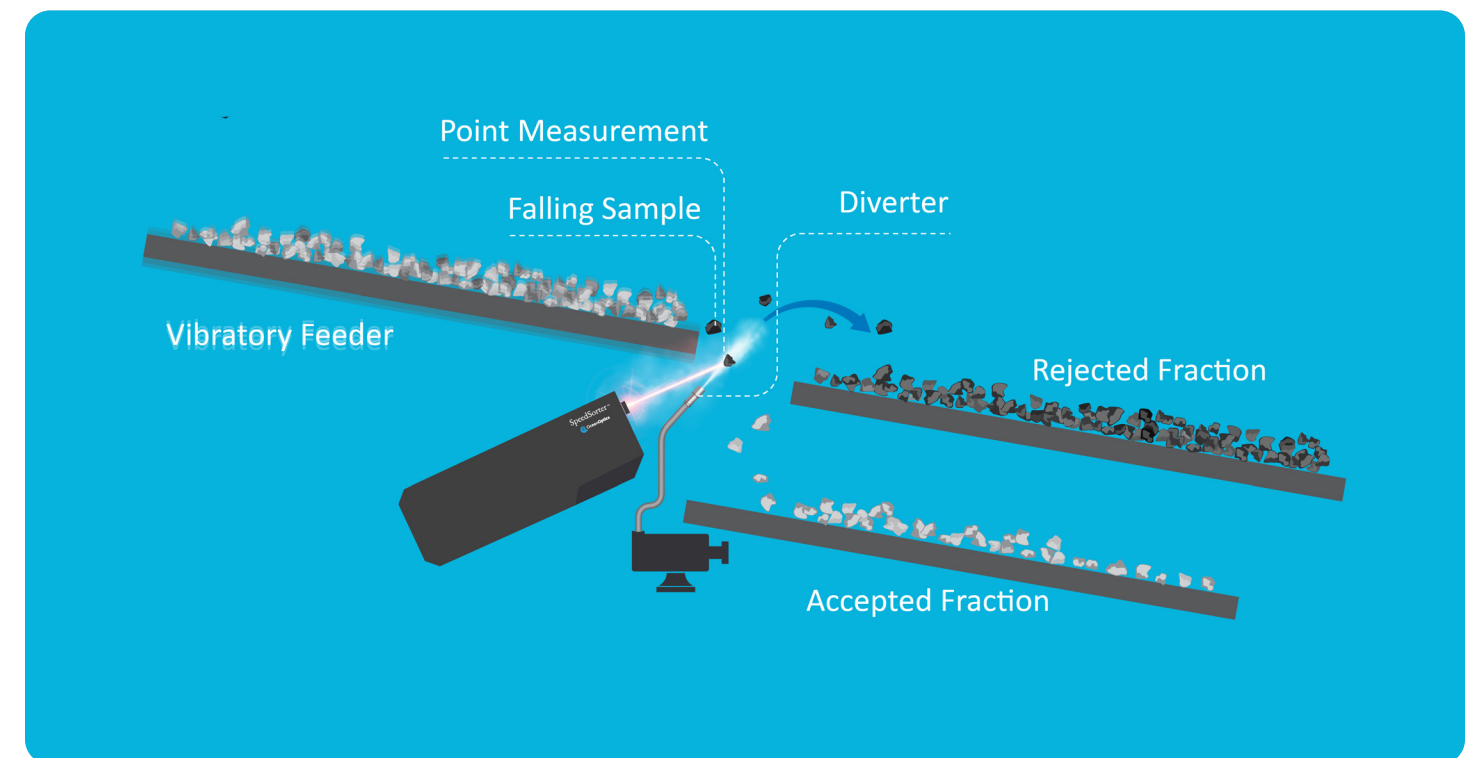
For aluminum recycling, the practical value of the LIBS-based sorting system is detecting elemental markers such as magnesium, silicon, and zinc that help distinguish target aluminum fractions within mixed non-ferrous scrap. Magnesium and silicon, for example, are important in many aluminum alloy families. Zinc can also be useful for separating certain high-strength aluminum grades. When the sorter is set up to identify a specific target fraction, these elemental signals can help recyclers separate material based on chemistry rather than appearance or bulk composition alone.

Today's recycling lines use multiple sensing and sorting technologies because no single method answers every material question. X-ray transmission, or XRT, is useful when density is the main sorting factor, while X-ray fluorescence,

or XRF, is widely used for many alloy and metal identification tasks. LIBS is especially useful when the sorting decision depends on light elements such as magnesium and silicon, which help distinguish certain aluminum alloy families. SpeedSorter brings that LIBS capability into the sorting line, supporting chemistry-based decisions for mixed aluminum scrap.

How SpeedSorter Turns Spectra into Sorting Actions

SpeedSorter brings LIBS out of the laboratory and onto the recycling line by integrating the sensor with industrial material handling equipment. Scrap pieces are presented to the measurement zone, a laser-safe enclosure controls exposure, the sensor collects emission spectra, and the software applies a decision method. In practical terms, the system is not simply looking at the shape or color of the scrap. It is using light emitted from the material itself to make a sorting decision. The resulting signal is sent to the sorting equipment so the piece can be diverted into the selected stream.



IMG 1 – Conceptual workflow for SpeedSorter-enabled aluminum scrap sorting: a scrap piece is presented to a laser-safe measurement zone, a focused laser creates a short-lived plasma, the spectrometer collects elemental emission data, software evaluates the spectral response, and the sorting system diverts the piece to the selected material stream

IMAGES COURTESY OF OCEAN OPTICS

Process factors: material quality and system capacity

In metal recycling, the economic value of a sorted fraction depends on whether that fraction matches the chemistry expected by the next processor. The value difference between mixed aluminum scrap and a cleaner, alloy-specific fraction can be significant. By helping recyclers direct more material into higher-value fractions, LIBS-based sorting can improve the usefulness of recycled metal while reducing the need for dilution, alloying corrections, downstream inspection, and other processing steps before the scrap is remelted for reuse.

Evaluating a LIBS-based sorting step requires characterizing the material stream first. Important variables include the fraction of target alloy present in the incoming scrap, the scrap size distribution, the degree of upstream separation, the allowable level of cross-contamination, and the consistency of the downstream specification. These factors determine whether elemental sorting will meaningfully change the quality of the output fraction. Validation should be based on representative scrap material and the quality requirements of the intended output fraction.

System capacity is governed by more than the spectroscopy measurement. The complete sorting process must present each piece to the measurement zone, provide reliable laser access, collect enough signal for the sorting decision, and actuate the diverter at the correct time. Conveyor speed, piece spacing and singulation, chute geometry, surface condition, and material size distribution all affect how consistently the system can classify and separate pieces in continuous operation.

Safety and deployment considerations

The laser-based sorting approach is still subject to the practical realities of LIBS measurement. Surface contamination, paint, oxidation, coatings, and inconsistent sample presentation can affect the signal and should be considered during method development. The sorting recipe should be built and validated with material that represents the actual process stream, not only ideal reference coupons.

Safety language also matters. The LIBS-based sorting approach does not rely on X-ray radiation, but it still uses a laser. In-line systems should be designed with appropriate enclosure, interlock, alignment, and operating controls.

Laser-based sorting can reduce certain regulatory burdens associated with X-ray systems while still requiring laser-safe engineering and operating practices.

A practical laser application for chemistry-based metal recycling

For recyclers, SpeedSorter helps address a practical sorting problem: directing the right aluminum fractions into the right material streams. When elemental differences determine whether scrap has the chemistry needed for remelting, in-line LIBS sorting provides the chemistry-based information needed to separate cleaner, higher-value fractions during production.

As an applied example, SpeedSorter is most useful when it is presented as part of a complete industrial sorting strategy. Used after appropriate upstream separation and validated against a defined target fraction, it can support cleaner, higher-value aluminum fractions, better use of melting capacity, and more confident supply of recycled material. For industrial markets that depend on controlled aluminum inputs, this is where spectroscopy, lasers, and sorting automation become practical tools for improving recycling performance.

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ABOUT THE AUTHOR



Yvette Mattley

Yvette Mattley is Product Scientist Manager at Ocean Optics. She brings more than two decades of spectroscopy application experience to technical training, sales enablement, and customer education, helping global teams

translate optical sensing technologies into practical measurement solutions for industrial, research, and applied science markets.



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Countdown to ICALEO

By the ICALEO Planning Committee

There's a particular kind of energy that builds in the weeks before ICALEO (October 5–8 in Denver, CO), and this year it's especially hard to ignore.

We're thrilled to congratulate **Jun Ye**, recipient of the 2026 Arthur L. Schawlow Award, LIA's highest honor, along with n²-Photonics, honored with the Steen Award. Both recognitions speak to work that has genuinely reshaped the field, and it's a privilege to celebrate it alongside our members. We're also proud to congratulate **Prof. Jie Qiao, Ph.D.** of Rochester Institute of Technology, newly elected as a Fellow of The Laser Institute, a distinction reserved for members whose contributions to the laser community leave a lasting mark.

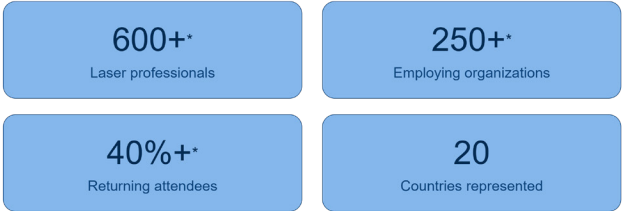
The ICALEO program itself spans three conferences, Microprocessing, Macroprocessing, and Additive Manufacturing, under one registration. Coverage ranges from ultrafast micromachining to high-power welding to powder-bed additive processes, with over 100 presentations from 73 organizations across 20 countries.

One thread running through several of those sessions this year: fusion. A dedicated session digs into the topic directly, and a handful of plenary talks pick up the thread too, from the physics behind ignition to the optical coatings that could make commercial fusion a reality. For anyone who wants to see that research in person rather than just hear about it, the Xcimer Energy Facility Tour offers a rare half-day look inside, though space is limited. Reserve your spot by September 30th as there will be no on-site availability.

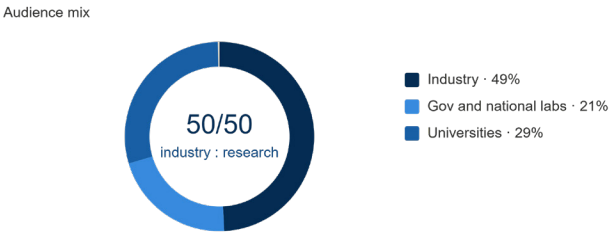
We can't wait to see everyone in Denver this October.

ICALEO 2026 by the numbers

Denver, Colorado · October 5–8



*Based on the three most recent congresses (Chicago, Los Angeles, Orlando)



Plenary speakers

Opening plenary — Monday, October 5

- TM Dr. Tammy Ma · Lawrence Livermore Natl. Lab
Ignition and the path to inertial fusion energy
- LA Dr. Lutz Aschke · Marvel Fusion
New laser technology advancing IFE
- CM Dr. Carmen S. Menoni · Colorado State Univ.
Redefining optical coatings for IFE

Closing plenary — Wednesday, October 7

- JG Dr. Jack Gabzdyl · TRUMPF
The real secrets of nanosecond welding
- JY Dr. Jun Ye · 2026 Schawlow Award recipient
Optical atomic and nuclear clocks

One registration includes every plenary and technical session

PHOTONICS

Two Megawatts per Zettabyte: Sizing the Femtosecond-Laser Market for Cold Data

By Peter Kazansky, CSO and Co-founder, SPhotonix

ABSTRACT

Archival “cold” data is already the majority of the world’s stored bits and is growing at more than 20% a year. 5D optical data storage writes that data into fused silica with femtosecond pulses, and its throughput requirement converts directly into laser demand: about 20 W of average power per 500 MB/s of write bandwidth. Working from public storage-shipment data, this article estimates how many ultrafast lasers the archive tier could absorb over the next two decades — and arrives at a volume larger than today’s entire ultrafast-laser industry.

A storage problem that is really a laser problem

The storage industry shipped roughly two zettabytes of new capacity in 2025: about 1.5 ZB of hard-disk capacity, several hundred exabytes of NAND flash and 160 EB of LTO tape [1,2]. Archive analysts have long estimated that over 60% of all stored data is archival — written once, kept for years, read rarely [3] — while hyperscale demand is pushing nearline exabyte shipments up at a mid-20s percent compound rate [4]. Cold data is the largest and fastest-growing category of bits on the planet, and almost all of it sits on media that must be powered, cooled and migrated every few years.

5D optical storage takes a different route. A tightly focused femtosecond pulse deposits energy through nonlinear absorption inside fused silica, leaving a self-organized birefringent nanostructure. The slow-axis orientation and retardance of that voxel are set by the polarization and energy of the writing pulse, so each voxel carries several bits on top of its three spatial coordinates. The medium is inert glass:

no power at rest, no refresh cycles, a lifetime measured in centuries. The physics, developed in Prof. Peter Kazansky’s group at the University of Southampton and now being industrialized by SPhotonix, is established [7]. The open question is throughput — and throughput is a laser question.

From 500 MB/s to 20 W

SPhotonix’s writer targets up to 8 bits per voxel, one voxel per pulse, at 20–30 nJ delivered to the focal volume. A 500 MB/s drive therefore writes 5×10⁸ voxels per second and deposits about 12.5 W in the glass. Real optical trains — splitting into tens of parallel channels, per-channel polarization and amplitude modulation, relay and focusing optics — lose 30–50% of the source power, so the practical source is a ~20 W, ~10 MHz, μJ-class femtosecond laser. Both fiber and solid-state sources have been run successfully against this specification in our development work, including Amplitude Laser. Pulse-to-pulse stability, polarization purity and round-the-clock reliability matter.

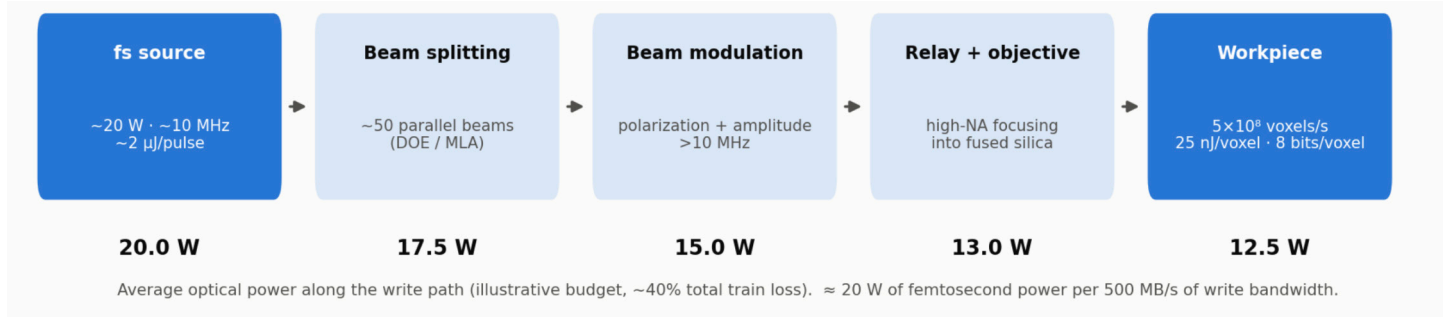
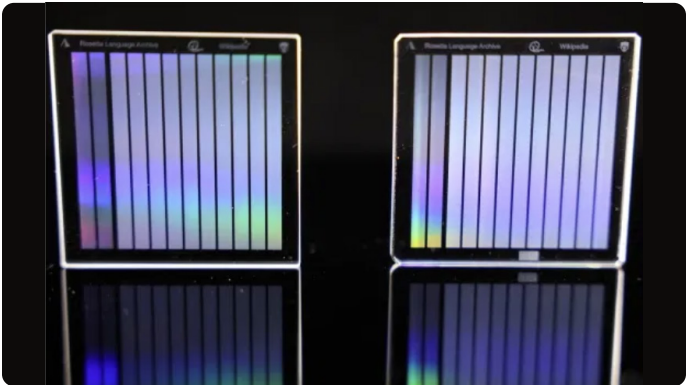
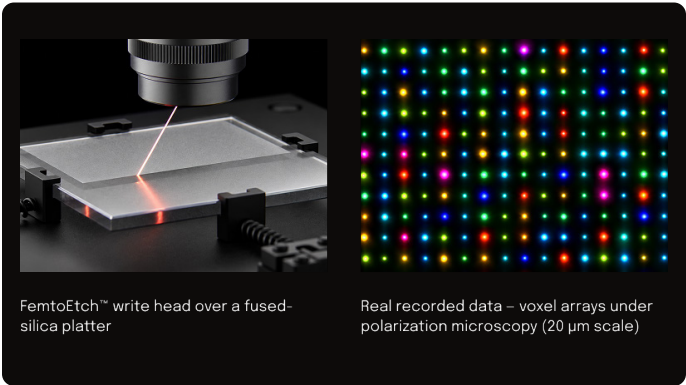


FIG 1 – Optical power budget of a 500 MB/s writer: ~20 W source → beam splitting → per-beam modulation → relay/objective → ~12.5 W delivered as 5×10⁸ voxels/s at ~25 nJ per 8-bit voxel (illustrative, ~40% train loss).



IMG 1 – A fused-silica 5D data platter.



IMG 2 – Polarization micrograph of birefringent voxels written in fused silica

The invariant is simple: roughly 20 W of femtosecond average power per 500 MB/s of archival write bandwidth.

From zettabytes to megawatts

Writing one zettabyte per year requires an aggregate 32 TB/s of write bandwidth. At 500 MB/s per drive and a realistic 60% duty cycle, that is about 105,000 write drives — and about 2 MW

of installed femtosecond-laser output. Two megawatts per zettabyte per year is the conversion factor between the storage market and the ultrafast-laser market.

Applied to the archive tier: 60% of the ~2 ZB shipped in 2025 gives ~1.2 ZB/yr of cold data today. At 22% growth to 2030, tapering to 15% thereafter, the cold inflow reaches ~3 ZB/yr in 2030, ~7 ZB/yr in 2035 and ~30 ZB/yr by 2045. A time-to-first-byte of ~15 seconds — what a robotic library of glass platters delivers — is acceptable for most deep-archive workloads; we assume three quarters is addressable.

If glass captures a quarter of that addressable inflow by 2035 and half by 2045 — a modest share for a medium that eliminates migration and standby power — the installed base grows to ~150,000 write drives in 2035 and about 1.2 million by 2045. With one 20 W source per drive and a six-year replacement cycle, annual laser shipments reach ~64,000 units (1.3 MW) in 2035 and ~360,000 units (7 MW) in 2045: roughly 190,000 femtosecond lasers in the first decade and about two million over twenty years (FIG 2).

What it means for the laser industry

The entire ultrafast-laser market was worth US\$2.4–2.9 billion in 2025 [5,6]. At a volume-manufactured price of US\$10,000–20,000 per module — a five-to-tenfold reduction from today’s bench-built systems, and a precondition for the storage economics to close — archival writers alone represent a cumulative US\$2–4 billion opportunity to 2035 and US\$20–40 billion to 2045, with annual demand in the 2040s exceeding the size of today’s whole ultrafast market. The architecture is a free variable — many smaller sources or fewer larger ones — and cost per watt delivered to the workpiece will decide.

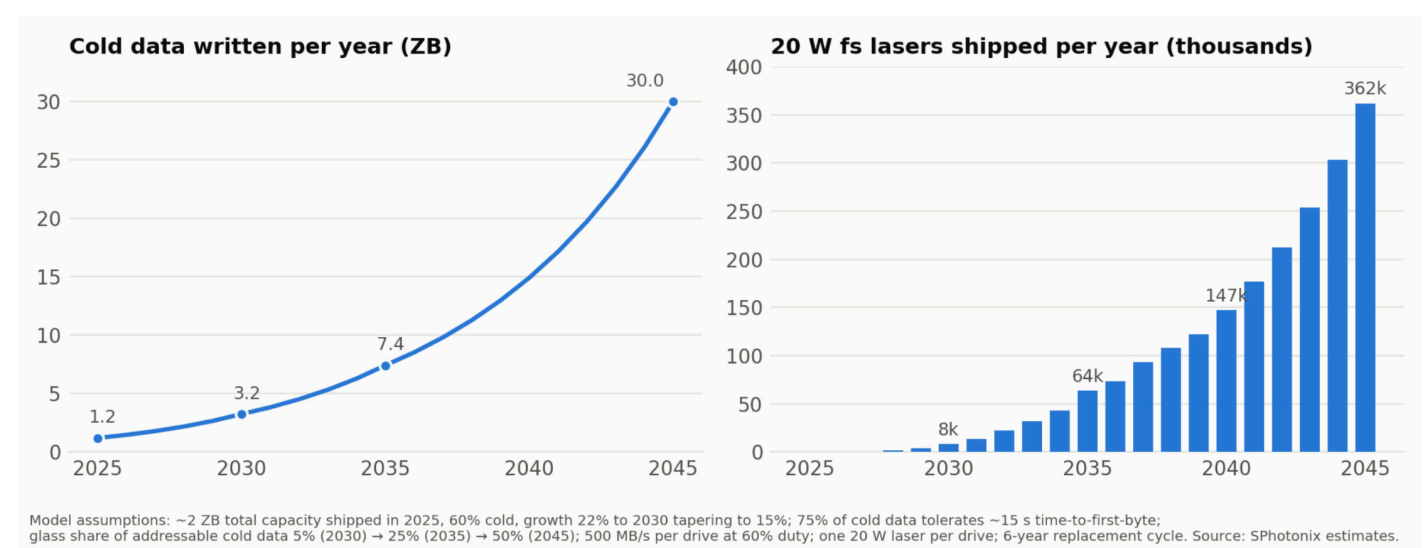


FIG 2 – Modelled cold-data inflow (left) and 20 W femtosecond-laser shipments (right), 2025–2045. SPhotonix estimates; assumptions listed beneath the chart.

What this market asks for is not a better laboratory laser but a different product: monolithic or alignment-free architectures, automated assembly and test, pump-diode lifetimes and telemetry designed for data-center duty, factory-sealed modules a technician can swap in a rack.

These disciplines took telecom diodes and industrial fiber lasers down their cost curves. Archival storage can do the same for femtosecond lasers — and the volumes would fund cost reductions for every other ultrafast application.

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Peter G. Kazansky Co-founder and Chief Science Officer of SPhotonix. Previously he was Professor at the Optoelectronics Research Centre, University of Southampton, where he has led research on light–matter interaction and ultrafast laser writing in transparent materials since 1992, and. He received his PhD from the General Physics Institute in Moscow under Nobel laureate Alexander Prokhorov. His group discovered self-organized nanogratings in glass, invented 5D optical data storage — recognized by Guinness World Records as the most durable digital storage medium — and developed the femtosecond-written S-waveplate polarization converter now used in high-power laser systems. He is a Fellow of Optica, has authored around 500 publications, and co-founded SPhotonix in 2024 to bring 5D storage to data-center scale. Contact: info@sphotonix.com

Ilya Kazansky

Ilya Kazansky is CEO and Co-founder of SPhotonix. A technology entrepreneur, senior executive and board director with more than 15 years’ experience in IoT, AI and big-data products, he has founded and built several companies, three of which he took to successful exits. At SPhotonix he leads strategy, commercial partnerships with the data-storage industry and the company’s fundraising, and is responsible for turning the 5D optical storage physics developed at Southampton into a data-center product. He led the company’s oversubscribed pre-seed round in 2025 and its ongoing engagement with the ultrafast-laser industry. Contact: ilya@sphotonix.com

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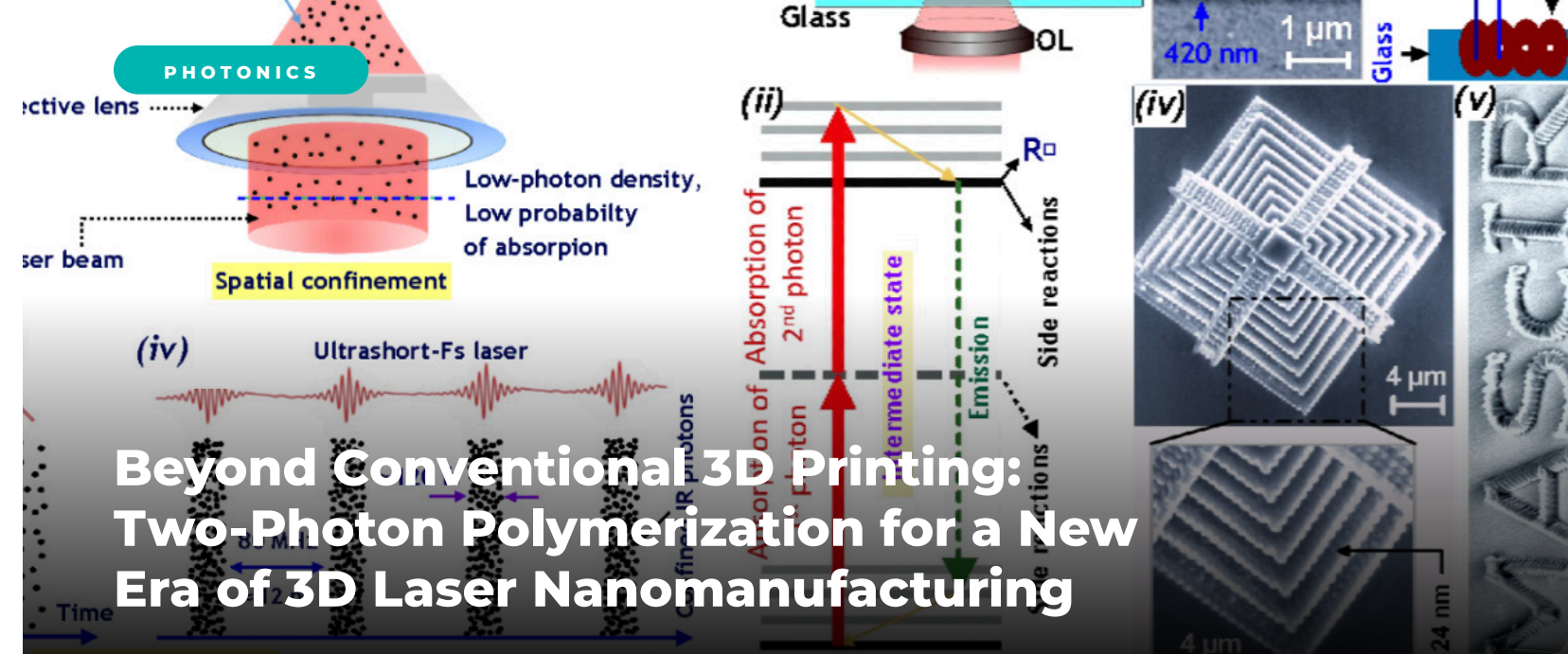
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Beyond Conventional 3D Printing: Two-Photon Polymerization for a New Era of 3D Laser Nanomanufacturing

By Yahya Bougdid

ABSTRACT

Two-photon polymerization (2PP) is transforming laser-based manufacturing by enabling direct fabrication of intricate three-dimensional (3D) structures with submicrometer precision. Tightly focused femtosecond (Fs) laser pulses confine polymerization to the focal volume, offering exceptional geometric freedom for micro-optics, photonics, biomedical devices, and advanced microsystems. This article explores 3D laser nanoprinting, focusing on voxel engineering and the fundamental trade-off between resolution and throughput. It highlights emerging strategies, including parallelized fabrication, advanced beam shaping, and AI-driven optimization, for scalable manufacturing. Applications across disciplines are reviewed alongside current challenges, recent innovations, and future directions for 3D laser nanomanufacturing today.

Introduction: The Rise of 3D Laser Nanoprinting

Why does 3D nanomanufacturing matter? Modern manufacturing increasingly demands structures that are not only small, but also three-dimensional, geometrically complex, and functionally integrated. 2PP offers a fundamentally different approach, using a tightly focused Fs laser to directly fabricate complex 3D architectures with submicrometer precision. This combination of resolution and geometric freedom has opened new opportunities in biomedical engineering [1, 2], micro-optics [3], photonics [4], and microrobotics [5], as shown in Fig. 1.

Why are conventional approaches not enough? Techniques such as extreme ultraviolet and electron-beam lithography provide exceptional nanoscale resolution but are primarily suited to planar fabrication and often require sophisticated processing [1]. 2PP overcomes this limitation by enabling

direct 3D fabrication through nonlinear light-matter interactions; i.e., 2-photon absorption (2PA) (Fig. 2a).

Understanding Two-Photon Polymerization: A New Paradigm in Laser 3D Printing

How does 2PP achieve 3D precision with light? 2PP relies on nonlinear 2PA, in which a photopolymer simultaneously absorbs two photons only within the high-intensity region of a tightly focused Fs laser beam, known as the voxel (volumetric pixel) (Fig. 2a). This confines polymerization to the focal volume while leaving the surrounding material largely unpolymerized [7-9].

What determines the achievable 2PP resolution? The polymerized voxel is the fundamental building block of 2PP (Fig. 2b). Its size and shape depend on laser power, exposure dose, scanning conditions, and photoresist properties, directly influencing resolution, structural fidelity, and mechanical performance.

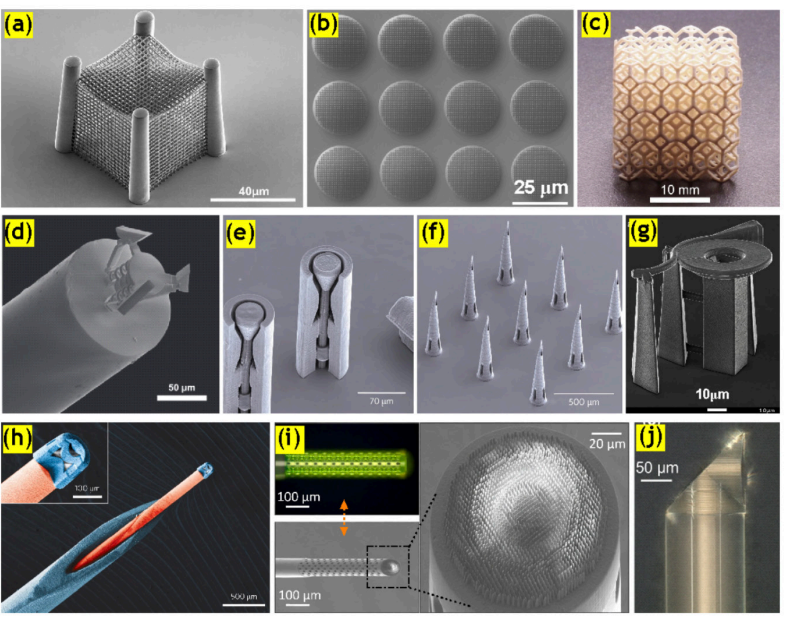
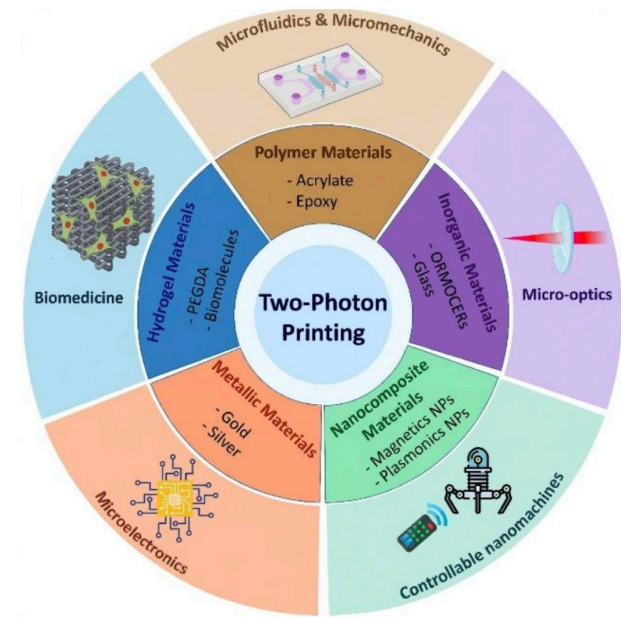


FIG 1 – (Left) Overview of 2PP printing: compatible material classes and their application domains (adapted from [1] under the CC BY 3.0 license). **(Right) 2PP-printed functional microdevices:** (a) Tissue-engineering scaffold (reproduced from [2] under the CC BY license); (b) Microlens array (reproduced under the CC BY-NC-ND 4.0 license [3]); (c) 3D nanoporous filter (reproduced from [4] under the CC BY license); (d) Microgripper robot (reproduced with permission [5], Wiley-VCH, © 2018); (e) Venous microvalve; (f) Microneedle array (e-f reproduced with permission [6], © 2009, Springer Nature); (g) Micro-ring resonator and waveguide (reproduced with permission [7]); (h) Triplet lens on fiber in syringe (reproduced with permission [8], © 2016, Springer Nature Limited); (i) Achromatic metafiber (reproduced under the CC BY license [9]); (j) Endoscope (reproduced with permission [10], © 2008, Optica Publishing Group).

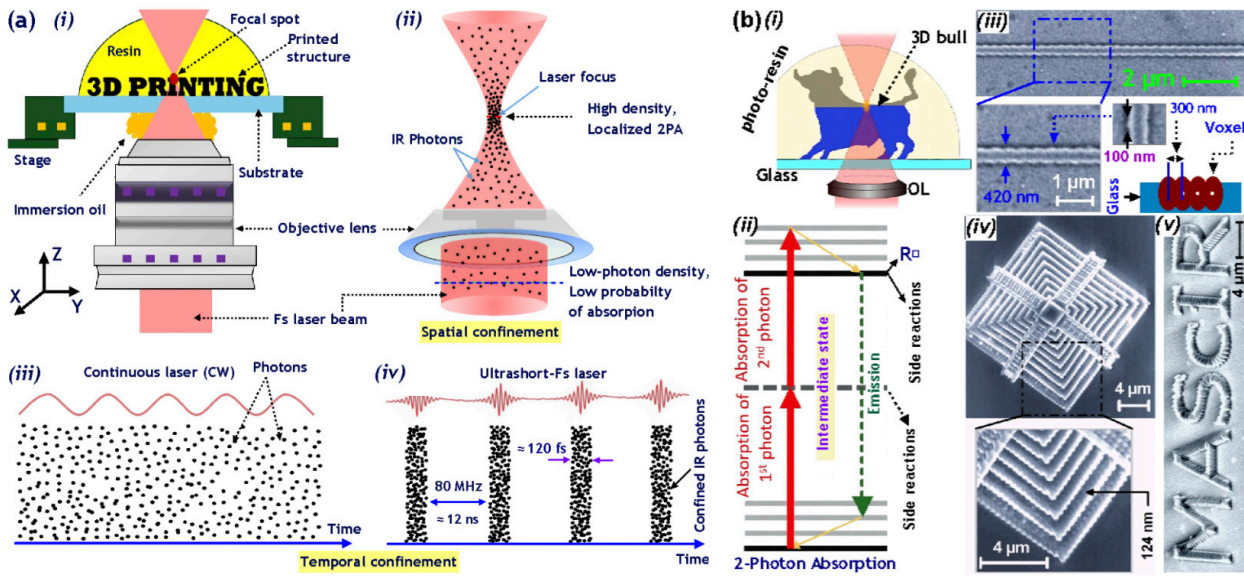


FIG 2 – Fs laser-assisted printing. (a) (i) 2PP setup; (ii) Spatial confinement of 2PA; (iii-iv) Temporal confinement: continuous-wave versus Fs laser (adapted from [1] under the CC BY 3.0 license). (b) (i) 2PP 3D printing (adapted with permission [11], © 2001, The Authors, Springer Nature); (ii) 2PA energy diagram; (iii) Voxel resolution; (iv) 3D micro-sized pyramid (iii-iv reproduced under the CC BY license [12]); (v) Printed MAScIR logo (reproduced with permission [13], © IOP Publishing). Representative 3D microstructures fabricated by Dr. Yahya Bougdid, marking the first implementation of 2PP technology in Morocco.

Optimizing Voxels for High-Performance Nanoprinting

How can 2PP maintain exceptional resolution without sacrificing throughput? In 2PP, voxel dimensions directly influence resolution and structural fidelity (Fig. 3). Excessive exposure enlarges voxels, while insufficient exposure causes incomplete polymerization. The throughput-resolution (Res) trade-off governing printing speed can be described by Tennant's law adapted for 3D lithography [1]:

$$Res = C \times T_{3D}^{0.3} \text{ or } T_{3D} = C' \times (Res)^3$$

Where $C = 1/c^3$ reflects process efficiency. The cubic scaling shows finer resolution drastically cuts throughput.

What controls the optimal voxel? Exposure parameters must be balanced with photoresist properties such as photoinitiator concentration, viscosity, polymerization kinetics, and shrinkage [11].

Emerging strategies; including adaptive laser modulation, parallelized and multifocus writing, advanced photoresists, optimized scanning, and AI-assisted process control; are helping bridge the gap between 2PP's precision and the throughput required for practical 3D nanomanufacturing.

What Can 2PP Actually Make?

The versatility of 2PP extends far beyond simple polymer structures. Its submicrometer precision and true 3D freedom enable applications in micro-optics, photonics, microrobotics, microfluidics, and biomedicine. In micro-optics and photonics (Figs. 1b-c-i) [3, 4, 9], 2PP fabricates complex lenses, optical components, and miniature optical systems. In microrobotics and microfluidics, it creates microactuators and intricate mechanical and fluidic architectures unattainable by planar manufacturing (Figs. 1d-g) [5, 7]. In biomedicine (Figs. 1a-e-f) [2,

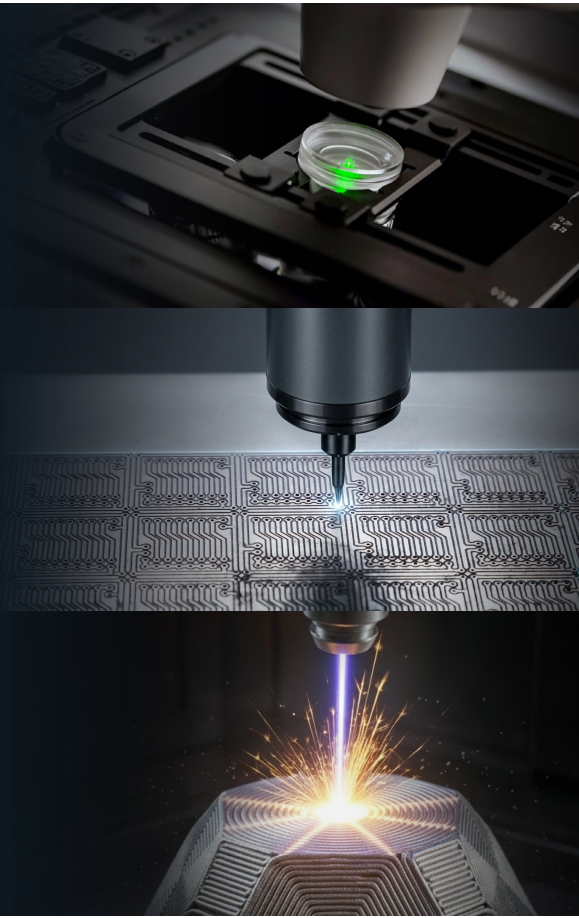


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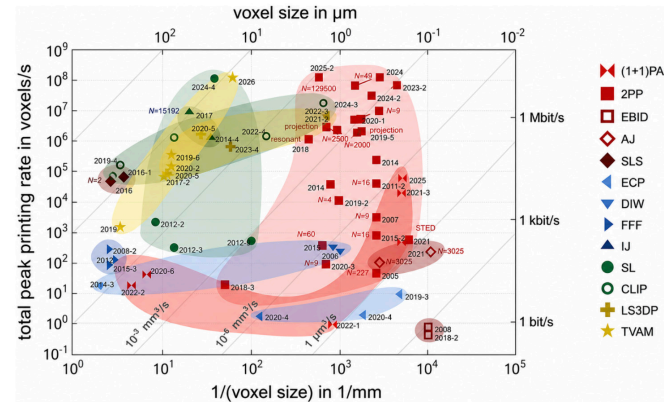


FIG 3 – Comparison of 3D-printing methods in terms of maximum printing speed (throughput) and voxel resolution. Voxel size = Average of lateral and axial dimensions. SLA: stereolithography; CLIP: continuous liquid interface printing; SLS: selective laser sintering; (1 + 1) PA: (1 + 1)-photon absorption; LS3DP: light-sheet 3D printing; TVAM: tomographic volumetric additive manufacturing; IL: interference lithography. Adapted with permission from: [14], © 2023, Springer Nature Limited, and [15] under the CC BY 4.0 license. Updated version: <https://3dprintingspeed.com>.

Why Is 2PP Still Relatively Slow?

The precision of 2PP inherently limits throughput. Conventional systems rely on serial scanning of a single focused voxel, requiring millions of discrete exposures for complex volumes. Consequently, fabrication time scales sharply with structure size, resolution, and geometric complexity, following Tennant’s law. This voxel-by-voxel paradigm makes large-area patterning impractically slow, constraining industrial adoption despite nanometer accuracy (Figs. 2–3).

Can 2PP Become Suitable for Larger-Scale Manufacturing?

How can 2PP increase productivity without sacrificing precision? A key strategy is parallelized fabrication, where multiple features are produced simultaneously rather than sequentially. Microlens arrays and diffractive optical elements can create multiple laser foci, while spatial light modulators, and holographic approaches enable programmable control of exposure patterns [8, 9].

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High-speed galvanometric and polygon scanning can further accelerate beam positioning.

Together, these approaches provide practical pathways to higher fabrication rates while preserving geometric freedom that sets 2PP apart from conventional manufacturing techniques.

Overcoming Challenges Toward Industrial Implementation

Despite its ability to produce highly complex 3D structures with exceptional precision, 2PP still faces key barriers to industrial adoption. Limited build volumes, material constraints, system complexity, and high equipment costs can hinder the transition from laboratory demonstrations to scalable production. Advances in automation, process stability, materials, and system efficiency will be critical to making 2PP more reliable, and economically viable for industrial applications [7, 15].

Future Perspectives

Future developments in 2PP are expected to move technology beyond high-resolution prototyping toward scalable fabrication of functional micro- and nanoscale devices. Multifunctional materials could broaden the capabilities and applications of printed structures, while advances in intelligent manufacturing could improve process adaptability. Hybrid manufacturing can combine the 3D precision of 2PP with the productivity of complementary techniques, expanding its application across advanced technologies [1-9].

The key question for next-generation 2PP is no longer simply, “How small can we print?” but rather, “How small, how fast, and how large can we print?”

Balancing resolution, throughput, functionality, and cost will determine how effectively 2PP evolves into a practical nanomanufacturing platform.

ACKNOWLEDGMENT OF SOURCES AND EXPLANATION

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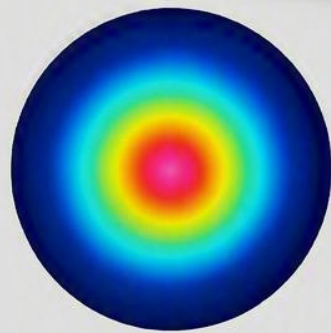
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Yahya Bougdid received his PhD in Photonics from Mohammed V University, Morocco. His doctoral research focused on 2PP printing, establishing 2PP technology in Morocco for the first time. He is currently a researcher at the University of Central Florida, USA, focusing on laser additive manufacturing, laser doping, and optical materials.

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OPTICS

DIELECTRIC OXIDE

FLUORIDE

Dielectric Oxide Vs Fluoride Deep-UV Coatings at 193nm

By Giedrius Kupčikas, Research Engineer at OPTOMAN

Argon fluoride (ArF) excimer lasers are deep ultraviolet lasers with a 193 nm wavelength, which is commonly used in semiconductor lithography, eye surgery, micromachining, and scientific research. However, operating at this wavelength presents unique challenges: exposure to high-energy photons accelerates optical degradation, making high reflectivity and low absorption essential. In addition, maintaining environmental stability is critical to ensure consistent laser system performance and uptime.

Meeting these optical performance demands requires the use of specialized coating technologies. Two primary approaches dominate: fluoride-based coatings, valued for their intrinsic UV transparency, and dielectric oxide-based coatings, known for their durability and environmental resilience. While both can deliver high reflectivity at 193 nm, they diverge in performance in real-world conditions.

This whitepaper addresses the growing demand for long-lifetime, low-maintenance, and high-stability optical coatings in 193 nm deep ultraviolet (DUV) laser systems. We present the advantages of dielectric oxide coatings across real-world ArF lithography systems.

Substrate Considerations: SiO₂ vs CaF₂

Two substrate materials have emerged as the primary choices for the 193-nm wavelength: fused silica and calcium fluoride.

Well-characterized, easy to fabricate, and thermally stable, fused silica is, in many ways, the material of choice for 193 nm. While fluoride crystals like CaF₂ are ultra-transparent in the DUV, dielectric substrates, especially UV-grade fused silica, offer superior readiness and operational advantages.

CaF₂ presents several notable drawbacks. It is pressure sensitive and exhibits a high coefficient of thermal expansion. These properties, combined with its single-crystal structure, make CaF₂ extremely difficult to fabricate to the required levels of optical smoothness. According to [John Bruning](#) of Tropel (Fairport, NY), the material “polishes terribly”. While it is possible to achieve a good surface finish, doing so is challenging and costly.

Fused silica substrates, by contrast, are robust, cost-effective, and widely available. When paired with IBS dielectric coatings, they enable long-lifetime, easy-to-maintain optics. However, the performance and longevity of the optical system are primarily dictated by its coating technology.

Coating Technologies at 193nm: Dielectric Oxide vs Fluoride

Dielectric coatings for 193 nm optics offer a combination of high reflectivity, damage resistance, and environmental durability that makes them ideal for demanding DUV applications. Multi-layer stacks, typically composed of Al₂O₃ and SiO₂, can achieve reflectivity levels of up to 98-99%, suitable for highly reflective mirrors. These coatings

IMAGE COURTESY OF OPTOMAN

PROPERTY	FUSED SILICA	CALCIUM FLUORIDE
Transparency (193 nm)	UV-grade fused silica transmits down to ~180 nm; absorption <0.002 cm ⁻¹	CaF ₂ absorption <0.0005 cm ⁻¹ excellent DUV performance
Availability & Cost	Abundant large blanks, mature manufacturing, lower cost	Brittle, hygroscopic, high cost, limited supply
Polishing	Easily polished to a few-angstrom surface roughness	Difficult and slow polishing, higher defect risk
Mechanical Stability	Excellent robustness, low birefringence, widely used	Brittle, mechanical risk under stress
Laser Exposure Stability	Prone to compaction over time — mitigated by coatings and grade selection	No compaction due to crystalline structure

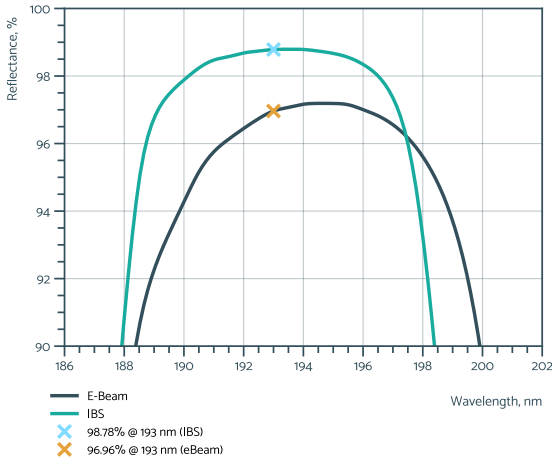
demonstrate strong resistance to DUV laser-induced damage, and enhanced versions have shown long operational lifetime at high repetition rates and moderate fluence levels. When deposited via Ion Beam Sputtering (IBS), oxide coatings also offer superior mechanical resilience, low moisture sensitivity, and minimal maintenance requirements.

Fluoride-based coatings, typically made from LaF₃ and MgF₂, also show high reflectivity of ~92-98% at 193 nm when properly deposited at elevated temperatures (up to 400 °C). However, they face significant challenges, including higher film stress, lower packing density, and sensitivity to environmental conditions. Fluoride coatings exhibit lower resistance to air humidity exposure and require more complex maintenance and upkeep, particularly under tightly controlled operating conditions. Unlike fluoride-based coatings, IBS oxide coatings are less sensitive to UV exposure and moisture.

These oxide-based coatings, particularly those deposited via Ion Beam Sputtering (IBS), exhibit excellent mechanical durability. They are scratch-resistant, humidity-resistant, and require minimal maintenance, preserving optical performance under challenging environmental conditions. From the measurements we have done, we observe that the dielectric-oxide coating, developed and produced by OPTOMAN, remains stable over time and has a higher reflectance value than the fluoride coating deposited using E-beam technology.

Practical Advantages of Dielectric IBS Coatings in DUV Optics

DUV optics with Ion Beam Sputtering (IBS) oxide coatings are durable, scratch- and humidity-resistant, and require minimal maintenance. They maintain optical integrity under demanding



Comparison of 193 nm E-beam-sputtered fluoride coating and IBS oxide coating reflectance spectrum measurements.

Precise characterization of 193 nm wavelength is challenging due to the limitations of standard spectrometers.

OPTOMAN employs “PhotonRT” by EssentOptics, a high-accuracy instrument tailored for [deep-UV](#) spectral evaluation. This ensures reliable and consistent validation of coating performance across production.

FLUORIDE	DIELECTRIC
Wide Bandgap: Fluoride materials have wider electronic bandgaps than oxides, which helps lower the absorption;	High reflectivity: Multi-layer stacks form dielectric mirrors and highly reflective coatings with reflectivity up to 98–99% at 193 nm;
High Catastrophic LIDT: Fluoride coatings offer superior resistance to single-pulse catastrophic damage (LIDT);	Operational lifetime: Our LIDT comparison showed that the lifetime of a dielectric-coated mirror under DUV laser exposure was longer compared to a fluoride-coated example, despite lower catastrophic damage threshold;
Low Refractive Index: Fluorides provide the lowest available refractive indices for thin films, allowing for specific high-performance interference designs that cannot be achieved with oxides alone;	Enhanced durability: Oxide coatings are durable, scratch-resistant, and humidity-resistant, requiring minimal maintenance. They maintain optical integrity under demanding conditions;
Reduced Thermal Lensing: Low absorption coefficients minimize heat absorption during high-peak-power pulses, reducing thermal distortion of the wavefront.	No Special Conditions: IBS oxide coatings are less sensitive to UV and humidity than fluoride coatings.

conditions, making them highly suitable for precision-driven lithography systems. The ease of handling, cleaning, and storing enhances the overall operational reliability and cost-effectiveness of dielectric optics in DUV systems, especially when uptime and maintenance predictability are critical.

Handling Guidelines Dielectric optics with IBS coatings are robust and user-friendly. Safe handling requires standard powder-free nitrile gloves, with optics manipulated at the edges using non-scratching tweezers or gloved hands. The mechanical resilience of these coatings significantly reduces the risk of accidental damage during handling compared to more fragile alternatives, such as fluoride-coated components.

Cleaning Made Simple Maintenance is straightforward and forgiving. Particulate contaminants can be removed using clean, oil-free air or nitrogen blowers. For smudges or residue, ethyl acetate serves as an effective solvent, applied gently with lint-free wipes or optical swabs made from polyurethane, polyester, or microfiber. IBS coatings exhibit strong resistance to cleaning-induced damage, unlike the more delicate fluoride-coated optics.

Storage Recommendations Dielectric optics demand no special storage infrastructure. Simply keeping them in their original, sealed packaging within a clean, dry, room-temperature environment is sufficient to prevent contamination. While it is advisable to avoid prolonged exposure to extreme humidity or UV, IBS oxide coatings are

far less sensitive to such factors compared to fluoride-based coatings, further simplifying storage and logistics.

Conclusions

When it comes to 193 DUV laser optics, UV-grade fused silica substrates, combined with advanced dielectric coatings, offer a superior balance of performance, reliability, and manufacturing repeatability. While fluoride coatings require strict environmental control and conditioning, dielectric coatings offer robust, long-term reliability in real-world DUV laser systems.

Applied using Ion Beam Sputtering (IBS) technology, these coatings exhibit exceptional durability, scratch resistance, and environmental stability, making them ideally suited for high-volume laser lithography systems. With proper material selection and coating design, fused silica optics are well equipped to consistently meet the rigorous demands of ArF excimer laser systems, both in terms of optical performance and long-term system reliability.

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Keeping Ultrafast Pulses Consistent Across the Scan Field

By Bill Murray, Ph.D., and Jay Small, Edmund Optics

ABSTRACT

Ultrafast scanning systems are often specified by spot size, scan area, and distortion. Those metrics do not show whether a femtosecond pulse remains spatially and temporally consistent across the field. Broad spectral bandwidth makes ultrafast pulses sensitive to chromatic aberration, group delay, and group delay dispersion. Treating these effects as optical design variables, rather than relying only on pre-chirp techniques, enables f-theta lenses to deliver more uniform peak intensity and processing performance from the center to the edge of the scan.

The workpiece sees the delivered pulse

Ultrafast lasers have moved from specialized research tools into production systems for micromachining, semiconductor processing, medical-device manufacturing, and processing of transparent materials. Their value comes from concentrating energy into picosecond or femtosecond pulses, enabling material removal with a smaller heat-affected zone than is typically possible with longer pulses. Unfortunately, the pulse specified at the laser output is not necessarily the pulse that reaches the workpiece.

Every component in the beam-delivery system changes the beam to some degree. In a scanning system, the f-theta lens has an especially difficult job: it must focus the beam onto a flat image plane while maintaining a predictable relationship between scan angle and spot position. For a narrowband laser, designers primarily optimize focal spot size, field flatness, distortion, wavefront error, telecentricity, and back reflections.

An ultrafast source adds another dimension. Its broad spectrum means the lens must control where the wavelengths focus and when they arrive across both the pupil and the full scan field.

Why conventional f-theta specifications are incomplete

An f-theta lens converts the scanner's angular motion into predictable movement of the focused spot across a flat work surface. This simplifies motion control and helps maintain processing speed across the field. However, it does not guarantee that every wavelength in an ultrafast pulse focuses at the same location.

Lateral chromatic aberration sends different wavelengths to different radial positions while axial chromatic aberration brings them to focus at different depths. Either effect spreads energy spatially, lowering peak intensity and changing the effective spot size at the workpiece. A laser compressor

Keeping Ultrafast Pulses Consistent Across the Scan Field

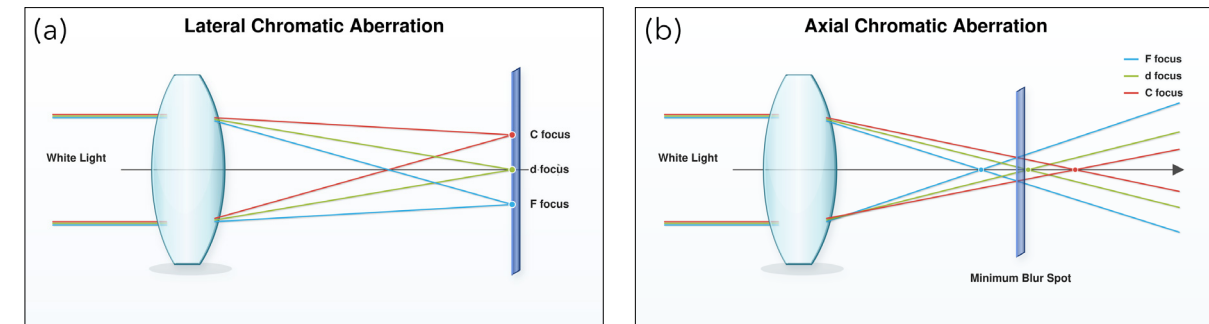


FIG 1 – Lateral (left) and axial (right) chromatic aberration in a conventional lens, illustrated using the standard C, d, and F Fraunhofer wavelengths.

or pre-chirp setting cannot correct these errors because it changes the relative arrival time of the wavelengths comprising the pulse, not their focal position. The lens itself must be chromatically corrected.

Pre-chirp is necessary, but it is not sufficient

Temporal behavior is commonly described using group delay (GD) and group delay dispersion (GDD). Group delay is the first derivative of optical phase with respect to angular frequency; GDD is the second derivative. In practical terms, GDD causes the spectral components of a pulse to arrive at different times, broadening the pulse and reducing its peak intensity.

A uniform amount of GDD can often be compensated upstream, however, the more difficult problem is nonuniformity. Different pupil locations can experience different delays, and those differences can change as the scanner moves from the center toward the edge of the field. A single compressor setting cannot simultaneously cancel a different amount of dispersion at every field position.

The result may be a process that is well tuned at the center but changes at the perimeter, even if the conventional spot diagram remains acceptable.

Figure 2 compares modeled field-dependent GDD variation for well- and poorly controlled f-theta designs. In the controlled design, Δ GDD remains between approximately 0.5 and 11 fs² across the scan field, whereas the comparison design varies from approximately 40 to 760 fs². A single pre-chirp setting can compensate a uniform GDD offset, but it cannot correct variation across the field.

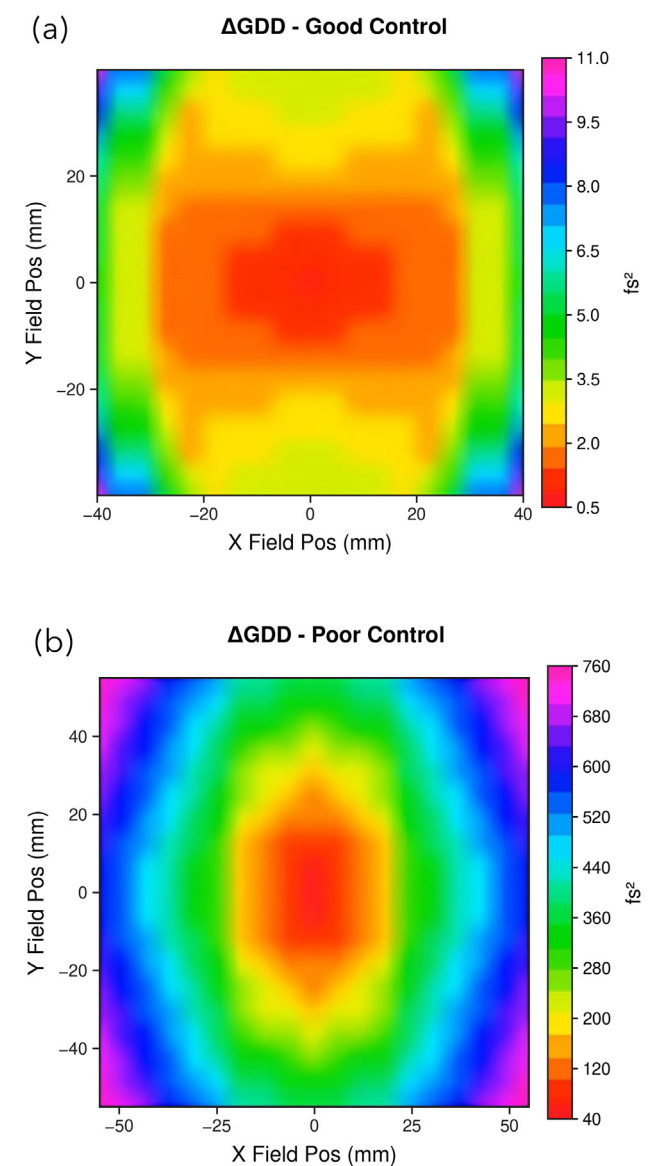


FIG 2 – Modeled GDD variation across the scan field for a well-controlled f-theta design (top) and a comparison design with poor field uniformity (bottom). The color scales differ by nearly two orders of magnitude.

Making temporal performance part of the optical design

Commercial optical design software is well established for optimizing wavefront error and geometric aberrations. With appropriate calculations and merit function targets, the same optimization framework can incorporate pulse delay, GDD, and higher-order dispersion. This allows designers to minimize temporal variations at selected pupil and field positions alongside conventional spatial requirements.

The solution is not simply to add more glass. Multi-element, multi-material designs can balance axial and lateral color, but every additional surface affects transmission, coating complexity, ghost paths, and back reflections.

Concave surfaces can form high-intensity reverse foci inside another element or near the scan mirrors. Glass selection and element geometry also influence bulk dispersion, manufacturability, thermal behavior, and laser-induced damage risk. The design therefore requires a system-level balance among spatial performance, temporal uniformity, scan geometry, transmission efficiency, and durability.

For that reason, the most useful design target is not a theoretically perfect pulse at one field point. It is a consistent, usable pulse across the entire working field. Residual bulk GDD is acceptable when it is uniform enough to compensate globally. Spatially varying chromatic error or GDD is more damaging because it changes the process as the beam scans.

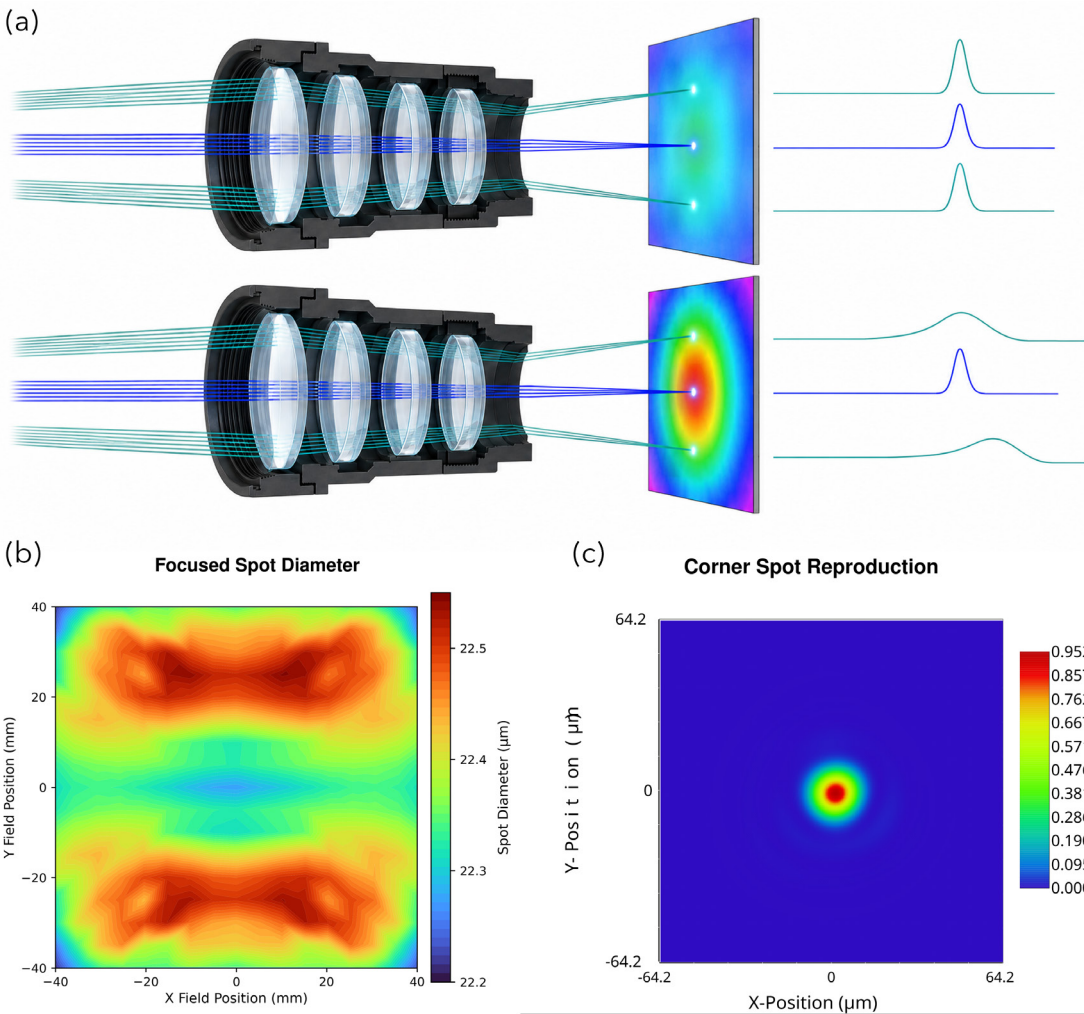


FIG 3 –System-level layout for evaluating field-dependent GD and GDD at center and edge scan positions (top), with modeled focused spot diameter across the scan field (bottom left) and corner-spot reproduction (bottom right) for Edmund Optics Stock No. 26-809.

Specify the pulse at the workpiece

System integrators should begin with the complete operating envelope: center wavelength and spectral bandwidth, pulse duration, input beam diameter and quality, scan angles, working distance, target flatness, and the available dispersion pre-compensation range. Conventional requirements such as spot size, distortion, and telecentricity remain essential, but they should be supplemented with chromatic focal shift and field-dependent GD/GDD performance. Average power, pulse energy, repetition rate, polarization, coating bandwidth, and back-reflection sensitivity must also be considered together rather than as isolated specifications.

Verification should follow the same system-level approach. Measurements at only the on-axis field point may miss the variation that governs real process uniformity. Characterizing focal spot behavior and pulse performance across representative field positions provides a more meaningful indication of what the material will experience during scanning. Figure 3 illustrates this system-level approach, showing representative center and edge scan positions along with modeled focused-spot behavior across the scan field.

From a small spot to a consistent process

The continued industrial adoption of ultrafast lasers is shifting attention from the source alone to the complete beam-delivery system.

For scan-based processing, success depends on more than creating a diffraction-limited spot. The optics must preserve the spatial and temporal characteristics that determine peak intensity and material interaction across the full field.

Chromatically corrected f-theta lenses address this problem by combining conventional scan-lens design with explicit control of broadband focus, GD, and GDD. When those quantities are optimized together, global dispersion compensation becomes more effective and the pulse delivered at the edge of the field more closely resembles the pulse delivered at the center. The result is not merely a better lens specification but also a more consistent manufacturing process.

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PHOTONICS

Are lasers still sexy?

By Geoff Shannon

Well, I'm not sorry to see the back of summer, in Los Angeles the valley temperatures were once again into triple digits, and call it climate change or whatever, we now have humidity, and frankly we'd like Florida to take it all back! All this came to head when our air conditioning unit decided it had had enough too. Anyway, let's get back on track.

Earlier in the year as part LIA Board of Trustees duties a few of us got together to discuss what moves the needle from a growth and interest perspective for laser OEMs, integrators and, more importantly, end users. To look forward, let's consider the last 3 years which have not been stellar for the industry. Lack luster growth, some big names exiting the industry (nLight and Coherent, ICYMI), all the air taken out of the US EV balloon and automotive in general, and all just a bit meh. The bellwether company here being Trumpf with three consecutive down years, however the most recent update indicates some light at the end of the tunnel. This is also reflected in the important market indicator that is the manufacturing purchaser's managers index (PMI) that for the US has been in growth for the last few quarters and at last for Europe as well, most notably Germany recently posting a 51 month high for August.

Back to the matter at hand — are lasers not sexy anymore? The answer is both yes and no.

During the discussion with the other industrial laser board of trustees, it crystalized that many processes and markets where the laser had typically outperformed the market, had matured to the stage where they now mirrored the market performance. And subsequently were no longer going to move the needle from an interest / new business perspective. Laser cutting, laser marking and dare I say additive manufacturing amongst others. Being a laser industry "lifer" to see the laser "come of age" as a mainstream tool for manufacturing is fantastic, finally ditching the fake ID and confidently heading to the bar! The slight hangover that comes with that is the laser sizzle in those markets has, quite rightly, faded. However, rest assured the laser sizzle remains strong, perhaps just a little harder to find.

What isn't hard to find is my ongoing hobby horse of laser welding. Starting with handheld laser welders (HLW), and the first HLW international conference held over summer organized by University of Alberta AWS/CWS student chapter, great job btw. The big take away from the event was the HLW market sits at the bottom of the hockey stick growth curve and is ready for take-off. So, if you want to be at the party, now is the time. The HLW growth will result in the inclusion of laser welding into standards, which to this point has been spotty at best. Not only does this provide the laser welding world with universal formalized testing, inspection and metallurgy, but puts laser welding on the radar for the current and next

Are lasers still sexy?

Left to right, clockwise: Show entrance, Pierson Cheng Trumpf, Google robot, myself, Fanuc robot with Corvette, SpaceX booth with great model of rocket, Laser OEM booths

generation welding engineers. Laser welding is riding the wave of HLW success, the shortfall of qualified welders estimated around 400k by 2030, and significantly increased affordability and availability of laser and robot solutions.

That's a good segway into the second part of the column that covers the IMTS manufacturing show.

This biannual show is the largest US manufacturing show pulling in over 90,000 attendees, that's roughly double Fabtech if you were counting. And by way IMTS is always in Chicago, hint hint SME!

As part of the IMTS conference the LIA hosted the industrial laser conference that offered the chance to hear about what's driving the industry, how we are getting there and network with those shaping it. Going back to laser sizzle, and where it is, the talks by process count for the event were laser welding 7, micromachining 2. Notable shout out to Pierson Cheng from Trumpf for providing the keynote on laser processing opportunities in data centers, which are considerable and happening now.

In the two days I attended IMTS it was packed, and from a laser perspective the usual suspects of IPG Photonics and Trumpf were present, plus many laser markers and additive manufacturing vendors however the highlight, at least for me, was to see the Rofin name back in lights. After a few rocky years with Coherent, the business unit was acquired earlier this year by Bystronic who restored the name, something we can all raise a glass to.

Something unique to the IMTS show is the Smartforce student summit that attracts many thousands of budding young engineers. Unfortunate to report that there was no representation by any laser companies, institute or organization — seems like a great opportunity to light the spark of lasers for the future generation. Above shows some show highlights, and in the lower right if you ever need a robot to swing your Corvette around, we've got you covered!

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PART 2 OF A 4-PART SERIES:
HANDHELD LASER DEVICES
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Before the First Beam: What Organizations Must Establish Prior to Deploying Handheld Lasers in the Field

By Randolph Paura, P. Eng., CLSO, B11 LMSS

Introduction

Part 1 closed on one point: safe use starts with compliant equipment. But that is only the floor. A certified, correctly labeled Class 4 handheld laser remains an uncontrolled hazard until the receiving organization has a program governing how, where, and by whom it will be used.

This is where many first-time adopters stall. The device may arrive with a manual, but not with an application hazard evaluation, designated Laser Safety Officer (LSO), Standard Operating Procedures (SOPs), trained operators, controlled area, or hot-work authorization process. Those are the employer’s responsibility and must exist before first use.

The encouraging news: almost none of it has to be invented from scratch.

Not Starting from Scratch

The ANSI Z136 series can help to keep employers from building workplace laser safety from first principles. Decades of stakeholder expertise are already organized into a framework that even a single owner-operator can follow.

Within the series, ANSI Z136.9 ‘Safe Use of Lasers in Manufacturing Environments’ is closest to this work and should be the first reference for fabrication shops. Its current edition is more than ten years old and under revision. ANSI Z136.1 ‘Safe Use of Lasers’ remains the parent standard and contains the control-measure and signage tables cited below.

SCOPE: WORKPLACE SAFETY GUIDANCE

This article is written as workplace safety guidance for anyone deploying handheld Class 4 laser devices for materials processing — whether as an owner-operator, fabrication shop, manufacturing facility, or mobile repair business.

For personal (non-commercial) use, the workplace program requirements may not apply in the same way, but the hazards do. Users should still be familiar with the beam and non-beam hazards, safe-use practices, and the consensus standards referenced here before operating the device.

Two parts of ANSI Z136.1-2022 are especially useful as a deployment roadmap.

Tables 12a through 12d list Class 4 control measures by type — engineering, administrative, Personal Protective Equipment (PPE), special considerations, and signage. Reading down the Class 4 column shows what is mandatory, what is recommended, and when a Nominal Hazard Zone (NHZ) analysis is required. Tables 13a through 13c cover controlled-area signs, equipment labels, and PPE marking.

IMAGE COURTESY OF IPG PHOTONICS CORP.

Before the First Beam

Note well: ANSI Z136 is a user safety standard; laser equipment labels are governed by equipment standards such as IEC 60825-1 and regulations such as US 21CFR1040.10/11.

Appendix A of ANSI Z136.1 is normative — part of the standard, not commentary. It defines LSO duties (A1), supervisor and employee responsibilities (A3), and Class 3B/4 training topics (A4). Employers building a first laser safety program can use Appendix A as the outline and Tables 12 and 13 as summary specifications.

Together, they give the owner-operator mobile service provider and a multi-site manufacturer the same starting structure.

Reading the Z136 Class 4 Column

Every handheld welding, cutting, cleaning, and ablation device in this market is a Class 4 laser. That single fact drives the requirements.

Engineering controls (Clause 4.4.2). Class 4 obligations include remote interlocks, key control, laser protective barriers and curtains where needed, area and emission warning devices, and a Laser-Controlled Area (LCA) with entryway controls per 4.4.2.10. Where the beam path is fully or partly open — the normal condition for many such handheld devices — an NHZ analysis is required under 4.4.2.7.

Administrative controls (Clause 4.4.3). Class 4 obligations include a written laser safety program (1.3, A4), written SOPs approved by the LSO (4.4.3.1), documented education and training (4.4.3.3), restriction of operation to authorized personnel (4.4.3.4), an established LCA (4.4.3.5), and alignment procedures (4.4.3.8). Incident history has repeatedly identified alignment as the task carrying the highest ocular risk (when one has access to the open beam).

Personal Protective Equipment (Clause 4.4.4). Laser protective eyewear with the specified optical density and wavelength is required. Skin protection and protective clothing are listed as recommended, but handheld processing makes them practically indispensable because of thermal, plasma, and spatter exposure. AWS Fact Sheet No. 46 states that ordinary safety glasses and conventional welding helmets do not protect against the beam; the expected protection is specified eyewear used with a laser welding helmet.

BUILT-IN FEATURES TO VERIFY ON THE DEVICE

Required for Class 4 laser products:

- Key control to prevent unauthorized operation
- Emergency stop that immediately terminates emission
- Provision for an external interlock connection to the controlled area

Additional features to specify or confirm (per ISO 11553-2 and AWS Fact Sheet No. 46):

- Two-stage trigger on the torch to prevent unintentional emission
- ‘Plasma’ detection that disables emission if no weld ‘plasma’ initiates
- Workpiece contact circuit enabling emission only at the part
- Optical interlock verifying integrity of the fiber connection between torch and power supply

If a supplier cannot confirm these in writing, that is a procurement finding — see Part 1.

A Controlled Area That Moves

The hardest part of handheld deployment is that the controlled area moves with the work.

For a fixed installation, the LCA is a room. For handheld field service, it may be a temporary enclosure in a customer bay, shipyard compartment, bridge deck, or service trailer. Clause 4.4.3.5 allows a temporary LCA, but the core requirements remain: defined beam path, suitable beamstops/barriers, diffusely reflecting nearby materials where feasible, restricted and posted entry, PPE inside, knowledgeable supervision, and a secured or disabled device when not in use.

Two points are easy to miss. First, Clause 4.4.3.6 directs outdoor laser use to ANSI Z136.6, which matters for mobile repair outside a building. An errant beam escaping a temporary LCA can also become an FAA airspace issue if it can project into navigable airspace. Second, specular and retroreflected beams from aluminum, copper, and similar

surfaces can travel well beyond the operator before coupling occurs. Assess reflective geometry before pulling the trigger.

The Other Half of the Hazard

Hot work means any operation producing flames, sparks, or significant heat; OSHA defines it as riveting, welding, flame cutting, or other fire- or spark-producing work.

A handheld laser welder is also hot-work equipment. ANSI/ AWS Z49.1:2021 makes laser beam cutting and welding subject to its applicable clauses (Clause 14), in addition to ANSI Z136.1.

That adds separate obligations: management and supervisor duties for combustibles and authorization; ventilation to keep contaminants below limits; relocation or shielding of fire hazards; extinguishers and fire watchers where needed; written hot-work authorization outside designated areas; container preparation for drums, tanks, or piping; and confined-space ventilation. NFPA 51B and CSA W117.2 align with these requirements.

Laser-generated air contaminants (LGAC) also need attention. ANSI Z136.1 Table 1 links irradiance thresholds to non-beam hazards — ignition, LGAC, plasma, and extreme ionizing-radiation potential — and to controls ranging from building ventilation to local exhaust and respiratory protection. Paint, primer, and coating ablation can create contaminants general shop ventilation was not designed to capture.

Assessing that profile is industrial hygiene work. An LSO is not necessarily trained as an industrial hygienist, so coatings, confined spaces, or sustained fume exposure should be assessed by qualified personnel.

One optical hazard belongs here too: plume and plasma emit intense ultraviolet and visible radiation, including blue-light retinal hazard. Laser eyewear for a 1070 nm beam does not attenuate it. That is the laser welding helmet’s job; eyewear and helmet protect against different hazards.

The Owner-Operator Question

A one-person mobile repair business is usually an employer under general duty provisions — and often the least likely to already have a program.

The standards do not exempt sole operators. AWS Fact Sheet No. 46 expects any organization — or sole operator outside

one — using Class 3B or 4 lasers to appoint a qualified LSO or be trained as one, maintain a documented laser safety program, and provide an LCA at each point of use, including demonstrations.

For a sole operator, the program is scaled, not absent: one hazard evaluation, SOP set, training record, incident response plan, equipment inspection log, and hot-work procedure. That documentation helps separate an insurable business from an uninsurable one.

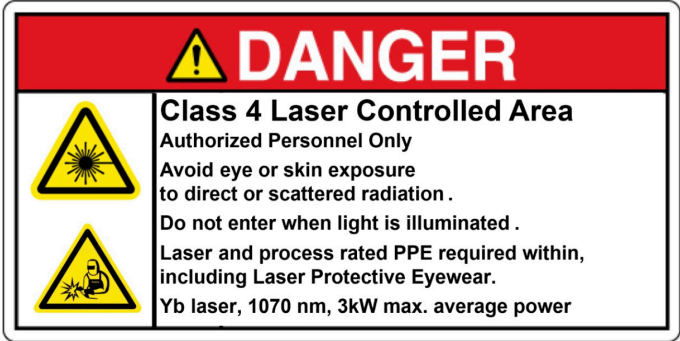
Appointing an LSO does not by itself prevent incidents. Incidents are prevented by operators who can recognize and control the hazards before them; the appointment exists to ensure that competency.

Conclusion: Build the Program, Then Pull the Trigger

Equipment compliance is purchased; workplace safety is planned before deployment, not after an incident.

ANSI Z136, ANSI/AWS Z49.1:2021, and allied hot-work frameworks already provide the structure. The employer’s task is to apply that consensus framework to its operation and document the result as due diligence for regulators, insurers, and customers.

Part 3 will examine how Occupational Health & Safety (OHS) agencies can extend this baseline to a market acquiring these devices without first encountering a consensus standard.



Example ANSI Z136 & ISO 3864 compliant area warning sign

Supporting Worksheets

Two companion worksheets accompany this article. Each is a two-page pathway: one page of eight sequenced steps, and one page of key resources with links. They are starting points,

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AT A GLANCE

Nine Program Elements Before Deployment

- 1. **Laser information** — class, type, wavelength, optics, beam parameters, and user/maintenance/service instructions on file.
- 2. **Hazard evaluation** — applicable Occupational Health & Safety (OHS) standard, eye/skin Maximum Permissible Exposure (MPE), hazard distances, PPE optical density, and non-beam hazards assessed.
- 3. **LSO appointed** — documented, qualified for Class 4 operations, and refresher interval set.
- 4. **Responsible persons** — named, reachable, and included in the written laser safety plan.
- 5. **Incident response** — developed, medically reviewed, and trained on.
- 6. **Records** — retention and review intervals set for evaluations, SOPs, inspections, training, and incidents.
- 7. **Regulations and standards** — applicable jurisdictional requirements and consensus standards identified and held.
- 8. **Risk reduction** — elimination, substitution, engineering, administrative, and PPE controls documented in order.
- 9. **Education and training** — delivered, competency verified, and recorded.

If any answer is negative or unknown, resolve and document it before deployment.

not comprehensive compliance documents, and highlight the essential actions to take before handheld deployment while introducing users to the noted consensus standards. They are informative only and complement, not replace, applicable regulatory requirements, consensus standards, and Authority Having Jurisdiction (AHJ) requirements.

Each step is written as a plain-language instruction with the governing clause beside it, so an owner-operator can see what

to do first and where to consult the full standard when the detail is needed.

- **Worksheet A** — Laser Safety: Pathway to Compliance. Eight steps to a workplace laser safety program for Class 4 handheld devices, running from appointing an LSO through hazard evaluation, engineering controls, procedures and training, the controlled area, PPE, signage, and incident readiness.
- **Worksheet B** — Hot Work: Pathway to Compliance. Eight steps for handheld laser cutting, welding, brazing, ablating, and allied processes — authorization, combustibles, fire watch, fume control, PPE, containers and confined spaces, reflections, and close-out — covering the hot-work domain that Clause 14 brings into scope alongside the beam controls of Worksheet A.

Links to both worksheets accompany the online edition of this article.

PRIMARY RESOURCES

- 1. ANSI Z136.1-2022 'Safe Use of Lasers' — in particular Section 4 (Control Measures), Section 7 (Nonbeam Hazards), and normative Appendix A
- 2. ANSI/AWS Z49.1:2021 'Safety in Welding, Cutting, and Allied Processes'
- 3. AWS Safety and Health Fact Sheet No. 46 'Handheld Laser Welding Safety' (September 2024)
- 4. Sliney, D., and Earley, D., 'Optical Safety for Handheld Laser Welding', Welding Journal, June 2024, pp. 58–61, American Welding Society
- 5. AWS Welding Digest, 'Handheld Laser Welding Safety' (January 2025)
- 6. NFPA 51B 'Standard for Fire Prevention During Welding, Cutting, and Other Hot Work'
- 7. LIA, 'Questions that an OSHA Inspector May Ask You about Laser Safety' Fact Sheet

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