Lawrence Livermore National Laboratory

7000 East Avenue
Livermore CA 94550

Contact
Hoang Nguyen

EXUDE Elite Spectral Beam Combining Optic

Prepared for:

2024
R&D 100
Award Entry

LLNL-MI-863416

Prepared by LLNL under Contract DE-AC52-07NA27344.

EXUDE Elite Spectral Beam Combining Optic

1. PRODUCT/SERVICES CATEGORIES

A. Title

EXUDE Elite Spectral Beam Combining Optic

B. Product Category

Process/Prototyping

2. R&D 100 PRODUCT/SERVICE DETAILS

A. Primary submitting organization

Lawrence Livermore National Laboratory

B. Co-developing organizations

N/A.

C. Product brand name

EXUDE Elite Spectral Beam Combining Optic

D. Product Introduction

This product was introduced to the market between January 1, 2023, and March 31, 2024. This product is not subject to regulatory approval.

E. Price in U.S. Dollars

Currently, Lawrence Livermore National Laboratory charges approximately $35,000 per optic in developmental quantities of less than five optics. Once available, we anticipate the commercial cost of EXUDE Elite to be $5,000 - $10,000, depending on size and quantity.

F. Short description

The EXtreme-power, Ultra-low-loss, Dispersive Element (EXUDE) Elite optical element makes possible the use of Spectral Beam Combining (SBC) for near-diffraction-limited quality laser systems with first-ever output powers approaching megawatt levels. EXUDE Elite concentrates light from multiple lasers with different wavelengths into a single, high-power beam with unparalleled compactness and damage-resistance.

G. Type of institution represented

Government or independent lab/institute

H. Submitter's relationship to product

Product developer

I. Photos

Attached inline

3. PRODUCT/SERVICE DESCRIPTION

A. What does the product or technology do?

Material processing techniques that utilize high-power lasers, such as marking, cutting, welding, and drilling, often require that a beam propagate over distance and that it be of excellent quality to minimize undesirable additional beam spreading. Diffraction-limited beams are beams of optimal quality and meet these requirements. As such, demand for high-power laser sources with diffraction-limited beam quality is increasing, leading to a significant scaling effort for laser systems' output power.

Efforts to scale the power of a single-output laser to hundreds of kilowatts and even megawatts, however, have encountered challenges in removing waste heat, maintaining beam quality, and avoiding damage to output optics. Electrically driven solid-state lasers have been demonstrated at >100 kW output, but thermo-optical distortions in the bulk laser materials result in degraded beam quality, which limits the irradiance that can be delivered to a target.

"EXtreme-power, Ultra-low-loss, Dispersive Element" (EXUDE) technology makes use of Spectral Beam Combining (SBC) of fiber lasers to achieve higher power, exploiting the broad gain bandwidth to enable large numbers of fiber laser channels to be combined with near-diffraction-limited beam quality. In the original EXUDE technology, many incoherent laser beams, each with a slightly different wavelength, are superimposed onto a single beam by reflection off of a delicate grating structure. The power in the resulting beam is the sum of the powers of the individual beams.

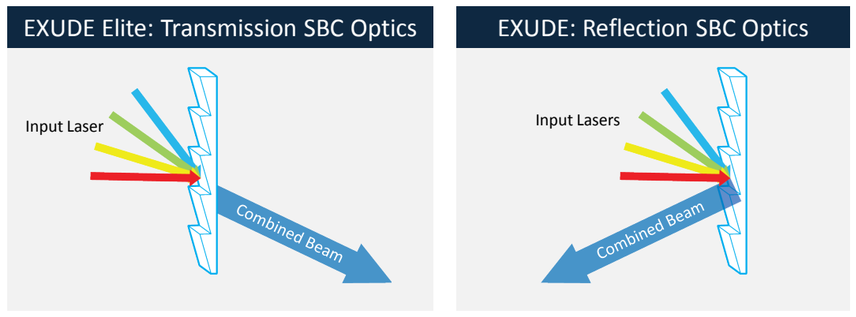


Figure 1: EXUDE Elite (L) utilizes transmission Spectral Beam Combining (SBC) optics to combine input laser beams into a single, combined beam. The original EXUDE's SBC optic (R), a reflection grating optic, reflects input beams into a combined beam, which requires a longer optical length. .

EXUDE Elite, this year's submission, significantly improves upon the original EXUDE technology to combine fiber laser beams via **transmission through a fused silica optic** (Figure 1). This is achieved in a less expensive, more compact system with a **100-fold improvement to the damage threshold**.

Since its availability in 2014, the original EXUDE technology has generated an estimated 4 billion dollars in industrial revenue. SBC laser systems are considered the leading technology for scaling output powers of 10 kW to 1 MW with superior beam quality, but the performance of SBC optics in the EXUDE technology has so far encountered reliability, quality, cost, size, and availability limitations. The original EXUDE optics are composed of a delicate grating surface-relief structure on top of a multilayer dielectric thin-film stack, a configuration which has demonstrated a low laser damage threshold, attraction of contaminants, and the need for a larger laser beam diameter. EXUDE Elite's single-material composition and transmissive configuration allow for a shorter optical length, smaller structure, and significantly larger damage threshold, demonstrated in Figures 2 and 4.

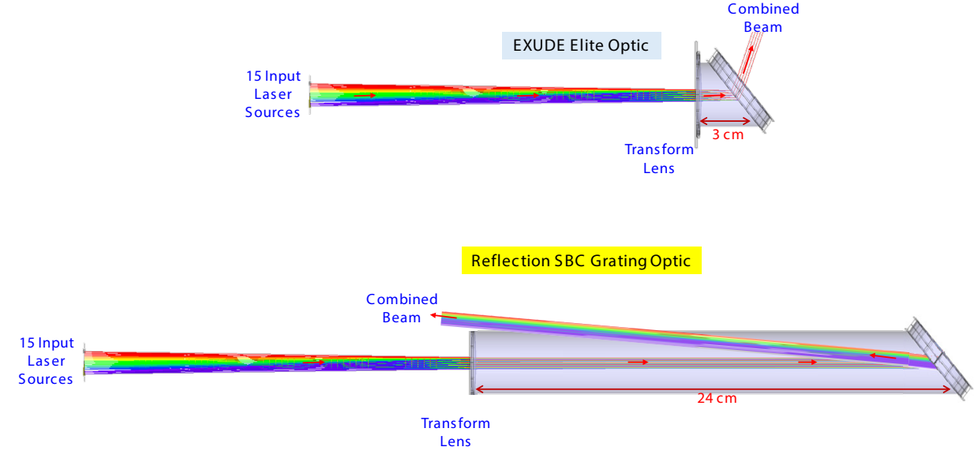


Figure 2: A visualization of the distance difference between the optic and transform lens for the EXUDE Elite transmissive optic (top) and the original EXUDE's SBC Reflection Grating Optic (bottom). EXUDE Elite can combine the same input lasers at a fraction of the size of the original system.

Current SBC systems require highly expensive and custom optics to minimize beam degradation, meaning the SBC lasers needed for industry to cut, drill, and fabricate are built only by large defense contractors. Now, with EXUDE Elite, wide access to the advantages of SBC can be realized for industrial systems in a more efficient and compact, lower-cost system than before.

B. How does the product operate?

Spectral Beam Combination (SBC) works by combining multiple laser beams with distinct, non-overlapping optical spectra into a single, powerful, coherent beam. Because fiber lasers can operate over a range of wavelengths and are robust, efficient, and compact, they are ideal candidates for beam-combining approaches. Combining fiber lasers requires a specialized wavelength-sensitive beam combiner that can withstand the combined power of multiple laser inputs.

Figure 3: Prototypical EXUDE Elite SBC system capable of combining 16 input laser beams into one 48 kW output laser. It can be held in one hand, demonstrating its impressive, compact size.

Dispersive combiners such as prisms and diffraction gratings reflect incident beams to different degrees according to the wavelengths present in the light, so they in turn propagate in the same direction. Other approaches rely on optical components with wavelength-dependent transmission, such as dichroic mirrors or volume Bragg gratings.

SBC laser systems, on the other hand, incorporate a single dispersive element—a grating optic—that spatially overlaps multiple fiber lasers into a single, coherent beam. We have previously demonstrated such an optic for this purpose, the "EXtreme-power, Ultra-low-loss, Dispersive Element" (EXUDE), which works by reflecting input wavelengths into a single, superimposed beam in an electrically efficient, near-diffraction-limited, multi-100-kilowatt laser system. EXUDE's grating optic must withstand intense light, which can lead to thermo-optical distortion of the combined beam, diminishing its output quality. Thus far, the original EXUDE has seen shortcomings in this area.

This year's submission, EXUDE Elite, is EXUDE's next generation—a precisely designed and fabricated surface-relief structure. EXUDE Elite is composed solely of fused silica, granting it a significantly heightened damage threshold compared to the original EXUDE's delicate grating structures and multilayer dielectric thin film stack. It works by transmitting light through the optic instead of reflecting it off the optic, as with the original EXUDE (Figure 1).

Shown in Figure 3 is a first-of-kind prototype of an EXUDE Elite SBC capable of up to 48 kW of laser output power in a single beam combined from 16 laser sources, demonstrating the simplicity, compactness, and low cost of this next-generation technology.

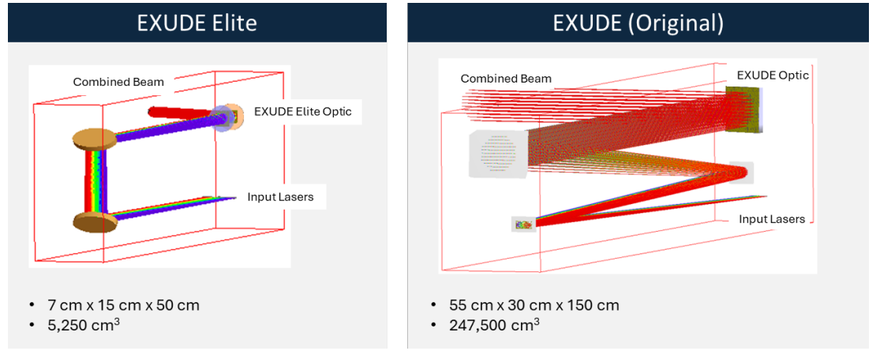


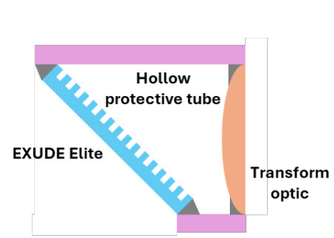
Figure 4: Comparison of the dimensions and volume of a system utilizing EXUDE Elite versus the original EXUDE. EXUDE Elite (L) features a transmissive configuration, enabling a drastically smaller design than the original EXUDE's reflective configuration (R).

A major attribute of EXUDE Elite is its transmissive configuration, allowing for a vastly simpler and more compact in-plane optical design compared to the original EXUDE. This configuration permits the required transform lens optic to be placed extremely close to the EXUDE Elite optic, thus greatly shortening the overall optical path length.

Conversely, with the original EXUDE reflection configuration, the overall optical path length is dictated by the distance required to separate the input and reflected beam from hitting the transform lens—the bigger the laser beam diameter, the larger the optical distance (Figure 4).

Furthermore, the compact distance between EXUDE Elite and the required transform lens allows the two optical components to be made monolithic. In this **monolithic structure**, the EXUDE Elite optic is fixed in position to the transform lens to provide mechanical robustness and ease of alignment. The monolithic structure allows the optic to be composed of a hollow tube with the critical grating surface oriented towards the middle and **isolated from environmental contamination**. The non-critical surface can be faced outwards (Figure 5). This monolithic structure, MOnolithic SPectral bEam Combiner (MOSPEC), is an LLNL patented technology.

Figure 5: Diagram of the monolithic spectral beam combiner (MOSPEC) containing the EXUDE Elite optic, a protective tube to shield its critical grating surface, and the transform optic (L). Photograph of MOSPEC (R).



C. Product Comparison

EXUDE Elite is a breakthrough that suggests a paradigm shift in high-power laser technology. Compared to conventional dichroic beam combining (DBC) laser systems, EXUDE Elite **improves the laser damage threshold by over 1000X** and **output power generation by over 80X**. DBC laser systems are hindered by the limited number of laser channels that they can combine, a result of large spectral bandpass width and the poor laser damage threshold of dichroic coatings.

When compared with the original EXUDE optic, which is an SBC-based reflection grating optic (RGO), EXUDE Elite **improves the laser damage threshold by over 100X**, prolonging the optic's lifetime and enabling **megawatt-level power handling capability**. The necessary optical components are **reduced by up to 50%** in EXUDE Elite's simpler, smaller design. EXUDE Elite is more robust overall—its monolithic, sealable assembly minimizes environmental contamination that the original EXUDE readily attracts via the enormous surface area of its grating surface-relief structures, which most end users are not equipped to prevent. The monolithic structure also has potential to be **self-thermally compensating**.

The original EXUDE optic's delicate grating surface-relief structure and multilayer dielectric thin film stack lend to a low laser damage threshold. In turn, the original EXUDE needs a larger laser beam diameter to reduce the irradiance the optic is exposed to. A larger laser beam increases the size, complexity, and cost of the system. EXUDE Elite is made of **100% all-bulk fused silica material**, which enables a 100-fold increase in the damage threshold and, therefore, a lower cost and smaller size. Optical ray trace simulations of a 115kW SBC laser system comparison between EXUDE and EXUDE Elite indicate that EXUDE Elite provides a substantial **reduction in volume (47X) and cost (36%)**, all in a simpler and more effective structure.

D. Competitors

Parameters	EXUDE Elite	Current SBC Technology Based Reflection Grating Optic (RGO)	Dichroic Beam Combining (DBC) Laser system	Improvement
Projected maximum output power[1]	>1000 kW	~50 kW	~12 kW	>80X higher than DBC and >50X higher than RGO
Laser system cost, for 115 kW output[2]	$8.6 Million	$13.6 Million	115 kW output not possible	>36% reduction in cost
Laser system volume, for 115 kW output[3]	5,250 cm3	247,500 cm3	50,000 cm3	>10X smaller than DBC and >47X smaller than RGO
Laser damage threshold[4]	>10 MJ/cm2	~0.1 MJ/cm2	~0.01 MJ/cm2	100X higher
Optic surface protection[5]	Yes	No	No	Near infinite improvement in optics reliability
Optical misalignment sensitivity[6]	Small	Large	Large	4X smaller

[1] 2-inch diameter optic, wavelength span from 1035-1075 nm
[2] Laser system cost only - no beam director, based on small quantities
[3] Comparison was completed with just freeform optics - no mounts
[4] Carbon contaminated laser damage values
[5] When EXUDE Elite is mounted in a monolithic structure
[6] Simulation shows that reflection optics are 4X more sensitive to misalignment than transmissive optics

Table 1: Comparison of EXUDE Elite with the current SBC technology-based Reflection Grating Optic (original EXUDE) and traditional dichroic beam combining laser system.

E. Limitations

EXUDE Elite has only recently been released for industry technology transfer. As such, it is not yet widely commercially available. LLNL is currently working with two public companies to explore commercialization for EXUDE Elite.

4. SUMMARY

EXUDE Elite revolutionizes the scaling effort for single-output laser power, utilizing SBC more effectively than its predecessor. With a hugely increased damage threshold, its unique, all-silica optic is capable of withstanding megawatt-level power inputs necessary for high-power laser sources with diffraction-limited beam quality. The device's monolithic assembly protects critical surfaces from environmental exposure, reducing further laser damage and improving optical performance against the original EXUDE. In addition, a laser system featuring EXUDE Elite is 47X more compact than the original, a size enabled by the transmissive mechanism by which it combines input beams. The lower price and improved overall optics performance of EXUDE Elite offer the opportunity for wider access to SBC for industrial laser systems, ushering the laser power-scaling effort forward on a larger scale than ever before.

5. CONTACT INFORMATION

Hoang Nguyen
Diffractive Optics Group Leader, OMST/NIF
Lawrence Livermore National Laboratory
925-423-6270
nguyen7@llnl.gov

Michael Rushford
Laser Physicist
Lawrence Livermore National Laboratory
925-424-6349
rushford1@llnl.gov

Brad Hickman
Engineer Technical Associate
Lawrence Livermore National Laboratory
925-422-6190
hickman10@llnl.gov

Candis Jackson
Process Technician
Lawrence Livermore National Laboratory
925-423-5007
jackson112@llnl.gov

James Nissen
Engineer Technical Associate
Lawrence Livermore National Laboratory
925-422-2766
nissen6@llnl.gov

Sean Tardif
Mechanical Technician
Lawrence Livermore National Laboratory
925-423-9074
tardif1@llnl.gov

Person who will handle R&D 100 event arrangements for winners and Media and public relations person who will interact with R&D's editors regarding entry material:

Charlotte Eng
Business Development Executive
Lawrence Livermore National Laboratory
925-422-1905
eng23@llnl.gov

6. AFFIRMATION

By submitting this entry to R&D Magazine you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product. You affirm that you have read the instructions and entry notes and agree to the rules specified in those sections. For more information, please call 973-920-7032 or email rdeditors@advantagemedia.com

7. ADDITIONAL SUPPORTING DOCUMENTS

LLNL US Patent 11,624,931 – Monolithic Transmitting Spectral Beam Combiner

LLNL Patent Pending, LLNS.026A/ IL-13689O1 – Spectral Channel Splicer for Spectral Beam Combining Laser System

Letters of Support

- Coherent Corporation - John Hostetler, PhD, Chief Engineer
- nLIGHT, Inc - John Edgecumbe, PhD, Vice President Directed Energy Laser Development
- nLIGHT, Inc. - Manoj Kanskar, PhD, Vice President of Advanced Technology
- Kord Technologies - Ben Allison, PhD, Chief Technologist
- EO Solutions – Craig A. Farlow, Chief Engineer, Spectral Beam Combiners