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HELD Gratings: High Energy Low-Dispersion (HELD) Multilayer Dielectric (MLD) Gratings for Ultrafast Laser Systems

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HELD Gratings: High Energy Low-Dispersion (HELD) Multilayer Dielectric (MLD) Gratings for Ultrafast Laser Systems

1. PRODUCT/SERVICES CATEGORIES

A. Title

High Energy, Low Dispersion (HELD) Multilayer Dielectric (MLD) Gratings

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

High Energy, Low Dispersion (HELD) Multilayer Dielectric (MLD) Gratings

D. Product Introduction

This product was introduced to the market between January 1, 2021, and March 31, 2022. This product is not subject to regulatory approval.

E. Price in U.S. Dollars

Multilayer dielectric (MLD) gratings are composed of a base substrate upon which layers of dielectric mirrors with varying refractive indices are stacked, finally topped by a layer of ion-etched photoresist that is fine-tuned to the desired diffraction specifications. The total price of the HELD MLD Grating is proprietary. However, the added value from a finished 80 cm x 70 cm substrate to the final product is approximately $378,000.

F. Short description

HELD Gratings, a novel design of multi-layer dielectric pulse compression gratings, enables a new class of high-energy, 10 PW ultrafast laser systems for extremely high and unprecedented peak power. Meter-scale HELD Gratings have the potential to facilitate future 100 PW-class ultrafast laser systems.

G. Type of institution represented

Government or independent lab/institute

H. Submitter’s relationship to product

Product developer

I. Photos

Attached inline

J. Video

https://youtu.be/X2scTmxpLQA

3. PRODUCT/SERVICE DESCRIPTION

A. What does the product or technology do?

To better understand both the origins of the universe and fusion energy, extraordinary amounts of laser energy must be concentrated onto a miniscule area to simulate extreme environments such as solar interiors and black hole horizons here on Earth. Today's laser systems, however, lack not only the ability to produce the desired level of energy, but the construction to contain, direct, and repeatedly withstand the energy.

High energy lasers employing a process known as chirped pulse amplification (CPA) make use of diffraction gratings in order to compress beam pulses into increasingly energy-dense states. Naturally, these gratings are susceptible to damage from redirecting beam pulses now capable of carrying petawatt (PW) loads. (Figure 1)

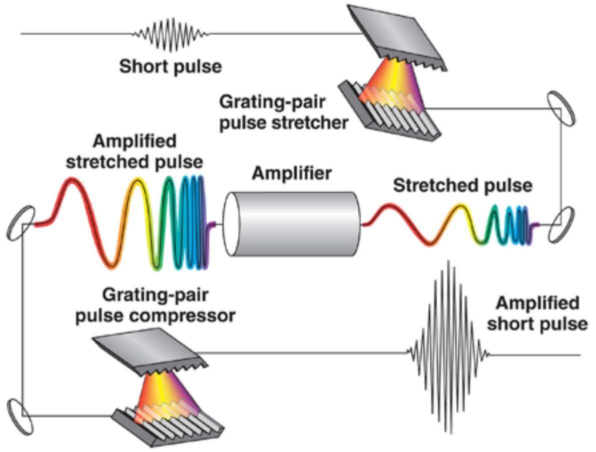

Figure 1. In chirped pulse amplification, an ultrashort laser pulse is amplified to the petawatt (PW) level, with the laser pulse being stretched out temporally and spectrally, then amplified, and then compressed again. However, the stretching and compression devices (gratings) that ensure different color components of the pulse travel different distances are susceptible to damage from redirecting beam pulses carrying PW loads.

In collaboration with Spectra Physics–Newport, National Energetics, and ELI Beamlines, Lawrence Livermore National Laboratory has developed high-energy, low-dispersion (HELD) multi-layer dielectric (MLD) diffraction gratings able to deliver 3.4 times more total energy as current state-of-the-art technology.

The use of all-dielectric components critically increases the grating's resistance to laser damage. Implementing these uniquely robust gratings allows for previously impracticable gigabar experimentation in high-energy-density physics (HEDP) and materials science. Replicating the temperature and pressure environments of massive stellar objects enables understanding of some of the most elusive phenomena at both the cosmological and quantum levels such as cosmic acceleration and quantum gravity (Hawking radiation). Instrument design is not limited to astrophysical applications; rather, these new levels of HEDP research allow for new insights to be applied to fields of enhanced medical diagnostics, industrial processing techniques, laser-driven particle acceleration, and nuclear materials detection. (Figure 2)

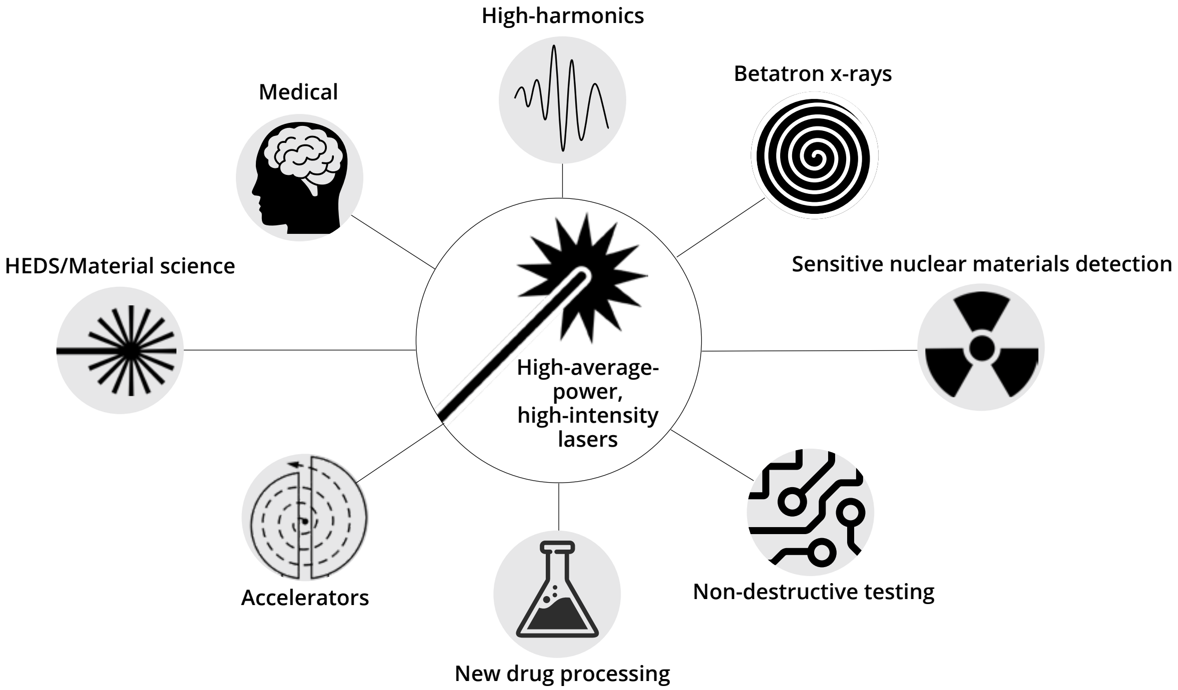

Figure 2. High-energy density research is vital to advancing health care and new science discoveries. LLNL's HELD gratings improve upon current gratings used to shape incident beam pulses into the extreme states required for experiments.

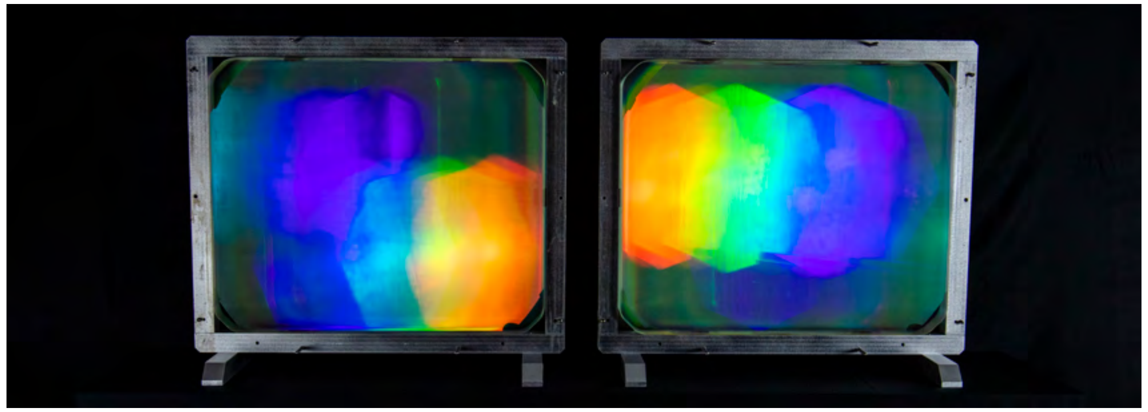

Figure 3. Meter-scale HELD Gratings will be incorporated into the ELI Beamlines L4-ATON laser system.

The gratings, scaled to meter size (85 cm x 70 cm), will be incorporated into the ELI Beamlines L4-ATON laser system, capable of generating an unprecedented 10 PW of power, 1.5 kJ in 150 femtosecond (fs) pulses [1,2]. A 10 PW laser pulse when focused on a diffraction-limited spot with a full-width half-max (FWHM) of 1 micron would result in an intensity of 10^{24} W/cm^2.

This light intensity is unprecedented in the history of laser-plasma/matter interaction.
At these high intensities new physics effects can be studied, such as:

- production of gamma-ray flashes
- generation of electron-positron pairs
- radiation-friction force
- relativistic flying mirror
- Unruh physics
- vacuum birefringence

The ELI Beamlines L4-ATON laser system will allow new research in particle acceleration. Laser-driven particle acceleration is a new, rapidly evolving field of physics thanks to the continuing development of high power laser systems that enable investigation of the interaction of ultrahigh laser intensities (> 10^{19} W/cm^2) with matter. As a result of such interactions, extremely high electric and magnetic fields are generated. Such tremendous fields, which can be supported only in plasmas, allow for the acceleration of particles at relativistic energies by way of very compact approaches.

B. How does the product operate?

The advent of high energy, high peak power laser systems through chirped pulse amplification (CPA) in broadband solid-state gain media has opened new avenues into High Energy Density, High Field and Material Science research. There are ongoing efforts at numerous institutions in the United States, Europe, and China that are striving to achieve output powers up to 200 PW [3]. One main limitation of total laser energy output is the damage threshold and physical size of diffraction gratings.

Employing HELD Gratings' high-performance design is essential to the operation of cutting edge, ultrahigh-energy laser systems. Diffraction gratings are vital components to the overall system that serially redirect and compress the beam pulse into dense, high-energy states. Consequently, the material must be able to withstand extraordinary energy levels throughout repeated firing. In short-pulse lasers that perform CPA, such as the ELI Beamlines system, damage to the grating material that results from free electron densities exceeding $10^{20\text{-}22}$/cm^3 necessitates the use of dielectric materials in its construction to shield against destructive electromagnetic fields.

Multilayer dielectric (MLD) gratings are composed of a base substrate upon which layers of dielectric mirrors with varying refractive indices are stacked, finally topped by a layer of ion-etched photoresist that is fine-tuned to the desired diffraction specifications. The design of the MLD diffraction gratings is of high importance to enlarge their spectral tolerance. The diffraction gratings can be optimized in one or two steps. In the case of a two-step optimization, the multilayer is first designed to optimize its reflectivity and spectral tolerance, without considering a periodic modulation of the top layer. The diffraction grating is then designed to maximize the diffracted efficiency in the spectral range of interest by considering the multilayer optimized in the first step. The grating can also be optimized in one step, i.e., by optimizing simultaneously the grating profile and the multilayer. The main idea is to define the optimal thickness of every single layer when considering periodic modulation. Figure 4 shows the theoretical diffraction efficiency of greater than 95% over 70 nm bandwidth for the HELD Grating.

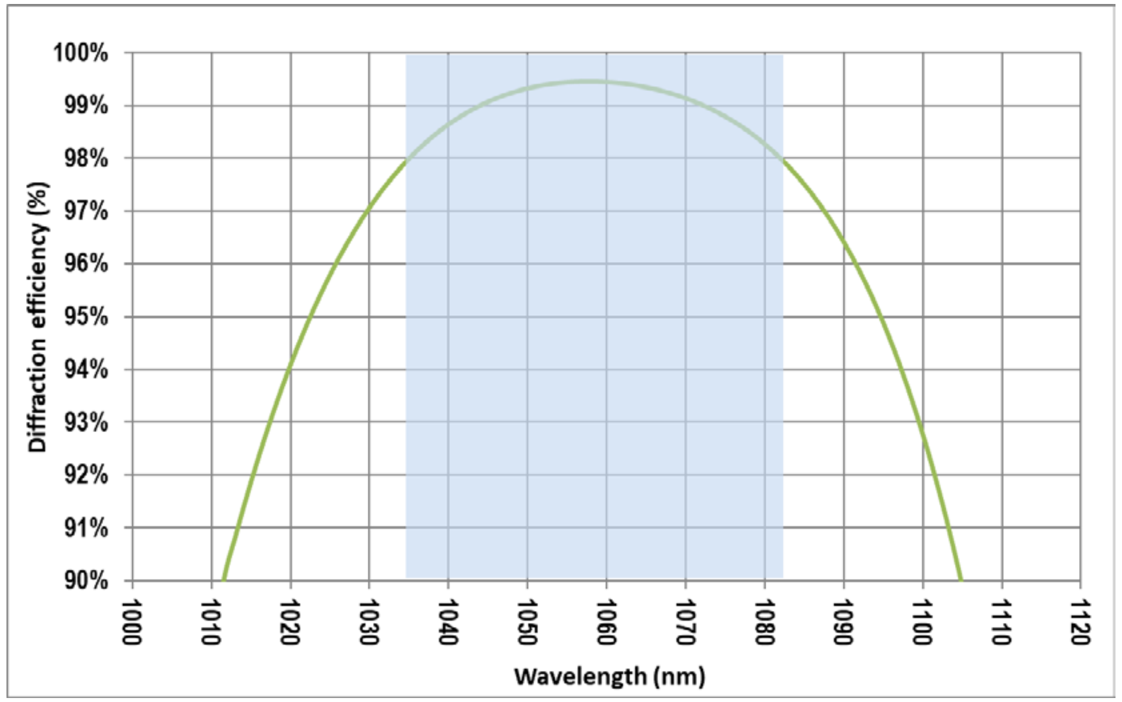

Figure 4. Modeling simulations predict >95% diffraction efficiency for >70 nm from 1022 nm to 1094 nm.

Eight meter-scale (85 cm x 70 cm size) 1136 lines/mm HELD gratings have been fabricated to date (Figure 5). The measured diffraction efficiency for one of the gratings as a function of position for SN02, λ=1040 nm, 1060 nm, and 1075 nm at an incident at 37° with S-polarization is shown in Figure 6A. A histogram of the region of interest (Figure 6B) shows an average efficiency of 98.2% across 35 nm bandwidth and a standard deviation of <0.6%. This excellent uniformity is due to a design with high efficiency over large range of groove widths and heights and well-controlled dielectric layer thickness.

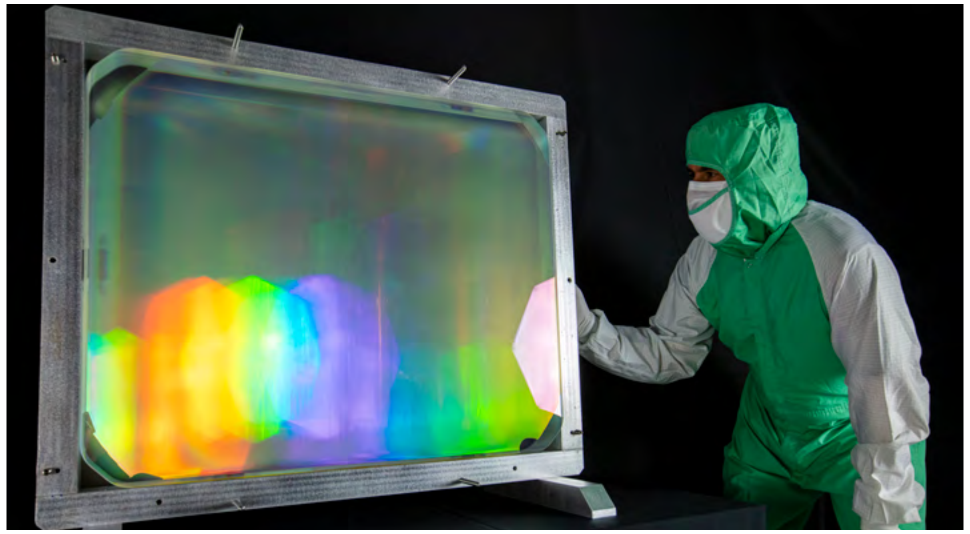

Figure 5. One of eight recently fabricated meter-scale, 85 cm x 70 cm size, 1136 lines/mm HELD Gratings undergoes visual inspection.

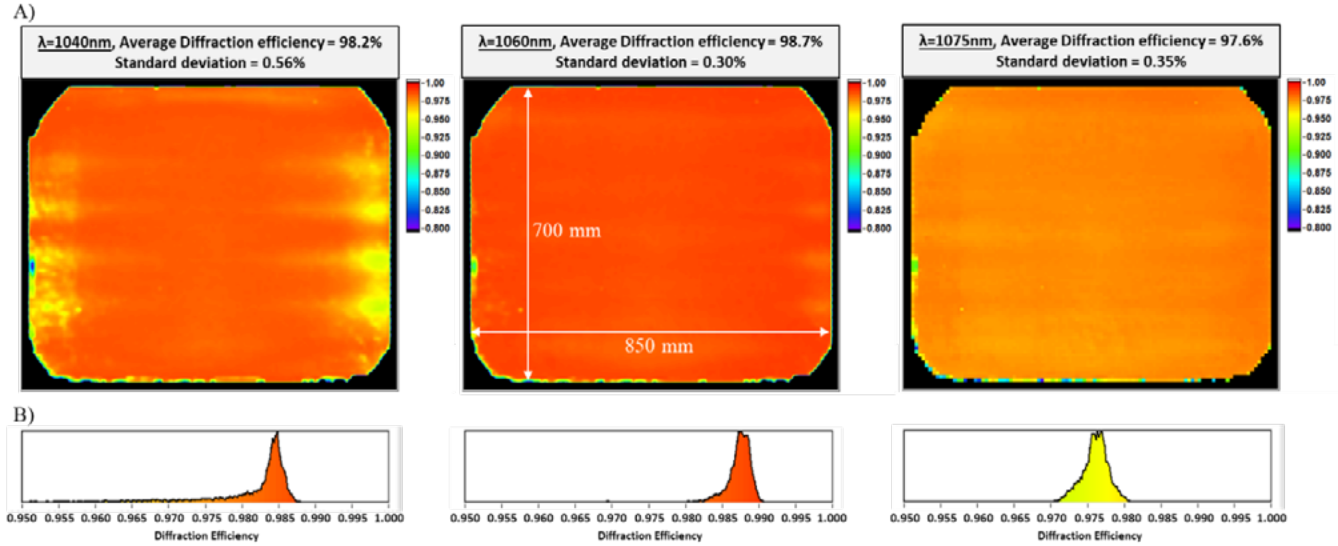

Figure 6. (A) Top images: Measured spatial variation of diffraction efficiency for first-of-its-kind, meter-scale HELD gratings (SN02) with dimensions of 850 mm x 700 mm. (B) Bottom images: Histogram for λ=1040 nm, 1060 nm, and 1075 nm at 37° incidence angle, 4 deg out-of-plane angle, and S-polarization.

A laser interference holographic technique is used to record the desired grating pattern in the photoresist. Holographic exposures were made by illumination of the photoresist-coated substrates with two plane waves in a fringe-stabilized interferometer that uses a single-frequency Kr-ion laser operating at 413 nm. Figure 7 shows examples of grating profiles in photoresist observed with a scanning electron microscope. These measurements were made on cleaved samples that had been coated with a thin layer (10 nm) of palladium to prevent charge buildup in the scanning electron microscope. Transfer of the photoresist pattern to the fused-silica MLD coating was accomplished by chemically assisted ion beam etching with CHF_3.

This method offers the practical possibility for fabricating at meter-scale. Specific procedures depend on the actual machine used. However, LLNL found that the primary variables were reactive gas concentration, ion energy, and ion flux. Just before the ion beam etching, the patterned substrate was exposed to an oxygen–argon beam. This oxygen scrub quickly removed a uniform layer of photoresist, thereby eliminating any residual photoresist remaining in the grooves. Following ion beam etching, excess photoresist still present on the substrate was removed in an oxygen barrel asher.

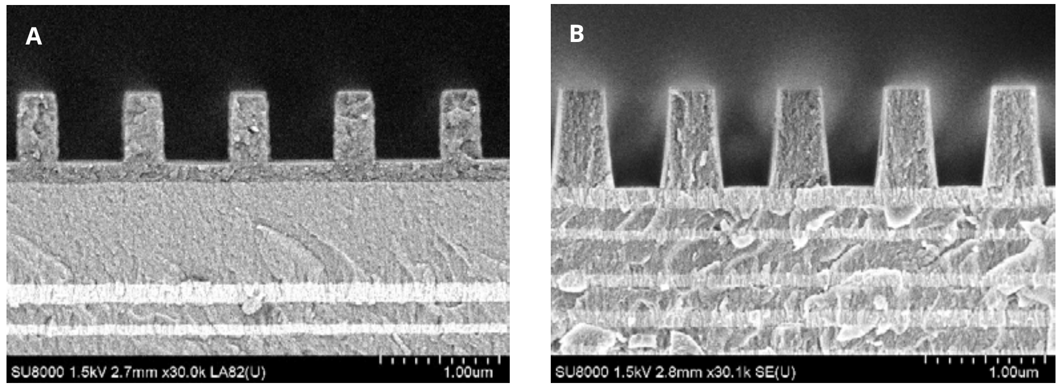

Figure 7. Scanning electron micrographs of (A) a photoresist grating profile, and (B) a HELD Grating profile etched into the top most layer of the deliectric coating.

C. Product Comparison

As shown in Table 1, today's most sophisticated high-energy laser systems rely on high-dispersion MLD gratings with 1680 to 1782 lines/mm; these gratings require angles of incidence between 56° and 76.5°. Prior to the HELD Grating technology, the Texas Petawatt Laser holds the record for the highest energy output 100 fs ultrafast laser system: 1 PW of power, 0.14 kJ in 140 fs pulses [4].

The HELD Grating design achieves 1.6 times lower dispersion as a result of lower grating line density, thereby lowering the requisite angle of incidence. This lower angle of incidence equates to a resulting projected angle that is 3.4 times smaller than when using conventional gratings. With a smaller projected angle, the system achieves over a 6.4 times larger beam normal aperture compared to previous standards. Current state-of-the-art gratings at higher groove densities require a complex laser design that splits the laser beam aperture over multiple gratings (phased or tiled together to act as a single grating) to reach similar energies to the HELD Gratings [5,6].

HELD Gratings enable the ELI Beamlines ATON laser to reach nominal 10PW operation while achieving unprecedented efficiency and uniformity over the unique laser beam aperture of 65 cm x 65 cm. In addition, meter-scale HELD Gratings have the potential to facilitate the transition towards future 100 PW class ultrafast laser systems. The stand-out parameter augmented by the new HELD gratings is the maximum total energy supported.

Figure 8 shows a comparison of maximum total energy on the gratings for LLNL's National Ignition Facility (NIF) ARC and ELI L4 ATON using beam sizes and grating laser-induced damage threshold (LIDT) and the limit of 1-meter scale optic. The NIF ARC curve is based on measured R-on-1 LIDT of 2.5 J/cm^2 at 1 ps [7] for a beam size of 17.5 cm x 35 cm (area of 613 cm^2). The ELI L4 ATON curve is based on measured R-on-1 LIDT of 0.7 J/cm^2 at 140 fs for a beam size of 62.5 cm x 62.5 cm (area of 3906 cm^2). Both curves were scaled using a τ=0.33 exponent. The HELD gratings allow for a larger beam width (62.5 cm). Increasing the beam height to produce a square beam and accounting for the difference in LIDT results in approximately 3.4 times more total energy on the grating compared to LLNL's NIF ARC high dispersion, 76.5 ° angle of incidence grating design.

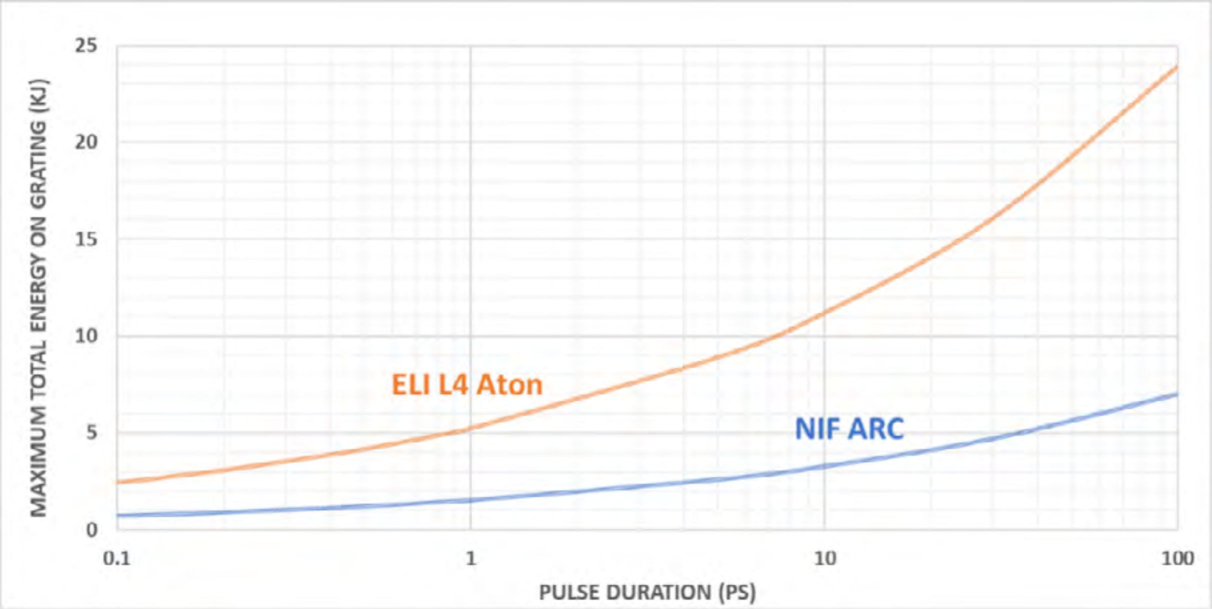

Figure 8. The newly-designed MLD grating can handle significantly greater energies as part of the ELI L4-ATON assembly versus NIF ARC system, the current state-of-the-art.

D. Comparison summary

	HELD Grating	Conventional Grating	Improvement
Maximum total energy on grating at 100 fsec	2.45 kJ**	0.72 kJ*	3.4x increase
Largest size grating substrate area* **	6375 cm^2	4095 cm^2	1.6x increase
Grating line density	1136 lines/mm	1782 lines/mm	1.6x reduction in dispersion
Angle of incidence	37.0 °	76.5 °	3.4x reduction in projected angle
Largest beam size	62.5 cm x 62.5 cm	17.5 cm x 35 cm	3.6x increase in dispersion axis
Projected beam size on grating	3906 cm^2	613 cm^2	6.4x increase

Table 1.

** Based on measured R-on-1 LIDT of 2.5 J/cm2 at 1 ps*
*** Based on measured R-on-1 LIDT of 0.7 J/cm2 at 140 fs*
**** Based on a limit of 1-meter diagonal optic*

E. Limitations

When compared to NIF's ARC system, the ELI L4-ATON design exhibits a relatively higher field enhancement that can negatively impact laser-induced damage threshold (LIDT) performance. Future designs will minimize the observed field enhancement to bolster LIDT performance while maintaining superior diffraction efficiency.

4. SUMMARY

Next-generation laser systems are necessary for high-energy density physics research enabling study of astrophysical and quantum phenomena difficult to replicate in a laboratory setting. Systems must compress and augment extraordinary energies while limiting physical damage incurred with each beam pulse for these experiments to succeed. LLNL's HELD Gratings, a novel design of multi-layer dielectric pulse compression gratings, enables a new class of high-energy 10 PW ultrafast laser systems. The technology enables extremely high and unprecedented peak power, and meter-scale HELD Gratings could facilitate future 100 PW class ultrafast laser systems. The design can handle 3.4 times the incident energy level of previous gratings, allowing the ELI Beamlines L4-ATON laser system to generate an unprecedented 10 PW of power, 1.5 kJ in 150 fs pulses, making possible previously unfeasible research. Components used at the energies required to observe and characterize quantum phenomena must perform under extreme conditions. With their improvements in materials and design, HELD gratings afford investigators unparalleled access to new realms of high-energy research benefiting cosmological advances, medical imaging, and national security capabilities.

5. CONTACT INFORMATION

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6. AFFIRMATION

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7. SUPPORT LETTERS

Daniel Kramer, ELI Beamlines
Erhard Gaul, National Energetics
Mark Feldman, Spectra-Physics

8. REFERENCES

[1] Information on ELI Beamline L4 ATON laser can be found of the following website: https://www.eli-beams.eu/facility/lasers/laser-4-aton-10-pw-2-kj/

[2] E. Gaul, G. Chériaux, R. Antipenkov, F. Batysta, T. Borger, G. Friedman, J.T. Greene, D. Hammond, J. Heisler, D. Hidinger, A. Jochmann, M. Kepler, A. Kissinger, D. Kramer, J.C. Lagron, A. Meadows, B. Rus, P. Trojek, S. Vyhlídka, T. Ditmire1,"Hybrid OPCPA/Glass 10 PW 1 shot a minute", CLEO 2018, OSA 2018.

[3] Colin N. Danson, Constantin Haefner, Jake Bromage, Thomas Butcher, Jean-Christophe F. Chanteloup, Enam A. Chowdhury, Almantas Galvanauskas, Leonida A. Gizzi, Joachim Hein, David I. Hillier, Nicholas W. Hopps, Yoshiaki Kato, Efim A. Khazanov, Ryosuke Kodama, Georg Korn, Ruxin Li, Yutong Li, Jens Limpert, Jingui Ma, Chang Hee Nam, David Neely, Dimitrios Papadopoulos, Rory R. Penman, Liejia Qian, Jorge J. Rocca, Andrey A. Shaykin, Craig W. Siders, Christopher Spindloe, Sandor ´Szatmari´, Raoul M. G. M. Trines, Jianqiang Zhu, Ping Zhu, and Jonathan D. Zuegel, "Petawatt and exawatt class lasers worldwide", High Power Laser Science and Engineering, (2019), Vol. 7, e54.

[4] Information on Texas Petawatt Laser can be found of the following website: https://texaspetawatt.ph.utexas.edu/

[5] J. Qiao, A. Kalb, D. Canning, and J. H. Kelly, "Realization of a Tiled-Grating Compressor for the OMEGA EP Petawatt Laser System," OSA/CLEO/QELS 2008.

[6] H. Azechi and FIREX Project Team, J. Phys.: Conf. Ser. 717, 012006 (2016).

[7] D. A. Alessi, C. W. Carr, R. P. Hackel, R. A. Negres, K. Stanion, J. E. Fair, D. A. Cross, J. Nissen, R. Luthi, G. Guss, J. A. Britten, W. H. Gourdin, and C. Haefner, "Picosecond laser damage performance assessment of multilayer dielectric gratings in vacuum," Opt. Express 23, 15532-15544 (2015).