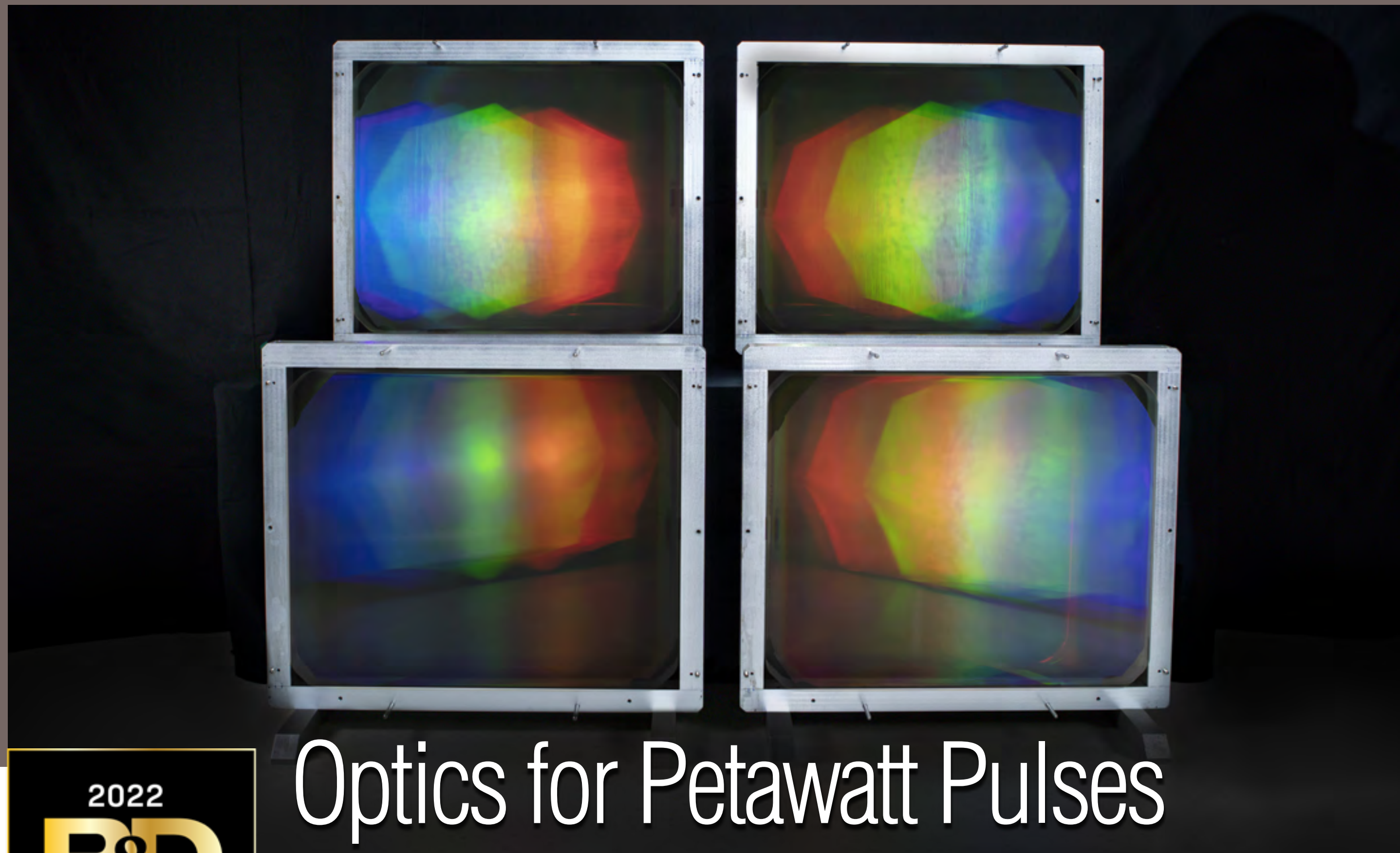

Optics for Petawatt Pulses

2022 R&D 100 WINNER

As the home of the world's largest and most energetic laser, Lawrence Livermore regularly stands at the forefront of high-energy-density physics research. The Laboratory's laser systems create extreme experimental conditions by exploiting a simple relationship: power is defined as energy transfer over time. By constraining a large burst of energy to a nearly instantaneous time frame, power grows enormously, allowing researchers to briefly mimic the intense environments of solar interiors and black hole horizons.

Through the Nobel Prize–winning method known as chirped-pulse amplification (CPA), scientists can spectrally and temporally stretch a short initial laser pulse, energize it, and finally compress it once again to produce a concentrated, high-energy blast. CPA warps and redirects light using a series of diffraction gratings—multilayer reflective panels composed of a base substrate and stacked films of dielectric material.

Such immense power cannot be generated nor withstood by just any ordinary gratings. Livermore senior laser scientist Hoang Nguyen has spent years researching technological solutions to identify laboratory equipment that can endure repeatable laser-based experiments involving petawatt (10^{15} watts) power levels. "Laser systems are breaking into the petawatt regime and allowing us to consider previously untenable experiments. While this is exciting news for scientists hoping to learn more about exotic physics, designing and manufacturing the right hardware to cope with these extreme energy levels is an incredible challenge," says Nguyen. Joined by industry partners, Nguyen's team at Livermore devised high-energy, low-dispersion (HELD) gratings made solely of multilayered dielectric materials that can withstand higher input laser energies than ever before.

Meter-sized high-energy, low-dispersion (HELD) gratings will be installed in the ELI Beamlines L4-ATON laser system.

Powering the Petawatt Era

According to Nguyen, HELD gratings can tolerate up to 3.4 times the incident energy of previous gratings to work effectively in emerging ultrafast laser systems, namely, the ELI Beamlines L4-ATON laser under construction in Prague, Czechia. Using HELD gratings, the laser will be able to fire off a 1.5-kilojoule laser beam in just 150 femtoseconds (10^{-15} seconds) to generate up to 10 petawatts of peak power. Performing CPA on this ultrahigh intensity setup will enable researchers to observe and better understand exotic astrophysical and quantum phenomena, namely gamma-ray flashes, electron–positron pair generation, radiation–friction force, relativistic flying mirrors, Unruh physics, and vacuum birefringence. Scientific insights could aid understanding of cosmic acceleration and quantum gravity. In the long term, incorporating plasma lenses could yield lasers with intensities approaching the Schwinger limit, above which electromagnetic fields are thought to become nonlinear.

Through technological innovation, Nguyen's team is driving the next generation of physics research, which can only be conducted with the world's most sophisticated lasers. Attempting to understand physical behavior at mindboggling scales of time and energy is a matter of conjecture unless researchers are provided with the right equipment. High-energy experiments such as those performed at Livermore's National Ignition Facility (NIF) rapidly degrade even the sturdiest hardware; NIF's components are regularly swapped out due to the sheer intensity of operation. "HELD grating technology is the culmination of significant investment from the Laboratory and our partners," says Nguyen. "The gratings we have fabricated will support laser systems at an unprecedented level of peak power. Seeing this project through to the end required a massive amount of infrastructure, custom-built equipment, and complex workflows."

Livermore development team for HELD gratings (from left to right): Sean Tardif, James Nissen, Hoang Nguyen, Candis Jackson, and Brad Hickman.

Scrupulous at Scale

Investment in each stage of the innovation helped Nguyen and his team navigate a host of challenges bridging laser theory, engineering, and logistics. At nearly one square meter, HELD gratings dwarf most optical components. The team devoted significant effort to scaling up methods and designs to such large proportions while maintaining submicrometer manufacturing precision. For example, they needed to carefully control the lithographic exposure process for the entire surface to exhibit the greatest possible spectral uniformity.

The team faced further challenges when carving out the gratings' surface profile, which is responsible for morphing the spectral and temporal characteristics of incident light to perform CPA. Each millimeter of the final grating surface contains more than 1,000 carved-out valleys of varied depth and spacing tailored to the specifications of each laser system. "Our meticulous process maintained ion-beam etching uniformity over an 80-centimeter aperture," says Nguyen, because the etching technique is not often applied to the grand scale of HELD gratings. "Beyond fabricating components with the desired specifications, we had to figure out the logistics of safely handling 136-kilogram optics throughout each step in the first place."

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Nguyen and his team ultimately produced the gratings through a Strategic Partnership Project with ELI Beamlines and a collaboration with the Optical Coating Group at Spectra Physics. "The partnership with ELI Beamlines and Spectra Physics was essential to bringing the gratings to full scale," he says. "The HELD technology emerged from four years of research and development rooted in collaboration and substantial support from Livermore's NIF and Photon Science Principal Directorate." With imminent integration into the ELI Beamlines project, Livermore's HELD gratings will bring the next echelon of physics research into view.

—Elliot Jaffe

Key Words: high-energy, low-dispersion (HELD) grating; laser; multilayer dielectric; National Ignition Facility (NIF); optics; petawatt; R&D 100 Award.

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