DOE | IMPROVING EFFICIENCY OF DIFFRACTION GRATINGS FOR HIGH ENERGY PHYSICS APPLICATIONS

May 2024

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Table of Contents

1.0 Introduction

This report is based on a need articulated in the *2023 Report of the Basic Research Needs Workshop on Laser Technology* which called for high-efficiency diffraction gratings. High-performance diffraction gratings are used in a number of scientific research areas, including ultrafast and high-power lasers, space flight instruments and astronomy, and synchrotron, free electron laser (FEL), EUV (extreme ultraviolent), or soft X-ray applications.[1]

High-intensity, ultrashort pulse laser systems are based on chirped pulse amplification (CPA) technology, which lays out a process of stretching or compressing and amplifying laser pulses using diffraction gratings that achieves much more intense laser pulses than was previously possible without damaging or destroying the gratings.[2, 3] In 2018, Gérard Mourou and Donna Strickland were awarded a Nobel Prize in Physics "for their method of generating high-intensity, ultra-short optical pulses" or chirped pulse amplification (CPA),[4] in recognition of CPA as a breakthrough technology with myriad applications in high-energy physics research, cancer treatment, laser eye surgery, precision machining for consumer electronics and other products, and so on.[5]

It is anticipated that the development of still more powerful lasers will enable revolutionary research and technological advancements in a variety of areas, such as industrial processing techniques, nuclear materials detection, enhanced medical diagnostics, plasma and high-energy-density physics, astrophysics and space flight equipment, and laser-based particle acceleration.[6] Failure of optical components is a key impediment, and innovations in grating technologies are needed improve performance of existing CPA-based ultrafast, high-energy laser systems and support the higher powered next generation of laser systems.[7, 8] Specifically, pulse compression gratings are identified as the "weakest link."[9] Advances in high-efficiency diffraction gratings are dependent upon grating structural design parameters, diffraction efficiencies, and laser damage thresholds – all of which are principal challenges for gratings manufacturing.[10]

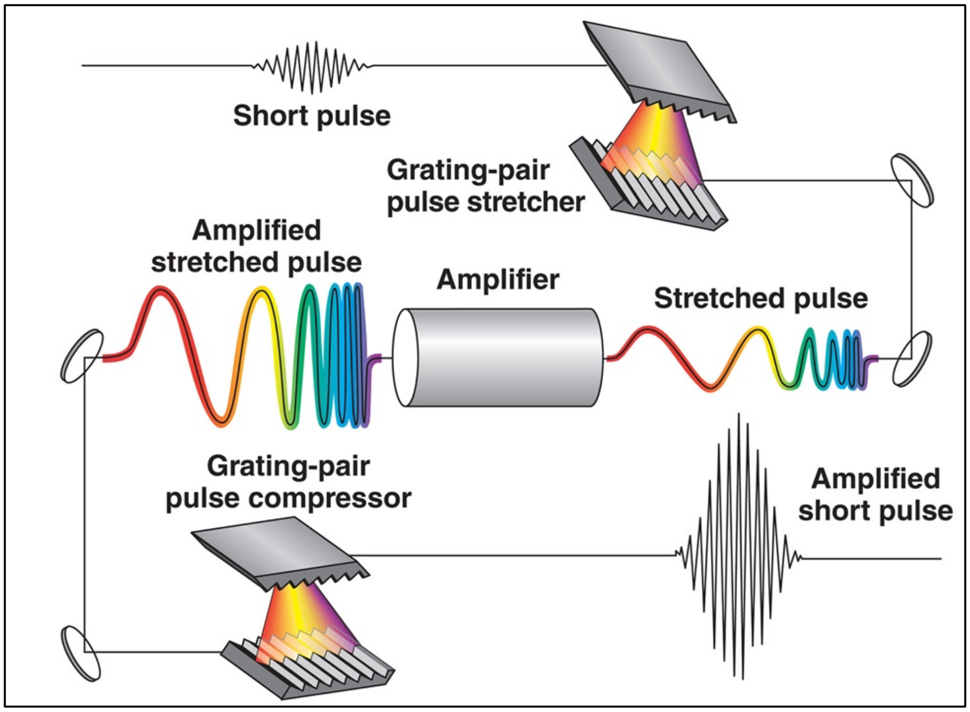

Figure 1: Chirped Pulse Amplification Process
Source: University of Rochester Laboratory for Laser Energetics[11]

Broadly speaking, the three principal diffraction grating options, by material type, are gold coated (used in ultrafast, high-power laser systems early on),[12, 13] dielectric, and hybrid gratings. Gold coated and dielectric gratings have been commercialized and are widely used in high-power laser systems worldwide, but hybrid grating options would require further development and testing before they become viable.[14] Multi-layer dielectric (MLD) gratings are widely used in ultrafast petawatt-scale laser systems due to their relatively high diffraction efficiencies and laser-induced damage thresholds (LIDT).[15, 16] Ultrafast, petawatt-class laser systems around the world, such as ZEUS at the University of Michigan and the three ELI laser systems in the EU, generally use **meter-scale, large-aperture MLD gratings** for the final laser pulse compression.[17]

In a typical CPA laser system, the last compression grating in particular, caps the system's maximum output power as the last grating is the most vulnerable to laser damage.[18] To mitigate this, large, meter-scale gratings are used in that last position. Only a handful of companies and research institutions worldwide produce these large-aperture gratings, however, and the higher-power ultrafast laser systems (>10 PW) under development are expected to require even larger final compression gratings of 1.5 – 2 m or larger.[19]

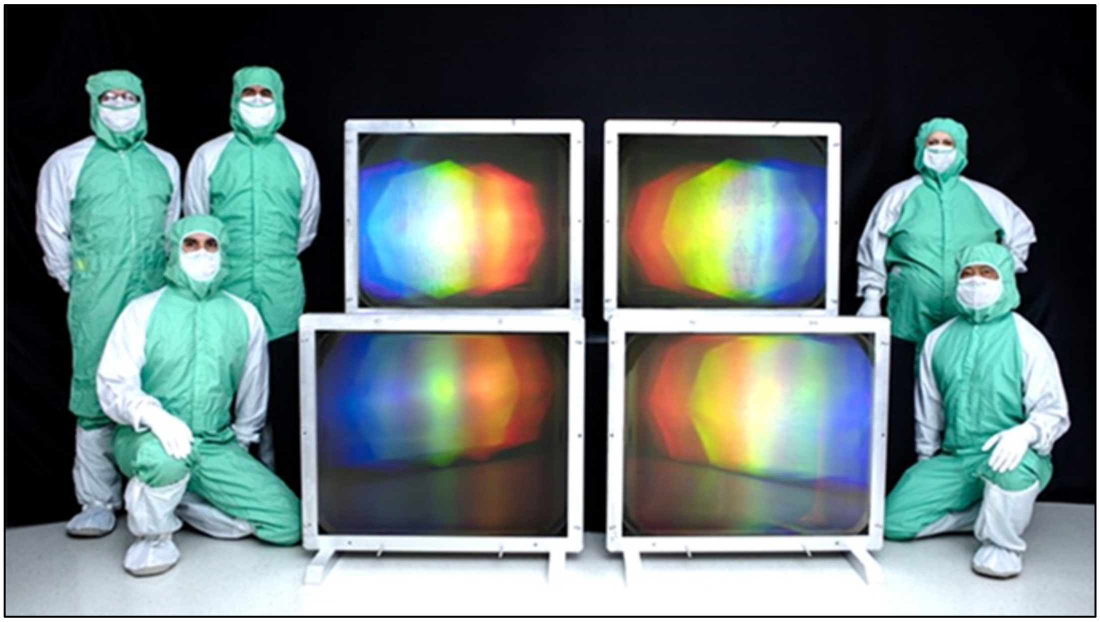

Figure 2: Meter-Scale Diffraction Gratings,
Lawrence Livermore National Laboratory (LNNL), 2022
Source: [Charlie Osolin, LLNL][20]

"Members of LLNL's Diffractive Optics Group with four of the 85x70-centimeter HELD gratings to be installed in the ELI-Beamlines L4-ATON laser system. Meter-scale HELD gratings have the potential to facilitate future 20-to-50-petawatt-class ultrafast laser systems."

2.0 Overview of Academic Programs in Advanced Diffractive Optics

Many of the companies that have developed the unique expertise required to develop diffraction gratings appear to be outgrowths of optics programs at U.S. universities. The goal of this section is to introduce U.S. academic institutions with programs focused on advanced diffractive optics.

2.1. University of Rochester

The University of Rochester received an award from the National Science Foundation to develop technologies for EP-OPAL, which is a new facility for the study of ultrahigh-intensity laser matter interactions. The plan is for the new facility to be built at the Laboratory for Laser Energetics (LLE) at the end of the design project.

The LLE houses the Omega Laser Facility which contains the OMEGA and OMEGA EP, two very powerful lasers used by scientists around the world. The OMEGA EP-coupled Optical Parametric Amplifier Lines (OPAL) which is part of the NSF project is being planned to incorporate two of the most powerful lasers and harness the capabilities of the OMEGA EP laser. The aim of the EP-OPAL project is to enable the highest-power laser in the world. Partner universities which will be explored in more detail in the following sections include the University of Buffalo, University of California-Irvine, University of Notre Dame, University of Maryland, University of Michigan, and Ohio State University, along with the private company, Plymouth Grating Laboratory.[21]

2.1.1 OMEGA Laser System

The OMEGA laser system is 10 meters tall and 70 meters in length and uses pulses of laser energy at targets to measure the resulting nuclear and fluid dynamic events. The 60 laser beams that form the OMEGA system can focus up to 30,000 joules of energy onto a target the size of >1 millimeter in diameter in the time of one billionth of a second.[22] Below is an image of the OMEGA laser system. To interact with the picture and see information each of the numbered areas, go here.

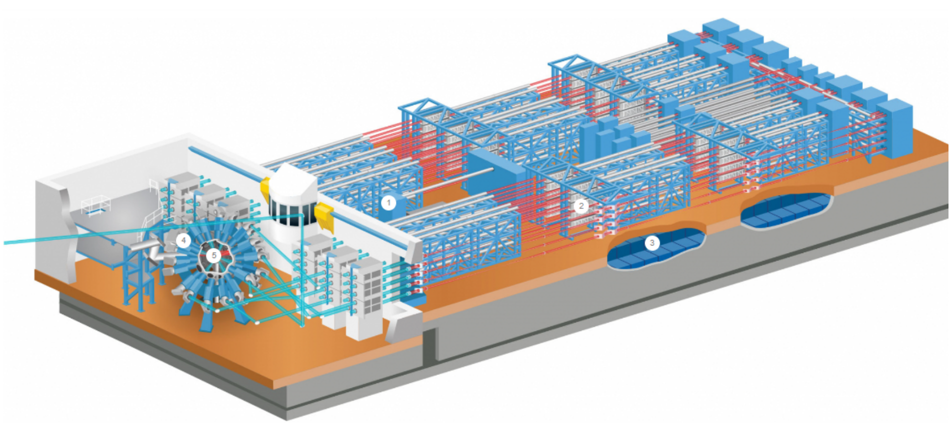

Figure 3: OMEGA Laser System
Source: University of Rochester, 2024[23]

2.1.2 OMEGA EP Laser System

The OMEGA EP is an extended performance laser system that has been in operation since 2008. It is an addition to the UV OMEGA laser system and has four, frequency-tripled, kilojoule class, independently configurable NIF-scale beamlines. The laser's combination of high-intensity and high energy short and long-pulse operation and flexible diagnostic systems allows for a range of experimental configurations for research areas such as plasma, high-field, high-pressure materials, and high-energy-density. A typical shot cycle is 1.5 h with 7-8 shots per day which can be shortened to a 45-minute cycle with two times the number of shots per day as needed.[24] The figure below is interactive on the website, which can be accessed here.

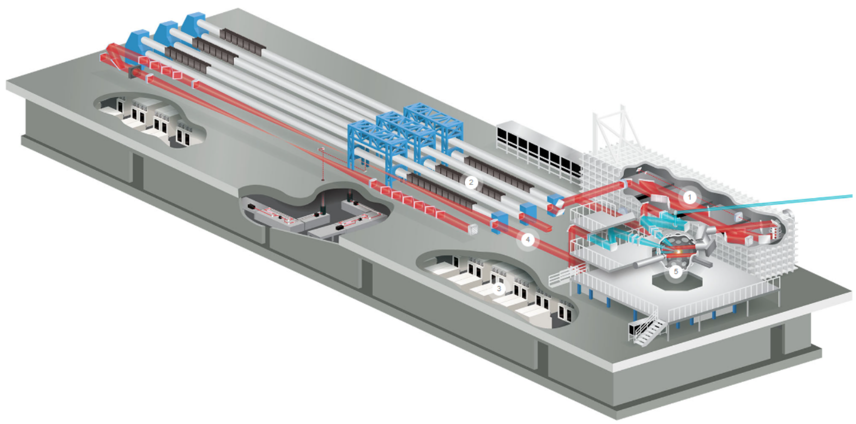

Figure 1: OMEGA EP Laser System

2.2. University of California-Irvine

Scientists from the Physics & Astronomy Department at the University of California, Irvine, are part of the team that received the NSF award mentioned in the previous section to design the most powerful laser. The team out of the University of California, Irvine will lead in the area of particle acceleration and light sources.[25] Their research interests include laser plasma interactions with ultrafast laser systems, performing high-intensity laser experiments with near and critical density plasmas for tabletop particle acceleration, and the generation of soft and hard x-rays.[26] The following are excerpts from the Dollar Research Group website which provides an overview of the research done and led by Professor Franklin Dollar.

2.2.1 Tabletop Particle Acceleration

With their intense fields, lasers are able to accelerate electrons to relativistic velocities in very small length scales. This occurs over such a small timescale that ion movement is negligible and extremely large fields form from the charge separation. Manipulating this charge separation enables acceleration of electrons and ions to energies to the MeV or GeV level. A university-scale laser can accelerate electrons to the same energies as a 100-meter, $100 million dollar synchrotron. Through the strongly nonlinear interaction secondary processes can be utilized to generate high brightness, MeV beams of neutrons or even beams of positrons.[27]

2.2.2 Coherent X-ray Generation

Light is produced by the acceleration of charged particles, and the very large, nonlinear acceleration that occurs in intense laser interactions provides a means for upconverting optical light to very high frequencies. The x-rays produced have some unique properties that enable unique spectroscopies, such as pulse durations on the order of single femtoseconds or less; and being spatially coherent so that the x-rays have laser like properties. Applications such as elemental specific dynamic studies and phase contrast imaging are possible with these sources. X-rays are produced from several different mechanisms from varying intensity regimes, and can have a wide variety of energies spanning from tens of eV to tens of keV.[28]

2.3. The Ohio State University

The High Energy Density Physics Scarlet Laser Facility at the Ohio State University is a research group that is investigating the interactions of ultra-short, ultra-intense laser pulses with matter. The Facility includes the Scarlet laser which is an ultra-short pulsed laser system that is capable of producing a peak power of 400 TW and peak intensity of 10^{21} W/cm^2.[29]

2.3.1 Scarlet Laser System

The following are the specifications of the Scarlet Laser, which are drawn from the facilities' website.

400 TW System:

- 10^{21} W/cm^2 intensity
- 400 TW peak power
- 800 nanometer wavelength
- 15 Joule per pulse
- 40 femtosecond pulse width
- 5-micron FWHM focal spot size
- 1 shot/minute repetition rate
- Greater than 10^{10}:1 pulse contrast ratio[30]

Laser Diagnostic Devices:

- On-shot energy
- SPIDER Single Shot Pulse Width
- On-shot intensity spectrum
- Third-order Cross-Correlator for Pulse Contrast
- On-shot focal spot diagnostic
- Water-cell nanosecond pulse contrast
- Spatial mode cameras
- Spatial chirp diagnostic[31]

Experimental Diagnostic Devices:

- Electron/positron magnet based spectrometers
- Thomson parabola ion spectrometer
- Bremsstrahlung x-ray spectrometer (HXBS
- 68 eV XUV imager
- 256 eV XUV imager
- 394 eV XUV imager developed in collaboration with BNL
- Front and rear side HOPG x-ray spectrometer with flat crystals
- Curved HAPG spectrometer and imager
- Cu K-alpha imager based on spherically bent Bragg crystal
- Zr K-alpha imager based on spherically bent Bragg crystal
- Si He-alpha imager based on spherically bent Bragg crystal
- Radiochromic film pack (RCF)
- Single hit CCD spectrometer
- Cherenkov spectrometer

- Scintillator array
- Neutron detector (scintillator based)
- Image plate reader[32]

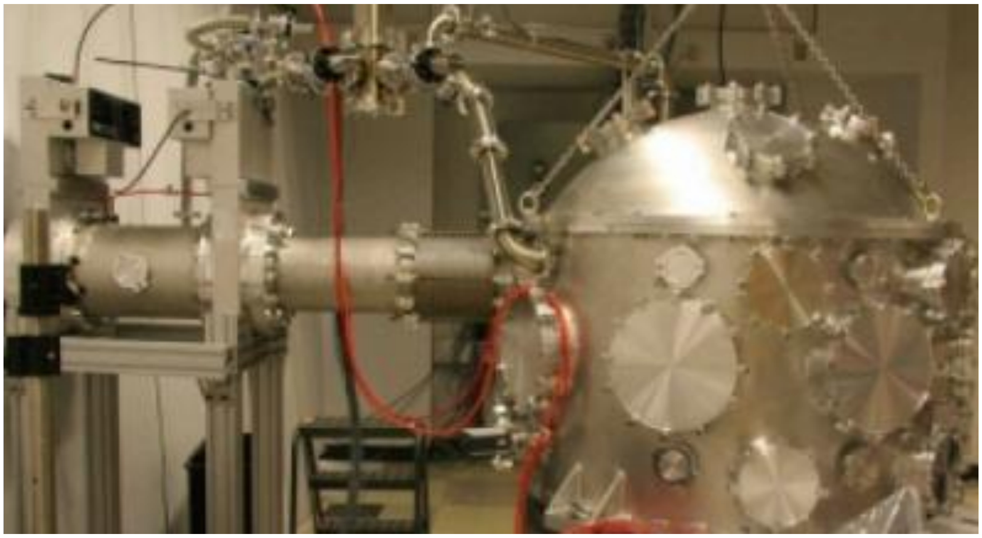

Figure 2 Scarlet Laser System
Source: Ohio State University, 2024[33]

2.4. Colorado State University

Colorado State University houses the Laboratory for Advanced Lasers and Extreme Photonics which develops advanced ultra-high intensity solid state lasers. Research being conducted at the Lab in addition to the development of the solid state lasers includes intense laser/matter interaction, advanced optical coatings, and the development of soft x-ray lasers and nanoscale metrology applications.[34]

2.4.1 Advanced Interference Coating Optics

Research under the Advanced Interference Coating Optics group includes optical thin film coatings by reactive ion beam sputtering. The group explores the optical and structural properties of the materials in optical thin film coatings and designs multilayer interference coatings for ultra-high power near infrared lasers and ultra stable cavities. One of current projects covers surface sculpting with ion beams.[35] An excerpt from the project's website, illustrates the importance of the work:

> "In this work we use assist ion bombardment at oblique incidence to pattern surfaces with periodic features of controlled size and period. These patterns have

high uniformity over large areas. **This work has significance for applications in the engineering of photonics structures such as grating.**"[36]

Surface Sculpting with Ion Beams

This project involves exploring the creation of sawtooth patterns that are covered with thin film multilayers for structures that resemble **blazed diffraction gratings**.[37]

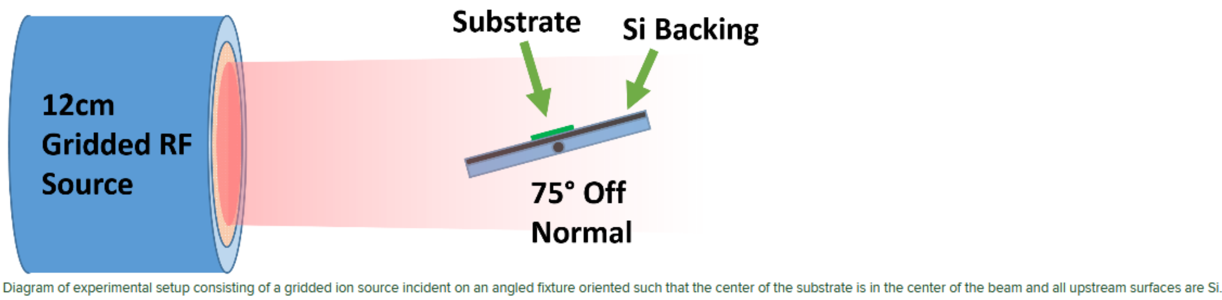

Figure 6: Diagram of Experimental Setup

Source: Colorado State University, 2024[38]

2.5. University of Michigan

The University of Michigan will host the newly constructed highest-power laser system in the US, named ZEUS which was funded by the National Science Foundation. The video below gives an overview of ZEUS and its many uses and applications.

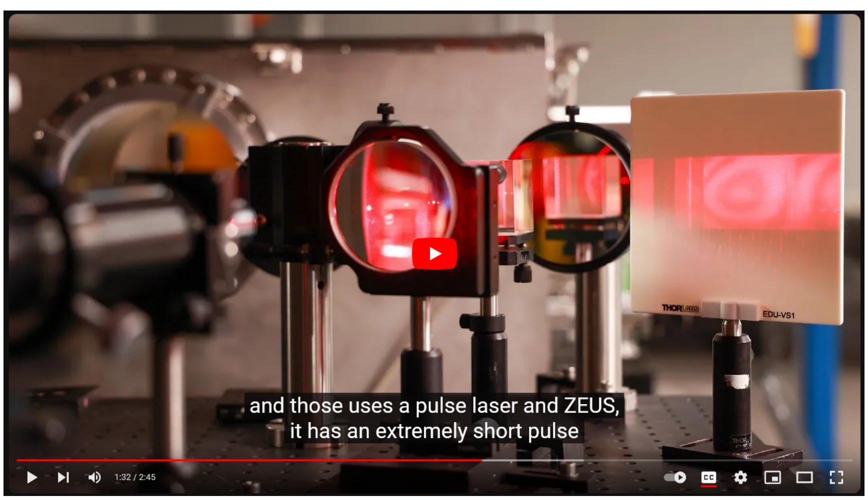

Figure 7: The Zeus Laser – Video

Click here to watch the video

ZEUS stands for Zettawatt-Equivalent Ultrashort pulse laser System which refers to the interaction of a petawatt laser pulse colliding with a GeV energy electron beam. The facility that houses ZEUS is an enclosed 16,000 square foot building with 5,000 square feet of cleanroom housing the laser and bean delivery system, 2,500 sf for shielded experimental labs, 1,250 sf of auxiliary fabrication, 2,500 sf of meeting and office space and additional space for other related activities.[39] The following is a layout of the facility.

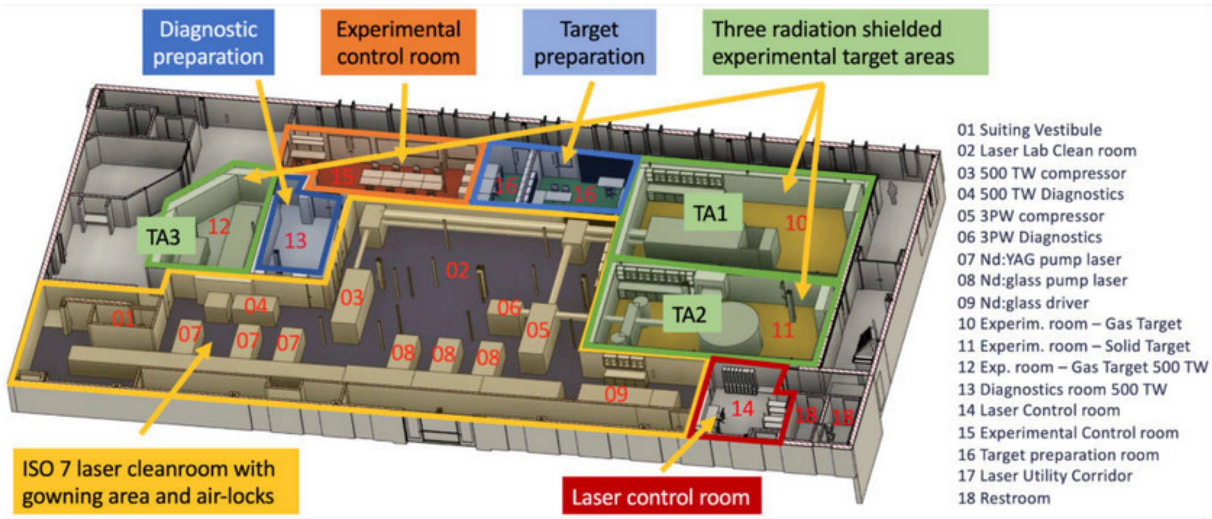

Figure 8: ZEUS Facility
Source: University of Michigan, 2024[40]

2.5.1 Laser System

The ZEUS laser is being constructed using mainly commercial components based on a design that will result in a reliable laser facility for experiments at the frontier of relativistic plasma physics. Proceeding clockwise, the Figure X shows: The Amplitude Technologies Pulsar, a double chirped pulse amplified laser with cross-polarization wave generation to improve contrast and bandwidth; two Pockels cells for isolation, a series of three amplifiers (brown) coupled by vacuum spatial filters and pumped by commercial pump lasers (green); an auxiliary programmable nanosecond drive pulse laser (dark red) which can also provide backup pump energy if needed; an atmospheric beam splitting and delay system (red lines); a 3 PW compressor with fused silica-based gratings and a 500 TW compressor with ultra low expansion glass-based gratings; and three target areas linked by evacuated delivery lines. In this configuration, the front-end Pulsar system and the compressor are being designed to maintain the bandwidth and phase compensation needed to support 20 fs compressed pulses with the final detailed spectral amplitude and phase being set by programmable acousto-optic filters (Mazzler and Dazzler, respectively).[41]

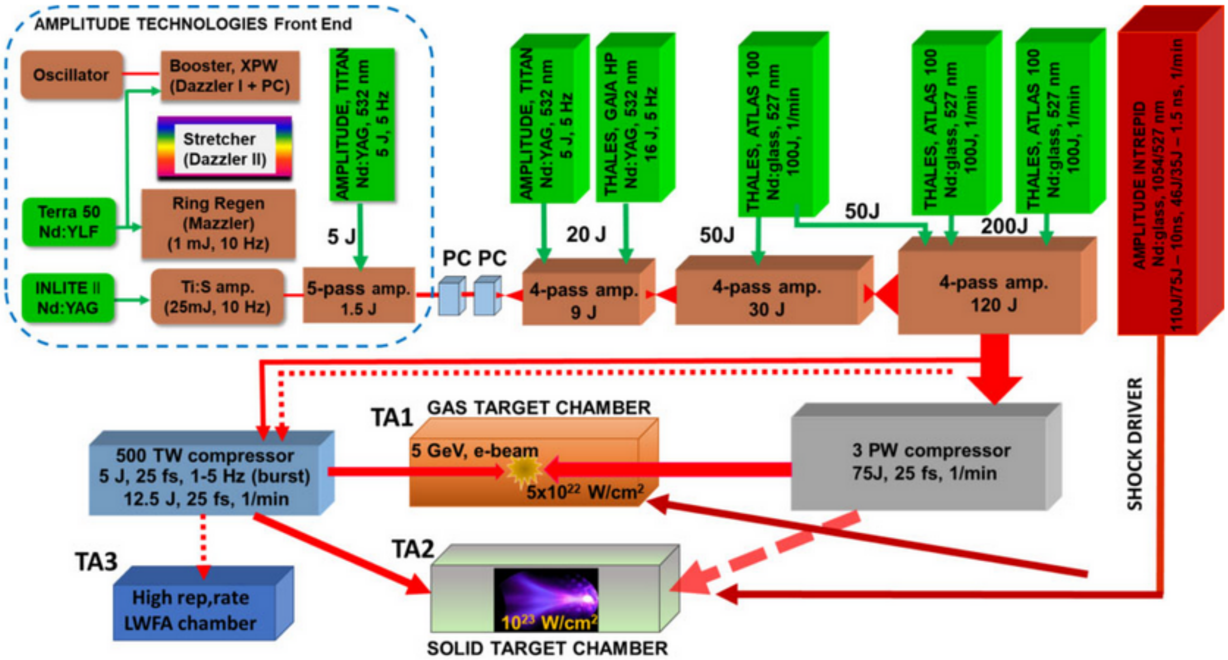

Figure 9: ZEUS Laser System – Amplitude Technologies Pulsar
Source: University of Michigan, 2024

2.6. University of Notre Dame

The University of Notre Dame is home to the Laser Precision Manufacturing Laboratory. The aim of the Lab is to explore light-matter interaction for manufacturing applications and includes several laser systems and optics capabilities. Some of the current research being carried out at the lab includes:

- Digital glass forming (3D printing glass)
- Instrumentation for in-situ inspection of metal additive manufacturing
- Ultrafast laser texturing
- Scalable metasurface fabrication using self-assembled microspheres
- Metasurface integrated uncooled mibrobolometers
- Thermoelectric coupled nanoscale antennas[42]

The following is a sample list of the equipment available at the Laser Precision Manufacturing Lab, the full list can be found here.

- Light Conversion Pharos PH1-20W: 20W Ultrafast laser (230 fs pulses, 200 kHz PRF, 1030 nm)

- Light Conversion Orpheus HE: Collinear Optical Parametric Amplifier (315 nm – 16 µm)
- Iradion 1625: 250 W CO_2 laser (CW, 10.6 µm)
- Coherent Diamond J-3: 250 W CO laser (CW, 5.5 µm)
- IPG YLR-500-AC: 500 W Fiber Laser (CW, 1070 nm)[43]

2.7. University of Maryland

The University of Maryland's Laboratory for Intense Laser Matter Interactions includes a wide range of lasers, experimental chambers, and diagnostics for experiments in the areas of high field nonlinear optics, laser-driven charged particle acceleration, structured light, and high intensity propagation.[44] The following are some of the laser systems available at the lab, the full list can be accessed here.

10 TW Laser System

Parameter	Value	Unit	Additional Information
Pulse energy (compressed)	0.4	J	*equipped with Dazzler pulse shaper and deformable mirror *main recent applications: filamentation, air waveguides
Pulsewidth	40	fs	
Rep. rate	10	Hz	
Central wavelength	800	nm	

Figure 10: 10 TW Laser System
Source: LaserNetUS, 2024[45]

mid-IR OPCPA system

Parameter	Value	Unit	Additional Information
Energy (compressed)	30	mJ	*mid-IR optical parametric chirped pulse amplifier system *auxiliary synchronized pulses at 1.45 microns (70 mJ, 50 ps), 1.06 microns (200 mJ, 100 ps), 1.03 microns (200fs, 1 mJ) *main recent applications: avalanche-based detection of radioactive materials, development of high efficiency plasma gratings
Pulsewidth	80	fs	
Rep. rate	20	Hz	
Central wavelength	3.9	µm	

Figure 11: Mid-IR OPCPA System
Source: LaserNetUS, 2024[46]

2.7.1 Diffraction Gratings

Howard Milchberg is an author on a study published in *Optics Letters* in 2021 which demonstrates the technique of a single-shot measurement of spatiotemporal amplitude of an ultrashort laser pulse. According to the abstract, “The method, transient grating single-shot supercontinuum spectral interferometry (TG-SSSI), is demonstrated by the space–time imaging of short pulses carrying spatiotemporal optical vortices. TG-SSSI is well suited for characterizing ultrashort laser pulses that contain singularities associated with spin/orbital angular momentum or polarization.”[47] Access to the full text of the published study can be found here.

2.8. Florida State University

The Spectroscopy Laboratory at the Florida State University hosts a variety of instruments for optical spectroscopy of solid-state samples. The lab is equipped for optical characterization via steady-state, using UV-VIS-NIR, FT-IR, Raman, fluorescence, and emission quantum yield measurements.[48] Access to information on all of the instruments available at the Spectroscopy lab can be found here. An example of one of the instruments is included below.

PerkinElmer Lambda 950 UV/VIS/NIR Spectrophotometer

Description:

The Lambda 950 is a wavelength scanning double-beam instrument operating in the ultraviolet, visible and near-infrared (UV/VIS/NIR) using either a deuterium or tungsten-halogen light source, one of two gratings – one for the UV/Vis, the other for the NIR – in the monochromator and two detectors – a Hamamatsu R6872 photomultiplier for the UV/VIS and a Peltier cooled PbS detector for the NIR.

Specifications:

- Wavelength range: 190-3300 nm
- Spectral resolution: ≤0.05 nm UV/VIS; ≤0.20 nm NIR
- Bandpass: 0.05-5.00 nm in 0.01 nm increments UV/VIS; 0.20-2.00 nm in 0.04 nm increments NIR
- Light beam passes through the sample compartment 90 mm above the base plate, 3-12 mm beam height

Rate:

Internal: $3/hr
External: $15/hr

Location:

CSL 116

COMPANY WEBSITE »

Figure 3: PerkinElmer Lambda 950 UV/VIS/NIR Spectrophotometer
Source: Florida State University, 2024[49]

2.9. Stanford University

The SLAC National Accelerator Lab at Stanford University was established in 1962 and is one of the 17 DOE national labs. The Lab’s research areas fall into the following categories:

- X-Ray & Ultrafast Science
- Advanced Accelerators
- New Technologies
- Physics of the Universe
- Science of Life
- Energy Sciences[50]

The following video gives a short overview of SLAC.

Figure 13: About SLAC
Source: Click here to view video

2.9.1 X-Ray & Ultrafast Science

SLAC's unique facilities for X-ray and ultrafast science – the Linac Coherent Light Source (LCLS), the Stanford Synchrotron Radiation Lightsource (SSRL) and megaelectronvolt ultrafast electron diffraction (MeV-UED) – attract thousands of researchers from universities, industries and laboratories around the world each year.[51]

The following video is an overview of X-ray Free Electron Lasers (Linac Coherent Light Source) and how they work.

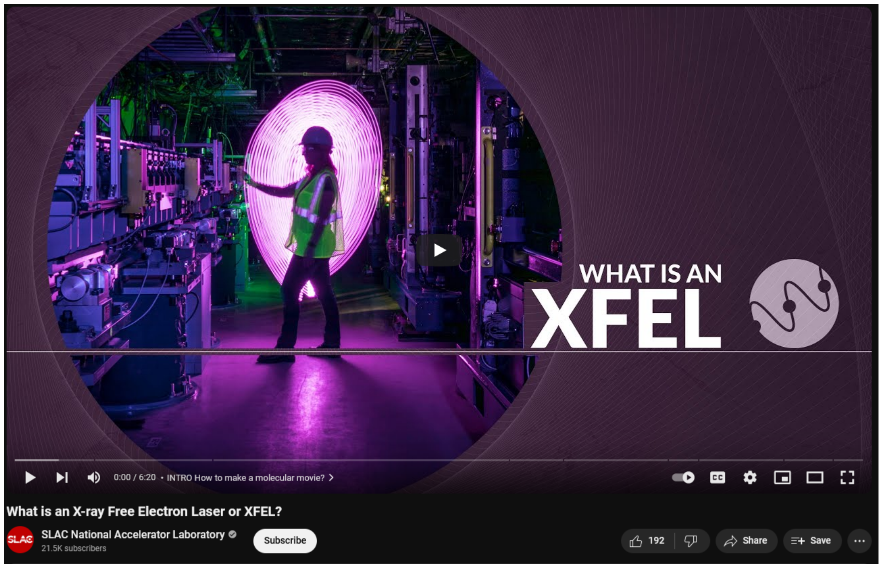

Figure 14: What is an X-ray Free Electron Laser or XFEL?
Source: Click here to watch the video

2.9.2 Advanced Accelerators

Accelerators form the backbone of SLAC's national user facilities. They are complicated machines, with hundreds of thousands of components that all need to be designed, engineered, operated and maintained to achieve the highest energy acceleration and the highest quality particle beams. Research at SLAC is continually improving accelerators, both at SLAC and at other laboratories, and is also paving the way to a new generation of particle acceleration technology.

Accelerator Physics

Accelerator science and technology have been at the core of SLAC's mission from the beginning. The Accelerator Directorate operates and maintains our existing accelerators to provide the highest possible level of performance by developing ways to preserve beam quality.

Accelerator R&D

New technologies, such as "plasma wakefield" accelerators, can boost electrons to very high energies in very short distances. This could lead to linear accelerators that are 100 times more powerful, boosting electrons to a given energy in one hundredth the distance.[52]

2.9.3 Diffraction Gratings

According to a news article on SLAC collaborating with small businesses published by SLAC, the Lab is looking to partner with small businesses in order to expand the capabilities of the X-ray Free Electron Laser (XFEL). To expand the XFEL's capabilities, there will be a need for highly specialized x-ray optics such as mirrors and **diffraction gratings that SLAC can't produce on its own.** The DOE awarded four early-stage SBIR contracts to companies that are developing the necessary x-ray optics for the XFEL, and more funding is expected for additional companies/technologies. A Massachusetts company, Izentis, was awarded a contract with DOE for work with LCLS's Optics and Metrology Laboratory to build high precision diffraction gratings.[53]

2.10. University of Arizona

The Ultrafast Fiber Lasers and Nonlinear Optics Group at the University of Arizona is led by Professor Khanh Kieu. The purpose of the group is to develop compact ultrafast fiber lasers to be used in multiphoton microscopy and dual-comb spectroscopy. The areas of fiber lasers, fiber optical sensors, nonlinear effects and devices in waveguiding structures are of particular interest and the group aims to develop new advanced components and instruments to advance scientific discoveries. The group also has multiphoton microscopes that have been used in various applications.[54]

2.10.1 New Laser Development

The focus in new laser development is on ultrafast laser sources for biomedical multiphoton imaging. For example, the group demonstrated a handheld all-fiber laser system that can produce ultrashort optical pulses with only a few cycles. In addition to this laser system, the research group is also developing new lasers for Terahertz spectroscopy, multiphoton microscopy, dual comb spectroscopy and more.[55]

3.0 Global Market for Diffraction Gratings

The global market for diffraction gratings is relatively small with demand coming primarily from three sectors: laser applications, spectroscopy and telecommunications. According to a press release by Business Research Insights, the estimated size of the global market for diffraction gratings in 2022 was $234.2M and is expected to reach $379.16M by 2031, with an estimated CAGR of 5.5% during the forecast period.[56] According to Lawrence Livermore National Laboratory (LLNL), petawatt and multi-petawatt lasers rely on chirped-pulse amplification, a Nobel Prize-winning technology[57] and set the stage for growth in the future. To put this in perspective, "a petawatt is about 1,000 times the capacity of the entire U.S. electric grid.[58]"

There are two primary types of gratings used with diffraction optics: (1) ruled gratings and (2) holographic gratings. According to Edmunds Optics these two types differ not only in how they are manufactured but also in the surface profile. "Ruled gratings have a sawtooth-shaped groove profile tilted at a specific angle (the blaze angle) that is designed to have maximum efficiency at a specific (blaze) wavelength. Holographic gratings however have a sinusoidal cross-section.[59]"

In the next section, a variety of the key players working with diffraction gratings of both types are introduced. The companies profiled were selected by conducting a review of subscription market research reports, industry news, conference proceedings, presentations, research publications, and open web keyword searches. The resulting information is divided below into U.S. companies and companies based outside the U.S.

4.0 Producers of Diffraction Gratings for Ultrafast, High-Energy Lasers System

While the focus was initially on U.S. companies, due to the small number of U.S.-based companies currently offering diffraction gratings for ultrafast, high-energy laser systems, the scope was expanded to include prominent producers of high-efficiency diffraction gratings worldwide – excluding those countries with which the U.S. does not have normal trade relations. The significant diffraction grating producers outside the U.S. that were identified are based in Europe and Japan.

4.1. U.S. Companies

Notable U.S.-based manufacturers of high-efficiency diffraction gratings include Edmund Optics, Holographix LLC, MKS Instruments (part of Newport and Spectra-Physics), Wasatch Photonics and Plymouth Grating Laboratory.

4.1.1 Edmund Optics

Edmund Optics is a global optics solutions company that serves a variety of application areas in Life Sciences, Biomedical, Industrial, Semiconductor, R&D, and Defense. The company was founded in 1942 and is headquartered in Barrington, New Jersey with over 1,250 employees. This corporate profile brochure published by Edmund Optics gives an overview of the company, their product/technology offerings, and their regional presence. The Department of Energy is one of Edmund Optics' customers.[60] In 2020, the company acquired Quality Thin Films, Inc. which was based in Tampa, FL and offered optical components with high laser damage and laser crystal coatings from UV to IR. This acquisition will help support Edmund's expansion of its laser optics manufacturing capabilities.[61] Edmund Optics' manufacturing capabilities in Ultrafast Laser Optics includes:

- Highly-dispersive mirrors, low GDD optics, and beam expanders
- Intra-and extra-cavity optics for high-power ultrafast lasers
- 3rd order dispersion of 0 fs^3, or negative values down to -2500 fs^3
- Cost-effective ultrafast-enhanced silver coatings with R>99% and GDD as low as 0 ±20fs^2 over common ultrafast wavelengths
- GDD values below -100fs^2 available through strategic partner, UFI[62]

In the area of Ultrafast Metrology, Edmund Optics has the capability to:

- Accurately measure GDD of multilayer ultrafast optics
- Ultra-broadband spectral coverage ranging from 250nm to 2100nm
- GDD accuracy of ±5 fs^2 at angles of incidence between 0-70°[63]

4.1.2 Holographix LLC

Holographix LLC (Malborough, MA), established in 1985, develops and manufactures custom, high-performance optical components for application areas such as aerospace and defense, automotive, consumer electronics, life sciences and medical lasers, industrial metrology, semiconductors, and telecommunications. The company was acquired by the photonics company Headwall in 2022.[64, 65, 66] Holographix specializes in development and high-quality replication of microlens arrays and diffusers; slanted, transmission, and blazed diffraction gratings; and diffractive waveguides. Its customers include BAE Systems.[67] Holographix provides diffraction gratings (including blazed diffraction gratings)[68] with absolute diffraction efficiencies above 90% with low stray light. Its Holographix's offerings include custom development and manufacturing of high-performance diffraction gratings for chirped pulse amplification laser systems, with an emphasis on low-cost replication.[69]

Holographix's 15,000 sq. ft. manufacturing facility near Boston is "equipped with thin-film coating and sputtering systems, phase-shifting interferometers, laser systems, spectrophotometers, and a full line of other metrology tools."[70] Specific equipment at the facility includes:

- "ADE and Zygo 4 phase-shift interferometers (Qty 4)
- ADT 7100 Dicing System
- AFM Workshop TT- Atomic Force Microscope (AFM)
- Amray 3600 Scanning Electron Microscope (SEM)
- Cary 500 UV-Vis-NIR Spectrophotometer
- Custom fully automated UV curing stations
- Denton DESK II sputtering systems (Qty 2)
- Denton Infinity 22 thin-film box coater
- Keyence VK-X260K Violet Laser Confocal Microscope
- March Plasma AP-1000 plasma treatment system
- Mitutoyo Vision Systems (Qty 2)."[71]

4.1.3 MKS Instruments (Newport, Spectra-Physics)

MKS Instruments, a publicly-traded company located in MA, purchased **Newport Corp.** and its **Spectra-Physics** laser brand in 2016.[72] Spectra Physics-Newport is one of the companies that teamed with Lawrence Livermore National Lab (LLNL) to develop a new high-energy pulse compression grating. Designed as a high-energy, low dispersion

(HELD) multi-layer dielectric grating, this will be installed in the L4-ATON laser system at the ELI-Beamlines Facility in the Czech Republic. LLNL's HELD gratings, received a 2022 R&D 10 Award as one of the top 100 industrial inventions worldwide. It can deliver 3.4 times more total energy than current state-of-the-art technology.[73]

Newport Corp. had acquired both Spectra-Physics Inc. and **Richardson Gratings** in 2004. Like Spectra-Physics, Richardson Gratings persists as a well-known name brand in the market space.[74] Founded in 1947, the Newport Corp. subsidiary **Richardson Gratings** remains headquartered in Rochester, NY. Richardson Gratings touts its "proud tradition of producing high-quality precision diffraction gratings." Newport and Richardson Gratings further describe the Richardson brand as,

> "A world leader in the design and manufacture of diffraction gratings for spectroscopic, telecommunications and laser applications, as well as for research and education. Since inception [Richardson's] focus has been on two key competencies: the generation of master gratings, both by mechanical ruling and by holographic recording, and secondly the replication of optically equivalent copies of those master gratings for cost effective commercial quantities of gratings."[75]

The Richardson Gratings brand offers plane ruled, plain holographic, echelle, transmission, concave ruled, and concave holographic diffraction gratings for scientific and OEM applications, including laser tuning, pulse compression, datacom and astronomy.[76]

4.1.4 Plymouth Grating Laboratory (PLG)

Located in Carver, MA, Plymouth Grating Laboratory's (PGL) innovative manufacturing techniques "push the boundaries of what is normally possible with grating manufacturing." The company's ability to make gratings with high diffraction efficiency is made possible by "PGL's exclusive use of the Nanoruler, based on the proprietary Scanning Lithography technology developed at MIT, and PGL's industry-leading process expertise.[77] In October 2023, PGL announced that they have been chosen by a multi-institutional team led by the Laboratory for Laser Energetics at the University of Rochester to develop the means to produce grating as large as two meters to support the design of the EP-OPAL laser.

4.1.5 Wasatch Photonics

Wasatch Photonics is a small privately held company and previous SBIR/STTR awardee that focuses on designing, manufacturing, and selling advanced spectrometers based on its patented, high-efficiency VPH (volume phase holographic) grating technologies.[78] Wasatch's VPH gratings for laser pulse compression can achieve up to 98% first order diffraction efficiency. Wasatch provides small quantity prototyping up through production at volume and provides custom solutions for OEMs.[79]

4.1.6 Thorlabs

Thorlabs was founded in 1989 and is headquartered in Newton, New Jersey, which is home to mechanics, optics, fiber optics, advanced systems, and laser division teams and four primary distribution warehouses. Thorlabs also has facilities in Michigan, Virginia, Maryland, South Carolina, California, New Hampshire, Colorado, New York and various countries outside the U.S.[80] According to LinkedIn, Thorlabs has about 2,500 employees at all their offices globally.[81] Government customers of Thorlabs' products/technologies include the Department of Health and Human Services, Department of Defense, Department of Commerce, NASA, EPA, Department of Agriculture, etc.[82]

Diffraction Gratings

Thorlabs' diffraction gratings come in transmission and reflective varieties and include blazed, volume phase holographic, holographic, echelle, and grating modulator.[83]

4.2. Companies Based Outside the U.S.

4.2.1 Gitterwerk

Gitterwerk (Jena, Germany) manufactures transmission gratings for wavelengths 800 – 1550 nm. Gitterwerk's transmission gratings are designed for ultrashort pulse, high energy laser applications. The company briefly describes its products as follows:

> "The **periodic 100% fused silica gratings provide efficiency of up to 99.5% (incl. AR-Coating)** and an excellent homogeneity for perfect beam quality. Our gratings are manufactured with a unique mask based full-field exposure process, so you will not find stitching artifacts or period variations in our products."[84]

4.2.2 Hamamatsu

Hamamatsu is a photonics products company founded in 1953 in Japan, with a US-based office located in Bridgewater, NJ, (Hamamatsu Corporation) as well as an additional office in San Jose, CA.[85] Hamamatsu has over 4,000 employees globally and their capital as of December 2023, is 35,095 Million Yen. Their net sales include $221,445 Million Yen for fiscal year ended September 30, 2023.[86] The company offers products such as optical sensors, light sources, and systems that these components are used in.[87] Customers of Hamamatsu Corporation include the U.S. Department of Commerce's National Institute of Standards and Technology (NIST), for which Hamamatsu will construct a factory building to increase its production capacity for semiconductor lasers.[88] Another customer includes NASA, for which Hamamatsu Photonics provided a phototube for the ASCA's Gas Imaging Spectrometers.[89] An exploration of Hamamatsu's mini-spectrometers with their grating components is included below.

Mini-spectrometers

The information below comes from the technical document published by Hamamatsu.

> Spectrophotometers for color measurement, chemical analysis, etc. are usually large devices so samples for measurement had to be brought into a chemical lab, etc. where these bulky devices are installed. This has led to rapidly mounting interest in recent years in devices capable of making on-site analysis by real-time measurements without having to bring samples into a special lab as well as monitoring measurements during constant observation. By merging image sensor technology accumulated over long years with MEMS technology such as etching, Hamamatsu succeeded in developing mini-spectrometer products that offer compact size along with low cost. These mini-spectrometers contain an optical system such as a **grating** (wavelength dispersing component) and a linear image sensor. Mini-spectrometers can be used in a wide range of measurement fields including chemical analysis, color measurement, environmental measurement, and process control in production lines. Hamamatsu also provides ultra-compact models specifically designed for assembly into portable measuring devices.[90]

4.2.3 Quantum Cascade Laser – Diffraction Gratings

In August of 2021, Hamamatsu announced that it had designed the world's smallest wavelength-swept quantum cascade laser (QCL). Under the company's current results, they used their advanced MEMS technology to redesign the MEMS diffraction grating, which takes up the most space in the wavelength-swept QCL and was able to develop a MEMS diffraction grating that is about 1/10th the size of the conventional gratings.[91]

4.2.1 Horiba Jobin Yvon (Horiba Scientific)

The optical instrument developer and manufacturer Jobin Yvon, has been part of Horiba Group since 1997.[92] Jobin Yvon later became Horiba Jobin Yvon,[93] and today it is **Horiba France SAS.**[94] Horiba France SAS still uses Jobin Yvon as a brand name. Within the Horiba Group, Horiba France is a subsidiary under the Horiba Scientific segment.[95][96] Horiba France develops and manufactures diffraction gratings for industrial OEMs and scientific research.[97] The gratings appear to be sold under Horiba Scientific in the U.S. Horiba Scientific is **one of the very few commercial sources for large-aperture gratings for high-energy laser applications**, along with Plymouth Grating Laboratory.[98, 99] Horiba makes master and replica diffraction gratings for scientific research applications that include astronomy, space flight instruments; synchrotron, FEL (free-electron laser), and extreme UV; and **laser pulse compression** for use ultrafast and high-energy lasers.[100]

Horiba's typical laser pulse compression gratings are gold-coated and made using holographic technology. Horiba states that these gratings "can achieve typically diffraction average efficiencies as high as 94% at 800 nm (TiSa), 910 nm (OPCPA), 1030 nm (Ytterbium), 1053 nm (Nd glass) or 1.55 µm."[101]

4.2.1 Ibsen Photonics

Ibsen Photonics headquartered in Farum, Denmark, specializes in developing transmission diffraction gratings and grating based spectrometer modules. The company's gratings are used in diverse industries such as telecom, sensing, lasers and spectroscopy. Ibsen tailors their gratings to customer specifications using unique processing technologies and must pass extensive metrology and quality inspections.[102] According to LinkedIn, Ibsen has between 51 and 200 employees and some of their US customers include MIT and the Michigan State University.[103] More about the company's transmission gratings are included in the following section.

Transmission Gratings

Ibsen manufactures fused silica transmission gratings that can be used in high power lasers, telecom devices, and spectrometers. The advantages of Ibsen's technology include being 100% dielectric which offers:

- Environmental stability as there are no coatings, polymers or epoxies used
- Low thermal expansion coefficient
- Low temperature sensitivity
- High energy/power damage threshold
- More flexibility in the optical design
- Combined wavelength dispersion and beam folding elements
- Absence of complex absorption issues
- High diffraction efficiency combined with high dispersion
- High tolerance to illumination angle of incidence
- Low stray light fused silica transmission gratings[104]

4.2.2 Jenoptik

Jenoptik, founded in 1990 in Germany, is an optical technologies company developing products and services to serve the photonics market. The company has about 4,600 employees worldwide and in fiscal year 2023, the company generated revenue of 1,066 million euros.[105] Jenoptik has a presence in the US, in Jupiter, Florida, Huntsville, Alabama, Rancho Cucamonga, California, and Rochester Hills, Michigan.[106] There two divisions are the Advanced Photonic Solutions and Smart Mobility Solutions. The key markets of interest to Jenoptik include semiconductor & electronics, life science & medical technology and smart mobility.[107] US customers of Jenoptik's products include the Army, Air Force, Navy, Smithsonian, Department of Defense, Department of Commerce, and the National Institute of Standards and Technology.[108] More in-depth information on their diffraction grating product offerings is included below.

Diffraction Gratings

Jenoptik has 25 years of experience in designing and developing diffractive micro and nano-optical elements. Jenoptik uses state-of-the-art lithographic technology and high-level flexibility to manufacture diffraction gratings with different profiles such as Binary, Multilevel, and Blazed into different materials.[109]

e^2 – Transmission Pulse Compression Gratings

> Diffraction gratings are one of the key elements in CPA (chirped pulse amplification) setups of **femtosecond lasers**. The diffraction efficiency of the pulse compression gratings (PCGs) has a huge impact on your laser performances in terms of efficiency and beam quality.
>
> The e²® – PCGs from Jenoptik are the right solution to enhance your laser performances. Besides **high diffraction efficiency, low wavefront error,** high laser induced damage threshold, the e²® – PCGs are protected against external mechanical damages and dusty due to the fact that the grating structure itself is embedded.
>
> The Jenoptik PCGs are custom designed and fabricated into high-purity fused silica guaranteeing **high laser damage threshold** and thermal stability.[110]

Fields of Application include laser material processing, pulse compression/stretcher in ultrafast laser system and laser systems for wavelength selection, tuning and bandwidth narrowing of high-power lasers. The **Benefits** of these gratings include their high efficiency with a maximum close to 100%, flexible to customer design and application needs, high line densities enable compact product design and high pulse compression, and durability from the encapsulated fused silica grating with both sides dielectric AR coating system.[111]

4.2.3 Knight Optical

Knight Optical, founded in 1991, produces and distributes scientific optical components and is located in the UK, and opened a US office in North Kingstown, Rhode Island in 2015. According to LinkedIn, Knight Optical has between 11-50 employees.[112] Knight Optical serves customers in industries such as defense, medical, optoelectronics, entertainment, education, laser, and engineering and manufacturing.[113] The company has received contracts from NASA for germanium-doped optical glass windows for infrared cameras, and from the Naval Sea Systems Command for bandpass filters and longpass filters integrated into closed-circuit TV camera boxes.[114] Information on their custom diffraction gratings is included in the following section.

Custom Diffraction Gratings

Knight Optical's custom diffraction gratings come in three grades, with both ruled and holographic gratings, line spacings down to 1μm and can be tailored to any requirement. These diffraction gratings are used in devices like monochromators and spectrometers, and other applications where isolating wavelengths of light is a part of the process. The holographic diffraction gratings that Knight provides are engineered to minimize the amount of stray light and are available with closer ruling spacings. Blazed holographic gratings can provide a comparable profile and efficiency to ruled gratings and are especially suited for UV wavelength applications. Part of the commercial range includes custom transmission gratings which include cost-effective transmission replicas mounted between glass plates. Knight has state-of-the-art metrology facilities that ensure each component is tested and adheres to high quality standards. Knight Optical offers reflective diffraction gratings, laser diffraction gratings, holographic diffraction gratings, and 2D gratings.[115]

Laser Technology

Knight Optical provides their optical components for laser optics used in laser technology. As the change in the way processes are performed in laser technology, Knight has kept up with investment into developing laser optic solutions, such as laser mirrors that can provide the necessary technology to support new laser applications. Knight Optical can meet the requirements of the necessary precision specifications to ensure the laser optical components are able to be used in demanding systems. These systems and applications include:

- LiDAR and laser scanning
- Laser ranging
- Spectroscopy and microscopy
- Laser guidance
- Laser sights
- Laser surgery
- Laser cutting, marking, and engraving
- Laser welding[116]

Knight's laser optical components include ultrafast laser mirrors with a low group delay dispersion (GDD) and high laser damage threshold (LDT), as well as custom laser components which can be tailored to customers' specifications including lenses, beamsplitters, wavelength separators, and filters.[117] The following is a sampling of Knight Optical's precision optics products.

4.2.4 NIL Technology

NIL Technology, founded in 2006 and located in Denmark, provides optical solutions by designing, developing, and manufacturing optical components using high-precision nanoscale features. The company has between 50-200 employees.[118] NIL combines meta-optics with diffractive and refractive optics which results in an optical design for next-generation sensing and imaging applications.[119] The following section contains more details on NIL's diffraction grating offerings.

Gratings

NIL provides services to their customers including design, fabrication, and replication processes for precision gratings. Diffraction gratings such as dot gratings, blazed gratings, and slanted gratings with extremely precise accuracy and uniformity are grating products that NIL provides to their customers and be customized to optical application needs. Some of the competencies that NIL offers for their diffraction gratings include high accuracy, excellent uniformity, high diffraction efficiency, and customizable key parameters of gratings.[120]

Use of Custom Diffraction Gratings

NIL Technology provides custom made diffraction gratings for which the parameters can be specified based on application. NIL's diffraction gratings include both binary line gratings, blazed, and slanted gratings.[121]

Blazed Gratings

NIL specializes in high-precision nanoscale features and optical structures. The company has many relationships with high-tech companies that use gratings for research & development, and innovative new products. All the blazed parameters can be varied according to customer needs, the anti-blaze can be 90 degrees or above/below, gratings are extremely accurate and have excellent uniformity.[122]

4.2.5 Zeiss

Zeiss was founded in 1846 and is headquartered in Germany and operates in the areas of optics and optoelectronics. The company has over 32,000 employees globally across their subsidiaries including Carl Zeiss Microscopy (US), Carl Zeiss Canada, Carl Zeiss Microscopy GmbH (Germany), Carl Zeiss Microscopy Limited (UK), and Carl Zeiss (Shanghai).[123] Zeiss has an annual revenue of 10 billion euros, the first in the company's history, in fiscal year 2022-2023.[124]

Zeiss in the US

Zeiss has had a North American presence since 1925 and accounts for 1.4 billion euros in revenue which is the largest market globally for Zeiss. The US employees number 4,000 across 20 locations.[125] Government customers of Zeiss' products include the Department of Health and Human Services, Department of Defense, Department of Agriculture, Department of Energy, and Department of Commerce.[126]

Optical Gratings

Zeiss optical gratings offer high performance, precision, and aberration correction for analytical devices. The optical gratings include plane gratings, Rowland circle gratings, Mono and Polychromator gratings, Grisms, Offner gratings, and Laser gratings.[127]

Laser Gratings

Zeiss offers homogeneous pulse compression gratings with high laser-induced damage threshold and variable groove densities. They also offer standard laser gratings for wavelength selection in modern laser systems. The benefits of Zeiss' laser gratings include high diffraction efficiency, transmission and reflection, low stray light, and choice of substrates. The gratings can be manufactured up to a size of 240 x 240 mm and available for spectral ranges between 400 nm and 2 µm. The gratings use monolithic fused silica, with high LIDT, low wavefront aberration, and can be standard or customized. Additionally, Zeiss offers replicated and coating gratings for wavelength tuning in low-mid power lasers for WDM and DWDM applications.[128]

4.2.6 Shimadzu

Shimadzu, located in Kyoto, Japan, has a US presence in Columbia, Maryland, as Shimadzu Scientific Instruments.[129] The company was established in 1875 and was formed as a limited company in 1917. Shimadzu offers solutions in human health, safety and security, and industrial development. One of their product areas is optical devices, including **diffraction gratings**, spherical/aspherical mirrors, special lenses and polarizers, and optical instruments.[130] As of March 2024, Shimadzu employees 14,219 people and their consolidated net sales for FY2023 were ¥511,895 million.[131] Shimadzu's US arm, Shimadzu Scientific Instruments has received contracts from the Department of Health and Human Services, the University of Texas Arlington, and the University of Rhode Island.

Diffraction Gratings

Shimadzu offers Concave Gratings, Plane Gratings, and Laminar Gratings for Soft X-ray Region. Their diffraction gratings for laser systems LA series (pictured below) have high diffraction efficiency, wide wavelength coverage, wide selection, and are customizable. These gratings are used for various laser applications such as external resonator, external cavity, and pulse control. The nine products in the LA series are customizable for laser resistance, substrate, size and other requirements.[132]

5.0 Summary and Conclusions

As noted in the introduction, the 2023 *Report of the Basic Research Needs Workshop on Laser Technology* called out the need for high-efficiency diffraction gratings. High-performance diffraction gratings are used in a number of scientific research areas, including ultrafast and high-power lasers, space flight instruments and astronomy, and synchrotron, free electron laser (FEL), EUV (extreme ultraviolent), or soft X-ray applications.[133]

This is a highly specialized field with relatively few companies having the capability to provide the required performance. As many of the existing companies appear to have their roots in academia, the first section of this report provided insight into the work currently accomplished in U.S. universities with a specialty in optics. After introducing the available data on the global market for diffraction gratings, a number of key players were introduced. Interested parties are encouraged to review the extensive end notes and explore the various approaches being undertaken to meet the new performance challenges.

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