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High-Average-Power Diffraction Pulse-Compression Gratings Enabling Next-Generation Ultrafast Laser Systems

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Abstract

Pulse compressors for ultrafast lasers have been identified as a technology gap in the push towards high peak power systems with high average powers for industrial and scientific applications. Gratings for ultrashort (sub-150fs) pulse compressors are metallic and can absorb a significant percentage of laser energy resulting in up to 40% loss as well as thermal issues which degrade on-target performance. We have developed a next generation gold grating technology which we have scaled to the petawatt-size. This resulted in improvements in efficiency, uniformity and processing as compared to previous substrate etched gratings for high average power. This new design has a deposited dielectric material for the grating ridge rather than etching directly into the glass substrate. It has been observed that average powers as low as 1W in a compressor can cause distortions in the on-target beam. We have developed and tested a method of actively cooling diffraction gratings which, in the case of gold gratings, can support a petawatt peak power laser with up to 600W average power. We demonstrated thermo-mechanical modeling of a grating in its use environment and benchmarked with experimental measurement. Multilayer dielectric (MLD) gratings are not yet used for these high peak power, ultrashort pulse durations due to their design challenges. We have designed and fabricated broad bandwidth, low dispersion MLD gratings suitable for delivering 30 fs pulses at high average power. This new grating design requires the use of a novel Out Of Plane (OOP) compressor, which we have modeled, designed, built and tested. This prototype compressor yielded a transmission of 90% for a pulse with 45 nm bandwidth, and free of spatial and angular chirp. In order to evaluate gratings and compressors built in this project we have commissioned a joule-class ultrafast Ti:Sapphire laser system. Combining the grating cooling and MLD technologies developed here could enable petawatt laser systems to operate at 50kW average power.

Background and Research Objectives

Since 1996 LLNL has been a world leader in the design, development, and fabrication of meter-scale diffraction gratings for femtosecond laser systems. In fact most energetic, ultrahigh irradiance ($\geq 10^{20}$W/cm^2) laser systems world-wide rely on LLNL's technology. The gratings are key to achieve highest laser irradiance and are used in the short pulse compressor in a scheme referred to as chirped pulse amplification (CPA). Existing petawatt CPA systems typically operate in the single-shot regime. Nevertheless, there is growing interest and investment in new high intensity laser capabilities for industrial and discovery science requiring high repetition rate laser driven, high brilliance, secondary sources and applications as shown in Figure 1 [1-3]. The main challenge to operate at high average power (>100W) is thermal management in the laser amplifiers and the control and mitigation of thermally induced distortions in the diffractive pulse compression gratings [4]. We have designed, developed and demonstrated new diffraction gratings and compressors capable of operating at 1-50 kW average power (a 100-5000x increase over current technology). During this project we successfully completed all 5 related objectives. Objective 1: Develop and engineer the process for fabricating broadband, metallic gratings capable of operating at 300W average power. This was completed with higher uniformity than expected and tested up to 600W power. Objective 2: Understand the impact on short pulse laser performance of deposited heat in large area gratings and implement active heat removal. This was successfully done with computational modeling and experimental benchmarking. Objective 3: Design and develop high-average power, high-efficiency, multi-layer-dielectric, diffraction gratings supporting 30fs pulses or better. This was completed with the simulation, design and fabrication of MLD gratings up to 100mm. Objective 4: Explore and develop a non-planar pulse compressor design utilizing multi-layer-dielectric (MLD) gratings. This was completed with modeling, design, construction and characterization of a novel compressor architecture. Objective 5: Build a short pulse test laser delivering 300mJ at 10Hz and capable of scaling to 100Hz repetition rate for testing above gratings. This was completed from the commissioning of an ultrafast Ti:Sapphire laser system.

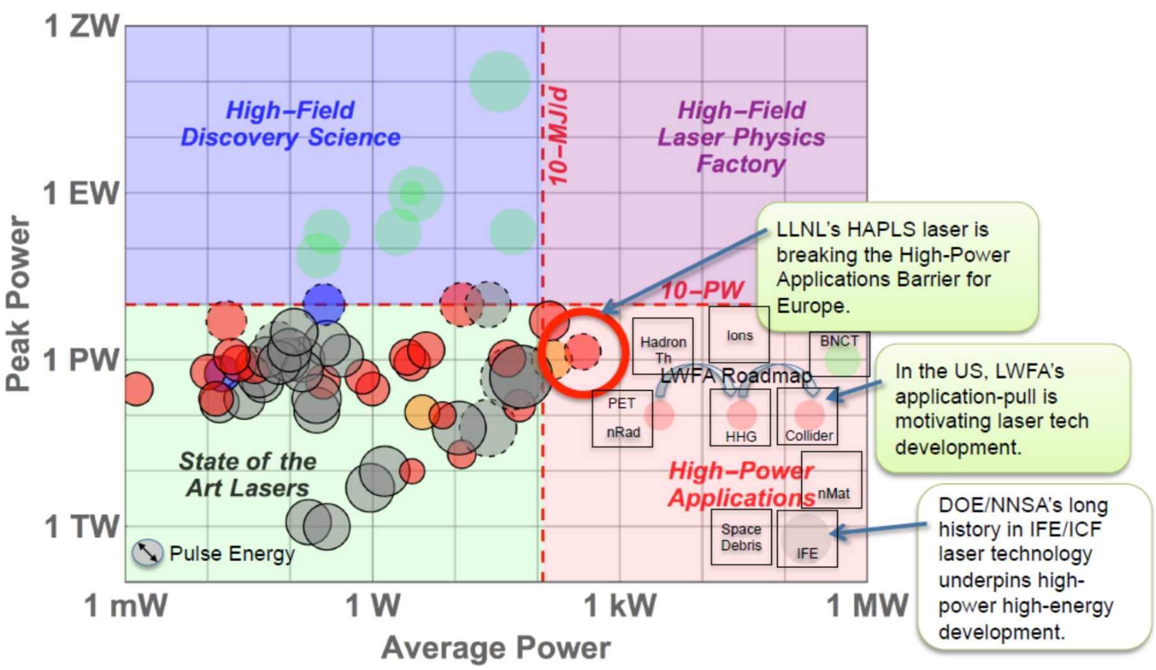

Fig 1: Laser systems (circles) and high power applications (squares).

Scientific Approach and Accomplishments

1. Develop an advanced process for gold metallic gratings

Gratings for sub-150fs pulse compressors have typically been fabricated with gold coated photoresist ridges [5]. It has been recognized that the plastic photoresist layer may be responsible for reduced performance and lifetime and problematic for HAP applications. As a result, gratings have also been fabricated by etching directly into the grating substrate to form ridges then overcoating with gold, eliminating the photoresist at the cost of a non-ideal groove shape. In this project we have produced a new class of gold coated gratings for high average power operation and demonstrated scaling to the petawatt size [6]. This fabrication process includes (1) depositing a layer of material to function as an etch stop and release layer onto a substrate, (2) Depositing a dielectric layer to become the grating ridge material, (3) holographic exposure of a photoresist layer deposited onto the dielectric, (4) refractory etching into the dielectric layer to form grating ridges, (5) stripping all remaining photoresist, and (5) gold overcoating. This process produces an engineered sidewall taper (Figure 2a) of the grating ridges that has improved diffraction efficiency when compared to substrate etched gratings.

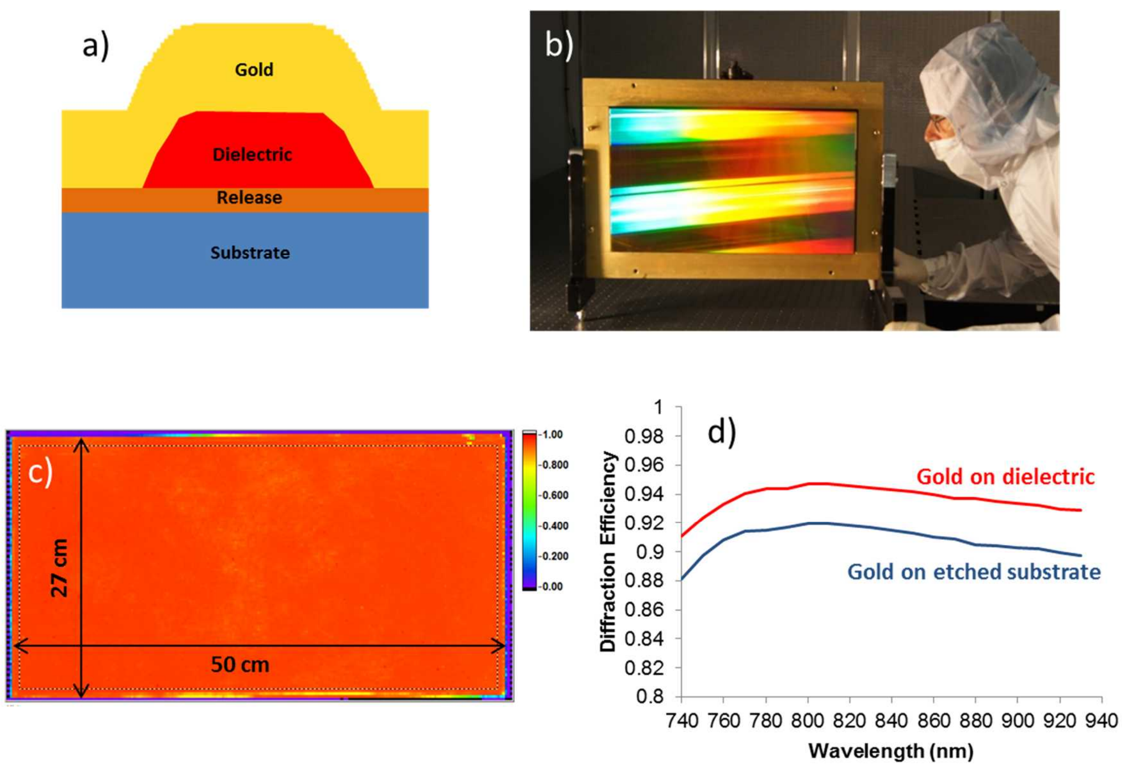

Fig. 2: (a) Diagram of the gold-on-dielectric grating components. (b) Photo, (c) efficiency vs. position, and (d) efficiency vs wavelength of a 50cmx27cm gold-on-dielectric grating fabricated in year 1.

Figure 2b and 2c show a 50cmx27cm gold-coated dielectric grating fabricated using the above process and a spatial map of the diffraction efficiency. The efficiency

(94.3%) is near the theoretical limit and the excellent uniformity (0.6%) is due to the well-controlled dielectric ridge height from the deposition process. The diffraction efficiency (Figure 2d) is 3% higher than the glass etched grating corresponding to 13% higher compressor efficiency. The re-processing of substrate etched gratings can be costly due to the fact that the re-polishing of very large (~1m) substrates may be required. Because our design includes a grating release layer, the gold and grating ridges can be chemically stripped, leaving the substrate intact. This can significantly reduce fabrication costs. We also demonstrated the re-processing process on the petawatt-size grating.

2. Develop active cooling to remove residual heat from diffraction gratings

Finite Element Analyses using ANSYS Workbench 17.0 were carried out to simulate the thermo-mechanical evolution of a single petawatt-class diffraction grating of a compressor under use conditions. Further details are described in [7]. To remove heat bars are attached to the top and bottom grating surfaces and held at a constant temperature. The grating substrate is corning Corning ULE glass [8]. The simulated steady-state surface temperature (Figure 3a) and surface height deviation (Figure 3b) are shown for an actively cooled grating for a 40J laser operating at 10Hz. The total absorbed power is 14W, which corresponds to 3.5% of the laser average power. Under these conditions the temperature varies by 14C across the entire grating surface and the surface deviation, from flat, has a 47nm peak to valley (PV) across the beam aperture, which is on the order of the manufactured surface figure for a substrate of this size. We examined the limits of this cooling technique by running simulations with varying absorbed laser power. Figure 3c shows the surface PV across the beam aperture vs absorbed power for a single grating with different substrates and with an without cooling. The limits are summarized in table 1.

Substrate material	Max. power absorbed (W)	Max. laser power for gold (W)	Max. laser power for MLD (W)
BK7 (uncooled)	0.04	1.2	142
ULE (uncooled)	4.7	130	16,000
ULE (cooled)	21	610	71,000

Table 1: Average power limits for various compressor technologies

An experiment to measure the surface deformation of a petawatt-size grating irradiated by 600W of laser average power was carried out in an air environment in order to demonstrate active cooling and benchmark the simulations. The grating surface normal reflected wavefront distortion was measured at different times up to 1 hour. The cooling bars were held to a constant temperature throughout the experiment via chilled water circulation. The peak deflection of the measured and simulated grating surface height is plotted as a function of time in Figure 3d.

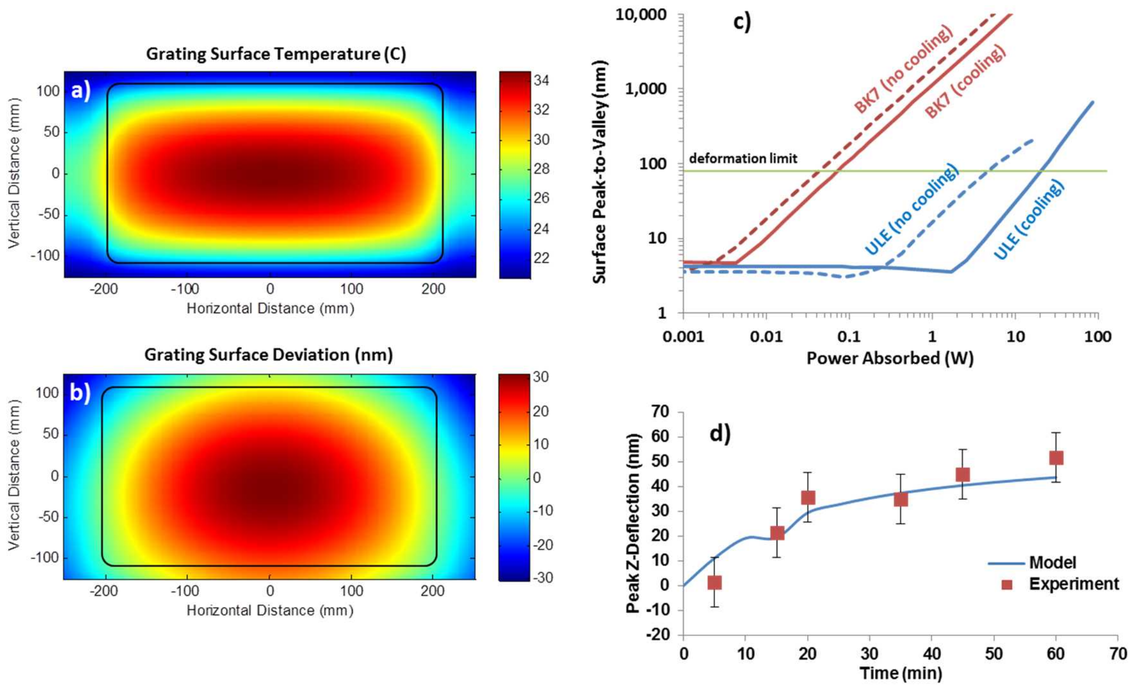

Fig 3: (a) Temperature, and (b) surface deviation from thermo-mechanical modeling of a grating exposed to a 400W average power petawatt laser. (c) Grating surface PV vs absorbed power for different grating tehchnologies. (d) Experimental and simulation results of a grating active cooling demonstration.

3. Develop efficient, non-planar MLD gratings for short pulse compression

The fabrication of MLD gratings suitable for lasers with sub-150fs pulse durations has been challenging [9]. There has not been a grating produced that simultaneously meets all of the desired design requirements: high efficiency, broad bandwidth, high damage resistance, low dispersion, and resonance free. Simply designing a multilayer stack with the top layer having the optimized 1480l/mm groove structure results in the green diffraction efficiency curve in Figure 4a. Spikes in the efficiency curve are due to guided mode resonances where very narrow bands of light are coupled by grating diffraction into specific regions of the stack which then behave like a planar waveguide. This can reduce damage performance as it can increase the electric field within the high index material in the stack. In order to understand these resonances we performed rigorous electromagnetic field modeling within a MLD grating using LightTrans Virtual Lab [10] with the Grating Toolbox. Using this information, we developed a modified MLD grating design (red curve) with suppressed resonances. Several of these gratings were made up to the 100mm square apertures, and subsequently cut to the 50x100 mm size. The grating top layer was fabricated in-house while the multilayer coating was fabricated by an offsite vendor. The fabricated efficiency curve is shown in blue (Figure 4a), and an efficiency map is shown in Figure 4b with a mean of 98.2% and uniformity of 0.1%. Laser induced damage testing of these gratings was performed using the fluence ramping method with the laser system developed in section 5. Initial damage testing for use conditions with 80fs pulses showed a 50% damage probability of 0.3J/cm^2, which was 30% lower than corresponding gold gratings at the same test conditions. For the stretched pulse duration (440ps), the 50% damage probability was 5.8J/cm^2, which was more than 4x the value of gold grating at these conditions.

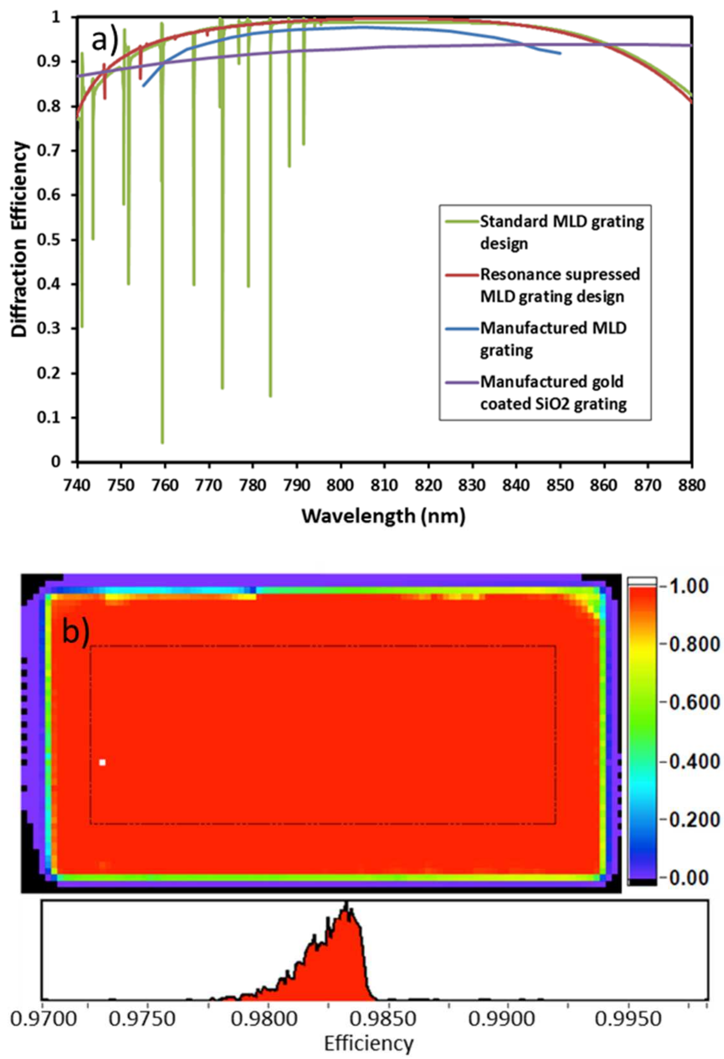

Fig 4: (a) Diffraction efficiency vs wavelength for MLD and gold gratings. (d) Diffraction efficiency map of fabricated 50mmx100mm MLD grating.

4. Design a high efficiency non-planar MLD grating compressor

The strong dependence of efficiency on the input angle (Figure 5a) requires the use of these MLD gratings at Littrow angle. In order to separate the input and output beams in a compressor we adjusted the input beam to be at Littrow but a few degrees OOP. To understand the performance of this novel compressor geometry we first derived an analytical form for the dispersion of a pulse compressor with an arbitrary input beam. We then developed raytrace models in FRED [11] of OOP compressors to compare with the dispersion from our analytical model and also evaluate the spatial/temporal coupling effects. During this process we discovered that a compressor with 4 separate gratings (Figure 5a) would be required because the standard 2 grating compressor with a roof mirror would have a residual spatial chirp in the OOP configuration. A 4 grating compressor operating at Littrow and 4° OOP was built and performance tested initially with gold gratings [12]. FROG measurements of pulses from a Ti:sapphire system compressed in this OOP compressor were performed and the resulting group delay is shown in Figure 5d in good agreement with the analytical model. The large residual group delay (mostly 3rd order) is due to the fact that the system is not optimized for this compressor design. This data indicates that 30fs pulses could be achieved by changing the stretcher design or using a dispersion corrector in the system. After fabrication, the MLD gratings from section 3 were installed in the same OOP compressor resulting in similar performance to the gold gratings. The total compressor efficiency with the MLD gratings was (Figure 5c) 90% for a pulse with 45nm of bandwidth. This is a 20-50% improvement over the efficiencies of gold grating compressors which are typically 60-75% efficient.

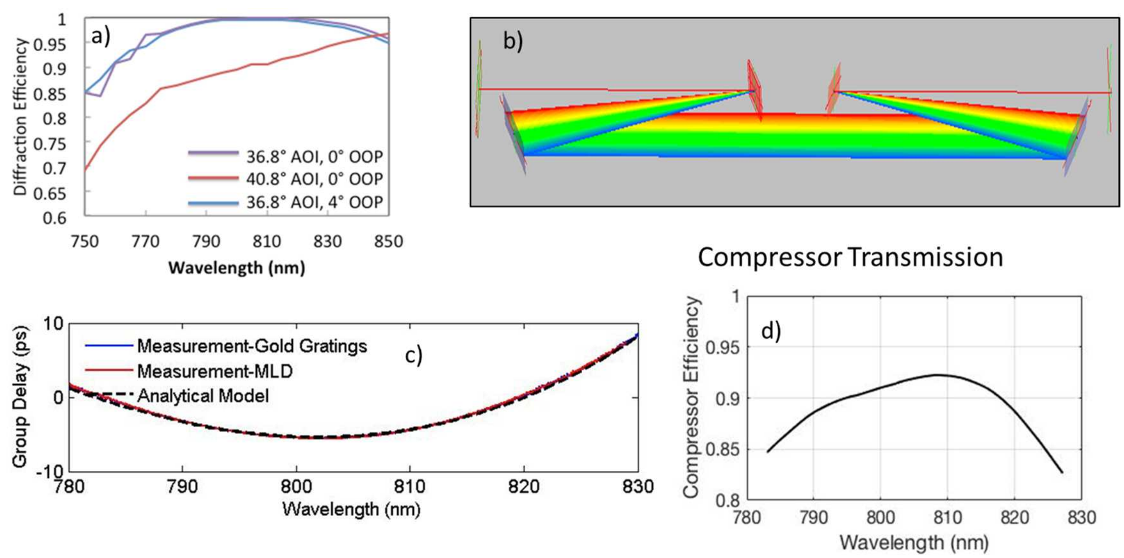

Fig 5: (a) Diffraction efficiency of a MLD grating with different angles of incidence. (b) Raytrace model of a 4 grating compressor with 4deg OOP. (c) Measured and calculated group delay from a compressed broadband laser pulse. (d) Measured compressor efficiency vs. wavelength.

5. Design and build the test laser system

A Ti:sapphire laser system was commissioned with mostly existing equipment for testing gratings and compressors developed in this project. The system is seeded with a femtolasers Synergy pro oscillator producing 8fs pulses at 80MHz repetition rate and 4nJ. These pulses are stretched to 1.5ns in an Offner-style stretcher. After the stretcher, pulses are sampled to 10Hz and directed through acousto-optical programmable dispersion filter. The pulses are amplified to 1mJ in a multipass amplifier resuling in a

Gaussian shaped spectrum with ~45nm FWHM bandwidth. Pulses are amplified up to 300-500mJ in an 8-pass power amplifier. Both amplifier stages are pumped by a single a 2J frequency doubled Nd:YAG laser operating at 10Hz. A traditional in-plane compressor and an OOP compressor built in section 4 are both in air-environment and used to compress pulses with reduced energy (<20mJ). The beam can be sent to a laser damage test station for measuring laser induced damage performance of optics developed in this project.

Impact on Mission

This project has significantly added to the work-for-others portfolio of the NIF Advanced Optical Technologies Program and is aligned under the newly formed NIF Advanced Photon Technologies division. New capabilities developed are next generation gold gratings up to petawatt-size, an active cooling technique, broadband MLD gratings, a novel compressor design (OOP), a high energy broad-bandwidth Ti:sapphire laser system, and a high average power test capability utilizing laser diodes. This work has directly impacted projects such as HAPLS and both the ELI L3 and L4 beamlines. The laser system is now a short pulse test lab under the Optical Materials Science and Technolgy division at NIF. The MLD grating work here has potential to impact the ARC project by leading to higher LIDT gratings. This project funded a significant portion of 2 postdocs, both of which transitioned to staff during the project.

Conclusion

During the course of this project we have: (1) Developed a new class of gold gratings, scaled to PW size and fabricated gratings for customers. (2) Examined average power limits and developed active cooling to enable high average power high energy ultrafast laser systems. (3) Designed and fabricated broadband, efficient, low absorption MLD gratings. (4) Designed novel out-of-plane (OOP) compressor that is free of spatial/temporal couplings, having >90% efficiency for 30 fs pulses, and (5) commissioned a ~joule-class ultrafast laser system which is a unique capability within the laboratory. The next steps are to design a laser system with an OOP compressor, design retrofitting capabilities for installing OOP compressor on existing system, scale MLD gratings to large area, measure MLD grating absorption, improve MLD grating damage threshold, and investigate different substrate materials and grating cooling methods.

References

[1] icuil.org
[2] str.llnl.gov/january-2014/haefner
[3] www.eli-beams.eu
[4] S. Fourmaux, C. Serbanescu, L. Lecherbourg, S. Payeur, F. Martin, and J. C. Kieffer (2009), "Investigation of the thermally induced laser beam distortion associated with vacuum compressor gratings in high energy and high average power femtosecond laser systems," Opt. Express, **17**, 178.
[5] J. A. Britten, M. D. Perry, B.W. Shore, and R. D. Boyd (1996), "Universal grating design

for pulse stretching and compression in the 800–1100-nm range," Opt. Lett. **21**, 540.
[6] J. A. Britten, D. A. Alessi, and L. C. Haefner (2014), "A new class of metal diffraction gratings tuned for maximum efficiency and bandwidth for the next generation high intensity petawatt lasers," Proc. International Conference on Ultrahigh Intensity Lasers (ICUIL), October 12-17.
[7] D. A. Alessi, P. A. Rosso, H. T. Nguyen, M. D. Aasen, J. A. Britten and C. Haefner "Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers," Optics Express (submitted)
[8] Datasheet for Corning ULE 7972 (August 16, 2006) obtained from www.corning.com
[9] N. Bonod and J. Neauport (2016), "Diffraction gratings: from principles to applications in high-intensity lasers." Advances in Opt. and Photon. **8**, 1.
[10] www.lighttrans.com
[11] www.photonengr.com/software/
[12] E. Sistrunk, D. Alessi, H. Nguyen, J. Britten and C. Haefner (2016), "Broadband Multilayer Dielectric Gratings and Compressor for High Efficiency Compression of Ultrashort Pulses," Proc. International Conference on Ultrahigh Intensity Lasers (ICUIL), September 11-16.