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Designing Damage-Resistant Multilayer Dielectric Gratings for Petawatt-Class Lasers

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FULL TECHNICAL REPORT

Designing Damage-Resistant Multilayer Dielectric Gratings for Petawatt-Class Lasers

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Abstract

We have successfully developed high efficiency dielectric gratings for chirped pulse amplification (CPA) pulse compression with a focus on improving damage thresholds for high peak power. Specifically, we focused on developing first-of-kind designs that operate at TM polarization. Unpublished modeling within our group shows that the electric field enhancement in the solid material for gratings operating at TM can be significantly less than for TE. Subsequently, the laser damage threshold of TM gratings should be higher by potentially a factor of 2X.

Background and Research Objectives

The critical components in all ultrafast laser systems are the diffraction gratings used to compress the pulse back to its transform limit. Overall, pulse compression gratings need to exhibit high efficiencies, to induce low wavefront distortions and to sustain high fluences.

Laser induced damage to dielectric optical elements is sensitive to surface properties and to the presence of structural imperfections that can enhance the electric field. In the theory, coupling of radiation energy into the material (and ultimately damage) occurs through the local electric field. It is the instantaneous local value of the electric field that drives damage. In the MLD grating, a complicated distribution of electric field occurs for an incident plane wave. The constructive interference that is responsible for the diffractive behavior of a grating or the reflective properties of a MLD stack can enhance the electric field above values that would occur in unstructured homogeneous material. In particular, local "hot spots" in the grating profile can increase the intrinsic susceptibility to damage. We have calculated the occurrence of such "hot spots" for practical grating designs and have seen how their location is affected by design parameters.

The concept of all-dielectric gratings to increase the resistance to laser damage threshold (LDT) was first proposed in 1991 and 1994 by Svakhin et al. considering a diffraction grating on top of an optical resonator [1, 2]. The first objective was to increase the resistance of the grating to the optical pulses by designing an all-dielectric grating. Often the fluence and power density limitations of the final compressor grating sets the energy, power, and beam size of the entire system.

There have been substantial efforts aimed at optimizing the grating profiles to minimize the electric-field enhancements to increase the laser damage performance of the MLD pulse compression gratings. Bonod and Neauport calculated in [3] the diffracted efficiencies and field intensity enhancements for a grating etched in silica for different grooves when considering a trapezoidal profile. The calculations showed that, among all the profiles offering reflected efficiencies in the −1st order, the electric field intensity in the grating pillars (made of silica) was experiencing an important drop when maximizing the groove width. They reported a drop of the maximum field intensity from 2.5X to 1.15X by simply increasing the groove width while considering a constant period. The importance of the groove shape was also highlighted a few months later by Liu et al. in the case of lamellar MLD gratings [4]. These numerical results were followed in 2007 by experimental investigations that aimed at quantifying the role of the grating profile on the final LIDT. The results show a linear dependence between the LDT and $1/|E^2|$. Unfortunately, the required precision control of the grating profiles to reduce the field intensity enhancements does not allow for a manufacturable process.

Prior to this LDRD effort, no work has been conducted at optimizing the incident polarization on the grating to minimize the electric-field enhancements to increase the laser damage performance. Consequently, all MLD CPA pulse compressions gratings are designed for TE polarization. Preliminary modeling indicates that the electric-field enhancements are reduced by 2X-3X for TM versus TE polarization. Furthermore, LDT testing of a polarization insensitive MLD gratings (measured >95% diffraction efficiency for both TM and TE polarization) developed for spectral beam combining (SBC) for DoD programs, shows up to a 2X higher LDT for TM versus TE polarization.

Scientific Approach and Accomplishments

Our efforts focused on 1) Modeling studies to explore the feasibility of a manufacture-able design for a high efficiency dielectric grating for CPA pulse compression for use with TM polarization. A successful design would allow for the fabrication of meter-scale grating optics, and 2) the fabrication of both TM and TE gratings optics utilizing identical processes (multilayer dielectric material composition, coating deposition, grating fraction processes, etc.) for apples-to-apples comparison.

We have successfully developed a first-of-kind high efficiency dielectric grating design for TM polarization. We believe the design is readily manufacturable utilizing current inhouse capabilities for optic sizes up to 5-inch in diameter. Gratings with a groove density of 1160 lines/mm were selected as a compromise between high dispersion and moderate Littrow angle. For a wavelength of λ=1.60μm this groove density results in a Littrow angle of 37°. The MLD grating design criteria seeks to minimize the electric field existing in the solid grating material and the underlying multilayers, while at the same time maximizing the efficiency. 18-layer pairs of alternating HfO_2/SiO_2 (high-low) indexes mirror stacks are deposited on the substrate. On top of the mirror, a solid SiO_2 layer was deposited, which was etched into for the fabrication of the grating structure.

The key design criteria for these gratings is a design which is free of guided mode resonances which cause narrow and deep dips in the diffraction efficiency and are suspected to reduce laser damage performance. We designed the grating by using a computer code based on rigorous coupled-wave analysis (RCWA). The choice of the number of layer pairs of the MLD mirror stack was made as a compromise between having a sufficiently high reflectance over the desired wavelength range, high LIDTs, and assuring good stability of the thin-film stack. The grating is required to operate at the Littrow angle due to the sensitivity of the bandwidth with AOI. Figure 1 shows the modeled diffraction efficiency for both TM and TE polarized light as function of grating etched depth and grating duty cycle at Littrow conditions. The modeled diffraction efficiency indicates that the required grating grove profile to obtain high efficiency is significantly different for the TM polarization versus the TE Polarization. For TM polarization, the grating grooves are 1250nm to 1450nm tall and ~55% duty cycle, where for the TE polarization, the grating grooves are about half as, ~680nm tall, and a bit narrower, ~50% duty cycle. It's important to note that with our inhouse plasma etching capabilities, as the grating groove height increases, the duty cycle decreases due to increased side wall etching.

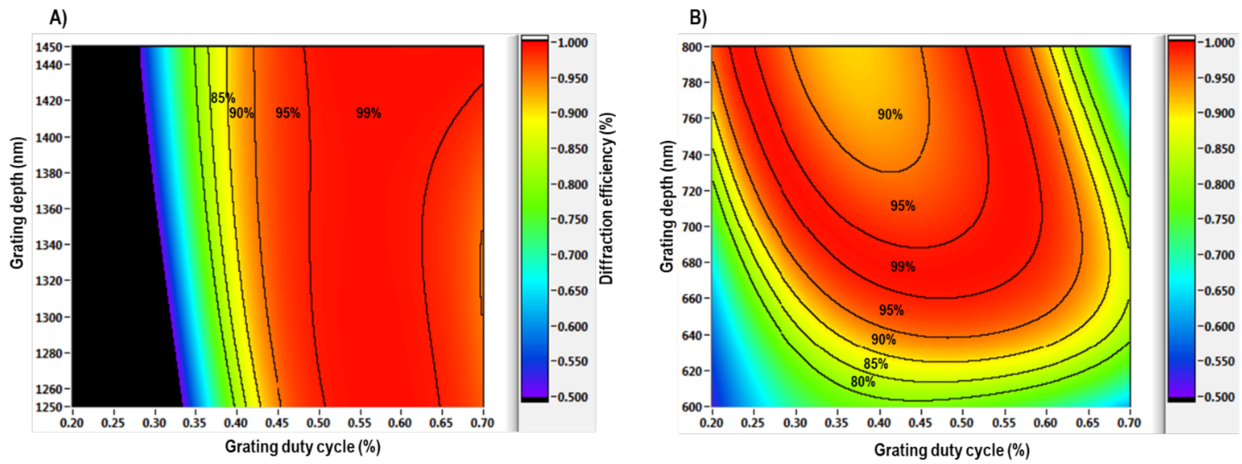

Figure 1. Modeled diffraction efficiency for both A) TM polarized light, and B) TE polarized light as function of grating etched depth and grating duty cycle at Littrow conditions.

Figure 2 shows that the modeled electric field enhancements characteristics for TM polarization are quite different to the TE polarized light at λ=1.60μm and Littrow conditions. The two main differences in the electric field enhancement for TM and TE polarizations are 1) for TM, the electric field runs up and down the grooves, while for TE, electric field runs perpendicular to the grating grooves, 2) the maximum electric field intensity within the grating groove is approximately 40% lower for TM versus TE polarization.

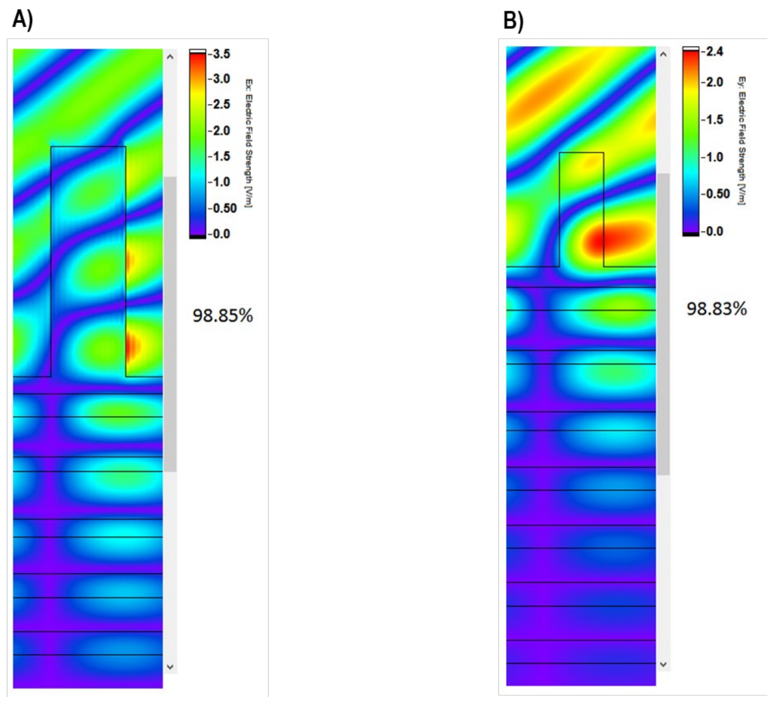

Figure 2. Modeled diffraction electric field enhancements for both A) TM polarized light, and B) TE polarized light at λ=1.60μm and Littrow conditions.

The gratings consist of an ion beam sputtered hafnia-silica multilayer mirror stack and a single corrugated top silica layer. The fabrication procedure of the grating etched into the top layer of the MLD stack consists of two basic steps: the lithographic generation of a grating in a resist layer by interference laser lithography and the transfer of this grating mask into the dielectric top layer by reactive ion beam etching using equipment that supports ~1-meter sized optics. For the work presented here, gratings were fabricated on 50.8 mm fused silica substrates. After grating structures are plasma etched into topmost layer of the multilayer stack, we utilize semiconductor-grade tetramethylammonium hydroxide solvent and sulfuric acid to remove the unused etch mask and as a final clean step.

Figure 3 shows measured diffraction efficiencies of some successfully fabricated 2-inch grating optics for both TM and TE polarization at the Littrow angle of incidence. The TE grating has a peak diffraction efficiency of 96.2% with a mean of 95.3%, while the TE grating has a peak diffraction efficiency of 98.7% with a mean of 98.2%. We attribute the higher efficiency of the TE grating to the fact that the shorter and narrower grating profiles are easier to fabricate. Additional process development is needed to improve the TM grating performance and to scale the aperture beyond 5-inches in diameter.

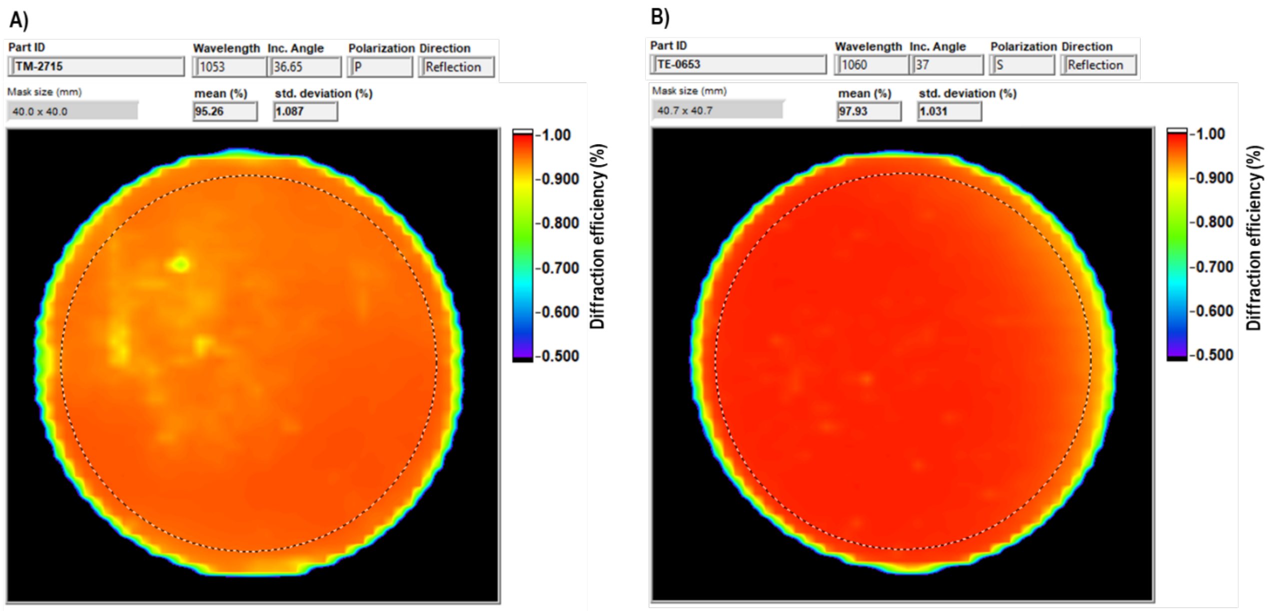

Figure 3. Measured diffraction efficiency for both for both A) TM and B) TE polarized 2-inch grating optics at the Littrow angle of incidence.

Mission Impact

The technique of chirped pulse amplification (CPA) has enabled the generation of Petawatt-class laser systems throughout the world. These laser systems today use meter-scale aperture, multi-layer dielectric (MLD) gratings to compress the final amplified chirped pulse. The realization of High-Energy Petawatt (HEPW) class laser systems, targeting laser pulses of greater >1000 J energy and pulse duration of <500 femtosecond time regime, has been hindered by the limitation of the laser damage threshold (LDT) of the MLD gratings. If successful, our novel TM grating optics could potentially allow 2X higher energy outputs.

Conclusion

Our feasibility study met and exceeded the proposed goals and objectives of determining whether a manufacturable design for a TM polarization, high efficiency, dielectric grating for CPA pulse compression is possible. We successfully developed high efficiency designs and fabricated 2-inch grating optics for both TM and TE polarization at the Littrow angle of incidence for apples-to-apples comparisons. The modeled electric field enhancements indicated that the maximum electric field intensity within the grating groove is approximately 40% lower for TM versus TE polarization, which should translate into 40% higher laser damage threshold for the TM grating optics.

Based on the results and findings of this study, it’s important to perform the additional follow-up efforts:

1. Compare the laser damage thresholds of the TM versus the TE gratings optics of the already fabricated grating optics – quantify if the modeled reduced electric field enhancements result increased laser damage thresholds.
2. Perform additional process development to increase the grating duty cycle for higher TM diffraction efficiency performance. The highest measured diffraction efficiency for TM polarized grating optic was 96.2% peak with a mean of 95.3%. Modeled diffraction efficiency for TM polarized grating are as high as 99%. We attribute the low efficiency results to the fact that our current fabrication process has difficulties producing grating profiles that are shorter and narrower than optimal.
3. Development to scale fabrication process for meter size optics aperture.

REFERENCES:

[1] A. Svakhin, V. Sychugov, A. Tikhomirov, and A. Mason, "Efficient diffraction elements for TE-polarized waves," Sov. Phys. Tech. Phys. 36, 1038–1040 (1991).

[2] A. S. Svakhin, V. A. Sychugov, and A. Tikhomirov, "Diffraction gratings with high optical strength for laser resonators," Quantum Electron. 24, 233–235 (1994).

[3] N. Bonod and J. Neauport, "Optical performance and laser induced damage threshold improvement of diffraction gratings used as compressors in ultra high intensity lasers," Opt. Commun. 260, 649–655 (2006).

[4] S. Liu, Z. Shen, W. Kong, J. Shen, Z. Deng, Y. Zhao, J. Shao, and Z. Fan, "Optimization of near-field optical field of multi-layer dielectric gratings for pulse compressor," Opt. Commun. 267, 50–57 (2006).