Gas and Plasma Final Optics for Inertial Fusion Energy Lasers

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Executive Summary

The transition from one-shot-per-day National Ignition Facility (NIF) experiments to the ~10 Hz operation likely required for an inertial fusion energy (IFE) facility poses substantial challenges for laser drivers. The target-facing final optics will be subject to significant x-ray, neutron, backscatter, and debris fluxes while delivering enormous per-pulse energy and average power to target. Here we discuss how a new type of optic—a transient gas or plasma volume grating produced by small secondary lasers—offers a solution for the final optical components of a high-repetition-rate IFE facility. These transmission optics are based on induced index of refraction modulation in a gas or plasma and can be used for beam steering and focusing. Critically, they are orders-of-magnitude more resistant to optical damage than glass, and, since they are reformed with each shot, are not affected by debris or radiation. As a secondary benefit, their short lifetime mean they act as fast optical shutters to protect upstream laser optics from all backscattering. Using plasma and gas gratings allows all solid-state optics to be removed from target line-of-sight, improving the resilience and lifetime of any future IFE facility. However, experimental demonstrations of these proposed optics, although promising, have only been carried out at the proof-of-principle level, and a substantial further effort will need to be made to demonstrate viability at scale.

Introduction

The demands that inertial fusion experiments place on their drivers have made NIF the largest laser facility in the world, including the large final optics that direct each beam to the target. A future IFE facility will need to provide more laser energy at a dramatically increased repetition rate, which poses two challenges: the optical components of these driving lasers must either be larger or more damage resistant to support higher energy and must be able to withstand many more shots before replacement. Since we can expect significant debris, x-ray, neutron, and backscatter fluxes from the target, protecting the final laser optics is a substantial challenge. Any effort to make a more compact laser for delivering IFE-relevant energies to target will also require a fundamental change in optics technology.

One potential approach to these challenges is the use of plasma optics: plasma-based analogues for standard optical components. Plasmas are fundamentally more resistant to optical damage and a plasma-based optic is generally orders of magnitude smaller than a solid-state equivalent that can handle the same energy or power. Plasma optics is a research area which has seen rapid progress in the past decade. Many new concepts have been invented and, in some cases, demonstrated in laboratory experiments, including plasma photonic crystals[1], waveplates and polarizers[2-4], diffractive lenses[5], frequency converters[6], fast and slow light in plasmas[7], or plasma gratings which are routinely used to tune the symmetry of ICF implosions on the NIF[8-10] or used for beam combiner designs and applications[11,12]. Another extremely promising area is the development of gas optics[13]: although these are not expected to reach the extreme fluence survivability of plasma-based concepts, they still raise the optics damage threshold by about two orders of magnitude compared to solids, which is already transformative. Gas optics, like plasma optics, also offer similar robustness to debris and radiation.

Here, we discuss a new concept for high-fluence-resistant gratings to be used as the final optics of an IFE facility, based on several possible plasma and gas mechanisms. These mechanisms rely on low-energy auxiliary lasers to imprint a grating structure in a gas volume; the grating can consist of a fully ionized plasma, a partially ionized gas (with plasma in the "grooves" of the grating and neutral gas between the grooves), or simply a non-ionized, neutral gas. The optical properties of the grating come from a modulated change in index of refraction produced by either a change of plasma density, a change in gas density, or alternating between plasma and gas. Plasma and gas optics offer several key advantages over the current state-of-the-art glass or solid optical elements used in high-power laser systems: (1) They are robust to debris, x-ray, and neutron fluxes and will not suffer damage when exposed to high-repetition rate high-gain shots. (2) A design based on these gratings allows all solid-state optics in the laser system to be removed from target line-of-sight, reducing potential damage for fixed components. (3) Gas or plasma gratings can be optically turned on and off, providing shutter-like protection of upstream optics and the laser itself from all backscattering. (4) Both plasma and gas have high optical damage thresholds, allowing substantially more compact final optic assemblies or significantly more energy in the same cross section. And finally (5), this type of grating naturally supports high-repetition rates (>10 Hz). A typical application for a beamline in an IFE facility might look like the schematic shown in Fig. 1, where the use of a plasma or gas grating keeps all the solid-state optical elements in shielded areas, with the driving laser steered around a debris shield.

However, neither gas nor plasma optics are currently sufficiently well developed to be used in a production system, with only a handful of completed proof-of-principle experiments. A substantial amount of work remains to determine whether and how these small-scale demonstration experiments can be scaled to ICF-relevant beam energy, which of several possible mechanisms offers the best performance, how to maximize the efficiency of the grating formation process, and what the actual damage thresholds for the components are. A general weakness of plasma optics, especially compared to conventional optics, is that they are difficult to control, and

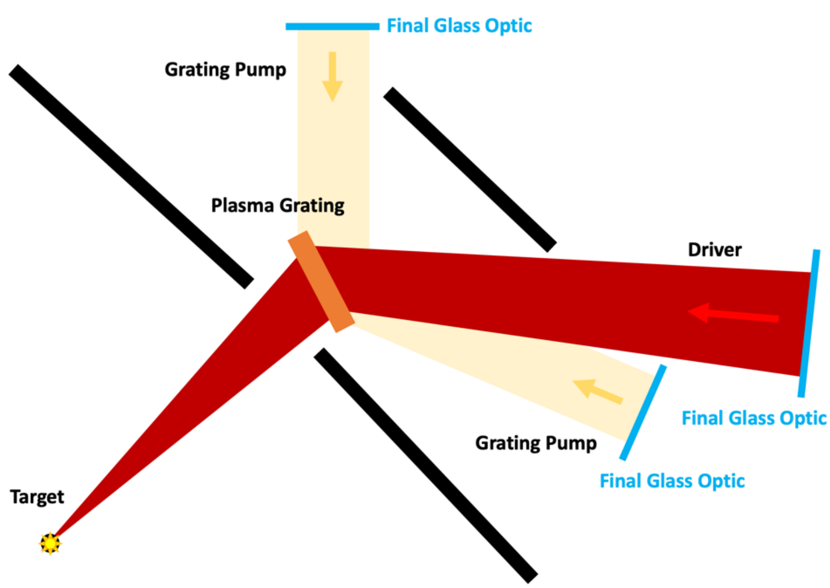

Figure 1: Scheme showing a plasma grating being used as the final optics in an IFE experiment. The plasma grating is in the target line of sight but can sustain the neutron and x-ray flux (and possibly the high fluence from the driver laser itself), while all the solid (glass) optics sit behind some shielding.

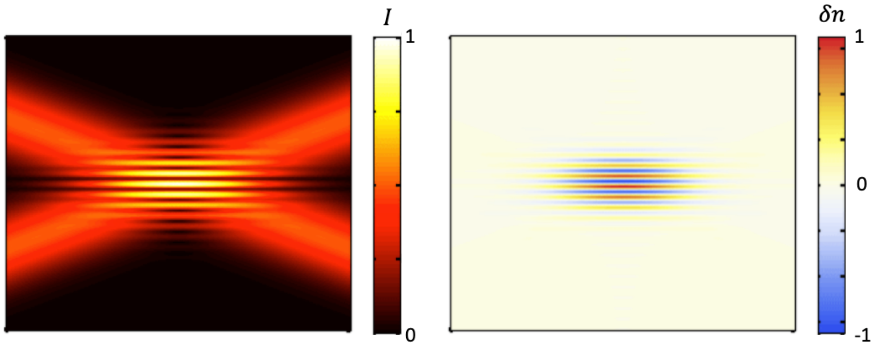

Figure 2: Illustration showing two crossing laser beams with their interference pattern (a) imprinting a refractive index modulation in a gas or plasma (b).

we must therefore make a substantial effort to both understand the underlying physics of their behavior and apply this understanding to build stable and reliable plasma devices. Although theory and computational approaches are important, a significant experimental push will be required to advance gas and plasma gratings from laboratory demonstrations to a reliable foundation for an IFE (or any other high-power laser) facility.

Physical Mechanisms for Plasma and Gas Optics

Plasma and gas gratings rely on the nonlinear response of a plasma or neutral gas to the intensity pattern of several overlapping lasers, allowing these lasers to create a refractive index modulation from their intensity interference pattern. The simplest example is that of a grating created by two lasers, as illustrated in Fig. 1. Once created, this grating can act as a Bragg mirror or grating for another laser beam incident at the Bragg angle. There are many nonlinear physical processes can in principle be exploited to create such a structured index modulation in a plasma, gas, or other material. For IFE applications, we focus on the schemes where the underlying medium has a significantly higher damage threshold than solid-state optics, either from optical damage from the laser itself or from the extreme x-ray and neutron flux from an IFE environment. Three mechanisms are of particular interest:

1. Index modulations generated by density modulation in a neutral gas[13];
2. Density modulations in a fully ionized plasma (e.g. plasma gratings used in ICF[9]);
3. Index modulations resulting from ionizing a neutral gas only in the brightest fringes[5,15].

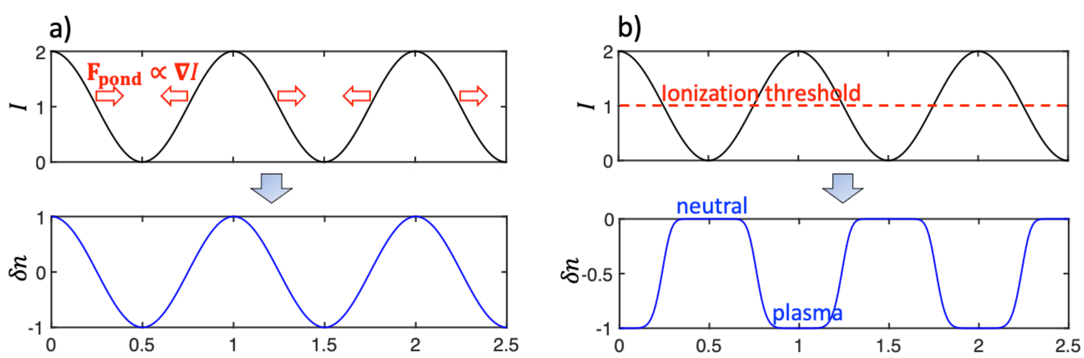

Figure 3: Illustration of two physical mechanisms behind the creation of an index modulation: a) via the ponderomotive force ("$\mathbf{F}_{pond}$") in a fully ionized plasma, which expells charged particles from high-intensity regions; b) from localized ionization, when the peak intensity of the interference pattern sits right above the ionization threshold.

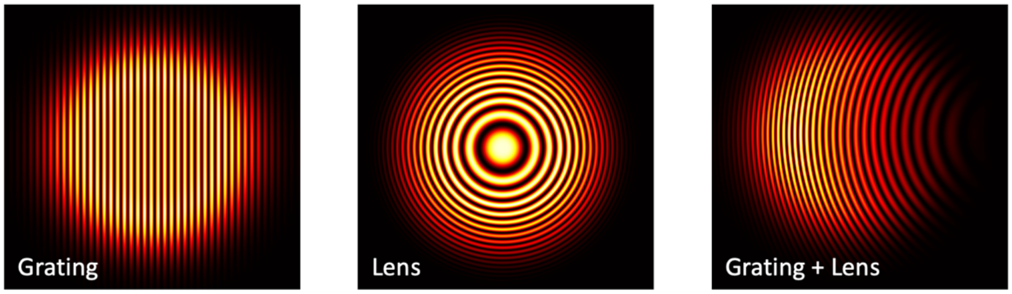

Figure 4: Examples of index modulations (i.e. pump lasers interference pattern) for a grating, a diffractive lens (i.e. a plasma-based Fresnel zone plate), and a focusing grating.

The second and third mechanisms are illustrated in Fig. 2. We propose investigating all three methods with theory, simulations, and experiments, focusing on their relative benefits and disadvantages as well as scalability to the IFE parameter space.

It is of course possible to extend this concept beyond gratings, which are essentially one-dimensional structures, and design two- or three-dimensional structures. One recently pertinent example is the diffractive plasma lens[5], created by two pump lasers with different focusing geometries, as opposed to two quasi-plane waves crossing at an angle for a grating. Following the same idea one can in principle design a focusing grating, as illustrated in Fig. 4, which may be useful for IFE applications in a geometry similar to Fig. 1.

Practical Considerations for the Design of a Plasma Optic

Several key properties govern the viability of a particular plasma or gas optic approach for a specific application. Here, we discuss values that current experimental results suggest different mechanisms can provide, as well as what is likely to be necessary for an IFE facility using gas or plasma optics.

Diffraction efficiency: A key parameter for assessing a grating – or any optic – is its efficiency; substantial losses due to inefficient diffraction will make a gas or plasma grating nonviable for IFE applications. However, despite the difficultly of working with plasma, experimental results here are promising. Gas gratings have been demonstrated that provide 95% diffraction efficiency[13]. Efficiency for fully ionized plasma gratings is estimated to be over 50% in many ICF experiments using significant crossed-beam energy transfer for symmetry tuning and in beam combiner experiments. Recent work has also shown efficiencies above 50% for ionization gratings[14].

Grating modulation strength: The strength of the refractive index modulation determines the optical path length inside the grating required for efficient diffraction: a stronger modulation allows a shorter grating. This then determines the spectral bandwidth that can be controlled. Index modulations of 10^{-2} for ionization gratings, 10^{-4} for plasma gratings, and 10^{-5} for gas gratings, all of which are sufficient for nanosecond ICF driving lasers.

Damage threshold: Ponderomotive gratings are likely to have the highest damage thresholds, above 10^{17} W/cm^2 for femtosecond and picosecond pulses, although likely longer for nanosecond pulses. Ionization gratings have short-pulse damage thresholds around 10^{14}-10^{15} W/cm^2, although again performance is unclear and likely to be lower for nanosecond pulses. Neutral gas gratings have been demonstrated with damage thresholds around 1 kJ/cm^2 for nanosecond pulses, orders-of-magnitude above the capability of glass optic.

Grating lifetime: Gratings in neutral ozone gas have standing-wave spatial structures that oscillate in time with periods of about 100 ns, making them particularly well-suited for manipulating long pulses, on the order of ns to tens of ns. Gratings in fully ionized plasma driven by the ponderomotive force (Fig. 2) can last for as long as the pump lasers are present to maintain them. Gratings based on localized ionization have lifetimes of tens to hundreds of picoseconds. While this, and the large index modulations possible, make ionization gratings more suitable for short-pulse manipulation, it may be possible for lifetimes to be extended to the nanosecond regime. Note, grating lifetimes no longer than the driving laser pulse is desirable for protecting the laser system from backscatter; for a target meters away from the grating, these mechanisms meet that metric.

Overall Efficiency: Here we mean the overall energy budget when including the laser energy required in the "pump" beams. Gas gratings can be created by UV beams with much lower energy than the beams being subsequently manipulated. It was estimated that the scheme from Ref. 13 would allow the control of a kJ laser of infrared or visible light using less than 50 mJ of energy for the pumps. Likewise, ionization gratings can be very efficient, requiring relatively modest energy in ultra-short (fs) laser beams to create index modulations that can last for tens or hundreds of picoseconds and manipulate lasers with much higher energies. Both schemes can be further optimized by selecting appropriate wavelengths for the pumps, to increase the absorption in the gas (for the gas grating) or ionization (for the ionization grating). Ponderomotive gratings can be very efficient for short (picosecond) durations by relying on ion motion inertia but for nanosecond pulses might require substantially more energetic pump lasers to hold the grating fringes in place.

The three methods we wish to investigate are at different stages of maturity. Ponderomotive gratings in fully ionized plasma are relatively well understood after the considerable efforts by the laser-plasma interaction community worldwide to understand their role in ICF experiments, particularly regarding crossed-beam energy transfer. Ionization gratings face some significant gaps in the characterization of ionization of neutral gas by high intensity lasers, at least at some wavelengths. And although gas gratings[12] have been demonstrated, a substantial amount of work remains to develop a predictive understanding for designing an optimal system.

Summary

We are proposing to investigate theoretically, and test in laboratory experiments, the creation of high-fluence-resistant gratings and lens using three novel techniques: density modulations in neutral gas, localized ionization in neutral gas, and ponderomotive force in fully ionized plasma. The strengths of these concepts for IFE applications are:

- High optical damage thresholds (several orders-of-magnitude above glass)
- Suitability for high repetition rates (>10 Hz)
- Robustness to debris, x-ray, and neutron fluxes
- Protection of solid-state optical components from direct exposure to targets
- Shutter-like protection of upstream laser optics from backscattering

The main challenges we wish to address are to better understand the underlying physics, particularly for the ionization and gas gratings, and the suitability of each approach to real application in IFE with respect to the criteria described above. The technology discussed in this white paper has the potential to transform the application of high-power lasers both within and beyond inertial fusion energy.

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