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High Efficiency Gratings For Beam Steering on the National Ignition Facility (NIF) Laser

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ABSTRACT

The design of the National Ignition Facility (NIF) is based on conversion of 1.05 μm wavelength light (1ω) into third harmonic light (3ω) by passage through KDP frequency conversion crystals. It is important for proper coupling of radiation into the targets that the final beam impinging upon the target should have little 1ω or 2ω light. It is also desirable to avoid direct line-of-sight for neutrons between the target and the KDP crystals, in order to prevent damage. These issues can be overcome by employing diffraction gratings immediately before the final NIF focusing lens to direct the 3ω beam to the target. A single grating design is highly dispersive, and may introduce intolerable divergence into the beam. In order to overcome this limitation, we propose to use a grating pair. This will provide transverse offset of the beam and eliminate the dispersion while offering several other advantages.

INTRODUCTION: THE CONCERN

The present design for the final stage of each beam of the National Ignition Facility (NIF) calls for the conversion of 1053 nm light (1ω) into third harmonic (3ω) in KDP frequency conversion crystals, after which a lens will focus the 3ω light, through a kinoform phase plate (KPP), onto the target. The NIF design calls for an off-axis lens to separate the fundamental (1ω) and second harmonic (2ω) light from the 3ω light. However, the present design (diagrammed in Figure 1) would permit, for neutrons, a direct line of sight between the target and the KDP crystals. The neutrons may damage the KDP crystals.

![Diagram of the present NIF design](image)

Figure 1 Diagram of the present NIF design.
PROPOSAL: BEAM STEERING GRATING

It has recently been recognized by several people that high efficiency gratings could be used at the final focus of NIF to diffractively steer the 3ω beam onto the target, thereby avoiding direct neutron line-of-sight between the target and the KDP. Figure 2 shows a conceptual design using a single grating to diffract the 3ω radiation with high efficiency while leaving the 1ω and 2ω light unaffected. The basis for such a design is a grating with spacing no larger than the 3ω wavelength. Such a grating will diffract only the 3ω light. Detailed calculations indicate that the transmitted efficiency in the -1 order approaches 98% when the angle of incidence is close to the Littrow angle (30 degrees); the remaining light is transmitted in the zeroth order.

![Conceptual design for single beam steering grating](image)

MODIFICATION: GRATING PAIR

A single grating design is highly dispersive. The 60 GHz bandwidth, needed for SBS suppression in the optical components, adds 75 μrad divergence to the beam along the dispersion direction. The 7m focal length lens converts this into a ~520 μm broadening of the spot in the focal plane. This would exhaust the divergence budget on NIF, leaving no allowance for beam aberrations or the KPP.

In order to overcome this limitation, we propose to use a grating pair. This will provide the transverse offset of the beam and eliminate the dispersion. The spectral dispersion of a grating pair is given by the expression

\[
\frac{\delta \theta}{\delta \lambda} = \frac{1}{d_1} \left[ \frac{d_1 \cos(\theta_{\beta_2})}{d_2 - \cos(\theta_{\alpha_1})} \frac{1}{\cos(\theta_{\beta_2})} \right]
\]  

(1)
where $d_1$ and $d_2$ are the periods of the two gratings. The needed angles, for given wavelength $\lambda$, are the incident angle $\theta_{i,2}$ for grating 2, and the transmitted angles $\theta_{o,1}$ and $\theta_{o,2}$ for gratings 1 and 2. This equation indicates that the spectral dispersion can be eliminated using two identical gratings in parallel configuration. Parallel grating configurations have been used in pulse compression/stretching operations here and elsewhere, and in SSD experiments at Rochester. Figure 3 shows a conceptual layout of a grating pair.

Figure 3 Conceptual design for a grating pair.

**DESIGN ADVANTAGES**

The grating-pair concept offers several advantages; some of these are listed below:

i) Neutron protection of the KDP by eliminating direct line-of-sight to the target.

ii) Separation of the $1\omega$, $2\omega$ residual light from the $3\omega$. Since the grating $G1$ is a subwavelength grating for $1\omega$ and $2\omega$ there will be no diffracted orders and this light will be transmitted straight through undiffracted. It could be then absorbed and prevented from entering the target chamber altogether.

iii) The above feature also eliminates the need for wedging the lens for diverting the $1\omega$ and $2\omega$ light from hitting the outside of the NIF hohlraum. The focus lens could then be made centered for each beamlet which could save some cost.

iv) The grating pair could also be used to introduce spectral dispersion needed for SSD. This could be accomplished by using dissimilar gratings and/or non-parallel operation.
v) The weak undiffracted (0th order) 3ω beam is available for diagnostics following the grating G1. No separate beam sampling grating will be needed. Note that this sampling can also be picked off outside the target chamber. This eliminates the need for placing optics in the harsh environment inside the NIF target chamber.

vi) The grating design permits high efficiency operation, thereby minimizing the loss of energy delivered to the target. Additionally, the placement of gratings outside the target chamber should simplify their handling.

POTENTIAL LIMITATIONS

The potential limitations of this approach are

i) the increased B-integral effect because of the grating substrates (this is offset to some degree by thinning the focus lens)

ii) increased hardware and cost of manufacture

iii) optical damage.

The impact of these issues needs to be addressed in the broader context of the NIF design. However, in our view the proposed design offers several technical advantages to warrant further design and fabrication investigations. If this concept is adapted into the NIF baseline, a full engineering layout would also have to be carried out at a future date.

BASIC DESIGN GOAL: HIGH EFFICIENCY TRANSMISSION

The efficiency of a grating depends on groove period, depth, grating profile, and angle of incidence. For suitable choice of these parameters the transmission efficiency can approach 100%. Our goal is to obtain high efficiency (better than 95%) of order -1 for a transmission grating etched into fused silica and illuminated by wavelength 351 nm.

The most efficient gratings are obtained when only two orders can propagate (order 0 and -1 say). This can be assured, according to the grating equation, by fixing the grating period d to be smaller than the wavelength λ. For light of wavelength 351 nm this implies a groove period of 350 nm or less. With this choice of spacing it is possible to achieve nearly complete deflection of the transmitted light, leaving no reflected light and no zero-order transmitted light.

When the grooves are not so closely spaced there will be additional orders present, and these diminish the maximum efficiency for any order. For example, when the groove period is increased from 350 nm to 500 nm, the peak efficiency drops from 97% to 87%.

To achieve high efficiency we desire a grating that allows only two orders, namely the zero order (specular reflection) and the -1 order (autocollimation). By suitably choosing the groove spacing d for given wavelength λ we can exclude all other orders. For this purpose we use the basic grating equation relating angle of incidence α to angle of diffraction βm for order m,

\[ \sin \beta_m = \sin \alpha + (m\lambda/d) \]
SEPARATION OF ORDERS

In all of these design cases there is a large angular separation between the zero order transmission and the -1 order transmission. For example, with period = 350 nm the Littrow angle (for order -1) is 30°. With this incident angle one has the following angles for reflection and transmission (into air after the grating)

<table>
<thead>
<tr>
<th>Incident</th>
<th>Reflect 0</th>
<th>Transmit 0</th>
<th>Transmit -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>30°</td>
<td>30°</td>
<td>-30°</td>
</tr>
</tbody>
</table>

Thus there will be a 60° angle between the two transmitted orders as they emerge into air.

With groove spacing this small, radiation at wavelengths of 1053 nm and 527 nm will not be diffracted; they will appear only in zero order.

EFFICIENCIES

Although the grating equation provides constraints on allowed orders, it does not provide information on how the radiant energy will be apportioned amongst those orders. This efficiency depends on the grating profile, i.e. on the groove depth and shape.

The basic design for this grating, deep near-rectangular grooves etched into a single dielectric material, poses no great theoretical problems.

Moharam and Gaylord [1], in 1982, applied their coupled wave method to a simple lamellar grating (as well as gratings with sinusoidal profiles) for which the groove spacing was equal to the wavelength and the grating was viewed at the first Bragg angle of 30 degrees. For a refractive index of 1.58 they predicted diffraction efficiencies of 88% at a groove depth of around 1.5 wavelengths, or \( d = \lambda \) and \( h = 1.5 \lambda \). High efficiency transmission gratings have been described in numerous places [2], and theoretical methods for predicting behavior are well known. It is desirable to find a design for which the groove spacing is as large as possible, consistent with the requirement of high efficiency.

RESULTS OF COMPUTATIONS

We examined a simplified model of a transmission grating, consisting of air above a fused silica substrate, into which were etched rectangular grooves, onto which falls TE polarized light i.e. the incident radiation has the electric vector parallel to the grooves. The wavelength and index of refraction for fused silica were taken from the Melles Griot Optics Guide 5

- wavelength = 351 nm, index = 1.477
- wavelength = 1064 nm, index = 1.450

Modeling indicates that the highest efficiency, for a given grating, occurs when the incident radiation impinges within a few degrees of the Littrow angle.

BASELINE DESIGN

Our design calls for a groove period of 350 nm to be used near Littrow angle for the 3\( \omega \) light (so that the deflection angle between order 0 and order -1 is 30 degrees). With this spacing there can be no diffraction of 1\( \omega \) and 2\( \omega \) light; this light will be transmitted directly
or specularly reflected. The grating will be etched into a fused silica substrate. Our design, predicting diffraction efficiency (into order -1) exceeding 95%, calls for a depth of around 600 nm. Figure 4 illustrates the profile and efficiency for this design.

![Grating Profile](image1)

![Transmission Efficiency](image2)

Figure 4. Theoretical transmission efficiency, $\lambda = 351$ nm, order -1 and TE polarization, as a function of groove depth (nm) and duty cycle for a rectangular-profile grating etched into silica. Incident angle is Littrow angle, groove spacing is $d = 350$ nm. The peak efficiency (97.6%) occurs for depth of 600 nm (or aspect ratio $h/d = 1.7$) and duty cycle 0.5.

In summary, the proposed grating is expected to have the following properties:
- Period = 350 nm,
- Depth = 600 nm,
- Rectangular profile, duty cycle = 0.5
- Etched into fused silica (index 1.477).
- Used at 30 degrees (from normal to surface)

The predicted efficiencies are:

<table>
<thead>
<tr>
<th></th>
<th>order 0 above</th>
<th>order 0 below</th>
<th>order -1 below</th>
<th>order -1 above</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \omega$</td>
<td>0.017</td>
<td>0.983</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2 \omega$</td>
<td>0.049</td>
<td>0.951</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3 \omega$</td>
<td>0.006</td>
<td>0.001</td>
<td>0.977</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Taking the groove spacing to be 350 nm, and with duty cycle of 0.5 (i.e. the grooves have width 175 nm), we found that there was a range of parameters at which the efficiency was 97% or better. Typically the highest efficiency occurs when the incident angle is near the Littrow angle (30 degrees for this groove spacing). One design is

<table>
<thead>
<tr>
<th>period</th>
<th>depth</th>
<th>duty</th>
<th>angle in</th>
<th>angle out</th>
</tr>
</thead>
<tbody>
<tr>
<td>98%</td>
<td>350 nm</td>
<td>600 nm</td>
<td>0.5</td>
<td>30$^\circ$</td>
</tr>
</tbody>
</table>
Comparable efficiencies (97%) can be obtained with depths ranging from 500 nm to 700 nm, and for duty cycles ranging from 0.2 (narrow ridges) to 0.6 (narrow slots). Any particular design will have only slight sensitivity to errors in depth and duty cycle.

This efficiency can be increased by taking a smaller period. We have found high efficiency solutions for \( \lambda/d = 1 \) and rectangular profiles (with aspect ratio \( h/d \) near 1.7). This groove spacing has Littrow angle of 30°, and the efficiency is a maximum at this angle.

Although it is true that groove spacing as large as \((3/2) \lambda = 526 \text{ nm}\) will still permit only two orders, my numerical modeling of such a grating indicates that the maximum efficiency will be around 85%. This is not high enough for our purposes.

CONCLUSIONS

We have presented a final optics design, involving two high efficiency 3ω gratings. Our design avoids direct line of sight for neutrons to the KDP crystals and offers several additional advantages. We have found high efficiency solutions for \( \lambda/d = 1 \) and rectangular profiles having duty cycle of 0.5 and groove depth 1.7λ. This groove spacing has Littrow angle of 30° and the efficiency is a maximum at this angle. Modeling indicates that the highest efficiency, for a given grating, occurs when the incident radiation impinges within a few degrees of the Littrow angle.

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