IMPROVED PERFORMANCE (TRANSMISSION) GRATINGS

Paul L. Csonka

Institute of Theoretical Science

University of Oregon

Eugene, Oregon 97403

1.

Desirable properties for X ray gratings

1. Possibility of large angular deviation produced by grating
2. High efficiency (close to unity) into chosen order
3. Absence, to high accuracy (below a fraction of 1%), of unwanted orders.
4. Large $\delta\lambda/\lambda$ (up to 10%) for well defined (i.e. small angular spread, $\Delta\theta$) beams. It is, of course, easy to increase $\delta\lambda$ for an optical element, but that often implies increasing $\Delta\theta$, and thus a loss of intensity for fixed slit size.
5. High resolution.
6. Resistance to permanent heat damage.
7. Performance stability under heating.

Property 3 contains 2, but not vice versa. For fixed slit size, 4 and 5 are contradictory requirements. (For X-ray laser applications, 3 and 5 are generally not needed.)

2.

Steps to be taken to improve grating performance

1. Increase line density by superimposing existing gratings.

The main limitation on line density of holographically imprinted gratings comes from the lower limit of the coherent light wave which is used for

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imprinting.

Once this limit is reached, a new approach is needed to increase line density.

One possible method consists of the following two steps:

- A. Reduce the wire-width in existing gratings by chemically dissolving material. A uniform solvent gently circulating should promote uniform dissolution.

I guess that successive molecules are removed essentially as statistically independent events.

Then, if original wire had n atomic layers, and we want to dissolve much of them (i.e. number of dissolved layers is of order n), the resulting relative statistical fluctuations in the wire-width will be $f \approx \sqrt{n}/n = 1/\sqrt{n}$.

When $n = 10^4$ (typical), one gets $f = 10^{-2}$, so that even a reduction by a factor 10^2 is not excluded by statistics.

Actually, to this fluctuation one has to add the unevenness of the original wire.

- B. Superimpose two or more gratings, interspace their wires to obtain a grating with increased line density.

Gratings would first have to be aligned, then their position sensitively controlled (perhaps by the piezoelectric effect, or a sequence of levers). When the combined gratings produce a diffraction pattern close to what is desired, their positions would be fixed. A third grating may then be added, etc.

Instead of dissolving wires as described in 1., one could instead probably

imprint them nonlinearly to reduce their thickness (as suggested by E. Spiller).

2. Tailored grating contours

Present gratings have sharp wire contours, produced by high contrast imprinting.

Such imprinting is useful for modeling microcircuits but is not ideal for gratings. Instead,

1. One should imprint gratings with "round" wire cross sections.
2. Where this cannot be achieved, one should
 - a. Round off subsequently the edges with a chemical solvent. The performance of existing gratings could be improved by this simple treatment.
 - b. Introduce random variation δz in the positions, z , of absorptive wires (see Fig. 1). Provided that $\delta z \lesssim \frac{1}{4} d_a$ (especially if $d_t \gg d_a$) this should decrease unwanted higher orders.
3. Eventually a technique should be developed to model any function $D(z)$, where D is the wire diameter.

To illustrate: For normal incidence, D should vary

in the first approximation as $D \approx \ln[\text{const.} \cos^2 nx]$, not a step function.

Fig. 1

There is no reason for continuing to produce gratings with "deep grooves" as opposed to ones with "gently undulating" surfaces.

3. Transmission grating vs. reflection grating

The former seems to be preferred for laser application, because

- a. Diffraction pattern produced by transmission grating is relatively

insensitive to planarity of grating, and thus to heat induced warping.

(Sideways buckling of wires could be a problem. One design to minimize it will be mentioned later.)

- b. Transmission grating is likely to absorb less heat (but may be harder to cool.
- c. High reflexivity is not needed. High transmission is automatic in vacuum, and independent of wavelength.

4. "Phase" grating vs. "absorption" grating

We refer to a grating as an "absorption" grating, if the diffraction pattern is the result of absorption.

When the diffraction pattern arises primarily as a result of phase shift in the wire material, we call it a "phase" grating. For best performance, a phase shifting of π is required.

Whenever permitted by the refractive index, phase gratings seem preferable, because

- a. Transmission is roughly 4-upled relative to absorption gratings, since the wires now do not absorb much, and the zero'th order is absent.
- b. Heating is less (possibly by a large factor), since absorption is small.

Objections can be raised:

- a. Since the index of refraction depends on λ , the thickness l_{Δ} , of a material which produces a phase shift of π depends on λ . Thus different gratings would be needed for different λ .

The above conclusion is wrong. The needed l_{Δ} varies as $\sim \lambda^{-1}$, but the optical pathlength of the wave in the phase shifting medium depends on the angle of grazing incidence, θ . The θ can be

so varied as to enable use of the same grating over a wide range of wavelengths, e.g. as shown in Fig. 2.

Figure 2

- b. To have a non-absorptive grating, D must be small. Wires with small D are hard to cool, and grating will not be able to resist heating.

This conclusion is wrong: When D is small, X-ray absorption is also small, so is heating; both heating and cooling $\sim D$.

5. "Symmetric" vs. "asymmetric" phase grating

In principle, asymmetric gratings would suppress one (say the negative one) of the two branches in every order, and increase intensity by two in the remaining branch.

The idea is illustrated below (Fig. 3). The geometry is unrealistic, and edge effects (including "waveguiding") are neglected for simplicity.

Figure 3

The maximum phase shifting needed in this arrangement is 2π .

The grating is capable of directing 100% of the incoming beam into the desired order (apart from edge effects).

6.) Point focusing with two phase gratings (line-zone plates)

The first grating in Fig. (4) focuses on a line, the second on a point

Figure 4

When both are phase gratings, the combined transmission efficiency into a chosen first order can be $\geq 16\%$. When both are asymmetric phase gratings, it can be $\approx 100\%$. (By contrast, if both are absorption gratings, it would be only $\approx 1\%$.)

A single phase-zone plate could focus on a spot, but to inscribe it, electron machines would have to etch circles. Present machines are not so programmed.

By contrast, on both plates in Fig. 4, only parallel straight lines have to be etched, and that is immediately doable with existing equipment.

7.) Zone plates

What was said for gratings under 3.), 4.), and 5.) can also be said for zone plates: Instead of absorptive zone plates, one should manufacture asymmetric phase zone plates. (But my topic here is gratings, not zone plates.)

8.) "Shingle" gratings

The best performance will probably be obtained from gratings of the following general construction.

Note the "bridges" inserted to insure buckling out of the plane due to heating.

Actual contours are not all sharp. They are so drawn only for clarity.

Figure 5

9.) An "Impossibility Theorem" for gratings

The following is a conjecture, intuitively appealing, but not proved.

If true, it gives limitations on the performance of gratings, no matter what their construction.

The "Theorem":

Assume: Plane wave with amplitude A_i travels along z axis.

"Black box" is located between (x,y) plane (at $z=0$) and the plane parallel to this at $z=L$.

Inside black box exists an arbitrary distribution of material.

Material at each point characterized by complex index of

refraction, or equivalently, by two real numbers at each point: l_α

and l_Δ . They are respectively the length within which

intensity changes by a factor $\frac{1}{e}$, and within which the

phase shifts by $\geq \frac{\pi}{2}$. Let $l_\alpha \lesssim$ of order l_Δ everywhere.

Denote the smallest of all l_α and l_Δ by l .

A_d is the amplitude of that Fourier component in the (x,y) plane which varies along x with period d.

Then: $A_d < \text{of order } \left[A_i \frac{d}{\ell} \right]$, if $d \ll \ell$.

This limits performance of general grating (i.e. the black box).

More generally: Let a plane wave with amplitude A_i and momentum component p_x along x impinge on a black object (with one surface in the (x,y) plane) along "the other side" of the object from the (x,y) plane.

Then $A_d < \text{of order } \left[A_i \frac{\lambda_x d}{\ell(\lambda_x - d)} \right]$;

if $\lambda_x d / (\lambda_x - d) \ell \ll 1$, and $\lambda_x \equiv h/p_x$.

10. Summary

Higher line density gratings could be produced immediately by superimposing existing gratings (after reducing wire widths).

Unwanted higher orders could be reduced by chemical treatment of existing "deep groove" gratings.

Symmetric phase gratings could be produced immediately by plating with a low absorbtion material instead of with gold.

Symmetric phase plates (gratings) can be etched with existing equipment.

A combination of two would focus beam on a spot, with up to 16% efficiency.

To improve performance, eventually one should manufacture asymmetric phase gratings, and "tailor" the contours of absorbtion gratings.

In the long run, probably "shingle gratings" will offer the best performance.

The conjectured "Impossibility Theorem" may limit the performance of gratings, no matter how they are constructed.