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MANN -- A PROGRAM TO TRANSFER DESIGNS FOR  
DIFFRACTIVE OPTICAL ELEMENTS  
TO A MANN  
PHOTOLITHOGRAPHIC MASK GENERATOR

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## INTRODUCTION

Optics is a discipline which deals with the control and manipulation of light. Although there are three basic mechanisms known for achieving this control, *i.e.*, refraction with lenses, reflection with mirrors, and diffraction with gratings, almost all optical systems utilize only the first two. The principal reason for this avoidance of diffraction is that whereas when the first two mechanisms bend, shape, focus, and redirect light they generally leave a single ray or beam as a single ray or beam, the third mechanism tends to divide any incoming rays into a multiplicity of rays. This splitting of light into different rays is sometimes useful, as in spectrometry, but it is generally not desired because the optical energy is divided up among the various beams. So most optical devices use only lenses and mirrors, with gratings generally being found only in spectrometers and monochromators, instruments used when the principal interest is spectral content or purity of optical waves, rather than their image content.

However, this last-mentioned application brings out the strength of diffractive elements: they bend light much more strongly than lenses and they are very wavelength sensitive, a characteristic that could be very desirable for some applications. In addition, the characteristic property of gratings, multiplicity of output, can be exploited in optical fanout, where it is desired to split an optical beam into a set of equivalent beams. Even if only a single output beam is desired, gratings can be designed so as to concentrate optical energy into a single refracted beam. In traditional optics, this is done by *blazing* a grating, and in the emerging field of diffractive optics, techniques for producing single beam output have also been developed. In sum, if the negatives of diffraction as applied to common optical applications can be exploited or eliminated, then the positive characteristics of diffractive elements such as light weight, small size, and minimal material, can be used to produce effective and efficient optical devices.

## DESIGN OF DIFFRACTIVE OPTICAL ELEMENTS

There are two basic areas of interest for diffractive optics. In the first, the property of wavefront division is exploited for achieving optical fanout, analogous to the more familiar electrical fanout of electronic circuitry. The basic problem here is that when using a simple uniform diffraction grating the energy input is divided unevenly among the output beams. For example, when using a traditional grating the output energy is basically described using a sinc function with most of the energy either undiffracted or in the first few diffraction orders. However, H. Dammann<sup>1</sup> showed that by designing a non-uniformly spaced grating, using the requirement that the coefficients of the Fourier transform of the grating's transmission function should be equal, the energy could be uniformly divided among the various orders. Thus by exploiting local variations in grating line spacing and depth, uniform optical fanout can be obtained. Since the basic design is a simple problem in Fourier analysis, calculation of the grating design is straightforward, although a computer must be used to obtain numerical solutions.

The other area of interest is the use of diffractive elements to replace or supplement standard refractive elements such as lenses. Again, local grating variations can be used to control

the amount of bending imparted to optical rays, and the efficiency of the diffractive element will depend on how closely the element can be matched to the design requirements. In general, production restrictions limit how closely the element approaches the design, and for the common case of photolithographic production described below, a series of binary masks is required to achieve high efficiency. G. Swanson<sup>2</sup> showed that, even with only four masks, efficiencies of over 95% can be achieved. The actual design process is much more involved than in the case of elements for optical fanout, as the desired phase of the optical wavefront over some reference plane must be specified and the phase alteration to be introduced at each point by the diffraction element must be known. This generally requires the utilization of a standard optical design program. Two approaches are possible. In the first approach, the diffractive element is treated as a special type of lens and the ordinary optical design equations are used. W. Sweatt<sup>3</sup> showed that the diffractive element could be treated as an extremely thin lens of very high index of refraction, and it is possible to design elements using this approximation. However, optical design programs tend to follow a second approach, namely, using the equations of optical interference derived from holographic theory and then allowing the introduction of phase front corrections in the form of polynomial equations. The output from these programs usually consists of a plot of the desired phase change as a function of radial distance from the optical axis, and a polynomial equation for the phase versus radius function. The required phase changes can be reduced modulo  $2\pi$  and then the transition locations where the phase changes by submultiples of  $2\pi$  can be used to determine the local spacing of the diffractive grating.

By using either of these two methods, diffractive elements can be used not only to compensate for distortions such as chromatic or spherical aberration, but also to perform the work of a variety of other optical elements such as null correctors, beam shapers, *etc.*

## FABRICATION OF DIFFRACTIVE OPTICAL ELEMENTS

Of course, having uses for diffractive optical elements and even being able to design them is of little importance unless they can actually be manufactured. Depending on the scale of the grating required, it might be possible to produce the grating by actually cutting it into a substrate with a diamond cutting tool. However, the small size of many gratings generally leads to efforts to produce them using well-established techniques developed in the microelectronics industry. This also has the advantage of integrating the fields of optics and electronics, an alliance which is being zealously pursued in today's environment of fiber optics and laser diodes. It is possible to produce continuous phase variations across a substrate by using e-beams to produce varying depth etch patterns, but the simpler technique of applying semiconductor photolithography methods to resist-coated substrates can be used if a discontinuous approximation to the desired phase map is acceptable. This approach is generally called *binary optics* because each step is a binary operation of etching or not etching at a particular location on the substrate, and the desired phase distribution is approximated by a series of mask patterns and etchings as described in the report by G. Swanson<sup>2</sup>.

The production of a binary optic is a complex and expensive process, requiring that a

series of binary masks be prepared, and then that these masks be used to expose a resist-coated substrate which is etched and then must be re-coated, re-exposed, and re-etched for each mask. This substrate can then be used as a master to make copies, just as in the electronics industry. However, mass production is required to achieve a reasonable cost per optic.

### FROM DESIGN TO FABRICATION -- MANN

One problem has not yet been discussed and that problem is the main focus of the project described in this report -- how is the design information from the lens design program incorporated into the photolithographic process? Optical design tends to be built around circular design elements (most designs are radially symmetric), while the electronic industry with its photolithography is built around straight lines. Optical programs output phase plots and give phase changes as a function of radial distance, while photolithographic machines use rectangular apertures to control areas of exposure on a substrate. The optical design program's output will look something like

$$\phi(r) = A + Br^2 + Cr^4 + Dr^6 + Er^8 \quad (1)$$

where  $\phi(r)$  is the phase as a function of radial distance and  $\{A,B,C,D,E\}$  are the set of constants approximating the equation to the desired phase distribution. Some programs may even give a list of those values of  $r$  where the phase change is a multiple of  $2\pi$ . However, the mask generator machine generally wants a list of apertures showing where the resist-covered substrate will be exposed. For example, for the MANN USG3000 mask generator used during this project the required input is an ASCII text file consisting of a long list of lines having the form

$$X15000Y-1200W310H150A721 \quad (2)$$

where X and Y are the location of the center of the aperture, W and H are its width and height, and A is the inclination of the aperture with respect to the horizontal x-axis, expressed in tenths of a degree. All length dimensions are in microns.

Going from (1) to (2) is a non-trivial task. Basically, to prepare the data from the first equation for producing a binary optic mask, an annular ring representing the area between two transition radii must be filled with rectangular boxes. This cannot be done without error, and as an additional constraint it is generally desired to reduce the number of exposures or boxes required to make the mask. To calculate the error introduced by using straight lines to approximate curves, the geometry of Figure 1 was used to determine the proper limits that stay within the maximum error. It is easy to show that the error, or sag, is approximately given by  $t = r^2/(2R)$ . Figure 2 shows the geometry used to fill an annular ring. Most of the geometry is self explanatory. For the project being described, the allowed error  $t$  was one micron. By calculating the width of the box using the sag calculated from the inner radius and then spacing the rectangles around the annulus using the outer corners of the rectangle, the annulus is filled with a minimal number of exposures subject to the limiting error distance  $t$ . The overlap between adjacent boxes is not harmful to the design and only represents the loss due to double-exposing the resist in the region of overlap.

A more difficult case occurs when the two rings defining the annular region intersect the boundaries of the binary optic cell being designed. An example of this is shown in Figure 3 which shows an annular ring clipped by the upper right corner boundaries of the mask cell. The central region of the segment may be filled using the method described above but the triangle-shaped areas at the ends need a different approach. In order to maintain the least number of exposures while still staying within the error limitation of 1 micron, a binary divide technique is implemented. Starting at the inner radius, the height of the box is chosen to extend halfway to the outer wall, and then the length is

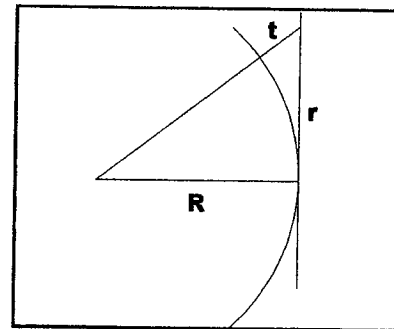


Figure 1. Geometry for calculating error between line and curve:  $t = f(r)$ .

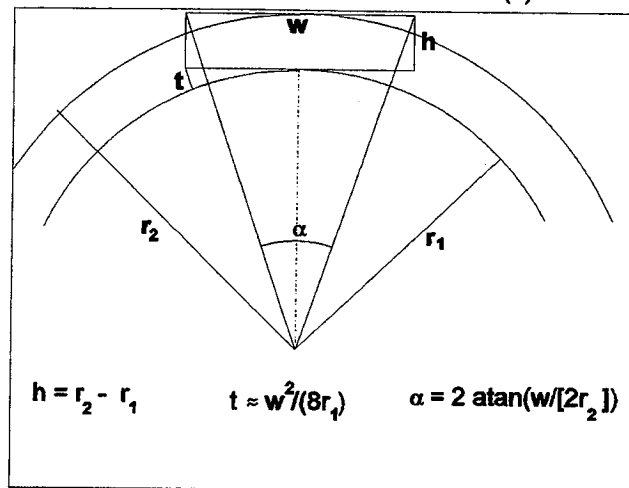


Figure 2. Filling an annular ring with rectangular boxes.

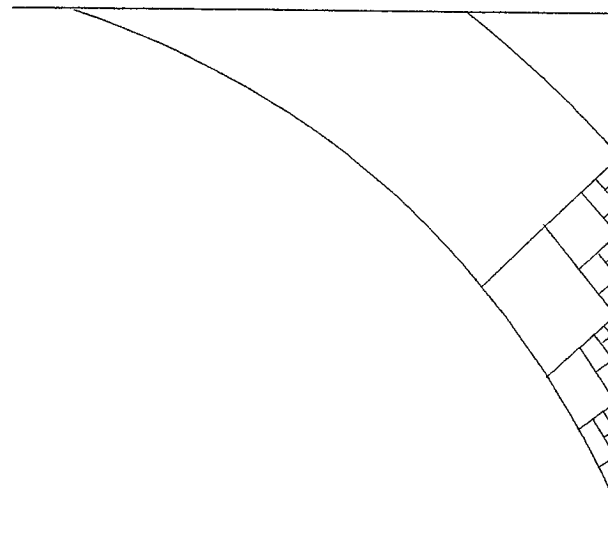


Figure 3. Filling triangular end of partial annulus in upper right corner of mask cell.

extended until it encounters the bounding wall. A second box is then placed adjacent to each side of the first box, with each of their heights extending half way to the boundary. This process is continued until the distances fall below a minimum feature size characteristic of the particular mask generator, in this case 10 microns. With these filling algorithms incorporated into the program, as well as a couple of other algorithms for special cases, procedures for generating box lists can be completed. It then remains to incorporate these routines into a complete program named *MANN*. As completed, *MANN* allows the generation of one- or two-dimensional Dammann gratings, using either data taken from published articles<sup>4</sup> or allowing the user to enter transition points for symmetric gratings of unit period. The program also allows the generation of masks to produce simple lenses or lens arrays, using simple built-in formulae for focal length and mask number.<sup>5</sup> In addition, for more complex designs, the program contains a text filter allowing radially symmetric designs from Code V (Optical Research, Inc.) to be incorporated. Finally, *MANN* contains a viewing routine which allows the mask box lists to be visually presented at varying magnifications on the computer monitor, allowing the user to see what the mask will look like. This mask image can be saved as a TIFF file to allow incorporation into documents and reports. The interface was designed to be friendly, with suggested values given for user inputs, and robust, with validation of all user responses. *MANN* thus fills the need for a link between lens design programs and mask generation controllers.

Further work on the program will incorporate additional text filters, to allow incorporation of designs from programs such as Mathematica (Wolfram Research), or other optical design programs.

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