Analysis and Performance Limits of Diamond Turned Diffractive Lenses for the 3-5 and 8-12 Micrometer Regions.

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ABSTRACT

Diffractive optical imaging elements have been proposed in numerous papers1'17 over the past decade. Few have been produced in quantities. The primary method of fabricating such dif tractive elements has been reactive ion etching of a multi-level surface relief grating on one side of a lens. This approximation is known as Binary Optics'.

Recent experiments have shown that single point diamond turning can be very effective in generating continuous diffraction phase profiles. Combined with the long established method of aspherizing, this machining process is especially suitable for applications in the infrared spectrum. It provides a means of reducing the number of lens elements otherwise required for an objective to correct existing aberrations.

1. INTRODUCTION

Single point diamond turning has been established for many years now as a reliable manufac- turing method for optical surfaces. Since the computer controlled machining process provides the flexibility to generate any rotationally symmetric surface, an asphere can be as easily produced as a sphere. Therefore, to include diffractive surfaces in this list of diamond turned optics is a logical and natural extension.

There are, however, some limitations which must be recognized. One is the relatively small number of optically transmissive materials available which can be diamond machined; the other is the smoothness (surface roughness) achievable with this machining process.

Fortunately, most of these materials are very suitable for the use in the infrared spectrum. Furthermore, the longer wavelengths in this region do not require an extremely smooth surface to reduce the scattering effects due to surface roughness.

2. BASIC CONSIDERATIONS

A single lens with spherical surfaces is afflicted with two primary on-axis aberrations,

1) Spherical aberration

and 2) Chromatic aberration.

Expressed by the thin lens, third order theory, the minimum angular blur spot for an object at infinity is:

$$\beta = \frac{N(4N-1)}{128(N-1)^2(N+2)(F/\#)^3} + \frac{1}{2v(F/\#)}$$

where N = index of refraction
v = relative dispersion
F/# = relative aperture

To correct these aberrations, a doublet made with two different materials is commonly used. If a properly chosen diffractive phase profile is placed on one surface of a single lens, both aberrations can be corrected within certain limits as shown in Figure 1.

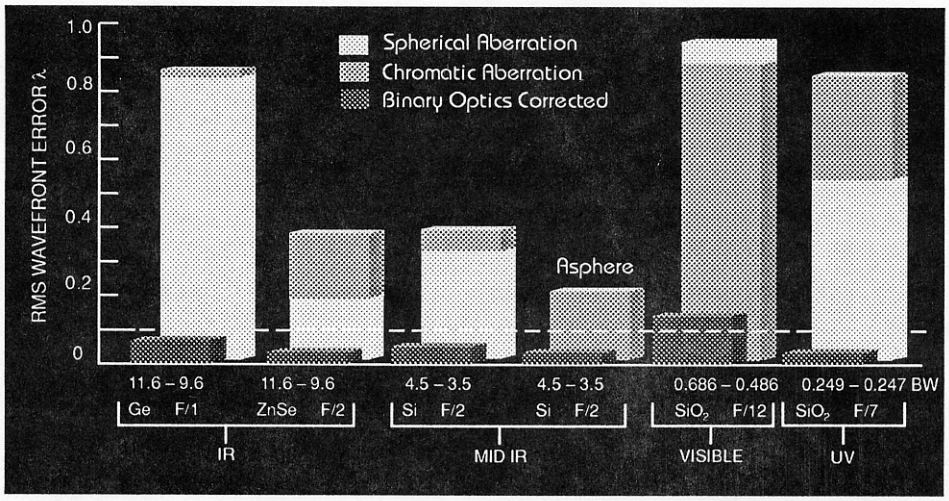


Figure 1. Examples of the chromatic and spherical aberration reduction possible by using a refractive/diffractive lens [With permission from Lincoln Laboratory[1]].

Figure 1 shows clearly how the degree of correction is dependent on the lens material, the spectral region, and the relative aperture. For example, the F/l germanium lens is overwhelmingly afflicted with spherical aberration and mildly affected by chromatic aberration over the 2 urn bandwidth. On the other hand, the quartz lens applied in the visible spectrum over a bandwidth of 0.2 pm, shows much chromatic and little spherical aberration. To achieve a reasonable correction, the relative aperture had to be increased to F/12.

Table 1 shows a summary of the lenses from Figure 1, analyzed with equation (1).

Lens #	Mat'l.	F/#	Region	Δλ (μm)	Spher. (mr)	Chrom. (mr)	Ratio
1	Ge	1	LWIR	2	8.7	0.2	43.5
2	ZnSe	2	LWIR	2	2.3	2.3	1
3	Si	2	MWIR	1	1.3	0.5	26
4	Si	2	MWIR	1	0	0.5	asphere
5	SiO2	12	VIS	0.2	0.04	0.5	1 / 12.5
6	SiO2	7	UV	0.002	0.6	4.6	1 / 7.7

Table 1. Performance analysis of lenses from Figure 1, based on thin lens 3rd order equations.

The fact that spherical aberration can be corrected by aspherizing one of the two lens surfaces has a great advantage. The diffractive phase profile can then be exclusively applied for color correction. The result is that a wider spectral band can be used. This is especially true for the mid- and long IR wavelength domain where the relative dispersions are higher than in the VIS and UV regions.

Tocorrectforcolor,one takes advantageof the fact that thechromatic aberration ofarefractive element is opposite in sign when compared to the chromatic aberration of a diffractive element. If the single lens is viewed as a combination of a refractive and a diffractive element, the following relations can be applied:

$$\frac{1}{F(\lambda)} = \frac{1}{F_r(\lambda)} + \frac{1}{F_d(\lambda)} \qquad (2)$$

Further, if the two focal lengths are chosen so that:

$$F_{r0} = [1 + \frac{\lambda_0}{\Delta\lambda v}] F(\lambda) \qquad (3)$$

and

$$F_{d0} = [1 + \frac{\Delta\lambda v}{\lambda_0}] F(\lambda) \qquad (4)$$

which means that if:

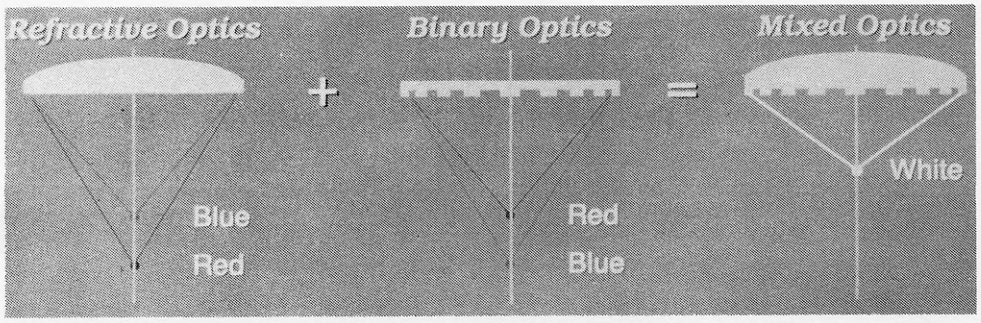
$$\frac{F_{d0}}{F_{r0}} = \frac{\Delta\lambda v}{\lambda_0} \qquad (5)$$

then:

$$\frac{1}{F(\lambda)} = \frac{1}{F_{r0}} + \frac{1}{F_{d0}} \qquad (6)$$

The focal length F is now independent of wave length. In these equations, F^ and F^ are the focal lengths of the refractive and diffractive portions of the lens for the center wavelength \. AX is the spectral band width, and v is the relative dispersion.

This leads to Figure 2, the frequently shown schematic of the color correction principle with a refractive/diffractive lens.



$$F_c = \frac{F_{r0}F_{d0}}{F_{r0} + F_{d0}}$$

Figure 2. The achromatic singlet[3].

For example, the germanium lens from Table 1 should have a focal length of:

$$F_{r0} = 1.001823F_c$$

and

$$F_{d0} = 549.4F_c$$

Notice that both focal lengths are positive and larger than the focal length of the combination. The diffractive power l/F^ls verv weak because of the very mild chromatic aberration.

3. THE DIFFRACTIVE PHASE PROFILE

The phase profile of a rotationally symmetric lens surface can be described with:

$$\varphi(r) = \frac{2\pi}{\lambda_0}[Ar^2 + Br^4 + Cr^6 + \ldots] \qquad (7)$$

where r is the radial coordinate of the phase profile andA ,B, C, etc. are the aberration correction coefficients which are determined with a lens design program such as CODE V, ACCOS, or OSLO during the optimization process. These programs treat such a phase profile as a special case of a HOE surface.

The maximum depth of the grating is:

$$d = \frac{\wedge_0}{N_0 - 1} \qquad (8)$$

with NQ = index of refraction and
\Q = the center wavelength of the spectral band of interest.

The first zonal radius ^ is determined for: (p (r;) = 2ic

The other steps occur when: (p (r) = 4n, 6n, SK etc.

As a quadratic approximation, the zone radii, r^ can be expressed by: r^ = r^n (9)

The diffraction efficiency is given by:

$$\varepsilon_1 = \left[\frac{\sin\left[\pi\left(\frac{\lambda_0}{\lambda} - 1\right)\right]}{\pi\left(\frac{\lambda_0}{\lambda} - 1\right)}\right]^2 \qquad (10)$$

which shows clearly the dependency of the spectral detuning. The approximate efficiency over a given spectral band AX is given by:

$$\varepsilon_1 \approx 1 - \left[\frac{\pi\Delta\lambda}{6\lambda_0}\right]^2 \qquad (11)$$

4. A DIAMOND TURNED SINGLET

To test the ability of producing a quality refractive/diffractive singlet suitable for the use in the LWIR region, a lens with the following prescription was designed, manufactured and tested.

Front surface:	Radius R1 = 72.56052 mm Aspheric parameters K = – 0.08067, A4 = 0.847608 E-9 and A6 = 0.265514 E-12.
Rear surface:	Radius R2 = 97.0608 mm Phase profile coefficient A = 2.2143 E-5 (no higher orders were required).
Lens thickness:	t = 8 mm
Lens material:	Germanium with N_0 = 4.003263 and ν = 861 (from 8-12 μm)

The F/1 lens had a clear aperture of 75 mm.

Using the equations from section 3, we find that the first zone radius is:

$$r_1 = \sqrt{\lambda_0 / A} = 21.251 \text{ mm}$$

followed by ^ = 30.053 mm and r, = 36.808 mm

Since the lens has a clear aperture of 75 mm, only three zones were required to correct the chromatic aberration over the 4 pm wide band. The average diffraction efficiency is:

$$\varepsilon_1 \approx 1 - [\frac{\pi 4}{6x10}]^2 \approx 96\%$$

\The remainder of approximately 4 is directed into higher orders and must be treated as stray radiation.

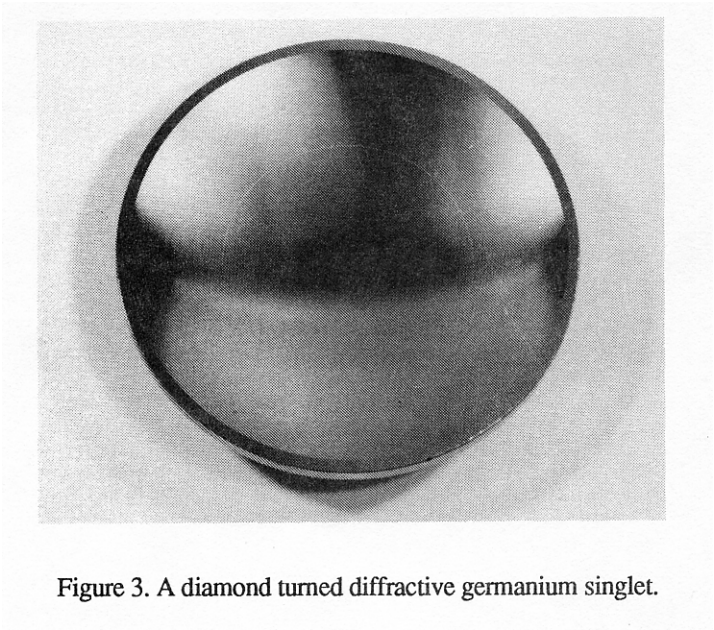
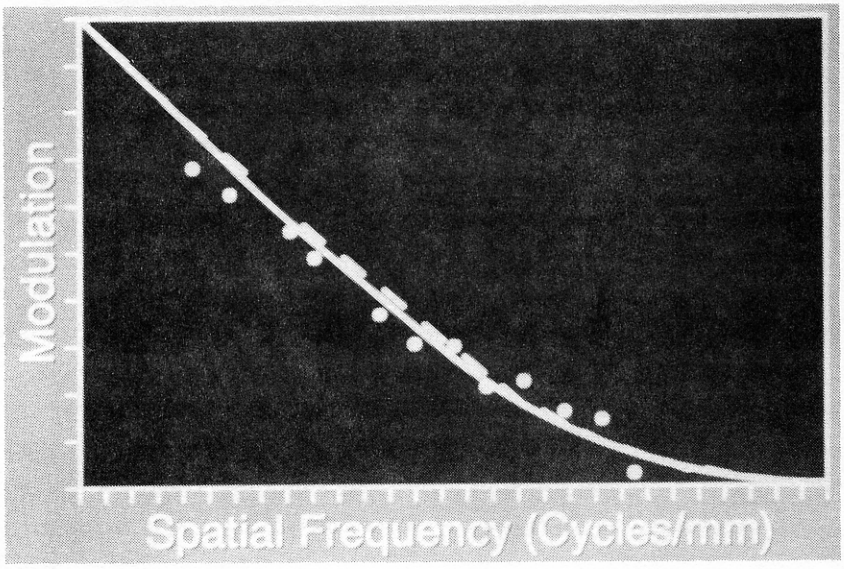


Figure 3. A diamond turned diffractive germanium singlet.

The modulation transfer function of the lens was measured and the result shows that the lens is practically diffraction limited over the full wavelength region.



---theoretical ———— predicted • • • measured

Figure 4. Measured MTF of diamond turned diffractive singlet.

5. GENERAL COMMENTS TO THE ASPHERIC/DIFFRACTIVE SINGLET

Table 2 shows a general relationship between lens material and possible degree of correction in the 3-5μm band for an F/1 singlet with a focal length of 75 mm. The front surface of the lens is aspherized and the rear surface has a diffractive phase profile.

Table 2 F/1 Singlet in the 3-5μm band.

Material	No. of Zones	80% Blur spot (μm)	Remark
ZnSe	34	9	diffr. limited
ZnS	52	11	diffr. limited
Amtir 3	33	20	good
Si	25	25	fair
Ge	55	60	poor
CaF2	442	214	very poor

Diffraction Blur = 2.44 λ F/# = 12.2μm

Table 3 indicates the same relations for the F/l Singlet in the 8-12pm band.

Table 3. F/l Singlet in the 8-12pm band.

Material	No. of Zones	80 Blur spot (pm)	Remark
Ge	3	5	diffr. limited
Amtir3	25	22	diffr. limited
ZnSe	50	38	good
ZnS	125	141	poor
GaAs	520	832	very poor

Diffraction Blur = 2.44 A. F/# = 29.3pm.

It can easily be reasoned that within a given wavelength region, and for a fixed focal length, the number of required correction zones increases as the relative aperture decreases. Furthermore, for a fixed relative aperture, the number of correction zones increases as the focal length increases.

6. A DIAMOND TURNED DOUBLET

To extend the application of diamond turned diffractive optical elements, a Petzval objective for the LWIR was produced and tested. The objective chosen was a modification of the F/l staring imager objective as described by T. A. Fritz and J.A. Cox 4. Fritz redesigned the system so that one aspheric front element with a diffractive phase profile on the spherical surface was used. The second element was a conventional spherical lens. The original design has two diffractive elements. Additional specifications for the system produced are:

Relative aperture	F/l
Focal length	3.3 inches
Spectral band	8-13 pm
Total field of view	8 degrees
Material for both elements	Germanium

The geometric blur spot diameter, containing 80 of the energy, was predicted to be somewhat smaller than the diffraction limited blur of .0012 inches.

The actual performance was somewhat worse than expected, but very close to the diffraction limit The degradation was due to the manufacturing procedure which resulted in a small amount of astigmatism in the front element. We know that the necessary process corrections can be made to meet the theoretical performance values.

This described doublet replaced a triplet. A comparison of both objectives is shown in Figure 5.

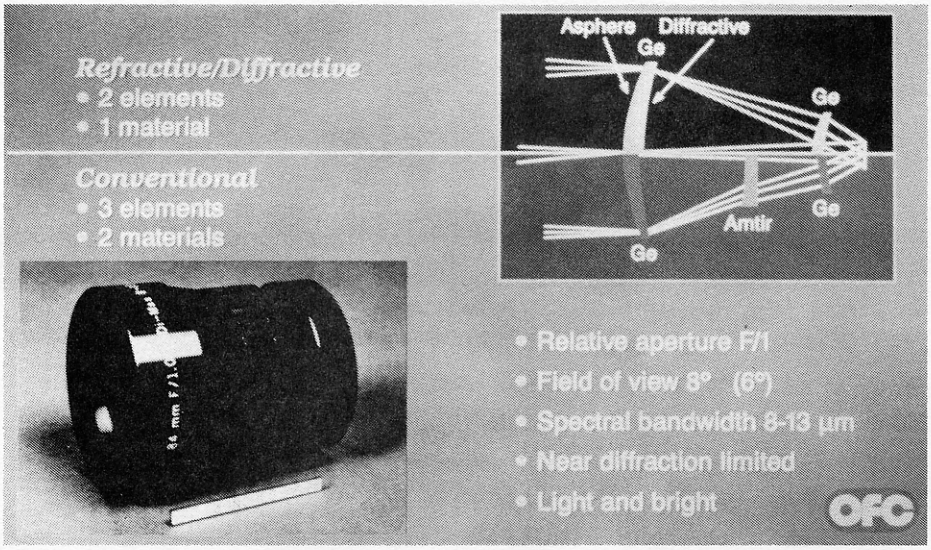


Figure 5. Comparison of a diffractive doublet which replaced a conventional triplet.

The aspheric/diffractive Petzval doublet has been installed into an IR system which uses an uncooled micro-bolometer staring array.

7. MANUFACTURING REMARKS

During the machining of any rotationally symmetric contour, the position and movement of the diamond tool is very precisely controlled. An accuracy ofO. 1pm can easily be achieved. How this affects the diffraction efficiency of the germanium lens used at 10pm for example can be seen from the following remarks:

From equation (8) the design groove depth of the grating is 3.33 pm. An error of O.lpm expressed as a fraction of the total depth is e = 0.03.

This relates to a reduction of the diffraction efficiency of less than 1 , which can be found from:

$$\varepsilon_1 = [\frac{\sin(\pi e)}{(\pi e)}]^2 \qquad (12)$$

This demonstrates clearly that the accuracy attainable with diamond turning is quite sufficient.

The scattering effects related to the surface roughness are not as well defined. However, results seen so far indicate that a roughness of 100A rms, which is routinely achievable with most IR materials, yields an acceptable optical performance, especially in the LWIR.

Figure 4 shows a section of a diamond turned phase profile in germanium. The smoothness of the surface is quite good. The measurement was made with the WYKO-TOPO non-contact surface profilometer.

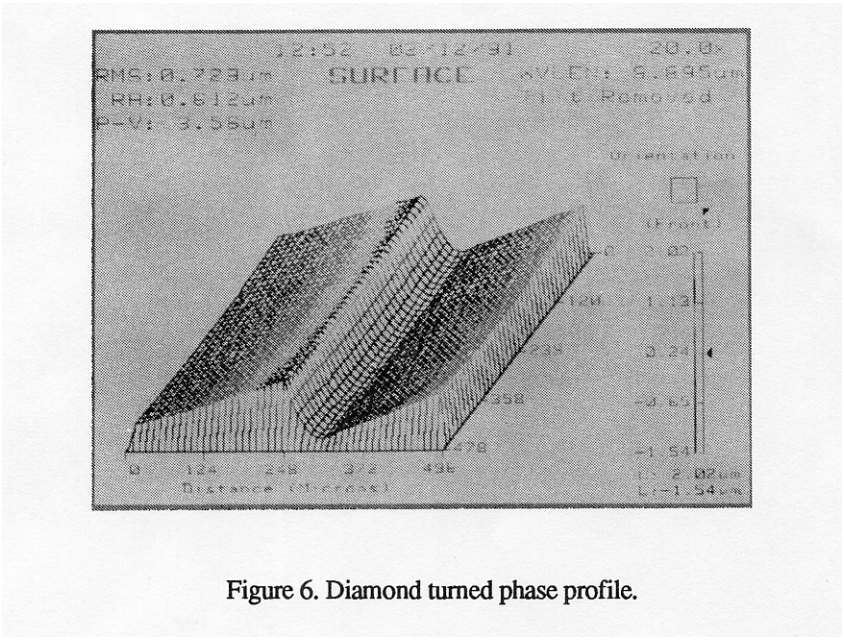


Figure 6. Diamond turned phase profile.

8. CONCLUSIONS

An attempt has been made to show that the process of single point diamond turning is a viable, cost effective method for fabricating diffractive optical elements. The method is especially well suited for the MWIR and LWIR regions. The combination ofaspheric and diffractive surfaces is powerful. Their application will help to develop new types of light-weight infrared optical systems.

9. ACKNOWLEDGEMENTS

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