Advances in Diamond Turned Surfaces Enable Unique Cost Effective Optical System Solutions

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ABSTRACT

Corning has developed a number of manufacturing and test techniques to meet the challenging requirements of imaging hyperspectral optical systems. These processes have been developed for applications in the short-wave visible through long-wave IR wavelengths. Optical designs for these imaging systems are typically Offner or Dyson configurations, where the critical optical components are powered gratings and slits. Precision alignment, system athermalization, and harsh environmental requirements, for these systems drive system level performance and production viability.

This paper will present the results of these techniques including all aluminum gratings and slits, innovative grating profiles, snap together self-aligning mechanical designs, and visible test techniques for IR systems.

Keywords:
Hyperspectral imaging, Offner spectrometer, Diamond turning, Diffraction grating

INTRODUCTION

Imaging Spectroscopy or Hyperspectral Imaging has become a powerful technique for many fields such as remote sensing. Early spectrometers such as the Multispectral Scanner flown on the Landsat series of satellites had limited spectral and spatial resolution; 6 wavelength and 4 spatial bands[1]. More recent designs take advantage of high resolution two dimensional detector arrays and diffractive element in the entrance pupil of the imaging system[2345]. Future possibilities include compact, lightweight imaging spectrometers that perform over a range of environmental conditions.

Corning has developed many useful manufacturing and test processes that enable future possibilities today. These processes include novel grating fabrication methods and diamond machining alignment datum into the substrate of the optical surface. These fabrication techniques allow "snap-together" systems that maintain precision alignment of the optical system without requiring tedious adjustments. The materials compatible with the diamond machining process allow the system to maintain alignment even over temperature extremes. Finally, Corning's experience with precision optical system metrology allows testing at the system level to validate the alignment and the performance of the optics.

This paper will present analysis of Offner imaging spectrometer design[6], grating efficiency data, alignment data, and visible wavelength testing of IR systems.

OFFNER SPECTROMETER DESIGN

The monocentric Offner design form offers some unique advantages in spectrometer design. Initially designed as a microlithography relay optic, this elegant form eliminates Seidal aberrations by using three mirrored surfaces that are concentric. This configuration will relay an arc object to an arc image at 1X magnification where both arcs are

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concentric with the axis of the optical system. Figure 1 illustrates the conceptual layout with the object being a slit at the upper left and the image being shown in the lower left of the figure 1. In this case, the primary mirror and the tertiary mirror are different surfaces with different radii. In many cases, the primary and tertiary can be part of the same curved surface.

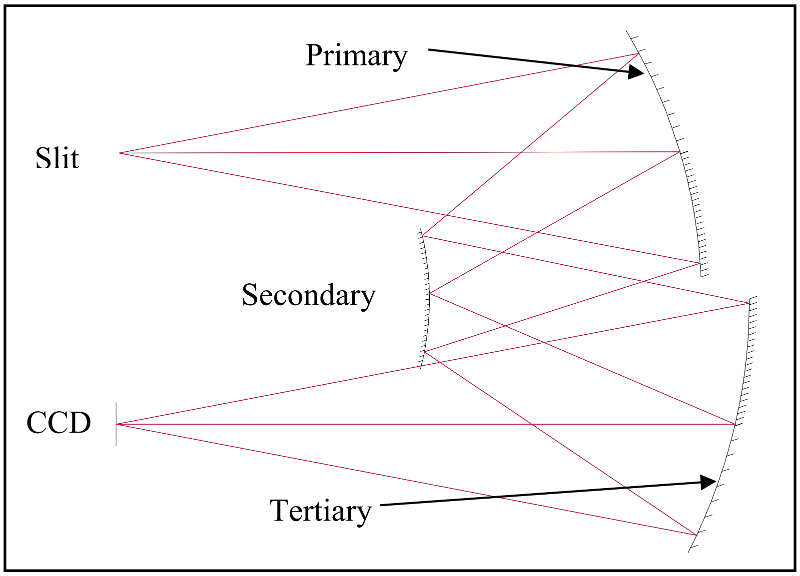


Figure 1Offner imaging relay

When this form is used in the design of a spectrometer, the diffraction grating is placed on the curved secondary mirror. This then spreads the spectrum of the slit onto a CCD camera. This is shown in Figure 2.

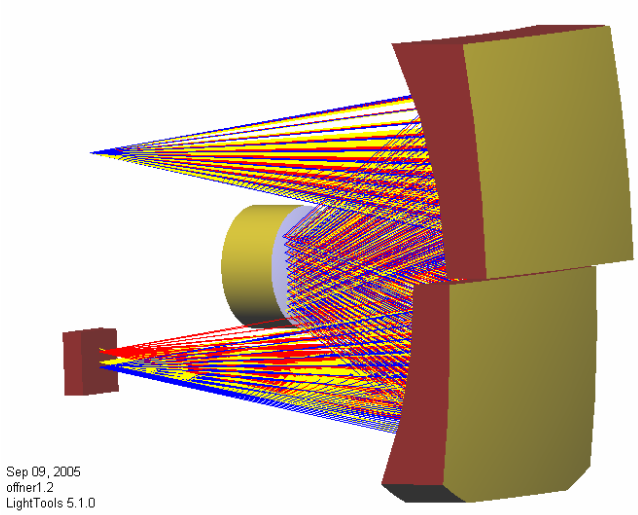
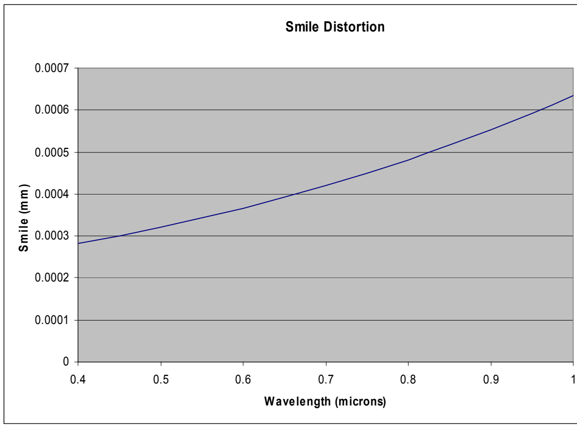


Figure 2 Offner spectrometer dispersion

The monocentric symmetry is broken when imaging a straight slit instead of a curved slit, and the design of the mirror curvatures must be compromised for different image heights due to the dispersion of the diffraction grating. Consideration must be made for the amount of spatial distortion and the amount of spectral distortion in the image. The spatial distortion manifests itself in two forms: smile distortion and keystone distortion.

Smile distortion is a measure of the bow in the image of the line slit while keystone distortion is a measure of the change in the length of the image of the line slit, both as a function of wavelength. Figure 3 shows an example of how smile distortion varies across a wavelength band, and Figure 4 shows an example of the variation of keystone distortion.



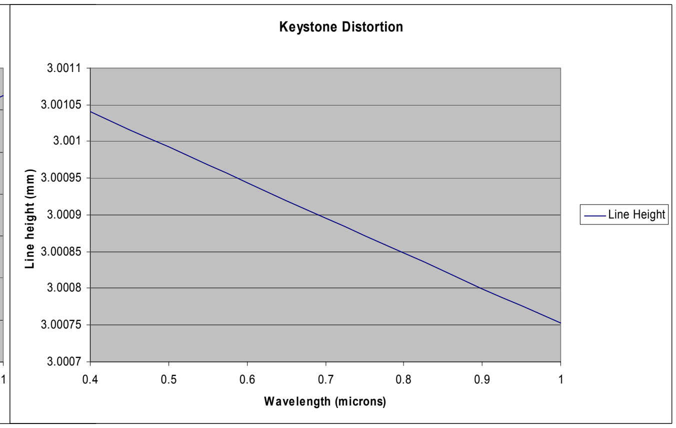


Figure 3 "Smile" distortion of Offner spectrometer   **Figure 4 Keystone distortion of Offner Spectrometer**

Spectral distortion shows the variation in dispersion on the CCD plane as a function of wavelength. This is an important parameter because the calibrated height of the image at the CCD is related to the wavelength, and any spectral distortion will make the conversion from CCD position to wavelength non-linear.

The optical system is also telecentric at the slit and at the CCD plane. Thus, the objective lens that forms the image on the slit must also be telecentric to match the pupil locations. It is also advantageous to have excellent color correction in the objective lens as the spectrometer is designed to work over a broad spectral range.

Typical tolerances

The positioning tolerances of the mirrors in an Offner spectrometer can be fairly tight. Typically, the position between the primary and secondary and between the secondary and tertiary should be held within about 10 microns or less. Diamond turning the mirrors and mechanics has an advantage of being able to hold very tight positioning tolerances as well as making the optical system insensitive to thermal variations.

DIAMOND TURNING EXAMPLES

A typical example of a common diamond machined optical component would be a reflective off-axis parabola, machined into an aluminum substrate, shown in figure 5. This monolithic component enables the mechanical designer to incorporate mounting features that will ensure precision alignment into a diamond machined housing of the same material, assuring system level thermal stability[7].

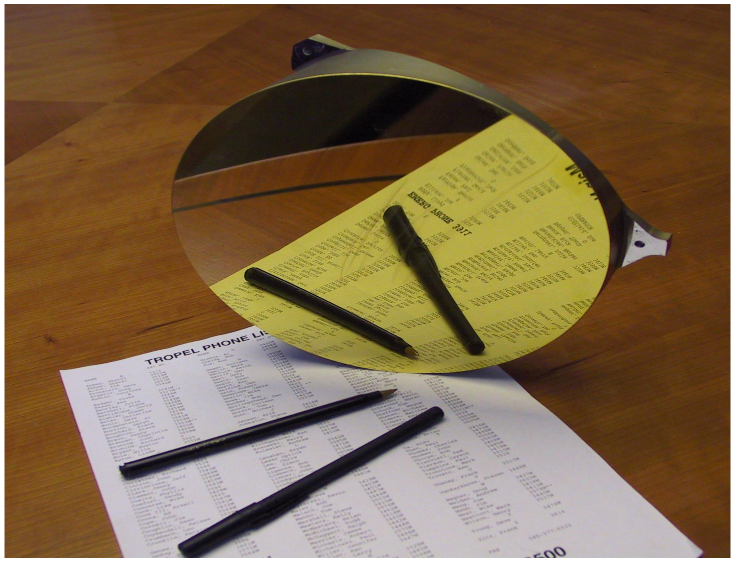


Figure 5
200 mm Aperture Off-axis Parabola

The term “Snap-Together” construction has been coined to describe such techniques. One can imagine the further downstream advantages with respect to assembly and test, as well as cost, which “snap-together” construction offers. Examples are shown in figure 6.

Figure 6
Offner-like “Snap Together” Reflective Assembly

Recent advancements in multiple axis diamond machining equipment combined with proprietary techniques and materials permit the direct machining of visible quality powered blazed gratings. These new processes allow great flexibility in the grating design including variable blaze angle, variable period, and aspheric toroidal base curves to name a few. An example is shown in figure 7. Measurements of a sample grating are shown in figure 8 and 9.

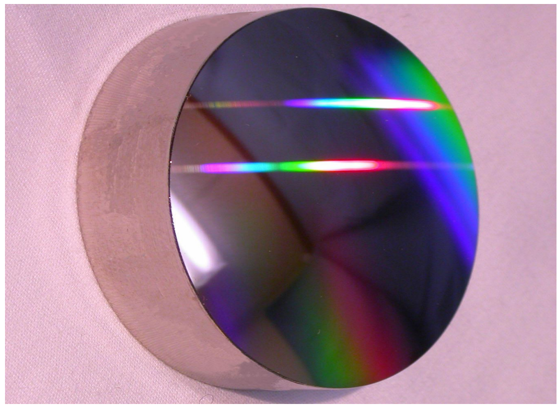


Figure 7 Diamond machined diffraction grating

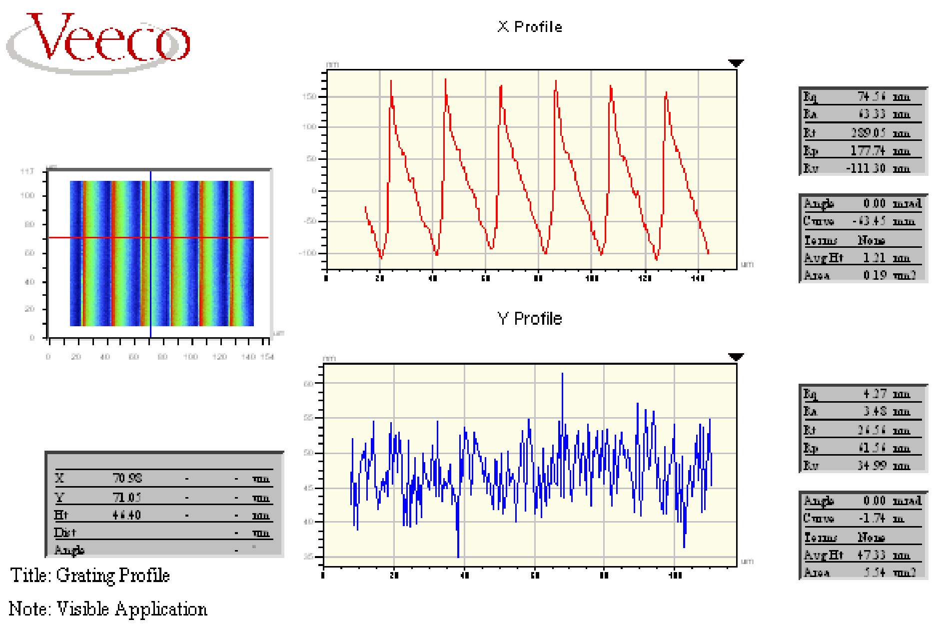


Figure 8 Profile and roughness measurement of diamond machined grating

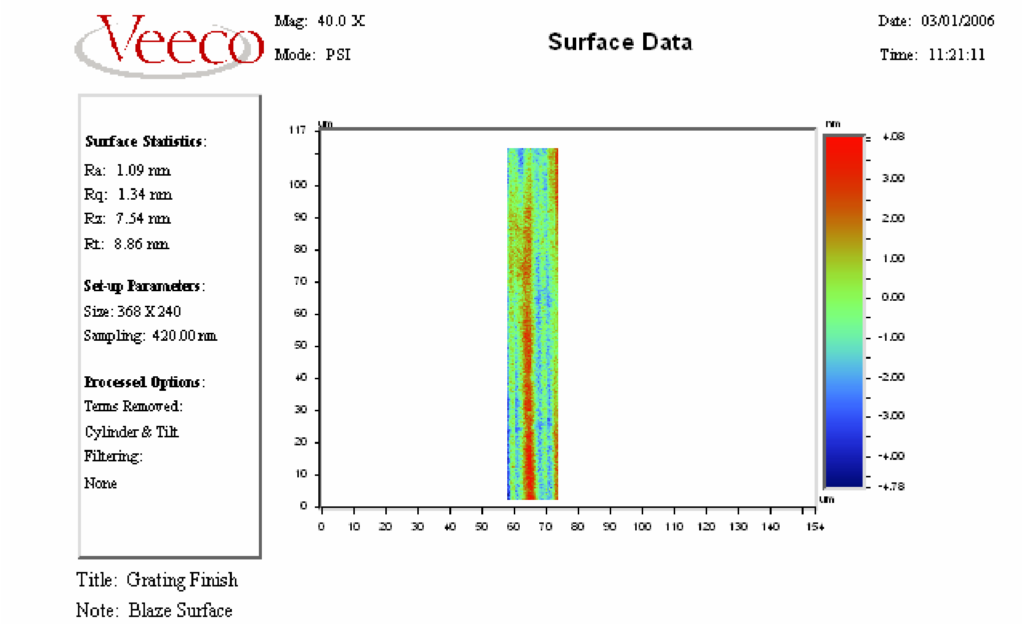


Figure 9 Finish of blazed surface of grating

Along with the grating surface, Corning has also developed a manufacturing process for directly diamond machining precision slits which serve as the spatial resolution element of Offner spectrometers. True knife edge slits have been produced with widths as small as 5 microns. The technique also allows for precision mounting features significantly simplifying the alignment process. An example of a diamond machined precision slit is shown in figure 10.

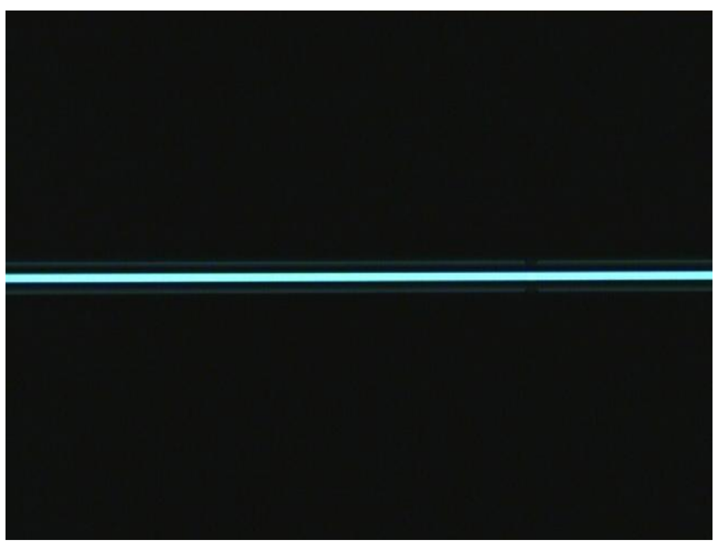


Figure 10
400X Image of 10um Slit

These techniques permit the production of imaging spectrometers that incorporate aluminum based optical components, including mirrors, gratings and slits, mounted into precision machined aluminum housing. The result is a lightweight, mechanically robust, and thermally stable system. Figure 11 shows the measured wavefront of a complete assembled Offner spectrometer. The system was measured on a HeNe interferometer operating in a double pass configuration. The design residual was 0.25RMS (1.0 PV) waves, and the assembled Offner achieves 0.24 RMS (1.3 PV) waves.

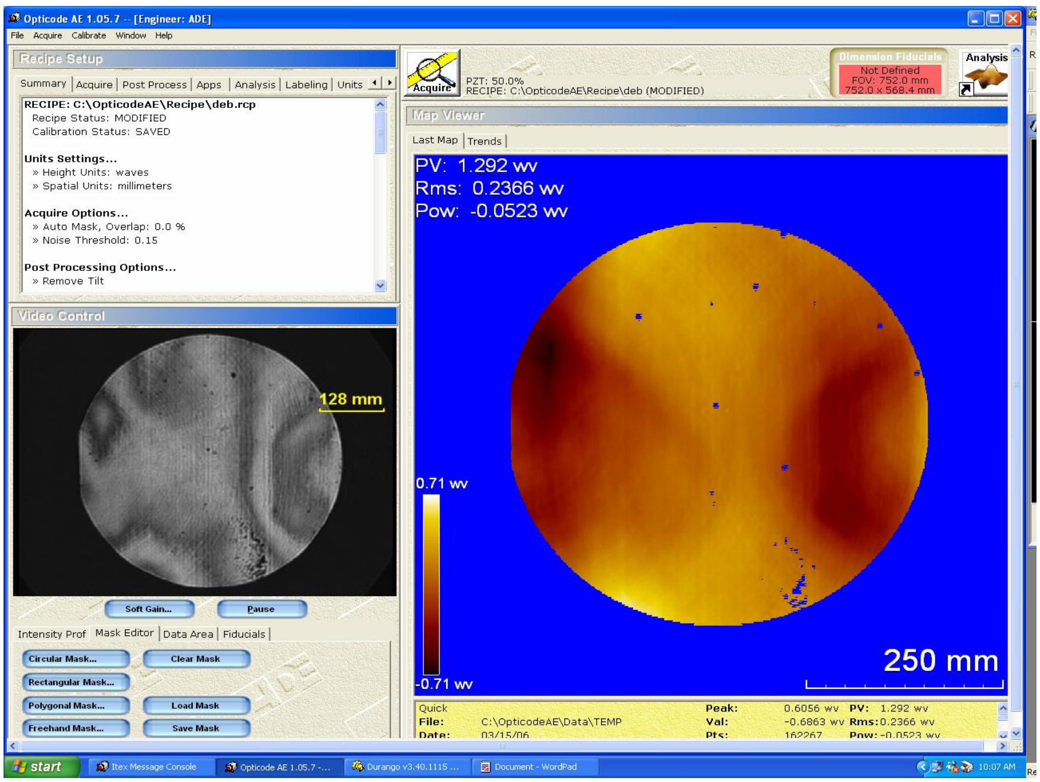


Figure11 Wavefront of Offner spectrometer

GRATING EFFICIENCY

The diffraction efficiency was calculated and measured for a blazed diamond machined diffraction grating. The pitch was 25µm and the blaze angle was 0.69 degrees. This diffracted most of the light into the first diffraction order. The grating efficiency was measured at 532nm and at 650nm. Figure 12 shows graphically the calculated and measured efficiency.

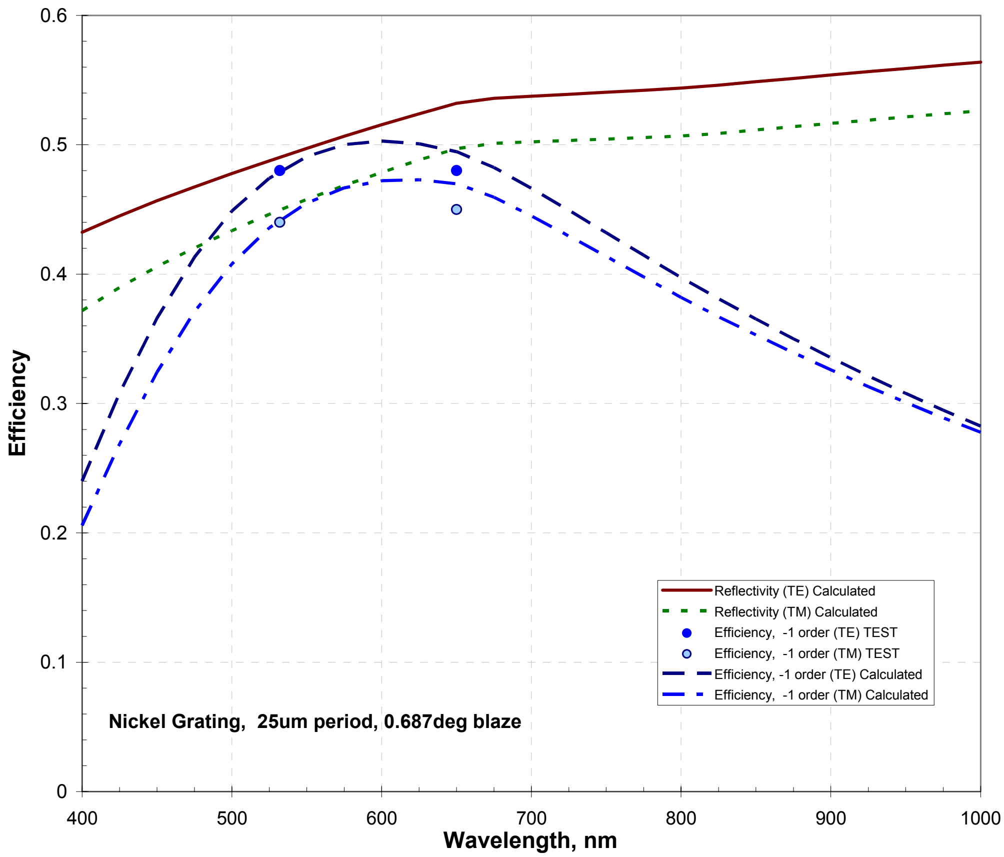


Figure 12 Calculated and measured diffraction efficiency

CONCLUSION

Corning has developed unique fabrication processes to allow precision fabrication of critical components, namely diffraction gratings and object slits, for Offner hyperspectral imagers. Gratings with variable periods and blaze angles can be manufactured directly on flat, spherical, aspherical, and even toroidal substrates offering unique design flexibility while simultaneously achieving high diffraction efficiency. Precision slit assembles limiting spatial resolution of the spectrometer can be machined with feature sizes as small as 5 microns. These components coupled with precision housing and diamond-machined mirrors with reference datums yield "snap together" alignment significantly reducing complexity and assembly time. Furthermore, as all components of the spectrometer can be fabricated from the same material, the resulting hyperspectral imaging system is thermally stable allowing high performance operation even in extreme thermal environments.

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