Low-Distortion Imaging Spectrometer Designs utilizing Convex Gratings

25-Word Abstract

Imaging spectrometer designs capable of submicron distortion in both spectral and spatial directions are described, utilizing novel types of convex electron-beam-lithography-generated gratings.

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The requirement for very low distortion in pushbroom imaging spectrometers has been recently recognized. It has been shown that the spectral response function of a pixel must be known with great accuracy.' A small uncertainty in the location of the peak of this function can lead to significant error in the calculated pixel radiance. A maximum shift of less than 1 % of the spectral response function (e.g. 0.1 nm in 10nm halfwidth) has been identified as desirable in order to produce data that are free of significant spectral calibration errors.

Although elaborate calibration methods can conceivably reduce the effect of such errors, it is nevertheless desirable to start with a design that lessens the need for and dependence on such methods. The 1 % maximum shift translates to a distortion value of 1/1 00th of a pixel, a value that is well outside the range of familiar optical designs. The designer was thus requested to investigate novel spectrometer forms that are capable of such low distortion both in theory and in practice.

The spectrometer designs that were found capable of such performance were based on the Offner reflective relay.[2] Concentric spectrometer forms have been recognized for their potential of providing good optical correction and compact size.[3,4] However, the requirement for submicron distortion has not been explicitly stated or evaluated previously. In addition, lack of an appropriate technology for grating fabrication has limited the practical realization of these designs.

Progress in electron-beam lithography techniques has permitted the fabrication of high-performance convex gratings that are a perfect solution to the above problems. Specifically, such gratings can be produced with the required substrate convexity, while providing flexibility in the following grating parameters: variation of the blaze angle (or lack thereof) across the grating, control of the shape of different blaze areas, control of the average diffracted phase difference between different blaze areas, control of the groove shape (beyond sawtooth or sinusoidal), and precise control of the grating pitch including any desirable variation. All these grating properties impact the distortion characteristics of the spectrometer.

An example of a low-distortion design is shown in figure 1. The input slit is perpendicular to the plane of the paper at the top left of the figure. The grating is formed on the convex mirror which is also the stop location. The design is telecentric, with a magnification of -1. Other characteristics of this design are: all spherical concentric surfaces, f/2.8, 18mm slit length, spectral range 1-2.5pm, greater than **82%** diffraction ensquared energy within a 27pm square pixel across field and wavelength, spectral resolution of 10nm, and total volume of 14x1 3x7cm (including slit and image). There is practically zero distortion. The optical design program gives a maximum distortion value of 0.00012% **(-10“6).** However, the percent distortion as commonly understood in optical design is not an adequate measure. The spectrometer distortion requirement involves a spectral as well as a spatial dimension.

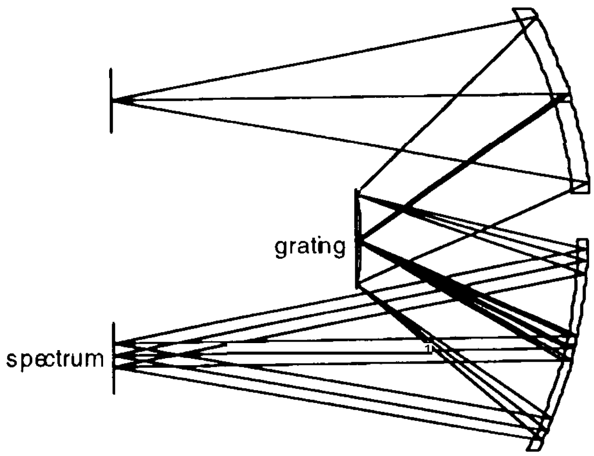

Figure 1. Schematic of a typical low-distortion Offner spectrometer design

Thus the first distortion requirement is that the monochromatic image of the slit remain straight to within a small fraction of a pixel for all wavelengths. A traditional way of relaxing this requirement is through the use of curved slits, but a straight slit is preferable in terms of ease of fabrication and alignment. On the assumption then that the monochromatic slit images are aligned with the columns of the detector array, the second distortion requirement is that the spectrum of any point along the slit be straight and parallel to a row. These two requirements have been called spectral and spatial distortion, but the names are not intuitively obvious since both can apply equally to either type of distortion; hence they are avoided here.

The design optimization utilizes a merit function in which appropriate rays are used, whose image plane intersections are representative of the centroid locations for the corresponding image points. The difference between the x or y coordinates of these locations is then set to zero to within a desired accuracy by assigning appropriate weighting factors in the corresponding operands. The remainder of the merit function is concerned with optimizing the spot size (or rms wavefront error) as usual.

Tolerance analysis performed on a sample design indicated that two of the three mirrors could be fitted to manufacturer’s testplates, while the radius of the third had to be controlled to wit hin 0.19’0. The system is sufficiently tolerant of tilts, decenters, or random wavefront error.

A system optimized in this fashion rests on the assumption that the grating has no imperfections in wavefront quality, and that the diffraction efficiency is uniform across its entire extent for all wavelengths. These requirements are in fact not normally satisfied, and must be addressed if the system is to approximate its design performance. Normally, the grating must be blazed for high efficiency. The electron-beam technique allows the fabrication of gratings in which the blaze angle remains constant with respect to the local grating normal. This cannot be done with ruling techniques unless the tool were made to change angle continuously for every groove. Ruled gratings will also suffer from wavefront irregularities, which will in general affect the centroid location and hence the distortion. Electron-beam gratings can approximate the true blaze profile without variation even over a curved surface, thus providing good wavefront quality and uniform pupil transmittance.

In some designs it has been found necessary to use two different blaze areas in order to obtain moderately high efficiency over a wider band than would be possible with a single blaze. The resulting wavelength-dependent anodization and phase difference between the two blaze areas can affect adversely the distortion as calculated on the assumption of a uniform grating. However, the electron-beam technique allows the production of concentric blaze areas, which, when coupled with lack of coma in the design, reduce the effect of the anodization to almost undetectable levels. In addition, the technique permits the control of the average relative depth of the two blaze areas. Specifically, the average depth difference can be made to be zero (within experimental error), which is also impossible with ruling techniques.

Low distortion designs have been produced over various bands within the range 0.2-12pm, with slit lengths up to 27mm, f-numbers down to 2.2, and all centered spherical optics, with sizes never exceeding 13x1 4x6cm. Electron-beam lithography allows the production of gratings that can satisfy the stringent distortion tolerances imposed by the spectrometer spectral calibration requirements.

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References

1. R. O. Green, "Spectral calibration requirement for Earth-looking imaging spectrometers in the solar-reflected spectrum", Appl. Opt. (1998) in print.

2. A. Offner: "Unit power imaging catoptric anastigmat", U.S. Patent No. 3,748,015 (1973)

3. L. Mertz: "Concentric spectrographs", Appl. Opt. 16,3122-3124 (1 977)

4. D. R. Lobb: "Theory of concentric designs for grating spectrometers", Appl. Opt. 33,2648-2658 (1 994).