Compact infrared spectrometers

Pantazis Mouroulis*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA USA 91109

ABSTRACT

Concentric spectrometer forms are advantageous for constructing a variety of systems spanning the entire visible to infrared range. Spectrometer examples are given, including broadband or high resolution forms. Some issues associated with the Dyson catadioptric type are also discussed.

Keywords: Imaging spectroscopy, infrared, Offner spectrometer, Dyson spectrometer

1. INTRODUCTION

Concentric spectrometer forms[1] have been recognized for their simplicity of construction as well as their potential for high degree of optical correction and lack of distortion. Of the two concentric spectrometer types, the all-reflective Offner form[2,3] has been the most popular and has received the most attention, finding application in several airborne and space instruments.[4-6] The catadioptric Dyson[7,8] form received less attention, although at least one instrument operating in the visible and near infrared has been based on it.[9] However, the ability of the Dyson spectrometer to handle very fast beams makes it uniquely suited to the infrared regime, where a fast system may be required to counter increased diffraction spread as well as reduced signal level. Figure 1 shows the basic Offner and Dyson forms.

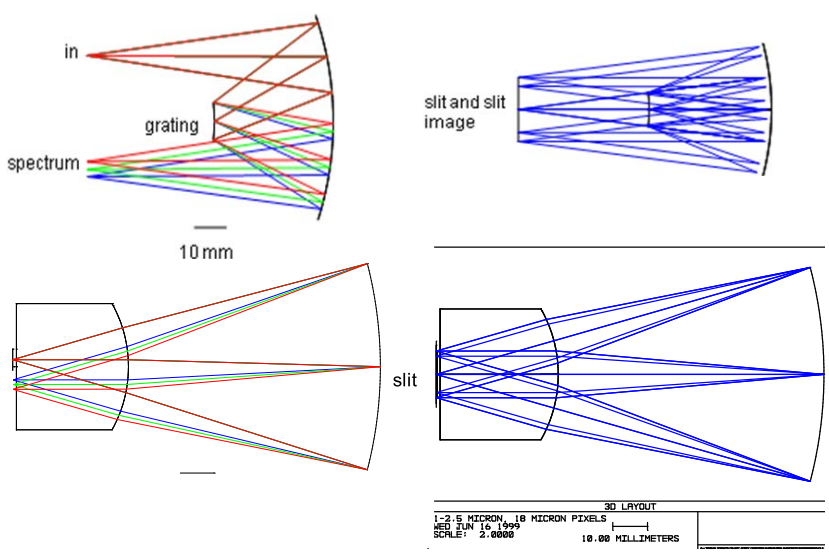

Fig. 1. Ray traces of the Offner (top) and Dyson (bottom) spectrometer types. The simplest form is shown in each case. Notice that the large concave mirror of the Offner form can be broken into two separated mirrors with some gain in performance or size.

Table 1 shows a comparison of the fundamental advantages of the two forms. Specifically, the all-reflective form of the Offner spectrometer can handle a wide band in a single order (for example, 400-3000 nm as in the Moon Mineralogy Mapper[6]) and can be passively athermalized if made of a single material such as aluminum. The Dyson form on the other hand, thanks to its immersion lens-type design can reach high numerical aperture much more easily, while maintaining a small size. As an example, a comparison of a F/1.6 Offner and Dyson spectrometers with the same specifications reveals that the Dyson spectrometer can be only 1/50th the volume of the Offner form, while in addition retaining only simple

spherical surfaces (the Offner requiring aspheres in order to reach such high aperture value). The size advantage of the Dyson form diminishes somewhat as the F-number increases.

Table 1. Comparison between Offner and Dyson spectrometer forms

Offner	Dyson
All reflective (broad band, athermalization)	High throughput
Can reach high spectral resolution	Miniature size
No ghost reflections	Easiest alignment

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Both types are telecentric in object and image space, which means that there is no convenient place for a cold stop, so the entire spectrometer must be kept at an acceptably low temperature. For the thermal IR, this can be an advantage in favor of the Dyson as it implies a significantly lower mass to cool. For shorter wavelengths, however, the advantage diminishes as it is not necessary to keep the spectrometer very cold.

Table 1 states that the Offner form can reach high spectral resolution. Of course, both types can be scaled in size to the point where a desired resolution is attained, but this can result in very large and impractical systems. The Offner type however offers two additional possibilities: it may be used in Littrow mode[10] or it may be used in an orientation where the spectrum is placed in the perpendicular direction to that shown in Fig. 1.[10,11] The Littrow mode offers the highest spectral resolution (typ. 3000-5000); placing the dispersion plane in the orthogonal direction to that of the symmetry plane permits a wider spectral range.

With respect to alignment, and assuming that the designs are constrained to spherical surfaces only (which, with appropriate design care is found not to be a severe restriction), it is evident that the Dyson form retains an advantage in that the only degrees of freedom (separation of lens and grating and grating tilt/decenter) can be controlled with a single spacer in the same way as with spherical lens assemblies. A simple interferometric method for assembling the Offner spectrometer has been given in ref. 12.

Two more characteristics of the Dyson spectrometer are relevant to the comparison, and both are dealt with in more detail below. The first is the limited detector clearance offered by the Dyson form, and the second is the possibility of ghost images formed by reflection from the detector surface.

2. BEAM FOLDING IN THE DYSON SPECTROMETER

The Dyson form achieves optimum optical correction when the detector and slit are in contact with the lens material. Evidently this is not easy to satisfy, and some clearance will be required at least for the detector (although one instrument has used an unfolded, half-aperture version[9]). Intertwined with this is the fact that the spectrum and the slit location are typically close together, since any substantial decentering of the slit will either make the system impossible or otherwise result in extreme off-axis angles and large aberrations. The detector clearance is best kept to a small value of ~1mm. No particular difficulty has been encountered experimentally in satisfying this constraint with a variety of detectors. However, having the slit and the detector on the same plane is too difficult to satisfy, as room must be made for the additional hardware surrounding the active detector area as well as the slit and foreoptics. This means that the beam must somehow be folded.

Figure 2 shows one potential way of folding the beam using a small right angle prism. The rest of the Dyson block has been broken into three pieces, a planoconvex lens and to plane parallel plates which can be cemented together. This is a low-cost arrangement, advantageous in the wavelength region where optical cements are not absorbing.

Where optical cements are not an option, optical contact can perhaps be attempted over a limited number of interfaces (preferably no more than one). Otherwise, monolithic fabrication of the block can be required. It is then helpful to

attempt folding the dispersed output beam. Figure 3 shows one such Dyson design in which the beam is very fast (F/1.4) and the material is fused silica.

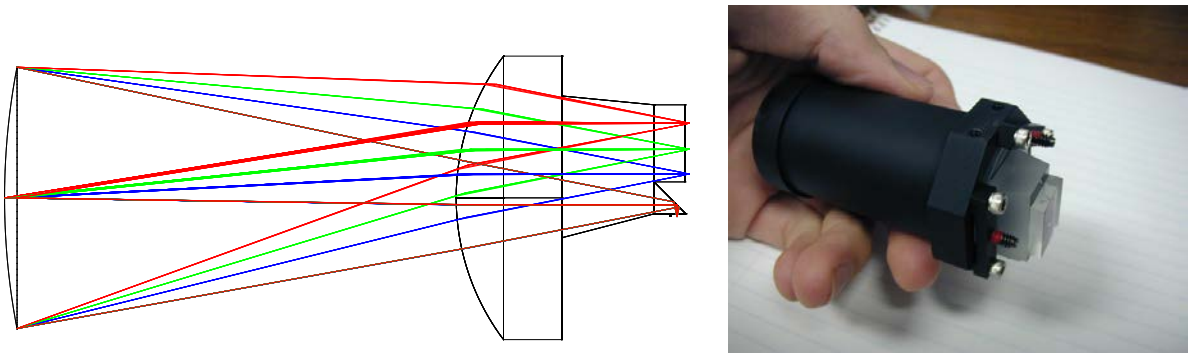

Fig. 2. Low-cost method for beam folding in the Dyson spectrometer using optical cements. Left: ray trace, showing constituent parts (thick planoconvex lens, two flats, one reflecting prism). Right: assembled optical system with grating. The assembly utilizes a single spacer between the two curved surfaces.

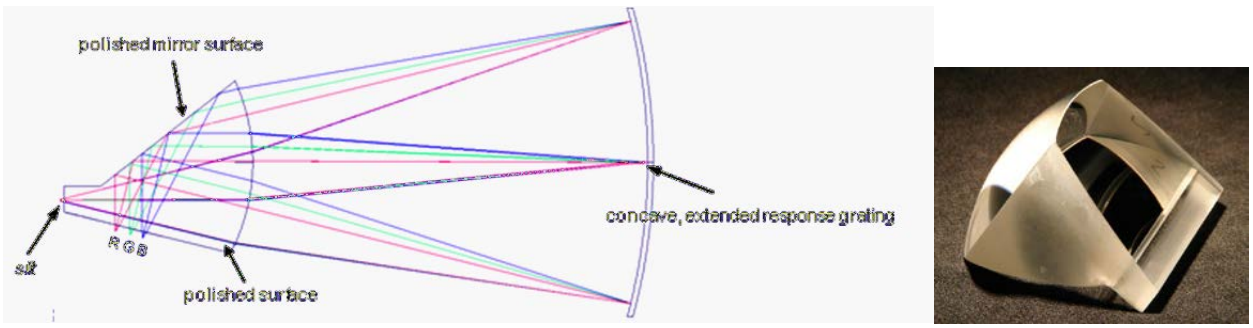

Fig. 3. Alternative way of folding the beam in a Dyson spectrometer using a monolithic block. Left: ray trace of the system (F/1.4). Right: fabricated fused silica block (Optimax) prior to coating.

A higher refractive index material may also be used. Figure 4 shows a thermal infrared spectrometer ray trace. The corresponding Dyson block is made from ZnSe.

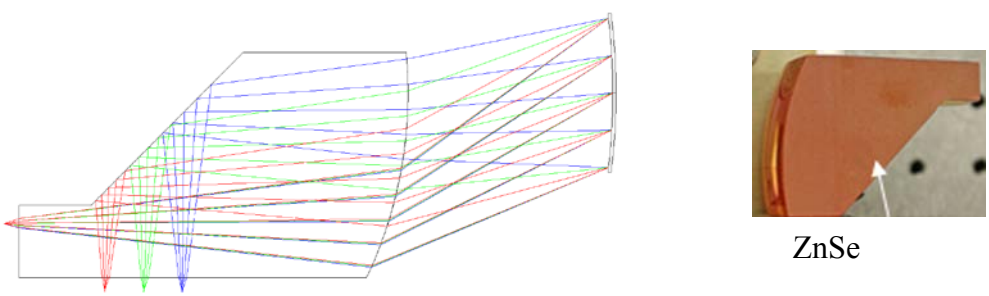

Fig. 4. A thermal infrared spectrometer covering the 8-12 μm range with 256 spectral channels. The maximum dimension (along the optics z-axis) of the ZnSe element (II-VI) is 6 cm. The F-no is 1.6.

Alternative beam folding arrangements have been discussed by Warren et al[13], who used either a fold of the input beam for a relatively slow-speed Dyson, or a separate fold mirror in air, by increasing substantially the clearance between slit/detector and block. Such increase however required the addition of an extra element between the main block and the grating, as well as aspheric or decentered surfaces, thus requiring a substantial departure from the simplicity of the basic Dyson form.

3. GHOST SUPPRESSION IN THE DYSON SPECTROMETER

Light reflected from the detector has the potential of creating ghosts. If the detector reflectivity is not suppressed, this problem can be troublesome in the Dyson form and must be ameliorated with appropriate design. The offending light path is detector →grating → detector (via a different order). This light path is theoretically possible in the Offner spectrometer also, except that the required orders are very high and thus carry no energy. This difference is due to the larger angle of incidence on the grating for the Offner spectrometer.

The 0th order is the most obvious one to avoid, but other orders can also enter. Conceptually, the easiest way to avoid all these ghosts is to allow the spectrometer to grow enough so as to accept a slit twice the size of the intended one, then decenter the slit to be fully above the plane of symmetry of the spectrometer, thus directing all detector ghosts outside the useful detector area. This however, may not be feasible if a minimum size is required. The alternative is then to have an efficient A/R coating on the detector.

When the displaced slit design is not feasible, it is necessary to consider carefully the grating diffraction efficiency in all significant orders as well as the detector reflectivity, and order-sorting filter transmittance. It is possible that special detector anti-reflection coatings will be required.

An example of detector ghost strength is shown in Fig. 5, for a broadband system operating with an extended response InGaAs detector in the 400-1700 nm region. The grating operates in the +1 order and its predicted efficiency is shown in Fig. W for the +1, -1, and -2 orders. The two negative orders are those that generate potentially noticeable ghosts. The detector reflectivity is assumed to vary between 10% and 30% over the entire band.

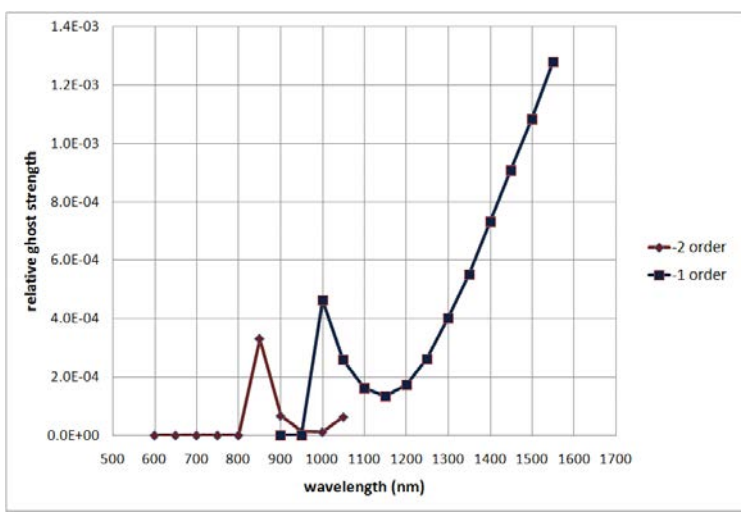

Fig. 5. Calculated detector ghost strength for a broadband Dyson spectrometer. Because of their specific location on the detector, the wavelengths below 800 nm (-2 order) and 950 nm (-1 order) are rejected by the order sorting filter. The ghosts are below a 1E-3 threshold except for the long wavelength end where it just rises above that level in the -1 order. The curve stops at 1550 nm because longer wavelengths fall outside the useful detector area (covering 400-1700 nm in +1 order). Reduction of the ghost strength at the long wavelength requires reduction of detector reflectivity.

Another stray light path arises from light reflected from the material surrounding the slit. In the Offner spectrometer this reflection can be directed outside the spectrometer aperture by tilting the slit substrate, and be blocked by appropriate baffles. In the Dyson spectrometer, the proximity of the slit to the refractive element may make it impossible to tilt the

slit enough, and may also send the reflected light back inside the element where it can still contribute to stray light. Thus a way of reducing the slit reflectivity is generally desirable. The offending path in this case is slit→grating→slit plane (via higher order)→ grating→detector.

Additional ghost paths are possible in the Dyson spectrometer and must be appropriately controlled with antireflection coatings on all surfaces. The availability of efficient, broadband A/R coatings can be a limiting factor in Dyson spectrometer stray light performance.

4. TECHNIQUES FOR GRATING FABRICATION

The diffraction grating is the most critical component of the spectrometer. To take full advantage of the potential of concentric spectrometer forms, new fabrication techniques have been developed. Early Offner forms used holographic gratings which are not well suited to the coarse groove spacing often required. The advent of electron-beam lithography as a grating fabrication technique[ref14] spurred the development of concentric spectrometer forms to achieve maximum performance, culminating in the Moon Mineralogy Mapper instrument, currently orbiting the Moon on board Chandrayaan I. E-beam gratings can be fabricated on a variety of substrates with different curvature and can be made to have a wavelength response tailored to the requirements of the application.[14,15] This can be achieved either by splitting the grating area into parts with different blaze angles (while maintaining perfect coherence or registration between them) or by altering the groove shape. E-beam gratings have now flown on three space missions as well as on airborne instruments.

An alternative technique via X-ray lithography was developed to cope with larger areas and curvatures than could be reasonably accommodated with the E-beam. This technique demonstrated high quality single blaze gratings[16] and is currently under further development to produce a modified groove profile for broadband response. The predicted response is shown in Fig. 6. The figure also shows the efficiency of two more orders that were used in the computation of ghost strength in Fig. 5.

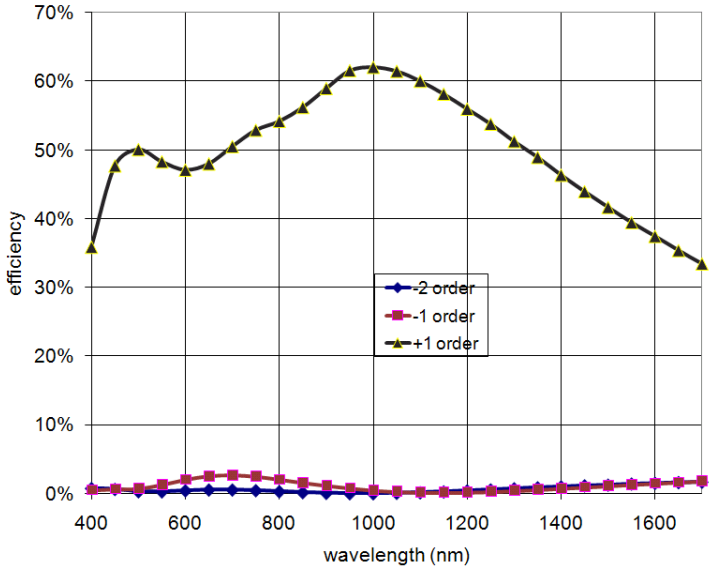

Fig. 6. Computed response of a broadband grating achieved by groove modification. The main (+1) order is shown together with the two orders that are of concern for detector ghost reflections (Fig. 5).

A more recent development is the use of single point diamond turning, which has been used to provide gratings operating both in the visible/near infrared and in the thermal infrared.[13] This technique has been demonstrated on aluminum substrates and can produce good quality sawtooth blazed gratings.

5. A FAST, BROADBAND DYSON SPECTROMETER FOR PLANETARY MINERALOGY

A breadboard version of this spectrometer is under construction at present, and is expected to utilize a grating fabricated with X-ray lithography with a diameter of 66 mm and 18μm pitch. The ray trace can be seen in Fig. 3; the results of figures 5 and 6 also pertain to this system. The main application for this spectrometer is planetary mineralogy for which wavelengths as long as 2500 nm and often longer are required. The breadboard under construction is limited to 1700 nm by the InGaAs array detector used, but it serves as a pathfinder for the other two systems. The comparison of the three systems is shown in Table 2.

Table 2. Three spectrometer systems for planetary mineralogy

	System A	**System B**	**System C**
Science target	Mineralogy of rocky bodies	Organics, Ices, Minerals	Mineralogy, proof of concept
Spectral band (nm)	400-2500	800-3600	400-1700
Sampling (nm)	9	9	4.6
Spatial pixels	600	600	640
Pixel size (μm)	27	27	25
F-no	1.4	1.4	1.4
Length (optics - cm)	12	12	12
Diameter (optics – cm)	7	7	7
Refractive material	Fused silica or CaF_2	CaF_2 , ZnSe	Fused silica or CaF_2
Detector	HgCdTe	HgCdTe or InSb	InGaAs
Operating temp. (K)	150	100	240

Spot diagrams for this design are shown in Fig. 7, where it can be seen that the spot energy is well contained within the pixel for all wavelengths and fields. Geometric distortions are limited to < 1% of a pixel (250 nm) across the entire field and spectrum.

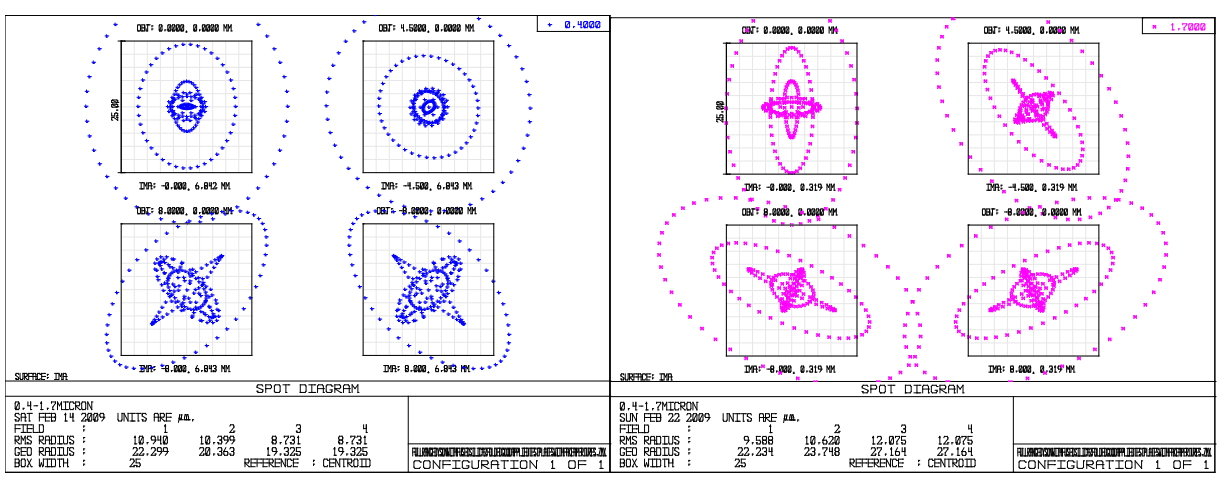

Fig. 7. Spot diagrams for spectrometer C of Table 2, with ray trace shown in Fig. 4.

The preliminary version of this spectrometer resembled that shown in Fig. 2 and was advanced to the point of performing initial characterization and receiving spectra. Figure 8 shows typical spectral response functions obtained with that breadboard, and Fig. 9 an image of Hg line across the entire spatial field.

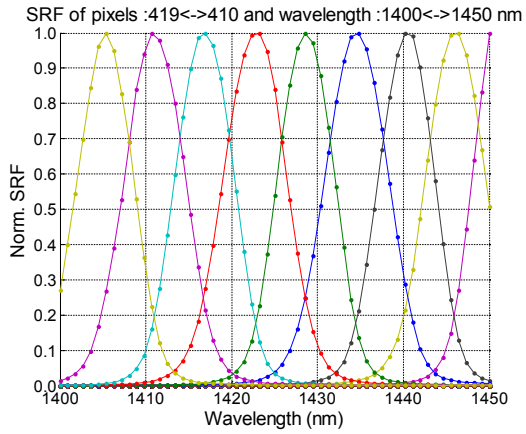

Fig. 8. Spectral response functions of eight typical channels in the region 1400-1450 nm for the spectrometer breadboard of Fig. 2.

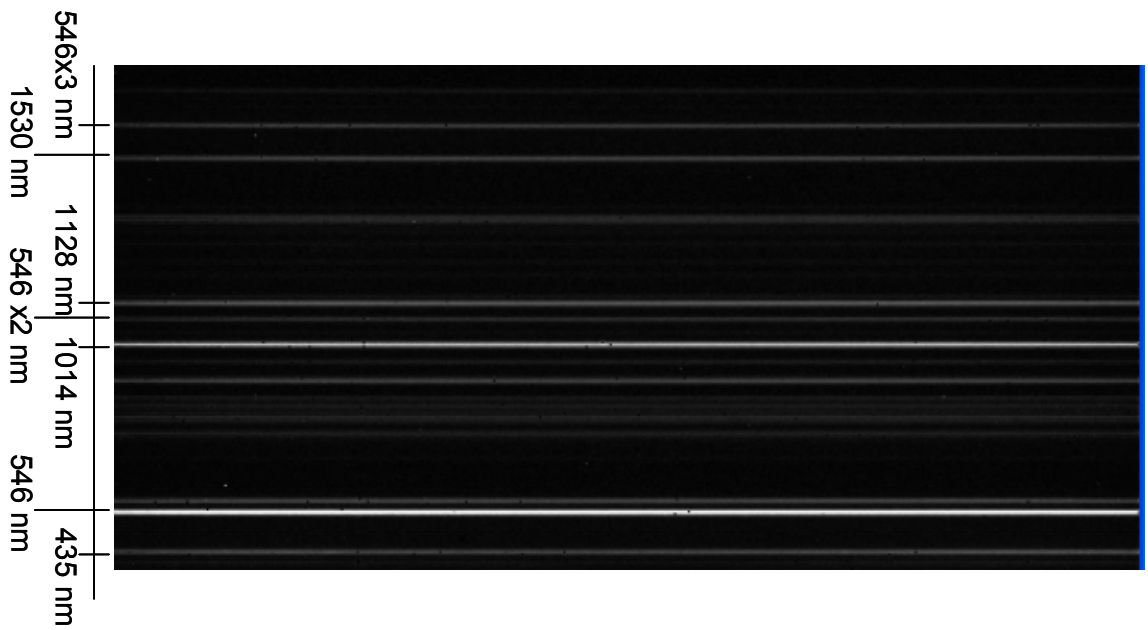

Fig. 9. Spectrum of a Hg source obtained with the spectrometer of Fig. 2. The wavelength of the main lines is identified on the left. No order-sorting filter.

6. OTHER SPECTROMETER EXAMPLES

The Dyson spectrometer can be readily adapted to other medium resolution applications. A more advanced version of a thermal IR spectrometer shown in Fig. 4 has been designed and is already under development. The spectrometer will operate in the 7.5-12 μm range with 256 spectral channels, and 512 spatial elements at F/1.6. The miniature size of the Dyson allows the entire spectrometer body to be cooled at 100K ensuring negligible emission. Spot diagrams are shown in Fig. 10. The same spectrometer with no change except in the grating pitch can also be used in the 3-5 μm region and will achieve the very similar performance.

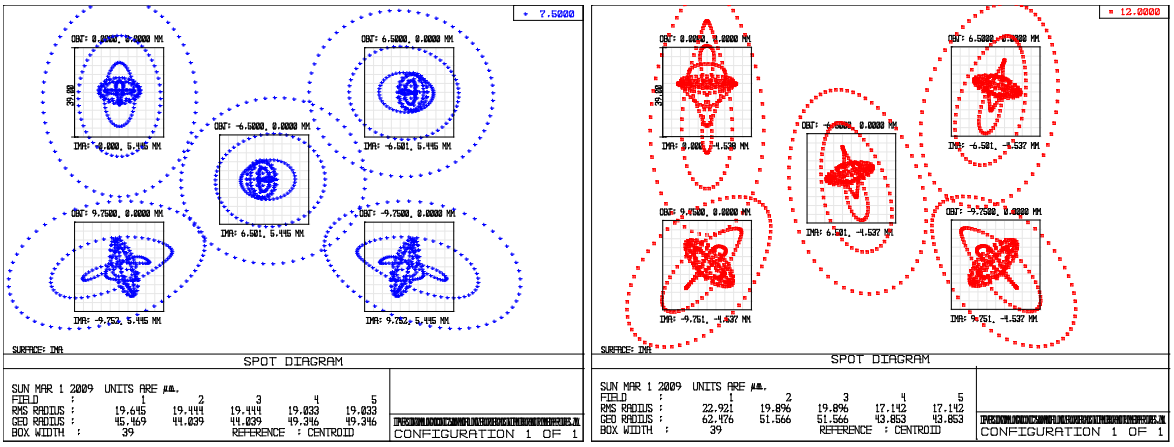

Fig. 10. Spot diagrams of a miniature F/1.6 Dyson spectrometer operating in the 7.5-12 µm range. The size of the box is equal to the slit width (39 µm).

As mentioned in the Introduction, the Offner design is capable of accommodating a broad band as well as provide high resolution. Two examples of Offner designs spanning these two extremes are shown below. The broadband example is provided by the Moon Mineralogy Mapper,[6] which spans almost three octaves (400-3000 nm) at 10 nm per channel. The optical design is shown in Fig. 11. It is possible to further miniaturize that design if the monolithic concave mirror is broken into two. The resulting design is also shown in Fig. 11, with the mass of the optical bench reduced by an estimated 70%. There are additional subtle differences between the two designs due to the differences in the detector arrays under consideration.

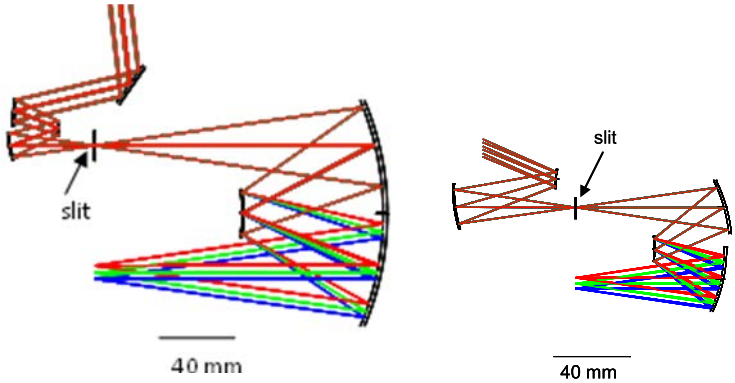

Fig. 11. The Moon Mineralogy Mapper design (left) and a miniaturized version of the same with the same specifications except a somewhat narrower spectral range (up to 2600 nm) and a wider field of view (36°).

Finally, a high resolution version of the Offner spectrometer, with the grating working in Littrow mode is shown in Fig. 12. This operates with a 640x480 detector array where the wide dimension is the spectral. This spectrometer operates at F/3, and achieves 0.6 nm resolution in the range 3300-3700 nm or a spectral resolving power of about 5800, with only two spherical elements and a fold. In addition, the spectrometer achieves near diffraction-limited performance, with 78-82% of the energy in a pixel (compared with 64% for a diffraction-limited beam) and has also negligible distortion.

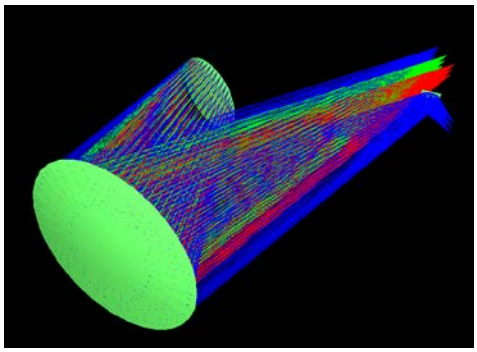

Fig. 12. A high-resolution (R~5800) MWIR spectrometer with the grating operating in Littrow mode.

7. CONCLUSIONS

Concentric spectrometer forms offer great flexibility for a variety of infrared applications spanning a broad range of requirements. Compact spectrometers can be constructed in the range from the visible to ~14 μm. The relative aperture can be as low as 1.4 without departing from the simple concentric form. Low, sub-kg mass can be achieved, while maintaining high uniformity of response. Broad spectral band of up to three octaves or even more can be obtained in a single spectrometer is first order with appropriate grating technology. High spectral resolution is also possible in certain configurations.

Acknowledgments

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