Manufacturing image slicing and image mapping mirrors

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ABSTRACT:

Micro-faceted mirrors are the core component of image-slicing and image-mapping spectrometers. Manufacturing these mirrors requires considerable care, with tolerances on the order of 2um, and angular tolerances of 2mdeg, across parts 50mm × 50mm in size. We show manufacturing methods for achieving these tolerances, and how these mirrors operate to achieve the amazing performance that image-slicing and image-mapping have demonstrated.

Keywords: Micro-faceted mirror, Image-slicing, Image-mapping

1. Introduction

Image slicing mirrors (or “slicers”) are the core components of an advanced technique for doing imaging spectrometry --- sometimes called image slicing spectroscopy (ISS) or image mapping spectroscopy (IMS). By slicing the image into thin strips, these specialized mirrors allow the optical system to reorganize the strips into one long stripe (appropriate for a large-format slit spectrometer) or to spread them out for use with an array of slit spectrometers. The latter format can be constructed compactly using an array of lenslets and an array of prisms.

Figure 1 shows a simplified optical layout of a spectral imaging system that uses the image slicing technique. Light from the object is imaged onto the surface of the slicer facets. Since the facets are cut at various angles, any light hitting a facet reflects at a unique angle. In the back end of the optical system, each lenslet is placed in a position to receive light from its designed facet angle. Light from all of the other angles does not reach the lenslet, and this opens up a large amount of empty space on the detector array. By passing the light through a prism, each lenslet is made to act as an independent slit spectrometer, where the slicer facets themselves act as the slit.

The advantage of using this complex optical layout is that the system can collect spectra for every pixel in a full 2D image without scanning. This provides a large increase in light collection efficiency, often by multiple orders of magnitude.[1] This is something we call the ``snapshot advantage'', as it supersedes the older Jacquinot and Fellgett advantages that were developed to describe instruments before the arrival of shot-noise-limited 2D detector arrays.

The original idea for image slicing came out of astronomy, where it was first mentioned by I. S. Bowen as a method to improve light collection efficiency for spectrometry.[2] Later, A. K. Pierce adapted the idea so that it could be implemented with faceted mirrors,[3] later to be modified once more by L. Weitzel *et al.* into the form generally used today.[4] Soon after Weitzel *et al.* built their first image slicing system, Robert Content discovered that using curved facets can further improve the performance of the instrument.[5] Due to the increased difficulty of manufacturing such a large array of curved elements, however, not all modern slicing mirrors use curved facets.

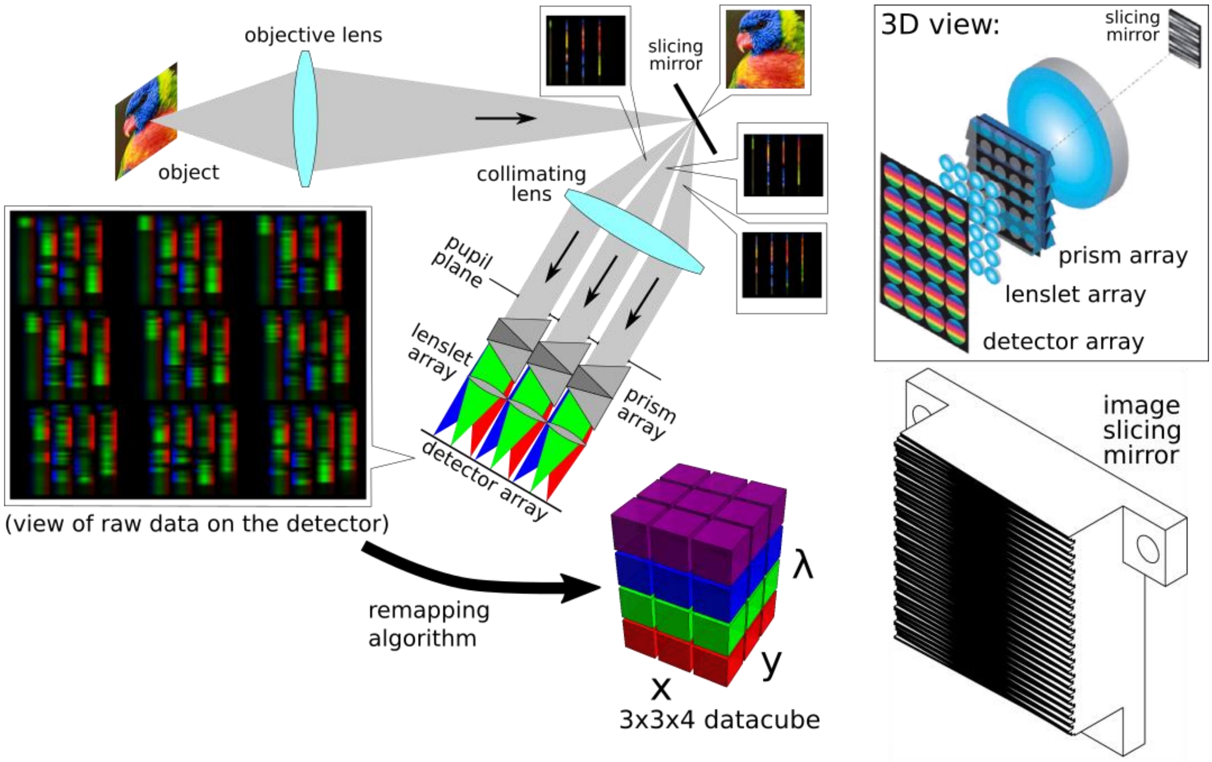

Fig. 1: A simplified layout of an image slicing or image mapping spectrometer. Although a 3×3×4 spectral image datacube is shown here, actual systems generally produce much larger datasets, such as 300×500×40.

2. Image slicing and image mapping

One of the basic features of image slicers is that each facet is tilted to a unique angle. Thus, the number of tilt angles equals the number of sampling elements in the *x*-direction, N_x. The number of sampling elements in the *y*-direction, N_y, is determined by the height of the image of the facet on the detector array. The number of spectral sampling elements N_w is determined by the distance between lenslets in detector pixels.[6] Since increasing the number of facets is the most difficult aspect of the design, these constraints generally mean that image slicing will produce datacubes that have large values for N_w, and maybe N_y, but small values for N_x. This works well for many astronomy applications, since they require high spectral resolution, and often do not require the highest spatial resolution (e.g. galaxies, nebulae, etc.).

In the case of microscopy, these tradeoffs are problematic. Microscopy applications generally use low spectral resolution (e.g. $0 < N_w < 40$) but require high spatial resolution (e.g image dimensions of 1000×1000). In order to achieve datacubes with these sizes, image slicing is inappropriate, so that the alternative layout of "image mapping" was developed. For image mapping, instead of using each unique tilt angle to represent one *x*-column in the image, we use the number of tilt angles to represent the spectral sampling rate, N_w.[7] For example, if we design a system for 40 tilt angles and $N_w = 1000$, then we will have 40 lenslets, with each slit spectrum behind a lenslet being 40 pixels wide, and 25 of these slit spectrum placed one after another. That is, the faceted mirror is manufactured to have each tilt replicated 25 times across the face of the mirror, with 39 facets between it and the next same-tilt facet.[8]

3. Manufacturing of image slicing mirrors

Early implementations constructed slicers by polishing the thin edges of many glass or stainless steel blades (see Fig. 2a). I will refer to this method as "blade polishing". Once polished to the appropriate tilt angle, the glass blades were then given a high-reflectivity coating and assembled together. If the sides of the glass blades are also polished, then they can be placed beside one another without spacers, so that they behave as a single faceted mirror. While this procedure allows for the use of conventional optical manufacturing methods, it is labor-intensive, requires difficult alignment procedures to make sure that all of the glass blades are aligned to one another to sufficient accuracy, and can only be used when the blades are thicker than ~250μm across their narrow dimension.

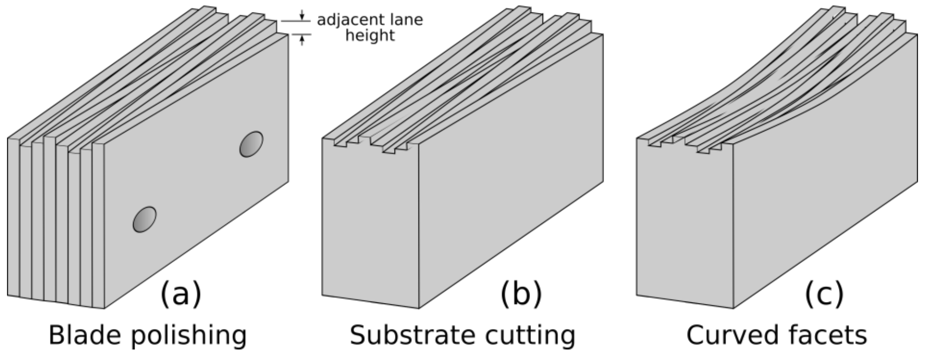

Fig. 2: A faceted mirror constructed with (a) a set of individually polished glass blades pressed together, (b) cutting a monolithic substrate with a diamond tool, (c) the facets may also be curved. The optically active surface is facing upwards. While all of the tilts shown here are along the long dimension of the facets, in practice the facets are tilted in 2D, so that each facet shown here would actually be composed of multiple thinner facets, each of which are tilted along the short dimension of the facets, as shown in Fig. 3.

In order to make the faceted mirrors more practical to make, manufacturing methods switched from using a set of glass blades (Fig. 2a) to cutting the facets into the surface of a monolithic substrate with a diamond tool (Fig. 2b).[9,10] I will refer to this method as "substrate cutting". Machining with diamond tools has made rapid progress in the last 20 years, so that ultra-precision lathes such as Moore Nanotech's UPL450 or Fanuc's Robonano can be driven with sub-nanometer position feedback resolution and can produce surfaces with nanometer-level RMS roughness. Substrates such as aluminum, bronze, and high-phosphor electroless nickel (NiP) are common choices, with each having different advantages. High-purity aluminum has the advantage that it achieves a highly reflective surface without the need for an extra coating, but has the disadvantage of being a very soft material. Electroless nickel is among the hardest of diamond-machinable metal substrates, but has a low reflectivity, and so a high-reflectivity coating must be applied to it after cutting. Some crystalline materials such as ZnS and Ge can also be diamond-ruled, but are uncommon choices because of the need to align the cutting plane with the material's crystal orientation in order to achieve a high-quality surface.[11]

One final possibility for manufacturing is hot press molding. This approach relies on first creating a master template with blade polishing or substrate cutting, then generating a negative mold of the surface. Inside the press, hot glass is pressed into the negative mold to generate the surface. While this is a promising approach for mass production of these parts, previous attempts have so far not been successful at creating surfaces with sufficient accuracy and quality.[12]

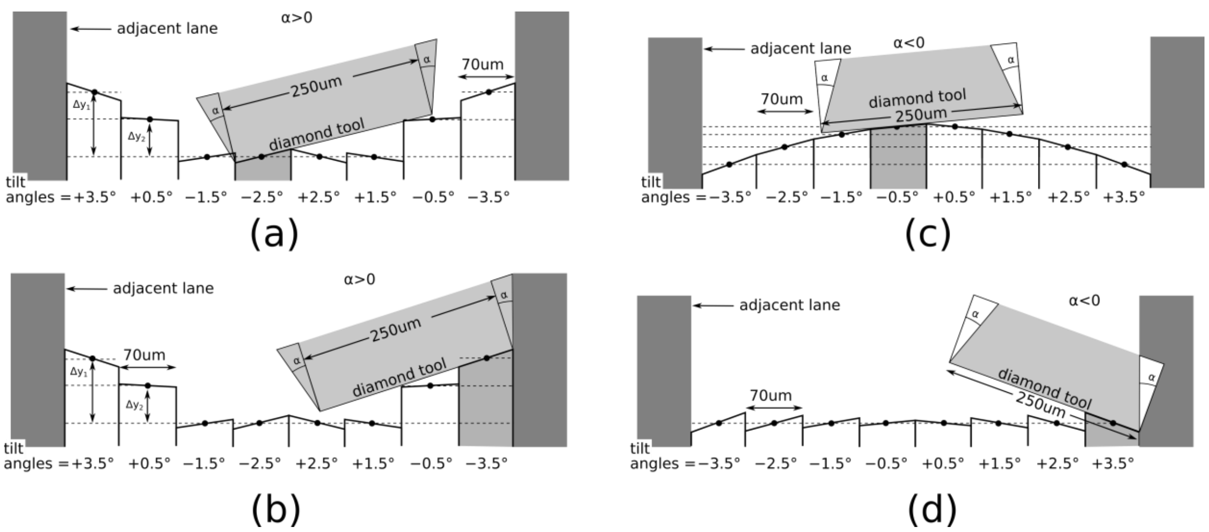

Fig. 3: Facet tilt layout for image slicing and image mapping. The "adjacent facet" at the left side and at the right side can be several millimeters tall at the edges of the slicing mirror, depending on the design. The diamond tool is shown to illustrate the position of the tool tip when the facets are cut. For (a) and (b) the outer facets are tilted inwards so that the edges of the diamond tool do not cut into the adjacent facets. For (c) and (d) layouts, the diamond tool must be designed so that the width of the tool decreases the farther it is from the tip.

4. Diamond cutting tool design

While substrate cutting is the probably the best method currently available for making faceted mirrors, the cutting procedure requires a lot of care, both with the ordering of the facets and with the design of the diamond tool. If the facet tilts are along only the short dimension of the facets, then a facet layout such as Fig. 3c is ideal. In this case, we can use a wide diamond tool for cutting, and we can use the strongest part of the tool (the middle) for cutting.

In order to differentiate between the two directions of tilt, we will call the group of facets (8 facets in the case of Fig. 3) that share the same long-dimension tilt angle as a "lane". Each of the cuts shown in Fig. 2 is a lane. Thus, each lane has a unique long-dimension tilt, and contains a set of short-dimension-tilt facets. When there are tilts in both the long and short dimension of the facets, then the "adjacent lanes" shown in Fig. 2 and Fig. 3 can become tall at the ends of the slicing mirror. In this case, the diamond tool either needs to be tilted inwards when cutting the facets --- in order to avoid unintentionally cutting the adjacent facets --- or the diamond tool needs to be designed with a negative back clearance angle α (also see Fig. 4). If the tool has a depth of cut longer than a couple millimeters, however, a negative back clearance makes for a thin and fragile diamond tool. In order to use a tool with a positive back clearance angle (also called a positive included angle), the more complicated layout shown in Fig. 3a,b can be used.

One of the advantages of image slicing over image mapping is that image slicing geometries often allow for minimizing the height of the adjacent lanes, so that the cutting geometries of Fig. 3c,d may be possible even with a tool having $\alpha > 0°$. Image mapping generally requires longer diamond tools and deeper cuts, so that the diamond tools are more fragile than those used in image slicing. However, if the diamond tool design is a problem, then one can cut each of the lanes separately and assemble them together after the cutting is complete. This allows all of the lanes to use the layout shown in Fig. 3c, effectively mixing the blade polishing and substrate cutting techniques as a sort of compromise method. Another technique that can be used is to split the slicer mirror into multiple pieces, so that the long dimension of the facets is shorter. This allows one to work with a diamond tool that has a shorter depth of cut, and thus a stronger tool.

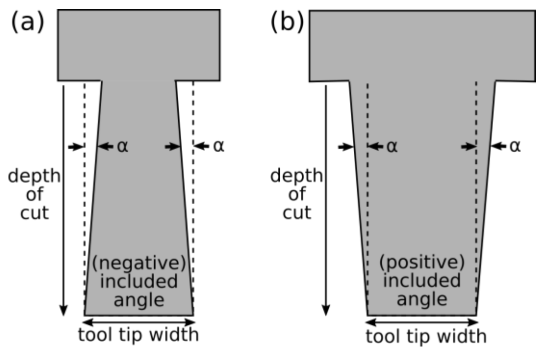

Fig. 4: The diamond tool design, showing a tool with (a) a negative back clearance angle α, and (b) a positive back clearance angle α.

5. Why do we need curved facets?

Figure 2c showed that the facets cut into slicing and mapping mirrors may be curved. Curved mirror faces allow the mirrors to act as field lenses, which improves the system optical performance. In order to show this, Fig. 5 shows an optical layout for a relay optical system before (Fig. 5a) and after (Fig. 5b) the introduction of a field lens at the image plane. Without the field lens, optical rays from a non-telecentric objective lens will continue to spread out, so that the collimating lens has to be quite large in order to catch the full set of rays without vignetting. A lens placed at an image plane has no first-order effects on the image, but bends the outer rays in towards the axis so that a much smaller collimating lens can be used.

This behavior is also useful for an image slicing/mapping spectrometer. For these systems, the faceted mirror is placed at the image plane, so that by curving the facets we allow the mirror to have optical power, just as the field lens does in the transmissive optical example.

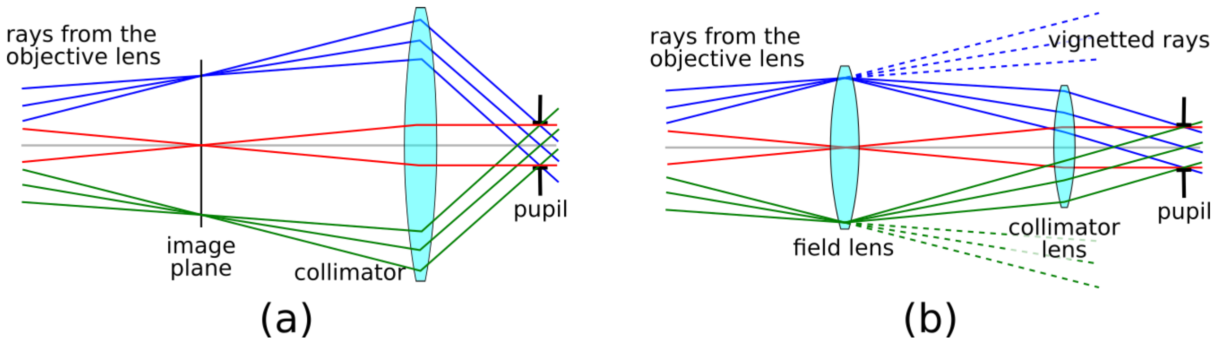

Fig. 5: In a relay imaging system, the rays from the objective lens reach the image plane and continue on towards the collimating lens. If we insert a field lens at the image plane, we can use a much smaller collimating lens without causing vignetting of the outer rays.

6. Ruling vs. flycutting

When using an ultraprecision lathe to cut the facets, one can use either ruling or flycutting methods to cut the facets. The primary advantage of the ruling method is that it is fast: a typical slicing mirror can be produced within well under 24 hours of cutting time. The disadvantage is that the surface roughness is higher for this method. For aluminum, one cannot expect to achieve roughnesses of better than ~20nm RMS, while for nickel-phosphor substrates this improves to ~10nm RMS.

The second cutting method option is flycutting, which has the advantage of producing surfaces with lower surface roughness. For aluminum substrates, achieving ~5nm RMS is not difficult, and ~2nm RMS for nickel-phosphor substrates, as illustrated in Fig. 6.[7] The disadvantage is that the cutting time is much longer. In the author's experience, a machining time of 12 hours by ruling can expand to a full 2 months days by flycutting.

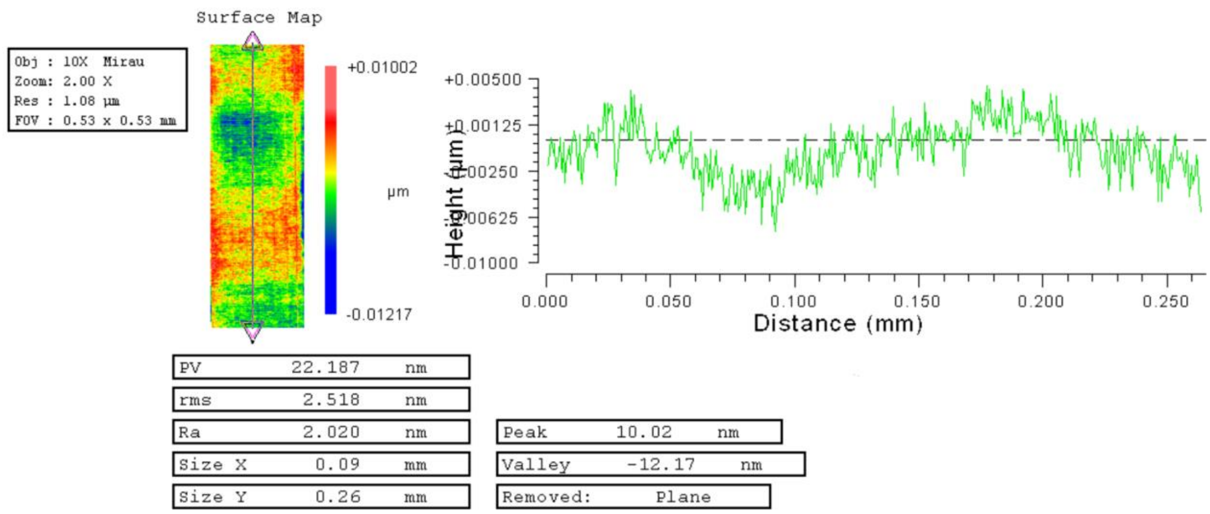

Fig. 6: The surface profile of an image mapper facet, cut from a NiP substrate, measured by white light interferometry. The data shows a 0.26 mm long section of the 90µm wide facet.

7. Conclusion

Slicing mirrors and mapping mirrors are essential components in snapshot imaging spectrometers --- an emerging technology for measuring the spectra at each pixel in a scene. Of all the techniques currently known for doing snapshot imaging spectrometry, image slicing/mapping has been shown to be the most efficient for large datacubes. Image slicing mirrors are the core element of these devices, and making them requires careful design and precision machining technology. The discussion above listed some of the constraints that existing manufacturing method face. To make these devices more practical, additional ideas are needed to further improve existing techniques.

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