euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
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Design, manufacturing, and integration of high precise slit assemblies for spectrometer applications

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Abstract

Slit and double slit assemblies are key components for optical spectrometers. The incoming light is diffracted at the slit edges which disperse the light into several wavelengths. Depending on the optical design of the spectrometer, e. g. the size of detector pixels, requirements for the mechanical accuracy of the slits down to the sub-micron range in absolute width and length are common. In addition, a variation of the width along the slits in sub-micron range is required. The needed slit planarity is less than 5 µm in most of the cases.

Depending on the required geometrical slit accuracies, the manufacturing of the slits and their integration concept is different. Mechanical parts, machined by single point diamond turning technology, can be used for slit assemblies. Furthermore, lithographic structured slits mounted in ultra-precise manufactured mechanical holders can be built. For the realization of double slit assemblies, laser structuring of metal foils or lithographic structuring of silicon wafers are used. In most cases, the combination of high precision mechanical manufacturing technologies and non-mechanical lithographic structuring is necessary.

The paper describes different design concepts of slit structuring. The mechanical designs of slit assemblies are illustrated, including the manufacturing, assembly and alignment challenges, and solutions. The results of mechanical and lithographic slit manufacturing are discussed on optical spectrometers applications for earth observation, which are used on the DESIS-, the Sentinel 4 - and the FLEX-instrument.

Keywords: Slit Assembly, Double Slit Device, Spectrometer, mechanical and lithographic slit structuring, Assembly, Alignment

1. Introduction

Slit and double slit assemblies are key components for optical spectrometers. The incoming light is diffracted at the slit edges which disperse the light into several wavelengths. If the incoming beam was splitted into two single beams, two single slit assemblies are necessary [1]. In [2] the two channels of the spectrometer are generated by passing a double slit. The generated single beams are guided by reflecting mirrors in different directions to reach the detectors. The position of the slit elements must be aligned with respect to the incoming beam, passing the telescope and to reach the detector pixels of the focal plane.

2. Requirements on Slit Devices

Depending on the optical design of the spectrometer, e. g. the size of detector pixels, requirements for the mechanical accuracy of the slits down to the sub-micron range in absolute width and length are common. In addition, a variation of the width along the slits in sub-micron range is also required. The needed slit planarity is less than 5 µm in most cases.
The structured slits must be integrated into mechanical holders to mount and align the slit structure to the optical path of the instrument. Thus, an alignment of the slit with respect to mechanical interface is necessary.

3. Manufacturing of slit structures

Depending on the required geometrical slit accuracies, the manufacturing of the slits and their integration concept is different. Mechanical parts, e. g. razor blades, can be used for building slit assemblies. Furthermore, lithographic structured slits mounted in ultra-precise manufactured mechanical holders can be realized.

The manufacturing of slit blade structures using single point diamond fly cutting technology is described in [3]. Two metal blades, plated with nickel phosphorous were structured to reach a straightness of 1 µm along the 24.6 mm blade lengths. The sharp edges were manufactured by ultra-precision fly cutting. After a conventional prefabrication and thermal treatment, a single blade will be attached in an upright position to a special mounting interface in an ultra-precision machining environment. A precise rotary table will be used to gain access to all functional surfaces (see figure 1). All blade surfaces are diamond machined, while an exact angular relation between the single surfaces of these mechanical parts is generated. Besides the generation of highly planar interfaces, sharpness and straightness of the slit edge are the

primary goals. Since the slit blades are foreseen to be coated with a thick layer (~200 µm) of nickel-phosphorous, all diamond machining steps must be carried out twice, before and after nickel-phosphorous plating.

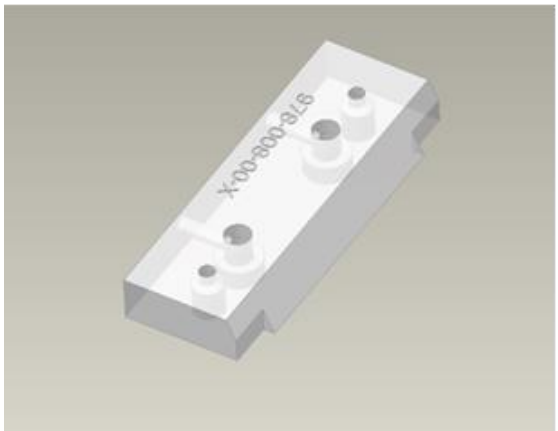

Figure 1. CAD model of slit blade

For the realization of double slit structures, the laser structuring of thin metal foils (5-200 µm thickness) is also possible [4]. If ultra-short (fs) laser pulses were used, the edge roughness of slit structures will meet the slit width variation requirements of ±1 µm -up to ± 4 µm, depending on the absolute slit width.

Lithographic structuring of Silicon wafers is used to reach geometric requirements of less than 1 µm in slit width, slit width variation, and length. Different structuring methods using different silicon wafer substrates were tested and evaluated in [1].
The fabrication of the slit structure described in [2] has been done by lithographic exposure processes in combination with anisotropic selective silicon wet-etching processes. The structure definition was performed by electron-beam lithography ensuring highest accuracy and resolution to comply with geometrical requirements.
The structuring process started from one side of a <100> silicon wafer only. The overall lithographic process flow is shown in figure 2. A cross section of the slit chip is shown in Figure 3:

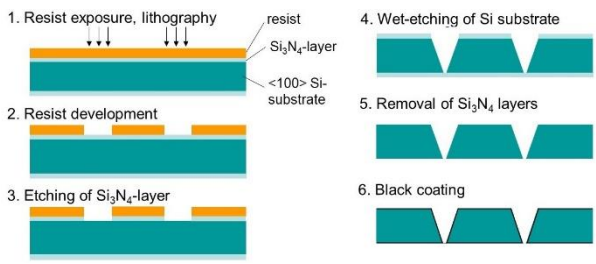

Figure 2. Manufacturing baseline sequence for the realization of the slits.

The lithographic structuring processes guarantees slit geometries with accuracies of less than 1 µm in slit width, length, and surface roughness. However, the challenges are the high costs and manufacturing times compared with the laser and milling structuring technologies.

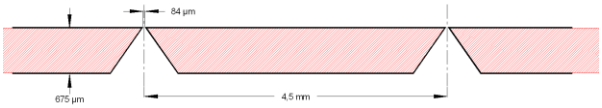

Figure 3. Cross-sectional sketch of the double slit diaphragm with geometric specification

Commonly, the slit surface must be coated by different layers, depending on the instrument specification. In [2] a black coating of the double-slit surface was applied. The variation of slit width before and after black coating was investigated. The measurements show a decrease of the slit width of < 4 µm after black coating application, see figure 4. The slit widths were measured in 500 µm steps along the slit length of 44 mm and in 1 µm steps along 168 µm according to the requirement specification of the slit width uniformity.

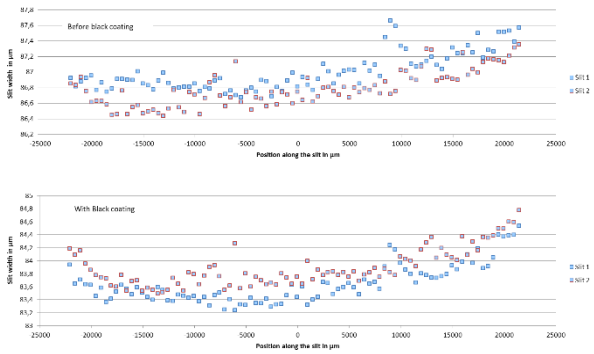

Figure 4. slit width measurements before and after black coating

4. Design and integration of Slit Devices

The integration of structured slits into slit devices can be realized in different ways.

The FLEX double slit device (SLIDS), described in [2], consists of a SLIDS upper frame and a SLIDS lower frame, see figure 5. The double slit chip is clamped in between both frames. The surface of the SLIDS lower frame is lapped to reach a planarity of less than 1 µm. The double slit chip is planarized by pressing it onto the lapped reference surface of the lower frame using mechanical springs. The spring forces guarantee the planarization and the mechanically stable fixation of the double slit chip with respect to mechanical loads. To hold the springs in place they are mounted into grooves of the SLIDS lower frame. In addition to the spring clamping, the double slit chip is fixed with a dot of two-component epoxy adhesive.

Invar was chosen as the material of the Slit assembly upper and lower frame to minimize the CTE mismatch between the frames and the silicon based double slit chip. The invar parts were plated with nickel-phosphorus as anti-corrosive plating. In addition, those parts were black coated for minimizing straylight effects.

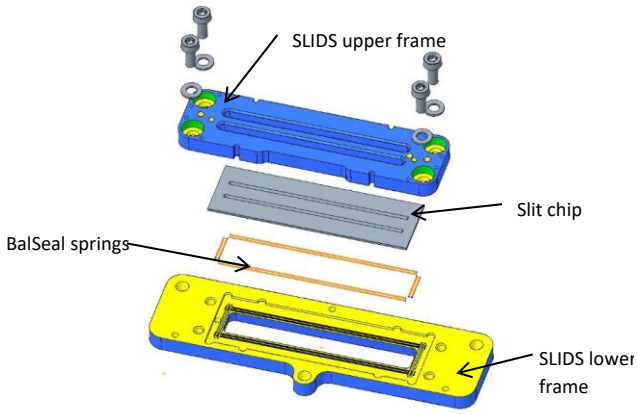

Figure 5. Design of FLEX double slit device

A similar design for slit assembly was chosen in [1] for realizing the Sentinel 4 NIR slit assemblies, see figures 6 and 7.

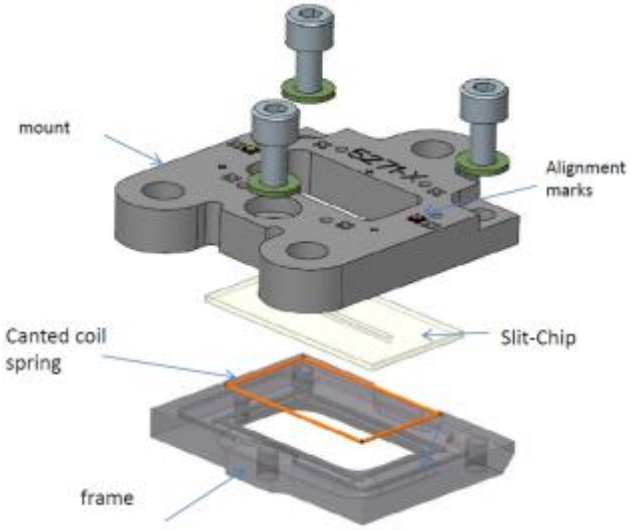

Figure 6. CAD – Sentinel 4 NIR slit assembly design

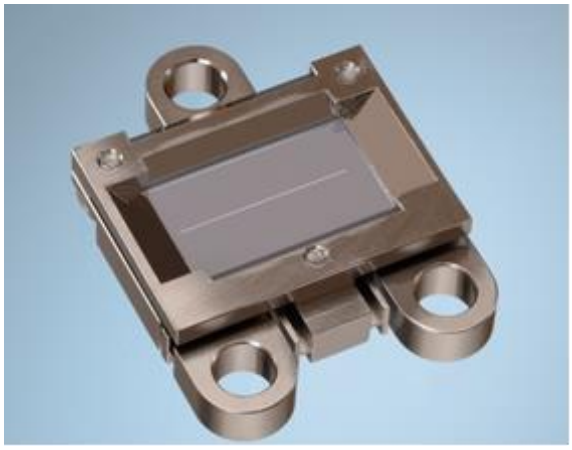

Figure 7. Sentinel 4 NIR slit assembly

The DESIS slit assembly, described in [3], consist of two blades and a mechanical holder, see figure 8.

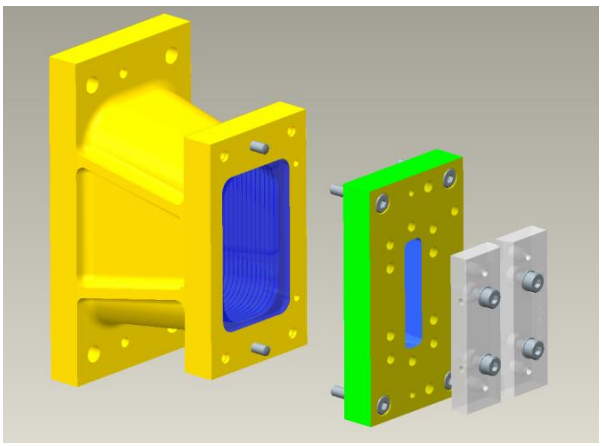

Figure 8. CAD – exploded view of the DESIS slit assembly

The two slit blades were mounted on the frame part in a first step (see figure 9). Both slit blades were attached via two screws to ensure a frictional connection. The slit distance was adjusted using gauge blocks and controlled optically on a coordinate measurement machine at numerous probe points along the lateral slit extension. The adjustment was checked using a calibrated optical microscope. After finishing the adjustment of the slit, blades and frames were connected using an adhesive bond after their final alignment.

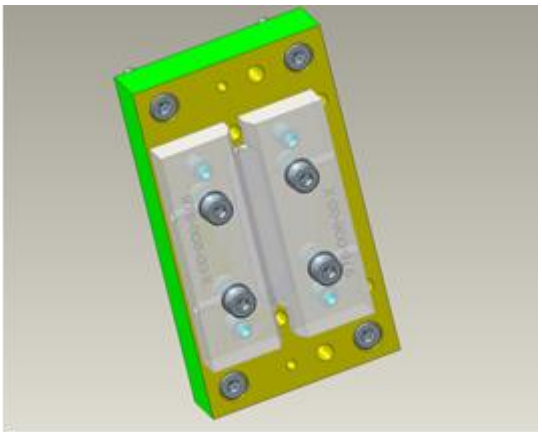

Figure 9. CAD – two slit blades integrated

Finally, the dimensions of the slit were measured with a camera system. An overall width of 23.9 µm with a variation of 0.5 µm could be achieved over a slit length of 24.6 mm. A straightness of the individual blades of 1 µm was achieved.

5. Environmental Testing of slit assemblies

The manufactured and integrated slit assemblies were environmental tested performing Thermal-Vacuum-Cycling tests, sine- and random vibration tests, and shock tests. The qualifications of the assemblies show the mechanical strength of all components, materials, and used coatings to withstand the mechanical loads during satellite launch and during the storage on ground (up to 10 years). In addition, they prove the stability during the lifetime in orbit during operation (up to 7.5 years).

For the Flex silt assembly, the most challenging mechanical test was the shock test with loads of 735 g from 20 Hz up to 20.000 Hz. Because of the very rigid design of the slit chip and the mechanical mounting the shock and the vibration

requirements were reached. Also, the stability of < 5 µm of the slit positions with respect to the mechanical interfaces were met after all tests.

For Sentinel 4 Slit assemblies the requirement of direct sun intrusion of up to 120 seconds was a challenging requirement. To meet this requirement silicon needed to be used as slit material with excellent thermal conductivity. In sum, all described slit assemblies with different materials and slit mounting concepts meet the environmental tests successfully.

Figure 10. DESIS slit assembly integrated onto Instrument

6. Summary

The design, manufacturing, and integration of different slit devices for spectrometer applications were shown. The manufacturing of slit structures using lithographic techniques was discussed. The results of manufacturing and integration of mechanical slit structures were shown. The mechanical design of different slit assemblies for spectrometers for earth observation were discussed. A combination of high precision slit structure manufacturing technologies combined with precision manufacturing technologies are important enabling factors to meet the requirements of slit length, widths, planarity, and slit positions. The lithographic structuring processes show good results but are long lead items and more cost extensive compared with milling and laser structuring technologies. However, the necessary slit structuring and mounting technologies are mainly defined by the required geometrical accuracies of future applications.

The manufacturing of mechanical parts for slit mounting showed identical efforts and costs for the discussed slit assemblies. All shown slit assemblies are successful environmental tested and space qualified. The DESIS instrument was launched and installed in 2018 and is working on board of the International Space Station (ISS) [5]. The Sentinel 4 mission will be launched in 2024 [6] and the FLEX mission [7] will be launched in 2025 by ESA.

Acknowledgements

The Sentinel–4 NIR and UV–VIS slit assemblies were developed with financial and technical support from the European Space Agency within the Sentinel–4 project as a part of the Copernicus program. The FLEX Slit Assembly was developed with financial and technical support from the European Space Agency (ESA) in the frame of the Earth Explorer - Fluorescence Explorer (FLEX) mission. The DESIS instrument was funded by German Aerospace Center (DLR) within the projects IRS-ServoTech and VISTEL under grant numbers 50EE1006 and 50EE1224, respectively.

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