A two-beam two-slice image slicer for fiber-linked spectrographs

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Abstract. For the FEROS fiber-linked high-resolution echelle spectrograph a two-beam two-slice image slicer was designed. It is used at the intermediate focus produced by the fiber-exit focal enlarger which converts the f/4.5 beams of the fibers into f/11 beams accepted by the spectrograph. The image slicer is based on the classical Bowen-Walraven design but merges two individual slicers into one device which is optimized to slice the output beams of two fibers (object + sky) simultaneously into two slices. This approach minimizes the defocussing of the sliced images. Air grooves are used to create the internal total reflections; the width of the grooves controls the number of sliced images to avoid light contamination outside the images produced by the two slicers. This is found to be particularly important for image slicers used in echelle spectrographs which are sensitive to inter-order straylight. In this contribution the very general design of this image slicer is presented in detail. The first measurements obtained with a prototype manufactured by H. Kaufmann Precision Optics already demonstrate the function and high efficiency of the device.

1. Introduction

The modified Bowen-Walraven image slicer which is subject of this contribution was developed for the Fiber-fed Extended Range Optical Spectrograph (FEROS) which is currently under construction for the ESO 1.52-m telescope at La Silla, Chile. FEROS is a state-of-the-art fiber-fed bench-mounted prism-crossdispersed echelle spectrograph working in quasi-Littrow mode and white-pupil configuration. With two fibers for the object and the nearby sky, the complete optical spectrum from 360−860 nm is recorded in one exposure with a resolving power of $R = 48\,000$. For a more detailed description of the FEROS instrument cf. Kaufer et al. (1997).

The high resolving power of the FEROS instrument critically depends on the image slicer (IS) which is used to slice simultaneously the images produced of the two blank exit surfaces of the object and sky fibers by a focal enlarger lens system (F/N-system).

The fibers have a core diameter of $100\,\mu$m and are fed by microlenses on the telescope's side (cf. Fig. 1). Two apertures with 0.29 mm diameter (= 2.7 arcsec in the f/15 focal plane of the ESO 1.52-m telescope) are imaged onto 90% of

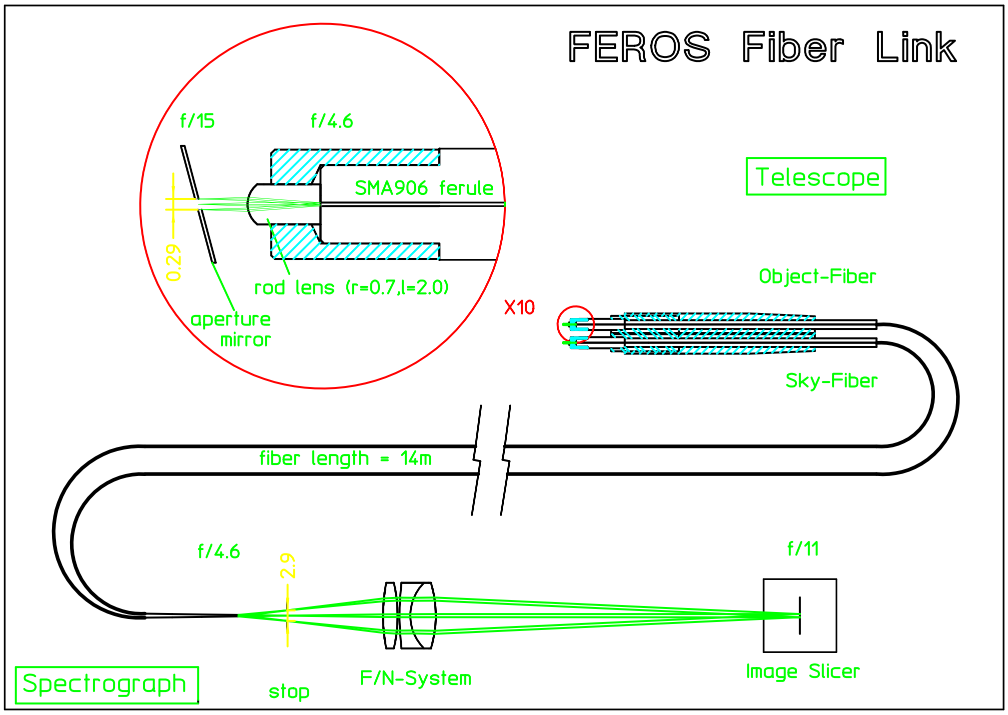

Figure 1. The FEROS fiber link (for details cf. text).

the fibers' entrance-surface diameter resulting in an effective f/4.6 feed which is well-suited to minimize focal-ratio degradation (FRD) effects on the fiber link. The microlens is a rod lens with a radius of curvature of 0.7 mm and a length of 2 mm and is directly glued with the flat surface to the fiber entrance surface. The microlens and the fiber are mechanically mounted in a modified SMA 906 connector.

The polished fiber exits are left blank and are re-imaged by the F/N-system which converts the f/4.6 fiber beams to f/11 beams accepted by the spectrograph. The F/N-system produces images of the fibers enlarged to 240 μm at the intermediate focus. Therefore, the image slicer described below is located at this intermediate focus and defines the "entrance slit" of the instrument.

The fiber coupling efficiency for an input/output focal ratio of f/4.6 is expected to be better than 85% for a fiber with a small FRD. The total efficiency of the complete fiber link including the microlens, 14 meters of fiber, the F/N-system, and the AR-coated IS is estimated to 60%.

2. Opto-mechanical layout of the image slicer

The FEROS IS is basically a Bowen-Walraven image slicer (Walraven 1972) which was modified to slice simultaneously the two beams emerging from the object and sky fibers with a minimum of defocussing introduced by the optical path differences (OPD) in the slicer. Therefore, an image slicer which merges two individual slicers in one was needed to be placed at the intermediate f/11 focus

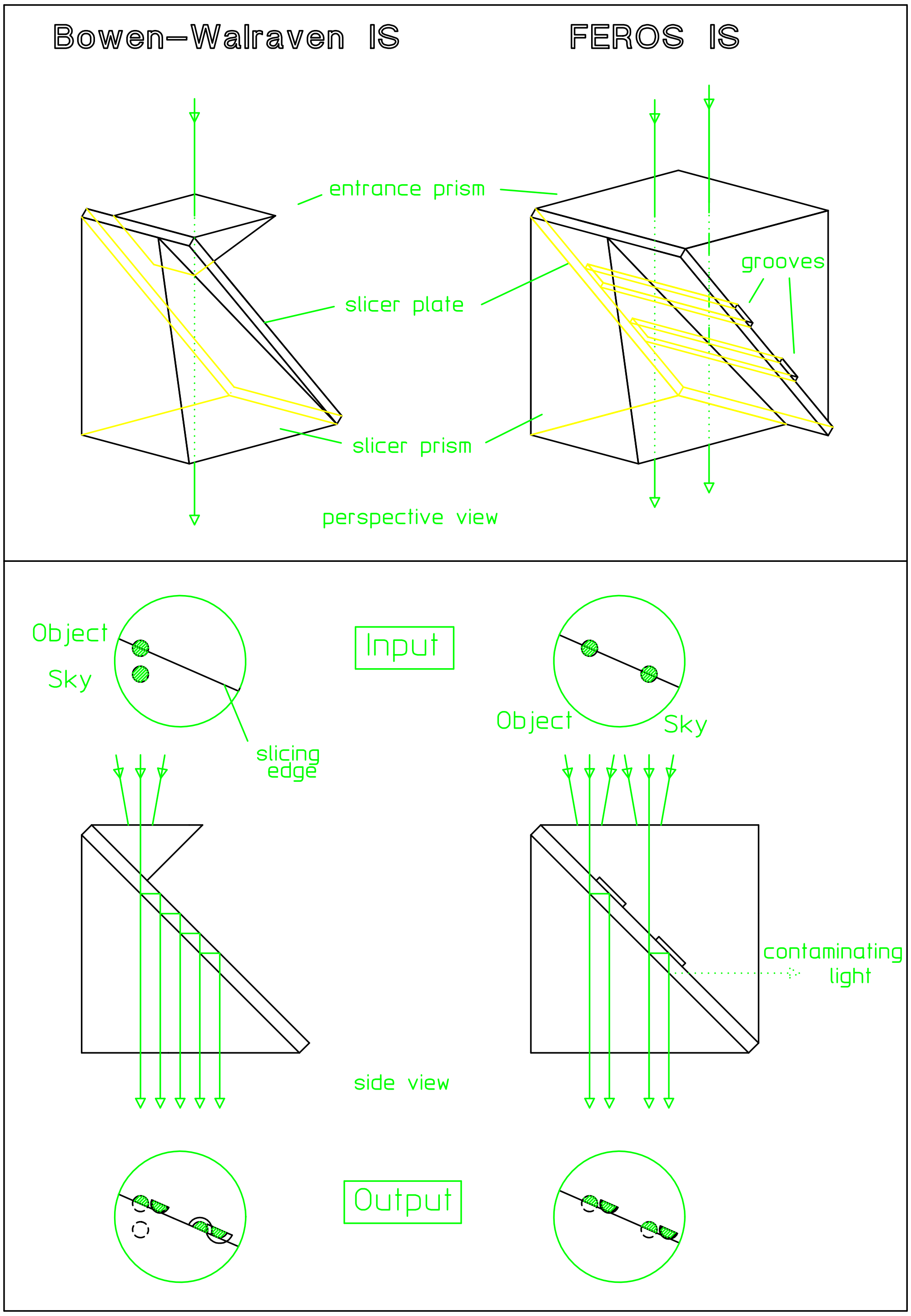

Figure 2. Layout of the classical and the modified Bowen-Walraven IS (for details cf. text).

feeding the FEROS spectrograph. This requirement is met by using *two air grooves* on the entrance prism of the slicer which provide the needed internal reflection of the sliced beams.

Figure 2 shows the layout and function of this IS in comparison with a classical Bowen-Walraven IS while Table 1 gives all details to compute the dimensions for this type of slicer and the specific values used for the FEROS image slicer.

As material for the FEROS slicer, quartz glass (Homosil) was selected. Quartz glass has a very high transmission over the whole optical wavelength range and good mechanical properties which allow to polish all surfaces with high quality – a prerequisite to assemble the parts of the slicer with optical contact only.

An IS completely manufactured from quartz glass in optical contact could be easily broad-band anti-reflection (AR) coated after assembly and test because of the low expansion coefficient of the material.

Due to the low refractive index of quartz glass in the case of the FEROS slicer the prism angle had to be changed from the commonly used 45° to 46.5° to maintain the total reflection up to wavelengths of 1 μm for the two f/11 beams entering the IS.

The use of two air grooves in the entrance prism results in several additional advantages besides the goal to realize two slicers in one device:

- the manufacturing of the IS is simplified because it then basically consists of two complementary prisms with large flat surfaces,
- the precisely polished flat surfaces allow to connect all surfaces with optical contact avoiding any cementing of the parts. Cementing usually reduces the important sharpness of the slicing edge. Further, even a little filling of the air grooves in the entrance prism with cement would result in a loss of the total reflection,
- on the other hand, the total reflection in the entrance prism can by controlled by the width of the air grooves, i.e., the maximum number of slices produced by the slicer can be controlled. Light entering a new, unwanted slice (e.g. due to a slight misalignment of the base prism or tolerances in the thickness of the slicer plate) is not directed into the direction of the output beam if the air groove does not provide the glass–air transition needed for the total reflection. The unwanted light is directed perpendicularly out of the slicer and does not contaminate the images produced by the two slicers (cf. Fig. 2, bottom right: 'contaminating light'). This is particularly important for image slicers used in echelle spectrographs which are sensitive to inter-order straylight. Light from a further slice could even affect and contaminate adjacent echelle orders.

3. Results with the first prototypes

A model of the proposed image slicer was built during the design phase from acrylic with the linear dimensions scaled by a factor of 15. The working principles of the slicer were checked on the optical bench with the acrylic slicer parts mounted together with index-matching oil.

Table 1. Dimensions of the modified Bowen-Walraven IS. All lengths are in mm, all angles in degrees.

	formula	FEROS IS
image slicer material	quartz glass	Homosil
refractive index	$n(1\mu\mathrm{m})$	1.45
total reflection angle	$\alpha_T(1\mu\mathrm{m})$	43.6
entrance beam focal ratio:	f/d	11
focal ratio in IS:	$(f/d)' \approx n(f/d)$	16
max. angle in IS:	$\alpha_T + \arctan(0.5(d/f)')$	45.4
chosen reflection angle:	α	46.5
fiber image diameter:	D	0.240
$\rightarrow$ effective 'slit' width:	$w = D/2$	0.120
transfer distance of sliced image:	t	$1.25D = 0.300$
$\rightarrow$ effective 'slit' length:	$s = t + D$	0.540
thickness of slicer plate:	$d = t\frac{\sqrt{2}}{(1+\tan\alpha)}$	0.207
slice angle:	$\beta = \arccos\left(\frac{D}{2t}\right)$	66.4
slice angle on slicer prism:	$\beta' = \arctan\left(\frac{\tan\beta}{\cos\alpha}\right)$	73.26
distance of the two beams:	a_b	0.90
distance of grooves on entrance prism:	$a_a = \frac{a_b \sin\beta}{\cos\alpha}$	1.2
width of grooves in slicer plane:	W_a	0.50–0.55
width of grooves on entrance prism:	$W_a' = W_a \sin\beta$	0.46–0.50 (0.48)
depth of grooves:	$\delta \geq 10\lambda$	0.025

The first prototypes made of Homosil quartz glass were manufactured by H. Kaufmann Precision Optics in Crailsheim, Germany. The outer dimensions of the slicer are $20 \times 20 \times 20$ mm to ease the polishing of the individual surfaces which results in lowered tolerances for the prism angles and the thickness of the slicer plate.

Figure 3 shows the CCD images taken with a microscope objective from the unsliced and sliced double-fiber images. The two slices produced from the circular fiber image with 240 μm diameter form an effective $120 \times 540\,\mu$m entrance slit for the FEROS spectrograph. The images were taken in the Gunn Z filter to prove the total reflection conditions up to a wavelength of 860 nm. The slicing efficiency was measured as the ratio of the intensities of the individual unsliced and the sliced fiber images neglecting the internal absorption of the quartz glass and the glass–air losses on the entrance and exit surfaces of the slicer. For both fiber images a value of 95% is found. Therefore, using broadband AR coatings the total efficiency of this type of slicer should be better than 90%.

4. Discussion

The modified Bowen-Walraven image slicer introduced in this paper was specifically developed to slice simultaneously the two beams emerging from the object and sky fibers in the intermediate focus available in most fiber-linked spectrographs. At this intermediate focus behind the fiber, problems like seeing noise and guiding which are usually introduced by image slicers in the telescope's focal plane are eliminated.

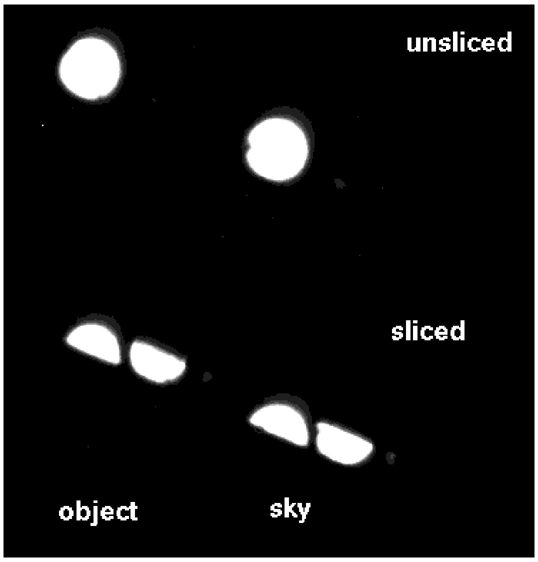

Figure 3. Images obtained with the first image slicer prototype.

In principle, two fibers can be sliced as one image fed to *one* classical Bowen-Walraven IS. The drawback of this approach is that the defocussing introduced by the slicer increases for each slice due to the increasing OPD and results in two sliced fiber images with different amounts of defocussing for each individual slice. Therefore, different effective slit widths and resolving powers of the spectrograph are obtained for the two fibers. The modified Bowen-Walraven image slicer basically merges two individual slicers in one device which gives a minimum and for both fibers identical amount of defocussing of the slices. For an illustration of the two situations cf. Fig. 2; especially note the different blur of the output fiber images for the two different slicers.

The use of two air grooves on the entrance prism eases the manufacturing of the IS and allows to build the complete device from quartz glass in optical contact. The resulting mechanically and temperature insensitive slicer can be easily broadband AR coated.

Measurements with the first prototype show that a highly efficient image slicer with a total efficiency of better than 90% can be obtained.

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References

Kaufer A., Wolf B., Andersen J., Pasquini L., 1997, The ESO Messenger 89, 1

Walraven Th. & J.H., 1972, Proc. ESO/CERN Conf. on Auxiliary Instrumentation for Large Telescopes, Geneva, eds. S. Lausten & A. Reiz., p. 175