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Multispectral Filter Spectral Characterisation Setup

Hans Thiele *(1), Michael Gisi (1), Bernhard Sang (1), Phil Daro Krummrich (2)
(1) OHB System AG, Manfred-Fuchs-Straße 1, D- 82234 Weßling / Oberpfaffenhofen, Germany
(2) OHB Digital Connect GmbH, Manfred-Fuchs-Platz 2-4, D-28359 Bremen, Germany

ABSTRACT

With the increasing demand on compact space instruments, using multispectral filters instead of complex spectrometer setups, the butcher-block filter technology is pushed to larger number of channels, more extreme length to width ratios of the individual filter bars. The resulting requirements on center wavelength and bandwidth and their tolerances are more and more demanding and require not only improved production technology but also a dedicated spectral characterization setup to verify the performance of the individual filter channels within such a butcher block filter assembly. The setup presented here operates in the spectral regime between 800nm and 2,5µm. Due to the geometry of the individual filter channels of a butcher block filter, the setup is designed for a measurement spot size down to 50µm and can operate at F-Numbers between 2,5 and 4. An absolute spectral resolution of 0,2nm is demonstrated, with a relative resolution of 0,1nm for homogeneity measurements along the individual filter stripes. The out of band blocking can be characterized better than OD3 over the full spectral range. A precision x/y position stage allows to position the small metrology spot (50µm) on individual filter channels and to scan along these channels to map their performance. This metrology setup allows to verify the final performance of multispectral filters assemblies, especially butcher block filters.

Keywords: butcher-block filter, multispectral filter, multi-zone filter, multispectral characterisation,

1 INTRODUCTION

Due to the increasing demand to fly small and compact optical payloads, there is a trend from complex and larger hyperspectral instruments to more compact and cost effective multispectral instruments, which use only a limited number of dedicated spectral filter bands to detect spectral features for remote sensing applications.
A mature fabrication approach for multispectral filters is the so called butcher-block technology, where individually coated filters are diced and then these thin bars of different spectral bands are mounted together by adhesive bonding to form one filter assembly. Individual spectral channels can have varying widths of down to a few 100µm and various spectral bands can be combined (including different substrates, if required by the transmission of the band). While the fabrication technology for this is mature and a number of these filters are already successfully in orbit, the spectral characterisation of a butcher-block filter prior to its integration in the instrument or in front of a detector is very demanding and requires dedicated metrology instrumentation. Figure 1 shows typical filter assemblies.

Due to the fabrication tolerances of the butcher block technology, minor assembly tolerances such as a minor tilt, bending, torsion of individual stripes add up to the fabrication tolerances of the pure coating. The resulting performance of each spectral channel needs to be verified on the assembled butcher-block filter, especially the spectral channel centre position and its width can be crucial. As these properties may vary along each filter stripe, these should be measured at several positions along the long axis of each filter stripe. Also the optical density to adjacent channels and crosstalk are parameters of interest. Due to very narrow filter stripes, this is not possible with standard commercial benchtop spectrometers.

*Hans.Thiele@ohb.de; phone 0049 81534002-280; www.ohb-system.de

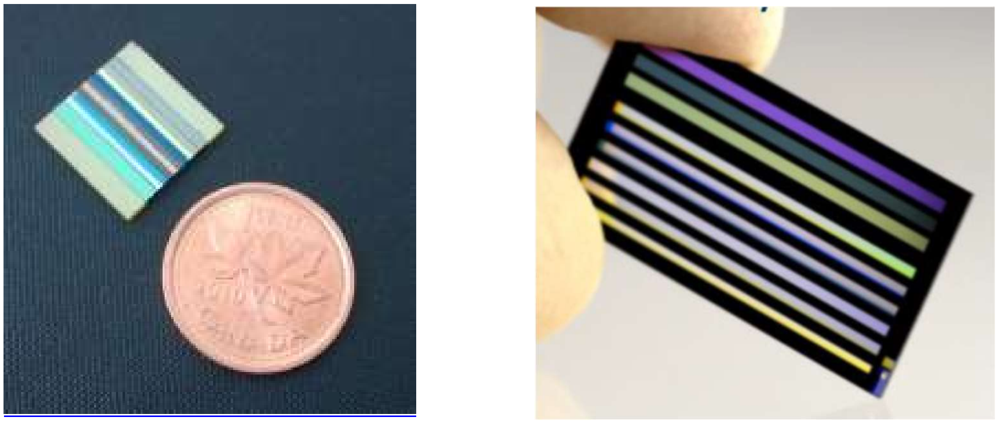

Figure 1 left: Multi-Zone Filter assembly by Iridian, Canada. (see: https://www.iridian.ca/product-mzf/)
right: Butcher Block filter array by Materion
(see: https://materion.com/resource-center/technical-papers/filters-and-optical-coatings)

In this paper we present a lab setup, which was designed and realized in the optical lab at OHB in Munich to measure and verify the performance of butcher-block filters in the NIR and SWIR.

The setup was targeted to achieve a small spot size of down to ~50µm to be able to focus even on very thin filter stripes. Various coupling optics of the optical path allow to tailor the measurement NA to be representative for the optical path of the payload. In order to detect inhomogeneity along individual filter stripes and to map a larger multispectral filter, a scanning functionality of the setup allows to scan along the stripes and the whole filter automatically.

A spectral range between 800nm and 2.5µm with a high spectral resolution below one nm was targeted to be able to characterize the crucial tolerances in centre wavelength and spectral width of the individual channels.

Goal of the dedicated lab setup is to characterize such a multispectral filter by measuring the following parameters for several positions on each individual filter channel:

- Transmission center wavelength
- homogeneity of the center wavelength along a filter stripe
- the channel bandwidth and its tolerance along a filter stripe
- the optical density (both for the transmission region but also outside (out of band blocking))

The target measurement capability characteristics were the following:

- operating spectral regime between 900 and 2,5 µm
- high spectral resolution in the order of 0,5 nm or below
- small metrology spot (below 200µm) to be able to target even very thin filter channels individually.
- optical beam operating the at a realistic F#, which is representative for application and the filter design F#.

Due to the dimensions, the (possibly) high number of the individual filter channels the setup should have scanning capabilities to map the fine structures of individual filter stripes (by automatically placing a number of measurement spots precisely along an individual filter stripe.

The metrology setup is presented in section 2, the achieved performance is demonstrated for a representative multispectral filter in section 3. Section 4 summarizes which performance is already achieved and which features will also be of interest in the future to verify multispectral filters for space borne instrumentation.

2 METROLOGY SETUP

The overall metrology concept for the transmission measurement of the individual filter channels is depicted on the following Figure 2. The whole setup is placed in a clean bench maintaining ISO5-equivalent cleanliness conditions, to keep the optics and the filters clean while measuring (see Figure 3)

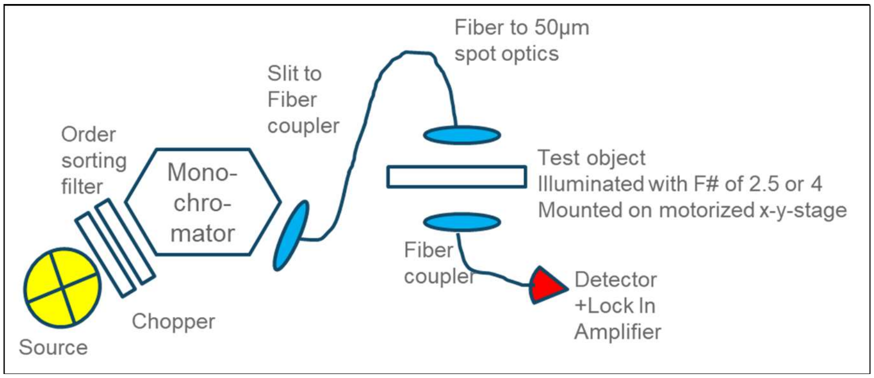

Figure 2 conceptual layout of the spectroscopic setup

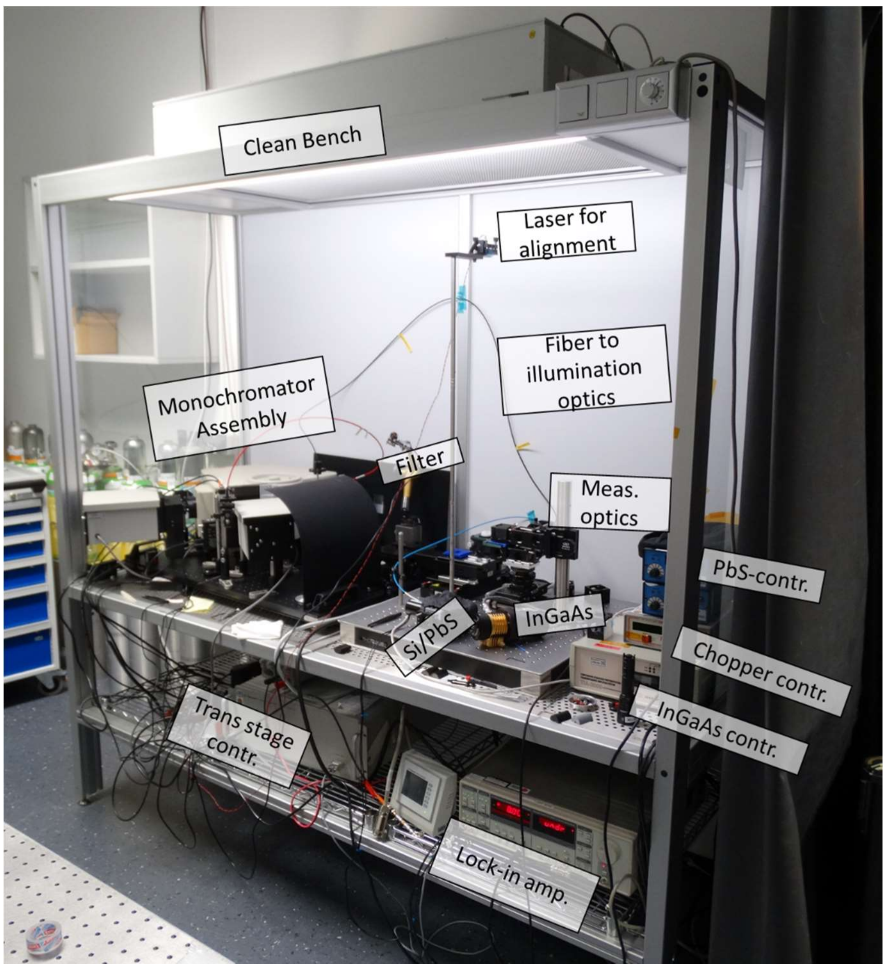

Figure 3 Metrology setup at optics LAB at OHB Munich

The following sections briefly describe the main components in the sequence along the optical path.

2.1 Light source:

As source for the radiation, a COTS halogen bulb (100W, 12V, Type Osram 64628 FDT A1/261 in a GY9.5 socket) is used. This radiation is then focused on the entrance slit of the spectrometer using a spherical mirror. The life time of the source is given as 50 hours, so it needs to be exchanged regularly. The IR-source assembly (type LSH-T100) is a part of the standard monochromator setup (Horiba IHR320).

2.2 Chopper

As the intensities received at the detector are very low, a chopper is used, together with a lock-in amplifier for the detector signal. The frequency used for the copper is 146.57Hz. The Chopper assembly is a part of the standard monochromator setup (Horiba IHR320).

2.3 Order sorting filter

The order sorting filter is a standard filter wheel from Thorlabs FW120C. It is equipped with 5 low pass filters and has 6 filter positions. The filters are low-pass filters, and can be used as order sorting filters for measuring the following spectral ranges:

1: 0.37-0.63µm
2: 0.63-1.1µm
3: 1-2µm
4: - not used -
5: 1.6-3.2µm
6: - not used - / no filter

The order sorting filter was first located at the exit of the spectrometer before the radiation is fed into the fiber. As the filter elements have wedges, however, which are not oriented in the same way, this led to a small change in the beam path so that the radiation did not enter the fiber for some filters. For this reason, the OSFs were placed in front of the spectrometer. The source image on the input slit is rather large, so that some small deviations have no or only minimal impact onto the signal strength.

2.4 Monochromator

The monochromator used is the grating spectrometer iHR320 from Horiba. The iHR320 is a Czerny-Turner type monochromator. The system consists of a motorized input slit that is imaged onto a motorized output slit via two concave mirrors. The collimated beam is reflected off a grating and thereby spectrally dispersed. The image of an infinitesimal small input slit illuminated with white light is thus a continuous spectrum in the plane of the output slit. The position of the spectrum with respect to the slit can be set by rotating the grating. The spectral properties of the light transmitted through the output slit depend furthermore on the properties of the used grating and the widths of input and output slit. A specific wavelength is selected by commanding the spectrometer to a specific wavelength. The transformation to the correct angle of the grating is taken over by the firmware itself. The following gratings can be selected:

Table 1 Monochromator gratings

	Type	grooves / mm	Blaze	Long wave cut-off	
				absolute	iHR320
Grating 1	Blazed holographic	1800	400 nm	1250 nm	1073 nm
Grating 2	Blazed holographic	1200	900 nm	1666 nm	1610 nm
Grating 3	Ruled blazed	600	2000 nm	3333 nm	3220 nm

The F-Number of the spectrometer is approximately 4.

The coupling of the radiation into the fiber after the monochromator was realized with 2 off axis parabolic mirrors (OPAs) of the same type as used for the optics in the proximity of the filter (see section below); both with a focal length of 2''. As this is a 1:1 imaging, the F-Number of the spectrometer matches the F-Number of the glass fiber.

2.5 Fiber coupling and front optics

The glass fibers used are made from ZrF_4, as these are capable to transmit radiation above 2400nm. Typical glass fibers have a transmission of 50%/m only at 2400nm, becoming even worse above that. The transmission for ZrF_4 is shown in the following figure.
Two fibers types were used:

- 110µm core diameter, NA=0.12 (F/# = 4.1)
- 200µm core diameter, NA = 0.2

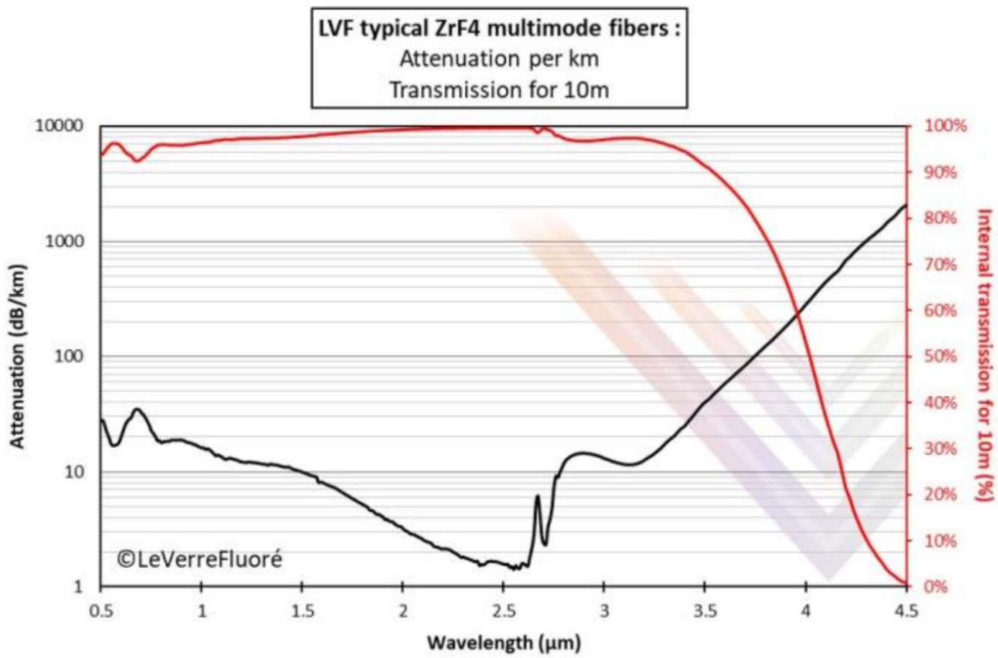

Figure 4 Transmission for a ZrF_4 Fiber

To create the measurement spot for the filter, a setup as shown in the following figure was chosen. The mirrors were off axis parabolic (OAP) mirrors with 1' diameter and protected gold coating. By changing the aperture diameter, the F-Number can be changed. When using higher F-Number (smaller apertures), a lot of radiation is blocked by the aperture.

For this reason, the setup can be changed with two OAPs of 2'' effective focal lengths, allowing to open the aperture while still having a small NA.

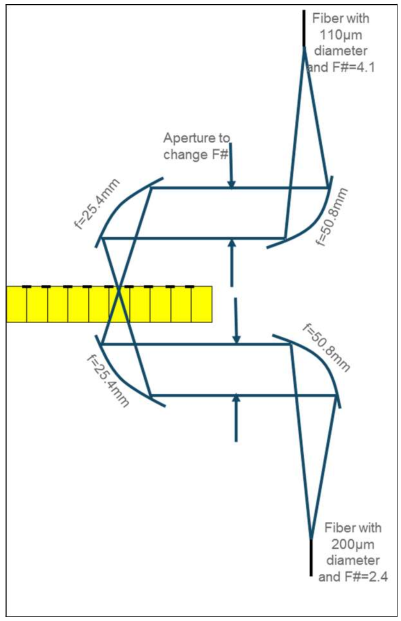

Figure 5 Optical path of the transmission optics with filter functional surface in the intermediate focus. The dark sections on the filter upper surface indicate the aperture mask, which separates the individual spectral channels and covers the glue gap between the individual filter bars.

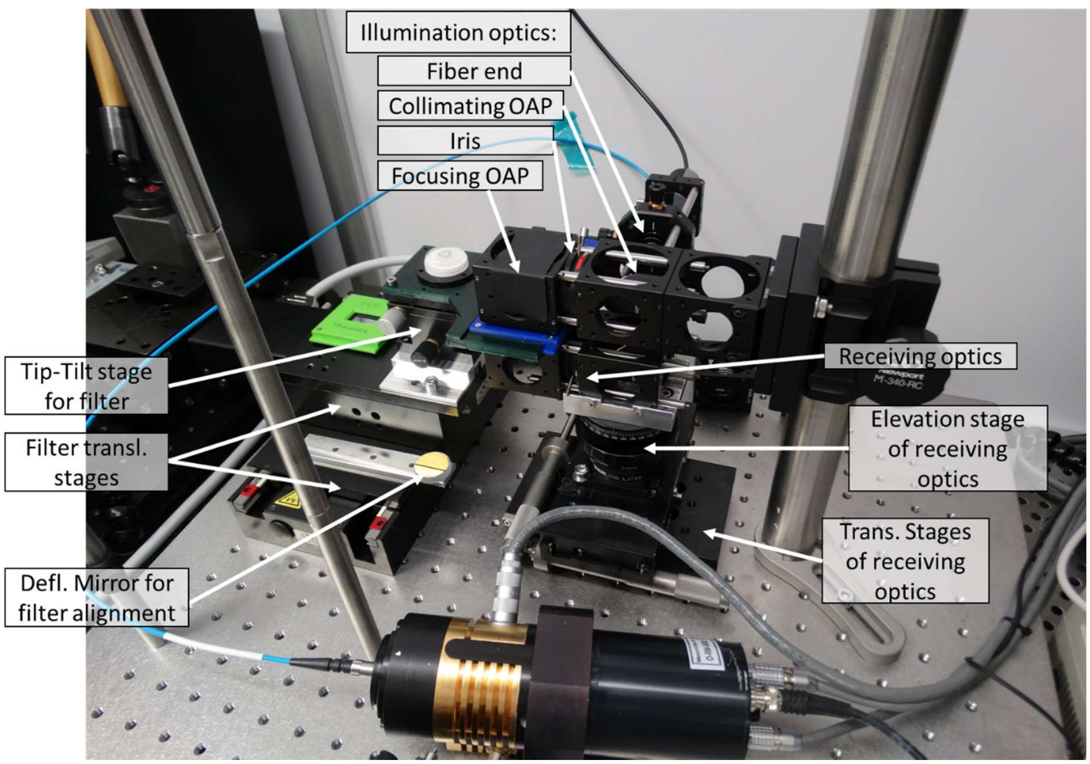

Figure 6 Front end fiber optic coupling optics and filter positioning stage (left) and Filter holder (blue) in between the optics

The following plots show the achievable spot sizes of ~50µm for F# 4 and F# 2.5:

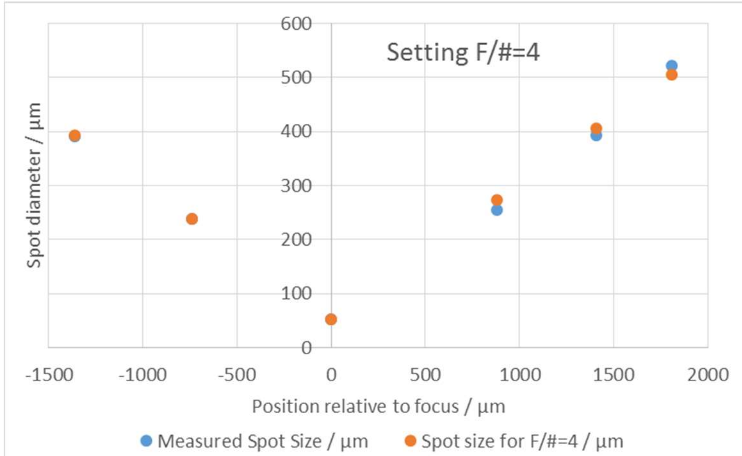

Figure 7 Spot size for F# 4

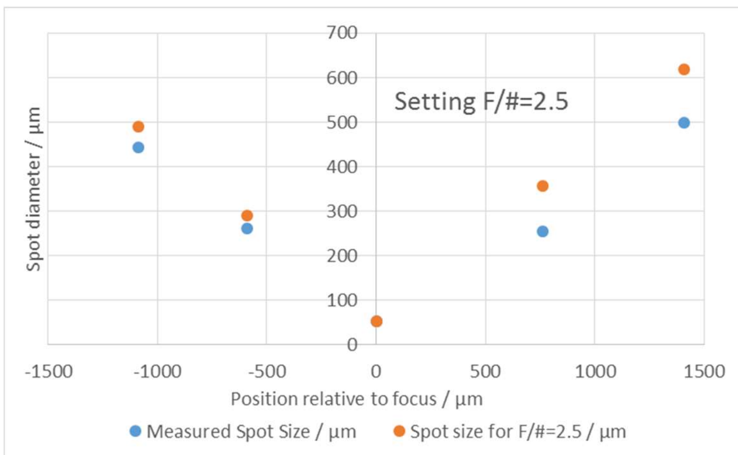

Figure 8 Spot size for F# 2.5

2.6 Detectors

3 alternative detectors can be applied to cover the full spectral range:

- Sandwich Si/PbS Horiba DSS-SP5050TC, cooled to -30°C
- Sandwich Si/IAS, Horiba DSS-SIA020TC, cooled to -30°C
- Extended InGaAs, cooled to -70°C: 19830-14ER from Gamma Scientific
  The responsivity is very high up to about 2400nm, however dropping very rapidly as shown in the following figure:

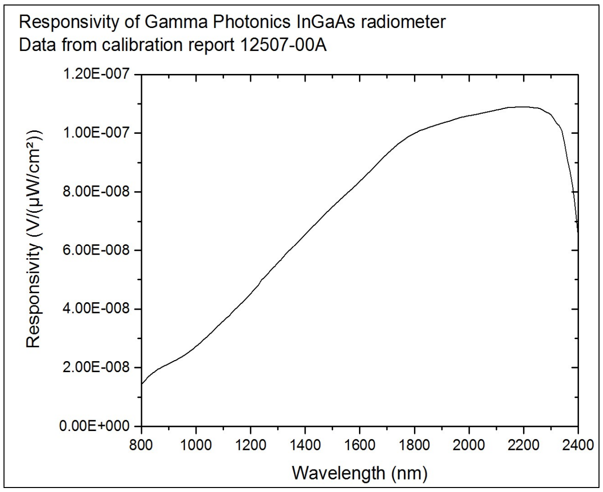

Figure 9 Responsivity of the Gamma photonics InGaAs radiometer

2.7 Scanning Translation stage and filter orientation

The filter is mounted on a precision x/y stage, which is capable to position each point of the filter under the measurement spot with a high spatial resolution of less than a µm.

In order to be able to scan along filter stripes, the orientation of the filter around vertical axis must be known, with respect to the directions the translation stages move the filter. For this, a "Translation Stage" coordination system X_T and Y_T and a "Filter Coordination System" X_F and Y_F was defined, as shown in the following sketch:

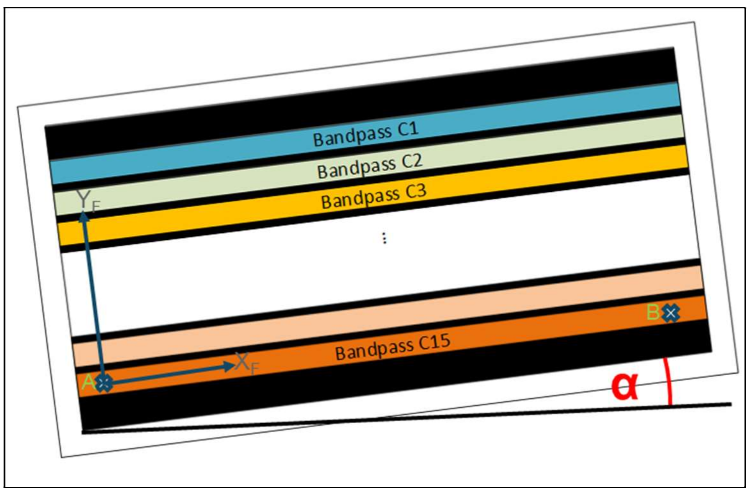

Figure 10 Coordinate system of the filter. The translation stage coordinates (not shown) were assumed to be exactly horizontal and vertical in the image. The clocking angle α is determined with the setup can compensated for each measurement spot.

The 2 coordinate systems are defined relative to each other by two points A and B. By translating the filter slowly in Y_T direction while observing the signal on the detector (of course the correct wavelength must be set in the spectrometer) it is possible to determine the positions of A and B (located exactly in the middle of the filter stripe). The positions along the long axis of the filter (X_F) can be chosen freely within the size the filter allows.

Having done this coordinate system determination, the controlling software enables a movement of the measurement spot in the Filter coordinate system

2.8 Spectral calibration and accuracy

To calibrate the spectral axis in order to have a good confidence in the spectral accuracy, a common method is to use calibration sources. For the current setup, the Xe emission source XE2 from Ocean Insight was purchased. Compared to other gases like Hg, Ne, Kr or Ar, Xe shows the best coverage of spectral lines in the spectral region of interest (800nm to 2500nm).

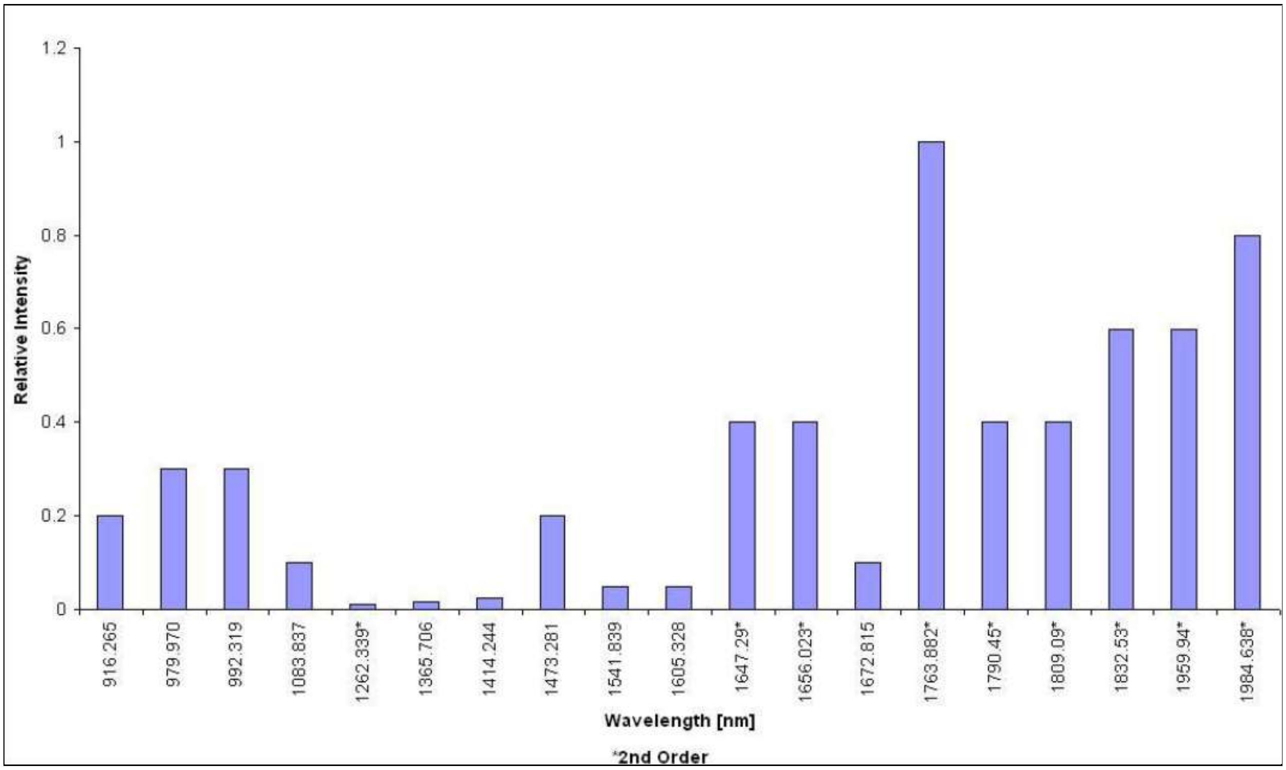

Figure 11 Xe lines as given by Ocean Insight. The lines marked with * are not real lines, but second orders of the grating when omitting an order sorting filter

A second way to calibrate the spectral axis is by using gas cells containing known gas mixtures which exhibit adsorption lines at well-known positions. In the spectral range of interest there are strong spectral bands from the following gases (not complete list):

H2O: 950nm, 1360nm, 1830nm,

CH4: 1650nm, 2300nm

CO: 2320nm

As the radiation passes through lab air anyway inside the spectrometer and at the optics surrounding the filter, there are always water vapour lines in the spectra. The CH4 lines can easily be created by adding some CH4 to the inside of the spectrometer. For CO, a gas cell would be necessary due to the toxicity. For CH4 and H2O no gas cell is needed, which has the advantage of both being very easy to be performed with little or no effort

Using these two methods and carefully optimizing the setup, the accuracy of the wavelength axis for the measurements achievable with this setup is estimated to be smaller than ±0.2nm.

2.9 Intensity Calibration

Several components have impact onto the accuracy of the intensity measured by the system. The main known sources are:

- Intensity variations of the source
- Focus shift of the glass / filter substrate wrt. to the position without substrate.
- Changes of alignment due to temperature, etc.

The source intensity variations are in the order of about ±0.7%, which is a typical value for this type of source
Due to the setup, the receiving optics below the filter must be positioned precisely relative to the illumination optics, so that the two foci of the optical elements are at the same position in space. A shift of the focus due to the refractive index of the filter must be compensated by re-positioning the receiving optics. As the reference measurement after each filter measurement was done at a glass substrate having the same thickness (1.4mm), there should be no shift of focus. To measure the transmission without any filter or glass substrate, however, the receiving optics needed to be re-positioned. This was done by maximizing the signal.

In total, the intensity accuracy is estimated to be in a range of ±1.5 to 2%.

3 MEASUREMENT RESULTS ON AN EXEMPLARIC MULTISPECTRAL FILTER

3.1. Filter under test

For testing and demonstrating the performance of the metrology setup, a 10 channel butcher block filter was selected. This filter was procured by OHB Digital connect in the framework of a remote sensing application and was characterized at OHB Munich in a joint activity. Supplier is Iridian, CA.

This butcher block filter features 10 individual spectral channels, each channel having a length of 20mm, and clear aperture widths varying from 550µm down to 330µm.
The overall filter substrate has a dimension of 28 x16 mm, including edges for mounting in front of the detector.
The spectral coverage of the individual channels ranges from 900nm up to 2.5 µm.
The channel bandwidth of the individual spectral channels ranges between 7nm up to 90nm.

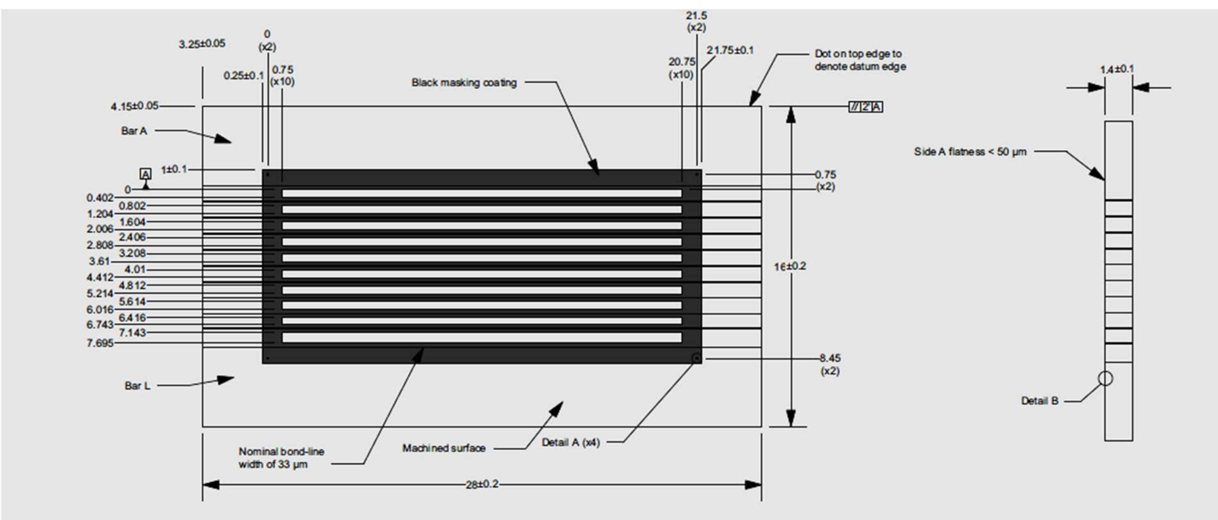

Figure 12 Geometry of filter under test – section of production drawing.

No further details on the individual channels, their specific line positions and tolerances, the foreseen detector and the application for this multispectral filter are mentioned here, as the focus of the paper is on the metrology setup and its performance and not on the filter itself.

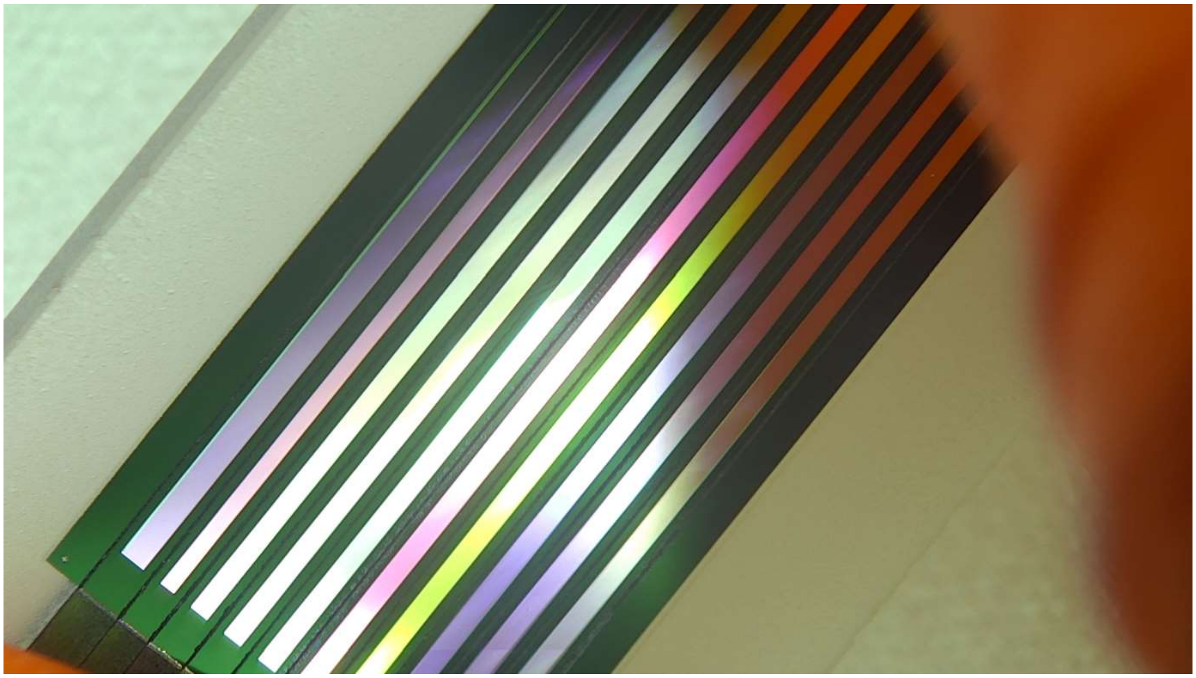

Figure 13 multispectral filter in visual inspection: glue gaps are visible as thin dark stripes, covered by the aperture mask of the filter.

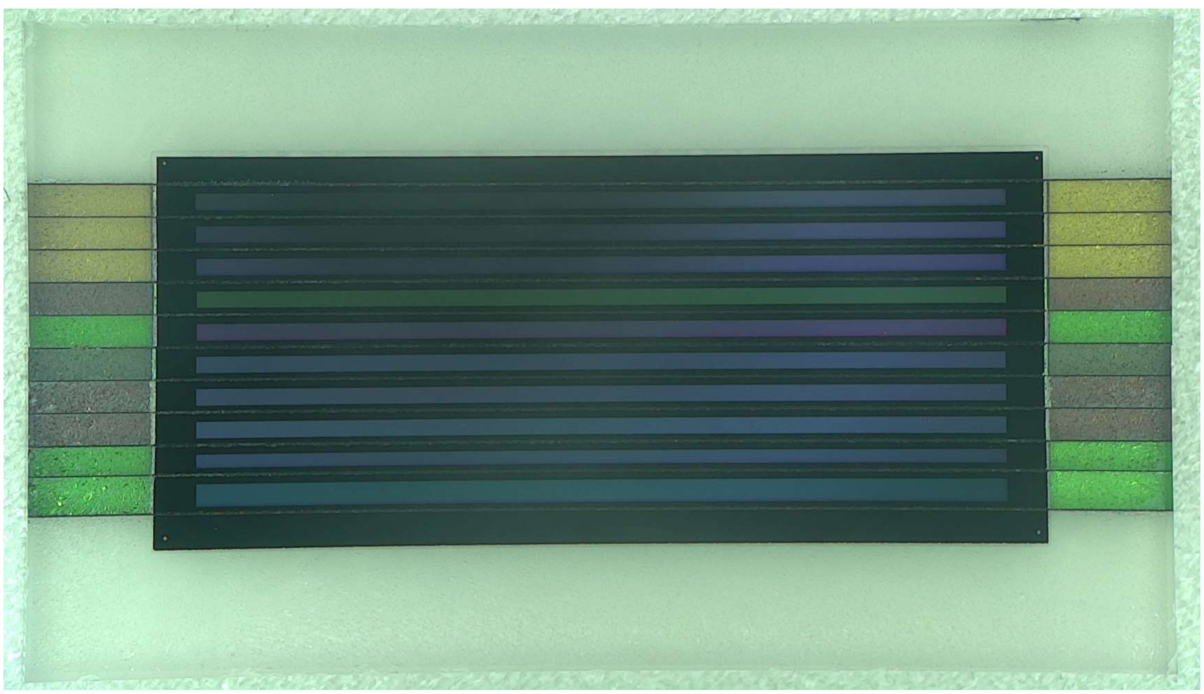

Figure 14 multispectral filter with aperture mask and outer edge unmasked (the individual filter bars and the glue gaps between them can be nicely seen).

3.2. Results for center wavelength and channel width

All measurements from all filter strips with 5 positions on each stripe are shown in the following figure, together with the transmission of the uncoated glass sample.

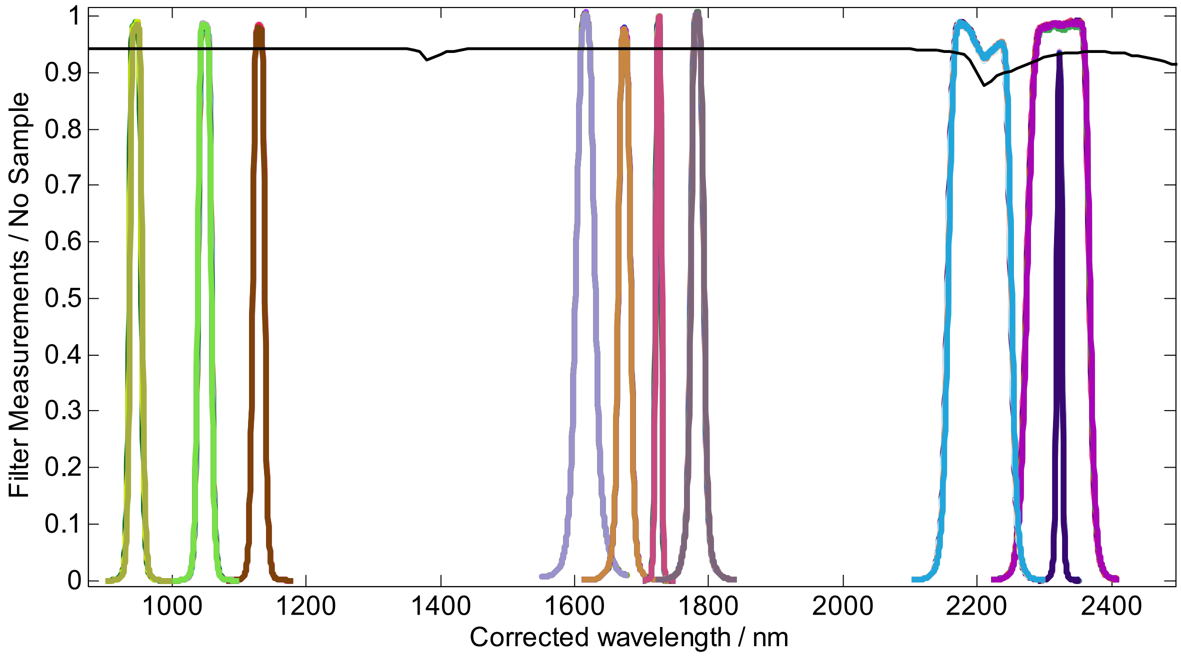

Figure 15: complete scan of all filters and substrate, measured with F# of 4.

It can be seen, that the maximum transmission is very high at the centre of each band. It is significantly higher than the uncoated glass sample (having reflection losses), indicating very good antireflection properties on both sides of the filter. The dip in band 5 (2200nm) clearly is no fault in the coating, but stems from the bulk absorption inside the substrate. The narrow band 10 at 2318nm expectedly has a lower value for the maximum transmission due to the F-number.

Two exemplary channels out of the 10 spectral channels of the filter are shown in the following section, to demonstrate the measurement of the centre wavelength tolerance along the spectral channels.

In the following plots, the solid lines are the five measurements along each filter stripe at positions 0, 5, 10, 15 and 19mm with the colours Red, Green, Blue, Yellow and Magenta, respectively. The black dotted lines are the measurements made by the filter supplier Iridian at wafer level (at higher F-number and, very probably, at different positions on the filter). The actual filter characteristics at the design F-Number of 2.5 will be slightly shifted and broadened compared to these measurements (up to -6nm as for the 2318nm band).

Table 2 Spectral Band 1, comparison of design values and measured results

	Design / nm	Measurement OHB / nm
Centre	945 ± 2	945.7
Homogeneity	2	1
FWHM	20 ± 2	18.85 ± 0.04

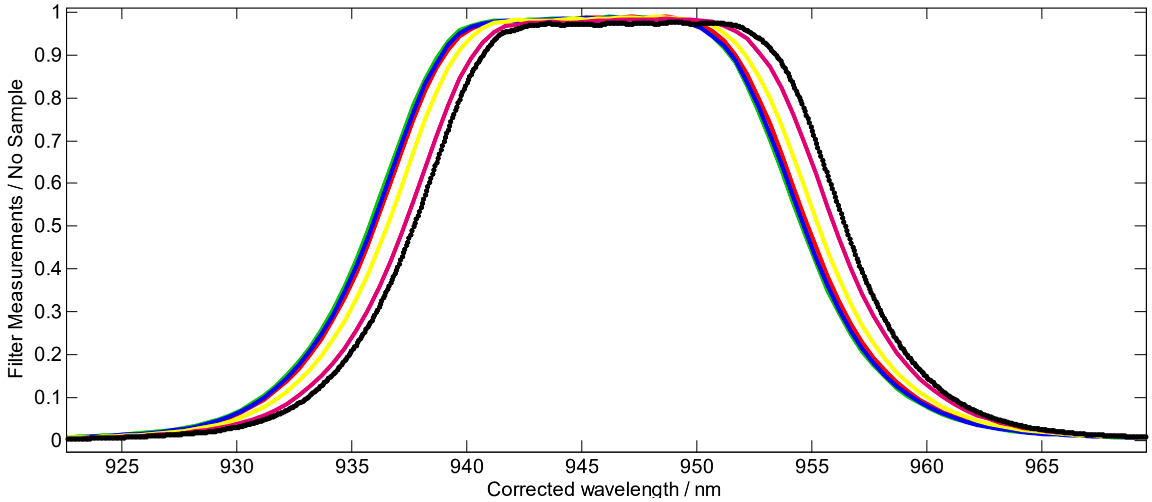

Figure 16: Band 1: The first 3 positions lie close together; there is a clearly visible inhomogeneity. Still the transmissions are well within the requirement.

The measurement by the supplier Iridian is shifted towards the higher wavenumber side, however still well agreeing to the OHB measurements. The shift is due to the infinite F-number measurements from Iridian compared to the OHB measurements made at F-Number of 4.

Table 3 Spectral band 7, comparison of design values and measured results

	Design / nm	Measurement OHB / nm
Centre	1725 ± 4	1725.1
Homogeneity	3	0.3
FWHM	10 ± 1	9.66 ± 0.04

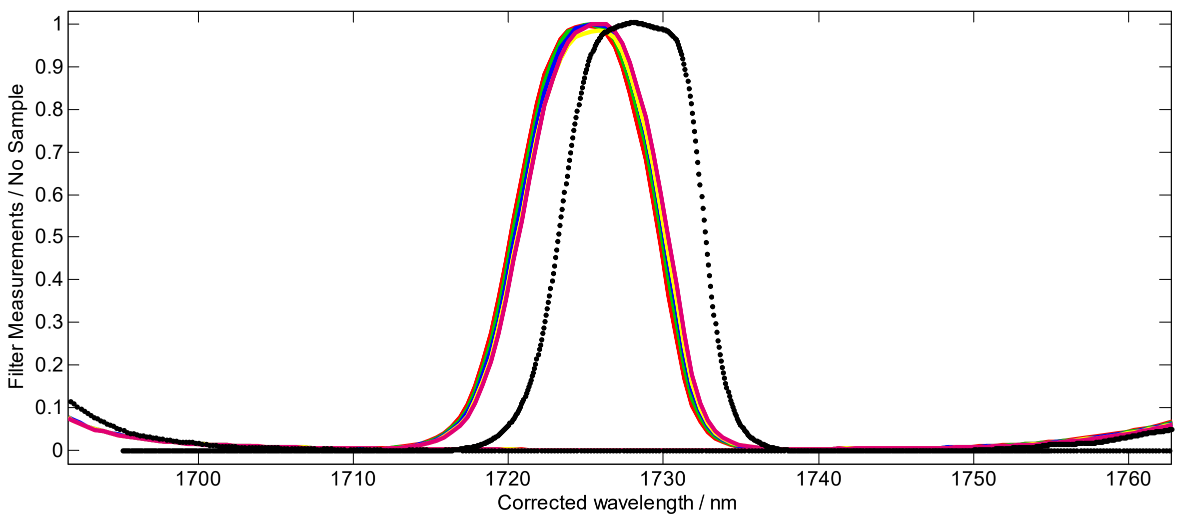

Figure 17: Filter band 7 with F/# of 4

Filter band 7 is perfectly within the requirement. The Iridian measurement is shifted by about 2.5nm to higher wavelengths.

The results for the two exemplary filter bands shown in Figure 16 Figure 17 demonstrate, that the measurement along the filter stripes can resolve minor inhomogeneity's in center wavelength and channel bandwidth.

Calculation of transmission measurements:

As described above, the glass substrate (both coated and uncoated) in between the measuring optics induces a shift of the focal point. Therefore, when the optics is aligned for the setup with a glass in between (e.g. the filter), it is not possible to move this filter out for measuring the intensity without filter. Due to the shift in focal position the focal point is not any more in the focal point of the receiving mirror, and therefore the light is not well coupled into the receiving fiber. For this reason the receiving optics has to be translated manually to compensate this effect. As this is not automatized, this cannot be done in between a measurement sequence. For this reason, directly after scanning a position on the filter, a reference measurement was done at a common position at the uncoated glass substrate, to avoid a shift in focal position. To cancel out the transmission characteristics of the uncoated glass substrate, this then was measured separately.

The accuracy of the transmission measurement is estimated to be ±1.5 to 2%.

Optical density:
To check the out-of-band blocking of the coatings outside of the transmission region, each filter bar was measured at 5 positions for the spectral range 630nm to 2500nm with a step size of 2nm. As different detectors, order sorting filters and gratings have to be used for specific spectral regions, and each measurement of a sample has to be followed by a measurement at a common position on the uncoated glass substrate, this measurement is rather complex and with a measurement time of about 20 hours (with the standard settings used) rather time consuming. In total, it consists of 500 single measurement sequences.

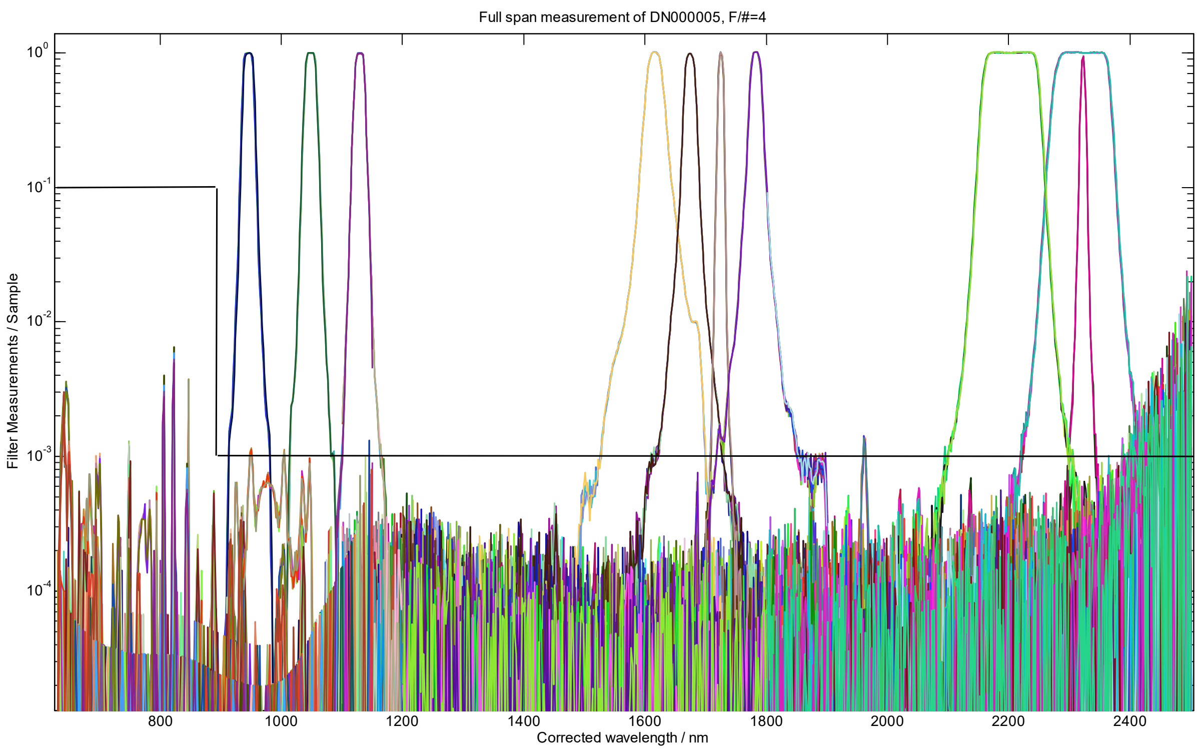

Figure 18 complete scan of all channels showing the requirement for out of band blocking as black line

It can be seen, the out-of-band blocking is well below the filter requirement (horizontal lines in the figure) except for very few positions. The metrology setup is capable to characterise this out-of-band blocking for optical densities of OD3 or even higher over the full spectral regime.

4 SUMMARY / CONCLUSION

The Metrology setup can characterize multispectral filters with a high spatial and spectral resolution, which allows to verify the final performance of multispectral butcher block filter assemblies.

Summary of the achieved metrology performance:

- Absolute wavelength accuracy: < ±0.2nm
- Relative wavelength accuracy (for homogeneity measurements): << ±0.1nm
- Linewidth (FWHM) of instrument with chosen settings: ~0.5nm.
  Note: if linewidth of band to be measured becomes <5nm, then the impact on the shape may become relevant.
- Intensity accuracy: ±1.5-2%.
- Spot diameter of:
  - ~53µm with F-Numbers 2.9 to 4.
    >4 with lower SNR (recoverable with longer integration time)
  - ~110µm with F-Numbers of 5.8 to 8 with exchange of optical elements around detector.
    >8 with lower SNR (recoverable with longer integration time)
  - ~40µm with F-Number of 2 to 3 exchange of optical elements around detector.
    >3 with lower SNR (recoverable with longer integration time)
- Measurement of optical densities of >OD3. OD4 can be achieved by longer integration time and/or accepting lower spectral resolution (>0.5nm)
- Spectral range 600-2420nm. Up to 2500nm with reduced SNR.
  Limit currently is the detector availability only.

The high spectral resolution allows to detect deviations from the original filter substrate prior to dicing, which are introduced by assembly specific tolerances such as minor tilt / torsion or bending of individual bars. With this high spectral resolution and spatially resolved measurements the performance of multispectral filters in butcher-block technology can be verified on assembly level.

The setup is flexible enough to adapt the F-Number and spot size of the measurement beam by changing optical fibers and front end mirrors to tailor spot sizes & NA within certain limits.

Crosstalk between different bands

The current setup is not capable for measuring all kinds of crosstalk possible between adjacent channels. One measurement that was performed is shown schematically in Figure 19.

With this setup, no signal could be detected, however. This means, that the crosstalk is >OD3, with the limitations, that the signal that is reflected into the fiber must stem from the “correct” angle range wrt. to the receiving optics. Radiation coming from larger angles, for example, is not detected as it does not hit and enter the glass fiber. To measure this radiation, a different receiving optics would be necessary, e.g. placing a detector element or an integrating sphere below the “adjacent” filter bar. This kind of measurement would also allow to deliver data which could be used to establish a realistic straylight model for this kind of filter.

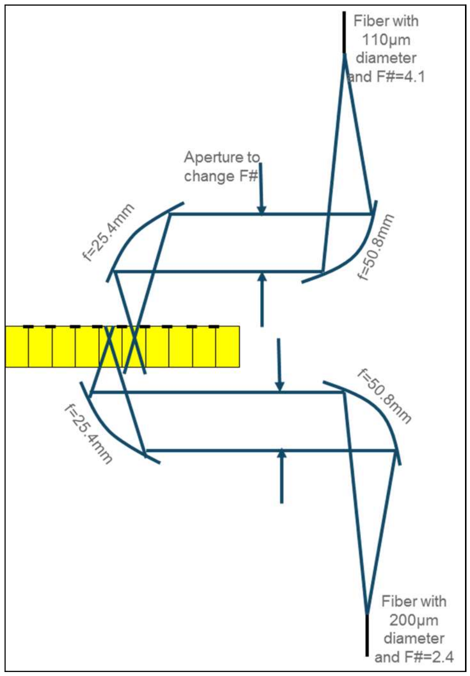

Figure 19 setup for measurement of crosstalk of the adjacent channel

5 OUTLOOK

With the increasing demand on compact space instruments, using multispectral filters instead of complex spectrometer setups, the butcher-block filter technology is pushed to its limits, going to larger number of channels, more extreme length to width ratios of the individual filter bars. Applications with 30 up to 100 channels are discussed, with demanding requirements and tolerances on centre wavelength and channel bandwidth. Especially with very long and thin filter bars the contribution of bending and torsion of these bars within the butcher block filter assembly will become crucial to achieve centre wavelength tolerances along the channels. The availability of large detectors with a high broadband spectral sensitivity from VIS to 2.5µm drive the technology to more demanding geometries and to higher channel numbers. With this development the spectral performance requirements are pushed towards very narrow channels, small channel separation and therefore very tight tolerances on the channels central wavelength and bandwidth. This not only pushes the fabrication technology and the tolerances during the butcher block filter assembly to new borders but will require even more powerful optical characterization tools to verify that such a filter assembly finally meets its requirements.

The spectral characterization setup presented here is targeted at this trend and allows to investigate the spectral performance and its tolerances, which are introduced during the butcher-block assembly process and complements the spectral characterisation measurements of the filter suppliers.

ACKNOWLEDGEMENTS:

- The work has been funded by OHB internal R&D funded project MUSFISCHMO (**Mu**lti-**S**pectral-**Fi**lter **S**pectral **Ch**aracterization & **Mo**unting)
- The Filter which was used to test and characterize the setup was provided by OHB Digital Connect in Bremen within the framework of a remote sensing instrument development.
- The multispectral filter under test was manufactured by Iridian, CA.