

## Spectral sensors



The power team  
for more performance



We make it visible.

## Team power

The following spectrometer module families have been developed at Carl Zeiss:

- MMS – Monolithic Miniature Spectrometer
- MCS – Multi Channel Spectrometer
- PGS – Plane Grating Spectrometer

A classic spectrometer or a classic monochromator typically consists of a dispersive medium, entrance and exit slits, and imaging components which produce a parallel beam path. To record a spectrum, a detector located behind the exit slit must sequentially record the incident light, while the dispersive component or the exit slit is moved. This mechanical movement requires time and is prone to failure. In many applications – in industry in particular – short measuring times and insensitivity to external influences are a major advantage. This is why, at the end of the 1970s, Carl Zeiss started to develop diode array spectrometers which feature a diode array instead of an exit slit and which simultaneously record a complete spectrum within a fraction of a second and hence make moving

components superfluous. The concept of the spectrometer module family of Carl Zeiss is based on reducing the opto-mechanical design and the number of components to the physical minimum and, at the same time, to use a maximum number of components jointly for all versions.

In the past few years Carl Zeiss has developed a large number of different spectrometer modules for a wide variety of applications and requirements, all of which offer a decisive benefit:

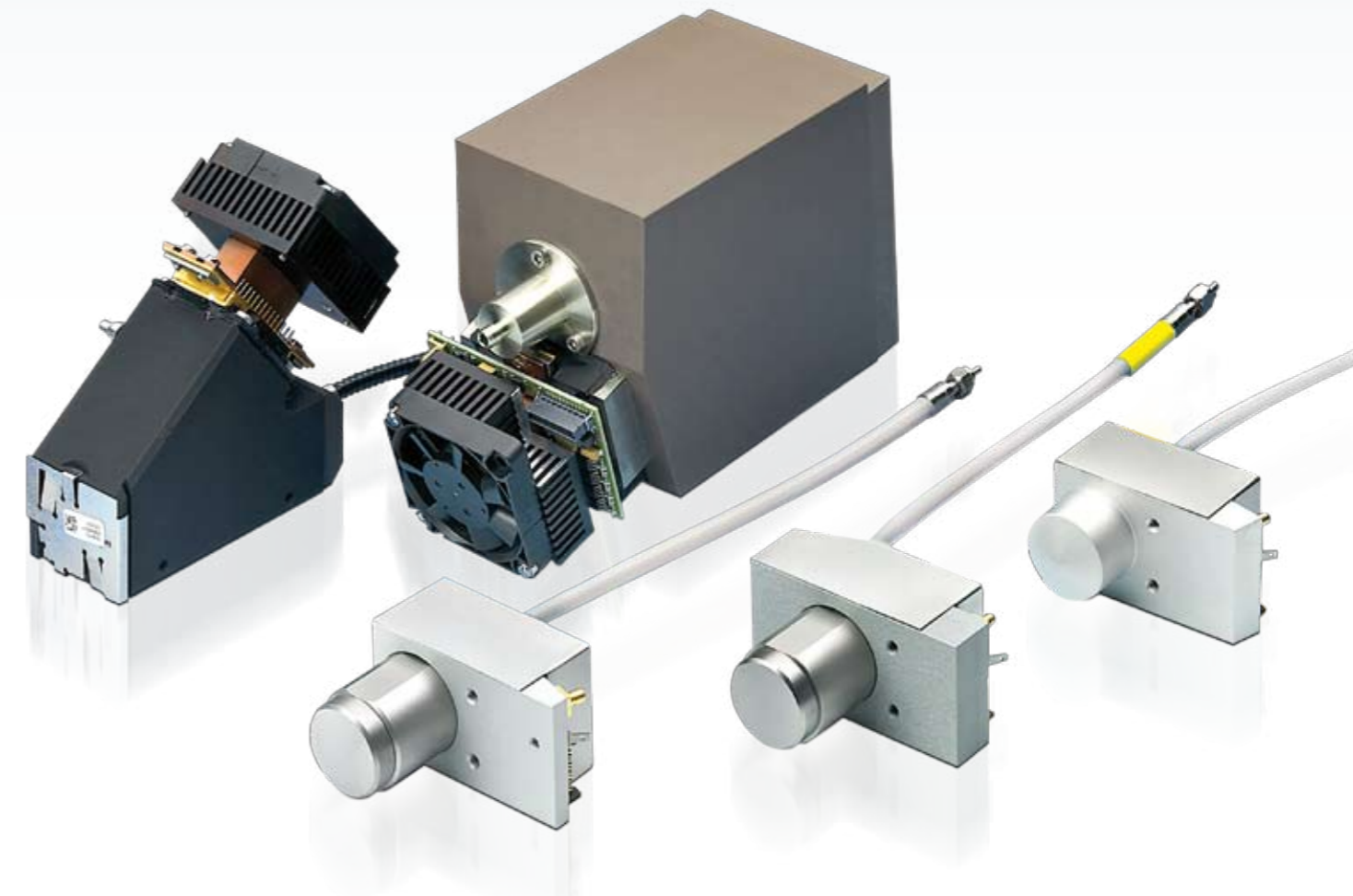
All the spectrometer components are permanently attached to each other. This results in a very high level of insensitivity to mechanical vibrations and therefore also to a high degree of reliability. In addition, the entire setup is maintenance-free, i.e. recalibration is not necessary.

The following benefits result directly from the design used:

- repeatability – reliability
- wavelength correctness – calibration standard
- small – compact – robust
- high degree of sensitivity
- versatility
- suitable for use in industry
- universal, easy-to-use interfaces

The basis of the high quality offered by the spectrometers is the technological know-how of Carl Zeiss for mathematical designs, structuring (grating production and replication), coating and material

processing. In addition, our assembly method is of key importance for the high level of insensitivity to such influences as vibrations and, above all, temperature changes.





## Trailblazing

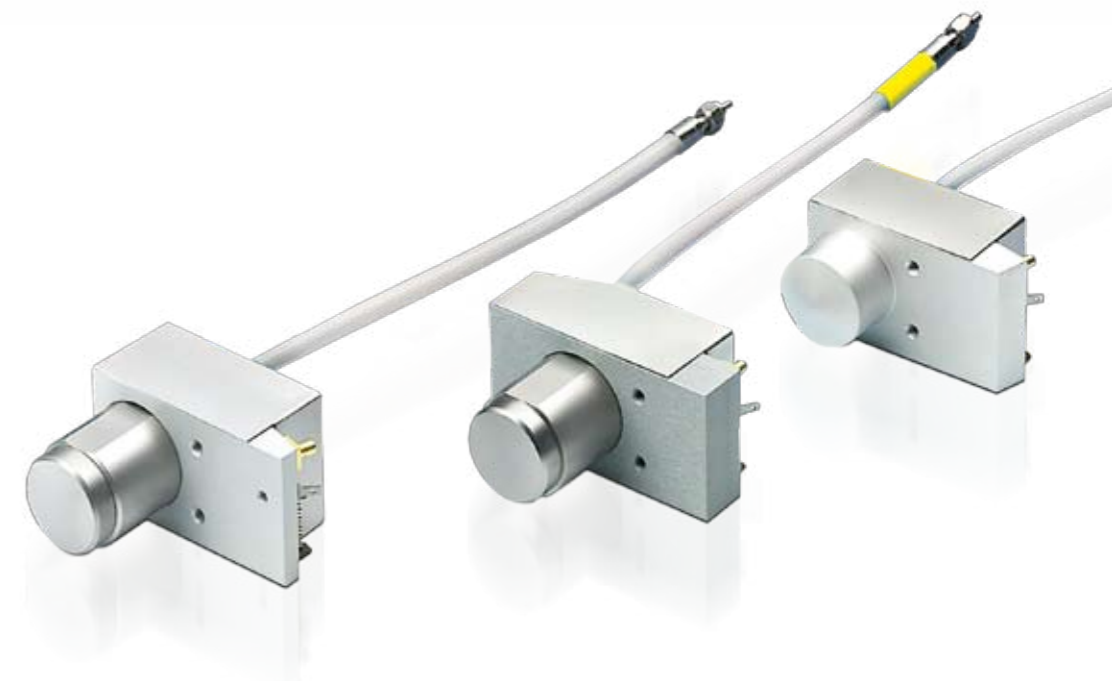
### MMS family

The extremely compact design is a characteristic feature of the spectrometers in the MMS family. Small designs are possible because high repeatability, not high resolving power is required for many applications.

### Optical components of the MMS family

- imaging grating
- cross-section converter as optical input
- diode array as opto-electronic output are arranged around a central body and are adhered to it.

Depending on the version, the central bodies have different designs. The two components important for the interfaces – the cross-section converter and detector – are common to all.



### Central body

In the MMS 1, the central body is a glass body similar to a lens. The imaging grating has been directly replicated on this glass body; the grating is thus permanently fixed and optimally protected against dust and gases. The use of an optically denser medium and the resultant larger aperture allows the use of small gratings. This leads to fewer aberrations.

For reasons of transmission, the solid glass body has been replaced in the UV-sensitive modules by a hollow body to which the grating and the detector have been cemented. The overall stability is not impaired by the tube design; the temperature-induced drift of the wavelength has even been reduced.

### Gratings

The gratings for the MMS family itself consist of so-called holographic blazed, flat field gratings. These gratings which are produced at Carl Zeiss in a stationary wave process achieve significantly higher degrees of efficiency (for non-polarized light) than gratings with a sinusoidal profile. In addition to its dispersive function, the grating must image the entrance slit on the detector array. By varying the groove density and using curved grooves, coma is

corrected and the focal curve flattened (flat field). This ensures that the focal curve is optimally adapted to the flat detector structure. Even with the short back focal distance of the MMS 1, flat spectra of a length of over 6 mm are obtained.

The same grating design is used for the VIS and the UV-VIS versions. The master grating has its efficiency maximum at approx. 220 nm. Due to the higher optical density, the efficiency curve of the VIS module is shifted by the factor of the refractive index.

### Cross-section converter

A fiber bundle, cross-section converter is used to further optimize the light sensitivity of the module. Single fibers in a linear configuration form the entrance slit (slit height  $h$ , determined by the number of individual fibers; slit width  $b \approx$  core diameter). The diameter has been adapted to the pixel size of the diode array used and the imaging and dispersive properties of the flat field grating. Thus, light intensities near the theoretical limit are achieved. The cross-section converter is an integral component of the spectrometer design and is therefore not easy to modify. There is a possibility, however, of modifying the length of the fibers and the design of the input.

In addition, it must be taken into account that quartz fibers which are used in older MMS UV-(VIS-) modules form so-called solarization centers when they are exposed to deep UV light below 220 nm. That means that the transmission of the fibers is reduced when they are exposed to high-energy light. The shorter the wavelength of the light (higher photon energy) and the higher the intensity and the longer the exposure time, the stronger and sooner this effect occurs. This means that the transmission can even be restricted in the range of more than 220 nm to 250 nm. This solarization effect can only be partly cancelled by heating, but it is possible to correct it by means of frequent reference measurements.

For measurements below 225 nm, it is possible to equip the MMS modules with solarization-

stabilized fibers. In the standard modules, the use of a Schott WG225 filter with a thickness of 3 mm is definitely recommended.

### Detector

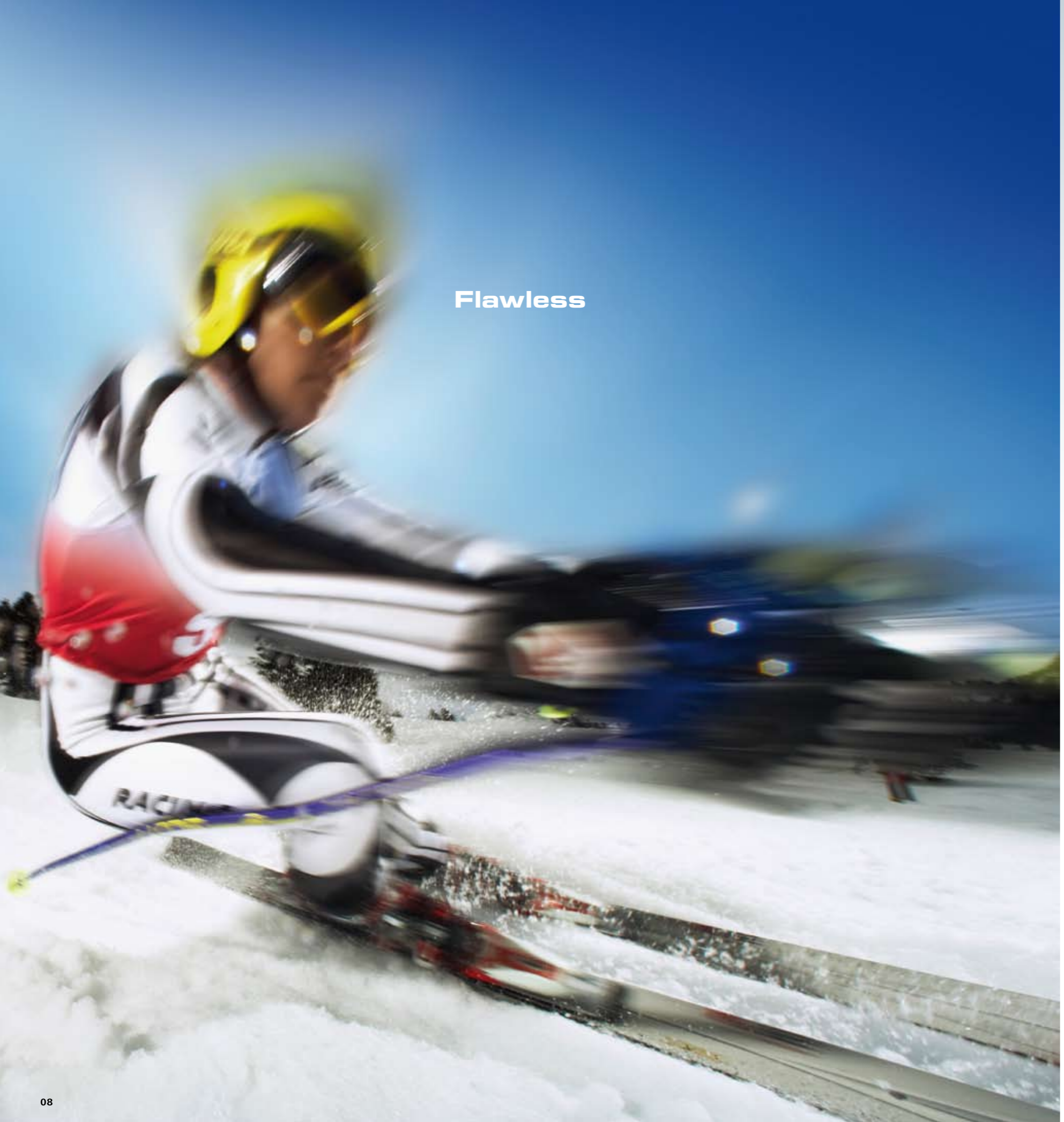
#### MMS

The silicon diode array S3904-256Q from Hamamatsu is incorporated in the MMS family. Only the MMS 1 NIR enhanced uses the Hamamatsu type S8381-256Q. This array is packed in a shorter special housing which results in a very small split-off angle, allowing an efficient grating design. When changing to a different detector, this angle and the approximate spectrum length of 6 mm must be taken into account. To suppress the second order, the diode array has been directly coated with a dielectric cut-off filter.

#### The following modules are available:



Module	Spectral range [nm]
MMS 1	350 – 1100
MMS UV-VIS	190 – 720 or 250 – 780
MMS UV	195 – 390



Flawless

**MCS family**

The MCS family offers spectrometers which feature both high repeatability and good resolving power. To achieve a robust design, all optical components are permanently connected to each other via a central body.

**Optical components of the MCS family**

- imaging, aberration-corrected grating
- fiber cross-section converter or slit as optical input
- diode array or cooled back-thinned CCD as opto-electronic output are arranged around a central body and are adhered to it.

In the MCS family, the different designs of the central body once again define the application of the system. The cross-section converter and detector can be retained for the different versions.



## Central body

For reasons of thermal stability, the central body of the MCS spectrometers is made of a ceramic material or a special aluminum alloy (coefficient of expansion  $\alpha \sim 13E-6$ ). The aberration-corrected grating, the cross-section converter (or mechanical slit) as the optical output and the detector are connected to each other via this body, ensuring outstanding stability and reliability. The hollow body design allows the use of the MCS for the complete spectrum from UV-NIR.

## Gratings

The gratings used for the MCS family are holographically blazed, flat field gratings. Through additional ion beam etching, the maximum grating efficiency was optimized for the various wavelength ranges. Plane spectra are achieved over a length of 25 nm via the aberration correction. The grating surface is dimensioned so that the light of a fiber with  $NA = 0.22$  is imaged.

## Cross-section converters

A fiber-bundle, cross-section converter is used for further optimization of the light intensity. The entrance slit is generated by the linear arrangement of the individual fibers (slit height  $h$ , defined by the number of the individual fibers, slit width  $b$  – core diameter). The slit is adapted to the pixel size of the diode array used and to the imaging and dispersive properties of the flat field grating. In this way, light intensities are achieved at the theoretical limit. The cross-section converter is an integral component of the spectrometer design and cannot therefore be easily modified. However, there is a possibility of changing the length of the fiber and the design of the input.

Furthermore, care must be taken as quartz fibers like those used in older MCS UV (VIS) modules form so-called solarization centers when exposed to deep UV light under 220 nm. This means that the transmission of the fibers decreases with exposure to high-energy light. This effect is more pronounced, the shorter the wavelength (higher photon energy), the greater the intensity and the longer the exposure time. This can also lead to limitation of the transmission above 220 to 250 nm. This solarization effect can only be partly reversed by baking, but can be corrected by frequent reference measurements.

For measurements below 225 nm, it is possible to equip the MCS modules with solarization-stabilized fibers. In the standard modules, the use of a Schott WG225 filter with a thickness of 3 mm is definitely recommended.

## Detector

### MCS PDA

In the MCS PDA the silicon diode array S3904-

512Q or 1024Q from Hamamatsu is employed. To suppress the 2nd order (and the 3rd order in the MCS UV-NIR), the diode array is directly coated with dielectric cut-off filters.

The following modules are available:



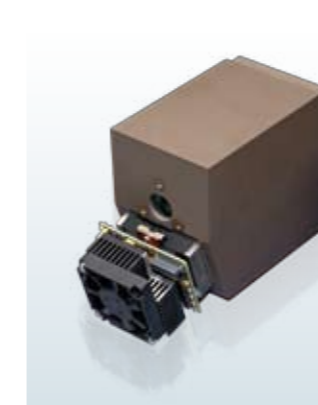
Module	Spectral range [nm]
<b>MCS UV-NIR</b>	190 – 1015
<b>MCS UV-VIS</b>	200 – 620
<b>MCS UV-VIS</b>	280 – 700
<b>MCS VIS</b>	360 – 780
<b>MCS NIR</b>	695 – 1100

### MCS CCD

In the MCS CCD modules, back-thinned CCDs S7301-0906Q or 1006Q from Hamamatsu are used. Back-thinned CCDs offer excellent direct sensitivity to UV light. To reduce the dark current,

this detector features an integrated Peltier element which has to be externally activated. In the MCS CCD, the heat removed by the Peltier element is routed to the ventilator-cooled cooling body.

The MCS CCD is available in 3 versions:



Module	Spectral range [nm]
<b>MCS CCD UV-NIR</b>	200 – 980
<b>MCS CCD UV</b>	200 – 600
<b>MCS CCD NIR</b>	600 – 1000

**Ultraprecise**

### PGS family

The spectrometers in the PGS family are designed for use in the NIR. InGaAs (indium-gallium-arsenide) is used as a detector material in this wavelength range. The special combination of aspheric collimator and focusing lens allows the use of plane gratings optimized for the NIR, while maintaining good flat field correction of the spectral imaging. Excellent long-term stability is ensured by the permanent connection of all optical components.

### Optical components of the PGS family

- blazed plane gratings
- aspheric lenses
- mono-fiber with slit as optical input
- cooled InGaAs photodiode array as opto-electronic output are arranged around a central body and are adhered to it.



### Central body

In the PGS family, a special aluminum alloy (coefficient of expansion  $\alpha \sim 13E-6$ ) is used for the central body. This body is the carrier of the blazed grating and of the aspheric collimator and focusing lens. The input fiber and the detector are permanently connected to the central body, therefore providing excellent stability.

### Gratings

The gratings for the PGS family are mechanically divided or holographically exposed plane gratings. The maximum efficiency is adapted to the special wavelength in the NIR. The grating surface with the clear diameter of the lenses is dimensioned so that the light of a fiber with NA of up to 0.37 is imaged.

### Input fiber

The coupling of light is performed in the standard way via a quartz monofiber. These fibers display a diameter of 600  $\mu\text{m}$  and a NA = 0.22. The end of the fiber features a slit with a height of 500  $\mu\text{m}$  (NIR 1.7) or 250  $\mu\text{m}$  (NIR 2.2). The slit heights are adapted to the pixel heights of the InGaAs arrays. A cross-sectional conversion similar to the silicon detectors is not needed.

### Detector

InGaAs detectors are used in the near infrared region. For the modules of the PGS NIR, arrays with InGaAs are utilized for the range to 1.7  $\mu\text{m}$ , and extended InGaAs for the range to 2.2  $\mu\text{m}$ . Here, arrays with an element number of 256 and 512 pixels (1.7  $\mu\text{m}$  only). For the extended InGaAs arrays, an order filter for suppressing the 2<sup>nd</sup> diffraction order is applied, as a function of the wavelength range, to the array.

The following modules are available:



Module	Spectral range [nm]
PGS NIR 1.7 – 256	960 – 1690
PGS NIR 1.7 – 512	960 – 1690
PGS NIR 2.0 – 256	1340 – 2000
PGS NIR 2.2 – 256b	1100 – 2150

## Warm-up

The most important criterion when selecting a spectrometer is the spectral range which must be covered by the spectrometer. In most cases, this range is clearly defined. The other two important criteria of a spectrometer – the spectral and the intensity-related (dynamic) resolution – are, however, very rarely clearly defined.

### Spectral resolution

The following four terms are often used to describe "spectral" resolution:

1. Rayleigh-criterion –  $\Delta\lambda_{\text{Rayleigh}}$  (DIN standard)
2. Line width, mostly full width at half maximum –  $\Delta\lambda_{\text{FWHM}}$
3. Sub-pixel-resolution (also termed "software resolution")
4. Pixel dispersion –  $\Delta\lambda/\text{Pixel}$

It is the actual application which provides a useful definition in this respect. There are mainly three different purposes for which a spectrometer is used (these can also occur in combination, of course):

1. Separation of two or more lines within a spectrum – analysis of compositions
2. Determining the line shape mostly determining the width of a line or band (FWHM or 1/e<sup>2</sup>-width)
3. Measurement of a line with respect to its peak wavelength and intensity at the maximum.

### Spectral resolving power

According to DIN, the Rayleigh criterion is relevant to the separation of spectral lines. The criterion indicates how wide the spectral distance between two lines  $\Delta\lambda_{\text{Rayleigh}}$  must be to allow their recognition as separate lines. Here, the spectral width of the individual lines  $\Delta\lambda_{\text{Line}}$  (see above) must be markedly smaller than their spacing. This is the only significant definition of spectral resolving power.

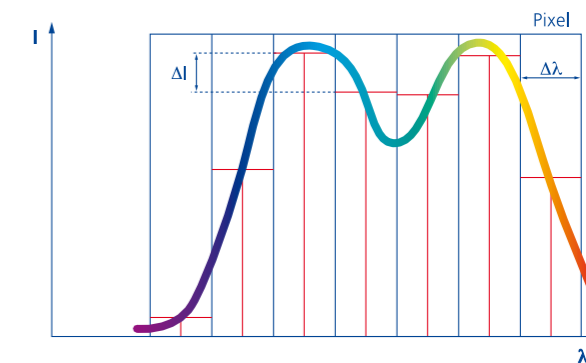
2 lines with  $I_{\text{max},1} = I_{\text{max},2}$  are separated if  $\Delta I_{\text{decrease}} \geq 19\%$ .

### Width of spectral lines

To enable the measurement of the width of a spectral line  $\Delta\lambda_{\text{Line}}$ , the expansion of this line by the spectrometer must be smaller than the spectral width of the line itself. To ensure this, it is important to know the expansion  $\Delta\lambda_{\text{FWHM}}$  produced by the spectrometer. This property is related to the Rayleigh criterion.

$$\Delta\lambda_{\text{FWHM}} = \lambda_2(I_{\text{max}}/2) - \lambda_1(I_{\text{max}}/2)$$

$$\Delta\lambda_{\text{FWHM}} \approx 0.8 \times \Delta I_{\text{Rayleigh}}$$



### Wavelength accuracy

To determine the spectral position  $\lambda$  – with a specific accuracy  $\Delta\lambda_{\pm}$  – of a single line, a spectrometer with at least this absolute wavelength accuracy  $\Delta\lambda_{\pm}$  is required. This parameter is dependent on the accuracy of the positions of the readout elements (pixels or slit/detector) or the stability of these positions characterized by repeatability. Contrary to this, the absolute wavelength accuracy only depends indirectly on the dispersive and focal properties of the spectrometer and is not "resolution" in the classic sense. The stability (or repeatability) of a spectral sensor is dependent on the mechanical stability of the module and the temperature-related wavelength drift. The former is completely uncritical in the MMS, MCS and PGS modules, and the drift can be more or less neglected.

### Dispersion

The term  $\Delta\lambda / \text{Pixel}$  ( $= \Delta\lambda_{\text{Pixel}}$ ) has nothing to do with spectral resolution; it is merely the linear dispersion of a diode array spectrometer. The pixel dispersion and the spectral resolution are related to each other via the width of the entrance slit and the imaging properties of the spectrometer. If the entrance slit is imaged on approx. 3 pixels, the triple of the pixel dispersion approximately corresponds to  $\Delta\lambda_{\text{Rayleigh}}$ .

$$\Delta\lambda_{\text{Rayleigh}} \approx 3 \times \Delta\lambda_{\text{Pixel}}$$

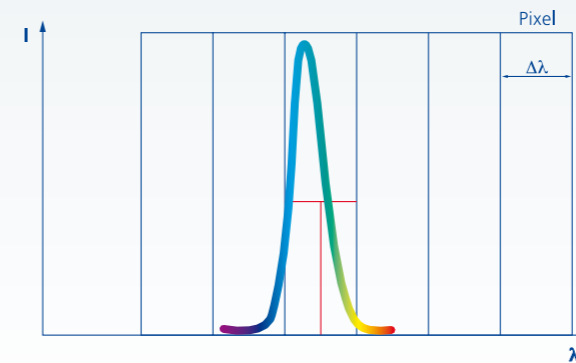
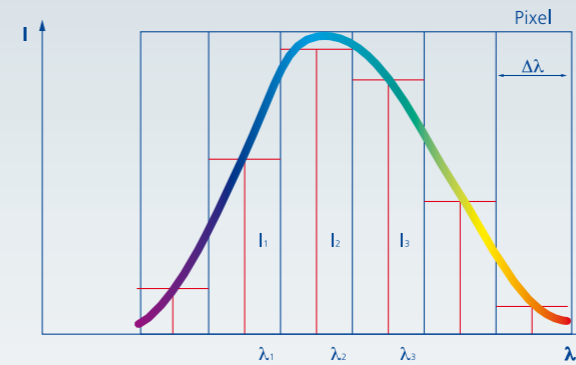
### Special features of diode array spectrometers (DAS)

#### Spectral resolution

Due to the fixed position of the pixels with respect to the wavelength of the incident light, the resolution provided by DAS differs from that provided by monochromators/spectrometers with moving components: resolution defined as the "separation of two adjacent lines" is dependent on the relative position of these lines with respect to the pixels:

If two adjacent lines are imaged on the pixels in such a way that the minimum falls on the central pixel ( $I_2$ ) and the maxima on the adjacent pixels ( $I_1, I_3$ ) the lines can be separated if the intensity displayed is  $I_2 < 0.81 \times I_1$  ( $I_3$ ),  $\Delta\lambda$  is then exactly two pixels ( $2 \times \Delta\lambda_{\text{Pixel}}$ ). In this case, it is sufficient to evaluate a total of 3 pixels; the locations of the maxima correspond almost exactly to the central wavelengths of the pixels displayed.

If the maximum of a line is imaged on the separating line between two pixels ( $I_1, I_2$ ) however, a total of 4 pixels is required to be able to detect a clear reduction in the pixel intensities. Both pixels record about the same intensity, with the result that a reduction to 81 % is not displayed until in the next pixel ( $I_3$ ). Here, the actual maxima are separated by fewer than 3 pixels; the DAS displays a spectral spacing of  $3 \times \Delta\lambda_{\text{Pixel}}$  as a diode array can only detect discrete values using the step width of the pixel dispersion. A total of 4 pixels are needed for processing.



#### Sub-pixel resolution or the parabola fit

To determine the peak wavelength  $\lambda_{\text{max}}$  (and/or peak intensity  $I_m$ ) the spectral line to be measured must be imaged on at least 3 pixels (see below). Three pairs of values (intensity per pixel  $I_{1,2,3}$  and the related central wavelength of the pixel  $\lambda_{1,2,3}$ ) allow relatively easy fitting of the line to a parabola. The equation for the parabola then gives the peak of the curve including the data for the peak wavelength and peak intensity. The accuracy of this method largely depends on the absolute accuracy of the central wavelength. In a diode array spectrometer, this wavelength can be determined, in principle, to almost any accuracy required. If necessary, each pixel can be individually calibrated. However, this will only make sense if the module

features the necessary stability. Otherwise, the wavelength specification will only remain valid until the next shock or temperature change.

If the imaging performance (and the dispersion) of a DAS has been chosen such that fewer than 3 pixels are illuminated, no extrema can be determined, resulting in a paradox: an apparently ideal situation – a line is very narrow at the output – leads to considerably increased inaccuracy. If, for example, a line is only imaged on a single pixel, the spectral inaccuracy is  $\Delta\lambda_{\text{Pixel}}$  in this case.

#### Parabola equation

$$I(\lambda) = a \times \lambda^2 + b \times \lambda + c$$

#### Coefficients

$$a = (I_3 + I_1 - 2 I_2) / 2 \Delta\lambda^2$$

$$b = (I_3 - I_1) / 2 \Delta\lambda - 2a \times \lambda^2$$

$$c = I_2 - a \times \lambda_2^2 - b \times \lambda_2$$

$$\text{Maximum at } \lambda_{\text{max}} = -b/2a$$

#### Determining the half-width

The parabola fit also supplies qualitative data on the half-width. For this,  $I_{\text{max}}/2$  must only be inserted in the parabola equation. There are only minor differences between the half-width of a parabola fit and that of a Gaussian fit (see below).

The half-width which is displayed by a DAS is also dependent on the position of a line relative to the individual pixels. Our specifications are valid for worst-case values.

More adequate, but more complex, are fits to

Gaussian or Lorentz curves which better correspond to the actual spectral distributions. These fits also have the advantage that the half-width calculated from them is not dependent on its position relative to the pixels.

$$\Delta\lambda_{FWHM} = 2[(b/2a)^2 - (c - I_{max})/a]^{1/2}$$

### Intensity resolution

To measure intensity, the following properties which are dependent on each other are of interest:

Relative:

- smallest detectable change
- signal stability
- detection or dynamic range
- linearity.

Absolute:

- lowest detectable amount of light or sensitivity.

### Accuracy

Measurements of minimal changes and stability are directly dependent on each other and are mainly limited by the noise present in the electronics, as the stability of the „light path“ is ensured in most spectrometers. As with all parameters, it is important how a value – here in the true sense of the word – is determined. For the data provided by the MMS, for example, an integration time of 10 ms is set and the standard deviation  $\Delta\sigma$  is computed using 20 recordings. This supplies a measure of the accuracy  $\Delta I$  with which an intensity value can be determined.

$$\Delta I = I_{noise} = \Delta\sigma$$

### Dynamic range and intensity changes

The dynamic response is defined as the ratio of the saturation value  $I_{sat}$  and the noise  $I_{noise} \leftrightarrow \Delta\sigma$  and thus corresponds to the signal-to-noise ratio S/N. (The usable range is reduced by the dark current.)  $\Delta\sigma$  does not only depend on the detector, but also on the digitization determining the smallest step width into which a measured signal can be decomposed.

$$\text{Dynamic range} = S/N = I_{sat} / I_{noise}$$

The weakest link in the chain, of course, determines the signal to-noise ratio to be achieved. For instance, when using a 14bit converter – this corresponds to 16,384 steps or increments and a noise of  $\Delta\sigma = 1$  count, a signal (full-scale display) can really be divided into 16,384 increments. Hence, the lowest measurable change is 1/16,384 of the saturation signal. At a noise of 4 counts an uncertainty of 4 counts also exists, i.e. a change of 4/16,384 of the saturation signal can only be definitively measured or the signal divided into 4,096 increments.

It should be noted here that a wide dynamic range is only obtainable if the PDA (photodiode array) is near the saturation limit. The aim is always to reach high light intensity – here, the high sensitivity of the MMS modules is beneficial.

$$\text{Dynamic range} = \text{range ADC} / \Delta\sigma$$

### Linearity

The previous remarks will be completely accurate only if the detector and the post-detector electronics provide ideal linearity, i.e. if the dependence of the measured charge on the irradiated intensity is exactly linear. For quantification, the admissible deviation must be specified. Fortunately, the behavior of modern semiconductor detectors is almost perfectly linear within a wide range. Before saturation (the extreme case of non-linearity) is reached, however, the increase of the current (carrier of the intensity information) supplied is no longer linear to the number of photons striking the photosensitive material. For this reason, the range of linearity is smaller than the dynamic range.

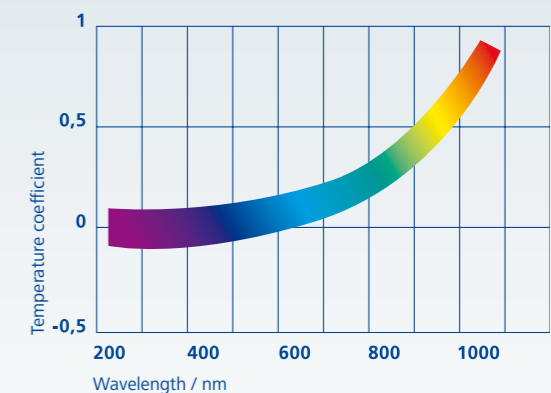
### External influences

As the graphic shows, a change of the temperature T does not cause any change in sensitivity of silicon, the sensitivity in fact increases slightly in the range of up to 1100 nm when the temperature is raised. In the case of InGaAs photodiode arrays, the sensitivity also changes by less than 1 % in the range of 1 to 1.55  $\mu\text{m}$  with temperatures ranging from -50 and +50 °C. Only outside the specified range, does the different coating lead to an increased influence of temperature. (Falling temperatures lead to reduced sensitivity on the band edge).

In addition, the signal-to-noise ratio of the photodiode array used does not degrade with increasing T. It is only the dark current  $I_{dark}$  which increases with rising temperature, resulting in a reduction of the dynamic range. Therefore, detectors, in particular InGaAs diode arrays, are often cooled.

In this context it should be mentioned that the amounts of light to be measured are also subject to fluctuations. The instability of the light source is often the limiting factor.

$$I_{dark}(T+7K) = 2I_{dark}(T)$$



### Sensitivity

The smallest detectable change is a relative specification. Much more difficult to specify is the lowest detectable amount of light or: how many photons are needed for the detection electronics to record a change. The difficulties result from determining the light intensity of a light source and the coupling efficiency. Furthermore, these parameters are wavelength-dependent. There is, on the one hand, a direct dependence, as all components feature wavelength dependent efficiencies – including the coupling – in device; on the other, there is a dependence, as the bandwidth is of decisive importance for sensitivity measurements. The simplest case is a light source with a very narrow band, as displayed by most of the lasers. If the bandwidth of the light source used is markedly smaller than the bandwidth of the spectrometer used, the situation is clear. The MMS value of more than  $10^{13}$  counts / Ws has been measured with a red HeNe laser.

## Scattered light

The specification of scattered light data is only useful in connection with the measuring instructions. Scattered light data for the MMS product line are determined using three different light sources to measure the different spectral components of scattered light: a deuterium lamp for UV, a xenon lamp for VIS and a halogen lamp for VIS-NIR.

The level of scattered light is defined as the ratio of the respective measurement using Schott GG495 and KG3 filters to the maximum useful signal and is therefore specified for the short wavelength range. This reveals that the main components of scattered light in the MMS modules come from the NIR range. These spectral components are easy to filter out as they are far away from the spectral range of interest. The scattered light value for the PGS NIR is reduced to 0.1 % (measured at 1450 nm, halogen lamp, Schott RG 850 filter and 10 mm water absorption).

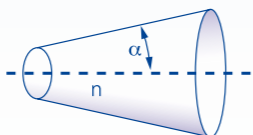
Scattered light influences the dynamic range as the full range is no longer available. However, changes in the radiation used only affect the dynamic range in proportion to the scattered light present: for example, a change of 10 % in the radiation used causes a change of  $10^{-4}$  if the scattered light component is 0.1 %. If the radiation causing the scattered light is not used, the amount of scattered light can be further reduced by filtering this radiation. A blocking of 103 results in a change of  $10^{-7}$  in the case described. Thus, the measurement of minimal changes is only impaired to a very limited extent, as noise is the bigger problem in most cases. In addition, if the signal causing the scattered light is known, the scattered light component can be eliminated by computation.

## Optical interface

Interfaces must be mechanically and optically defined. A useful mechanical interface for optical systems is the SMA connector as used in the modules. Together with the well-defined light guidance factor of a fiber bundle, this results in a unique interface.

### Light guidance factor

The light guidance factor  $G$  is the product of the light entrance area  $F$  and the aperture angle  $\Omega$  of the light beam, with the refractive index  $n$  also having to be taken into account. The first factor corresponds to the cross-section of the fiber bundle, the second factor is derived from the numerical aperture NA. In the case of the e.g. MMS 1 family, the fiber optical light value is calculated at  $G = 0.157 \text{ mm}^2\text{sr}$ .



$$G = F \times \Omega \times n^2$$

$$\Omega = 2\pi \times (1 - \cos \alpha)$$

$$\alpha = \arcsin NA$$

For the optimum adaptation of an existing light source (whether fiber, illuminator, imaging system) it is recommended to determine the respective light guidance factor. A comparison of the factor obtained for the light source with the MMS light guidance factor permits an estimate to be made of the possible coupling efficiency. In addition, Fresnel losses of 4 % (index jump at glass fiber) must also be taken into account.

## Increase in transmission

If round light spots are assumed, the use of a cross-section converter (CSC) results in increased transmission  $\eta_{FF, QSW} / \eta_{FF, slit}$  compared with the classic slit. This increased transmission can be calculated from the ratio of the amount of light transmitted by the CSC to the amount of light transmitted by a rectangular slit.

In the CSC, the transmitted amount of light is given by the fill factor  $\eta_{FF, QSW}$ . The fill factor is defined as the quotient of the optically effective surface  $A_{eff}$  and the overall illuminated area  $A_{Apt}$ .

In the CSC,  $A_{eff}$  is the product of the fiber core cross-section and the diameter  $d_{fiber}$  and the number of fibers  $N$ ; in the slit,  $A_{eff}$  is the area obtained from the slit width  $b$  and slit height  $h$ . The total area is the circular area with the diameter  $d_{slit} = h$ .

$$\eta_{FF, QSW} = N \times d_{fiber}^2 / d_{Apt}^2$$

$$\eta_{FF, slit} = 4 b / (\pi \times d_{slit})$$

$$\eta_{FF, QSW} / \eta_{FF, slit} = 16 \text{ (MMS)}$$

## Optimization of a diode array spectrometer

In addition to the selection of the most efficient components possible (blazed grating, cross-section converter, sensitive diode array), dispersion, imaging properties, entrance slit and pixel size must be matched to each other. To obtain maximum light sensitivity it is important that – with monochromatic light – only just a little more than the 2 pixels are illuminated which are required for spectral resolution. In a first approximation, the grating provides a 1:1 ratio image, i.e. the entrance slit should be

2 to 3 pixels wide. If more pixels are illuminated, the signal-to-noise ratio and the sensitivity will worsen (1 pixel does not cover the optimal bandwidth). If fewer than 3 pixels are illuminated, the wavelength accuracy will worsen. The selection of  $70 \mu\text{m}$  individual fibers (effective slit width approx.  $60 \mu\text{m}$ ) for the MMS 1 CSC, for example, is thus ideal for a pixel width of  $25 \mu\text{m}$ . The number of fibers is obtained by dividing the pixel height by the outer diameter of the individual fibers.



## Control Diode array / CCD array

### Diode array

Depending on the resolution and wavelength required, different semiconductor technologies are used for array detectors. However, not only the quality of data capture but also the further processing of the data is decisive for the measuring result. Spectroscopy makes special demands on line detectors. Pixel geometry, the suitably selected semiconductor technology, cooling and signal dynamics, in addition to other factors, have a key influence on the performance provided by the line detector-based spectral sensors – and therefore also determine where they can be used. In order

to image the entrance slit with minimum energy loss, very high individual pixels are required. In 2-dimensional CCD detectors this is achieved through the line binning of the pixels. Quadratic pixels or pixels with low height lead to energy losses which impair the signal dynamics. It is important to know that light losses here cannot be compensated for by greater detector sensitivity or higher amplification without impairing the signal dynamics.

The individual N pixels of a diode array which represent capacitors are discharged by incident light. The information on the amount of light is gained in the subsequent charging process. The time integral over the charging current is proportional to the light intensity. Thus, the diode array operates as a so-called self-scanning multiplexer:

The individual pixels are read out one after the other. The external clock frequency f determines the frequency for switching from pixel to pixel or, in other words, the time per pixel  $t_{\text{Pixel}}$ . This way, the minimum possible integration time  $t_{\text{int, min}}$  is determined – even in the case of the Hamamatsu diode array. This also determines the minimum possible integration time  $t_{\text{int, min}}$ .

$$t_{\text{Pixel}} = 1/f$$
$$t_{\text{int, min}} = (N+1) \times t_{\text{Pixel}}$$
$$f_{\text{max}} = 2 \text{ MHz} \rightarrow t_{\text{int}} > 127 \mu\text{s}$$

(256 silicon diode arrays)

The integration time itself is selected via the temporal distance of the sequential start pulses. The start pulse triggers the charging process. The integration time is realized technically over the time up to the following start pulse (the time until the following process of selection).

In the case of InGaAs diode arrays, the situation is slightly more complex. Here the process of exposure is separated from the process of selection. If the exposure time, i.e. the time during which the diode array is sensitive, can be as short as required, this results in a connection for the selection time comparable to the silicon array cell. It is relevant for spectroscopy that the detector is insensitive during the process of selection. Blind periods of up to 3.5 ms need to be taken into account.

### Preamplifier

The electronic control of the Hamamatsu diode array is described in the corresponding data sheet. The installed Zeiss pre-amplifier guarantees a low-noise amplification of the video signal to  $3 V_{\text{SS}}$ . In addition, it converts external TTL levels for the array management to the levels required by the diode array. All InGaAs arrays are read-out with pre-amplifiers which supply a voltage of  $4 V_{\text{SS}}$  on the differential amplifier output.



# Applications

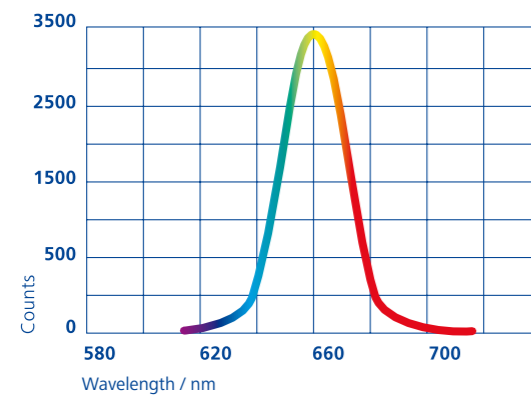
The flexible design of the MMS makes it suitable for use in many applications. They can be classified according to the measurement principles used, the fields of use or the materials to be analyzed. However, the most important benefit is the compactness and the insensitivity to external influences. This allows them to be directly integrated into processes. In most of the applications mentioned in the following, an on-line inspection possibility is present.

## Measurement principles

1. Emission
2. Diffuse reflection
3. Reflection
4. Transmission – absorption
5. White line interference

## Emission

To determine the spectral emission of a light source, part of the light is directed to the spectrometer module. In view of the high light sensitivity, it is in many cases sufficient to bring the coupling fiber bundle close to the light source. For optimization, an achromatic collecting lens can be used.

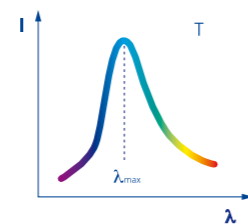


## Examples

- Checking illuminators (aging)
- Determining the wavelength of LEDs or (tunable) lasers (see page 17)
- Luminescence, fluorescence
- Monitoring the solar spectrum, burns, discharges or plasma
- Determining the temperature T in accordance with the Wien displacement law, e.g.: 3000 K  $\leftrightarrow$  966 nm

## Requirements

The wavelength accuracy, which is very high considering the size of the module, allows an exact determination of the wavelength of light sources which emit a single line, such as LEDs (calibration), using the sub-pixel resolution procedure. The MMS modules are not suitable for the analysis of emission radiation containing spectrally adjacent lines which are too close together.



$$\lambda_{\max} \times T = 2.8978 \times 10^3 \text{ m} \times \text{K}$$



## Diffuse reflection

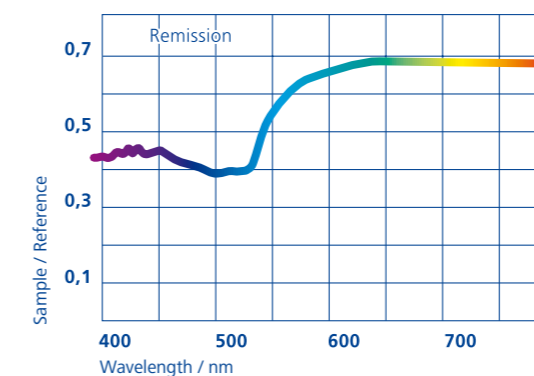
The diffuse reflection of scattered light (from rough surfaces) supplies information on the color of the surface. Important for this procedure (in addition to the spectrometer used) are the light source and the position of the detector (angle with surface normal). In most cases, a light source with a wide-band emission, e.g. a halogen lamp, is used. Here, too, it is often sufficient to bring the input of the cross section converter close to the colored surface to be measured without using additional optics.

## Examples

- Color measurement of different surfaces (materials)
- Condition of coatings
- Analysis of paper quality

## Requirements

The MMS 1 module has been specially designed for color measurement. Its high repeatability and light intensity, combined with moderate spectral resolution, exactly meet the demands made in this field.

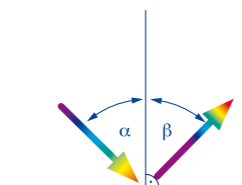


## Reflection

Reflection is a special case of diffuse backscatter and refers to the directionally reflected light thrown back from low-scatter, smooth surfaces. In addition to the sensor, a light source is needed. It should be noted that reflectivity is strongly dependent on the angle  $\alpha$ . The most simple setup for measurements at  $\alpha = 0^\circ$  can be obtained using a special light guide which supplies the light and also directs it to the detector.

## Examples

- Coatings in general
- Antireflection coatings of surfaces using metals or dielectric coatings
- Ellipsometry
- Determining the fat content of meat and sausages
- Determining the humidity content in cereals, food and cellulose
- Plastic identification for recycling and disposal



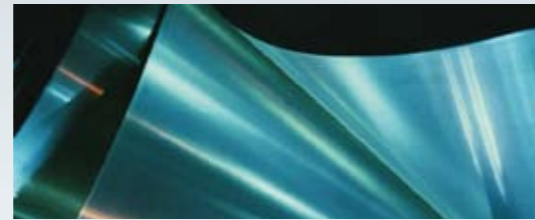
$$\alpha = \beta$$

### Requirements

Many reflection spectra do not display any marked structures. For this reason, high absolute wavelength accuracy is considerably more important in many cases than good spectral resolution.

### White light interference

When white light is incident on optically (partially) transparent layers, interference occurs, as the path difference between specific wavelengths is exactly a multiple of the optical layer thickness  $n \times d$  ( $\lambda_1, \lambda_2$ : position of the extrema, spaced at a cycle). If the refractive index  $n$  is known, the geometric layer thickness  $d$  can be calculated. The fiber interface ensures easy coupling to microscopes or the flanging to coating systems. If the layer thickness  $d$  is known, dispersion  $n(\lambda)$  can be determined.



### Examples

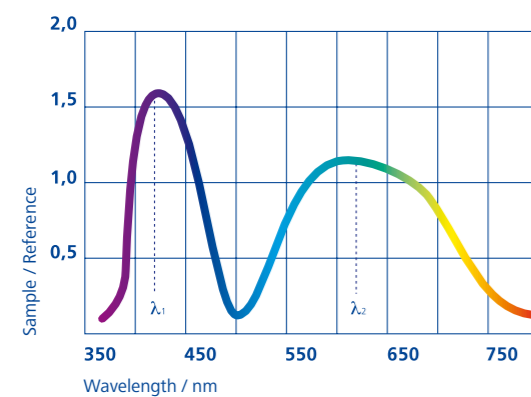
- Layer thickness measurements of photoresists, films and dielectric layers

### Requirements

To ensure exact thickness measurements, high absolute accuracy of the wavelength is again required. The maximum measurable thickness is linked to the spectral resolving power (separation of two interference maxima), the minimum thickness to the spectral range to be covered (recording of at least one half-cycle). The measurement of even thinner layers (evaluation of less than a half-cycle) requires that absolute intensity values be known.

E.g. MMS 1,  $n = 1.5$

$d_{max} \approx 25 \mu\text{m}$ ,  $d_{min} \leq 0.2 \mu\text{m}$

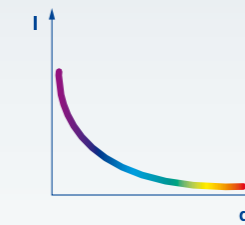


$$2 n \times d = \lambda_1 \times \lambda_2 / (\lambda_1 - \lambda_2)$$



### Transmission

The transmission of material with a thickness  $d$  supplies information on the spectral dependence of the absorption constant  $\alpha(\lambda)$  ( $I_0$ : incident intensity,  $I(d)$ : transmitted intensity). Immersion probes connected to a light source and an MMS module using fibers is the simplest system for measuring the concentration  $c$  of liquids. The concentration is related to the absorption constant via the absorbance coefficient  $\epsilon$ . In other cases it is advisable to set up a collimated beam path. Measurements where the input of the cross-section converter is in direct contact with the object to be measured can also be performed.



### Lambert-Beer-Law

$$I = I_0 \times e^{-\alpha \times d}$$
$$\alpha = \epsilon \times c$$

### Examples

- Measurement of filters (color filters, interference filters)
- Measurement of the concentrations of liquids
- Thickness measurement if absorption coefficient is constant
- Determination of the sugar and alcohol contents in beverages
- Quality control in the petrochemical industry

### Requirements

Here, too, very high spectral resolution is less important than a very good wavelength accuracy and high dynamic resolution – as provided by the MMS modules.



**Carl Zeiss Microlmaging GmbH**

07740 Jena, Germany

Industrial | Jena Location

Phone : + 49 3641 64 2838

Telefax: + 49 3641 64 2485

E-Mail : [info.spektralsensorik@zeiss.de](mailto:info.spektralsensorik@zeiss.de)

[www.zeiss.de/spectral](http://www.zeiss.de/spectral)

**tec<sup>five</sup>5 USA**  
Technology for Spectroscopy

80 Skyline Drive  
Plainview, NY 11803  
[www.tec5USA.com](http://www.tec5USA.com)

Tel.: 516-653-2000  
Fax: 516-939-0555  
[info@tec5USA.com](mailto:info@tec5USA.com)