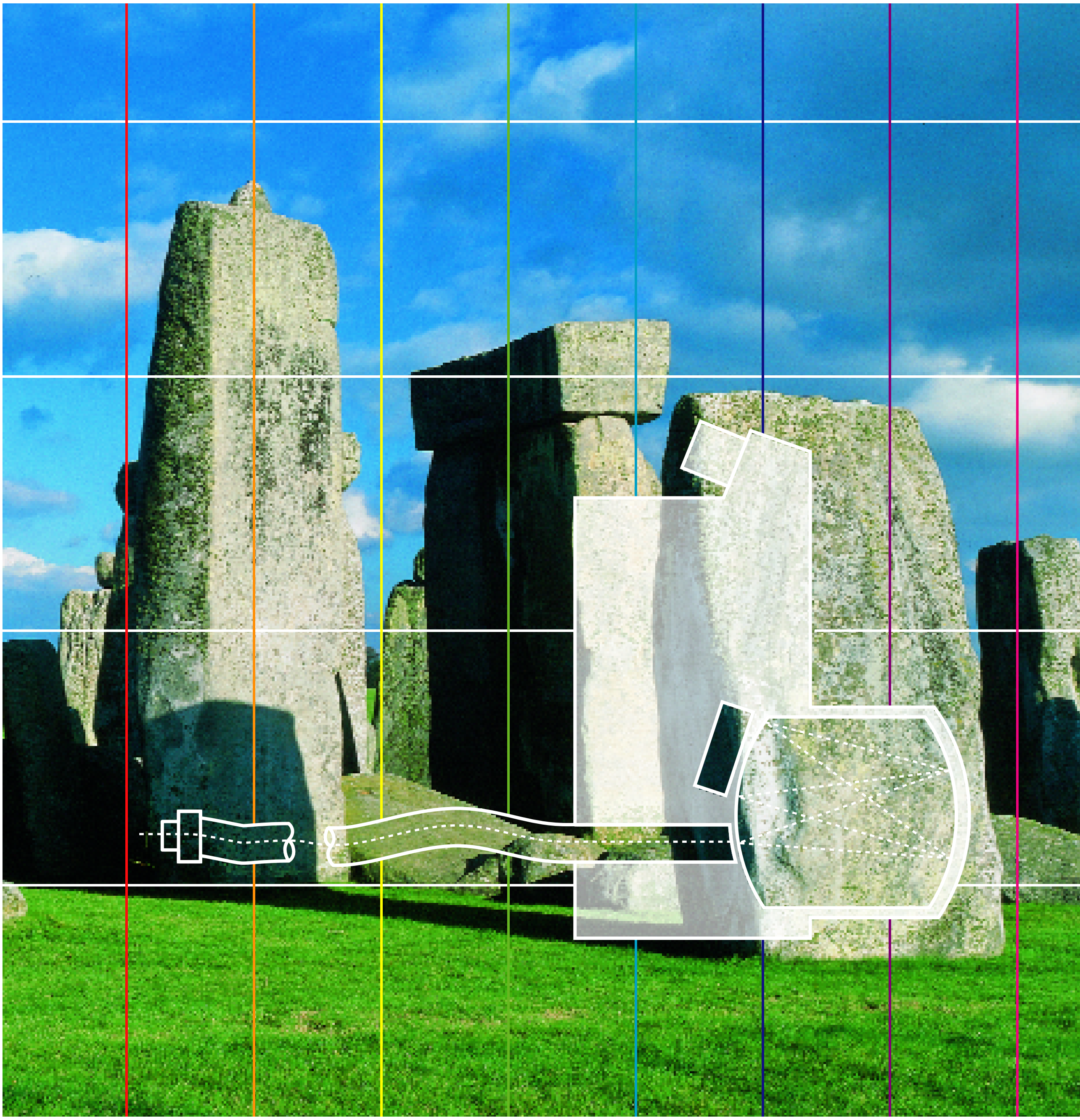
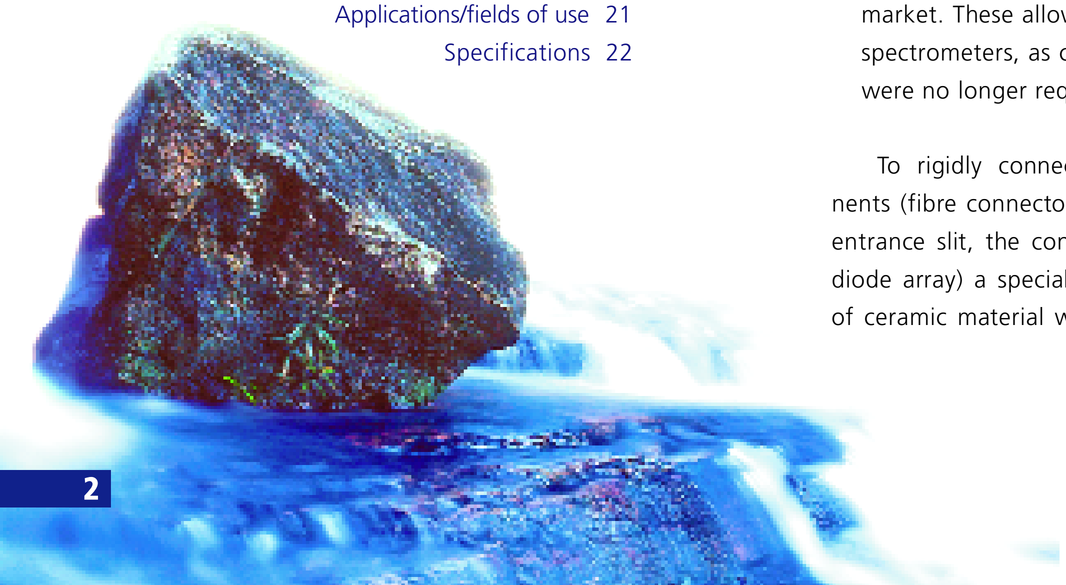
# MMS ĐMonolithic Miniature-Spectrometer



株式会社　スペクトラ・コープ
〒164-0011 東京都中野区中央4-4-5第一小林ビル
Tel:03-5328-2858　Fax:03-5328-2859
URL http://www.spectra.co.jp

# Origins





A classic spectrometer or a classic monochromator typically comprises 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 defects. In many applications – in industry in particular – short measuring times and insensitivity to external influences are a major advantage. Since the end of the 70's, when several developments converged, Carl Zeiss has been working on diode array spectrometers.

- Diode arrays which – used in place of the exit slit – simultaneously recorded a complete spectrum within a fraction of a second (and made moving components superfluous) became attractively priced, making their wider use possible.

- Imaging gratings developed at Carl Zeiss made lens elements or concave mirrors superfluous. This greatly reduced the number of components needed for instrumentation.

- Quartz light fibres were launched on the market. These allowed a modular design of spectrometers, as complex coupling devices were no longer required.

To rigidly connect the remaining components (fibre connectors for the light supply, the entrance slit, the concave imaging grating and diode array) a special spectrometer body made of ceramic material was developed. All components were permanently glued to each other, resulting in a quasi-monolithic module. Its benefits: ruggedness, permanent alignment, high speed. The potential read-out speed was considerably faster than the available computers were capable of processing. This led to the creation of specific processing electronics on the basis of a microprocessor.

These developments merged in the MCS module which had its first public showing in 1982 and met with enormous acclaim. In 1985, the first appliances fabricated in series were supplied and immediately won the „IR 100" Award and the „Innovation Award of German Economy". The main fields of application of these spectrometer modules are the field of industrial analysis and varnish and film thickness measuring technology.

During this period, the idea of a miniature spectrometer for portable measuring instruments or for use as a general „spectral sensor" was born. Sponsored by the German Ministry for Research and Technology, Carl Zeiss developed a monolithic spectrometer using a glass body as its basis. This module featured a further reduced number of components. in 1993, the module baptized MMS 1 (Monolithic Miniature Spectrometer) was presented to the public for the first time. In 1994, it won the „Photonics Award" and was therefore considered one of the 25 best products of the year.

A NIR version for the range of 0.9 to 1.7 µm was introduced in 1997. Further versions of up to 2.2 µm or 2.4 µm sensitivity followed or are currently being developed.

This means that miniaturised spectrometer modules, in other words expanded imaging gratings, are available for most of the interesting spectral ranges and have revolutionised measuring technology. The days when every manufacturer of spectral analysis built his own spectrometer from discrete components are a thing of the past in the same way as the IC has replaced the individual electronic components.

# The quasi-monolithic principle

## Concept

The size of a spectral device is technically determined by the mounts for the gratings, slits, detectors, imaging components etc. In terms of physics, the size is only determined by the resolution required. As many applications do not require high resolution, but a high repeatability, small sizes are sufficient.

The concept of the MMS and MCS family is based on reducing the opto-mechanical design as well as the number of components to their physical minimum and, in addition, to use as many of the same parts for the individual versions as possible.

In the meantime, a multitude of different MMS and MCS variations are on the market, the specifications of which are described on page 22. They are different with regard to their design and parameters but they are all based on the same principle described further below. For the purpose of simplification, the illustrations in the following text are generally related to the MMS 1.

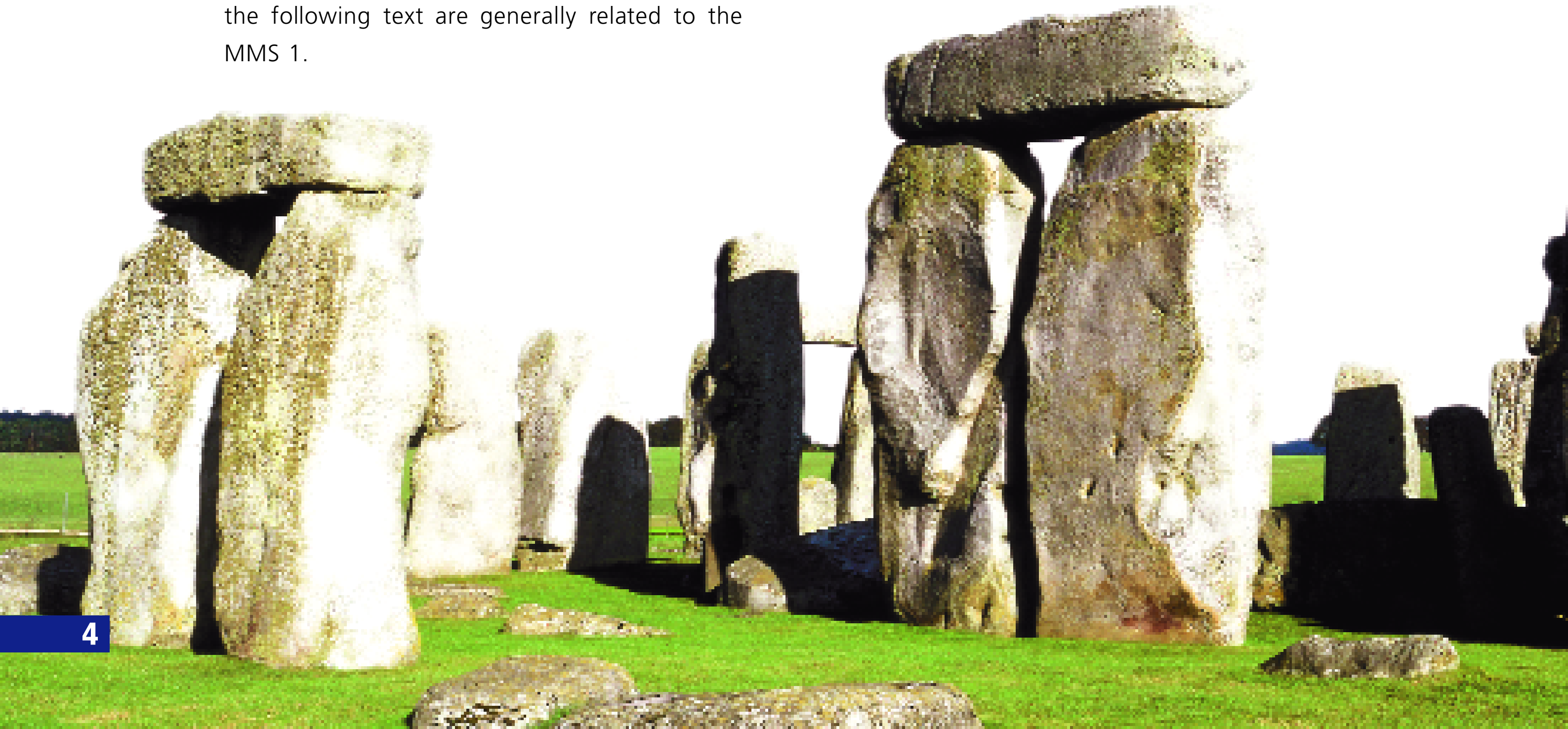
## Optical Components

The optical components are:

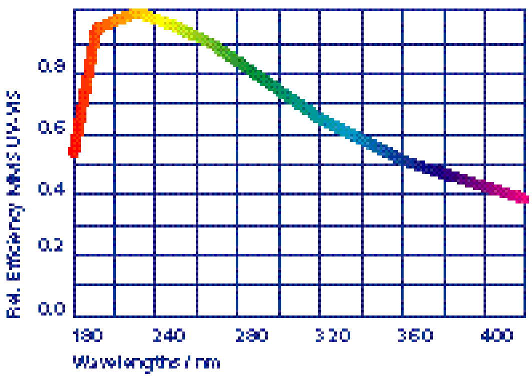
- imaging grating
- fibre cross-section converter as the optical input
- diode array as the opto-electronic output
- these are arranged around and cemented to a central body. The central body has a different design for different versions. The components important for the interfaces, i.e. the cross-section converter and the diode array, continue to be used.

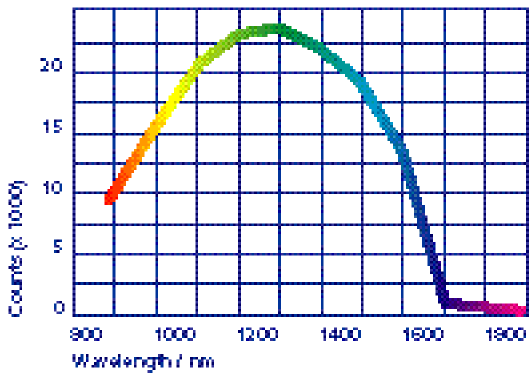
**Central body**

In the MMS 1, the central body is a lens-type glass device made of UBK 7. 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 more dense medium and the resultant larger aperture allows the use of small gratings. This leads to fewer aberrations.



Grating for MMS 1 and MMS UV-VIS: 366 l/mm in the centres, t-number 1.6; imaging ratio 1:1



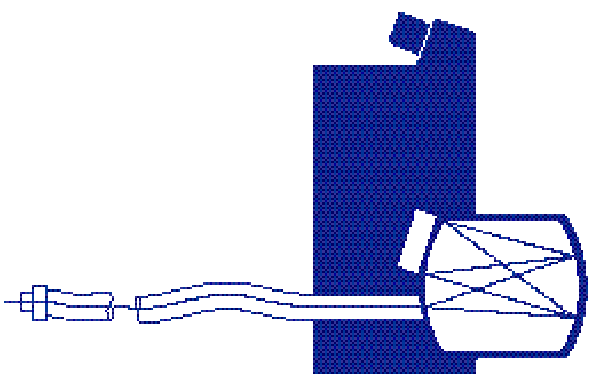

MMS NIR 1.7 efficiency for PDA and grating

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 front plate have been cemented. The overall stability of the tube design compares favorably to the glass body design because the wavelength drift due to temperature changes has been reduced.

**Grating**

The gratings for the MMS family itself consist of so-called holographic blazed (optimised efficiency degree) flat field gratings. These gratings which are produced at Carl Zeiss in a stationary wave process achieve significantly higher efficiency degrees (for non-polarised light) than gratings with sinusoidal profile. This grating produced by Zeiss using the standing-wave technique achieves considerably higher efficiencies (for non-polarised light) than gratings with a sinusoidal profile. In addition to its dispersive function, the grating must image the entrance slit on the diode array. By varying the groove density and using curved grooves, coma can be 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. 215 nm. Due to the higher optical density, the efficiency curve of the VIS module is shifted by the factor of the refractive index.



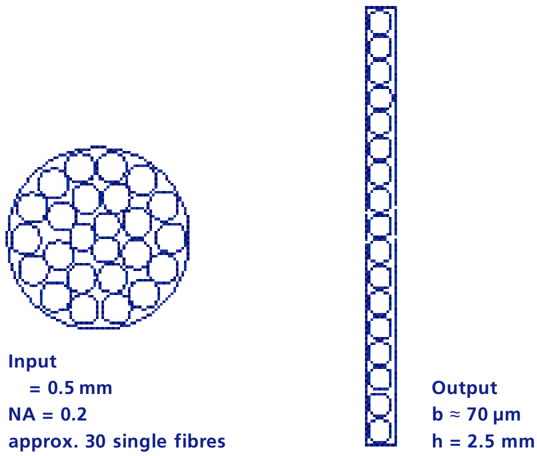
MMS 1 including housing

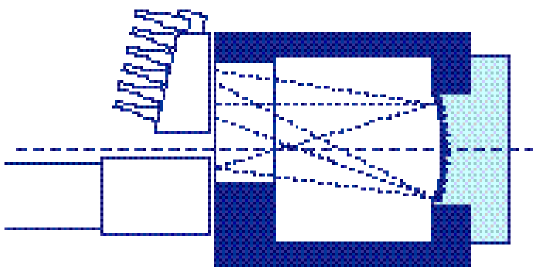
## Cross-section converter

A fibre bundle cross-section converter is used to further optimise the light sensitivity of the module. Single fibres in a linear configuration form the entrance slit (slit height h determined by the number of individual fibres; slit width b ≈ 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 fibres and the design of the input.

In addition, it must be taken into account that quartz fibres which are used in older MMS UV- (VIS-) modules form so-called solarisation centres when they are exposed to deep UV light below 220 nm. That means that the transmission of the fibres 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 solarisation effect can only be partly cancelled by heating, but it is possible to correct it by means of frequent reference measurements.

If however no measuring values below 225 nm are necessary, it is recommended to use a WG 225 filter with a thickness of 3 mm until solarisation-free fibres are available!



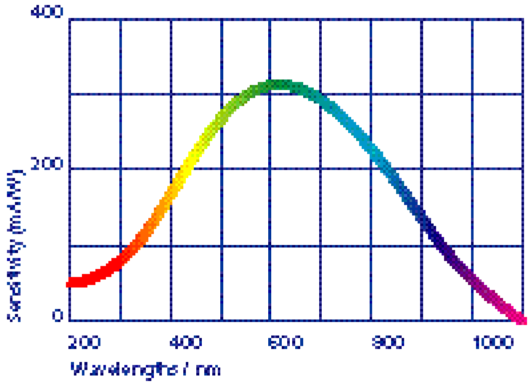



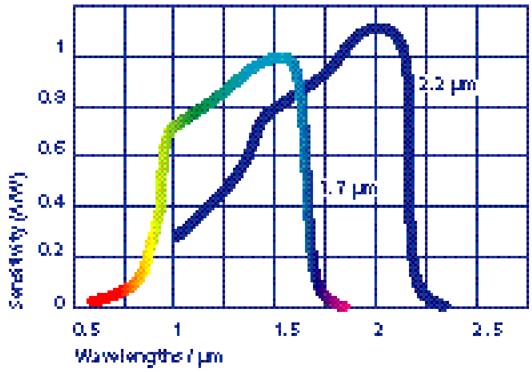
MMS UV-VIS

## Detector

The silicon diode array S3904-256Q from Hamamatsu is incorporated in the MMS family. Only the MMS 1 NIR enhanced uses the Hamamatsu – Type S4874-256Q. This array is packed in a shorter special housing which results in a very small split-off angle, allowing an efficient grating design (see page 15). When changing to

Spectral sensitivity of the diode array S3904-256Q, number of pixels: 256, area: 25 x 2500µm², pitch: 25 µm




Spectral sensitivity of standard-InGaAs (1.7 µm) and extended-InGaAs (2.2µm)

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 cutoff filter.

Due to the longer wavelength an Indium-Gallium-Arsenide-(InGaAs)-diode array is used in the MMS NIR instead of the silicon diode array. Standard InGaAs is sensitive between 0.9 to 1.7 µm, extended InGaAs on the other hand exhibits a sensitivity of up to 2.2 µm or 2.4 µm. As all diode arrays are equipped with a Peltier cooling, a favourable signal-to-noise ratio is also achieved in this case.

Diode arrays have the following advantages over CCDs:

- larger dynamic range (for non-cooled devices)
- better UV sensitivity
- intensity-independent noise
- minimum cross-talk
- no trailing effect.

## Total package

The whole configuration including a preamplifier board is accommodated in a protective housing. The grounding is important for the performance (signal-to-noise ratio) of the MMS and MCS modules.

The basis for the high quality of the miniature spectrometers is the wide range of technical experiences gained in the Zeiss Group regarding mathematical design, structuring (grating manufacture and replication), coating and materials processing. Furthermore, the expertise in cementing technology provide for MMS modules which are extremely insensitive to mechanical shock and temperature changes in particular. The wavelength accuracy changes only by 0.012 nm/K in the MMS 1; the drift in the UV-modules is even lower.

# Back to the basics: The specifications or The Jungle of Resolutions

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 – $\Delta\lambda_{Rayleigh}$ (DIN standard)
2. Line width, mostly full width at half maximum – $\Delta\lambda_{FWHM}$
3. Sub-pixel-resolution (also termed „software resolution")
4. Pixel dispersion – $\Delta\lambda$ / 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 $1/e^2$ width)
3. Measurement of a line with respect to its peak wavelength and intensity at the maximum.

**Spectral resolving power**

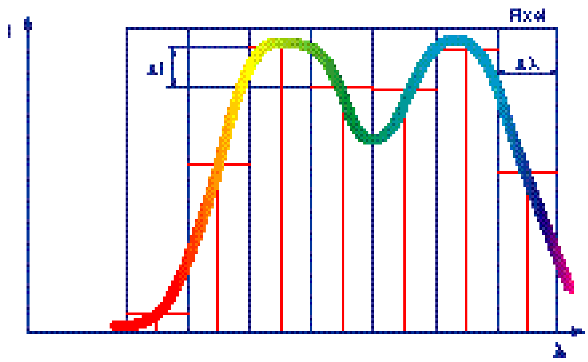
According to DIN, the Rayleigh criterion is relevant to the separation of spectral lines. The criterion indicates how wide the spectral distance between two lines $\Delta\lambda_{Rayleigh}$ must be to allow their recognition as separate lines. Here, the spectral width of the individual lines $\Delta\lambda_{line}$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

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

**Width of spectral lines**

To enable the measurement of the width of a spectral line $\Delta\lambda_{linie}$ 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 $\Delta\lambda_{FWHM}$ produced by the spectrometer. This property is related to the Rayleigh criterion.

$$\Delta\lambda_{FWHM} = \lambda_2 (I_{max}/2) - \lambda_1 (I_{max}/2)$$
$$\Delta\lambda_{FWHM} \approx 0{,}8 \times \Delta\lambda_{Rayleigh}$$



### Wavelength accuracy

To determine the absolute 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 wavelength drift due to temperature changes. The former is completely uncritical in the MMS and MCS modules, and the drift can be more or less neglected.

### Dispersion

The term $\Delta\lambda$/Pixel (= $\Delta\lambda_{Pixel}$) 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 approx. corresponds to $\Delta\lambda_{Rayleigh}$.

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

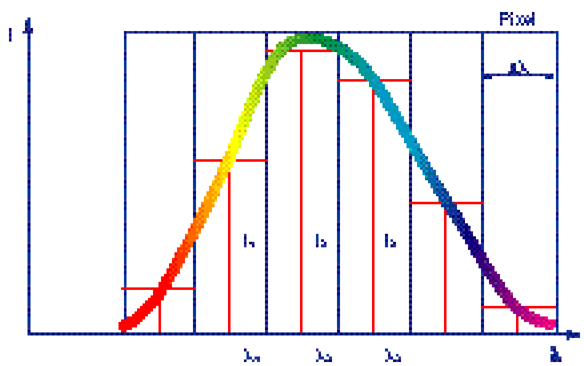
## Special features of diode array spectrometers (DAS)

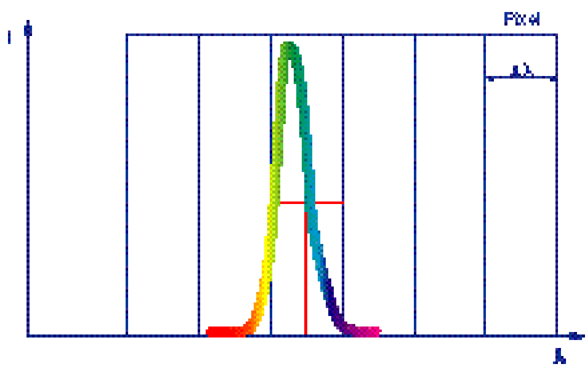
### Spectral resolution

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 $I_2 \leq 0{,}81 \times I_1$ ($I_3$), $\Delta\lambda$ is then exactly two pixels ($2 \times \Delta\lambda_{Pixel}$). 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 x $\Delta\lambda_{Pixel}$ as a diode array can only detect discrete values using the stepwidth of the pixel dispersion. A total of 4 pixels is needed for processing.




**Sub-pixel-resolution or the Parabola Fit**

To determine the peak wavelength $\lambda_{max}$ (and/or peak intensity $I_{max}$) 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 $\lambda_{I,2,3}$) 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 principie, 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 parodox: 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 $\Delta\lambda_{Pixel}$ in this case.

**Parabola-equation**

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

**Coefficients**

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

$$b = (I_3 - I_1) / 2\,\Delta\lambda - 2a \times \lambda_2$$

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

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

### Determining the half-width

The parabola fit also supplies qualitative data on the halfwidth. For this, $I_{max}/2$ must only be inserted in the parabola equation. There are only minor differences between the halfwidth of a parabola fit and that of a Gaussian fit.

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 correspond better 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.) S/N 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. The weakest link in the chain, of course, determines the signal to-noise ratio to be achieved.

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

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 a benefit.

**Dynamic range = ADC/Δσrange**

For instance, when using a 14bit converter – this corresponds to 16,384 steps or increments and a noise of Δσ = 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.

**Linearity**

The previous remarks will be completely accurate only if the detector and the post-detector electronics provide ideal linearity. For quantification, the admissible deviation must be specified. Fortunately, the behaviour 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.

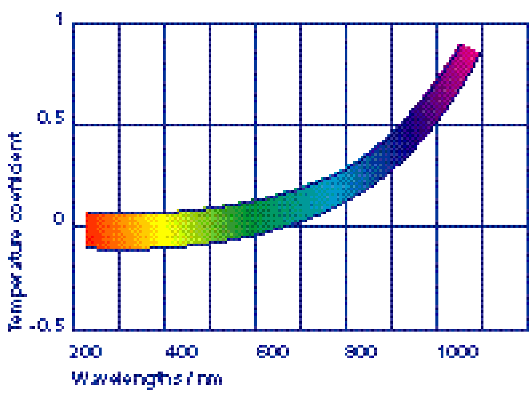
**External influences**

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 photo diode arrays, the sensitivity also changes by less than 1% in the range of 1 to 1.55 µm with temperatures ranging from -50 and +50 °C. Merely outside the specified range, does the different coating lead to an increased influence of the 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.

$$I_{dark}(T+7K) = 2I_{dark}(T) \text{ (Silicon)}$$
$$I_{dark}(T+10K) = 2I_{dark}(T) \text{ (InGaAs)}$$

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.



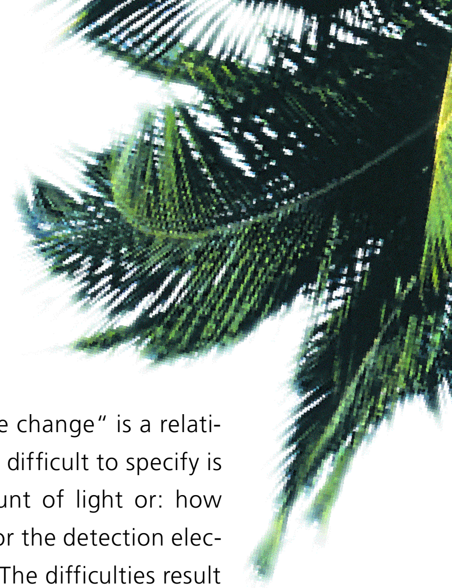

**Sensitivity**

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. At 1550 nm, the MMS NIR still exhibits a sensitivity of more than $10^{14}$ counts/ Ws (in the case of a 14 bit conversion).

## Scattered light

The specification of scattered light data is only useful in connection with the measuring



instructions. Scattered light data are determined for the MMS program 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 an OG570 or KG3 filter 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 MMS NIR is reduced to 0.1 % as transmission of 10 mm water at 1450 nm, exposure with halogen lamp.

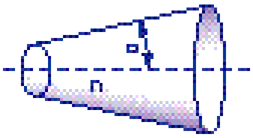
Scattered light reduces the dynamic range, as the full range is no longer available. However, changes in the radiation used only affect the dynamic range in proportion to the scattered light present: for example, a change of 10 % in the radiation used causes a change of $10^{-4}$ if the scattered light 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 $10^{3}$ 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 MMS. Together with the well-defined light guidance factor of a fibre 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 Ω 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 fibre bundle, the second factor is derived from the numerical aperture NA. In the case of the e.g. MMS 1 family, the fibre optical light value is calculated at G = 0.157 $mm^2 sr$.




$$G = F \times \Omega \times n^2$$
$$\Omega = 2\pi \times (1-\cos\alpha)$$
$$\alpha = \arcsin NA$$

For the optimum adaptation of an existing light source (whether fibre, 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 fibre) must also be taken into account.

### Increase in transmission

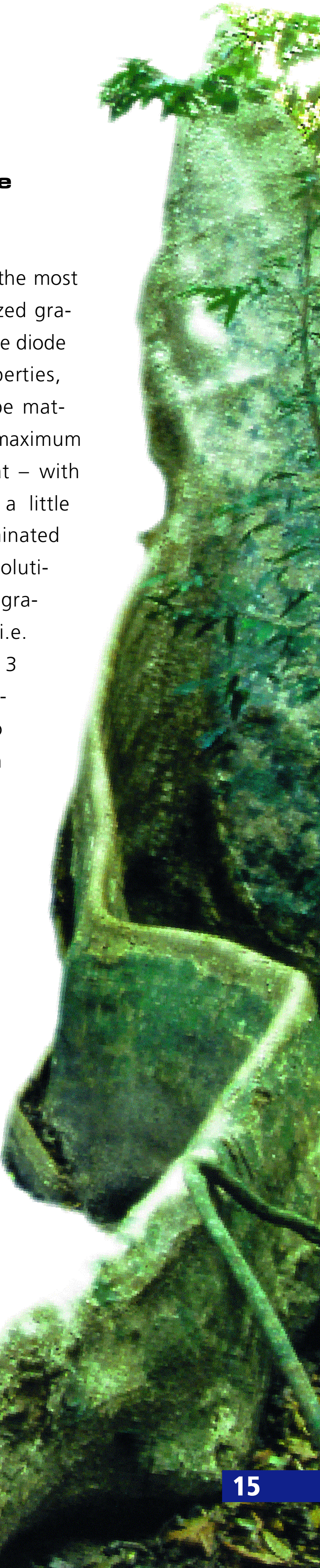
If round light spots are assumed, the use of a cross-section converter CSC results in increased transmission $\eta_{FF,\,CSC}/\eta_{FF,\,Slit}$ compared with the classic slit. This increased transmission can be calculated from the ratio of the amount of light transmitted by the CSC to the amount of light 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 area $A_{apt}$ illuminated. In the CSC, $A_{eff}$ is the product of the fibre core cross-section and the diameter $d_{fiber}$ and the number of fibres 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 $d_{Spalt} = h$.

$$\eta_{FF,\,CSC} = N \times d_{Fiber}^2 / d_{Apt}^2$$
$$\eta_{FF,\,Slit} = 4\,b/(\pi \times d_{Slit})$$
$$\eta_{FF,\,CSC} / \eta_{FF,\,Slit} = 16 \text{ (MMS)}$$

## 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 µm individual fibres (effective slit width approx. 60µm) for the MMS 1 CSC, for example, is thus ideal for a pixel width of 25 µm. The number of fibres is obtained by dividing the pixel height by the outer diameter of the individual fibres.



# Control
# Diode array

### Diode array

The spectrometer modules of the MMS/ MCS family are equipped with silicon diode arrays of the type S3904-256Q or S3904-512Q or even S3904-1024Q from the company Hamamatsu, with 256 – 1024 pixels. Only the MMS 1 NIR enhanced uses the Hamamatsu Type S 4874-256 Q, which exhibits a higher degree of sensitivity for longer wavelengthes (up to 1100 nm). A special housing which is shorter than the standard housing permits the detector to be positioned very closely to the optical input. The small split-off angle thus obtained results in optimised grating efficiency. For this reason, only detectors with a similarly small housing can be used.

Indium-Gallium-Arsenide (InGaAs) diode arrays of different manufacturers are used for all MMS NIR. However, they are all equipped with a Peltier cooling. Zeiss supplies a matching control board for the control of the Peltier elements.

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 readout 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 $t_{Pixel}$. This way, the minimum possible integration time $t_{int,\,min}$ is determined – even in the case of the Hamamatsu diode array. This also determines the minimum possible integration time $t_{int,\,min}$.

$$t_{Pixel} = 1/f$$

$$t_{int,\,min} = (N+1) \times t_{Pixel}$$

$$f_{max} = 2\text{ MHz} \rightarrow t_{int} \geq 127\ \mu s$$

**(256 silicon diode arrays)**

$$f_{max} = 2\text{ MHz} \rightarrow t_{int} \geq 64\ \mu s$$

**(128 InGaAs 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 realised 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. (See also Operating Instructions of the MMS NIR).

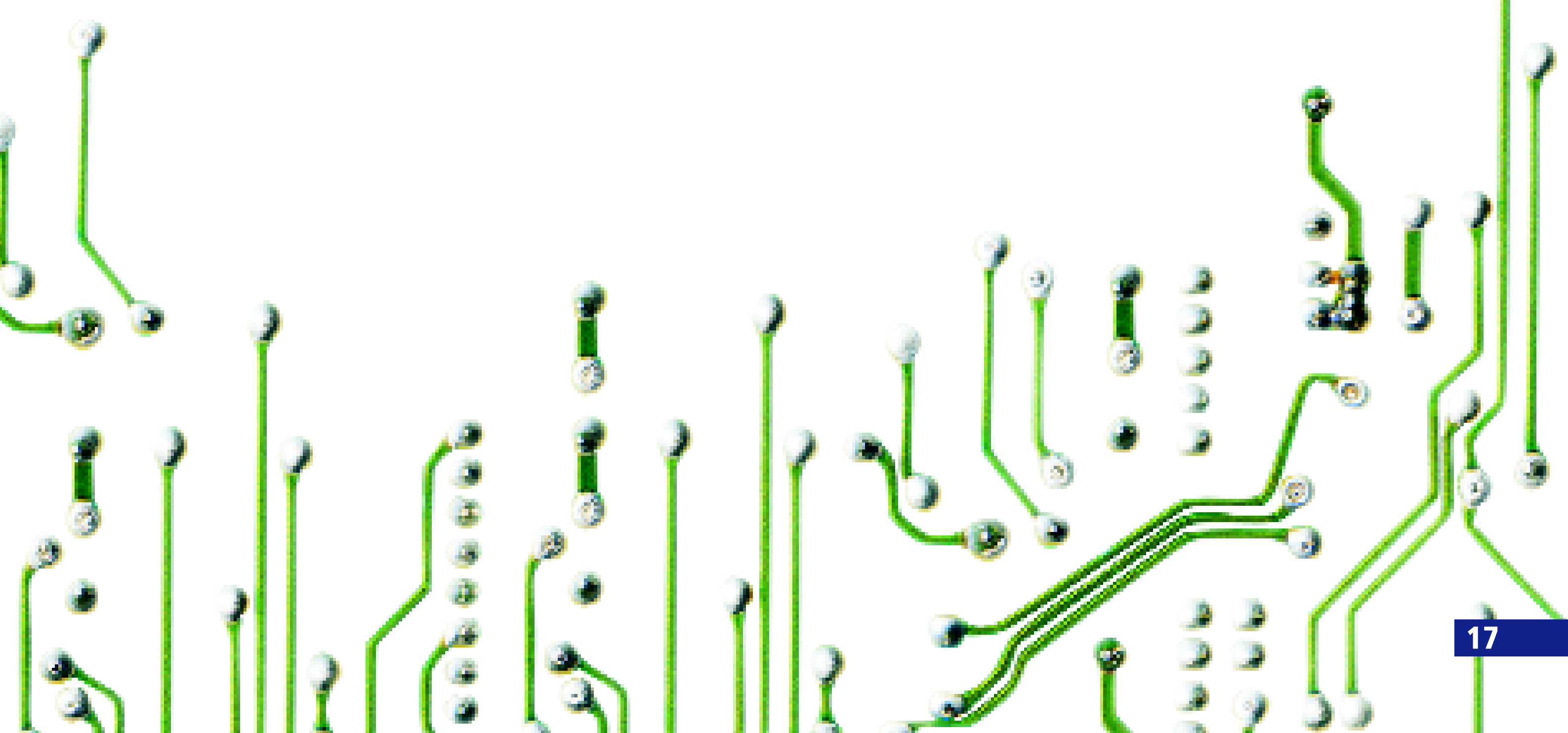
## Preamplifier

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 $V_{ss}$. 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 $V_{ss}$ on the differential amplifier output.

## Control electronics for MMS family and MCS

All MMS/ MCS modules are equipped with pre-amplifier electronics. An operating electronic is required to control and read-out of the diode array, which also executes the transformation from analogue to digital.

The deciding factor in this electronic system is the resolution in the intensity axis. Currently, Zeiss offers operating electronics with a resolution of 12, 14 and 16 bit. If the measurement is carried out with the highest resolution of 16 bit, this results in a separation into 65 536 ($2^{16}$) individual steps (counts) with a driving ratio of 100 %. It is possible to detect changes of intensity with this of less than $10^{-4}$.



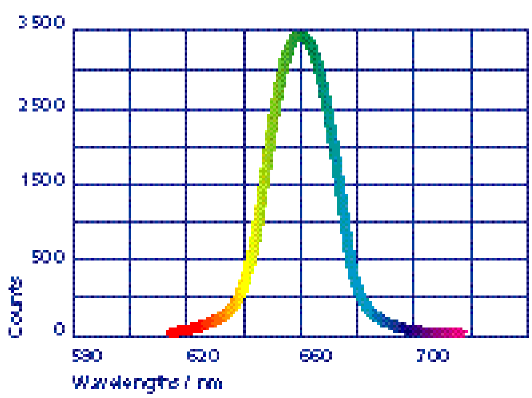
# Applications

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. The MMS modules using cross-section converters as optical inputs offer specific benefits in practical work. It is very easy to connect other fibres using the SMA connector.

In addition, the round input offers considerably better conditions for most illumination situations than the classic entrance slit. However, the most important asset of the MMS modules is their compactness, light sensitivity and insensitivity to external influences. This allows them to be directly integrated in processes; for example, the MMS modules can be built into printing machines for the on-line inspection of paper or colour quality. In most of the applications mentioned in the following, an on-line check is highly interesting.

**Measurement principles**

1. Emission
2. Diffuse reflection
3. Reflection
4. Transmission – absorption
5. Interference spectrum




## Emission

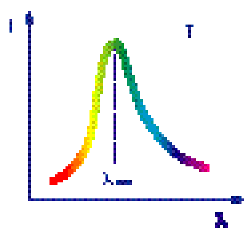
To determine the spectral emission of a light source, part of the light is directed to the spectrometer module. In view of the high light sensitivity of the MMS modules, it is in many cases sufficient to bring the fibre near the light source. For optimization, an (achromatic) collective lens can be used.

**Examples**

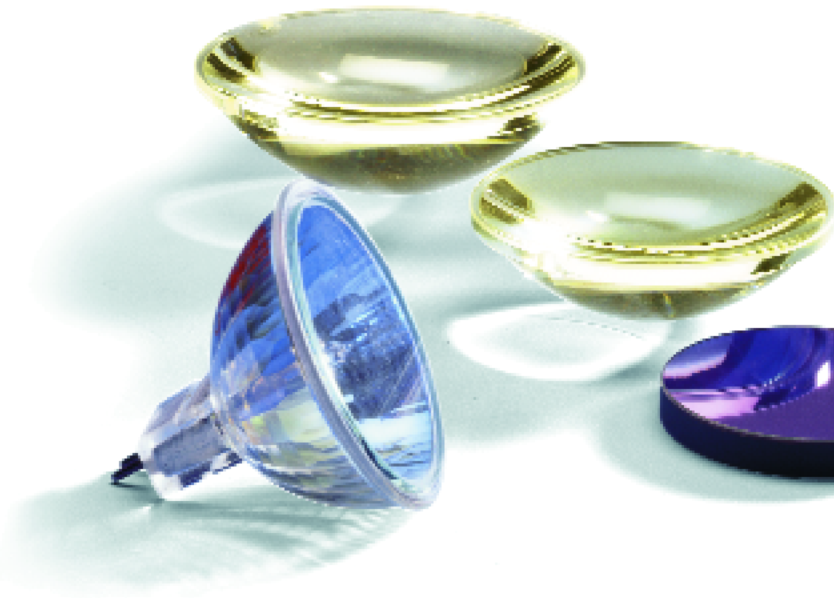
- Checking illuminators (aging)
- Determining the wavelength of LEDs or (tunable) lasers (see page 9)
- Luminescence, fluorescence
- Monitoring the solar spectrum, burns, discharges or plasma
- Determining the temperature T in accordance with the Wien displacement law. e.g.: 3000 K ↔ 966nm

**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 (see page 8).




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



## Diffuse reflection

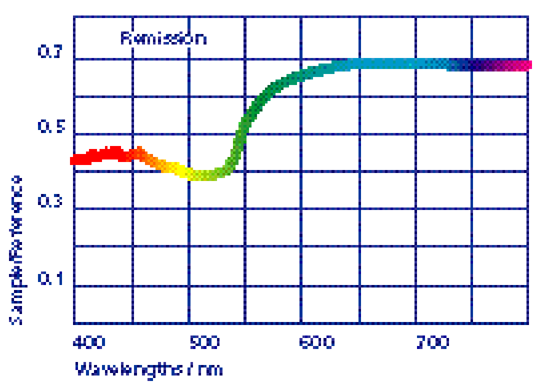
The diffuse reflection of scattered light (from rough surfaces) supplies information on the colour of the surface. Important for this procedure (in addition to the spectrometer used) is the light source and the position of the detector (angle with surface normal). In most cases, a light source with a 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 coloured surface to be measured without using additional optics.

**Examples**

- Colour measurement of different surfaces (materials), e.g.
- Condition of coatings
- Analysis of paper quality
- Determination of fat contents in meat and sausages
- Determination of the humidity content in cereals, food and cellulose

**Requirements**

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




## Reflection

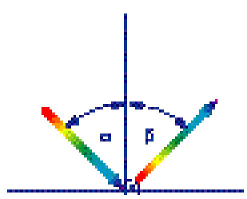
Reflection is the directionally reflected light thrown back from (low-scatter) surfaces. In addition to the sensor, a light source is needed. It should be noted, that reflectivity is strongly dependent on the angle α. The most simple setup for measurements at α = 0° can be obtained using a special light 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
- Elipsometry
- Plastic identification for recycling and disposal

**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.




$\alpha = \beta$

## Interference spectrum

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 x 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 fibre Interface ensures easy coupling to microscopes or the flanging to coating systems. If the layer thickness d is known, dispersion n (λ) can be determined.

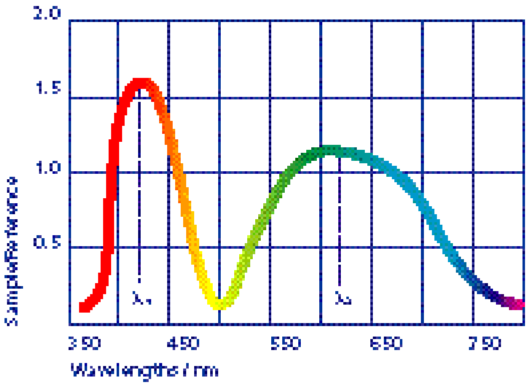
**Examples**

- 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 halfcycle) requires that absolute intensity values be known.

**E.g. MMS 1, n = 1,5**
**$d_{max}$, ≈ 25 µm, $d_{min}$, ≤ 0,2 µm**




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

## Transmission

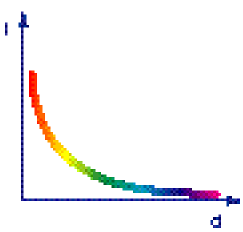
The transmission of material with a thickness d supplies information on the spectral dependence of the absorption constant α(λ) ($I_0$ : incident intensity, I(d) : transmitted intensity). Immersion probes connected to a light source and an MMS module using fibres is the simplest system for measuring the concentration c of liquids. The concentration is related to the absorption constant via the absorbance coefficient ε. 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.

**Examples**

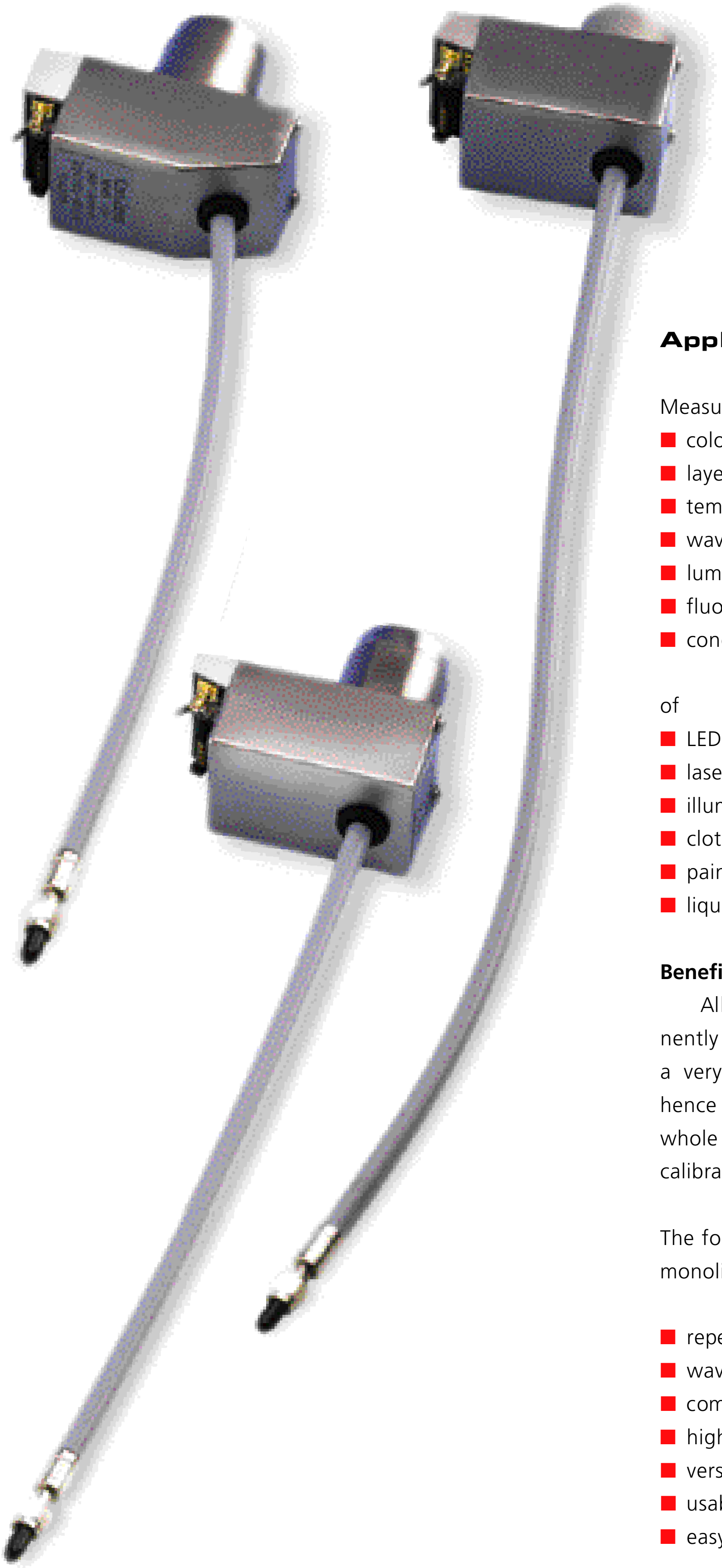
- Measurement of filters (colour filters, interference filters)
- Measurement of the concentrations of liquids
- Thickness measurement if absorption coefficient is constant
- Determination of the sugar and alcohol contents in beverages
- Quality control in the petrochemical industry

**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,




**Lambert-Beer-Law**
**$I = I_0 \times e^{-\alpha \times d}$**
**$\alpha = \varepsilon \times c$**



## Applications/fields of use

Measurement of
- colours
- layer thickness
- temperature
- wavelengths
- luminescence
- fluorescence
- concentration

of
- LEDs
- lasers
- illumination
- cloth
- paints
- liquids

in
- monitoring
- process control
- quality control
- calibration
- recycling.

**Benefits of the MMS modules**

All spectrometer components are permanently connected with each other. This results in a very high insensitivity to mechanical shock, hence ensuring high reliability. In addition, the whole configuration is maintenance-free, i.e. recalibration is not necessary.

The following benefits result directly from the monolithic design used:

- repeatability – reliability
- wavelength accuracy – calibration standard
- compactness – ruggedness
- high sensitivity
- versatility
- usability in industry
- easy-to-use interfaces

# Specifications

| Past Modules | | | | | | |
|---|---|---|---|---|---|---|
| **Modules** | MMS 1 | MMS UV-VIS | MMS UV | MMS NIR 1.7 t1 | MMS NIR 2.2 tc | MCS |
| **Spectral range [nm]** | 310 – 1100 | 190 – 720<br>or<br>250 – 785 | 195 – 390 | 950 – 1700 | 900 – 2200<br>or<br>1500 – 2200<br>(Depening on the number of pixels) | 190 – 1100<br>different ranges<br>(Depening on the number of pixels) |
| **Specified spectral range [nm]** | 360 – 900<br>400 – 1100<br>(NIR enh.) | 220 – 720<br>or<br>250 – 785 | 220 – 390 | 950 – 1700 | see above | 220 – 1000 |
| **Spectral resolution [nm]** | <10 | <7 | <3 | <18 | <18 | <3 |
| **Pixel dispersion [nm]** | approx. 3.3 | approx. 2.2 | approx. 0.8 | approx. 6 | approx. 6 | approx. 0.8 |
| **Δ-precision [nm]** | 0.3 | 0.2 | 0.2 | 0.6 | 0.6 | 0.3 |
| **Diode array** | Hamamatsu S3904-256Q with 256 pixels of 25 x 2500 $\mu m^2$<br>S4874-256Q for NIR enhanced | | | InGaAs | InGaAs | S3904-512Q<br>S3904-1024Q |
| **Optical input**<br>input slit | Fibre bundle cross-section converter<br>= 0.5 (0.4) mm; NA = 0.22;<br>mounted in SMA plug | | | see MMS 1<br>= 0.2 mm | see MMS 1<br>= 0.2 mm | = 0.5 mm<br>NA = 0.22; SMA |
| output slit | 70µm x 2500µm | | | 0.1 x 1.0; 0.5; 0.25 $mm^2$<br>(Depending on diode split) | | 80µm x 2400µm |
| **Electronic output** | Pre-amplifier, video output 3 $V_{ss}$ | | | 4 $V_{ss}$ | 4 $V_{ss}$ | see MMS 1 |
| **Strip management** | In acc with Hamamatsu data sheet, TTL level | | | see operating instructions | see operating instructions | see MMS 1 |

**Carl Zeiss Jena GmbH**
OEM – Spectral Sensors

D – 07740 Jena
Phone: + 493641642838
Fax: + 493641642485
E-Mail: info.spektralsensorik@zeiss.de

Internet: http://www.zeiss.de

For further details, please contact: