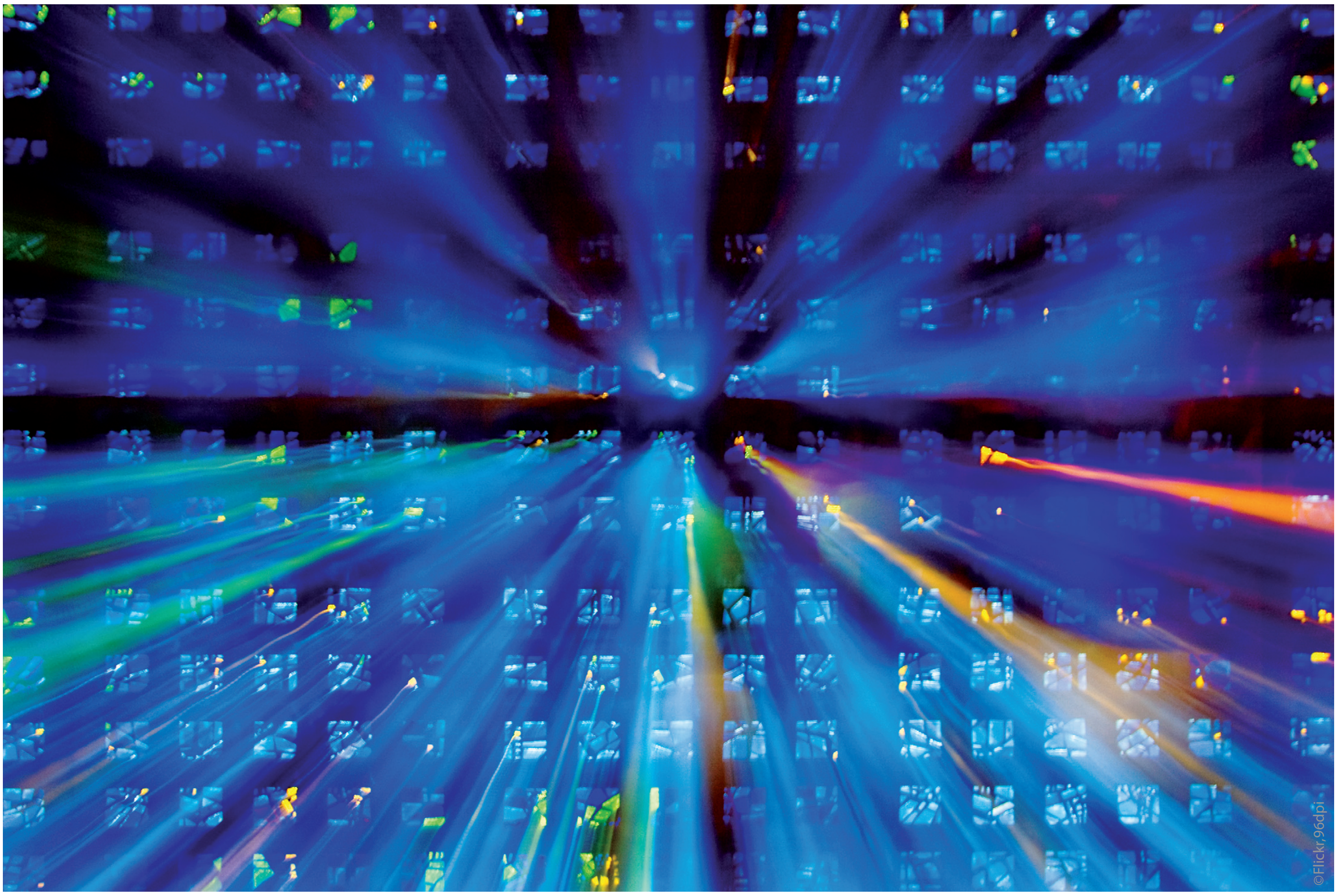
# Fan of Rays

## Optical Metrology Basics: Spectral Sensors



A spectral sensor is a miniaturized spectrometer equipped with a detector array. The spectrometer spreads the incoming bunch of rays according to wavelengths, and the detector array captures the complete spectrum simultaneously during the exposure time. Spectral sensors thus provide detailed access to the spectral information of the incoming radiation. This article describes some of the optical principles of spectral sensors.

The linear dimensions of a typical miniature spectrometer (see fig. 1) are in the range of some centimeters. Versions with Si-photodiode-arrays or CCD-arrays are available for the spectral range from 250 nm to 1,100 nm. The NIR-range from 900 nm to 1,700 nm is covered by InGaAs-detectors. Spectral sensors usually are designed for a spectral bandwidth (resolution) of about 10 nm. Some companies have focused on a rugged design and offer spectral sensors optimized with respect to compactness, stability and the requirements of mass production. Miniature spectrometers are mature components and well suited as spectral sensors for industrial applications such as colour measurements or inspection of thin films in the production line. They may even be used in harsh environments like in mining or precision farming [1].

Fig. 1: Spectral sensor with dimensions $7 \times 6 \times 4\ cm^3$ incl. front-end electronics (Photo: Carl Zeiss MicroImaging GmbH)

## Concepts

The system elements of spectral sensors are the optical input for pick-up of radiation from a target or a light source, the miniature spectrometer, which spreads the incoming radiation according to its wavelength distribution along a small strip in the dispersion plane, a linear detector array, and the front-end electronics. Two different configurations are in use for the spectrometer component, the so-called Czerny-Turner mount with a plane grating and a modified Rowland-circle mount with a spherical grating [2]. For both designs, a small entrance slit is illuminated with the radiation sampled by the optical input. The Czerny-Turner mount, shown schematically in figure 2, images the entrance slit to infinity by means of a spherical mirror, thus producing a bundle of parallel rays which illuminates a plane grating. Diffraction produces different bundles of parallel rays emerging from the grating under different angles, each angle depending upon the wavelength of the radiation within this bundle. A second spherical mirror focuses these bundles to different points in the dispersion plane. The spectral distribution is thus transformed to a distribution of intensities along a line, which can be picked-up by a detector array. Such a design basically is a miniaturized optical bench with discrete optical components. A typical entrance slit has a width of 100 µm, the length of a spectrum is about some millimetres. This concept has been employed by Ocean Optics, e.g., for their miniature spectrometers. The alternative approach, depicted in figure 3, is based on a concave grating, which combines focusing and diffraction within a single optical component. The intention of the optical design is to allow for a very long entrance slit and to image this slit very precisely to a flat strip in the dispersion plane [3, 4]. Such imaging, aberration-corrected flat-field gratings are a masterpiece of technical optics and are produced with holographic methods. Typical representatives of this technique are the miniature spectrometers from Zeiss or Jobin-Yvon. Some designs, the so-called monolithic spectrometers, are based on a rigid block of glass with a curved backside, where the grating is embossed.

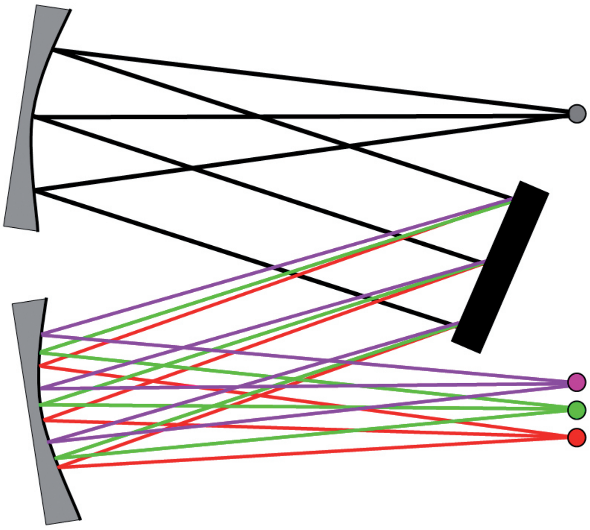


Fig. 2: The Czerny-Turner-mount with a plane grating in parallel light

## Pros and Cons

The footprint of a spectral sensor is substantially determined by the dimensions of the detector array and the front-end electronics. Thus, the optical design usually is tailored to the pixel-pitch and the dimensions of an available detector array. The concept of the optical bench with discreet elements can utilize simple optical components, but proper mounting and adjustment require much care and effort. The monolithic concept with the spherical grating in a massive block of glass is promising with regard to stability and robustness. It requires a special optical element, but has a single reflecting surface and can handle a very long entrance slit, resulting in high efficiency for

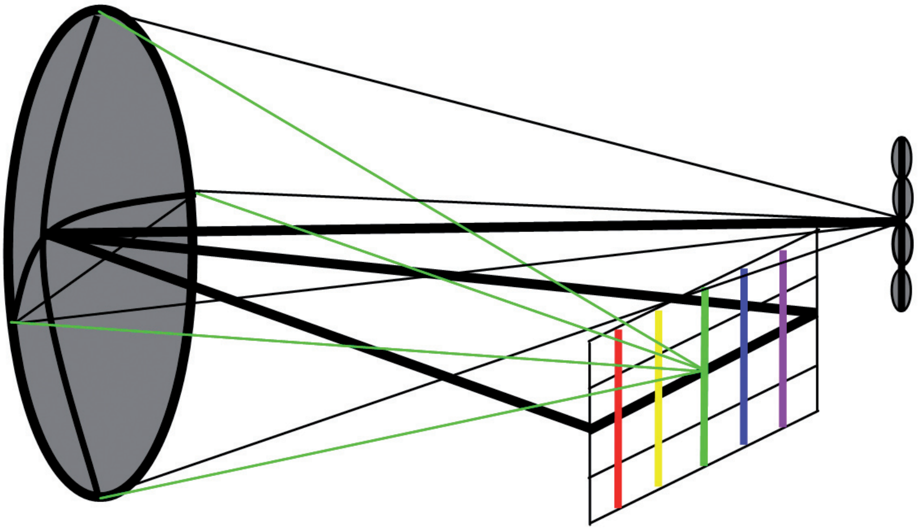


Fig. 3: A concave imaging grating produces images of the long rectangular entrance slit in the focal plane, separated according to their wavelength

pick-up and throughput of the radiation emitted by a target or a light source.

The optical input for spectral sensors usually is a fibre-optical element. Simple sensors use a single fibre with an effective diameter of typically 100 µm. The output of the fibre is directly used as the entrance slit. The magnification often is about 1, resulting in an image of the fibre with a diameter of about 100 µm on the detector under ideal conditions. This diameter sets the lower limit for the spectral bandwidth of the system, since the optical parameters of the grating determine the relationship between the scaling in the dispersion plane and the wavelength-scale. The corresponding figure of merit is the linear dispersion, which might have a value of 150 nm/mm, e.g., resulting in a bandwidth of 15 nm for the system mentioned above, where the diameter of the image of the entrance slit in the focal plane of the spectrometer is 100 µm. The bandwidth usually is sampled with 3 or 4 pixels of the detector. Oversampling would result in lower signals in the pixels, but not in a better bandwidth. Undersampling, however, would not fully exploit the optical bandwidth with the detector signal and would result in a deterioration of the resolution of the sensor. The minimum diameter of the image of the entrance slit on the detector depends upon the width of the entrance slit and upon the optical properties of the grating and the other imaging components. The optical elements and the dimensions of the entrance slit thus must be carefully tailored to the geometry of the detector. Spectral sensors with aberration-corrected optical elements can handle not only circular, but also long rectangular entrance slits. For this purpose, several single fibres are used for the optical input, which are mounted in a straight line as the entrance slit or integrated in a cross-section converter. The Zeiss MMS-1, e.g., uses a cross-section converter from a circular fibre-bundle with a diameter of 0.5 mm as the input and a rectangular slit with a width of 70 µm and a height of 2,500 µm as the output. This device utilizes the 15-fold optical input area compared to a simple 100 µm-fibre. The pixels of the detector array of the MMS-1 have a width of 25 µm and a height of 2,500 µm and are well suited for this geometry.

The dispersion along the detector array is not necessarily constant. The pixel scale thus has to be calibrated with well-known wavelengths to establish a proper transformation of pixel coordinates to the wavelength scale. The remaining uncertainty may be important for some applications. For industrial applications, the thermal drift of the wavelength scale sometimes is a critical parameter. When high dynamic range is the most important requirement, like in chemometrics, the stray light level may be not negligible. Stray light may produce pseudo-signals in some regions of the spectrum or can contribute to a diffuse background in the signal. Therefore, it is a good idea to pick up radiation from those parts of the spectrum only which are within the specified spectral range of the spectrometer. For the same reason, it may be helpful to restrict the wavelength range to a single octave, like between 380 nm and 760 nm or between 500 nm and 1000 nm and so on, to avoid the problems originating from signals due to diffraction into higher orders [2]. The optical performance of the spectrometer is an important issue, but the properties of the detector array and the front-end electronics have a huge influence upon the quality of the signal of the spectral sensor. The effective dynamic range, the sensitivity and the signal-noise-ratio may be much more important for certain applications than the spectral bandwidth. These parameters will usually vary as function of the wavelength and may thereby determine the effective spectral range of the sensor, even when the miniature spectrometer is optically well suited for a larger spectral range.

## Conclusion

Spectral sensors are devices for the measurement of the spectral distribution of radiation. Their key optical element is a miniaturized spectrometer. They are designed for a spectral bandwidth of about 10 nm and are well suited, when compactness and robustness are more important than spectral bandwidth. Spectrometers with similar optical data may well be quite different with regard to signal quality, like dynamic range or noise, depending upon the type of detector array or the performance of the front-end electronics. The figures of merit for spectral sensors are complex concepts. For a comparison of spectral sensors from different sources, the underlying definitions and the methods used for the determination of theses figures should be carefully examined.

## References

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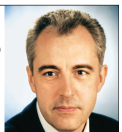
2 Author
Prof. Dr. Christoph Heckenkamp



2 Contact
Darmstadt University of Applied Sciences, Germany
Department of Technical Optics and Machine Vision
heckenkamp@h-da.de
www.fbmn.h-da.de