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Application Note

Introduction And Applications Of Multitrack Spectroscopy

Introduction – what is multitrack spectroscopy and why would you use it?

In many applications of optical spectroscopy, it is useful and/or necessary to simultaneously observe several input sources to gain more information from a sample; for example, measuring and correlating spectra at separate locations or improving efficiency and speed through parallel acquisition of signals.

While it is possible to use a separate spectrograph for every signal input, challenges arise when scaling up the number of channels to dozens or hundreds. Multitrack spectroscopy is a technique which only requires a two-dimensional camera on a single spectrograph to measure multiple input signals on separate rows on the sensor.

Multitrack spectroscopy can be applied to any common spectroscopic technique such as emission spectroscopy, photoluminescence, fluorescence, absorption, transmission or Raman spectroscopy. Next generation spectrographs in combination with large area detectors are designed for true multitrack spectroscopy capabilities using dozens to hundreds of source channels simultaneously. At the same time, good multipurpose wavelength region, spectral systems still offer the ability to easily adapt to changing experimental conditions, for example by using multiple gratings to change the resolution and to optimize efficiency to different wavelength ranges. They are also compatible with a wide range of cameras to adapt to measurement tasks from the UV to the near and short-wave infrared.

Multitrack techniques increase efficiency and reduce overall time for spectroscopic measurement tasks, making them optimal for new developments in fundamental research, but also for industrial research and development, quality and process control applications.

In the following we will illustrate the capabilities of next generation spectroscopy systems for multitrack measurement tasks. We explain how multitrack spectroscopy works, illustrate the optical properties of a good multitrack spectrograph and highlight a few applications from scientific research showing the potential of multitrack spectroscopy.

What is multitrack spectroscopy?

The basics: How a spectrograph works

Figure 1 shows the elements of a spectrograph. First, incoming light enters the instruments through the entrance slit. Input sources are coupled into the spectrograph using free space optics, or optical fibers. In comparison, multitrack applications often use fiber optic bundles that distribute individual fibers along the entrance slit.

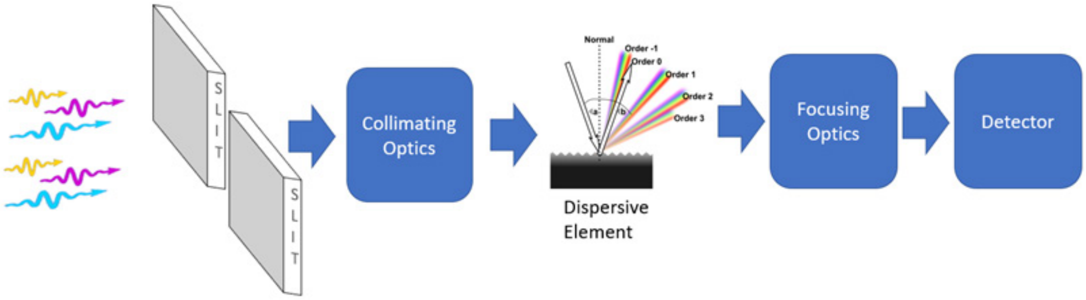

Figure 1: *Schematic view of the elements of an optical spectrograph*

The dispersive element splits the light up into its color components. It is typically a diffraction grating and can be selected to achieve best spectral resolution and efficiency. Advanced spectrograph designs allow the wavelength range of observation to be adjusted by rotating the grating.

The optical imaging system, consisting of collimating and focusing optics, creates an image of the slit in the focal plane. The slit image will be reproduced at a different location in the focal plane for every discrete color in the input signal (see Figure 2). Note that the entrance slit width determines the bandpass for each image at the focal plane.

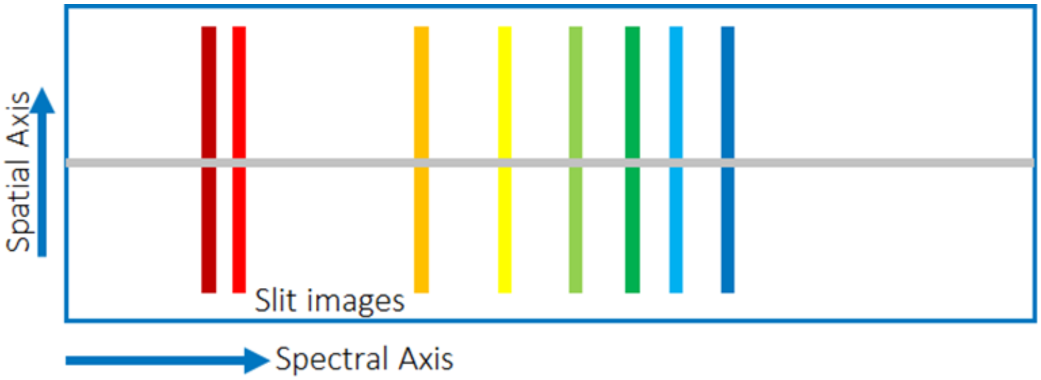

Figure 2: *Spectral and spatial information on a two-dimensional spectroscopy camera*

Creation and readout of the multitrack image in the focal plane

The signal in the focal plane is encoded along a spectral and spatial axis of information (see Figure 2). The spectral axis is oriented along the horizontal direction, in which light of different wavelengths dispersed by the diffraction grating is imaged on different columns of the detector. The spatial axis is oriented in the vertical direction. As the spectrograph optics creates an image of the entrance slit within the focal plane, any incoming light that is in a different position along the entrance slit will be mapped onto a different row on the detector. For multitrack spectroscopy, multiple light sources are positioned along the entrance slit. The signal from each source is acquired as a distinct horizontal line on the detector. Multiple sources will show discrete spectral traces separated vertically, visually looking like stripes on the detector (see Figure 3). Note that the height of each line depends on the size of the input source (for example the core of an optical fiber).

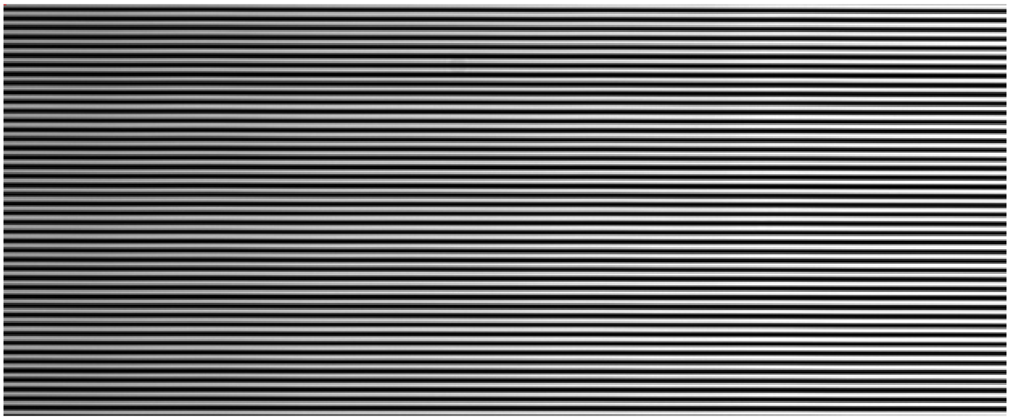

Figure 3: *Multitrack spectroscopic signal. Each horizontal track originates from sources at different positions along the entrance slit*

The detector for signal acquisition is positioned at the focal plane of the spectrograph. Most low light spectroscopy applications, from the UV to the NIR, use back illuminated and deep depleted CCD cameras. By design, CCD cameras readout all imaging pixels in series through a single readout node, making them well suited for standard spectroscopy measurements, but relatively slow for imaging tasks. For standard, single track spectroscopy applications CCDs are often operated by binning the signal increasing readout speed and signal to noise of the signal. However, binning scrambles the spatial information by reducing the spectral image on the sensor to a single spectrum. Unlike single track spectroscopy, the spatial information on the detector can't in general be neglected in multitrack measurements where separate input tracks could be distributed across the whole sensor. CCDs also require the use of a mechanical shutter, blocking light accumulation on the sensor during readout. In absence of a mechanical shutter, signal on the detector would smear and mix between spectral tracks.

Large format CCD sensors often feature multiple (two to four) readout modes to compensate for slower readout times and are a good detector of choice for multitrack experiments with low light levels that don't require high frame rates, but long exposure times. EMCCDs and sCMOS cameras are faster camera choices combining large sensor sizes with fast readout speeds. They do not require a mechanical shutter and are more suitable for measuring multitrack spectra of dynamic, rapidly changing events. The large sensors are able to support applications using dozens to hundreds of input channels. InGaAs focal plane arrays are an alternative detector choice and required for detection of wavelengths between 1000nm – 1700nm

Optical imaging quality and low aberrations; optical properties of multitrack spectrographs

The optical imaging quality of the spectrograph is of crucial importance for multitrack spectral applications. Because the image area is composed of multiple channels covering a wide spectral range, it is essential that the spatial image resolution is high with minimum optical aberrations across the entire focal plane. Optical aberrations (astigmatism as shown in Figure 4) will decrease the number of input tracks or channels that can be detected simultaneously as inputs have to be spaced further apart to not eliminate overlapping signals.

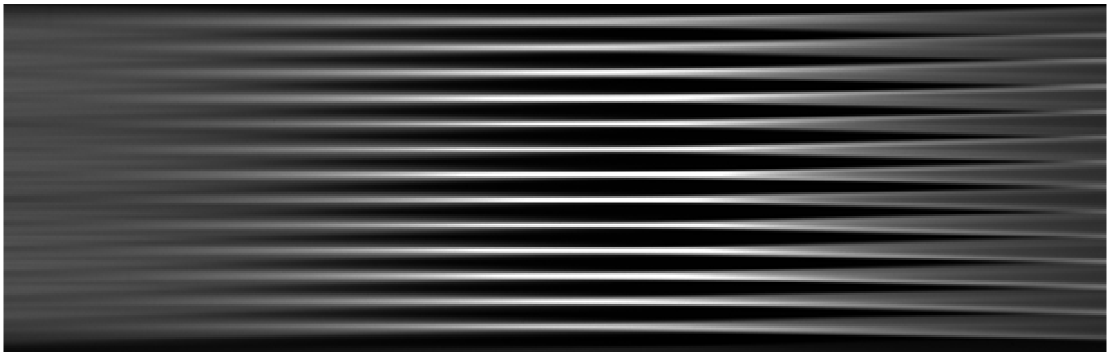

Figure 4: *Multitrack spectroscopy on a Czerny-Turner spectrograph. The signal traces are broadened vertically by astigmatism with increasing severity towards the edges of the focal plane.*

Figure 4 shows an optical multitrack image taken on a spectrograph with a traditional Czerny-Turner design. Image aberrations in Czerny-Turner instruments can be large. This severely reduces the number of input channels such as astigmatism that can be detected without signal overlap.

Czerny-Turner systems use a toroidal mirror to correct for astigmatism. While toroids can fully correct astigmatism at the focal plane center, it re-appears at positions left and right of center resulting in a bowtie shaped image as shown in Figure 4. Reducing the input aperture, for example, using a longer focal length system, will significantly improve aberrations and increase multitrack capabilities.

However, this is only achieved by compromising spectral bandwidth and light collection efficiency. Next generation, aberration corrected spectrograph designs remove this limitation (see referenced technote, "Better Imaging with a Schmidt-Czerny-Turner Spectrograph").

How many tracks can be resolved?

The total number of channels that can be detected by a spectrograph depends on the density of the channels on the detector and the size of the detector. High optical imaging power and low aberrations increase image quality of the spectrograph, the the density of optical channels that can be observed simultaneously.

For proper evaluation height the spectrograph specifications should therefore not only include spectral resolution (measured in nanometers), but also spatial resolution (measured as resolvable line pairs per millimeter) across the focal plane, giving a measure for the usable amount of spectral tracks that can be observed per millimeter of detector height.

Large format imaging sensor (13-27mm sensor width and height) encompass a large area of the focal plane and therefore achieve both, covering a wide spectral range and operate with a very large number of optical tracks. While it is instructive to theoretically estimate the limiting number of tracks for such a detector, it is good to see in practice how many spectral channels can be used.

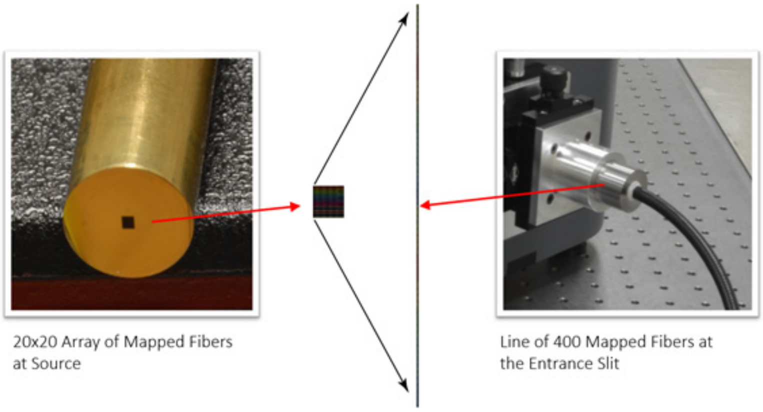

Figure 5: *Fiber bundle for 400 fiber multitrack acquisition connected to the entrance slit of an Isoplane SCT-320 spectrograph*

Figure 5 shows a setup that was implemented involving 400 discrete fiber optic channels. The measurement system was based on an Isoplane SCT-320 spectrograph combined with a KURO 2048B back-illuminated sCMOS camera with 2048x2048 pixels. The fibers in the custom-made bundle were arranged in a square 20 x 20 matrix on the input side and distributed along the height of the entrance slit of the spectrograph on the output side. The fibers had 40µm core diameter and the distance between fibers was 55µm. The large sCMOS detector not only guarantees high sensitivity in the visible wavelength region, but can be readout quickly, so data from all 400 tracks can be acquired at video rates.
Figure 6 shows the image on the detector when illuminated with fluorescent room light, with a center region zoom highlighting the separation of the discrete fiber optic channels. In general, all channels are well resolved and visible with good contrast between lines.

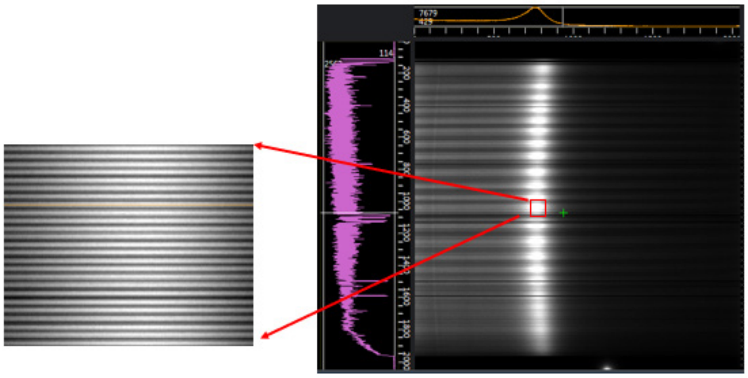

Figure 6: *Multitrack signal detected by a KURO 2048B camera from 400 fibers placed along the spectrograph entrance slit*

Applications of high-density multitrack spectroscopy

In the following we discuss specific application examples of multitrack spectroscopy using free space coupling and fiber coupling of light into the spectrograph.

Application example 1: confocal micro Raman spectroscopy

Confocal spectroscopy is one of the most important techniques for Raman measurements in physical and life sciences. Confocal measurements achieve high spatial resolution around the diffraction limit and provide high suppression of any background signal outside of a small probe volume. However, confocal spectroscopy can be slow when location dependent data from a larger object needs to be acquired since samples need to be scanned point by point.

Hiro-o Hamaguchi and Sohshi Yabumoto from Japan developed a confocal technique that illustrates the potential of multitrack spectroscopy to reduce observation time (see reference Sohshi et al). Instead of a single laser spot, their system uses an array of multiple laser excitation spots. Using a smart arrangement of optical elements, the signal from each location is directed to a different height along the entrance slit plane. Figure 7 shows the arrangement of signal spots in the entrance slit plane as well as the spectral tracks on the sensor.

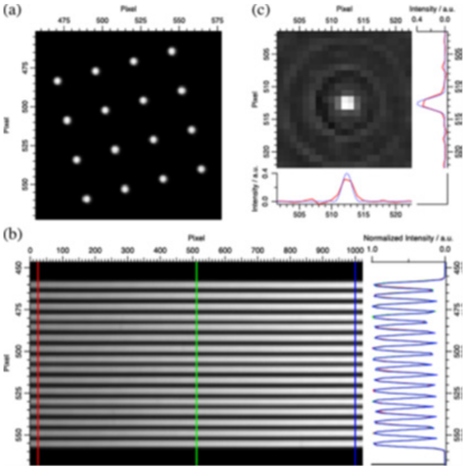

Figure 7: *Multitrack confocal Raman spectroscopy developed by researchers from Japan. The top images show signal spots at the entrance slit plane; the bottom shows the spectral tracks on the detector. Figure from reference Yabumoto and Hamaguchi*

The spectrograph system used consisted of an Isoplane SCT-320 spectrograph and a ProEM EMCCD camera with 1024x1024 pixels with size of 13µm. EMCCD cameras use a fast, electronic shutter, eliminating cross talk between spectral tracks during readout, and are great detectors for multitrack spectroscopy applications.

A total of 16 tracks were measured, but the researchers were looking into increasing the number of tracks to 100. An order of magnitude improvement in acquisition time for a Raman scan was achieved by scanning a surface with all spots in parallel. The researchers emphasize the importance of the imaging quality of the spectrograph for multitrack experiments.

Application example 2: Characterizing Plasmas

Non-contact optical spectroscopic methods play an important role in the characterization of plasmas. Plasma monitoring requires collecting data from various positions within the plasma. Optical fibers are commonly used for collecting the optical signal. Gonzalez-Fernandez et al. implemented a spectral tomographic technique based on collection of optical signals along multiple lines of sight into the plasma from various angles and directions (see Figure 8). The signal is collected by 49 fibers that are arranged in a bundle along the entrance slit of an Isoplane 160 spectrograph, with a ProEM-HS 1024 EMCCD camera for fast detection of the signal.

The increase in information from the large number of spectral channels allows for the tomographic reconstruction of the location dependent temperature and electron density within the plasma.

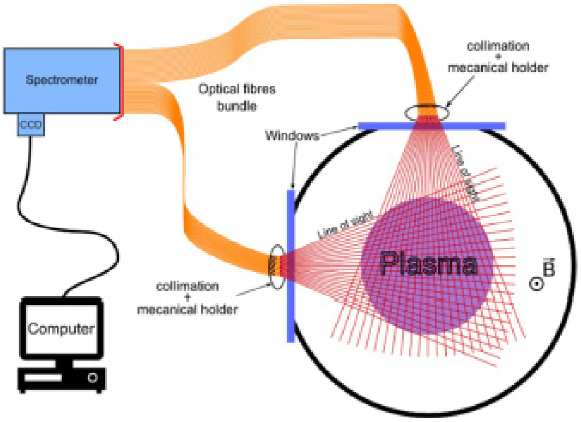

***Figure 8:** Spectral monitoring of plasmas using multiple optical fibers. Figure shown in reference Gonzalez-Fernandez et al.*

Summary

Multitrack spectroscopy using a single spectrograph-camera system can have important impacts on measurement efficiency, speed and information collection by detecting signal from multiple input signals in parallel. Multitrack measurements require spectrographs with high imaging power. Next generation, multi-purpose spectrographs such as the Teledyne Princeton Instruments Isoplane series can operate with dozens to hundreds of parallel inputs. Applications include fundamental research from life science and condensed matter physics to plasma monitoring and astronomy, as well as industrial research, development, quality and process control.

References

- Technote, Better Imaging with a Schmidt-Czerny-Turner Spectrograph
- Tilted Two-Dimensional Array Mutlifocus Confocal Raman Microspectroscopy” Yabumoto and Hamaguchi, Anal. Chem. 2017, 89, 7291–7296
- Gonzalez-Fernandez et al, Spatially resolved determination of the electronic density and temperature by a visible spectro-tomography diagnostic in a linear magnetized plasma, Scientific Reports 10 (2020), Creative Commons 4.0 International License