Continuously Variable Bandpass Filters for Hyperspectral Imaging

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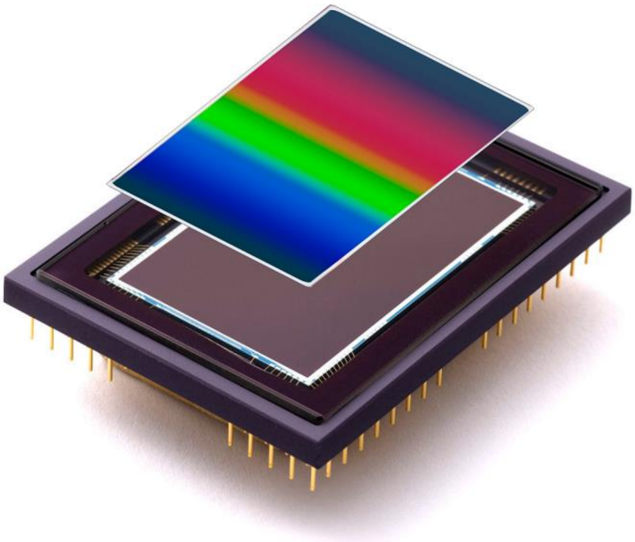

Figure 1: Continuously Variable Filter based Hyperspectral Imaging detector

Introduction

Hyperspectral imaging (HSI) has been used for a couple of decades in applications such as satellite imaging, air reconnaissance and other not overly price sensitive markets. Still, there is no clear definition of the term hyperspectral imaging. Sometimes techniques that produce 2D images with more than the typical three RGB colours (or spectral channels) – for example by inclusion of a near-infrared channel – are already called hyperspectral. Mostly though, this is not considered sufficient. Typically, even ten spectral channels are still to be called multi-spectral rather than hyperspectral.

In the following, we require that certain criteria are fulfilled for an imaging technique to be hyperspectral:

- For every pixel in the image, we measure the spectrum of the incident light or radiation.
- The measured spectrum is continuous and not discretised to a limited number of channels or bands.
- The spectrum covers more than one sub-wavelength range, for example UVA, visible and near-infrared or NIR and SWIR.

The advent of alternative approaches makes HSI attractive for volume markets or even consumer products, for example cancer detection, precision farming with unmanned aerial vehicles (UAV) or directly at the plant, food testing in supermarkets and many more.

Alternative approaches comprise sensors that are coated at wafer-level with fixed wavelength bandpass filters (e.g. PIXELTEQ or imec). Common are also thin film coatings on glass substrates that can be patterned during deposition (in situ), or by using a photolithographic process over the coating to block the addition or subtraction of materials deposited on the substrate surface (e.g. Materion). These micro-patterning techniques allow (a) filters that have a staircase of different centre wavelengths in one direction (also called stepped filters, suited for the so-called push broom technique) or (b) 2D mosaics (suited for the so-called snapshot technique).

However, according to the above criteria, strictly speaking these solutions do not provide hyperspectral capability but are inherently multispectral due to their discrete changes in centre wavelength. Typically, between 10 and 100 different wavelengths or channels are offered. A truly hyperspectral sensor offers a continuous change in centre wavelength and as such a virtually unlimited number of channels.

Delta Optical Thin Film A/S follows a different approach to filters for hyperspectral imaging. Based on our extensive experience with Linear Variable Filters we develop and manufacture custom Continuously Variable Bandpass Filters (CVBPF) for mid-size and full-frame CCD/CMOS sensors (e.g. 25 mm x 25 mm or 24 mm x 36 mm). These filters offer very high transmission levels and are fully blocked in the light-sensitive wavelength range of silicon-based detectors (200 nm to 1150 nm or higher). The combination of CVBPFs with silicon detectors allows the design of very compact, robust and affordable HSI detectors that offer several advantages and benefits over conventional approaches:

- Huge aperture compared with grating and prism
- Higher transmission than grating and prism
- Short measurement time
- High suppression of stray light
- Excellent signal to noise ratio

The first filter from Delta that was used for hyperspectral imaging was a Linear Variable Bandpass Filter with a centre wavelength range from 400 nm to 700 nm. It was actually designed for a non-imaging application in an absorbance reader. Although it was not fully blocked in the silicon range and was rather large, customers saw its potential for HSI and built prototypes and products. A second LVBPF extending the wavelength range to 1000 nm was developed and produced on customer request.

As a result of further customer projects, filters with the following specifications are available as standard products:

- Centre wavelength range 450 nm to 880 nm, bandwidth approximately 2% of centre wavelength, transmission 60% to 90%, blocking range 200 nm to 1150 nm, blocking level OD4, for sensor size 24 mm x 36 mm
- Centre wavelength range 450 nm to 850 nm, bandwidth approximately 4% of centre wavelength, transmission 70% to 90%, blocking range 200 nm to 1100 nm, blocking level OD4, for sensor size 25mm x 25 mm
- Centre wavelength range 800 nm to 1000 nm, bandwidth approximately 0.6% of centre wavelength, transmission >70%, blocking range 200 nm to 1200 nm, blocking level OD4, for sensor size 19 mm x 8 mm
- Centre wavelength range 796 nm to 1084 nm, bandwidth approximately 1% of centre wavelength, transmission >85%, blocking range 200 nm to 1150 nm, blocking level OD4, for sensor size 32 mm x 18 mm

The sizes are given as height x length, where height is perpendicular to the wavelength gradient and length is along the wavelength gradient. The filters can be diced to smaller sizes.

Delta's CVBPFs are thin film filters that are coated with silicon dioxide and metal oxides on a single fused silica substrate without the use of glue, colour glasses or thin metal layers. The resulting filters are very robust against environmental conditions like temperature and humidity, and spectrally and mechanically stable. The filters are ideally suited for long-term use in airborne or space application without any degradation.

Delta produces its filters in coating chambers that are specifically modified to create a thickness gradient of the deposited coating material along one direction of the filter substrates. As the centre wavelength of a bandpass filter depends on the optical thickness of the interference layers, the thickness gradient creates a filter, whose centre wavelength changes *continuously* along the filter length.

Figure 2 shows the transmission characteristics of an LVBPF that covers a centre wavelength range from 450 nm to 880 nm with a bandwidth of approximately 2% of its centre wavelength. In a wide wavelength range, the transmission is higher than 90%. The transmission below 550 nm is underestimated due to the limited ability of our spectrophotometer to resolve narrow bands. A new camera-based test system is under development and will reproduce the peak transmission of narrow bands more accurately. But even more important than the peak transmission, all undesired light from 200 nm to 1150 nm is suppressed better than OD4.

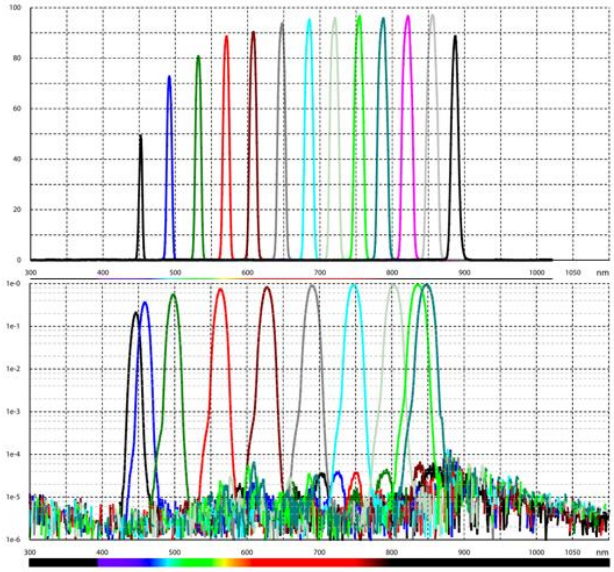

Figure 2: Transmission and blocking characteristics of Linear Variable Bandpass Filter

Comparison with grating and prism based systems

Due to the diffractive nature of gratings or prims, their use requires a certain large distance between sensor and diffractive element. This results in a large instrument that is prone to misalignment due to mechanical influences. Furthermore, a slit is needed to obtain high spectral resolution (see Figure 3). The slit limits the light throughput considerably. The signal to background light level is typically not better than 1000:1.

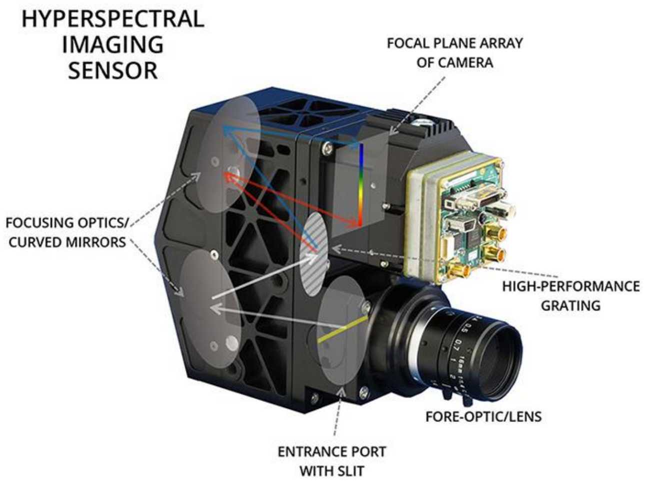

Figure 3: Design of a classical Hyperspectral Imaging camera with grating (by courtesy of Headwall Photonics)

Continuously Variable Bandpass Filters, on the other hand, can be mounted directly on top of or close to the sensor. Options include gluing onto the sensor surface, replacing the cover glass with the filter or a mechanical holder. The resulting detector is very compact and robust at the same time. The optical design does not require the use of a slit. Light is collected through the full aperture of the lens. Together with the high transmission and the optical bandwidth of the filter, the hyperspectral imaging camera becomes very light efficient. The deep broad-band blocking of the filter ensures a high signal-to-noise ratio (SNR) end eliminates spectral crosstalk.

Without a slit, every acquired image shows the complete scene. This makes it possible to use the so-called step-and-stare technique. It allows to arbitrarily image the scene from different positions without the need for precise synchronisation of lateral movement and image acquisition like with the push broom technique. With the step-and-stare technique, it is possible to construct the hyperspectral data cube using image pattern recognition techniques
(see Figure 4).

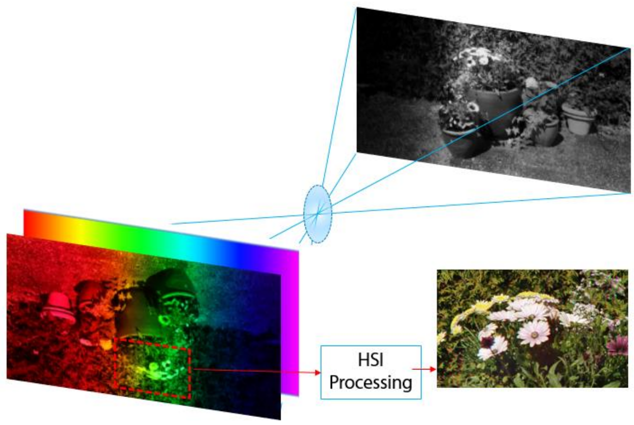

Figure 4: Image acquisition and workflow with filter based Hyperspectral Imaging camera.

Comparison with wafer-level coated detectors

What makes wafer-level coated detectors attractive is the possibility to coat filters in arbitrary patterns also on small imaging sensors. Small size can be a crucial factor in certain applications. The same is true for snapshot capability (acquisition of the hyperspectral data cube with only one image). In this case, the sensor is coated with a 2D pattern of bandpass filters with different but constant centre wavelengths. The snapshot capability of course comes at the cost of reduced spatial resolution. Another typical trade-off of coating at wafer level is the limited spectral complexity of the filters. Imec for example offers simple Fabry-Perot filters that do not create sharp bands and have strong side bands that limit the overall wavelength range and the obtainable SNR[1].

Delta’s filters are suited for larger sensors. To maintain their high performance and large wavelength range the filters cannot be made much smaller than 20 mm in the variable direction with current production technology. An approach to enable snapshot Hyperspectral Imaging with Linear Variable Bandpass Filters is currently investigated and makes use of 2D lens arrays (plenoptics cameras) that are for example used in light field cameras[2].

3D Hyperspectral Imaging

For some applications, for example precision farming or quality control of manufactured components, it is advantageous to combine hyperspectral data with 3D surface information. In precision farming this provides both information on nutrition and health of crop as well as its height and growth. However, it is hard to imagine how the height information could be extracted from traditional hyperspectral cameras that use slits and only image a narrow slice of the object, especially under imaging conditions in which the relative movement between camera and object cannot be precisely controlled like with UAVs. Even with snapshot cameras that might prove difficult because of their limited spatial resolution that might not be sufficient for 3D reconstruction.

On the other hand, hyperspectral cameras using a LVBPF or CVBPF have superior spatial resolution that allows 3D reconstruction of the imaged scene by standard stereoscopic image processing. This makes use of the fact that each object in the scene is viewed from different angles while passing by (see Figure 5).

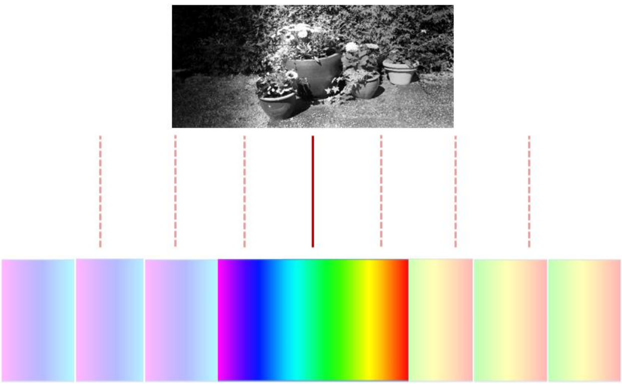

Figure 5: Relative movement between camera and object enables 3D Hyperspectral Imaging

Conclusion and outlook

All three approaches have their specific strengths. Classical hyperspectral cameras with gratings and prisms achieve the highest spectral resolution and are well suited for demanding applications in research. Sensors that are coated at pixel level allow the most compact cameras, offer total flexibility with respect to filter pattern and are readily suited for snapshot imaging. Cameras based on Delta's CVBPF combine high light efficiency, high SNR and high spectral resolution with compact- and robustness.

Although some of the filters that are discussed above are usually called linear variable filters, they are typically not perfectly linear with respect to centre wavelength versus position on the filter. This can easily be compensated for by a calibration curve or a one-time calibration of the assembled detector. However, there are good reasons for designing filters that deliberately are non-linear.

As can be seen from the transmission curves in Figure 2, the bandwidth is proportional to the centre wavelength. This is a natural property of the multi-cavity design that is used in the filters. As a consequence – if we for example compare light with 450 nm and 900 nm – there are twice as many neighbouring pixels on the sensor that see light of 900 nm as there are pixels that see light of 450 nm. This can be compensated for with an exponential relation between centre wavelength and its spatial position on the filter. Other design targets are possible.

Desirable are filters that cover a larger wavelength range over a shorter length. Currently, filter designs are under development that for example cover 400 nm to 950 nm over 36 mm.

Although the emphasis of this article lies on hyperspectral imaging, it should be mentioned that the same technology can be used to replace gratings in compact spectrometers – making them even more compact. Thanks to Delta's ultra-hard coating technology, the filters can be diced to very narrow stripes that can be mounted in front of a line scan detector. This concept is for example used in wearable devices to measure the oxygen content of blood.

Another promising application is the fusion of fluorescence microscopy and hyperspectral imaging as hyperspectral fluorescence microscopy. The technology is applicable to both laser scanning microscopy and wide-field microscopy[3,4].

[1]http://www2.imec.be/content/user/File/Brochures/2015/HSI%20activity.pdf; slides 17 and 25

[2] Z. Zhou, Y. Yuan, B. Xiangli: Light Filed Imaging Spectrometer: Conceptual Design and Simulated Performance, Frontiers in Optics 2010/Laser Science XXVI OSA Technical Digest; DOI10.1364/FIO.2010.
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[3] L. Gao, R.T. Smith: Optical hyperspectral imaging in microscopy and spectroscopy – a review of data acquisition, J. Biophotonics 8, No. 6, 441–456 (2015) / DOI 10.1002/jbio.201400051

[4] P. F. Favreau et al.: Excitation-scanning hyperspectral imaging microscope, Journal of Biomedical Optics 19 (2014) 4 (April), 046010; DOI:0.1117/1.JBO.19.4.046010