Development of a new linearly variable edge filter (LVEF)-based compact slit-less mini-spectrometer

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Abstract. This paper presents the development of a compact charge-coupled detector (CCD) spectrometer. We describe the design, concept and characterization of VNIR linear variable edge filter (LVEF)-based mini-spectrometer. The new instrument has been realized for operation in the 300 nm to 850 nm wavelength range. The instrument consists of a linear variable edge filter in front of CCD array. Low-size, light-weight and low-cost could be achieved using the linearly variable filters with no need to use any moving parts for wavelength selection as in the case of commercial spectrometers available in the market. This overview discusses the main components characteristics, the main concept with the main advantages and limitations reported. Experimental characteristics of the LVEFs are described. The mathematical approach to get the position-dependent slit function of the presented prototype spectrometer and its numerical de-convolution solution for a spectrum reconstruction is described. The performance of our prototype instrument is demonstrated by measuring the spectrum of a reference light source.

1. Introduction

Optical spectrometers are widely used in variety of applications in many fields relating to analysis of light sources and luminaries as well as analyzing distant objects in space missions, earth observation applications among others. Where today is the age of scaling-down and miniaturization, so the need of mini-spectrometer arises and becomes of great interest. Moreover, the need of miniaturization appears and becomes essential for some industrial and scientific applications. For instance, in space missions’ applications, instruments need to be compact and small in weight. Hence, developing a compact and light spectrometer is of great interest for scientists in variety of fields [1,2]. Many approaches tried to address this need by constructing mini-spectrometers in which, for example, the traditional optical elements, e.g. gratings and prisms, were replaced by optical filters. The main drawback of a traditional filter instrument is that it is always dedicated to a specific task and, as far as it is concerned, no other spectral data exist. Recently, new technology provides a filter known as a linear variable optical filter (LVOF), which is capable of providing a set of continuously changing wavelengths across its length.
A very compact and simple micro-spectrometer can be produced by combining one of these filters with a CCD/CMOS array. There are different types of filters that can be used in spectrometers, e.g. bandpass transmission filters [3-6].

With this type of mini-spectrometers, the peak/edge wavelength of the transmission filter is moving along one direction of the filter, such that each line of a two-dimensional array detector, equipped with this filter, will detect radiation in a different wavelength band. One of the candidates from this type is the bandpass filter based spectrometer. Using graded bandpass filters has some drawbacks, e.g. limited resolution, so using a linear variable edge filter instead with a well-prepared mathematical algorithm can have significant advantages due to our concept.

In this paper, we describe our new instrument and its basic concept, we characterize our instrument to test the behaviors which are directly related to our application, e.g. measuring transmittance at different positions of the filter, test edge steepness, test the linear relationship between edge wavelength and position throughout the filter and finding the slit functions at different positions throughout the active area of our instrument. At end, we show preliminary results of our initial measurements, by applying our model with de-convolution algorithm, of reference light source with comparing the results with those of reference traditional spectrometer.

2. Working concept

2.1. Construction of prototype

Our approach to develop the prototype LVEF-based spectrometer is based on two main parts, first the design and construction of the device using a LVEF filter in front of CCD sensor and second to develop the optimal algorithm for treatment of the output digital image data. The off-the-shelf linear variable filters can cover the spectral region ranging from 350 nm to 1000 nm [7,8]. This approach permits wide operating wavelength ranges but, wider is the spectrum; greater are the difficulties of instrumentation design, fabrication and mathematical algorithm.

As shown in figure 2, our hardware module comprises the linearly variable edge filter and CCD monochrome (B/W) digital sensor (Sony, model ICX205AL, 1280 × 1024 pixels, pixel size 4.65 μm × 4.65 μm with 8 bit analog-to-digital converter). On top of the CCD array, we place LVEFs with some main characteristics, e.g. having “very steep edges”, “~90% transmission or more”, “low ripple”, better than OD3 blocking (short wave rejection). We cut the main filter, which covers the spectral range from 300 nm to 850 nm, into 4 identical pieces to construct four replaceable filters; A: 300-430 nm, B:440-570 nm, C:580-710 nm and D:720-850 nm set on the sensor fitting its transversal dimension (see Figure 1). To achieve the best measurements, the variable filter should be mounted as close as possible to the sensitive area of the sensor, this helps to have the optimum spectral resolution and avoid any light divergence. To reduce the effects of the back reflection, an antireflection coating deposited on the sensor sensitive area is necessary. We made a special designed filter holder so that it can accommodate one filter in a time to fulfil the important criteria as mentioned above, e.g. installing each filter securely and easily as close as possible to the sensor surface and to make it easy for each filter to be changed in order to scan through its specified wavelength range. We described the main idea of this work and its flow chart in [9]. The main concept and the mathematical model of our approach will be explained in the next section.

![LVEF and Filters](image-url)
2.2. Concept of the mathematical algorithm

In literature many algorithms for data treatment and image post-processing are described. The main issue with the available algorithms is that it always addresses specific cases. Using optimum mathematical software algorithms, it is possible to obtain correct spectral information about the samples under study. Generally, spectral data processing can be divided into two successive steps: preprocessing of raw data and extracting the necessary information. Superimposed or convolved spectral components can be only partly separated by spectral data processing usually referred to as deconvolution. Deconvolution is the transformation of the measured spectrum into the one which is as close as possible to the true spectrum [10-13].

Figure 2 shows the schematic diagram of the hardware module (prototype) which is supposed to receive the radiation from the test source. It is shown that at different points throughout the horizontal axis the different pixels will receive light corresponding to different “cut-on” band and the adjacent pixels receive another band and so on. Let’s suppose that, each channel (bundle of detectors/pixels) in the array will receive some signal $y_i$ corresponding to its position in the horizontal axis within the array, this defines which spectral component this channel will receive, so the mathematical concept for the model can be understood due to the following steps.

The output signal $y_i$ of each sensor $D_i$ ($i = 1 \ldots n$) can be expressed as

$$y_i = \int S(\lambda) \cdot R(\lambda) \cdot T_i(\lambda) d\lambda$$

(1)

where $S(\lambda)$ denotes spectral power of the input radiation, $R(\lambda)$ the spectral responsivity of the sensor (which is assumed to be same for all the sensors in the array after being corrected, with the normal procedures, for the photoreponse non-uniformity), and $T_i(\lambda)$ the spectral transmittance of the linearly variable edge filter (LVEF) at the position of the sensor $D_i$. Without loss of generality, we assume that the LVEF is a long-pass filter attached to the sensor array with the shortest cut-on wavelength at $D_1$ and the longest cut-on wavelength at $D_n$.

Figure 2. Schematic diagram of the hardware module.

We consider the difference $\delta_i$ ($i = 1 \ldots n-1$) between two sensors $D_i$ and $D_{i+1}$ as the raw data of the spectrometer:

$$\delta_i \equiv y_{i+1} - y_i = \int S(\lambda) \cdot R(\lambda) \cdot [T_{i+1}(\lambda) - T_i(\lambda)] d\lambda$$

(2)

Figure 3 shows the change of positions of $D_i$ throughout the captured frame to make the idea visible and showing the direction of change of transmission change throughout the filter/sensor combination.

For the LVEF, each position on the filter can be assigned to a cut-on wavelength of the long-pass filter edge with a linear function. We can define the “slit function” $\Lambda(\lambda, \lambda_i)$ of this spectrometer as

$$\Lambda(\lambda, \lambda_i) \equiv R(\lambda) [T_{i+1}(\lambda) - T_i(\lambda)]$$

(3)

with $\lambda_i$ is the cut-off wavelength assigned to the filter position at the sensor $D_i$. Then, Eq. (2) can be re-written as

$$\delta(\lambda_i) \equiv \delta_i = \int S(\lambda) \cdot \Lambda(\lambda, \lambda_i) d\lambda$$

(4)
Note that the slit function \( \Lambda(\lambda, \lambda_i) \), which is the characteristic property of the spectrometer instrument, can be experimentally determined at the position of each sensor \( D_i \) \((i = 1 \ldots n-1)\) by using a tunable monochromatic source. We will show the experimental results of studying the slit function and its position dependency in subsequent section.

Note also that the slit function can be, in general, different for each sensor position so that \( \Lambda(\lambda, \lambda_i) \) forms a two-dimensional matrix. The task of the Data Acquisition (DAQ) unit is to calculate and plot \( S(\lambda) \) from the measured raw data array \( \delta(\lambda_i) \) by using the slit function matrix \( \Lambda(\lambda, \lambda_i) \) of the instrument via a numerical de-convolution.

Now we consider an idealized special case where the spectral transmittance \( T(\lambda) \) satisfies the following relation:

\[
T_{i+1}(\lambda) = T_i(\lambda - \delta \lambda)
\]  

(5)

This means that the spectral transmittance of the LVEF shifts by a constant amount on the axis of wavelength without any change of its shape, as the sensor position varies by one step. Moreover, the responsivities of the sensors are wavelength-independent. Then, the shape of the slit function in Eq. (3) will be a fixed symmetric function with the symmetry center at the cut-on wavelength \( \lambda_i \), which moves by a fixed value of \( \delta \lambda \) as the sensor position changes by one step. We can simplify Eq.(4) for this case of the constant slit function to

\[
\delta(\lambda_i) = \int S(\lambda) \cdot \Lambda(\lambda - \lambda_i) \cdot d\lambda
\]  

(6)

Eq. (6) has the same form as a scanning grating spectrometer with a position-independent slit function, and its de-convolution solution is well described in the literature.

3. Experimental results

3.1. LVEF characterization

3.1.1. Spatial transmittance measurements

Figure 4 shows schematically the setup for transmittance measurement of our filters at different positions throughout the filter surface, noted in eq 1 as \( T_i \). Following our concept to determine the slit function at different positions, we should first determine the value of \( T_i \) and \( \Delta T_i \) in order to determine the “slit function” \( \Lambda(\lambda, \lambda_i) \) at different positions “i” considering that the responsivity is uniform throughout the whole sensor active area.

The apparatus to measure the graded transmission comprises QTH based monochromatic light source and CCD sensor. Light source part constitutes QTH lamp, double-grating monochromator; for minimizing spectral stray light and optimizing the resolution with keeping spectral bandwidth within appropriate limits and achieving excellent spectral purity, and set of order sorting filters for out-of-band stray rejection. Six-inch integrating sphere painted with PTFE-based high reflective material used with one-inch output and entrance ports and half-inch north-pole port for installing reference
detector. Collimating and focusing fore-optics comprising two off-axis focusing mirrors and set of stops used for imaging the exit slit at integrating sphere entrance plane and for beam shaping. Integrating sphere, working as perfect diffuser, provides uniform illumination at filter/sensor plane to keep the general principle of uniform response of the CCD sensor valid.

Figure 4. Setup for spectral transmittance measurements.

Figure 5 shows some measurements of transmittance at different horizontal positions which has been recorded by the CCD sensor at different channels (regions of interest –ROIs-). These measurements made by using a tunable monochromatic source described above. The steepness of transmitted spectra at different spatial positions are of 10 to 20 nm, which are reasonable to set our concept into practice with a good accuracy. As discussed earlier, we cut the filters into small sizes to have them nearly fitting the sensor area. Each filter covers smaller spectral range with the set of replaceable four filters allowing our device to cover a wide spectral range from 300 nm to 850 nm. We present transmittance data of three of our filters in figure 5 showing the movement of the edges throughout each filter.

![Figure 5](image)

Figure 5. (a) Transmission spectrum of LVEF filters showing the wavelength-dependent behavior, (b) image of the filter on the CCD illuminated at different wavelengths.

In Figure 6 the variation of the edge wavelength along the surface of three of the used filters over 3 mm in each case is shown. Linear relationship between position and wavelength has been proved with
these measurements. Knowing that the linear movement of the edges throughout the filter is important factor to be proved, where in our concept in developing the numerical algorithm for collected images’ post-processing, the relationship between the spatial position at the filter and the wavelength should be linear. To present this relationship, we plot the sum of pixel counts (intensities) in adjacent ROIs with the same sampling and steps of 100 pixels (~ 0.5 mm) in the transversal direction as a function of position throughout the filter. The linear relationship in this case proves the linear displacement of edge wavelength throughout the filter, which is the main advantage of linearly variable filters technology.

Figure 6. Linearity of the edge displacement along the direction of variation presented for filters A, B and C.

3.1.2. Determination of the slit functions
To determine slit function of our instrument we should have the spectral transmittance $T(\lambda)$ and responsivity $R(\lambda)$ while knowing $T(\lambda)$ at each ROI with index “i” (see figure 3). Then, according to the mathematical model described in the previous section we can calculate the slit function at each ROI which denoted as $\Lambda(\lambda, \lambda_i)$ in eq 3.

Figure 7 represents set of calculated slit functions with different sampling intervals throughout different filters. Change the sampling by changing the position of “i+1” in eq 3 with respect to “i” yields different bandwidth (FWHM) at this position “i”.

Figure 7. (a) slit function at different positions throughout different filters at representative positions (filters B, C and D) with same sampling. (b) slit functions with filter B with different sampling.

In figure 8, we show the shape and spectral width of the slit function for one position at two of the filters, while having different sampling in each case with respect to the other. It should be noticed that, the shape of the slit function is ideal; triangular profile. It is clearly shown that by changing sampling,
we can different “FWHM” of our slit function. This clearly shows that, in our instrument, we can have different flexible and tunable wavelength band through mathematical modeling. That’s one of the big advantages of our mini-spectrometer. With mathematical modeling, we can change sampling to get boarder band for getting higher signal-to-noise ratio (SNR). The numerical algorithm is a key factor in the success of any model in all similar cases [10-13].

3.2. Test
To implement and test a de-convolution algorithm for target spectrum reconstruction which can be considered as an initial part of a validation process, we took the measurements of continuous light source in comparison with measurements taken with same conditions with reference spectrometer. Using our numerical algorithm (software), we could get preliminary results of the reference source spectrum, we initially measured using our prototype instrument and in comparison we used traditional spectrometer (Instrument Systems, model: CAS-140-CT) measurements, both of the measurement results shown in figure 9.

![Figure 8](image1.png)

Figure 8. (a) Slit function at 470 nm with FWHM of 15 nm, filters B. (b) slit function at 810 nm with FWHM of 30 nm, filter D.

![Figure 9](image2.png)

Figure 9. Spectrum of reference light source from 400 nm to 700 nm measured with our compact slit-less mini-spectrometer in comparison with measurements of traditional spectrometer.

4. Conclusions
Prototype instrument of a compact, slit-less mini-spectrometer is demonstrated. It comprises LVEF and CCD array. Characterization of the LVEFs using monochromatic light proves the operation of the LVEF reported. We determined the spectral transmittance and slit functions to realize our concept. This new spectrometer is expected to have a potential of modern applications.

Placing the LVEF directly on the top of a detector array strongly reduces the problems associated with diverging light. Thin film deposition over large format sensor surface can be a good alternative
which can be a part of future work. Also the radiometric calibration to obtain a calibration matrix assigning absolute irradiance values to each ROI to get the true spectrum of the test samples is subject of future work.

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