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DEVELOPMENT OF A NEW LINEARLY VARIABLE EDGE FILTER (LVEF)-BASED COMPACT SLIT-LESS MINI-SPECTROMETER

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ABSTRACT:
The construction of a small charge-coupled detector (CCD) spectrometer is described in this work. The rationale, construction, and characteristics of the VNIR mini-spectrometer, which operates on linear variable edge filter (LVEF) principles, are described. The innovative device's operational wavelength range is 300 nm to 850 nm. A linear variable edge filter is placed in front of a CCD array to form the instrument. In contrast to commercially available spectrometers, linearly variable filters provide small size, light weight, and low cost without the requirement for mechanism-driven wavelength selection. This summary provides an overview of the fundamental characteristics of the components, the central concept, and the main advantages and downsides addressed. The LVEFs' experimental properties are detailed. The described mathematical method generates both the position-dependent slit function of the prototype spectrometer on display and the numerical de-convolution solution required for spectrum reconstruction. We show the prototype apparatus's functionality by examining the spectrum of a conventional light source.

Keywords: *Linearly Variable Edge Filter; Spectrometer; charge-coupled detector (CCD); Bandpass.*

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1. INTRODUCTION

Optical spectrometers are used in a variety of fields for purposes such as researching light sources and lamps, assessing distant objects for space missions, monitoring the earth, and more. The demand for mini-spectrometers is a hot topic right now, as everything is growing smaller and smaller. Miniaturization appears and becomes an imperative necessity in several scientific and industrial settings. Tools used on space missions, for example, must be small and light. Making a compact light spectrometer is therefore critical for professionals in a variety of fields [1,2]. Several approaches were considered to address this demand, including creating miniature spectrometers out of optical filters rather than more typical optical elements like prisms and gratings. One of the primary issues with classic filter instruments is that they can only accomplish one thing at a time and cannot provide additional spectrum information. Recent technological improvements have resulted in the development of a filter known as a linear variable optical filter (LVOF). This filter can emit a variety of colors that shift during its length.

A CCD/CMOS array and one of these filters can be combined to create a very small and simple micro-spectrometer. Bandpass transmission filters are one type of filter that can be used in spectrometers [3-6].

Here's how these tiny spectrometers work: The transmission filter's peak/edge frequency shifts in only one way. As a result, each line of a two-dimensional array detector with that filter can detect radiation in a certain wavelength range. A spectrometer with a bandpass filter is one option in this category. When using graded bandpass filters, other issues can arise, such as reduced sharpness. So, our method implies that there may be significant advantages to employing a mathematical technique to determine a linear variable edge filter.

In this work, there is an account of a peculiar instrument and an explanation of how it operates. It is defined in detail so that we can determine how the instrument will interact with our program. This requires measuring the transparency at various filter positions, determining how the slits work at various points in the instrument's active region, and examining the edge steepness and the linear relationship between the edge wavelength and position across the filter. Finally, we present the preliminary findings obtained by measuring the reference light source using our model and deconvolution method.

2. WORKING CONCEPT

Construction of prototype

The initial step in developing the prototype LVEF-based spectrometer is to construct and design the device. An LVEF filter is now placed in front of the CCD sensor. The second challenge is to determine the appropriate technique to handle the digital picture data generated by the instrument. There are linear adjustable filters available on the market that cover the wavelength range of 350 nm to 1000 nm [7, 8]. This approach allows for very vast wavelength ranges, but as the spectrum grows larger, it becomes more difficult to design, build, and develop mathematical formulas for the equipment.

Our gear consists of an 8-bit analog-to-digital converter, a Sony ICX205AL black-and-white digital sensor, and a linearly adjustable edge filter with pixels measuring 4.65 m 4.65 m. Figure 2 depicts a diagram of these components. We prioritized LVEFs with "extremely steep edges," "90% or greater transmission," "low ripple," and superior short wave rejection (OD3 blockage) than other LVEFs with similar qualities. The main filter was divided into four comparable parts with a color range of 300 nm to 850 nm so that they could be used together or independently. A (540-570 nm), B (300-430 nm), C (580-710 nm), and D (720-850 nm) are the wavelength ranges. It is advisable to place the changeable filter close to the sensitive area of the sensor for the most accurate results. These filters were applied to the sensor based on its width (see Figure 1). This prevents the light from diverging and ensures maximum spectral purity. To reduce the effects of rear reflection, apply an antireflection coating to the sensitive area of the sensor. To achieve the aforementioned requirements, a bespoke filter holder was developed that could hold one filter at a time, make it safe and simple to put each filter close to the sensor surface, and make it simple to swap filters so that scanning could occur across the needed wavelength range. The fundamental idea and plan for this investigation were outlined

in [9]. The following section will go over our approach's main premise and mathematical model in further depth.

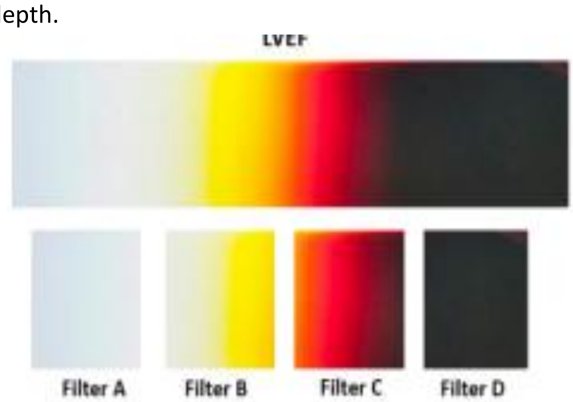


Figure 1. The primary sections of the LVEF are created by a rigorous cutting procedure

Concept of the mathematical algorithm

The books contain several descriptions of algorithms for working with data and manipulating images. One major issue with present techniques is that they only address a few scenarios. Using the correct mathematical software can assist you in obtaining precise spectrum information about the materials you are investigating. To process spectral data, you must normally perform two things: Pre-process the raw data to extract the most critical information. De-convolution is a common word for processing spectral data, however it only partially separates overlaid or mixed-up spectral components. Deconvolution is the process of converting the observed spectrum into a representation that is very close to the true spectrum [10-13].Figure 2 depicts a diagram of a hardware module (prototype) that is designed to absorb radiation from the test source. It is demonstrated that pixels along the horizontal line get light from various "cut-on" bands at various places. Light from a different band is received by neighboring pixels, and so on. Assume that the information received by each channel (group of detectors or pixels) in the array is proportionate to its location on the array's horizontal axis. This indicates the type of frequency component the channel will receive. Follow these steps to obtain a better understanding of how the model is mathematically put together.

The output yi of each sensor Di, where i = 1 through n, can be represented as

$$y_i = \int S(\lambda)\cdot R(\lambda)\cdot T_i(\lambda)d\lambda \quad (1)$$

In this case, S() is the spectral power of the input radiation, R() is the sensor's spectral responsivity (which is assumed to be the same for all sensors in the array to account for photoresponse non-uniformity), and Ti() is the spectral transmittance of the linearly variable edge filter (LVEF) at the sensor Di. We believe that the sensor array's long-pass filter (LVEF) has the longest cut-on wavelength at Dn and the lowest cut-on wavelength at D1. This is true without sacrificing generality.

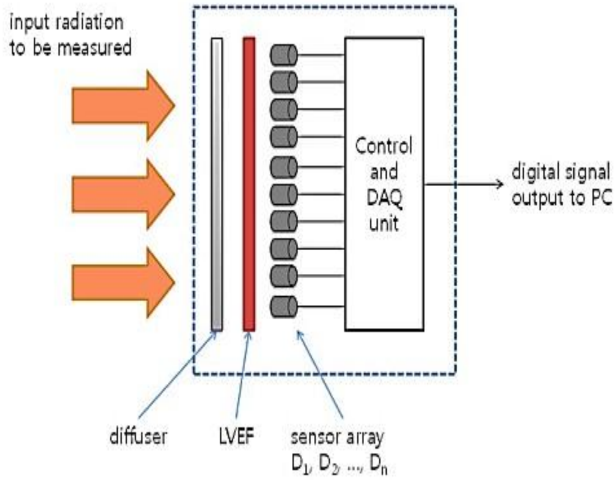


Figure 2. The hardware is depicted as a schematic.

The raw data from the spectrometer is the difference i between two sensors, Di and Di+1. The value of i can range between 1 and n-1.

$$\delta_i \equiv y_{i+1} - y_i = \int S(\lambda)\cdot R(\lambda)\cdot\left[T_{i+1}(\lambda) - T_i(\lambda)\right]d\lambda \quad (2)$$

Figure 3 helps to clarify the concept by showing how the direction of transmission varies across the entire filter/sensor pair and how Di advances along the length of the collected frame.

Each point on the LVEF filter can be assigned a cut-on wavelength of the long-pass filter edge using a linear function. Consider the spectrometer's "slit function" (,i) as

$$\Lambda(\lambda,\lambda_i) \equiv R(\lambda)\left[T_{i+1}(\lambda) - T_i(\lambda)\right] \quad (3)$$

The filter point at the sensor Di is given the cut-off wavelength, represented by i. As a result, Equation (2) can be rewritten as

$$\delta(\lambda_i) \equiv \delta_i = \int S(\lambda)\cdot\Lambda(\lambda,\lambda_i)\cdot d\lambda \quad (4)$$

Notably, a variable monochromatic source can be used to calculate the spectrometer's slit function (,i) at the position of each sensor Di (where i is an integer between 1 and n-1). The following section will demonstrate the testing findings obtained by examining how the slit function changes with position.

It's also worth noting that the slit function can vary depending on where the sensors are located. As a result, (,i) is a two-dimensional matrix. To discover and display S(), which is derived from the observed raw data (i), the Data Acquisition (DAQ) unit must numerically deconvolution the instrument's slit function matrix (,i).

Now consider a fictitious case in which the spectral transmittance Ti() follows the pattern described below:

$$T_{i+1}(\lambda) = T_i(\lambda - \delta\lambda) \quad (5)$$

This demonstrates that a one-step adjustment in sensor placement causes the LVEF's spectral transmittance to travel consistently along the wavelength axis without any discernible changes in form. Furthermore, the instruments are responsive regardless of wavelength. As a result of Equation (3), the slit function becomes a fixed symmetric function with the symmetry center at the cut-on wavelength i. At the same moment, the sensor's position will move one step. The slit function moves, as indicated by the constant number. In the case of the constant slit function, equation (4) can be simplified to

$$\delta(\lambda_i)=\int S(\lambda)\cdot\Lambda(\lambda-\lambda_i)\cdot d\lambda \quad (6)$$

Equation (6) is used in the literature to explain the deconvolution answer to a position-independent slit function scanning grating spectrometer.

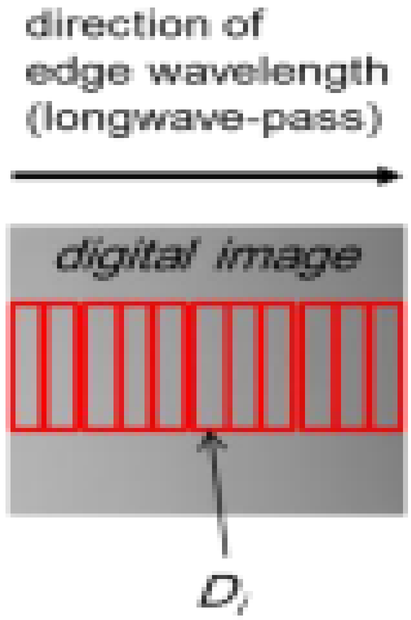


Figure 3. The spectral frame depicts the broadcast channels as they pass through the sensor and filter.

3.EXPERIMENTAL RESULTS

LVEF characterization

Spatial transmittance measurements

Figure 4 shows a diagram for figuring out how much light passes through our screens at different points on their surface, which is shown as Ti in equation 1. According to our method, we need to find the values of Ti and Ti before we can figure out the "slit function" (,i) at different points "i." We assume that the response is the same across the whole active region of the sensor.

A CCD camera and a monochromatic light source based on QTH make up the measuring equipment for graded transmission. It has a QTH lamp, a double-grating monochromator (to reduce spectral stray light and improve resolution while keeping spectral bandwidth within acceptable limits and achieving exceptional spectral purity), and a set of order sorting filters (to get rid of out-of-band stray light). A high-reflectivity PTFE sphere that is six inches in diameter and has one-inch output and entrance ports as well as a half-inch north-pole port can be used to mount a reference detector. To picture the exit aperture at the entrance plane of the integrating sphere and shape the beam, a set of stops and a focusing and collimating fore-optic system made up of two off-axis focusing mirrors are used. The integrating sphere creates light that is evenly spread at the filter/sensor plane because it is a perfect diffuser. This keeps the basic principle of the CCD sensor's uniform reaction.

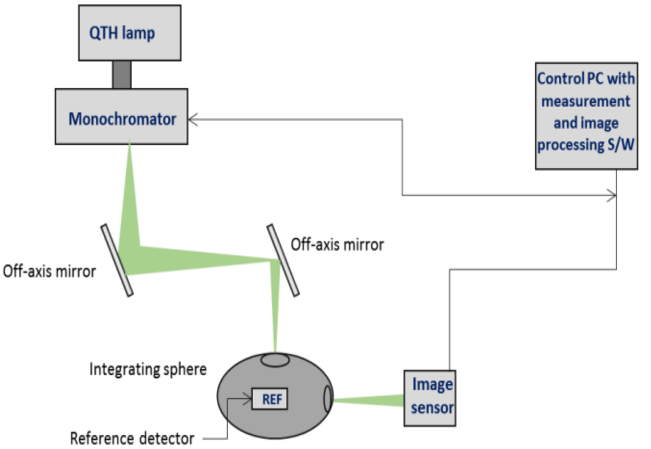


Figure 4. Setting up for measuring spectral transmittance.

As shown in Figure 5, the CCD sensor measured transmittance at various horizontal points and channels, which are also known as ROIs (regions of interest). These measures were taken with the adjustable monochromatic source that was previously shown. The measured steepness of transmitted spectra at different locations ranges from 10 to 20 nanometers, which is a good range for putting our idea into practice. As was already said, the filters were shrunk down so much that they took up most of the sensor space. The device has four changeable filters that work together to cover a wide range of wavelengths, from 300 nm to 850 nm. Each filter covers a smaller area of the spectrum. In Figure 5, we can see how the edges move across the transparency data of three of our filters.

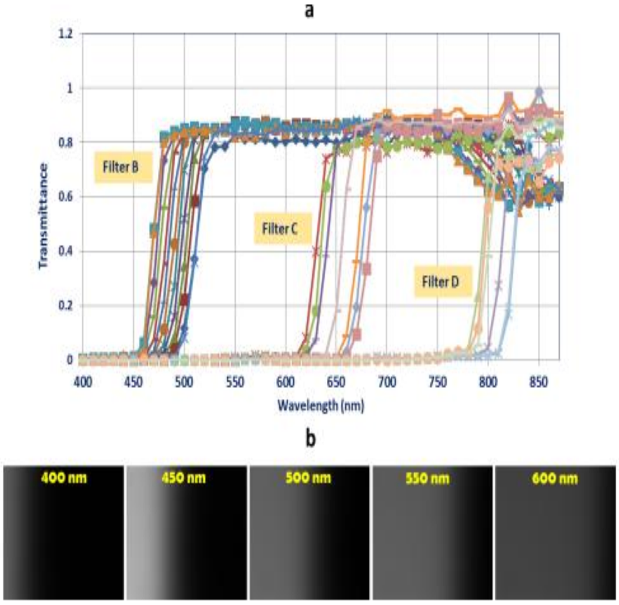


Figure 5. ((a) The transmission spectrum of LVEF filters that change with wavelength; (b) A CCD picture of the filter lit up at different wavelengths.

Figure 6 shows how the edge frequency changes along the surface of three of the filters that were used over a distance of 3 mm. Based on these data, a straight line link was found between position and wavelength. It is very important to check that the edges move linearly through the filter. On the other hand, figuring out the linear relationship between where the filter is and the wavelength is one of the most important parts of our plan to create a numerical method for processing gathered images after they have been collected. To show this connection, we plot the sum of the pixel counts (intensities) in neighboring ROIs with the same sampling and transversal steps of 100 pixels (0.5 mm). This is done as a function of position within the filter. This shows the main benefit of linearly variable filter technology: the edge wavelength is moved along a straight line across the filter, as shown by the linear link.

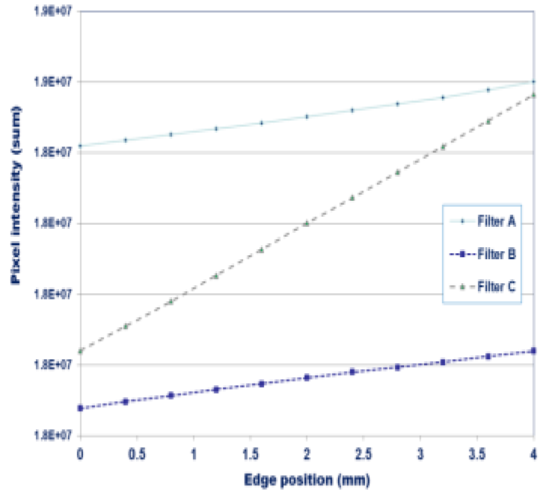


Figure 6. What is shown for filters A, B, and C is that the edge displacement is linear in the direction of change.

Determination of the slit functions

Get the spectral transmittance T (or R) and responsivity at each ROI, shown by the index "i" in Figure 3, in order to figure out how the slit function of our device works. Then, using the math model shown in the last part, we can find the slit function at each ROI, which is shown in equation 3 as (,i).

Figure 7 shows a range of predicted slit functions with different sampling intervals across a number of filters. Changing the sampling position of "i+1" in equation 3 from "i" to a different point gives a different bandwidth (FWHM) at position "i."

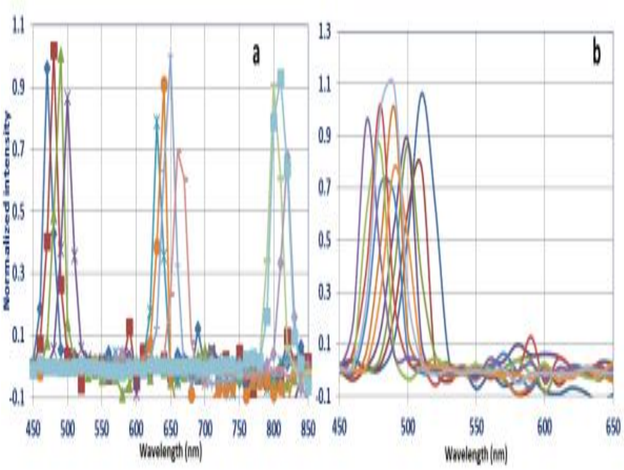


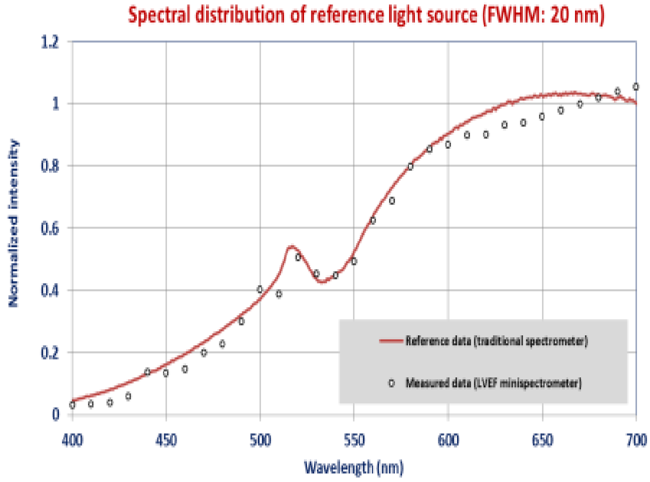
Figure 7. (a) The slit function was run across several filters at normal places (filters B, C, and D), using the same sample at each location. The slit in Filter B works at different sample rates.

Figure 8 shows the form and spectral width of the slit function at a single point across two different filters, where sampling is different for each case compared to the other. One important thing to notice is that the slit function has a great triangular shape. It is clear that the "FWHM" of the slit function can be changed by changing the sample rate. This clearly shows that our device can have a number of flexible and adjustable wavelength bands by using mathematical modeling. One of the best things about our mini-spectrometer is that it can do that. We can change sampling to get a border band with a better signal-to-noise ratio (SNR) by using mathematical modeling. In these situations, the numerical algorithm is an important part that affects how well any model works [10–13].

Figure 8. (A slit function at 470 nm with a full width at half maximum (FWHM) of 15 nm and filter B. A slit function at 810 nm with a full width at half maximum (FWHM) of 30 nm and filter D.

Test

We compared measurements from a reference spectrometer that was used in the same way as the target spectrum reconstruction with measurements from a continuous light source in order to come up with and test a de-convolution method. You can think of this part as the first step in the validation process. Using our numerical algorithm (software), we were able to get some preliminary data of the reference source spectrum. The first set of tests were done with our trial instrument, and then the results were compared to those from a regular spectrometer (Instrument Systems, model: CAS-140-CT), as shown in figure 9.



Our very small, slit-less mini-spectrometer was used to measure the spectrum of a reference light source from 400 nm to 700 nm, which is different from what regular spectrometers could do.

4.CONCLUSIONS

A tiny, slitless sample of a mini-spectrometer is being shown. An LVEF and a CCD grid make up the parts. The disclosed LVEF's function is shown by using monochromatic light to describe the LVEFs. The spectrum transmittance and slit functions were worked out so that our idea could be put into action. The new spectrometer shows potential for use in modern situations.

By putting the LVEF right on top of a detector array, the problems caused by light diverging are greatly lessened. Thin film deposition on big sensor surfaces might be a good idea for future research. Radiometric calibration will also be used in later studies. This will create a calibration matrix where absolute irradiance values are given to each ROI. This will allow the real spectrum of the test samples to be found.

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