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A NEW TECHNOLOGICAL APPROACH FOR DEVELOPING A PORTABLE PHOTOSPECTROMETER FOR MONITORING THE ENVIRONMENTAL CONDITIONS

The environmental condition monitoring and climate change is becoming more and more important in today's fast growing technological and industrial world. The sensing devices which are providing proper analysis of multiple environmental parameters such as water, soil, air, and intensity of radiation using the spectroscopy are not easily accessible because of the device’s size, weight and cost. The studied and developed portable photospectrometer is aimed at solving these issues with its functionality, single photodetector technology, dynamic range of spectral measurements (200 … 1100 *nm*), high resolution of sensing (~5 *nm*), small footprint, portability, and low cost properties which would be accessible for anyone as a multipurpose environmental condition monitoring and analysis tool.

Keywords: nano-biosystems, portable photospectrometer, photodiode, spectrometer, environmental monitoring.

Introduction. The number of sensors deployed around the world is growing at a rapid speed. Over the past decade, the number of sensors installed has significantly growth and has predicted a significant increment of the growth rate in the future. These sensors continuously generate enormous amounts of data. However, in order to add a value to the raw sensor data we need to understand it.

For monitoring the environmental conditions, there is an urgent need for the development of portable optical sensors for measuring small spectral composition changes, for the selective (with accuracy close to 1nm) registration of the spectral intensity of radiation (based on their natural behavior and their response to specific excitation). The off-the-shelf spectrometer devices that are available for the spectral analysis of 200…1100 *nm* are highly expensive and are not feasible for the environment monitoring porpoises, as of its fixed fixtures and calibrations issues.

A reliable portable device has been developed which accommodates an optical sensor insight for studying the nano-biosystems and ecological conditions of the environment. The device could work independently as portable photospectrometer and be able to transmit the analyzed data to the centralized server infrastructure for an advanced analysis and distributed data consolidation. This new portable photospectrometer is designed to cover the specter of 200…1100 *nm* and be the low cost to be accessible for the distributed and personal use of environment monitoring activities.

The signal processing, data mining, modelling and centralization of distributed results in relation to sensor data play a critical role in this challenge.

The current state of computational platforms and communication technologies used for the portable devices in the market

CPU based (Central Processing Unit) computation is a commonly used technology in the market for the computational power in both PC and mobile platforms. But the high frequency CPU running devices have a solid amount of energy consumption which is a significant problem for devices, having a battery.

FPGA technology (FPGA chip) adoption across all industries is driven by the fact that FPGAs combine the best parts of application-specific integrated circuits (ASICs) and processor-based systems. FPGAs provide hardware-timed speed and reliability, but they do not require high volumes to justify the large upfront expense of a custom ASIC design [1].

Reprogrammable silicon also has the same flexibility of software running on a processor-based system, but it is not limited by the number of processing cores available. Unlike processors, FPGAs are truly parallel in nature, so different processing operations do not have to compete for the same resources. Each independent processing task is assigned to a dedicated section of the chip, and can function autonomously without any influence from other logic blocks. As a result, the performance of one part of the application is not affected when you add more processing [2,3] (Fig. 1).

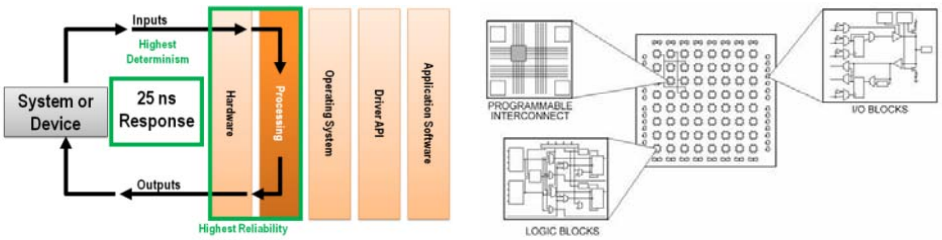

Fig. 1. One of the benefits of FPGAs over processor-based systems is that the application logic is implemented in hardware circuits rather than executing on top of an OS, drivers, and application software

The current state of communication technologies in the market for the data transferring functionality between two computers using different ways of physical communication. Here are the most commonly used data transfer methods between the client and the server architectures.

Wired technologies are, roughly, from slowest to fastest transmission speed. Computer network cabling (wired Ethernet as defined by IEEE 802.3) consists of 4 pairs of copper cabling that can be utilized for both voice and data transmission. The transmission speed ranges from 2 million bits per second to 10 billion bits per second. Each form comes in several category ratings, designed for use in various scenarios.

Wireless technologies are the fastest growing in general communications where the radio and spread spectrum technologies – Wireless local area networks use a high-frequency radio technology similar to digital cellular and a low-frequency radio technology. Wireless LANs use spread spectrum technology to enable communication between multiple devices in a limited area. IEEE 802.11 defines a common flavor of open-standards wireless radio-wave technology known as Wi-Fi. And the cellular technologies widely known as 3G/LTE are commonly used to transfer data between the mobile devices and centralized locations [4, 5].

The problem. The goal is to select the technology and the platform to be able to develop a portable device which will perform the measurements and analysis with its connected photodetector sensor (a new type of photospectrometric photodetector for the UV and visible spectrum which has been developed by our team). The developed device should combine the signal processing, data analysis (with spectral analysis algorithm) and the data transmission (to the remote located server computer for distributed data consolidation and centralized analysis and classification coming from the device(s)) functionalities. Meanwhile, the technology solution should have compact dimensions and low power consumption. On the other hand, the communication technology and the computational platform-based solution should be low cost, to allow to spread the solution in high volumes.

The research objective. The research objective is to find a technology combination for the small footprint computational platform with the data communication alternatives to be able to measure the signals from the photodetector (for efficient high-accuracy registration of narrow spectral bands or specific wavelengths a specially designed sensor has been used (the high-tech semiconductor material – silicon)), to carry out the signal processing and analysis algorithm processing.

The portable device should include:

- An integrated photodetector for investigating the bio-probe;
- A small-sized source of integral electromagnetic radiation with the required intensity and spectral range.
- The ability of signal processing,
- The real-time algorithm execution, spectral analysis and real-time spectral view of the results
- The proper computational power to perform the networking capability
- The data transmission functionality to the centralized data enrollment server

Meanwhile, the device should be able to carry out the data transmission to the central server for the distributed analysis where the advanced data processing algorithms and the result classification should be performed.

During the research process, multiple technologies have been tested for the data acquisition from the sensors and signal processing on both PC-based platforms and on mobile-based processor architectures.

As the primary goal was to have a small size, low power consumption, ease of usage and ability to produce the device in high volumes, a decision has been made to focus the attention on using the platform where both the Central Processing Unit (CPU) and the FPGA technologies could be combined. This approach allows to distribute our algorithm into two parts, the data acquisition and signal processing pieces accommodate on the FPGA and the mathematical calculations and visualization host on real-time CPU where the final results would be displayed on the screen and preform the real-time spectral view. As for the communication, the wired and wireless technologies are used (USB (Ethernet) connection to PC and wireless cellular 3G/4G for the remote communication to server infrastructures) [6].

The research process. During the research, the single-board RIO (sbRIO) platform from National Instruments has been used, as NI Single-Board RIO product and LabVIEW embedded software to solve this embedded dilemma with products that combine a real-time processor, a reconfigurable field-programmable gate array (FPGA), and I/O all on one printed circuit board (PCB). The entire board is programmable with NI LabVIEW embedded programming tools including the LabVIEW FPGA and LabVIEW Real-Time modules with built-in middleware drivers, making prototyping and deployment more dynamic for ongoing changes during the prototyping and development process (Fig. 2).

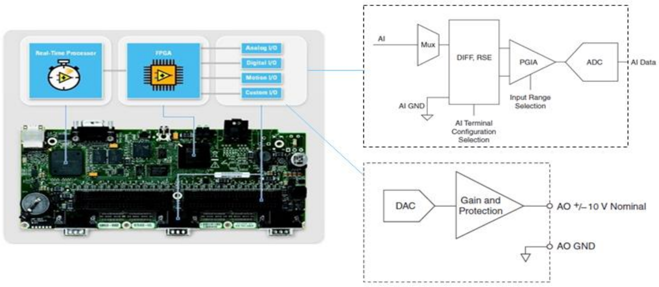

Fig. 2. The sbRIO platform architectural diagram

The photodetector is connected to the sbRIO board through its Analog input and output channels. We have used the Analog output channel as a power source for the sensor (power sourcing the sensor with increasingly changing the voltage from 0 to 1.5 *V*). The incremented step of the sourcing is programmable changing parameter from the software and could be set from 0.001 *V* to 1 *V*. The photovoltaic current measurement was done through the Analog input channels (the AI channels are connected to the sensor as differential, to measure the difference of potentials in between the two channels). One Analog output and four Analog input channels are used to power-source and measure the signals from the photodetector (Fig. 3) [7-9].

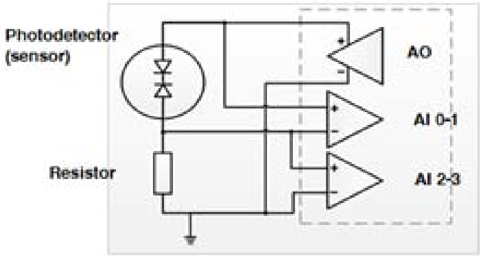

Fig. 3. The photodetector (sensor) electrical connection schematics to the analog channels.

Table

The analog channels have the following technical characteristics

Analog Input characteristics		***Analog output characteristics***	
Number of channels	16 single-ended	DAC resolution	16 *bits*
		Max update rate1	336 *kS/s*
ADC Resolution	12 *bits*	Range	±10 *V*
Maximum aggregate sampling rate	500 *kS/s*	Overrange operating voltage	
		Minimum	10.3 *V*
Input range	0-5 *V* nominal	Typical	10.6 *V*
		Max	10.9 *V*
Input impedance		Output impedance	0.4 *Ω* typical
Powered on, idle	250 *MΩ*	Current drive	±3 *mA/channel max.*
Acquiring 500 *kS/s*	325 *kΩ*	Protection	Short-circuit to ground
Powered off/overload	1 *kΩ*	Power-on state2	0 *V*

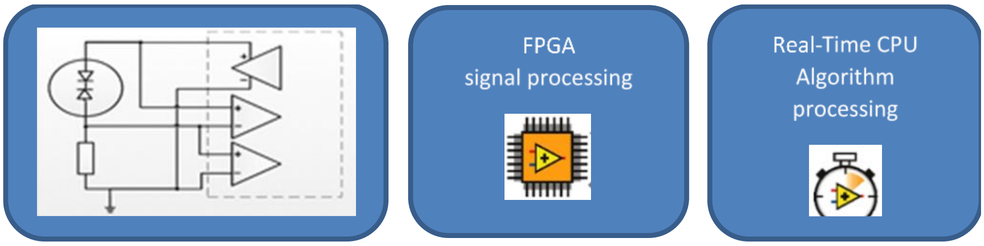

Fig. 4. The sensor connected to the computational platform for the data processing in both onboard and for the advanced distributed data analysis, data transfer to the remote server.

The device should communicate the centralized server through the wireless or 3G/LTE networks, to send the spectral analysis from the device to the server with synchronized time stamp on every set of data points (Fig. 4, Table).

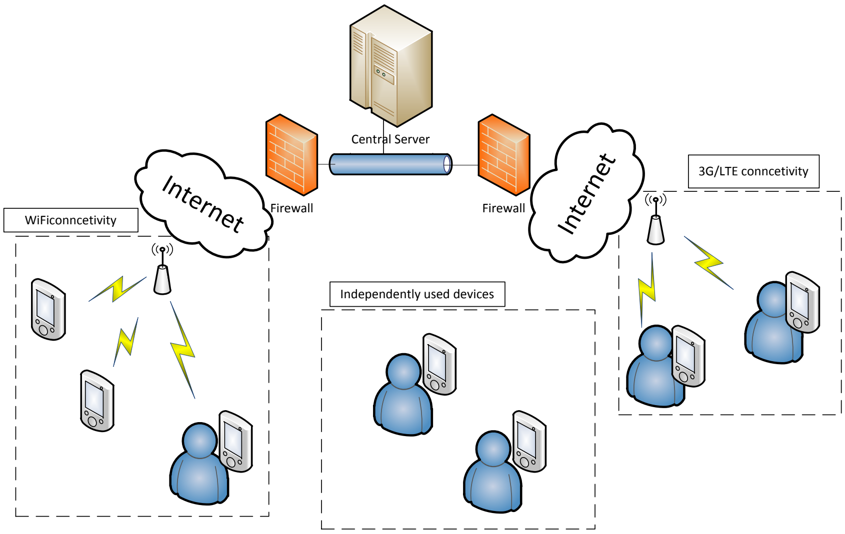

Fig. 5. The device general use as standalone and network connected

The centralized server is running the software which is managing the connections of the connected devices and getting data from them. The collected distributed data is stored into the database and processed by the software to analyze the environmental conditions of the particular geographic place (Fig. 5) [10, 11].

The algorithm. For determination of the spectral composition of the integral flux of electromagnetic radiation and the definition of its change, the UV radiation of the Sun has been studied. The photocurrent corresponding to the biggest value of x_m was conditioned by the most deeply penetrated wave. Under these conditions, the process of the selection of separate waves and their intensities from the integral flux of radiation was the following. Assume the informative signal to be the photocurrent.

By the external voltage supply of the photodiode, we can obtain the biggest values of $x_m - x_{m1}$ and x_{m2} with the difference of 1 *nm*, and the corresponding photocurrents I_1 and I_2. From Lambert's law of the radiation absorption in the homogeneous environment, we will have the coefficient of the wave absorption [12]:

$$\alpha_i = \frac{1}{\Delta x_m} \ln \frac{I_2}{I_1} \tag{1}$$

where $\Delta x_m = x_{m2} - x_{m1}$.

Then, with the help of $\alpha = f(\lambda_i)$ and with the corresponding program we can determine the length of the wave for the initial material of the photodetector (for silicon) (Fig. 6) [13].

With the help of the expression (1) for the summed current,

$$\sum_{i,j} I_{Ph.i,j} = \sum_{i,j} I_{dr.i,j} + \sum_{i,j} I_{diff.i,j} = Sq\sum_{i}\sum_{j} F_o(\lambda_i)\left(e^{-\alpha_i x_{mj}} - \frac{e^{-\alpha_i d}}{1+\alpha_i w}\right) \tag{2}$$

the intensities of separate waves of the absorption radiation,

$$F_o(\lambda_i) = \frac{I_{Ph.i,j}}{Sq\left(e^{-\alpha_i x_{mj}} - \frac{e^{-\alpha_i d}}{1+\alpha_i w}\right)}. \tag{3}$$

Fig. 6. Optical absorption spectrum in pure silicon

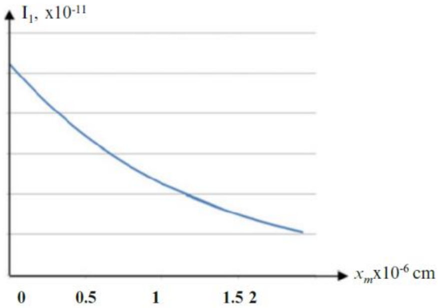

Fig. 7. Dependence of the photocurrent created by a separate wave on x_m

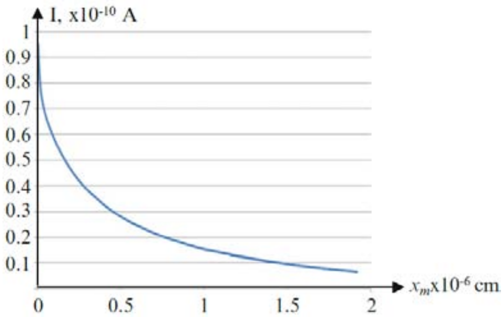

Fig. 8. Dependence of the summed photocurrent on x_m

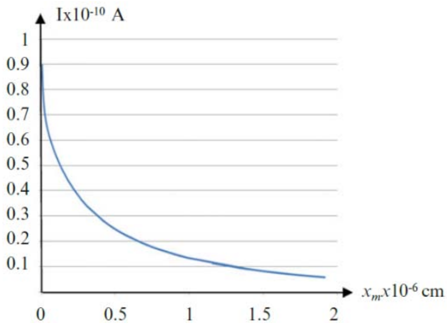

Fig. 9. Dependence of the summed photocurrent on x_m, when the determined wave is absent

Here, W is the width of the x > d section of the structure, q is the electron charge, and S is the photosensitive surface. Thus, with the help of (1) and (3), the absorption coefficient of the most deeply penetrated wave, the wavelength and the intensity of the wave are determined.

Then, with the help of the expression

$$I_{Ph.j} = SqF_o(\lambda)\left(e^{-\alpha x_{mj}} - \frac{e^{-\alpha d}}{1+\alpha w}\right) \quad (4)$$

by forming the dependence $I_1 = f(X_{m1})$ as shown in (Fig. 7) and subtract it from the dependence obtained by (2) (Fig. 8).

As a result, there is a new dependence from the x_m of the summed photocurrent, without the dependence (Fig. 9). By using the developed software, this method helps us to successively determine the lengths and the intensities of all the waves in the radiation, and to obtain the dependences of the photocurrent conditioned by those waves on x_m . Then, the dependence for the spectrum is obtained [14, 15].

The results. The developed device prototype has an isolated enclose covered with aluminum foil (Fig. 12). To avoid the environmental noises and to power the device, a Li-po battery is used not to deal with 50 *Hz* noise from the electric power grid (Fig. 10, 11).

Fig. 10. The measured photo current in a real-time mode.

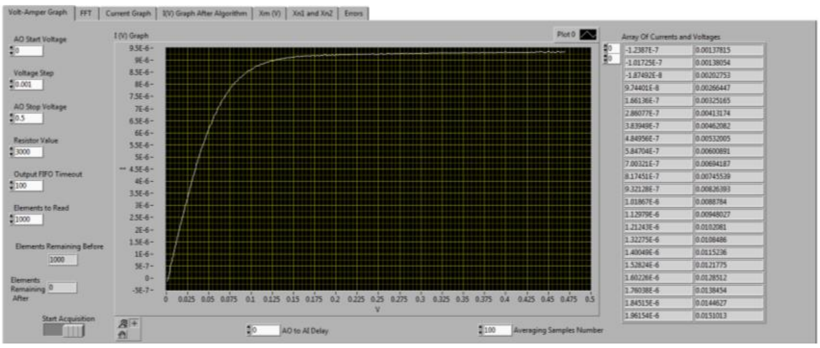

Fig. 11. The real-time signals processed (filtered and averaged) waveform of the measure photo current

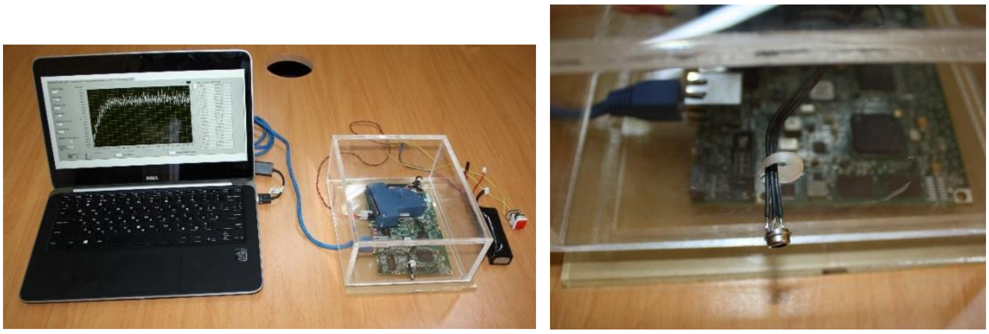

Fig. 12. The device prototype connected to the notebook computer

Conclusion. The investigated and developed portable photospectrometer is aimed at solving the issues connected to the environmental condition parameters' analysis and measurement of data as a standalone device, or the distributed use of consolidation in centralized server infrastructures for the advanced analysis and environmental condition change dynamics studies. The photospectrometer device with its functionality, single photodetector technology, dynamic range of spectral measurements (1 - 1200 *nm*), high resolution of sensing (~5 *nm*), small footprint, portability, and low cost properties would be accessible for anyone as a multipurpose environmental condition monitoring and analysis tool.

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Ս. Հ. ԾԱՏՈՒՐՅԱՆ

ՇՐՋԱԿԱ ՄԻՋԱՎԱՅՐԻ ՎԻՃԱԿԻ ՄՇՏԱԴԻՏԱՐԿՄԱՆ ՀԱՄԱՐ ՆԱԽԱՏԵՍՎԱԾ ԴՅՈՒՐԱԿԻՐ ՖՈՏՈՍՊԵԿՏՐՈՍԿՈՊԻ ՄՇԱԿՄԱՆ ՆՈՐ ՏԵԽՆՈԼՈԳԻԱԿԱՆ ՄՈՏԵՑՈՒՄ

Շրջակա միջավայրի և կլիմայական փոփոխությունների մշտադիտարկումը մեր օրերում զարգացող տեխնոլոգիական և արդյունաբերական աշխարհում դառնում է ավելի ու ավելի կարևոր գործոն: Առկա սպեկտրոսկոպիկ տվիչները, որոնք հնարավորություն են ընձեռում կատարելու բազմակի պարամետրերի ճշգրիտ չափումներ (աղտոտվածությունը ջրում, հողում, օդում և ճառագայթումը), ոչ միշտ են հարմար դաշտային օգտագործման համար իրենց մեծ չափերի, քաշի և թանկարժեքության պատճառներով: Մեր հետազոտության արդյունքում մշակվել է դյուրակիր ֆոտոսպեկտրոմետր, որը թույլ է տալիս հաղթահարել վերը նշված սահմանափակումները: Առաջարկված սարքի հիմքում ընկած է ֆոտոընդունիչ, այն ունի լայն դինամիկ միջակայք և թույլ է տալիս կատարել սպեկտրալ չափումներ 200 – 1100 *նմ* տիրույթում, ունի բարձր ճշտություն (˜5 *նմ*), փոքր չափսեր, ցածր գին և շարժական կիրառություն: Այս հատկությունների շնորհիվ սարքը կարող է օգտագործվել որպես ընդհանուր նշանակության անալիտիկ գործիք և հասանելի բոլորին, ովքեր ցանկություն ունեն կատարելու շրջակա միջավայրի պարամետրական չափումներ դաշտային պայմաններում:

Առանցքային բառեր. նանո-բիո համակարգեր, շարժական ֆոտոսպեկտրոսկոպ, ֆոտոդիոդ, սպեկտրոմետր, բնապահպանական մոնիթորինգ:

С.У. ЦАТУРЯН

НОВЫЙ ТЕХНОЛОГИЧЕСКИЙ ПОДХОД К РАЗРАБОТКЕ ПОРТАТИВНОГО СПЕКТРОФОТОМЕТРА ДЛЯ МОНИТОРИНГА ОКРУЖАЮЩЕЙ СРЕДЫ

В условиях быстрого роста технологической и промышленной базы в мире постоянно растет роль мониторинга окружающей среды и климатических изменений. Классические спектроскопические датчики, позволяющие производить анализ нескольких параметров состояния окружающей среды (загрязнение воды, почвы, воздуха и радиации), не всегда могут быть использованы из-за большого размера и веса, а также высокой стоимости подобных устройств. В результате исследований был разработан портативный спектрофотометр, позволяющий преодолеть эти ограничения. Предлагаемое устройство основано на фотоприемнике, обладающем широким динамическим диапазоном спектральных измерений (200 - 1100 *нм*), высоким разрешением (~5 *нм*), небольшими размерами, обеспечивающими возможность портативного применения, и невысокой стоимостью. Устройство может быть использовано в качестве аналитического инструмента общего назначения и будет доступно всем кто желает заняться многосторонним мониторингом состояния окружающей среды.

Ключевые слова: нано-биосистемы, портативный спектрофотометр, фотодиод, спектрометр, фотоспектрометр, мониторинг окружающей среды.